

EEVC/CEVE

European Enhanced Vehicle-safety Committee

EEVC Working Group 17 Report

**Improved test methods to evaluate pedestrian protection
afforded by passenger cars**

December 1998

Summary

The main task of EEVC WG17 Pedestrian Safety was to review the EEVC WG10 pedestrian protection test methods from 1994 and to propose possible adjustments taking into account new and existing data in the field of accident statistics, biomechanics and test results. The mandate of 12 months to complete this task has been extended by 3 months. Since the final report was required by December 1998, several decisions had to be taken by majority votes. This means that for certain test methods or aspects of test methods full agreement was not achieved. The following chapters in this EEVC WG17 report describe the background of the decisions taken and the various minority statements made.

Recent accident statistics have been analysed, showing among other findings a decrease in the proportion of injuries caused by the bonnet leading edge of modern streamlined passenger cars. Moreover, it is found that the windscreen and A-pillars of these cars are important injury areas, not covered by the EEVC test methods. Future research in this field is recommended.

Biomechanical tests were analysed and additional accident reconstructions have been performed. Based on this work, injury risk functions have been developed, especially for leg and pelvis injuries. This has resulted in an increase of the acceptance levels for the upper legform to bonnet leading edge test. This was required because an imbalance between recent accident statistics and the performance of modern cars in pedestrian tests (e.g. Euro-NCAP) was observed. Further evaluation of these tests showed that specific areas of some car models already meet the EEVC WG10 requirements, however no car fulfilled all requirements.

Mathematical model simulations indicated that the test conditions for the upper legform to bonnet leading edge test are too severe for passenger cars with a low, streamlined front. The required test energy has been decreased, up to a factor of 2, for these vehicles. This has led to a significant increase in the proportion of cars for which no bonnet leading edge test is proposed.

Since 1994 the sub-system impactors have been further evaluated and improved. EEVC WG17 has included new impactor specifications in the test methods. Final evaluation of some impactor improvements is still going on. Final versions will be available by mid 1999.

Based on this review the following major improvements have been included in the EEVC test methods:

Legform to bumper test

- Improvement of the legform impactor by means of a damper to avoid vibrations (will be finalised shortly).
- Improvement of the certification procedure of the impactor, to better reflect the actual use in a bumper test.
- Extension of the test methods with an upper legform to bumper test for vehicles with a high bumper, since the legform test seems less feasible for these vehicles.
- Reduction of the impact speed tolerance to decrease the variation in impact conditions.

Upper legform to bonnet leading edge test

- Reduction of the impact energy for vehicles with a low bonnet leading edge in order to compensate for the rotational and sliding motion of the pedestrian's upper leg which can

not be simulated by the guided impactor. According to the opinion of the French EEVC representative, the new required impact energy is still too high.

- Recommendation to limit the maximum required impact energy based on a maximum feasible deformation depth required to absorb the impact energy (this is only relevant for vehicles with a high bonnet leading edge and small bumper lead).
- Reduction of the impact speed tolerance to decrease the variation in impact conditions.
- Increase of the acceptance levels based on accident reconstructions, which will result in a better balance between test requirements and injury risk.

Headform to bonnet top test

- Change of impactor material to improve durability and avoid vibrations.
- Improvement of the certification procedure of the impactor, to better reflect the actual use in a bonnet test.
- New definition of child head impact zone on the bonnet to avoid overlap with the upper legform test (this is only relevant for vehicles with a high bonnet leading edge).
- New definition of bonnet top rear boundary to avoid windscreen impacts.
- Reduction of the impact speed tolerance to decrease the variation in impact conditions.

Although some impactors are called ‘prototypes’, they are an extension of previous versions which have been used in large test programmes. Proposals for further improvement resulted from these tests and the impactors are now in their final stage of development. This can be said also for the test methods, they have existed for many years and were used in a lot of test programmes. Current changes include improvements of definitions, interpretations and test repeatability. There is no *need* for further validation in terms of an evaluation of the test methods using recent cars, since the test methods were designed to work for cars generally. Assessing the benefit of such a pedestrian test method by evaluation or validation of modified cars was not in the scope of WG17. The German EEVC representative stated that with respect to discussions concerning a pedestrian protection Directive, new research results with respect to validation in the form of assessing modified vehicles, should be taken into account.

Appendix 2 of this report includes the new EEVC test methods with respect to the protection of pedestrians and other vulnerable road users. If the test methods can not be introduced completely in an European Directive, i.e. if it is decided that it would be desirable to introduce the procedure progressively, there are at least three possibilities: firstly only a proportion of the test areas could be required to meet all test requirements initially, with the proportion gradually increasing to 100 per cent over a fixed period (which is the method already suggested by EEVC WG10 in 1994), secondly the acceptance limits could be introduced at a higher level initially, gradually reducing to the limits proposed in this report or thirdly, the tests could be introduced progressively. If the latter option is selected, the following priority order for the test methods is proposed by EEVC WG17:

1. Headform to bonnet top tests (higher priority for child headform test);
2. Legform to bumper test (up to 500 mm bumper height, above that height an optional, alternative upper legform to bumper test);
3. Upper legform to bonnet leading edge test.

It should be noted that these test methods are linked to each other with respect to several definitions, test areas, tools and requirements.

Finally EEVC WG17 have also made some remarks with respect to the application and administrative provisions of a future Directive in this field.

Contents

Summary	2
Contents	4
1 Introduction	6
2 Accident statistics	7
2.1 <i>Introduction</i>	8
2.2 <i>Lower leg and knee injuries</i>	8
2.3 <i>Upper leg and pelvis injuries</i>	9
2.4 <i>Head injuries</i>	11
2.5 <i>Conclusions</i>	12
3 Biomechanics and accident reconstructions	14
3.1 <i>Introduction</i>	14
3.2 <i>Lower leg and knee</i>	14
3.3 <i>Upper leg and pelvis</i>	17
3.4 <i>Head</i>	19
3.5 <i>Conclusions</i>	19
4 Test results and simulations	22
4.1 <i>Introduction</i>	22
4.2 <i>Performance of current vehicles</i>	22
4.3 <i>Computer simulations with respect to BLE impact</i>	23
4.4 <i>Conclusions</i>	26
5 Impactors	28
5.1 <i>Introduction</i>	28
5.2 <i>Legform impactor</i>	28
5.3 <i>Upper legform impactor</i>	29
5.4 <i>Headform impactors</i>	29
5.5 <i>Conclusions</i>	30

6 Input from other organisations	32
6.1 Introduction	32
6.2 MIRA cost-benefit analysis	32
6.3 JAMA/JARI proposals	32
6.4 ACEA evaluation	32
6.5 Others	33
6.6 Conclusions	33
7 Improved test methods	34
7.1 Introduction	34
7.2 Legform to bumper test	34
7.2.1 Test method	34
7.2.2 Impactor	35
7.2.3 Requirements	35
7.3 Upper legform to bonnet leading edge test	35
7.3.1 Test method	35
7.3.2 Impactor	36
7.3.3 Requirements	37
7.4 Headform to bonnet top tests	37
7.4.1 Test method	37
7.4.2 Impactor	40
7.4.3 Requirements	40
8 Recommendations	42
8.1 Introduction	42
8.2 Directive	42
8.3 Further Research	44
9 Conclusions	46
References	48
Appendix 1: Members of EEVC WG17	56
Appendix 2: EEVC WG17 test methods / proposed technical requirements for a Directive	57

1 Introduction

In the European Union more than 7000 pedestrians and 2000 pedal cyclists are killed every year in a road accident, while several hundred thousands are injured. However, differences between the individual member countries are remarkable. Annual pedestrian fatalities per million inhabitants rank from 10 in the Netherlands to 47 in Greece. Pedestrian fatalities per 100 road accident fatalities rank from 12 in France to 32 in Great Britain [1]. A large proportion of pedestrians and cyclists are impacted by the front of a passenger car. This was recognised by the European Enhanced Vehicle-safety Committee (the former European Experimental Vehicles Committee) and several studies in this field were performed by Working Groups of EEVC [2, 3, 4]. Based on this research various recommendations for the front structure design of passenger cars were developed. Moreover, test methods and regulations have been proposed to assess pedestrian protection. In the Spring of 1987 one of these proposals was discussed by the EEC ad-hoc working group 'ERGA Safety' [5]. It was concluded that the basis of the proposal was promising, however, additional research was needed to fill up some gaps. The EEVC was asked to co-ordinate this research and at the end of 1987 EEVC Working Group 10 'Pedestrian Protection' was set-up.

The mandate of this group was to determine test methods and acceptance levels for assessing the protection afforded to pedestrians by the fronts of cars in an accident. The test methods should be based on sub-system tests, essentially to the bumper, bonnet leading edge and bonnet top surface. The bumper test should include the air dam; the bonnet leading edge test should include the headlight surround and the leading edge of the wings; the test to the bonnet top should include the scuttle, the lower edge of the windscreen frame and the top of the wings. Test methods should be considered that evaluate the performance of each part of the vehicle structure with respect to both child and adult pedestrians, at car to pedestrian impact speeds of 40 km/h. The different impact characteristics associated with changes in the general shape of the car front should be allowed for by variations in the test conditions (e.g. impact mass and velocity, direction of impact).

EEVC WG10 started its activities in January 1988. Both governments (mostly represented by research institutes) and automobile industry were represented in the working group. A programme was set-up intended to develop the required test methods as described by the mandate. The studies necessary to develop test methods have been summarised in a first report of EEVC WG10, presented to the 12th ESV Conference in 1989 [6]. These development studies included full scale dummy tests, cadaver tests, accident reconstructions, analysis of accident data and computer simulations. Furthermore the developed test proposals had to be tested against representative cars of current designs to determine the feasibility of the proposals. The compatibility with existing regulations, other safety features and basic operational requirements for cars was assessed. These studies were performed in 1989/1990 by a European consortium acting under contract to the European Commission and under the auspices of EEVC. The consortium consisted of BAST, INRETS, LAB/APR, TNO and TRL. The studies were completed in June 1991 and were summarised individually in technical reports [7-12]. The summary report [13] included an Annex called "Frontal surfaces in the event of impact with a vulnerable road user - proposal for test methods". This work was also summarised in a second EEVC WG10 report, presented to the 13th ESV Conference in 1991 [14].

The third and final report of EEVC WG10 was written in 1994 [15] and focused especially on the changes and improvements with respect to the previous version of the proposed test methods, as described in [13] and [14]. The test methods were up-dated and included in the Annex "Frontal surfaces in the event of impact with a vulnerable road user -

proposal for test methods". Also general background information was given and choices explained. Working Group 10 has been dissolved in November 1994. A summary of the

1994 final report and an overview of the activities performed by the former members of WG10 since the end of 1994, has been presented in 1996 to the 15th ESV Conference [16]. Figure 1 summarises the EEVC WG10 pedestrian protection test methods.

[MIRA report page 1-3]

Figure 1. Pedestrian protection test methods proposed by EEVC WG10 [17].

In May 1997 the former members of EEVC WG10, on request of the EEVC Steering Committee, met again to discuss technical progress and new developments with respect to the EEVC pedestrian protection test methods. Based on these discussions the Steering Committee decided in June 1997 to set-up a new EEVC working group -WG 17 Pedestrian Safety- with two main tasks:

1. Review of the EEVC WG10 test methods (final report 1994) and propose possible adjustments taking into account new and existing data in the field of accident statistics, biomechanics and test results (to be completed within one year).
2. Prepare the EEVC contribution to the IHRA working group on pedestrian safety.

The activities of WG17 with respect to the first task only are summarised in this report. New data in the field of accident statistics, biomechanics and test results are described in Chapter 2, 3 and 4 respectively. Further improvements to the sub-system impactors are described in Chapter 5. Several international organisations have studied or evaluated the 1994 EEVC test methods and impactors. Their conclusions and proposals are summarised in Chapter 6. Based on this review and input several changes to the test methods are proposed in Chapter 7. Chapter 8 includes some recommendations with respect to the application of the new test methods in an EU Directive. Chapter 9 summarises the conclusions of this report. Appendix 1 includes the WG17 member list and Appendix 2 contains the new test methods.

2 Accident statistics

2.1 Introduction

In most EU countries the number of road traffic fatalities is decreasing over the last 20 years and the figures for pedestrians have dropped even more than for passenger car occupants. Car design technical evolutions concerning both active and passive safety, as well as accident avoidance countermeasures, including improvements in the field of infrastructure, driver and pedestrian behaviour, emergency medical services and enforcement of traffic regulations, have contributed to this trend.

Since a large proportion of pedestrians and cyclists are impacted by the front of a passenger car, WG17 has analysed the influence of car design changes in the last 20 years with respect to injury causation. In particular the bonnet leading edge of modern car designs is more 'smooth shaped' than earlier car designs which had a more 'rectangular' shaped front. Results of recent accident studies are summarised in this chapter.

2.2 Lower leg and knee injuries

The Accident Research Unit of the Medical University of Hannover (Germany) studied 762 cases in which pedestrians were impacted by the front of a passenger car¹ resulting in an injury [18, 19, 20]. The accidents occurred between 1985 and 1995.

The analysis showed that 75% of the pedestrians suffered an AIS 1+ leg injury. More than 50% of these injuries concerned the lower leg and approximately 1/3 concerned the knee. Approximately 3/4 of the lower leg injuries and 40% of the knee injuries were caused by the car bumper.

The accidents were divided in two groups: involved car model was first introduced on the market before 1990 and involved car model was first introduced on the market in 1990 or later. The impact speed distribution in these two groups showed only slight differences. Table 1 shows the incidence of AIS 1+ leg injuries for different car model years and car impact speeds, as well as AIS 2+ lower leg (without foot) and knee injuries.

Table 1. Percentage of pedestrians sustaining a leg injury in German accidents between 1985-1995 [19, 20].

Injury level	AIS 1+ leg injuries		AIS 2+ lower leg / knee injuries	
	< 1990 car model	≥ 1990 car model	< 1990 car model	≥ 1990 car model
≤ 40 km/h	75%	65%	25%	32%
> 40 km/h	86%	69%	52%	53%
all speeds	77%	66%	33%	38%

It can be seen that the proportion of AIS 1+ leg injuries is lower in the case of newer vehicles than for older vehicles, however still 2/3 of the victims sustained a leg

injury (note: all pedestrians in this database sustained at least one AIS 1+ injury). Further analysis of the German database showed, for newer vehicles, an increase in the proportion of pedestrians suffering an AIS 2+ lower leg or knee injury, especially for impact speeds below 40 km/h (note: only 17 AIS 2+ cases were included for post-1990 cars and speeds above 40 km/h) [20].

¹ Mini-buses and other vehicles without bonnet were excluded from this analysis!

TRL analysed pedestrian accidents in Great Britain. Two sources of data were used, separately and in combination: a database extracted from police reports on fatal accidents, and the Scottish Hospitals In-Patients Statistics (SHIPS) database which consists of hospital injury data linked to the national road accident database. About 300 police reports including a post-mortem report and several thousand cases from the SHIPS database were analysed [21, 22].

The SHIPS data was used to analyse injury trends over time (1980-1994). The effect of old versus new car models could not be analysed in this study. The results showed an increase by about a third (AIS 2+) and by about a half (AIS 3+) of pedestrians suffering lower leg and knee injuries, resulting in a proportion of 40% AIS 2+ and a proportion of 5% AIS3+ lower leg and knee injuries (see also figure 2 in § 2.3). (note: the SHIPS data do not contain information on the car impact speed).

Since 1995 a total of 1001 pedestrian accidents that occurred in the Rhône department in France have been studied [23]. Approximately 2/3 of the victims sustained a MAIS 1+ lower extremity injury (including pelvis). More than 30% of the elderly (i.e. 60+) sustained a MAIS 2+ lower extremity injury. In this age-group MAIS 2+ pelvis injuries ranked first (12%), closely followed by the foot/ankle, lower leg and knee. For children and adults (i.e. < 60) the highest proportion of MAIS 2+ injuries was found for the lower leg, 7% and 9% respectively, while the proportion of knee injuries found in these age-groups was 1% and 5% respectively.

In a French accident study [24] pedestrian accidents were analysed that occurred in 1994/1995, while the cars involved were designed after 1989 (so introduced to the market in 1990 or later). In 395 cases the pedestrian was impacted by the front of the car.

AIS 2+ tibia/fibula injuries and knee injuries were found in 42% and 18% respectively of the pedestrians older than 12 years. These figures were 8% and 2% respectively for children younger than 12 years.

The results of this study were compared with a previous study including 282 accidents that occurred between 1974 and 1983, thus involving 'old' car designs. It was found that the proportion of pedestrians sustaining an AIS 2+ knee injury did not change between both studies (i.e. 11%), while a significant reduction in tibia fractures was observed (i.e. from 39% to 30%). Moreover, it was found that with new car models the fracture was less frequently an open, severe fracture than with the older car models (9% versus 43%) [24].

2.3 Upper leg and pelvis injuries

The Hannover study described in the previous paragraph showed that 17.4% of the AIS 1+ injuries were caused by the bonnet leading edge (BLE) [19]. This total proportion varied only slightly for short versus tall pedestrians, however the injured body regions were different. For pedestrians taller than 120 cm the legs (50%) and pelvis (30%) were the body regions most frequently injured by the bonnet leading edge, while it were the arms (35%) and thorax (20%) for pedestrians shorter than 120 cm.

The accidents were divided in two groups: involved car model was first introduced on the market before 1990 and involved car model was first introduced on the market in 1990 or later. The impact speed distribution in these two groups showed only slight differences. Table 2 shows the incidence of the bonnet leading edge as cause of an AIS 2+ upper leg or pelvis injury for different car model years and car impact speeds.

Table 2. Percentage of pedestrians sustaining an upper leg or pelvis injury caused by the bonnet leading edge in German accidents between 1985-1995 [20].

Injury level	AIS 2+ upper leg / pelvis injuries caused by BLE	
	< 1990 car model	≥ 1990 car model
Impact speed		
≤ 40 km/h	8%	0%
> 40 km/h	17%	24%
all speeds	11%	7%

No AIS 2+ upper leg or pelvis injuries caused by the bonnet leading edge were found for post-1990 car models impacting a pedestrian at a speed below 40 km/h. From the 58 pedestrians impacted by a post-1990 car model, only three obtained a femur fracture and these fractures occurred all at impact speeds above 40 km/h. It can be seen from table 2 that the incidence of injuries through impact with the bonnet leading edge decreases at lower impact speeds (for all car models).

In the French study described in the previous paragraph [24], AIS 2+ pelvis and femur injuries were found in 15% and 2% respectively of the pedestrians aged 12 years and older. These figures were 13% and 8% respectively for children younger than 12 years. For children younger than 6 years, taking their anthropometry into account, these injuries are most probably caused by the bumper, rather than by the bonnet leading edge. For children younger than 12 years, pelvis injuries are ranked second in frequency priority, after head injuries. 6% of the children younger than 12 years suffered a thorax/abdomen AIS 2+ injury, which could have been caused by the bonnet leading edge, taking the sizes of cars and children into account.

The results of this study were compared with a previous study including 282 accidents that occurred between 1974 and 1983, thus involving 'old' car designs. It was found that the percentage of pedestrians between 12-49 years old sustaining a femur fracture decreased from 20% in the previous study to 0% in the current study (see table 3). For pedestrians older than 49 years and for children up to 12 years the reduction was also very significant (see also table 3). The trends for pelvis fractures were different: from 21% to 0% for adults, while children and elderly showed a non-significant increase in the proportion of victims suffering a pelvis fracture (see table 4). Since the car part involved was not studied, these fractures could be caused by other sources than the bonnet leading edge.

Table 3. Percentage of pedestrians sustaining a femur fracture in French accidents [24].

Age	< 1983 car model	≥ 1990 car model
< 12 years	38%	8%
12 - 49 years	20%	0%
> 49 years	19%	2%

Table 4. Percentage of pedestrians sustaining a pelvis fracture in French accidents [24].

Age	< 1983 car model	≥ 1990 car model
< 12 years	8%	12%
12 - 49 years	21%	0%
> 49 years	22%	25%

The risk for elderly people to sustain a pelvis (or hip) fracture is higher, due to osteoporosis (i.e. 'weak' bones), and even a fall on the ground can lead to a fracture.

The UK study described in the previous paragraph [21, 22] showed over the time period 1980-1994 a reduction by about a third in the proportion of pedestrians injured (AIS 2+ and AIS 3+) in the upper leg and pelvis region. The analysis showed that there continues to be a much higher proportion of AIS 3+ injuries to the upper leg and pelvis than to the lower leg and knee body region (see Figure 2). The effect of old versus new car models could not be analysed in this study. (note: the SHIPS data do not contain information on the car impact speed).

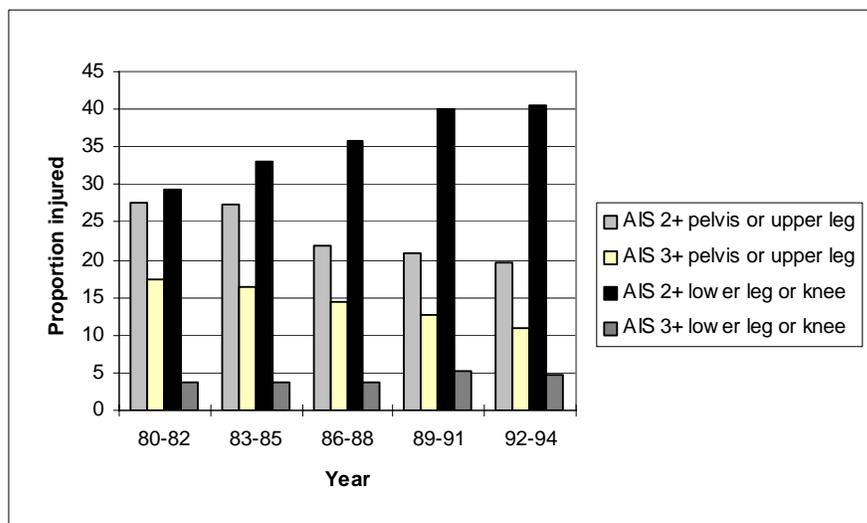


Figure 2. Proportion of pedestrians injured to the pelvis/upper leg and knee/lower leg in UK accidents [21].

2.4 Head injuries

The Hannover study described in § 2.2 [18, 19, 20] showed that in 83% of the cases the impact speed was 40 km/h or below, while in 66% of the cases that suffered an AIS 2+ head injury the impact speed was 40 km/h or below. AIS 1+ head injuries were found in 59% of the cases, with little differences for pre-1990 and post-1990 car models [19]. A slight reduction was found, for the newer car models, in the proportion of pedestrians suffering an AIS 2+ head injury: from 18% to 15% at impact speeds below 40 km/h [20]. At impact speeds above 40 km/h the proportion of AIS 2+ head injuries is still high: 55% for pre-1990 car models and 53% for post-1990 car models.

Table 5 shows that there seems to be a slight reduction in the proportion of AIS 1+ injuries caused by the bonnet. Almost 50% of the injuries caused by the bonnet are to the head, while 20% are thorax injuries [18].

Table 5. Percentage of pedestrians sustaining an AIS 1+ injury caused by the bonnet in German accidents between 1985-1995 [18].

Impact speed	< 1990 car model	≥ 1990 car model
≤ 40 km/h	24%	21%
> 40 km/h	39%	33%

all speeds	26%	21%
------------	-----	-----

The French study described in § 2.2 [24] showed that severe/fatal head injuries (AIS 3+) are very often caused by the scuttle area of the car, almost 30% of the cases. In 46% of the cases in which the pedestrian suffered an AIS 3+ head injury, the head contacted the bonnet, wings or scuttle. These areas are covered by the EEVC WG10 headform test method (note: In this French study the scuttle is defined as a small area at both sides of the lower windscreen frame. An impact through the windscreen on the inside scuttle area is not covered by the WG10 method). In 41% of the cases a car part was contacted that is not covered by the EEVC WG10 headform test method (e.g. A-pillars, windscreen) and in 13% of the AIS 3+ head injury cases the head contacted the ground.

AIS 2+ head injuries were found in 42% of the child (< 12 years) cases and in 54% of the adult (> 12 years) cases. 95% of the children suffering a fatal head injury and 80% of the children receiving a severe head injury had a head contact to a vehicle part covered by the EEVC headform test method². For adults these figures were 37% and 32% respectively, since the A-pillars and windscreen were contacted more frequently [24].

Comparison between the results of the new and previous study (see also § 2.2) showed that the proportion of pedestrian casualties sustaining an AIS 2+ head injury decreased significantly for children and adults, however for the elderly, the decrease was not significant [24].

2.5 Conclusions

A high proportion of the injured pedestrians sustain an injury to the lower leg (i.e. tibia/fibula) or knee. Some studies indicate that the frequency and severity of lower leg and knee injuries is increasing over time, while another study indicates that the frequency and severity is decreasing. WG17 concluded that lower leg and knee injuries are still frequently seen.

It seems that the proportion of pedestrians, impacted by the front of a car, suffering a femur injury has dropped substantially over time. This could be caused by the more streamlined design of modern cars, where the bonnet leading edge is no longer a 'sharp' corner. This is confirmed by studies showing that the bonnet leading edge of modern cars is causing less injuries to pedestrians than older designs (i.e. pre-1990 models). Femur fractures in relation to bonnet leading edge contact for car impact speeds below 40 km/h were not found in the German study. However, a percentage of the other body areas (e.g. pelvis, abdomen or even thorax area) was probably injured by the bonnet leading edge of

modern cars. WG10 already concluded that the upper legform to bonnet leading edge test also covers this kind of injury. Moreover, the test methods should cover all (future) car designs and not only the current 'streamlined' designs. This position was not shared by the French EEVC representative.

Head injuries, caused by an impact against the bonnet, wings, scuttle or windscreen frame, are still frequently seen. However a significant proportion of the adults have a head contact with a car part that is not covered by the EEVC test method (e.g. the A-pillar or windscreen), especially when they are impacted by a modern car (i.e. short, more steep bonnet). Future studies should focus especially on these car parts.

² An impact through the windscreen on the inside scuttle area is not covered by the WG10 method.

The French EEVC representative stated that recent accident data clearly indicate the following priorities for protection in the framework of the proposed test method:

1. Child head injury;
2. Lower leg and knee injury;
3. Adult head injury.

Moreover the French EEVC representative stated that upper leg injury assessment is not supported by accident data and that high BLE vehicles may be considered, but this was not indicated by these accident studies.

3 Biomechanics and accident reconstructions

3.1 Introduction

In the final EEVC WG10 report [15] acceptance levels, based on biomechanical studies and accident reconstructions, were proposed for all three test methods. However, many of them were placed within brackets and required confirmation:

Leg/knee

- Maximum lateral knee bending angle $\leq 15^\circ$;
- Maximum lateral knee shearing displacement ≤ 6 mm;
- Maximum lateral tibia acceleration $\leq [150$ g].

Upper leg

- Maximum instantaneous sum of femur forces $\leq [4$ kN];
- Maximum femur bending moment $\leq [220$ Nm].

Head

- HPC³ adult head ≤ 1000 ;
- HPC child head $\leq [1000]$.

Since 1994 some additional biomechanical studies and accident reconstructions with respect to pedestrian protection have been performed, that will be summarised in this chapter.

3.2 Lower leg and knee

In [25] quasi-static shearing and bending tests are described using 20 cadaver legs. By using a stethoscope it was possible to account for the first internal disturbances of the knee in the lateral shearing tests, which occurred after a lateral tibia displacement of about 12 mm in relation to the femur. However, no preload was applied to the knee joint, which probably influenced the results. First macroscopic lesions in the bending tests started at an average lateral bending angle of 18.9° . Comparison with results from two dynamic test series showed that the acceptable lateral bending angle is significantly lower under dynamic conditions (i.e. 11.4° in average).

A recent paper [26] concerning the shearing and bending effects in the knee joint at high speed (i.e. 40 km/h) lateral loading was studied by WG17. When the preloaded knee joint of cadavers was exposed to a bending deformation the two most common initial damage mechanisms occurred when the knee was bent laterally at an average angle of 15° for ligament avulsion failure or at an average angle of 16° for diaphysis/metaphysis failure. When the preloaded knee joint of the cadavers was exposed to a shearing deformation the two most common initial damage mechanisms occurred at an average lateral shearing displacement of 16 mm for epiphysis failure or an average 28 mm for diaphysis/metaphysis failure. The average peak shearing force acting at the knee joint level in these latter cases was 2.4 kN and 2.9 kN respectively, while the peak bending moment in these shearing tests was 400-500 Nm.

The fixation method of the cadaver's femur in combination with the severity of the impacts caused extreme damage to the bones and ligaments in several cases. The most

³ Head Protection Criterion based on HIC calculation.

common injury mechanisms in both the bending and the shearing test were all related to bone fractures, indicating the severity of these tests.

The authors reproduced these bending and shearing tests using the prototype TRL legform impactor (without damper, see § 5.2) in order to find a transfer function between cadaver output and impactor output [27]. Using a similar test set-up and similar analysis techniques (i.e. looking for initial damage values) they found a lateral bending angle of 15° in the legform bending test, which is identical to the average angle found in the cadaver tests. However, the final legform bending angle was larger, because the bending continued due to the high impact energy. The shearing test could be performed only at a lower speed (i.e. 20 km/h) to avoid reaching the shearing displacement endstop at 8 mm.

It is important to note that the 6 mm shear displacement defined as the acceptance level by WG10 was based on a 4 kN shear force, which is rather close to the (almost) 3 kN shear force measured in the cadaver tests [26]. WG17 believes that reproducing the actual displacement is less important than reproducing the actual force, since the displacement is rather small and will not significantly influence the kinematics of the leg. Therefore 6 mm shear displacement, which equals to a 4 kN shear force, and 15° bending angle proposed by WG10 were considered by WG17 to be appropriate acceptance levels for the EEVC legform to bumper test.

Based on the same cadaver tests an acceptance level has been proposed by JARI/JAMA, consisting of a combination of a maximum bending angle and a maximum shear displacement [28, 29]. WG17 is not in favour of this approach since these phenomena occur at a different point in time and therefore should not be combined.

The cadaver tests discussed above confirm the lateral bending stiffness of the legform knee ligaments of 300-330 Nm, as chosen by WG10. It was already mentioned in the final WG10 report that the 100-150 Nm knee bending moments obtained from low speed cadaver tests seemed to be unrealistic [15]. This statement is confirmed by WG17.

In [30] a series of cadaver tests with recent cars is described. The standard test speed was 32 km/h, but some cars were tested at 25 km/h or 39 km/h. In 5 of the 11 cases tibia fractures were found, while 8 cadavers sustained AIS2 and/or AIS3 knee injuries. The maximum tibia acceleration for the cadavers sustaining a tibia fracture was 170g-270g (average 222g), while the maximum tibia acceleration for the cadavers sustaining no tibia injury was 185g-243g (average 202 g). These data suggest an 'average' (i.e. 50% risk) tibia fracture protection criterion of 200 g to 220 g (see also figure 3).

An attempt has been made by JARI/JAMA to develop injury risk functions for tibia fractures based on lateral tibia accelerations [28]. However, WG17 believes that the cumulative Weibull distribution method, used by JARI/JAMA to analyse only the fracture case data, results more in a fracture distribution curve rather than in an injury risk curve. The Weibull distribution can be used to generate injury risk curves, but only if both fracture and non-fracture cases are included. Moreover, one of the fracture distribution curves is based on 4 cadaver tests only. The other is based on 20 cadaver leg tests performed by Bunketorp et al. [31]. Bunketorp used both rigid bumpers resulting in tibia accelerations all above 200g and compliant bumpers resulting in tibia accelerations all below 120g. The 10 rigid bumper tests resulted in 7 lower leg fractures and the 10 compliant bumper tests in 2 lower leg fractures. These fractures included intra-articular (i.e. knee joint) fractures of the tibia.

TRL evaluated the cumulative normal distribution method⁴ (similar to the Weibull method used by JARI) using only fracture cases from the Bunketorp data, and compared it to the logistic regression method (i.e. dose-response) which uses all the data, both fracture and non-fracture. The cumulative normal distribution method plots the cumulative curves from the mean and standard deviation of the fracture case accelerations. Cumulative distribution methods using only injury cases should be used with caution, since they produce a credible curve, regardless of whether there is any meaningful correlation between acceleration and

⁴ The Weibull parameter estimation software was not available within TRL.

fracture. The logistic regression method uses all the data and also estimates the correlation. For these data it gave a significance level⁵ of 4% from the correlation between acceleration and fracture, showing that a useful injury risk curve can then be generated. This method is preferred since it gives a true injury risk curve. For comparison, a significance level of 48% was found for the correlation between acceleration and fracture using the cumulative distribution method [32].

Figure 3 compares the results of both the TRL analyses. WG17 recommended an injury risk level of 20%, resulting in approximately 80g for the logistic (dose-response) risk and approximately 160g for the cumulative normal risk. The French representative in WG17 proposed a level of 200g, based on the cadaver test series [30] described above. WG17 concluded not to change the WG10 acceptance level of 150g for lateral tibia accelerations, assuming a good correlation between cadaver and impactor tests, as shown in the study presented above [27]. So a tibia acceleration of 150g indicates almost 40% risk for an AIS 2+ lower leg fracture according to the logistic regression method and almost 20% risk according to the cumulative normal method (see figure 3).

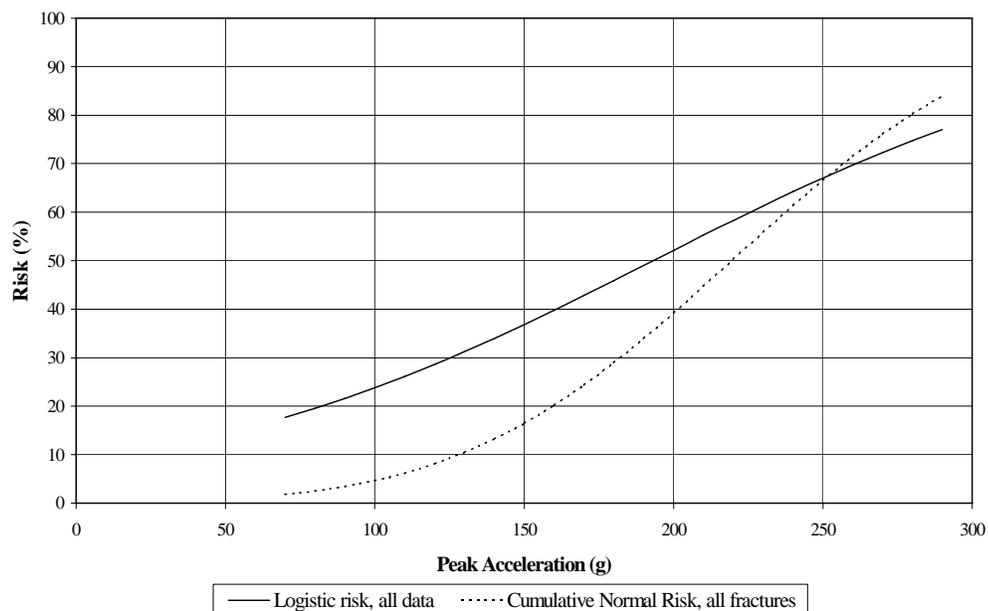


Figure 3. Comparison of AIS 2+ lower leg injury risk functions based on a logistic method and based on a cumulative normal method using 20 cadaver leg tests [32], obtained from [31].

⁵ Significance values of 5% or less are generally accepted as indicating a true hypothesis, i.e. the probability of the data occurring by random chance is 5/100 or less.

3.3 Upper leg and pelvis

WG17 considered new accident reconstructions using the upper legform impactor necessary for three reasons:

- The proposed WG10 acceptance levels still had to be confirmed;
- The impactor was modified after a hidden load path was found (see § 5.3);
- There seems to be an imbalance between the current test requirements on one hand and the injury risk in real accidents with modern cars on the other hand, since modern cars do not pass the current bonnet leading edge test requirements (see § 4.2), while few femur injuries occur in reality (see § 2.3).

In [33] static and dynamic lateral bending tests on the lower leg are described. This results in a dynamic to static coefficient of 1.69 for the tibia bending moment to failure. If this coefficient is applied to the static femur bending moment to failure of 310 Nm for male subjects (source: Messerer), this would result in a dynamic bending moment to failure of 524 Nm. The average length of male femurs is 455 mm [34], while the ‘working length’ of the EEVC upper legform impactor is only 310 mm. The corrected bending moment measured by the impactor would then be 357 Nm. The French representative in WG17 proposed an acceptance level of 360 Nm for the lateral upper legform bending moment.

JARI performed a series of 12 accident reconstructions using the upper legform impactor. Based on these tests injury risk functions for femur and pelvis AIS 2+ injuries based on lateral femur forces⁶ and bending moments have been developed [35]. The results seem to be influenced considerably by the age of the pedestrians. WG17 believes that the approach used results more in a fracture distribution curve rather than in an injury risk curve. Moreover, the zero risk values were chosen at a quite high level, i.e. at the WG10 acceptance levels.

In 1997 TRL repeated some previously performed accident reconstructions using the latest version of the upper legform impactor (see § 5.3) and conducted some additional reconstructions [36]. In 1998 a new series of accident reconstructions was performed by TRL, where the cases were selected from the Hannover database described in § 2.2 [37]. The results were combined with the above mentioned JARI reconstructions, resulting in a database of 39 cases. Based on this database, TRL used the logistic regression method and the cumulative normal distribution method to develop injury risks for maximum lateral force (see figure 4) and for maximum lateral bending moment (see figure 5) [38]. Three outliers were removed from the database. These were non-fracture cases with the highest forces (above 9.4 kN) and highest bending moments (above 662 Nm) of all 39 reconstructions. Obviously these were very strong people, not representative for the population at risk. Due to this correction the significance level of the logistic regression method improved considerably (from 12% to 1% for fracture risk against force and from 42% to 5% for fracture risk against bending moment).

WG17 recommended an injury risk level of 20%, resulting in 4.23 kN and 226 Nm for the logistic (dose-response) risk and 5.58 kN and 362 Nm for the cumulative normal risk. WG17 decided to increase the WG10 acceptance levels to the mean value of both methods. This increase in acceptance levels will contribute to a better balance between test results (§ 4.2) and real accident injuries (§ 2.3). The mean values from both methods at a 20% injury risk level are 4.9 kN and 294 Nm, which are rounded to 5.0 kN and 300 Nm respectively.

⁶ JARI used the inertia forces (mass x accel), which are according to JARI 20% higher than the measured impactor forces (see also § 5.3).

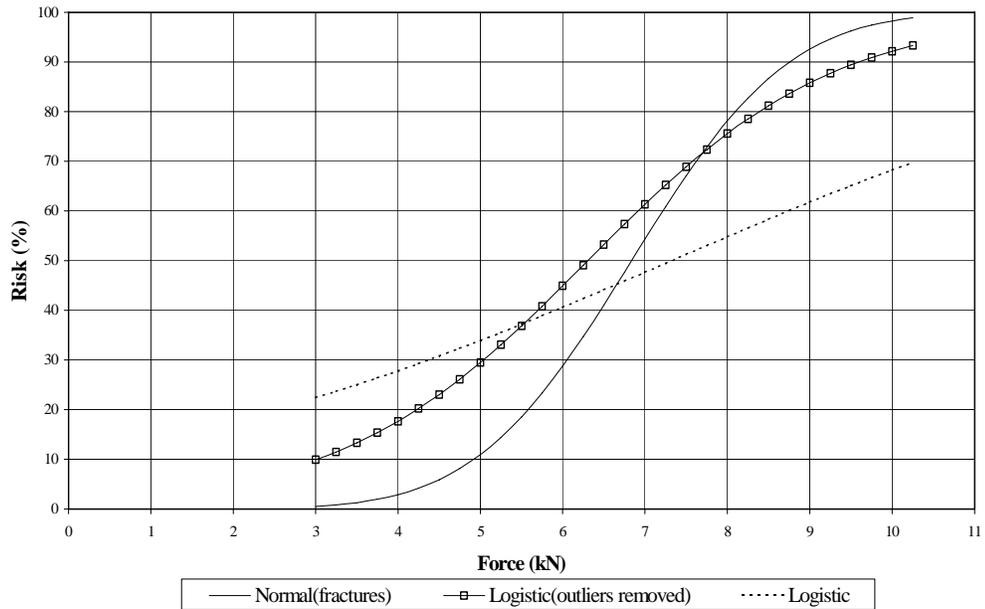


Figure 4. Comparison of AIS 2+ femur/pelvis injury risk functions based on logistic method and based on cumulative normal method using the maximum upper legform impactor force, obtained from 39 accident reconstructions [38].

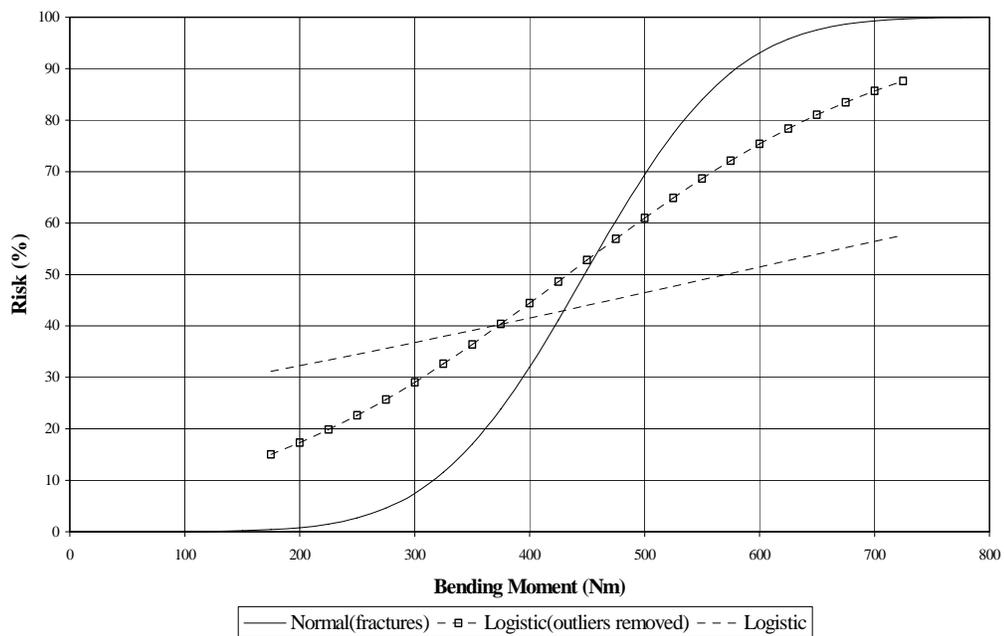


Figure 5. Comparison of AIS 2+ femur/pelvis injury risk functions based on logistic method and based on cumulative normal method using the maximum upper legform impactor bending moment, obtained from 39 accident reconstructions [38].

3.4 Head

In § 3.5.3 of the final report of EEVC WG10 [15] the following sentence is included:

“Confirmation is still necessary for the child acceptance level of 1000, although it is mentioned in literature that a HIC value of 1000, when used with the NHTSA head impact system, was verified as an accurate indicator of the threshold of serious head injury through experimental reconstruction of real pedestrian cases involving adults and children.”

Recently NHTSA has evaluated different techniques for developing child dummy protection values [39]. Several techniques, including scaling of adult data and accident reconstructions, have been evaluated and it was concluded that no single method or set of data stands out clearly as the best choice, because actual biomechanical data are insufficient and of limited applicability. Therefore it is recommended by NHTSA to use HIC 1000 for a 6-yr child, since this value has been an established limit for both adult and child dummies for many years, and is proven to be effective in limiting serious injury.

WG17 accepted this NHTSA recommendation. ISO/TC22/SC12/WG6 is currently discussing the HIC protection value for children and this may lead to new considerations.

3.5 Conclusions

Dynamic cadaver tests showed knee bending angles of 15° and knee shear forces of 3 kN when initial knee damage occurred. Since the proposed acceptance level for shear loading in the legform test is 4 kN, measured as 6 mm shear displacement, it can be concluded that these values are similar or quite close to the acceptance levels proposed by WG10. A tibia acceleration of 150g indicates almost 40% risk for an AIS2+ lower leg fracture according to a logistic regression method and almost 20% according to a cumulative normal distribution method. It is important to note that for leg and knee injuries not only the AIS level (i.e. life threatening injuries) should be considered, long term disability risk should also be taken into account. For car occupants it is known that for instance AIS 2 leg injuries show a risk of 15% for permanent disability, which is the highest disability risk of all body regions suffering an AIS 2 injury [40]. In this respect it is concluded that the acceptance levels⁷ for the legform test can be confirmed:

- Maximum lateral knee bending angle $\leq 15.0^\circ$;
- Maximum lateral knee shearing displacement ≤ 6.0 mm;
- Maximum lateral tibia acceleration ≤ 150 g.

The French representative in WG17 stated that the acceptance level for tibia acceleration should be increased to 200g, based on a test series where cadavers are impacted by modern cars [30]. The Italian representative in WG17 stated that the acceptance level for tibia acceleration should be higher and placed within brackets.

A new series of accident reconstructions has been performed to study the acceptance levels for the upper legform to bonnet leading edge test. Two different methods have been applied to develop injury risk functions. A combination of these methods results in an increase of the WG10 acceptance levels, which will contribute to a better balance between the performance of cars in the bonnet leading edge test and the real accident injury risk.

WG17 concluded that the acceptance levels for the upper legform to bonnet leading edge test, based on a 20% AIS 2+ injury risk level, should be:

- Maximum instantaneous sum of femur forces ≤ 5.0 kN;
- Maximum femur bending moment ≤ 300 Nm.

⁷ To avoid excessive rounding of the measured values in tests, one decimal is included for acceptance levels below 100.

The French representative in WG17 stated that the acceptance level for lateral femur force should be 7.5 kN [30] and for lateral femur bending moment should be 360 Nm (based on the method described in the beginning of § 3.3). According to the French EEVC representative further discussion is needed in relation to above mentioned biomechanical data. The Italian representative in WG17 stated that the injury risk level of 20% should be increased, resulting in higher acceptance levels.

There are no new child biomechanical data available with respect to head injuries and HIC, and it is outside the scope of WG17 to perform these kind of tests. The evaluation by NHTSA recommended using HIC 1000 for a 6 year dummy, which is the age of child represented by the EEVC child headform. Therefore WG17 recommends to retain a Head Protection Criterion based on HIC 1000 for the child headform to bonnet impact. So the acceptance levels for the headform test presented in § 3.1 can be confirmed. However, to be in line with other pedestrian test proposals (e.g. ISO), WG17 have decided to use a 15 ms time window (instead of unlimited) for the HIC calculation in both the child and adult headform tests:

- HPC adult head ≤ 1000 (15 ms HIC);
- HPC child head ≤ 1000 (15 ms HIC).

4 Test results and simulations

4.1 Introduction

The performance of real vehicles with respect to the EEVC test methods has been evaluated by WG10 in several programmes. The results have been presented in earlier reports [15, 16]. Since then more experience was gained from the Euro-NCAP programme, in which tests according to the EEVC WG10 test methods are performed on new vehicle models. A summary of the test results is presented in this chapter.

Computer simulations are used more and more in the development process of new vehicles or components. Computer simulations were also used by WG10, beside dummy and cadaver tests, to define the input conditions for the sub-system impactor tests. Recently performed computer simulations including modern, streamlined cars seem to indicate that the impact energy of the currently described upper legform to bonnet leading edge test is too high for these vehicle shapes. WG 17 studied this phenomena in detail and further computer simulations have been performed. A summary of the computer simulation results is presented in this chapter.

4.2 Performance of current vehicles

A summary of the pedestrian test results from the Euro-NCAP programme⁸ is presented in Table 6. In the Euro-NCAP programme 2 tests were performed in every head impact zone rather than 3 as described in the EEVC WG10 test method. Moreover, from the third phase of Euro-NCAP onwards, half of these test locations and 1/3 of the bumper and bonnet leading edge test locations could be selected by the car manufacturer. These locations were probably not the locations ‘most likely to cause injury’ as described in the EEVC WG10 test method. However, the results are still useful for further analysis.

Table 6 summarises the number of tests and those passing all proposed EEVC WG10 requirements⁹ for that specific test (see § 3.1). It can be seen that a significant number of child headform tests did fulfil the HPC 1000 requirement. The proportion of tests passing is much lower for the other tests. The upper legform criteria were not fulfilled in any test. All three legform requirements were passed in 9 tests, corresponding to a proportion of 7%, while the individual criteria were met in more tests (i.e. from 12% for the bending angle and up to 43% for the shear displacement). Only one car passed all three legform to bumper tests, while none of these 41 cars passed all tests.

The number of tests which are close to passing the requirements is also of interest. Table 6 shows the number of tests and their proportion passing a value set at an arbitrary 25% above the proposed WG10 acceptance levels. It can be seen that in a substantial number of test sites the performance is close to the proposed criteria. Only the upper legform test results are not improving significantly.

⁸ Phase 1-4, i.e. 41 cars.

⁹ See § 4.4 for an estimate of the tests/cars passing the new WG17 requirements.

Table 6. Summary of pedestrian test results from Euro-NCAP programme (41 cars).

Test type	Number of tests	Number of tests passing	Proportion of tests passing	Number of tests passing or within 25%	Proportion of tests passing or within 25%
Child headform	246	91	37%	132	54%
Adult headform #	225	25	11%	56	25%
Upper legform	123	0	0%	1	1%
Legform	122	9	7%	17	14%

For 7 small cars the number of adult headform tests was reduced because the test area was small.

4.3 Computer simulations with respect to BLE impact

An impact of a family car and of a small car against a 50th percentile pedestrian was simulated by ECIA using the computer programme MADYMO [41]. A validated, human-like model was used as a pedestrian and the most important parts of the car were modelled (i.e. bumper and bonnet). Both cars have a rather low bonnet leading edge, respectively 695 mm and 669 mm above the ground, representing modern car designs. The analysis focused especially on the bonnet leading edge impact.

The simulations showed that, for these streamlined cars, the motion of the pedestrian's upper leg is a combination of translation and rotation (i.e. sliding), which is a continuous motion with two important phases:

- Firstly a high speed, low mass impact when the bonnet leading edge impacts the upper leg;
- Secondly a low speed, high mass loading of the bonnet leading edge when the upper leg is already accelerated and is rotating and sliding over the bonnet, while an increasing proportion of the body mass is involved.

The simulation results seem to indicate that the impact angle and impact mass for these vehicle shapes, as described by the EEVC WG10 upper legform test method, correspond to the impact angle and mass in the simulation at about 30-40 ms (i.e. end of the upper leg impact). The impact velocity required by EEVC corresponds to the upper leg velocity in the simulation at 10 ms (i.e. beginning of upper leg impact). The maximum contact force in the simulation occurs around 15 ms, when the speed is already reduced and the angle and mass are still low.

The EEVC upper legform test is a guided impact, combining both main impact phases into a 1-D motion. Since the rotation/sliding effect is stronger in the more streamlined cars, this could explain the difference between the simulation results and the WG10 test conditions for the upper legform test. Moreover, injuries like fractures are caused by the rapid translation or normal forces applied to the upper leg, rather than by the sliding motion or tangential forces.

Further simulations by ECIA, where the height of the bonnet leading edge was varied between 500 mm and 800 mm, seem to indicate that for vehicles with a bonnet leading edge height below 700 mm the upper leg is sliding over the bonnet [42]. This results in an impact energy which is much lower (i.e. up to a factor of 4) than the impact energy described by EEVC WG10.

This 'sliding' effect was also studied by JARI [43] using a MADYMO pedestrian model and a MADYMO model of the upper legform impactor. The test conditions for the upper legform simulations were based on the EEVC test method where the required impact energy is based on the shape of the car. It was found that the resulting impactor force from the impactor model was larger than the femur/pelvis contact force from the pedestrian model, especially for low vehicle fronts. For instance, a ratio of 1.5 between impactor force and femur/pelvis contact force was found for a vehicle with a bonnet leading edge height of 650 mm. It was thought that this difference is caused by the translational motion of the guided impactor as it can not reconstruct the sliding mechanism at the contact surface. To eliminate this effect, a new method of impact energy calculation was used by the authors. Only the normal impact force and penetration from the pedestrian model simulations were used, so the tangential component or friction was excluded. This means that the sliding component is excluded in the calculation of the impact energy. This resulted in a ratio of 1 between impactor force and femur/pelvis contact force, so the impactor model simulated the pedestrian model behaviour much better. The resulting impact energy, calculated from this new method, for a car with a bonnet leading edge height of 650 mm is a factor of 2 lower than required using the EEVC WG10 test method.

The angle of the resultant force in the bonnet leading edge, caused by impact with the pedestrian, is also analysed from these simulations, indicating that this angle is more dependent on the bonnet leading edge height than described in the EEVC test method [43]. Particularly for low vehicles the impact angle found from these simulations is higher than the EEVC impact angle. This is contrary to the simulations in [41], where lower impact angles were found, however the method used for calculation of these impact angles differed from the EEVC calculation method, which uses results from full-scale pedestrian dummy tests, as described in [44].

TRL performed 54 computer simulations using LS-DYNA3D, representing various defined car shapes impacting a walking pedestrian [45]. The deformation properties of the bonnet leading edge and bumper were set so as to represent a 'safe' vehicle. A 50th percentile dummy model was modified for this purpose and validated against full-scale dummy tests, performed earlier to define the bonnet leading edge impact energy [46]. The pedestrian/car model was also validated against the cadaver tests used to validate the simulations described above [43].

Simulation outputs included the deformation energy of the bonnet leading edge impact. This included energy to deform the 'flesh' of the pedestrian in the region impacted by the bonnet leading edge, but did not include kinetic energy imparted to the pedestrian. Although there was friction between the pedestrian and the car, and energy was absorbed by friction (i.e. from the sliding motion), this energy was not included in the deformation energy shown in Figure 6. The results showed that the energy for many car shapes, especially for cars with a low bonnet leading edge height and/or large bumper leads, is considerably lower than the impact energy described by EEVC WG10. For instance for a vehicle with a bonnet leading edge height of 650 mm and a bumper lead of 100 mm, the difference is a factor of 2.

The results of the three computer simulation studies, described above, are combined in one figure that shows the impact energy against the bonnet leading edge height of the car, with the bumper lead as a parameter (see figure 6). It can be seen that the results are following the same trend, however the influence of the bumper lead is significant in the TRL simulations only. The energy curves obtained from the ECIA, JARI and TRL simulations are encompassed by the 50 mm bumper lead and 350 mm bumper lead TRL curves.

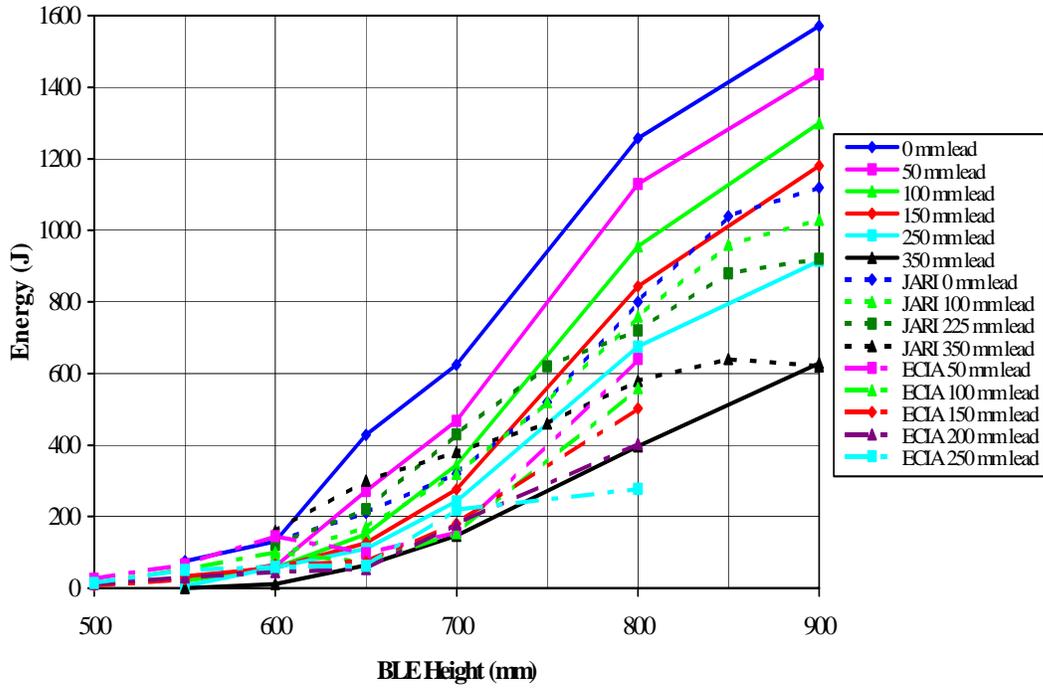


Figure 6. Upper legform impact energy against bonnet leading edge height, with bumper lead as parameter, obtained from several computer simulations [41, 43, 45].

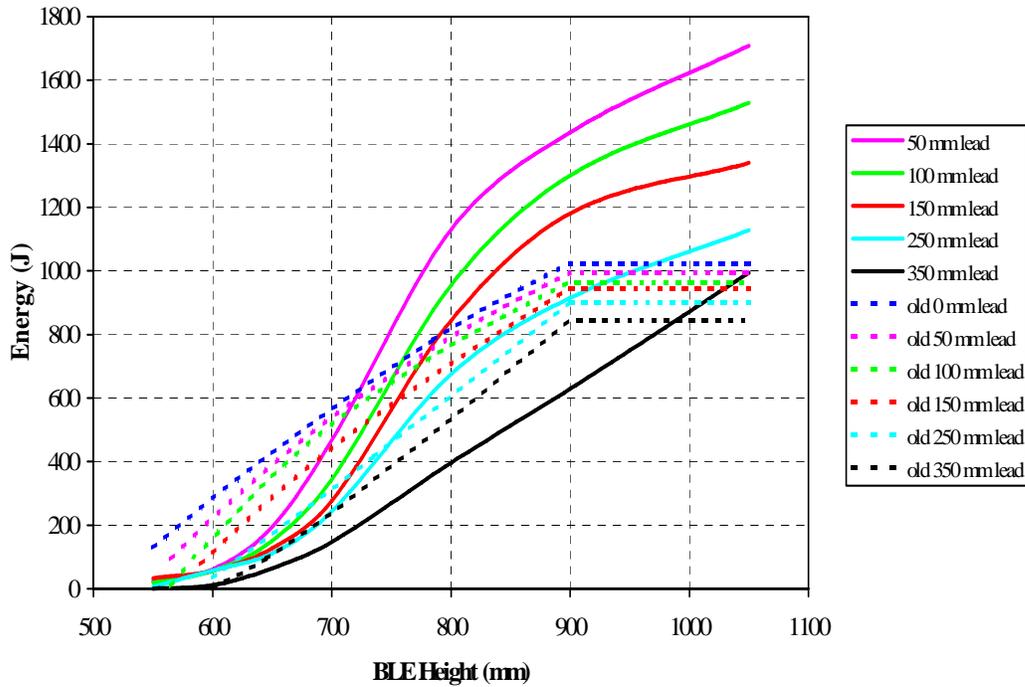


Figure 7. Comparison of WG10 and new kinetic energy curves of upper legform to bonnet leading edge tests with respect to vehicle shape (note: no test is proposed below

200 J and recommended maximum required energy is 700 J - see § 7.3.1).

WG17 decided to use the TRL results, without the zero bumper lead curve¹⁰, to describe the impact energy for the bonnet leading edge test, since the TRL results showed a clear influence of the bumper lead, which is an important car shape parameter.

Figure 7 shows the smoothed new curves compared with the EEVC WG10 impact energy curves. Extra curves, obtained by interpolation, have been added to the WG10 curves for comparison purposes. It can be seen that for many of the more streamlined vehicles, the new required impact energy is much lower.

4.4 Conclusions

Modern passenger cars do not fulfil all EEVC WG10 (or Euro-NCAP) test requirements. However, these cars were not designed to meet these requirements. Car models with substantial areas meeting or close to meeting the requirement have been found from the Euro-NCAP data, especially for the child headform to bonnet top test¹¹. A point of concern is the fact that the upper legform test was not passed by any of these 41 modern cars, while recent accident studies seem to indicate that the bonnet leading edge of these modern cars is more ‘pedestrian friendly’ than earlier designs (see § 2.3).

Mathematical model simulations seem to indicate that the test conditions for the upper legform to bonnet leading edge test are too severe for vehicles with a low, streamlined front. When a pedestrian is impacted by such a vehicle the upper leg kinematics are a combination of translation and rotation (or sliding). This latter effect can not be simulated by the guided legform impactor, so all the energy (i.e. impact velocity and mass) is concentrated in the translational motion, resulting in an impact which is too severe. This rotation or sliding effect plays no significant role for vehicles with a high bonnet leading edge. WG17 concluded that new test conditions are required for low fronted vehicles.

The simulations showed that lower kinetic energies are required for streamlined vehicles, if the friction (or sliding) energy is not included in the calculations. Computer simulations conducted by ECIA, JARI and TRL showed similar curves for energy versus BLE height, however the energy levels are sometimes different. The corridor of energy curves considered by WG17 includes all these simulation results. WG17 decided to use the results of the TRL simulations, since these results show a clear influence of the bumper lead. This is an important parameter defining the shape of the car and therefore defining the bonnet leading edge impact conditions. The French representative in WG17 stated that the energy calculated from the TRL simulations is too high, in particular for streamlined cars, since the deformation energy is calculated during all the duration of the contact with the bonnet, whereas the guided impactor hits the bonnet leading edge at one point. The UK representative stated, however, that the sliding energy is not included in the calculations. The IT representative in WG17 stated that more in-depth study and more analyses are necessary to conclude on this subject

¹⁰ This means that a vehicle with a bumper lead < 50 mm should be tested as for 50 mm, i.e. at a lower energy level.

¹¹ Two rather than three tests were performed in every head impact zone and one of these points could be selected by the manufacturer.

The new bonnet leading edge impact energy curves are lower than those required by EEVC WG10 for many of the more streamlined cars. This means, for example, that the test energy for a Mk1 Ford Mondeo has gone down from 319 J to 160 J (note: below 200 J no test is proposed!). The EEVC representative from the UK estimated, based on the results of Euro-NCAP phases 1, 2 and 3, that almost 1/3 of the current cars would comply to the *new*

acceptance levels for the bonnet leading edge test, taking the *new* energy test conditions into account. For cars with high bonnet leading edges the new curves indicate higher test energies. However, the recommended energy cap of 700 J (see § 7.3.1) will mean that in practice very few car shapes would be tested at higher energies than before using the WG10 curves.

5 Impactors

5.1 Introduction

Since WG10 was dissolved in 1994, a lot of effort has been spent by individual organisations in the evaluation and improvement of the impactors. Several aspects have been summarised already in the 1996 ESV paper [16]. In this chapter further developments will be presented.

5.2 Legform impactor

The original legform impactor was developed by INRETS and a lot of effort was spent in the optimisation of the characteristics of the deformable elements to control the lateral bending and shearing motion of the knee joint. WG10 had already considered an alternative TRL knee design, in which the shearing is controlled by a leaf spring [15]. The EEVC specifications of the legform were also fulfilled by this second design. Evaluation of this TRL prototype design by BAST and TNO showed satisfactory results. It was concluded that the TRL prototype legform meets the requirements of an acceptable test device. However, vibrations were observed in the system, probably caused by the leaf spring [16]. This was also found in an ACEA test programme [47]. No mechanical failures or transducer failures were found in a large test programme on real vehicles, while the repeatability of the impactor was good, showing Coefficients of Variation¹² of 5% or less [48].

TRL reported these developments to WG17 which accepted the TRL prototype legform as the EEVC prototype legform. A summary of the impactor development and performance, including a clarification or reply with respect to some technical concerns raised by third parties, can be found in [49]. Further developments are focusing mainly on damping the leaf spring vibrations. A prototype damper has been developed and tested by TRL which shows satisfactory results [49, 50]. A smaller, less vulnerable damper, with similar characteristics became available in November 1998 and further evaluations are being performed.

Another point of concern is that the shearing displacement of the knee is limited to 8 mm, when an endstop is reached, while the proposed acceptance level is 6 mm. This means that even in an extreme overload situation, the measured shearing displacement is never larger than 8 mm. So the measurement will in that case not show how far the performance of the car is away from the acceptance level. To overcome this problem, it is suggested that car manufacturers might wish to use a damper with a variable (in this case higher) viscosity while undertaking vehicle development testing.

A new dynamic certification procedure is proposed, which better reflects the actual use of the legform impactor in a bumper test [49]. The legform is supported horizontally by wires and impacted by a concave shaped impactor of 16 kg at a speed of 7.5 m/s. The impact conditions, including the impact location on the legform, have been chosen such that the output of the instrumentation, including bending and shear, is comparable to that of a real bumper test.

¹² CV = standard deviation / mean value

The static legform certification procedures have been improved. Energy limits are described for the bending test, to minimise the variation in performance of the deformable elements. The certification corridor for the shear test is shifted slightly downwards, adjusting the stiffness of the shear spring to compensate for the opposing damper force [51].

5.3 Upper legform impactor

In 1995 BAST performed a series of upper legform tests and found a ‘hidden load path’ from the impact point at the front to parts of the impactor behind the load cells [16]. The impactor foam seems stiff enough dynamically to transmit these forces. TRL has improved the impactor by reducing the area of the foam sheets that cover the impactor, to create ‘gaps’ between the foam and the support system behind the load cells. After this revision a series of impact tests was performed to confirm that the load transducers accurately report the impact. For this the impactor impulse, derived from the impactor acceleration and mass behind the load cells, was compared with the impulse derived from the force vs. time histories. The results were within 1% in all tests and the amended design is now considered to be satisfactory for this aspect [49]. JARI reported that the measured forces are still lower than the inertia forces, which could be due to the defined load cells [35]. WG17 believes that side loads to the upper legform impactor, which could occur in car tests, create this difference and that it is important to use low friction bearings for the impactor guidance system, insensitive to off-axis loading.

The repeatability of the impactor in certification tests is good, showing CV’s of 2% or less. ACEA found a ‘repeatability’ of $\pm 10\%$ for the whole test procedure (i.e. including the variation in the vehicles), however this value is defined as the maximum deviation of a single test from the average of the 3 repeatability tests performed [47], and is not based on the standard deviation of a large test series.

A summary of the impactor development and performance can be found in [49], including a clarification or reply with respect to some technical concerns raised by third parties.

5.4 Headform impactors

In their evaluation programme ACEA found a ‘repeatability’ (see definition above) of $\pm 5\%$ for the whole headform test procedure. ACEA reported durability problems with the headform sphere, parts chipped off when a hard object was struck [47].

TNO has been looking for a new material to improve the durability of the headform and to make machining more easy, because the original ‘bowling ball’ sphere is somewhat brittle. Since tests with poly-urethane spheres were not successful, it is proposed by TNO to change to an aluminium sphere covered by a PVC skin. The background of this idea is that a more Hybrid-like headform would better meet the original biofidelity requirements used by the BAST to develop the headform than a plastic sphere covered by a rubber skin.

The specifications of the headforms have been updated in this respect. The PVC skin is 12 mm thick, similar to the Hybrid III (fore)head. The outer diameter and mass of the headforms are not changed. A prototype aluminium adult headform has been developed that can fulfil the original certification requirements obtained from a droptest [52]. This prototype design has been accepted by WG17.

The current headform certification speed is only 20-25% of the impact speed on the bonnet [53]. A new dynamic certification procedure is proposed by TNO, which better reflects the actual use of the headform impactors in a bonnet test. The headform is supported by wires and impacted by a flat faced impactor of 1 kg at a speed of 7 m/s. The impact conditions are chosen such that the output of the instrumentation is comparable to that of a

real bonnet top test. WG17 concluded that new headform designs should also fulfil the original headform drop test requirements.

5.5 Conclusions

EEVC WG10 specified the impactors to be used in the EEVC pedestrian protection test methods. Further evaluations and developments have been conducted by some former members of WG10. This work has been accepted by WG17 and some new specifications have been defined. However, additional work is required to finalise the impactors:

- Legform impactor including 'shear' damper:
 - a prototype damper has been developed and successfully tested, evaluation of a smaller production version of the damper mounted in the prototype legform is planned;
 - the specifications of the legform include the damper and should be checked.
- New dynamic legform certification procedure:
 - further tests of the final damped legform are required to define the final dynamic certification requirements.
- Reduced skin/foam covering for upper legform impactor:
 - already extensively tested and evaluated.
- Aluminium headforms covered by PVC skin:
 - adult prototype developed and tested, further tuning of skin is being conducted;
 - development of child headform based on same design principle is planned;
 - further testing of both headforms in real tests is required.
- New dynamic headform certification procedure:
 - further tests of the final headforms are required to define the final dynamic certification requirements.

Although some impactors are called 'prototypes', they are an extension of previous versions which have been used in large test programmes. Proposals for further improvement resulted from these tests and the impactors are now in their final stage of development. The revised legform and headform impactors, including the final certification requirements, will be available by mid 1999.

The final production and sales of the impactors is not a responsibility of EEVC, the current (prototype) impactors are manufactured and sold by TNO and TRL. However, EEVC could evaluate and accept impactor designs with respect to the defined specifications and EEVC could co-ordinate the evaluation of the impactors manufactured by third parties.

6 Input from other organisations

6.1 Introduction

When EEVC WG17 was set-up, it was suggested by the Steering Committee to study the MIRA report concerning a cost-benefit analysis of the proposed EEVC WG10 test methods. This MIRA report and other documents/reports which were sent to WG17 by several organisations have been studied. In this chapter a summary is presented.

6.2 MIRA cost-benefit analysis

The MIRA report dealing with the costs and benefits of pedestrian protection [17] was studied by WG17. From a scientific point of view some important shortcomings were observed:

- Overestimation of the costs of injuries;
- Old and limited data used for benefits;
- Underestimation of benefits for pedal cyclists;
- Underestimation of benefits due to ‘underreporting’ of data.

Moreover, WG17 had doubts and questions concerning the operational costs (e.g. insurance) included in the costs calculation. Finally it was felt that the report was not transparent, in particular because confidential information has been used by MIRA. The report and therefore the conclusions could not be supported by WG17. However, it is recognised by WG17 that extra effort and costs are required to improve passenger cars with respect to pedestrian and pedal cyclist protection. In a further addendum to their report, MIRA considered these shortcomings and calculated a new lowest cost to benefit ratio of 1.7 against 5.3 in the original calculations [54].

6.3 JAMA/JARI proposals

JAMA and JARI have sent several documents to WG17 concerning the test conditions, impactors and acceptance levels described in the EEVC WG10 test methods [28, 29, 55, 56]. A response document was sent to JAMA [57] and a JARI expert was invited to present research results at the 5th meeting of WG17. Several items have been mentioned in the previous chapters of this report and were used as input for Chapter 7.

6.4 ACEA evaluation

ACEA has evaluated the EEVC WG10 test methods, including the (prototype) impactors. The results of this evaluation are summarised in a report [47]. Moreover, ACEA produced a document with ‘technical concerns’ [53], that was sent to WG17. Both documents have been reviewed by WG17 carefully. Answers and clarifications were included in two response documents that were sent to ACEA [58, 59]. The ACEA documents included useful solutions and proposals, which were discussed further by WG17.

Several items have been mentioned in the previous chapters of this report and were used as input for Chapter 7.

6.5 Others

Recent conference papers and other documents (e.g. from University/ETH Zürich [60]) have been studied by WG17.

6.6 Conclusions

EEVC WG17 received input from several organisations, especially from the joint European (ACEA) and joint Japanese (JAMA) car manufacturers, and several of the adjustments proposed in Chapter 7 are based on these contributions.

7 Improved test methods

7.1 Introduction

Based on the review presented in the previous chapters and based on additional considerations, described below, changes to the EEVC WG10 test methods will be presented in this chapter. The basis of the test methods is described in the final report of WG10 [15] and further improvements are described in an ESV paper [16]. This work has been used by Directorate-General III of the European Commission to draft a proposed Directive in 1996 [61]. The lay-out of this proposed Directive differs from the original WG10 lay-out and therefore the proposed Directive will be used as basis for the new EEVC test methods. Small changes and typing errors included in [61] will not be described or explained in this chapter. See Appendix 2 for the new EEVC test methods.

A general improvement concerns the repeatability of setting up and testing identical vehicles: the ride height and attitude of the vehicle can be set to the design height if the vertical difference between both is within 25 mm.

7.2 Legform to bumper test

7.2.1 Test method

Three legform tests to the car front are required in all cases, for any shape of the vehicle. Although this is referred to as the legform to bumper test, it actually tests all parts of the vehicle front the legform contacts during the test, for instance spoiler, bumper, air grill, lights, bonnet and wing leading edges. One possible exception is described below.

The legform test is representative for a complete dummy test if the bumper impact occurs at or below the knee joint level, i.e. 500 mm or less above the ground [15]. The upper body mass, which is not simulated by the legform impactor, becomes more important if the upper leg rather than the lower leg is impacted by the bumper. Some vehicles, like off-road vehicles, have high bumpers for certain functional reasons. These high bumpers will impact the femur part of the legform impactor, where no acceleration is measured to assess the risk of fractures. Moreover, there is often no structure below the bumper to restrain the tibia part of the legform, for instance because an off-road vehicle needs a certain ramp angle and ground clearance [62]. Therefore WG17 decided to include an optional, alternative horizontal upper legform test with an impact speed of 40 km/h, when the lower bumper height is more than 500 mm above the ground. The standard upper legform impactor mass for this test is 9.5 kg, the lowest practical value for this impactor and as close as possible to the (effective) femur mass of the legform impactor. This femur mass is 8.6 kg, however the effective mass in a test will be higher, since the lower leg is connected to the femur part. This test seems to be more feasible for vehicles with a high bumper, however the test is quite demanding (i.e. acceptance levels based on 20% AIS 2+ femur injury risk) to avoid a design trend towards high bumpers.

The tolerance on the impact velocity has been decreased from ± 0.5 m/s to ± 0.2 m/s in order to further improve the repeatability of the test method and test results. The effect of gravity must be taken into account when the impact velocity is obtained from measurements taken before the time of first contact, which is normally the case.

7.2.2 Impactor

The description of the legform impactor has been improved by further specifying the diameter, the mass tolerance, the moment of inertia. The specification includes brackets and pulleys for launching the impactor, as well as a damper connected to the knee shear spring (see § 5.2).

The static and dynamic certification procedures have been improved, in order to have a better control on the performance of the knee ligaments and to better reflect the actual use of the impactor in a test (see § 5.2).

7.2.3 Requirements

No changes are proposed with respect to the original WG10 acceptance levels for the legform to bumper test (see also §2.2, 2.5, 3.2 and 3.5):

- Maximum lateral knee bending angle $\leq 15.0^\circ$;
- Maximum lateral knee shearing displacement ≤ 6.0 mm;
- Maximum lateral tibia acceleration ≤ 150 g.

The French representative in WG17 stated that the acceptance level for tibia acceleration should be increased to 200g, based on a test series where cadavers are impacted by modern cars. The Italian representative in WG17 stated that the acceptance level for tibia acceleration should be higher and placed within brackets.

7.3 Upper legform to bonnet leading edge test

7.3.1 Test method

Three upper legform to bonnet (and wings) leading edge tests are still required by WG17. The French and Italian representatives in WG17 are of the opinion that this test nowadays, according to the recent accident statistics and the new frontal shape of recent cars, is not fully necessary and they consider the actual test method unrealistic and not working properly as it is. The German representative in WG 17 expressed his doubts concerning this test method because of the absence of the 'sliding motion' (see also § 4.3), but accepted the bonnet leading edge test method as it is.

The test conditions, like impact velocity and impact angle, are based on the shape (i.e. bonnet leading edge height and bumper lead) of the vehicle. New look-up graphs are included to determine the test conditions. Moreover, a computer programme that calculates the test conditions can be supplied by TRL. The impact energy curves have been up-dated, based on the results of several computer simulation studies (see § 4.3), indicating a lower impact energy for streamlined vehicles. The French representative in WG17 stated that the new required energy is still too high, in particular for streamlined cars. The Italian representative in WG 17 stated that more research is required on this subject.

The impact velocity and mass are related to the impact energy by $E = \frac{1}{2} mv^2$. The velocity look-up curves have been adjusted in order to prevent the mass being less than the practical lower limit of 9.5 kg, due to the lower kinetic energy required for the more streamlined cars. The tolerance on the impact velocity has been decreased from $\pm 5\%$ to $\pm 2\%$ in order to further improve the repeatability of the test method and test results. The impact angle has not been changed, except that the curves have been extrapolated to a bonnet leading edge height of 1050 mm.

It is recommended by WG17 to limit the impact energy curve at the lower end and at the higher end. According to the EEVC WG10 method, a test is not required if the impact energy is 200 J or less, because very few injuries were found in cadaver tests and accident reconstructions with impact energies below 200 J. WG17 recommended to include this lower limit in the new energy curves. This is a practical value found for current cars. If the stiffness of cars will change significantly in future, the 200 J limit should be reconsidered,

since injury risk is linked to the stiffness and not to the test energy. At the higher end the energy required by the WG10 test method is levelled off for vehicles with a bonnet leading height above 900 mm, i.e. vehicles with bonnet leading edge heights above 900 mm should be tested as for 900 mm. Another approach is proposed by industry [53], a maximum energy level based on a maximum deformation depth to absorb the energy. Based on a feasible deformation depth of 150 mm and an acceptance level of 5.0 kN, a ‘capping’ of the impact energy at a level of 700 J is proposed [45, 63]. WG17 recommended to support this approach. As an example, the minimum and maximum energy level of 200 J and 700 J respectively are shown in the energy look-up graph and in the proposed text for the test method (Appendix 2, Annex V).

The definition of the bonnet leading edge reference line has been extended. Firstly, it is made more clear that the upper edge of the bumper should be considered as bonnet leading edge, if contacted by the stick described in the procedure. This means that a legform test and an upper legform test have to be performed on that bumper. Secondly the bonnet reference line is defined at a wrap around length of 1000 mm for vehicles with a steep bonnet angle, where only the top end of the stick described in the procedure is contacting the bonnet¹³.

Pop-up head lights should be considered, since these could be ‘impact points most likely to cause injury’. Including these lights will influence the height of the bonnet leading edge reference line and therefore will influence the test conditions.

The upper legform impactor should be aligned using the bonnet leading edge reference line, however the point of first contact is not necessarily located on that line (as often thought). Rotations of the upper legform impactor around any axis, other than around the torque limiting joint, are not allowed during the impact.

It is known that the hipjoint of a 95th percentile male, wearing shoes, is somewhat more than 1000 mm above the ground. For some vehicle configurations, like off-road vehicles, the bonnet leading edge reference line is located higher than 1000 mm above the ground, resulting in an upper legform impact location higher than the human hip [53, 62]. However, a vehicle structure at 1000 mm above the ground could also impact the abdomen of a 15-yr old child or small adult, the chest of a 10-yr old child or even the head of 6-yr old child [64]. For these tall fronted vehicles an abdomen impactor or chest impactor might be more appropriate. However, WG17 believes that design changes to meet the upper legform test would result also in an improvement from current practice and would reduce injuries, as the upper legform requirements are considered to be roughly similar to those for the protection of the abdomen or chest. Therefore an upper legform test is required also for vehicles with a high bonnet leading edge.

7.3.2 Impactor

The description of the foam has been improved, while the mass specification for the foam and skin was changed due to a design change (see § 5.3). The use of one standard impactor mass, rather than a mass depending on the shape of the vehicle, has been proposed by JAMA/JARI [43]. WG17 believes that this change is not necessary, however the tolerance on the impactor mass has been increased (keeping the energy level constant), to avoid small changes to the impactor mass and velocity for different test locations on one vehicle.

¹³ The child head impact zone starts then at 1130 mm wrap around length (see §7.4.1).

7.3.3 Requirements

The acceptance levels for the upper legform to bonnet leading edge test have been increased to 5.0 kN and 300 Nm respectively (see also §2.3, 2.5, 3.3, 3.5, 4.2 and 4.4). The French representative in WG17 stated that the acceptance level for lateral femur force should be 7.5 kN and for lateral femur bending moment should be 360 Nm. According to the French EEVC representative further discussion is needed in relation to abovementioned biomechanical data. The Italian representative in WG17 stated that the injury risk level should be increased, resulting in higher acceptance levels.

7.4 Headform to bonnet top tests

7.4.1 Test method

The EEVC child head impact area covers a large majority of the head impact points found in accidents, whereas for the adults a majority of the impact locations are outside the zone considered by the EEVC test method. WG 17 decided that both the child and the adult headform to bonnet top test are still required.

In the EEVC WG10 test method the bonnet top is divided in two impact areas, one for the child headform with boundaries at 1000 mm and 1500 mm wrap around distance, and one for the adult headform with boundaries at 1500 mm wrap around distance and at the lower windscreen (or A-pillar) frame or 2100 mm wrap around distance. Figure 8 illustrates these impact areas for different vehicle types. WG17 has considered the definitions and consequences of using these boundaries.

For some vehicle configurations, like off-road vehicles, the bonnet leading edge is located higher than 1000 mm above the ground, resulting in an overlap of the upper legform impact area and the child headform impact area [53, 62]. Since a 50° downward headform impact against the grill and headlight area seems not realistic, this would change to a horizontal impact of the child headform. Since the test conditions (i.e. energy) and requirements of the upper legform and (horizontal) child headform test are quite different, this could demand opposite design solutions, as shown in an ACEA pilot study. WG17 believes that the upper legform test should be kept, since this test contributes also to injury reductions for other body areas (see § 7.3.1).

Mathematical model simulations have shown that a high speed child head impact on the bonnet top just behind the bonnet leading edge of high fronted vehicles is unlikely [65]. This area is normally not impacted by the head or only at low speeds, when the bonnet leading edge impacts the shoulder area.

To obtain a feasible test method, WG17 decided to separate the bonnet leading edge reference line for the upper legform impact and the lower boundary of the child headform impact area by at least 130 mm (i.e. the diameter of the child headform). This means that the child headform impact area starts at the bonnet leading edge reference line plus 130 mm if this is further rearward on the bonnet top than the 1000 mm wrap around distance, unless no test is required on the bonnet leading edge (e.g. required energy below 200 J). This will not make a difference for most vehicle types, since the 1000 mm wrap around distance is already more than 130 mm behind the bonnet leading edge (see Figure 8).

Different test conditions, i.e. impact angle and mass, exist also at the boundary of the child and adult headform impact areas. Within these areas the minimum distance between two impacts equals the diameter of the respective headform, however at the 1500 mm wrap around distance both headform impacts can be required on the same location. Therefore a transition or exclusion band is proposed by ACEA [53]. Since this area can be impacted by the head of children as well as by the head of adults in real accidents and since the design solution to reduce the injuries of these impacts is not fundamentally different, WG17 is not supporting this proposal.

figure 2-13 MIRA

Figure 8. Pedestrian impact zones by vehicle category, showing the potential overlap in upper legform impact zone and child headform impact zone for 4x4 off-road and utility vehicles [17].

The definition of the rear-end of the bonnet top seems not clear. The windscreen and A-pillars are excluded, while the scuttle and lower windscreen frame are included in the definition of the bonnet top. Moreover, it is stated by WG10 that the point of first contact should be on the bonnet top. If the point of first contact is on the windscreen (or another area not part of the defined bonnet top), then the rear boundary should be moved forward. However, in many tests the windscreen is impacted, sometimes quite soon after the first contact of the headform with the bonnet top. A headform test where the headform just touches the bonnet rear-end and then fully impacts the windscreen, for instance on a vehicle where the wiper spindles are covered by the bonnet, would be a test according this definition, but it was not the intention to test the windscreen. The main impact should be to the defined bonnet top. In order to clearly define the rear-end of the bonnet top, WG17 has

developed an additional procedure. A rear-end reference line has been defined and headform impacts should be conducted 82.5 mm (i.e. half diameter adult headform) or 65 mm (i.e. half

diameter child headform) forward of this line. This procedure is comparable with that for the bonnet side reference line.

The impact location and velocity of a pedestrian's head on the vehicle depends on several parameters, like vehicle impact speed, vehicle shape, standing height and leg position of the pedestrian. Computer simulations and experimental studies have shown that the head impact velocity on the bonnet (or windscreen) of a passenger car can vary between 0.7 and 1.6 times the vehicle impact speed [30, 66, 67, 68]. For a vehicle impact speed of 40 km/h this results in a head to bonnet impact velocity between 28 km/h and 64 km/h, depending on the vehicle shape, pedestrian stature and standing position, etc. The ISO working group on pedestrian protection developed a relation between the head impact velocity and the vehicle velocity [69]:

$$y = 0.977x + 10.226$$

For a vehicle impact velocity ('x') of 40 km/h this results in a head impact velocity relative to the bonnet ('y') of 49 km/h. This was already recognised by WG10, however it was decided not to increase the head impact velocity above 40 km/h, in order to keep the deformations depth required to absorb the headform energy within feasible limits [15, 16]. Recent cadaver tests using modern cars indicated a head impact velocity below the car impact speed (i.e. between 0.7 and 1.0 times) [30]. Computer simulations also showed, for small pedestrians (i.e. 5th percentile) and car impact speeds of 32 km/h, a head impact velocity below the car impact speed (i.e. between 0.7 and 1.0 times), as well as lower, more horizontal, head impact angle [30]. This is confirmed by other recent computer simulations using small cars with impact speeds from 24 km/h up to 48 km/h. However, small pedestrians impacted by medium sized passenger cars showed head impact velocity equal to the car impact speed. Moreover, these simulations showed that for average sized pedestrians the head impact velocity is 20% to 45% higher than the car impact speed [68]. In particular for off-road vehicles with high fronts, the head impact velocity found in these simulations was lower than the car impact speed.

It was decided not to use the shape of the vehicle or the vehicle category to determine the head impact velocity and angle, but to select one standard test condition. WG17 accepts that this is a compromise, but believes that it still is a feasible test method taking into account all possible accident, vehicle and pedestrian (and cyclist!) variations. Therefore WG17 concluded not to change the prescribed headform impact velocity of 40 km/h. The French and Italian representatives in WG17 stated that the headform impact velocity and impact angle (with respect to ground level) should be reduced, taking into account the results of the above mentioned simulations and cadaver tests on real, modern cars. The Swedish EEVC representative stated that the relation between bonnet leading edge height and car impact speed should be (re)considered.

To cover all possible impact locations it was decided by WG10 to require 3 headform tests each to the middle and outer thirds of the forward (i.e. child) and rearward (i.e. adult) bonnet top sections. The impact locations are those 'most likely to cause injury'. It has been suggested to perform the tests on predefined locations [53]. WG17 believes that it might be necessary to define these points in terms of structure, rather than XY locations, for instance over the bonnet/wing joint, over the suspension system. These will also be the points 'most likely to cause injury', so in fact this will not make a difference. Therefore WG17 decided not to change the original procedure.

The tolerance on the impact velocity has been decreased from ± 0.5 m/s to ± 0.2 m/s in order to further improve the repeatability of the test method and test results. The effect of gravity must be taken into account when the impact velocity and impact angle are obtained from measurements taken before the time of first contact, which is normally the case.

It has been proposed to prescribe a minimum time (e.g. 2 hours) between two impacts using the same headform skin, so that the skin could 'recover'. Another possibility would be to select another impact location on the same skin by rotating the headform around

its symmetrical axis or exchange the complete skin. It is left to the authorities or test house to decide on the most appropriate solution in a specific case.

7.4.2 Impactor

The material of the adult and child headform impactors has been changed. Moreover, the moments of inertia are described. A new dynamic certification procedure has been developed (see §5.4), however new headform designs must fulfil the original drop test requirements.

7.4.3 Requirements

No changes are proposed with respect to the original WG10 acceptance levels for the headform to bonnet top test (see also §2.4, 2.5, 3.4, 3.5 and 4.4).

8 Recommendations

8.1 Introduction

In this chapter some EEVC WG17 recommendations are presented with respect to the application of the EEVC test methods as technical requirements in a Directive relating to the protection of pedestrians and other vulnerable road users in the event of a collision with a motor vehicle. Moreover, a recommendation with respect to further research is presented.

8.2 Directive

Directorate-General III of the European Commission has announced that it will use the work of EEVC WG17 to draft a proposed Directive concerning the protection of vulnerable road users. Moreover DG-III has requested EEVC to supply not only the final report of WG17, but also the full text of the improved test methods. Therefore the EEVC Steering Committee decided that the full text of the EEVC test methods should be included in the current report (see Appendix 2).

The EEVC test methods or proposed technical requirements for a Directive consist of a series of tests to the front of a passenger car. To gain the maximum benefit, all parts of the vehicle likely to strike the pedestrians, which is the whole surface of the car front, should be as 'pedestrian friendly' as possible. The EEVC tests cover the whole car front up to the windscreen and A-pillars (see also § 8.3). It has been suggested to start with only one or two of the EEVC tests or test areas in the Directive. The following remarks should be considered in this respect:

- Current accident statistics suggest that the 'bumper' is the most important area to reduce severe and disabling injuries, followed by the 'bonnet top'. Many head injuries are caused by windscreen or A-pillar contacts, areas not covered by the EEVC test method. However head injuries caused by the bonnet top are often quite severe or fatal injuries, so the priority of the 'bonnet top' is not necessarily lower in this respect.
- Current accident statistics suggest that the number of injuries caused by the bonnet leading edge is decreasing, probably caused by the more streamlined design of current passenger cars¹⁴. However, it can not be foreseen what the influence of the frontal off-set impact Directive or other Directives will be on the future shape and stiffness of the car front. Moreover, the pedestrian Directive itself will also influence the shape and stiffness of the car front. The test methods should not cover current designs only, but should be applicable to future car designs as well.
- The applicability of the Directive must be considered. If N1 vehicles are included in the Directive the relative importance of the test methods may change, since the shape and stiffness of these vehicles may differ from that of M1 vehicles and N1 vehicles derived from M1.

¹⁴ In one of the studies, bonnet-type vehicles only were studied (see § 2.3).

EEVC WG17 believes that the improved test methods should be adopted as one, complete package. The French and Italian representatives in WG17 do not support the upper legform to bonnet leading edge test method. The French representative expects no benefits from the adult headform to bonnet top test method. The German representative in WG17 stated, that in consideration of the complexity of the subject and in consideration of the different scientific results in some extent, a stepwise approach of the test methods could be conceivable.

If the test methods can not be introduced completely in an European Directive, i.e. if it is decided that it would be desirable to introduce the procedure progressively, there are at least three possibilities: firstly only a proportion of the test areas could be required to meet all test requirements initially, with the proportion gradually increasing to 100 per cent over a fixed period (which is the method already suggested by EEVC WG10 in 1994), secondly the acceptance limits could be introduced at a higher level initially, gradually reducing to the limits proposed in this report or thirdly, the tests could be introduced progressively. If the latter option is selected, the following priority order for the test methods is proposed by EEVC WG17:

1. Headform to bonnet top tests (higher priority for child headform test);
2. Legform to bumper test (up to 500 mm bumper height, above that optional an upper legform to bumper test);
3. Upper legform to bonnet leading edge test.

It should be noted that these test methods are linked to each other with respect to several definitions, test areas, tools and requirements.

With respect to the application and administrative provisions of the Directive, the following remarks are made by WG17:

- It should be considered if the Directive applies to vehicle types approved, before the date of entrance of the current Directive, pursuant to Directive 74/483/EEC (exterior projections) and/or to Directive 96/79/EEC (frontal protection) (see Article 2, §3 in [61]).
- It should be made clear that the ‘vehicle representative of the vehicle type to be approved’ shall be a complete vehicle or a sub-system of the vehicle (see Annex I, §1.3 in [61]).
- It should be considered if for the Conformity of Production tests the test locations should be those tested for the type approval.
- It should be considered which modifications to the vehicle shall require a repetition of the tests. It seems not clear if a modification affecting ‘the general form of the frontal structure’ (see Annex I, §3.2 in [61]) includes for instance changes to the under bonnet components or changes to the normal ride height of the car. Moreover the influence of vehicle mass changes on pedestrian protection seems not clear. WG17 proposes the following sentence: “Any modification of the vehicle which in the judgement of the authority would have a marked influence on the results of the appropriate test(s) shall require a repetition of the test(s) as described in Annex II”.
- It should be considered if and what repairs are allowed between two impacts of an approval test.
- The leadtimes of the Directive should be considered, taking into account that important vehicle changes could be necessary. Such changes generally necessitate that a ‘pedestrian friendly’ vehicle needs to be designed for the earliest concept stage and not by modification of an existing vehicle.

8.3 Further Research

Some important vehicle parts with respect to pedestrian protection, like the windscreen and A-pillars, were not included in the mandate of EEVC WG10. It is clear that these areas are impacted quite often by the pedestrian's or cyclist's head (see also §2.4). Further research in this area is recommended in order to see if a future extension of the Directive is required.

9 Conclusions

The main task of EEVC WG17 Pedestrian Safety was to review the EEVC WG10 pedestrian protection test methods from 1994 and to propose possible adjustments taking into account new and existing data in the field of accident statistics, biomechanics and test results. Between October 1997 and November 1998 more than 100 documents were presented, analysed and discussed in six WG17 meetings. Input has been received from several organisations, including ACEA, JARI and JAMA.

Recent accident studies show changes in injury distribution over the pedestrian's body areas with respect to previous studies. It is obvious that the bonnet leading edge of modern, streamlined cars is causing less injuries to the adult upper leg. Therefore WG17 reviewed the upper legform to bonnet leading edge test method very carefully and proposed some changes. Since the test methods should cover all car shapes (and locations) and not only those of streamlined cars, it was decided not to delete this specific test, except for cars where the calculated energy is lower than the recommended lower energy limit.

Accident statistics show that a considerable number of head injuries is caused by the windscreen or A-pillars, car areas not covered by the EEVC WG10 test methods. WG17 proposes to perform further research in this field and not to include these areas already in the test methods.

Based on (new) biomechanical studies it was decided to confirm the WG10 acceptance levels for the legform to bumper test and for the headforms to bonnet top test. The French and Italian representatives in WG17 did not agree with the acceptance level for tibia acceleration. Based on new accident reconstructions it was decided to increase the acceptance levels for the upper legform to bonnet leading edge test, which will result in a better balance between real accident injury risk and test requirements. The French and Italian representatives in WG17 did not agree with this decision.

Tests on current car models (i.e. Euro-NCAP programme) show that these cars do not fulfil all EEVC WG10 test requirements. However, in spite of the fact that these models were not designed for pedestrian protection, specific areas in some car models already or almost fulfil these requirements. None of the Euro-NCAP cars passed an upper legform test. Mathematical model simulations showed that, besides the acceptance levels for this test, also the test conditions should be adjusted. Lower impact energy levels are described now for vehicles with a low bonnet leading edge. It has been estimated that almost 1/3 of the cars tested in the Euro-NCAP programme would fulfil the new upper legform to bonnet leading edge test. The French representative in WG17 stated that the new required energy is still too high, in particular for streamlined cars. The Italian representative in WG 17 stated that more research is required on this subject.

Especially for vehicles with a high bonnet leading edge, the child head impact zone has been separated from the upper legform test zone to avoid overlap. These vehicles very often have a high bumper, making the legform to bumper test less realistic and feasible. Therefore WG17 decided to describe an optional, alternative upper legform to bumper test for these vehicles.

The impactors and associated certification procedures have been improved. WG17 included the updated specifications in the new test methods. Further development and evaluation of the legform and headform impactors, based on previous impactor versions which have been used in large test programmes, is currently still going on.

References

1. Fontaine, H.:
Typological analysis of pedestrian accidents.
Journée D'Études sur les Accidents de Piétons, Paris, September 1997, EEVC WG17 document 12.
2. European Experimental Vehicles Committee:
Pedestrian injury accidents.
Presented to the 9th ESV Conference, Kyoto, November 1982.
3. European Experimental Vehicles Committee:
Cycle and light-powered two-wheeler accidents.
Presented at the 9th IRCOBi Conference, Delft, September 1984.
4. European Experimental Vehicles Committee:
Pedestrian injury protection by car design.
Presented to the 10th ESV Conference, Oxford, July 1985.
5. Commission of the European Communities:
Frontal surfaces in the event of impact with a vulnerable road user.
Ad-hoc Working Group ERGA Passive Safety, document ERGA S/60, Brussels.
6. European Experimental Vehicles Committee:
Study of test methods to evaluate pedestrian protection for cars.
EEVC Working Group 10 report, presented to the 12th ESV Conference, Gothenburg, May 1989.
7. Janssen, E.G., Nieboer, J.J.:
Protection of vulnerable road users in the event of collision with a passenger car, Part I - Computer simulations.
TNO Report No. 75405002/I under Contract No. ETD/89/7750/M1/28 to the European Commission, December 1990.
8. Janssen, E.G. et al.:
Protection of vulnerable road users in the event of collision with a passenger car, Part II - Sub-systems test method evaluation and compatibility study.
TNO Report No. 75405002/II under Contract No. ETD/89/7750/M1/28 to the European Commission, December 1990.
9. Lawrence, G.J.L. et al.:
Development of a bonnet leading edge sub-systems test to assess protection for pedestrians.
TRRL report under Contract No. ETD/89/7750/M1/28 to the European Commission, January 1991.
10. Glaeser, K.-P.:
Development of a Head Impact Test Procedure for Pedestrian Protection.
BAST report under Contract No. ETD/89/7750/M1/28 to the European Commission, June 1991.

-
11. Cesari, D., Alonzo, F.:
Assessment of Test Methods to evaluate the protection afforded to pedestrians by cars.
INRETS report under Contract No.
ETD/89/7750/M1/28 to the European Commission, December 1990.
12. Brun-Cassan, F.:
Assessment of Test Methods to evaluate the protection afforded to pedestrians by cars - Compatibility.
APR report under Contract No. ETD/89/7750/M1/28 to the European Commission, July 1991.
13. Commission of the European Communities:
Summary of the work of the consortium developing test methods to evaluate the protection afforded to pedestrians by cars (including test proposals).
European Commission Study Contract No: ETD/89/7750/M1/28, July 1991.
14. European Experimental Vehicles Committee:
Proposals for test methods to evaluate pedestrian protection for cars.
EEVC Working Group 10 report, presented to the 13th ESV Conference, Paris, November 1991.
15. European Experimental Vehicles Committee:
Proposals for methods to evaluate pedestrian protection for passenger cars.
EEVC Working Group 10 report, November 1994.
16. European Experimental Vehicles Committee:
EEVC test methods to evaluate pedestrian protection afforded by passenger cars.
EEVC Working Group 10 report, presented to the 15th ESV Conference, Melbourne, May 1996.
17. Davies, R.G. and K.C. Clemo:
Study of research into pedestrian protection costs and benefits.
MIRA report no. 97-456502-01, 1997.
18. Otte, D.:
Pedestrian impact at front end of car.
Accident Research Unit Hannover, EEVC WG17 document 10rev.
19. Otte, D.:
Injuries to pedestrians caused by impact with the front edge of car bonnets.
Accident Research Unit Hannover, November 1997, EEVC WG17 document 56.
20. Kalliske, I.:
Comparison of the evaluations of pedestrian injuries caused by the bonnet leading edge looking on AIS 1+ and AIS 2+ injuries.
BASt, June 1998, EEVC WG17 document 57rev.
21. Hardy, B.J.:
EEVC WG10 Committee paper on Pedestrian leg injuries.
TRL, May 1997, EEVC WG17 document 7.
22. Hardy, B.J.:

Analysis of pedestrian accidents, using police fatal accident files and SHIPS data.
TRL, April 1998, EEVC WG17 document 55.

23. Laumon, B. and J.L. Martin:
Injury description of the pedestrian impacted by a car.
INRETS, EEVC WG17 document 11.

24. Foret-Bruno, J.Y. and G. Faverjon:
Accidentology of Pedestrians Struck by Cars.
LAB, EEVC WG17 document 13.

25. Ramet, M. et al.:
Shearing and bending human knee joint tests in quasi-static lateral load.
Proceeding IRCOBI Conference, 1995, EEVC WG17 document 117.

26. Kajzer, J. et al.:
Shearing and Bending Effects at the Knee Joint at High Speed Lateral Loading.
SAE paperno. 973326, 1997, EEVC WG17 document 30.

27. Ishikawa, H.:
Presentation at EEVC WG17 meeting.
September 1998.

28. Ishikawa, H. et al.:
A Study on Injury Criteria of EEVC Pedestrian Legform Test.
JARI/JAMA, June 1998, EEVC WG17 document 85.

29. JAMA:
JAMA proposal regarding the Criteria of Pedestrian Protection Test Procedure.
June 1998, EEVC WG17 document 83.

30. Cesari, D.:
Pedestrian Protection - synthesis of experimental and simulation researches performed in France.
INRETS, August 1998, EEVC WG17 document 92.

31. Bunketorp, O. et al.:
Experimental Study of a Compliant Bumper System.
SAE paperno. 831623, 1983.

32. Rodmell, C. and G.J.L. Lawrence:
Comparison between dose-response and cumulative methods of injury risk analysis and implications on the JARI injury risk analysis.
TRL, November 1998, EEVC WG17 document 111.

33. Schreiber, P. et al.:
Static and dynamic bending strength of the leg.
Proceedings IRCOBI Conference, September 1997, EEVC WG17 document 61.

34. Leung, Y.C. et al.:

Study of "Knee-Thigh-Hip" Protection Criterion.

SAE paperno. 831629, 1983, EEVC WG17 document 62.

35. Matsui, Y., Ishikawa, H. and A. Sasaki:

Validation of Pedestrian Upper Legform Test - Reconstruction of Pedestrian Accidents.

Presented to the 16th ESV Conference, 1998.

36. Lawrence, G.J.L. and S.T. Thornton:

Reconstructions of Pedestrian Accidents and Their Implication on the EEVC Upper Legform Test.

TRL, September 1997, EEVC WG17 document 14.

37. Rodmell, C. and G.J.L. Lawrence:

Further Pedestrian Accident Reconstructions with the Upper Legform Impactor.

TRL, August 1998, EEVC WG17 document 90.

38. Rodmell, C. and G.J.L. Lawrence:

Further pedestrian accident reconstructions with the upper legform impactor.

TRL, November 1998, EEVC WG17 document 113.

39. DeSantis Klinich, K. et al.:

Techniques for developing child dummy references values.

NHTSA, October 1996, partly included in EEVC WG17 document 31.

40. Gustafsson, H. et al.:

Rating system for serious consequences (RSC) due to traffic accidents. Risk of death or permanent disability.

Proceedings 10th ESV Conference, 1985, partly included in EEVC WG17 document 98.

41. Glasson, E.:

Analysis of the pedestrian to bonnet leading edge impact.

ECIA, January 1998, EEVC WG17 document 34.

42. Schueler, F. and E. Glasson:

Analysis of the pedestrian to bonnet leading edge impact - evaluation of the impact energy.

ECIA, June 1998, EEVC WG17 document 86.

43. Konosu, A., Ishikawa, H. and A. Sasaki:

A Study on Pedestrian Impact Test Procedure by Computer Simulation - The Upper Legform to Bonnet Leading Edge Test.

Presented to the 16th ESV Conference, 1998.

44. Lawrence, G.J.L.:

The upper legform test explained and justified.

TRL, January 1998, EEVC WG17 document 35.

45. Lawrence, G.J.L. and B.J. Hardy:

Computer simulation of pedestrian to bonnet leading edge impact.

TRL, November 1998, EEVC WG17 document 108.

46. Lawrence, G.J.L.:

The influence of car shape on pedestrian impact energies and its application to sub-system tests.

Presented to the 12th ESV Conference, 1989.

47. ACEA:

Evaluation of the EEVC WG10 pedestrian protection test method.
Brussels, January 1998, EEVC WG17 document 64.

48. Lawrence, G.J.L.:

EEVC WG10 Committee paper on the TRL Legform impactor.
TRL, May 1997, EEVC WG17 document 16.

49. Lawrence, G.J.L. and B.J. Hardy:

Pedestrian Safety Testing using the EEVC Pedestrian Impactors.
Presented to the 16th ESV Conference, 1998.

50. Rodmell, C. and G.J.L. Lawrence:

Assessment of experimental pedestrian legform impactor and improved certification method.
TRL, April 1998, EEVC WG17 document 63.

51. Rodmell, C. and G.J.L. Lawrence:

TRL Legform Shear Spring and Damper.
TRL, September 1998. EEVC WG17 document 96.

52. Philippens, M. and E.G. Janssen:

New headform impactors.
TNO, November 1998, EEVC WG17 document 109.

53. ACEA:

Pedestrian protection draft Directive - summary of technical concerns.
Brussels, April 1998, EEVC WG17 document 65.

54. MIRA:

Addendum discussion of research into pedestrian protection costs and benefits.
Report no. 98-456502-02, 1998.

55. Sasaki, A.:

Request regarding EEVC pedestrian protection test procedure.
JAMA, April 1998, EEVC WG17 document 66.

56. Sasaki, A.:

JAMA Comment on EEVC Pedestrian Test Procedure.
JAMA, June 1998, EEVC WG17 document 84.

57. Janssen, E.G.:

EEVC pedestrian protection test procedure.
EEVC WG17 letter to JAMA, May 1998, EEVC WG17 document 77.

58. EEVC WG17:

Reply to ACEA Summary of Technical Concerns Regarding Pedestrian Protection Draft Directive.
EEVC WG17 letter and document to ACEA, July 1998, EEVC WG17 document 75.

59. EEVC WG17:

Comments on ACEA report Evaluation of the EEVC WG10 Pedestrian Protection Test Method.

EEVC WG17 letter and document to ACEA, July 1998, EEVC WG17 document 76.

60. Frei, P. and M. Muser:

Comments on component pedestrian subsystem tests proposed by EEVC-WG17 pedestrian safety.

UNI/ETH, August 1998, EEVC WG17 document 97.

61. European Commission:

Draft proposal for a European Parliament and Council Directive relating to the protection of pedestrians and other vulnerable road users in the event of a collision with a motor vehicle.

Document reference III/5021/96 EN, 1996.

62. Green, J. and Y. Otubushin:

Off-Road Vehicle Geometry and the Implications for the Pedestrian Protection Test Procedure.

Rover Group, January 1998, EEVC WG17 document 37.

63. Green, J.F.:

Energy Capping of Upper Leg Impact Tests.

Rover Group, September 1998, EEVC WG17 document 94.

64. Janssen, E.G.:

Vehicle front and pedestrian dimensions.

TNO, June 1998, EEVC WG17 document 79.

65. Green, J. and A. Young:

Head Impact Speeds against Off-Road Vehicles from MADYMO Simulation of Impacts with Different Sized Pedestrians.

Rover Group, April 1998, EEVC WG17 document 71.

66. Glaeser, K-P.:

Der Anprall des Kopfes auf die Fronthaube von Pkw beim Fussgängerunfall.

Berichte der Bundesanstalt für Strassenwesen, Fahrzeugtechnik, Heft F14, 1996.

67. Janssen, E.G.:

Child head-to-bonnet impact.

TNO, October 1997, EEVC WG17 document 19.

68. Green, J. and A. Young:

Head Impact Speeds from MADYMO Simulation of Impacts with Different Sized Pedestrians.

Rover Group, April 1998, EEVC WG17 document 33rev1.

69. ISO:

Passenger cars and light commercial vehicles - Pedestrian protection - Impact test method for pedestrian head.

ISO/TC22/SC10/WG2 doc. N553, working draft #4.

Appendix 1: Members of EEVC WG17

<u>Name</u>	<u>Country</u>	<u>Role</u>	<u>Organisation</u>
Mrs. F. Brun-Cassan	France	Expert FR	LAB
Mr. D. Cesari	France	Representative FR	INRETS
Mr. J. Green	United Kingdom	Expert UK	Rover Group
Mr. W. Hahn	Germany	Expert GE	Adam Opel A.G.
Mr. E. Janssen	Netherlands	Representative NL & Chairman	TNO
Mr. I. Kalliske	Germany	Representative GE	BASt
Mr. G. Lawrence	United Kingdom	Representative UK	TRL
Mr. A. Lie	Sweden	Representative SWE	Swedish Nat. Road Administration
Mr. P. Massaia	Italy	Representative IT	FIAT
Mr. H. Mooi	Netherlands	Secretary	TNO
Mrs. I. Skogsmo / Miss. E. Karlsson	Sweden	Expert SWE	Volvo CC / Saab Automobile AB

Appendix 2: EEVC WG17 test methods / proposed technical requirements for a Directive

The basis of the test methods is described in the final report of EEVC WG10 [15] and further improvements are described in an ESV paper [16]. This work has been used by Directorate-General III of the European Commission to draft a proposed Directive in 1996 [61]. The lay-out of this proposed Directive differs from the original WG10 lay-out and therefore this proposed Directive has been used as basis for the new EEVC WG17 test methods.

The mandate of EEVC WG10 was to determine test methods and acceptance levels for assessing the protection afforded to pedestrians by the fronts of cars in an accident. The test methods should be based on sub-system tests, essentially to the bumper, bonnet leading edge and bonnet top surface. The windscreen and A-pillar areas were excluded. Test methods should be considered that evaluate the performance of each part of the vehicle structure with respect to both child and adult pedestrians, at car to pedestrian impact speeds of 40 km/h. The different impact characteristics associated with changes in the general shape of the car front should be allowed for by variations in the test conditions (e.g. impact mass and velocity, direction of impact).

The mandate of EEVC WG17 was to review the EEVC WG10 pedestrian protection test methods and to propose possible adjustments taking into account new and existing data in the field of accident statistics, biomechanics and test results. This work was performed within 15 months, which is 3 months longer than the mandate given to WG17 by the EEVC Steering Committee. Since the final report was required by December 1998, several decisions had to be taken by majority votes. This means that for certain test methods or aspects of test methods full agreement was not achieved. The preceding chapters in this EEVC WG17 report describe the background of the decisions taken and the various minority statements made.

The Italian EEVC representative stated that Italy mainly agreed on the approach developed in the report, nevertheless pointed out the following remarks:

1. The upper leg to bonnet leading edge test should be deleted, because it is unrealistic, not completely validated and it seems nowadays not fully necessary.
2. The impactors are in a prototype stage, some further evaluations are still required.
3. The performance criteria agreed by the majority of WG17, should be placed in square brackets, for the time being, in order to point out the need for further evaluations.

The French EEVC representative stated that square brackets should be placed at:

- Annex II, § 1.1, "... and to N1 vehicles derived from M1..."
- Annex II, § 3.2, 3.3 and 3.4 for all requirements mentioned
- Annex II, § 3.5, "... 40 km/h ..."
- Annex III, § 3.2, "... minimum ..."
- Annex III, § 4.6, "... it can be mounted ... system."
- Annex IV, §2, §3.3, §3.4.1, §4 and Figure 1
- Annex V, §2, §3.4.1, §3.4.2.8, §4, Figures 1, 3, 4 and 5
- Annex V, §3.2, "... minimum ..."
- Annex V, §3.2, "However, the test point ... is available."
- Annex V, §3.3, "A test is not ... 200 J or less."
- Annex V, §3.4.2.7, "The required velocity ... in Paragraph 3.4.2.5."
- Annex VI, §3.4.2.5, "... 65° ± 2° ..."
- Annex VI, §3.4.2.7, "... 11.1 ± 0.2 m/s ..."
- Annex VII, §3, Figures 5a, 5b and 6