Vehicle design and speed and pedestrian injury: Australia's involvement in the International Harmonised Research Activities Pedestrian Safety Expert Group

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ABSTRACT

Australia is contributing to the International Harmonised Research Activities Pedestrian Safety Expert Group (IHRA PSEG) through research undertaken at the Road Accident Research Unit, and funded by the Commonwealth Department of Transport and Regional Services. The IHRA PSEG is charged with the development of test procedures for assessing the protection afforded by the vehicle to a pedestrian in the event of a collision. The Group is seeking to develop these test procedures based on field data on pedestrian accidents. Importantly, the test procedures will take into account different vehicle shapes and pedestrian anthropometry. As with procedures developed by the European Enhanced Vehicle-safety Committee, these procedures will be based on sub-systems representing the head, upper leg and full leg. The Road Accident Research Unit has contributed field data collected in the period 1977-2000, showing the importance of protecting the head and lower extremities in a pedestrian collision. The Unit has also participated in an extensive computer simulation task to develop test conditions for different car shapes. A validated MADYMO model of a 50th percentile male pedestrian was positioned in front of vehicles that represented a range of frontal shapes. The results of the computer simulations were analysed to extract the equivalent subsystem test conditions that reproduce the impacts predicted by the model. Parallel studies were undertaken in Japan and the USA with alternative models, and the results have been compiled and compared. The results showed that the test conditions required in subsystem tests depend on the profile of the car. The study will be extended to models of children and adults of different stature, to produce a comprehensive set of test conditions for pedestrian subsystem tests.

INTRODUCTION

Pedestrian fatalities account for approximately 16 percent of Australia's road toll [1]. The number of pedestrians killed in Australia is declining, with a fatality rate per 100,000 population similar to other industrialised countries [2]. Pedestrian fatalities as a proportion of road fatalities is much higher worldwide, with some estimates putting pedestrians as high as 40-50% percent of the world's annual road toll [3].

One strategy being pursued to reduce the numbers of pedestrians killed and injured, is the introduction of specific test methods to measure the levels of protection afforded to pedestrians by a vehicle, should a collision occur. The European Enhanced Vehicle-safety Committee has devised a set of impact tests to measure the risk of injury to the head of adults and children using free flight headforms, the upper leg of an adult using a guided impactor and the knee and tibia of an adult using a free flight leg impactor [4, 5]. The International Standards Organisation (ISO) and the International Harmonised Research Activities Committee (IHRA) are also developing test procedures for pedestrian protection, largely based on the work of the EEVC [6].

Australia is contributing to the IHRA PSEG through its representation on the committee, through the analysis of pedestrian injury and fatality data, and by contributing to a cooperative computer simulation activity. These investigations have revealed the most commonly injured parts of the body, and the object struck, and the vehicle speeds at which injury is occurring. Further, the computer simulation study will be used to determine set-up conditions in the test procedures themselves.

PEDESTRIAN INJURIES: INJURY SOURCES AND VEHICLE SPEEDS

Data

The data were compiled from two separate studies; the second Adelaide In-Depth Accident Study [7], completed at the end of 1979, and a more recent study of the effects of vehicle design and speed on pedestrian injury, undertaken between 1998 and 2000 [8]. The second Adelaide In-Depth Accident Study (1975-1979) was designed "to evaluate the effectiveness of many existing safety measures and to identify other factors related to accident or injury causation in road accidents in metropolitan Adelaide." [7]. This at-the-scene study was of a representative sample of accidents to which an ambulance was called in the Adelaide metropolitan area. It comprised 304 accidents including 40 pedestrian accidents of varying severity. Cases ranged in severity from those of a minor nature, with insignificant interaction between pedestrian and car, through to fatal accidents.

Between 1998 and 2000, 77 pedestrian accidents were investigated at the scene for the Australian Commonwealth Department of Transport and Regional Services. 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.

Analysis

Injuries sustained by the pedestrian(s) were coded according to AIS90 in the recently collected cases and AIS76 in the cases from the second Adelaide In-Depth Study. The AIS codes in the latter series were updated only in respect of the body region classification for each injury. Table 1 lists the body regions as defined by AIS90, in descending order of the incidence of AIS3+ injuries. As an impact may cause more than one severe injury (skull fracture and a brain injury, for example), only the single most severe AIS score for each body region of each pedestrian was considered. On inspection, Table 1 seems to justify the focus of protection strategies on the head and lower extremities (which by the AIS90 definition, includes the pelvis), as these account for 50% of seriously injured regions in the sample of cases.

Table 1 Incidence of AIS3+ injuries by body region (using the single most severe injury to the region)

Body region (by AIS code)	Body region count	
Head	19	(30%)
Lower extremity	13	(20%)
Thorax	12	(14%)
Abdomen	10	(12%)
Spine	10	(12%)
Upper extremity	5	(6%)
Face	2	(2%)
Neck (exc. Spine)	2	(2%)
Total	**83**	**(100%)**

The incidence of specific injuries targeted by the EEVC test procedures is listed in Table 2. This table includes the single most severe injury, greater or equal to AIS 3, in that body region targeted by each test procedure. The incidence of the injuries is expressed as a percentage of the total number of collisions in the sample of accidents. For example, the Table 2 suggests that approximately 15% of pedestrian accidents result in a head injury of AIS 3, or greater.

Table 2 Incidence of injuries scoring AIS3+ in the sample (one per injury type per pedestrian)

AIS 3+ injury type	Number	Proportion of total sample
Head injury	19	15%
Fractured femur	3	2%
Fractured tibia and /or fibula)	7	6%
Fractured pelvis	4	3%
Ruptured ligament in knee	2	2%
Total	**45**	**36%**

Table 3 shows the source of injury to various body regions. While the road and roadside objects were the most common source of injury to the head in these cases, they were not the source of any AIS3+ injury to the head. The impact with the road is often (but not always) similar in energy to a fall from a person's own height, and the types of injuries attributed to the roadway reflect this. The most common sources of serious head injuries were the base of the windscreen and trailing edge of the bonnet, the A-pillar and adjacent windscreen, and the bonnet itself.

Table 4 categorises the head impact locations on the vehicles (where the head impact point could be identified) by the head impact zones defined by the EEVC WG10 procedures. Here, and in the remaining tables, only the accidents investigated between 1998 and 2000 are considered, as the required data was not collected in the earlier series of crash investigations. This table indicates that there is some overlap in the distribution of impacts for children and adults. A significant number of adults also strike their heads beyond the limit of the adult headform test area, suggesting that structures beyond this line should be included in considerations of pedestrian head protection.

Table 5 lists the structures identified as coming into contact with the head of a pedestrian of adult height, irrespective of the head impact severity. This table also indicates that the head commonly comes into contact with structures that are usually beyond the 2100 mm line, such as the windscreen, A-pillar and base of windscreen.

The severity of a given impact is also determined by the speed of the striking vehicle. Of interest is the speed at which serious injuries are caused to a pedestrian in an impact, and hence, the speed at which the vehicle should be tested The EEVC procedures are designed to test the protection offered at an impact speed of 40 km/h. Figure 1 shows the MAIS (maximum AIS score) for the head of every pedestrian in all cases (older and newer combined), plotted against the estimated impact speed of the striking vehicle. As would be expected, there appears to be general trend for higher impact speeds to be associated with higher MAIS scores. An ordinal logistic regression was performed on the data. First, head injuries of any severity were considered (MAIS > 0), and the regression determined the probability of encountering a head injury of any severity, for a given impact speed. Secondly, head injuries with an MAIS of 3 or greater were considered. For these the regression determined the probability of encountering a severe injury in the sample, for a given impact speed. Figure 2 illustrates the result of the regression. The regression analysis shows that the risk of causing a serious head injury (MAIS = 3) to the head is 1 in 5 at 40 km/h, rising to 1 in 2 at around 60 km/h. It should be noted that the analysis is hampered somewhat by the small numbers of cases with impact speeds above 60 km/h.

Table 3 Contact areas resulting in head injury in the sample

Contact category	All injuries		AIS 3+ injuries	
Windscreen	5	(9%)	2	(11%)
External vehicle component	2	(4%)	0	-
Road surface and roadside objects	15	(28%)	0	-
Upper windscreen and leading roof rail	2	(4%)	1	(5%)
A-pillar and adjacent windscreen	4	(7%)	3	(16%)
Base of windscreen and trailing edge of bonnet/plenum	6	(11%)	4	(21%)
Bonnet	10	(19%)	3	(16%)
Outer edge of bonnet and top surface of mudguard	4	(7%)	2	(11%)
Leading edge of bonnet	1	(2%)	1	(5%)
Lower grille, bumper and valence panel	2	(4%)	1	(5%)
Under wheels and under vehicle	3	(6%)	2	(11%)
Total	**54**	**(100%)**	**19**	**(100%)**

Table 4 The incidence of head strikes within the EEVC head test zones on passenger vehicles, irrespective of severity

Contact zone	Age range (years)			Total
	7-10*	13-16	19 +	
WAD < 1000 mm	0	0	0	**0**
1000 mm = WAD < 1500 mm (child headform zone)	2	0	1	**3**
1500 mm = WAD < 2100 mm (adult headform zone)	2	5	10	**17**
WAD = 2100 mm	0	0	7	**7**
Total	**4**	**5**	**18**	**27**

* No data for ages 11, 12, 17 and 18

Table 5 Structures on passenger cars with identifiable head contacts, for collisions with pedestrians aged 13 and older (irrespective of severity)

Head contact zone	Count	
Windscreen	8	(35%)
A-pillar and adjacent windscreen	3	(13%)
Base of windscreen and trailing edge of bonnet/plenum	6	(26%)
Bonnet	1	(4%)
Outer edge of bonnet and top surface of mudguard	1	(4%)
Lower grille, bumper and valence panel	1	(4%)
Road surface and roadside objects	2	(9%)
Upper windscreen and leading roof rail	1	(4%)
Total	**23**	**(100%)**

SIMULATION TO DETERMINE TEST CONDITIONS IN TESTING

The PSEG are devising a testing regime that will seek to classify a vehicle by the shape of its profile, and this will determine the test conditions required to test the vehicle for protection in an impact with the pedestrian's head. Headform test conditions (location, speed and angle) for each class of car profile will be determined from simulations of collisions between representative car shapes from the profile class with pedestrians of different statures. This simulation activity is being undertaken by the Japan Automobile Research Institute (JARI), the National Highway Traffic Safety Administration (NHTSA) in the United States of America, and by the Road Accident Research Unit (RARU) in Australia.

Vehicle profiles

The IHRA PSEG has defined three classes of vehicle profiles; the 'One Box' which includes vans and people-movers, the 'sedan, light vehicle and sports type' including sedans and their derivatives, and the 'SUV', encompassing high ground clearance four-wheel drive vehicles (Figure 3). These categories were compiled from the profiles of vehicles sold in the countries and regions represented on the IHRA SPEG. The heavy lines shown in Figure 3 indicate the upper and lower bounding profiles of each category. These two profiles along with a third 'middle' profile (the average of the upper and lower profile) were used for the simulation task, giving a total of nine profiles in the simulation matrix.

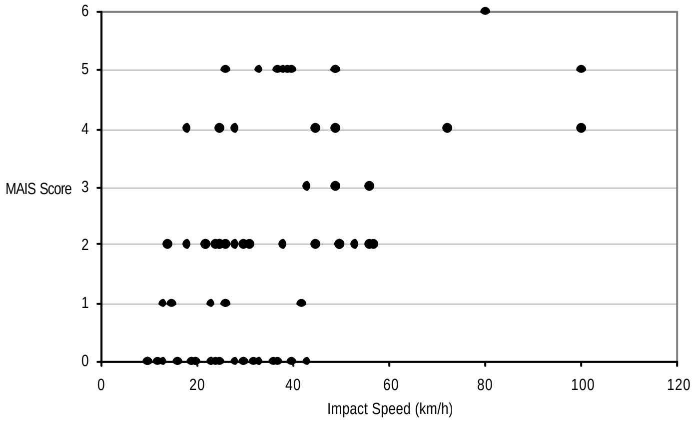

Figure 1 MAIS of the head and vehicle speed in the sample

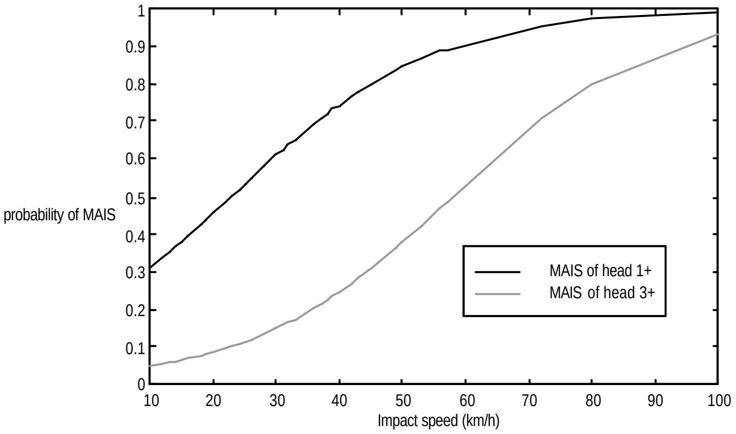

Figure 2 Probability of encountering an injury of a certain severity in the sample

Pedestrian models

Each of the three groups participating in the simulation study is using a model of either their own design or choice. JARI is using a model first developed by Ishikawa et al. [9] and NHTSA is choosing to use the pedestrian model provided by TNO after unsuccessfully using a dummy database. RARU is using a model it has developed.

The details of the RARU pedestrian model have been previously presented [10, 11]. Briefly, the model consists of 17 rigid segments linked by kinematic joints that are largely based on the model proposed by Ishikawa [9] although some joints have been added while others have been modified (see [10]). Recently the neck has been redesigned to better reflect the findings of human volunteer tests [12, 13].

The model has been validated using different car profiles and validation corridors specified by JARI, and which were constructed on the basis of post-mortem human subject (PMHS) tests, carried out in Hannover [9]. The models that were run by the other groups also satisfied these corridors.

Simulation matrix

The aim of the simulation was to determine the head impact test conditions for the three categories of vehicle. For each category of vehicle, three profiles representing the upper, middle and lower profiles were used, each at speeds of 30, 40 and 50 km/h. Two pedestrian stances were tested, one specified by JARI and the other by NHTSA (Figure 4 and Figure 5). At this time, both of these stances are of a 50th percentile male. This resulted in 54 simulation results from each of the three institutions being compiled.

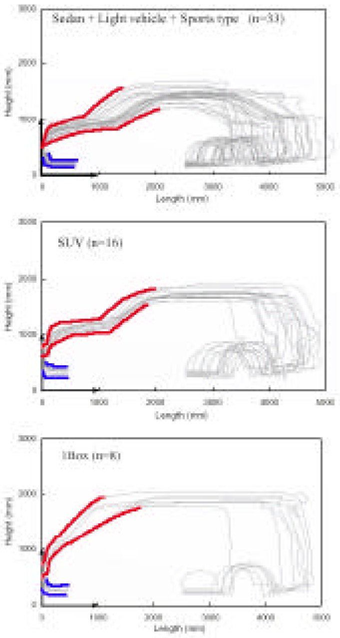

Figure 3 Groups of vehicle profiles identified by the IHRA PSEG (reproduced from [6])

Figure 4 First standard posture

Figure 5 Second standard posture

Results of simulation study and discussion

Figure 6 shows the results of the simulations performed by each group. The ratio of the head impact speed to the vehicle impact speed ranges from around 1.0 for the sedan profiles, down to 0.6 for the One Box type vehicles. The results, however, display a spread of values that indicate that the differences in the models and in the initial conditions of the stance of the pedestrian have a significant bearing on the result of the simulation. For example, the RARU model produces much lower head impact speeds in some of the One Box simulations than the other models. For this class of vehicle, it is also clear that changing the stance of the pedestrian also changes the result significantly.

A possible explanation for the variation in results between the models may lie in the differences in the upper body regions of each model, specifically the shoulder and neck of the pedestrian. During the simulation, the relative velocity of the head and the vehicle is initially the speed of the striking vehicle. As the collision progresses the relative velocity may increase slightly before dropping rapidly. The rapid drop in the head velocity is due to the acceleration of the body of the pedestrian as a whole, from the impact with the lower body. Although the head is accelerated toward the surface of the vehicle, this mainly occurs in the vertical direction, while the relative velocity in the direction of the horizontal longitudinal axis of the car actually drops throughout the collision. This effect means that the behaviour of the shoulder and neck of the pedestrian affects the relative impact speed not only through the transfer of energy to the head from the impact, but through any delay in the impact. For example, if the shoulder joint is too stiff in any of its modes of deformation, it may unduly support the neck and head, delaying head contact with the vehicle. The delay allows the velocity of the head to further decrease relative to the vehicle before contact is made.

This effect is most prominent if the profile of the vehicle is relatively high to the height of the pedestrian. In the converse case, the vertical velocity of the head is the main determinant of the relative impact velocity, as the relative horizontal velocity is reduced to low levels before impact, and so delays in head contact do not affect the results as much.

The head impact angle is also affected in the same way. The behaviour of the shoulder and neck may also greatly influence the head impact angle as the shoulder contact, which usually precedes the head contact, causes the head to pivot through large angles on the upper and lower neck joints. This contact and the subsequent rotation determine the head orientation (and relative magnitudes of the components of the head velocity) at the time of head contact.

These observations are reflected in the results of the simulation with the three computer models providing very similar results for sedan shape cars and markedly different results for higher profile vehicles. For One Box profiles, where the main component of the velocity is horizontal, the differences in the models are most marked.

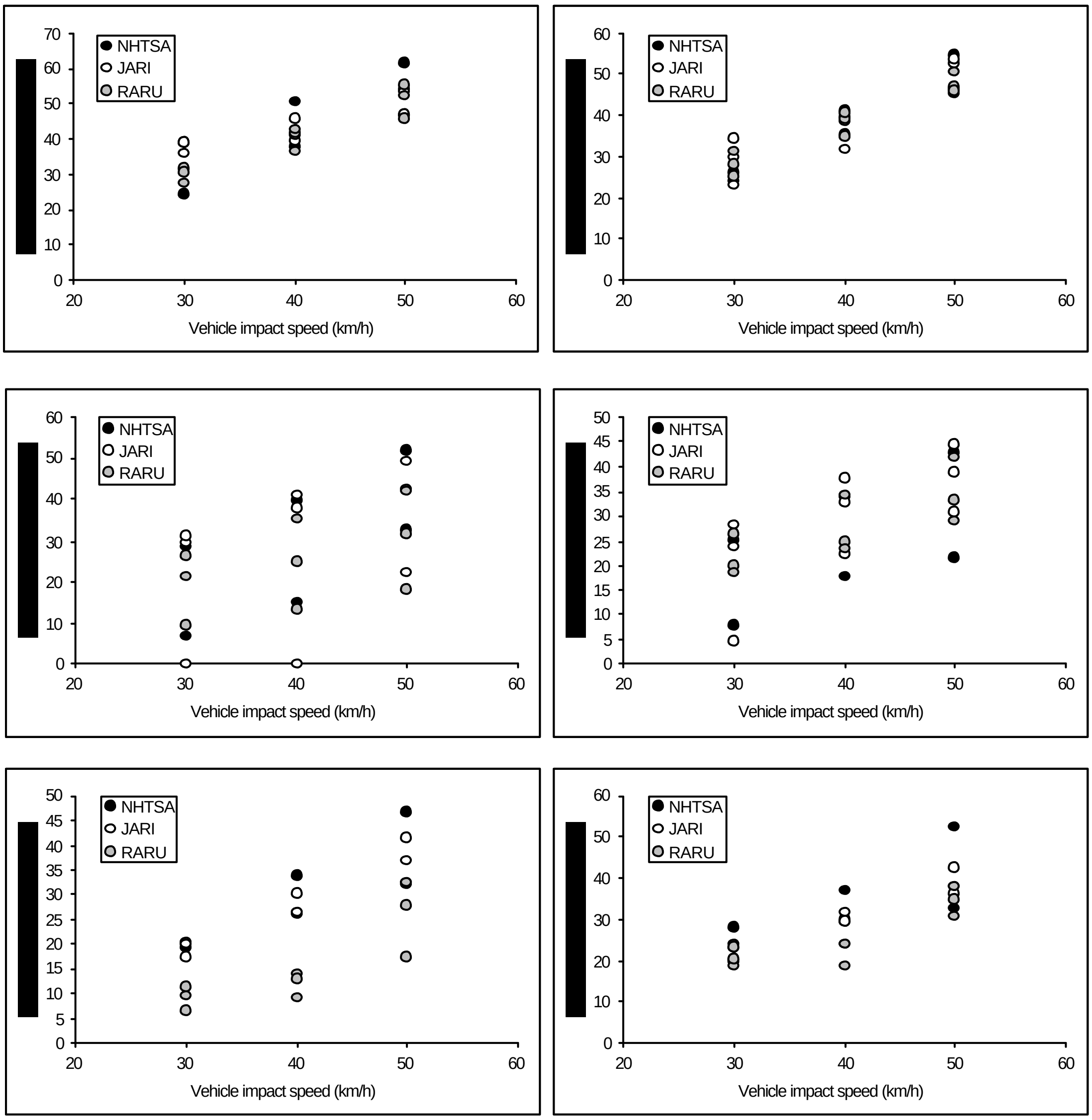

Figure 6 Head impact speed results from each of the three groups; JARI, NHTSA and RARU: Sedan with JARI posture (top left); Sedan with NHTSA posture; (top right); SUV with JARI posture (mid left); SUV with NHTSA posture; (mid right); 1Box with JARI posture (bottom left); 1 Box with NHTSA posture; (bottom right).

CONCLUSIONS AND FUTURE WORK

The data collected on pedestrian collisions in Adelaide lends support to the position that the focus of pedestrian protection strategies should be on the protection of the head and lower extremities. 30% of AIS3+ injuries in pedestrian accidents are to the head and a further 20% are to the lower extremities. The data also suggests that 15% of pedestrians involved in a collision with a car will suffer a head injury of severity AIS3 or worse, and around 13% will suffer a lower extremity injury of severity AIS3 or worse. Test conditions that assume a vehicle impact speed of 40 km/h will cover situations where the risk of sustaining a severe head injury is about 1 in 5.

To determine actual test conditions for a given vehicle speed, computer simulation will by used by the IHRA PSEG. However, for the simulation process to become a credible method of determining test conditions, the first step must be to resolve differences between the models. Despite each model satisfying the validation criteria to more or less the same precision, in certain circumstances the models produced large variations in head impact velocity. At this time, no validation data from simulated pedestrian collisions using PMHS subjects exists to verify the behaviour of the pedestrian model in a collision with high profile vehicles. For this data could be used to verify the model in specific areas (side impact data, for example). Further validation using a component approach is warranted.

Once these issues can be resolved, other impact conditions will be examined including

?? pedestrian orientation,
?? pedestrian gait (collisions throughout the gait cycle),
?? pedestrian stature (Child, 10th percentile female, 50th percentile male, 95th percentile male)
?? vehicle stiffness

This process will produce a range of head impact velocity conditions. They may be combined with the relative occurrence of certain impact configurations to provide a statistical database of head impact conditions. This will be used to determine the most effective set of test conditions required for the headform sub-system test.

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