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25, avenue François Mitterrand - 69500 BRON (France)

Tel: +33 4 72 14 24 20, Fax: +33 4 72 14 26 66, E-mail: [charpenne@inrets.fr](mailto:charpenne@inrets.fr)

## SEVERITY AND TYPE OF PEDESTRIAN INJURIES RELATED TO VEHICLE IMPACT LOCATIONS AND RESULTS OF SUB-SYSTEM IMPACT RECONSTRUCTION

Robert Anderson, Jack McLean, Luke Streeter, Giulio Ponte,  
Marleen Sommariva, Tori Lindsay and Lisa Wundersitz

Road Accident Research Unit, The University of Adelaide, Australia

### ABSTRACT

This paper examines the relevance of the EEVC pedestrian subsystem tests and the extent to which they predict the severity of specific injuries.

Ten accidents were reconstructed using numerical and laboratory methods to estimate the severity of impacts to the pedestrian's head and lower extremities. Headform impacts that exceeded a HIC of 1000 were strongly and positively associated with head injuries rated AIS3 and above. The acceleration of the Legform appears to be positively associated with the severity of injuries to the leg below the knee. However, the level of bending and shearing of the Legform knee joint greatly overestimated the risk of ligamentous damage to the knee.

**Keywords:** PEDESTRIANS, ACCIDENT RECONSTRUCTIONS, COMPONENT TESTS, EEVC, IMPACTORS.

THE PREVENTION OF PEDESTRIAN INJURY by vehicle design is now a part of the New Car Assessment Programs (NCAP) in Europe and Australia, and is a topic of regulation in Europe and Japan. There are three international committees working on the further development of tests to assess the level of pedestrian protection afforded by a vehicle in the event of a collision. They are Working Group 17 of the European Enhanced Vehicle-safety Committee (EEVC), the International Harmonised Research Activities Pedestrian Safety Expert Group and the International Standards Organisation Working Group on Pedestrian Impact Test Procedures (TC22/SC10/WG2).

The EEVC was one of the first organisations to examine the possibility of developing a test procedure to evaluate the degree of pedestrian protection afforded by the front of a vehicle. EEVC Working Group 7 examined injury patterns and sources of injury among pedestrian casualties and fatalities in Europe (EEVC, 1982). The data collected indicated that the most commonly injured regions of the body were (in descending order) the head, lower limbs, the arms, the thorax, and the pelvis. When only severe injuries were examined, the head and lower limbs were most frequently involved (EEVC, 1994). EEVC Working Group 10 was formed as a result of the report of an ad hoc group of the EEVC that examined further research findings that followed the final report of Working Group 7. Working Group 10, which was given the mandate to determine test methods and acceptance levels, devised a set of impact, or subsystem, tests to measure the risk of injury to the head of an adult and a child pedestrian from an impact with the striking vehicle using free flight headforms (the Adult and Child Headform); the risk of injury to the upper leg of an adult using a guided impactor (the Upper Legform); and the risk of injury to the knee joint and tibia of an adult using a free flight leg impactor (the Legform) (EEVC, 1994). WG17, which revisited the work of WG10 in 1997, further refined the subsystem tests and test devices (EEVC, 1998, with a final report due later this year). The extent to which these subsystem tests predict the occurrence and severity of real-world pedestrian injuries is clearly a matter of considerable importance. Where a test is used to represent an impact that occurred in an actual pedestrian accident, the results of the test should reflect the nature and severity of the injuries sustained from that impact. The study reported herein was designed to compare the injuries resulting from head and leg impacts incurred in pedestrian collisions with the results from the corresponding subsystem test.

The aims of this study were:

- To determine the incidence of the injuries addressed by the EEVC subsystem tests.
- To reconstruct the head and leg impacts sustained by pedestrians when struck by a vehicle, through a combination of accident investigation, computer simulation and physical reconstructions using the EEVC subsystem tests, and
- To examine the validity with which the results of the subsystem tests predicted the occurrence and the severity of the injuries caused in the actual pedestrian collisions.

## ACCIDENT INVESTIGATION AND ANALYSIS

Eighty pedestrian accidents were investigated at the scene in a recent study of the effects of vehicle design and impact speed on pedestrian injury conducted for the Australian Commonwealth Department of Transport and Regional Services (Anderson et al., 2000a). The focus of the data collection was on items of information that would allow an estimation of the vehicle travel and impact speeds, contacts between the pedestrian and the vehicle, injuries sustained in the accident and the likely source of those injuries. Ten of these cases were selected for the purpose of reconstructing the impacts using subsystem procedures.

The accident investigation typically began with notification from the South Australian Ambulance Service that they were to attend the scene of a pedestrian accident. In fatal cases, the investigation often began with a member of the research team attending the Coronial autopsy. The scene of the accident was surveyed, and the lengths of any skid-marks left by the vehicle were measured, along with the location of the impact point and final position of the pedestrian, scuff marks on the road, debris, and any other feature of relevance. If the pedestrian was fatally injured, their injuries were recorded at the autopsy, along with their height, weight and the dimensions of various body segments. In non-fatal cases, the pedestrian was interviewed to determine the nature and severity of their injuries and, where possible, the circumstances of the collision. Consent was sought for access to hospital medical records, from which information on their injuries was also collected. The South Australian Trauma Registry was consulted in cases where data on the pedestrian's injuries were not complete. Furthermore the vehicle involved in the accident was inspected, either at the scene of the accident or, if the accident was fatal, at the vehicle compound of the South Australian Police. The vehicle was inspected for signs of contact with the pedestrian, which could usually be identified by dents, scratches and scuffs in the body of the vehicle. The location of the head contact could be identified not only by a dent in a panel or crack in the windscreen, but also often by the presence of hair on the contact area. The location of each contact location was also measured, so that the fidelity of the motion of the computer simulation could be verified, and to identify the impact point on the test vehicle.

Injuries sustained by each pedestrian were coded according to AIS90. Table 1 lists the incidence of AIS3+ and AIS 2+ injuries affecting body regions as defined by AIS90. (Only cases in which the striking vehicle was one of a category of passenger vehicle that is being considered by the IHRA Pedestrian Safety Expert Group - sedan, SUV, and one-box - are included in this table). As an impact may cause more than one severe injury in a given body region - skull fracture and a brain injury for example - only the single most severe AIS score for each body region of each pedestrian is listed in Table 1. On inspection, Table 1 supports the focus of protection strategies on the head and lower extremities (which, by the AIS90 definition, includes the pelvis), as they account for more than 50% of MAIS 2+ injured body regions in the sample of cases. (Note that here MAIS is used to refer to the most severe injury in a specified body region, not necessarily to the most severe injury sustained by the individual pedestrian.) It is worth noting however, that the spine, thorax and abdomen are as important, or more so, when considering more severe injury (MAIS3+). These body regions are not considered by the test methods, and this is worthy of further investigation.

The incidence of injuries to body regions targeted by the EEVC subsystem test procedures is listed in Table 2. This table includes the single most severe injury of its type to the pedestrian. The incidence of the injuries is expressed as a percentage of the total number of pedestrians struck in the

sample of accidents. For example, Table 2 shows that approximately 24% of pedestrians sustained at least one head injury rated AIS 3, or greater.

**Table 1 Incidence of AIS3+ injuries by body region (using single most severe injury to the region) in pedestrians struck by passenger vehicles**

| Body region (by AIS code) | MAIS 3+ |        | MAIS 2+ |        |
|---------------------------|---------|--------|---------|--------|
| 1 Head                    | 16      | (43%)  | 25      | (28%)  |
| 2 Face                    | 1       | (3%)   | 6       | (7%)   |
| 3 Neck                    | 0       | (0%)   | 1       | (1%)   |
| 4 Thorax                  | 6       | (16%)  | 6       | (7%)   |
| 5 Abdomen                 | 4       | (11%)  | 7       | (8%)   |
| 6 Spine                   | 6       | (16%)  | 7       | (8%)   |
| 7 Upper extremities       | 0       | (0%)   | 13      | (15%)  |
| 8 Lower Extremities       | 4       | (11%)  | 23      | (26%)  |
| Total                     | 37      | (100%) | 88      | (100%) |

**Table 2 Incidence of injuries to pedestrians struck by passenger vehicles, corresponding to the subsystem tests (one per injury type per pedestrian)**

| Injury type               | Count | Proportions of total sample (N=67) |
|---------------------------|-------|------------------------------------|
| Head injury (MAIS 3+)     | 16    | 24%                                |
| Fractured femur           | 0     | 0%                                 |
| Fractured pelvis          | 9     | 13%                                |
| Fractured tibia/fibula    | 14    | 21%                                |
| Ruptured ligament in knee | 1     | 2%                                 |

## COMPUTER SIMULATION AND IMPACT RECONSTRUCTION

Ten cases were selected for computer simulation and reconstruction based on the level of certainty about the dynamics of the accident, and that the injuries sustained by the pedestrian were known and could be related to impacts with the vehicle. The selection of cases was also designed to encapsulate a range of impacts that are covered by the EEVC-type subsystem tests: the Upper Legform test, the Legform test and the Adult and Child Headform tests. The list of cases is presented in Table 3, together with the impacts that were reconstructed from each case. Note that in Case PED061 the Child Headform test was used as the fatally injured pedestrian was a ten year old female.

**THE PEDESTRIAN MODEL:** The model that was used for the simulation part of this study was developed specifically to simulate pedestrians in car-pedestrian collisions. The model has been presented previously, and used for accident simulation purposes (eg: Garrett, 1996, Anderson et al., 2000b). The model consists of 17 rigid segments linked by kinematic joints that are largely based on the model proposed by Ishikawa et al. (1993) although some joints have been added while others have been modified. Recently the neck has been redesigned to better reflect the findings of human volunteer tests (Thunnissen et al., 1995; Wismans et al., 1986). The model has been implemented in the dynamic simulation program MADYMO (TNO, Delft, The Netherlands).

**MODEL VALIDATION:** The model was checked to ensure that it satisfied validation corridors that were constructed on the basis of post-mortem human subject (PMHS) tests, carried out in Hanover (Ishikawa et al., 1993). The model's behaviour is in accordance with the corridors drawn from those PHMS tests (Anderson et al., 2001).

**Table 3 Cases selected for the study**

| Case number | Age | Sex | Car year, Make and model | Relevant injuries   | MAIS |       |      |       | Physical reconstructions |       |       |
|-------------|-----|-----|--------------------------|---|------|-------|------|-------|--------------------------|-------|-------|
|             |     |     |                          |   | Head | U/leg | Knee | L/leg | Head                     | U/leg | F/leg |
| PED011      | 13  | F   | 1988 Holden Camira       | Fatal head and neck injuries  | 3    |       |      |       | ●                        |       |       |
| PED018      | 79  | F   | 1982 Nissan Bluebird     | Fatal head injuries. Pelvic fractures, tibia and fibula fractures               | 4    | 2     | 0    | 2     | ●                        | ●     | ●     |
| PED035      | 83  | F   | 1991 Ford Falcon         | Ankle fracture  | 2    |       | 2    | 0     | ●                        |       | ●     |
| PED043      | 52  | M   | 1992 Ford Fairmont       | Fatal head injuries, laceration of right hip                                    | 5    | 1     | 0    | 1     | ●                        | ●     | ●     |
| PED049      | 15  | F   | 1997 Ford Falcon         | Head injuries, knee contusions  | 3    |       | 0    | 1     | ●                        |       | ●     |
| PED056      | 35  | M   | 1983 Holden Commodore    | Open fracture of tibia and fibula   | 1    |       | 3    | 0     | ●                        |       | ●     |
| PED057      | 15  | F   | 1973 Holden Kingswood    | Brief loss of consciousness and concussion, open knee wound, fracture of pelvis | 2    | 2     |      |       | ●                        | ●     |       |
| PED061      | 10  | F   | 1997 Mitsubishi Magna    | Fatal head injuries   | 5    |       |      |       | ● <sup>1</sup>           |       |       |
| PED064      | 19  | F   | 1993 Holden Commodore    | Deep bruising of knee   | 0    |       | 0    | 1     | ●                        |       | ●     |
| PED076      | 79  | F   | 1996 Ford Falcon         | Brief loss of consciousness, tibia fractures                                    | 2    |       | 3    | 0     | ●                        |       | ●     |

1. Child Headform

**SIMULATION OF THE ACCIDENTS:** The cases that were modelled in this study involved pedestrians of varying ages and statures. The model was based on and validated against the behaviour of a fiftieth percentile adult male. Therefore the model had to be scaled appropriately for the simulation of each case. The anthropometric data for each pedestrian (body segment dimensions, masses and moments of inertia) were derived from GEBOD (Baughman, 1983), a program which generates anthropometric segment data using regression equations derived from a database of human body measurements. In several cases, the resulting dimensions could be checked against body dimensions of the actual pedestrians, measured by a member of the research team, either during interview, or at autopsy for fatal cases. In cases where the dimensions could be cross referenced in this way they corresponded closely.

The next step in the simulation process was to determine the posture of the pedestrian prior to impact. It was assumed that the both the walking velocity and the velocity of the limbs during locomotion could be ignored. The orientation of the pedestrian relative to the car was known in each of these cases, either from the pedestrian themselves or from drivers, witnesses and/or marks on the body. In some cases the posture of the body of the pedestrian could be similarly determined. The impression of the bumper or other component of the vehicle often indicated the orientation of the pedestrian, and the alignment of marks on the body of the pedestrian often indicated the position of limbs and torso as they were struck. However, in many cases it was not possible to determine the exact position or posture of the pedestrian. In these cases, body postures representative of the human gait cycle were used to generate separate simulations.

**VEHICLE MODELLING:** Vehicles that corresponded to the make, model and series of those involved in the cases were obtained for the physical reconstruction process. These cars also provided the geometry of the cars for the simulation exercise. A Geodimeter (usually used in surveying) was used to measure the main geometrical features of the car in Cartesian coordinates. These were used as a basis of the geometry created in MADYMO. The geometry was imported into Easi-CrashMAD (a MADYMO pre-processor) and the vehicle geometry was then approximated by defining planes, elliptical cylinders and ellipsoids. Where the vehicle in the case was braking heavily at the moment of impact, the front of the vehicle was lowered by 100mm and the vehicle rotated by 3 – 5°.

**EFFECTIVE MASS AND VELOCITY CALCULATIONS:** The EEVC WG10 Upper Legform test procedure is intended to reproduce the angle, velocity and inertia of an impact with the upper leg of a pedestrian. The relationship between the vehicle geometry and the test conditions are

encapsulated in a series of charts that are used to look up the test conditions. In these reconstructions of actual collisions the impact speeds were obviously not the standard 40km/h as is assumed in the EEVC test procedures. Consequently the charts used to determine the test conditions could not be used. Instead the simulations were analysed using the same methods that were used to generate the charts used in the EEVC test procedure. The methods for determining test conditions are described in Janssen and Nieboer, (1990) and reviewed in Konosu et al., (1998).

In this study, each simulation was analysed using post-processing software specifically written for the task. The upper leg velocity, the penetration of the upper leg ellipsoid/leading edge, and the forces associated with this interaction were extracted from the simulation. For the purposes of determining the test angle, the kinetics of the upper leg/leading edge interaction were examined in the interval where the impact force was greater than 40 percent of the peak impact force. This restricted the examination of the kinetics to the main part of the impact. The components of the impact force in the vertical direction and the longitudinal direction of the car were used to calculate the angle at which the impact force was acting over the interval of the contact.

The effective mass of the upper leg in the simulation was calculated by examining the peak elastic energy stored during the impact. The elastic contact force ( $F$ ) was integrated with respect to the penetration ( $p$ ) from the beginning of the contact to the peak penetration ( $p_{max}$ ). The speed of the upper leg relative to the vehicle just prior to its contact with the leading edge ( $v$ ) was then used to determine the effective mass of the upper leg at peak penetration. The effective mass,  $m_{eff}$  was calculated as follows:

$$m_{eff} = \frac{2}{v^2} \int F dp$$

The minimum mass of the Upper Legform (as implemented in our laboratory) is 8.75 kg, and so where the calculated effective mass of the upper leg was less than this, the velocity of the Upper Legform was adjusted to maintain the energy of the impact, as follows:

$$v_{adjusted} = v \sqrt{\frac{m_{eff}}{8.75}}$$

The velocity of the head was determined by simply taking the velocity of the head relative to the car at the time step prior to initial contact with the vehicle surface. Similarly, the Legform velocity was taken from the impact speed of the vehicle.

## PHYSICAL RECONSTRUCTION

The final step in the study of each case was the reconstruction of the head and leg impacts. The car used to reconstruct impacts from each case was a vehicle of the same make, model and series as that involved in the actual accident. Where possible, a vehicle of the same year of manufacture was obtained. The results of the simulation of each accident were used to determine the initial conditions.

The severity of the Headform impact was measured by the Head Injury Criterion (HIC). Impacts that produce HIC values of more than 1000 are considered to be unacceptably severe, and the EEVC criterion is that the HIC value of the test should not exceed this value.

The Upper Legform consists of a tubular steel "femur" section that is simply supported at its ends. Force transducers at each end record the loads on the supports, and three strain gauges measure the bending moment. The EEVC WG10 criteria are that the support forces should not exceed 4 kN and the bending moment should not exceed 220 Nm.

The Legform consists of a femur and tibia section, connected by a deformable knee joint. The Legform measures the risk of ligamentous injury and dislocation of the knee, and the risk of a fracture of the tibia. The EEVC WG10 criteria are that the tibia acceleration should not exceed 150g, the knee rotation should be less than 15°, and the knee shear displacement should be less than 6 mm.

## RESULTS

The results of the simulations were used to choose initial conditions for the impact reconstructions. In two cases, the impact speed of the vehicle could not be determined accurately from the evidence. In these cases, the simulations were run at the upper and lower limits of the estimate of the impact speed of the vehicle.

The results of the simulations are summarised in Tables 4, 6 and 7. The simulation results given in each table are those that defined the set up of the impact reconstruction. These tables also describe how the test conditions were determined for each test, and the actual test conditions measured during the test.

Note that:

- In Case PED011, the head impact reconstruction produced much less damage to the car than was expected. In this case, the test was repeated until the damage observed in the accident was replicated. In all other cases, the damage produced was consistent with that seen in the accident.
- In Case PED057, the test speed in the Upper Legform test was lowered as it was thought that the impact would be severe enough to damage the test equipment. It was decided that if the test at the lower speed did not fail, the test would be repeated at a higher speed.
- Similarly, in Cases PED018 and PED056, the speed of the Legform test was lowered to avoid damage to the test tool.
- The head impact velocity estimated in the simulation of Case PED076 was relatively low, and the design of the launcher is such that it is not possible to fire the Headform at such a low speed, at the angle specified. This is because gravity would cause the Headform to interfere with the launcher before it exited. The only feasible alternative in this case was to launch the Headform vertically.

**Table 4 Summary of target Headform test conditions from the simulations**

| Case Number | Simulation results |        | Target test conditions                            | Actual set up |        | Results |                     |
|-------------|--------------------|--------|---|---------------|--------|---------|---------------------|
|             | Speed              | Angle  |   | Speed         | Angle  | HIC     | Peak accel.         |
|             | (m/s)              | (deg.) |   | (m/s)         | (deg.) |         | (m/s <sup>2</sup> ) |
| PED011      |                    |        | based on simulation (first attempt)               | 8.47          | 42     |         |                     |
|             | 8.5                | 42     | based on simulation (second attempt)              | 8.42          | 42     |         |                     |
|             |                    |        | based on damage to bonnet                         | 12.67         | 42     | 2953    | 232                 |
| PED018      | 11.6               | 65     | based on simulation                               | 11.48         | 64     | 3765    | 281                 |
| PED035      | 8.2                | 52     | based on simulation                               | 8.1           | 52     | 491     | 97                  |
| PED043      | 9.9                | 47     | based on simulation                               | 9.76          | 47     | 1177    | 126                 |
| PED049      | 10.6               | 46     | based on simulation                               | 10.37         | 46     | 1678    | 193                 |
| PED056      | 15.5               | 45     | based on simulation                               | 15.32         | 45     | 524     | 168                 |
| PED057      | 13.8               | 54     | based on simulation (high end of estimated range) | 13.65         | 54     | 3558    | 326                 |
|             | 12.3               | 55     | based on simulation (low end of estimated range)  | 12.21         | 55     | 4109    | 319                 |
| PED061      | 6.4                | 39     | based on simulation                               | 6.45          | 39     | 1718    | 229                 |
| PED064      | 6.5                | 47     | based on simulation                               | 6.51          | 47     | 136     | 96                  |
| PED076      | 4.4                | 61     | based on simulation (high end of estimated range) | 4.41          | 90     | 28      | 46                  |
|             | 2.9                | 70     | based on simulation (low end of estimated range)  | 2.89          | 90     | 128     | 47                  |

**HEAD IMPACT RECONSTRUCTIONS:** The relationship between the results of the head impact reconstructions and the head injuries sustained by the pedestrians in the study is presented in Figure 1. The figure plots the values of the Head Injury Criterion for each test against the severity of the head injury in the associated head impact. There appears to be a positive association between the value of HIC and the severity of the injury. The exception appears to be the reconstruction of Case PED057. This case was unusual in that the pedestrian was not as severely injured as we might have expected, given the high speed at which she was struck. The bonnet of the car involved in the collision was pushed upward some distance by the initial impact at the front of the bonnet. We hypothesise that

this increased the clearance between the bonnet and the car structure beneath in the vicinity of the head impact. This increased clearance may have softened the impact considerably. If this is the case, the head impact may have been far less severe in the accident than predicted by the reconstruction. Nevertheless, there is a statistically significant positive association between the severity of the head injury in the case and the severity of the impact assessed by the EEVC criteria. Table 5 summarises the severity of the injuries in the cases by the impact severity, estimated by the reconstruction process. Fisher's exact test applied to this data supports the hypothesis that head injuries MAIS 3 or greater are associated with HIC values greater than 1000 ( $p = 0.0238$ ).

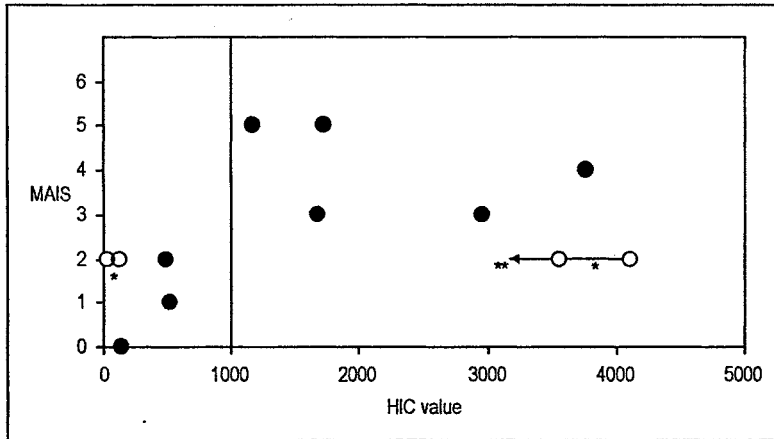


Figure 1 Head injury severity in the cases studied, and the HIC values measured in the impact reconstructions. (\*The graph includes results of two tests each for Case PED057 and PED076. \*\*The likely severity of the head impact in PED057 was probably less than the reconstruction - see text).

Table 5 Summary of the data on impact severity and the related level of injury

|                          |          | Head injury severity |       | Total |
|--------------------------|----------|----------------------|-------|-------|
|                          |          | AIS≤2                | AIS>3 |       |
| Result of reconstruction | HIC<1000 | 4                    | 0     | 4     |
|                          | HIC≥1000 | 1                    | 5     | 6     |
|                          | Total    | 5                    | 5     | 10    |

$p = 0.0238$  by Fisher's exact test

Table 6 Summary of target Legform test conditions from the simulations

| Case Number | Impact speed from collision analysis (m/s) | Target test conditions                             | Measured test speed (m/s) | Tibia acceleration (g) | Knee bending (degrees) | Knee shear (mm) |
|-------------|--|--|---------------------------|------------------------|------------------------|-----------------|
| PED018      | 13.6                                       | Reduced impact speed to avoid damage to test tool  | 10.85                     | 169.2 (min)            | 32.3(min)              | 4.1 (min)       |
| PED035      | 9.4  | Based on impact speed                              | 9.24                      | 289.6                  | 29.1                   | 7.9             |
| PED043      | 9.7  | Based on impact speed                              | 9.74                      | 293.4                  | 32.2                   | n.a.            |
| PED049      | 11.9                                       | Based on impact speed                              | 11.55                     | 165.8                  | 32.5                   | 3.9             |
| PED056      | 16.7                                       | Reduced impact speed to reduce damage to test tool | 11.80                     | 283.7 (min)            | 33.1 (min)             | 7.5 (min)       |
| PED064      | 10.0                                       | Based on impact speed                              | 10.00                     | 199.4                  | 29.9                   | 2.8             |
| PED076      | 6.1 / 8.1                                  | Based on impact speed (low / high)                 | 6.08 / 7.72               | 233.7/338.0            | 15.9/21.7              | 3.4/3.7         |



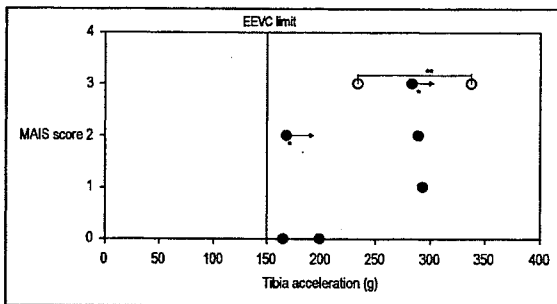
**Table 7 Summary of target Upper Legform test conditions from the simulations**

| Case Number | Simulation results |         |                | Target test conditions   | Actual set up |        | Results           |                     |
|-------------|--------------------|---------|----------------|--|---------------|--------|-------------------|---------------------|
|             | Speed              | Angle   | Upper leg Mass |  | Speed         | Angle  | Max support force | Max. Bending moment |
|             | (m/s)              | (deg.)  | (kg)           |  | (m/s)         | (deg.) | (kN)              | (Nm)                |
| PED018      | 10.5               | 47      | 8.75           | Based on simulation  | 10.4          | 47     | 5.07              | 423                 |
| PED043      | 6.8                | 60      | 8.75           | Based on simulation  | 6.6           | 50     | 4.49              | 344                 |
| PED057      | 17.6 / 15.5        | 38 / 30 | 8.8 / 9.5      | Simulation results too severe, therefore a lower impact speed was chosen | 12.1          | 30     | 7.86              | 605                 |

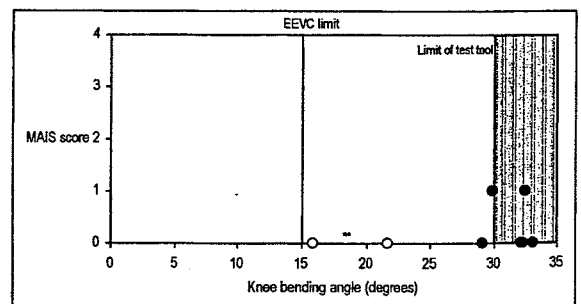
**LEG IMPACT RECONSTRUCTIONS:** The results of the leg impact reconstructions are shown in Figure 2 to Figure 6. The severity of injury below the knee appears to be positively associated with higher tibia accelerations in the tests. However, all tests in this study failed the EEVC criteria, on the basis of the tibia acceleration, including two tests that were associated with no injury in the actual case. (Note that two tests were made using less severe test set up conditions to protect the test tool from damage.) This would imply that the EEVC WG10 limit is too low.

There seems to be little association between knee injury severity and the parameters that describe the kinematics of the knee in the test (Figure 3 and Figure 4). This may be because the test is specifically designed to measure lateral loading to the knee, and the loads applied to the knee in real life collisions are rarely purely lateral. Even if the leg is orientated so that the load is initially applied in a lateral direction, the impact may produce rotation of the leg during the impact, decreasing the lateral loads.

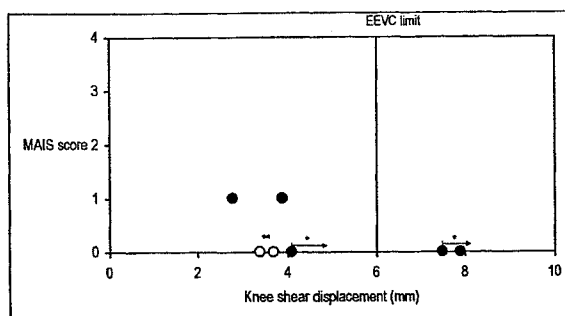
The final two graphs (Figure 5 and Figure 6) show the relationship between the reconstruction of the upper leg impact and the injuries produced by the associated impact in each case. Although all injuries were associated with impacts that failed the EEVC criteria, the number of reconstructions is too few to make any conclusions about the relationship between the results of the tests and real life injury. In Case PED057, the test was conducted at a lower speed than that indicated by the simulation. This was done because of the stiffness of the structure being struck and the associated risk of damaging the test device. Therefore, the result of this test should be considered a low estimate of the actual impact severity. We predict that had the test conditions been set to those indicated by the simulation, a much more severe impact would have resulted.



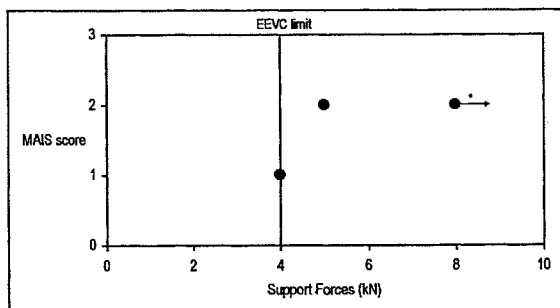
**Figure 2 Lower leg injury severity in the cases studied, and the tibia acceleration measured in the impact reconstructions (\*The likely severity of the impact in Cases PED018 and PED056 was probably greater than the reconstruction. \*\* The graph includes results of two tests for Case PED076-00 - see text)**



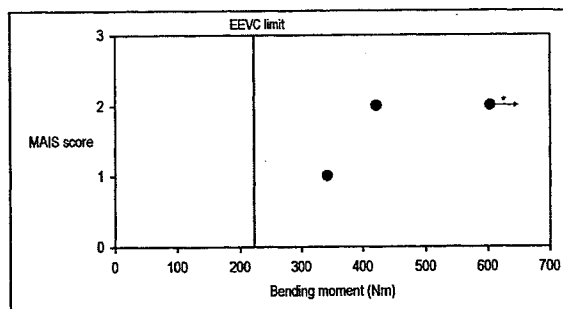
**Figure 3 Knee injury severity in the cases studied, and the knee bending angle measured in the impact reconstructions (\*\* The graph includes results of two tests for Case PED076 - see text)**



**Figure 4** Knee injury severity in the cases studied, and the knee shear displacement measured in the Legform in the reconstructions (\*The likely severity of the impact in Cases PED018 and PED056 was probably greater than the reconstruction. \*\*The graph includes results of two tests for Case PED076 - see text)



**Figure 5** Upper leg/pelvis injury severity in the cases studied, and the support forces measured in the Upper Legform in the reconstruction (\*The likely severity of the impact in Case PED057 was probably greater than the reconstruction - see text)



**Figure 6** Upper leg/pelvis injury severity in the cases studied, and bending moment in the Upper Legform in the reconstruction (\*The likely severity of the impact in Case PED057 was probably greater than the reconstruction - see text)

## DISCUSSION AND CONCLUSIONS

Test procedures such as those developed by the EEVC provide a means of assessing the performance of technology that is introduced to protect pedestrians in collisions. However, the EEVC tests are based on available data on human tolerance to impact. The aim of the research reported here has been to assess the validity of these tests with reference to the levels that have been assumed for impact tolerance. We have been able to demonstrate that the EEVC WG10 Headform impact test, when used to reconstruct a real-world impact, does relate to the severity of the injury. While the number of cases was small, there was a positive and statistically significant relationship between the results of the reconstruction tests using the EEVC WG10 Headforms, as measured by the Head Injury Criterion, and the severity of the injury in the cases, as measured by the Abbreviated Injury Scale.

The relationship between the Legform acceleration and below-the-knee leg fractures appears to be positive, although the criterion for fracture appears to be too low. More tests are required before the Legform's predictive ability can be proven statistically. The results from the Legform that pertain to the kinematics of the knee appear more problematic, as there is no apparent relationship between the kinematics of the knee in the reconstruction test, and the injuries observed in the cases but, again, the number of cases is small. The knee of the Legform is designed to replicate the behaviour of the human knee in lateral bending. It could be argued that the test is not appropriate in the reconstruction of impacts where the knee was not loaded in a purely lateral fashion. Nevertheless, even when knee bending was more than double the EEVC WG10 pass criterion, no ligamentous damage was caused in the actual collision. A recent study concluded that the criterion for knee bending and shear should be increased, to account the effect of bending in the lower leg (Konosu et al, 2001). The lower section of the Legform is rigid, whereas the human lower leg has some flexibility. An impact of a given force will tend to bend the long bones in the lower leg, as well as generating bending and shearing in the

knee joint. The bending of the bones will reduce the amount of knee bend and shear. However, the rigid tibia section in the Legform means that the energy in an equivalent impact is expressed only in knee bending and shearing, and these kinematics are amplified. Konosu et al, (2001) argue that this effectively means that the limit for knee bending should be increased to 20°, and the shear limit to 23 mm (a displacement not possible with the current design). They argue that it would be more appropriate to redesign the lower section of the Legform to allow some bending.

As mentioned above, this study appears to confirm that the reconstructed level of the tibia acceleration is associated with the severity of injuries to the tibia and fibula, as defined by AIS90. It may be observed, however, that the tolerance level that has been set by the EEVC WG10 appears too low. Stiffening the knee would be likely to reduce the acceleration of the tibia during the impact, as would the introduction of a deformable or frangible tibia element. Therefore, for a given injury severity, either of these modifications would probably reduce the associated tibia acceleration. It is possible, therefore, that it is not the criterion that is too low, but that the Legform may be producing accelerations that are too high, by the nature of the knee and/or the tibia section. It is clearly important that the Legform be evaluated further.

The number of accidents used to examine the Upper Legform test is too low to make a meaningful conclusion on this part of the study. A more comprehensive study has been completed, albeit using a slightly different methodology, on the ability of the Upper Legform to predict real world injury (Rodmell and Lawrence, 1998). That study suggested injury thresholds of 5kN and 300 Nm, and the three cases presented here are consistent with that finding.

The incidence of spinal, thoracic and abdominal injuries in our sample highlights the types of serious injuries that are not addressed by current subsystem testing protocols. Although the sample was small, the incidence of these injuries does not appear to be associated with particular age groups in our sample.

We recommend that consideration be given to further evaluation of the subsystem impactors and their associated test methods. This report contains results that support the use of the Headform test for the evaluation of pedestrian protection. The number of cases at our disposal has not been adequate to draw any supportable conclusions about the Legform and Upper Legform subsystem tests, but the results that we have obtained imply that further research is needed.

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