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Implications of easing head impact criteria in pedestrian crash standards

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TITLE

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ABSTRACT

Pedestrian headform testing is used to measure the relative safety of structures that may cause head injury to a pedestrian in the event of a collision. Examples of this testing include the Australasian New Car Assessment Program (ANCAP), the new Global Technical Regulation (GTR) on pedestrian safety, and AS 4876.1 on bull bars. In these tests, the Head Injury Criterion (HIC) is used to measure the risk of head injury in a given impact. For each of these test protocols, choices were made regarding the conditions of the test, and the HIC required in order to pass the test. These choices have implications, in that they may be expected to guide the development of structures designed to meet that test criteria. This report examines the differences in test outcomes that can be expected for test protocols which specify more relaxed criteria than others. A speed distribution obtained from in-depth crash investigation was used derive the distribution of HIC values across real crash speeds, for structures that meet different test criteria. The results indicate that what may seem like relative small changes in test conditions and acceptable HIC levels may result in significant changes in HIC, and the proportion of real crash speeds that a given structure could be considered safe for.

KEYWORDS

Pedestrian Safety, Safety Testing, Vehicle Design

Summary

Safety standards often include some form of headform testing. For example, headform tests are included in AS 4876.1, AS/NZS 2512.3.1 and AS/NZS 4422. These tests are designed to ensure that, in the case of protective devices, the product provides an adequate level of head protection. In other cases, the tests are used to ensure that elevated head injury risk is minimised where such a risk is incidental to a product's intended use.

In the area of pedestrian protection, tests are conducted on structures that may cause head injury should a collision occur. This type of testing is conducted by launching a headform into the structure being tested. Accelerometers mounted inside of the headform are used to measure the acceleration of the headform during the impact, and this is used to calculate the Head Injury Criterion (HIC), a number representing the relative risk of head injury.

In this report, three pedestrian headform testing protocols that have relevance in Australia are examined. The first is the European New Car Assessment Programme (EuroNCAP) pedestrian testing protocol, which is used for the pedestrian testing component of the Australasian New Car Assessment Program (ANCAP). This protocol changed in 2010: new headforms were introduced, and changes were made to which areas of the vehicle surface are tested with each headform. The second testing protocol considered is the draft Global Technical Regulation (GTR) on pedestrian safety. The GTR test is similar to a EuroNCAP test, but it uses a lower impact speed, and a more relaxed HIC limit for up to 1/3 of the testable area. The third protocol considered is the test specified in AS 4876.1 'Motor vehicle frontal protection systems' (bull bars).

A method is presented for scaling HIC between two sets of test conditions on the same structure. In this report, this method is used to estimate that a structure tested under the GTR would have a HIC 30% lower than if it were tested by ANCAP. Additionally, the change in HIC was estimated for structures tested under the current and previous versions of the EuroNCAP pedestrian testing protocol. Under the newer version of the protocol, HIC values can be expected to decrease by just over 30% for current ANCAP child test locations, and be roughly the same for current ANCAP adult test locations.

For the purposes of this report, four theoretical structures are envisaged, each meeting one of the four different test criteria, that is: (1) the ANCAP pass criteria, (2) the GTR pass criteria, (3) the GTR relaxation area pass criteria and (4) the AS 4876.1 pass criteria. For each structure, a 'safe' speed was estimated. The equivalent safe speed is the impact speed at which the theoretical structure returns a HIC of 1000, the generally accepted threshold for injury. The safe speeds for each structure were (1) 40 km/h, (2) 35 km/h, (3) 28 km/h and (4) 26 km/h. These equivalent safe speeds may be interpreted as the safe operating speeds for structures that comply with their respective standards.

Finally, a real crash speed distribution was obtained from in-depth crash investigation of pedestrian accidents. This speed distribution was used to estimate the percentage of real world crash speeds that each structure would be considered 'safe' for. These percentages were: (1) 50%, (2) 39%, (3) 26% and (4) 21%. For these estimates, the impact speed was assumed to be equal to the crash speed.

These results indicate that consideration needs to be given when selecting test conditions and acceptable HIC limits for pedestrian headform tests. Relatively small changes in test speed and headform mass may have a significant effect on the HIC obtained in an impact test. If a structure is designed to meet the requirements of a certain test, the implications of this in terms of real crash speeds should also be considered. This report presents a framework for the considerations of real world crash speeds in setting such a standard.

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1 Introduction

1.1 Headform testing

Impact testing is used to test the relative level of safety of many structures and products that may cause or protect against injury to the human body. Such testing is integral to several Australian Standards including: AS 4876.1 Motor Vehicle Frontal Protection Systems Part 1: Road User Protection; AS/NZS 2512 Methods for testing protective helmets; and AS/NZS 4422 Playground surfacing - Specifications, requirements and test method (Standards Australia 1996, 2002 & 2007) as well as to international vehicle safety standards in the area of pedestrian protection (McLean 2005).

Some areas of crash testing use a full-scale dummy, which is used to represent the mechanical response of the entire human body. In other cases it is easier to test using separate models for different parts of the body. This is referred to as ‘sub-system’ testing.

A typical component used in sub-system testing is a headform. This is a model for the human head, and it is typically dropped, or launched, into the structure being tested. Examples of structures that are tested using headforms include vehicle interiors, playground equipment surfaces, bicycle helmets, bull-bars, and the frontal area of a vehicle that is likely to strike the head of a pedestrian.

The drafting of test standards requires the specification of test conditions (for example, headform mass and speed) and of acceptable performance criteria (such as the Head Injury Criterion). In the process of specifying the test conditions, regard is given to the tolerance of the human body to impact, biofidelity (the degree to which the test reflects the response of a real person subject to the impact) and feasibility (the extent to which products can comply with performance criteria under specified test conditions).

There are inevitable trade-offs in the drafting of such standards. Ideal protection may not be technically feasible to achieve, or may fail benefit-cost criteria. The specifications contained within standards are usually the result of such trade-offs. In some cases, it may be possible to overcome technical limitations in meeting stringent safety criteria by modifying the use of the product. An example is rating a soft fall surface in terms of the maximum height of equipment installed above it. In other cases, the use of the product is more difficult to specify without impeding the product’s normal use. In that case, trade-offs will need to be made between how stringent the test is, against the proportion of impacts for which the product can protect.

1.2 Considerations in the specification of pedestrian headform testing

This report focuses on pedestrian head impact protection, although the concepts discussed in it may find relevance more broadly. The level of pedestrian head impact protection offered by vehicles on the road depends on those vehicles’ structural characteristics and the interaction of the vehicles involved in crashes with pedestrians who have the misfortune to be struck by those vehicles. As this Introduction has outlined, the relevant structural characteristics of a vehicle may be measured using an appropriate impact test, and such testing is specified in several test protocols (these are described in more detail later). The interactions between pedestrians and vehicles include the speed and the physical configuration of the collision. Crash configurations are reflected in test protocols by the specification of structures on the vehicle that should be tested and the mass of the headform to be used, while the speed of the collision is reflected in the specified test speed.

As will be described in more detail in the next Section, the specification of headform mass and speed in a standard determines the severity of the resulting impact for a given structure, and so it is critical that the test specification reflects the conditions of impacts that are likely to be encountered in use, in at least that proportion of impacts for which the standard is intended to protect people. Where test specifications are eased, the ‘safe level’ implied by the standard will necessarily apply to a smaller proportion of crashes.

The particular issue examined in this report is the consequences of choices made in, or changes to, test standards. The consequences are described in terms that relate to the effectiveness of a given standard in protecting people in real-life impacts. Specifically, the report presents how trade-offs made for the sake of feasibility in standards written for pedestrian protection can affect the proportion of collisions for which such standards are effective. The report considers the physics of the impact test and typical impact conditions encountered in real crashes. It proposes a method of summarising the effect of differences between test protocols using the concept of an equivalent ‘safe speed’; the equivalent ‘safe speed’ is the speed, implied by a given combination of test specifications, at which the structure under test would be considered safe. It is a method of normalising test results from different test protocols. Combined with a distribution of real impact speeds, it provides a method for examining the proportion of crashes for which a proposed standard will be effective.

1.3 Pedestrian test protocols

Figure 1.1 shows a sequence of high-speed video stills from a pedestrian headform test on the bonnet of a vehicle. The headform is launched from the machine in the upper-right corner of each frame, and strikes the bonnet of the vehicle at an angle. During the impact, the bonnet deforms as it absorbs the energy of the impact.

An accelerometer mounted inside of the headform measures the level of acceleration (or deceleration) experienced during the impact, which is used to calculate the Head Injury Criterion, or HIC. The HIC is a measure of the relative risk of head injury for a given impact, and is typically used in headform testing to assess the relative level of safety of the structure being tested.

The equation for calculating HIC is derived from the Wayne-State tolerance curve for head impacts (Versace 1971), and is based on the premise that the risk of head injury increases with the duration and magnitude of the acceleration experienced by the head. A HIC of 1000 is commonly used as an acceptable ‘safe’ limit.

Headform testing is used as part of three pedestrian testing protocols, which have particular relevance in Australia. The first of these is the EuroNCAP protocol, which is used by the Australasian New Car Assessment Program (ANCAP), the second is the Global Technical Regulation (GTR) on pedestrian safety, and the third is AS 4876.1 ‘Motor vehicle frontal protection systems’ (bull bars).

Figure 1.1
Headform test on the bonnet of a vehicle

1.3.1 EuroNCAP/ANCAP protocol

For the last 10 years, the Australasian New Car Assessment Program (ANCAP) has conducted pedestrian impact testing on selected new vehicles. The test protocol used by ANCAP is the same as that used by the European New Car Assessment Programme (EuroNCAP 2009a). The protocol includes sub-system tests using a full-length legform, an upper legform, and adult and child headforms.

The headform testing component of ANCAP focuses on the areas of the vehicle that are most likely to strike a pedestrians head – that is, the bonnet and windscreen. The adult headform is heavier than the child headform. Version 4 of the EuroNCAP protocol was used up until 2009. Under Version 4 of the protocol, the child headform had a mass of 2.5 kg and a diameter of 130 mm, while the adult headform had a mass of 4.8 kg and a diameter of 165 mm. The test speed for both headform tests was 40 km/h.

Whether a child or adult headform is used depends on the wrap-around distance (WAD) to the location being tested. The WAD is the distance measured from the ground in front of the vehicle, along the vehicle surface, to the location in question (Figure 1.2). Under EuroNCAP, the child headform is used for WADs between 1000 mm and 1500 mm, and is fired at an angle of 50º to the ground. The adult headform is used for WADs between 1500 mm and 2100 mm, and is fired at an angle of 65 º to the ground.

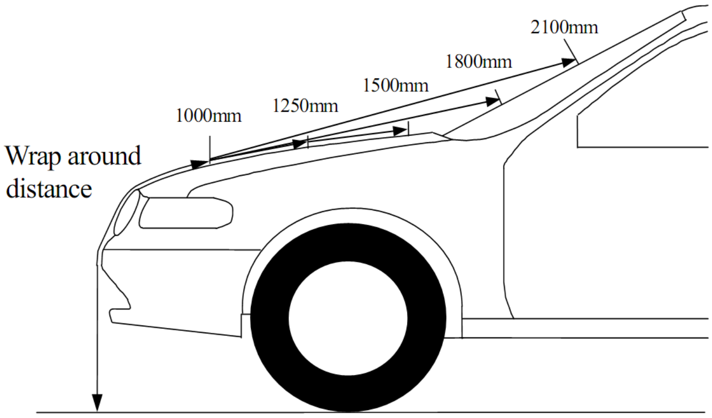

Figure 1.2
Wrap-around distance (WAD) measurement (EuroNCAP 2009a)

In 2010, EuroNCAP adopted Version 5 of the pedestrian testing protocol (EuroNCAP 2009b), which differs significantly from Version 4 (EuroNCAP 2009a). ANCAP have also started conducting pedestrian testing under the new Version 5 protocol. Under Version 5, different headforms are used. The child headform mass is now 3.5 kg (instead of 2.5 kg) and the adult headform mass is now 4.5 kg (instead of 4.8 kg). Both of the new headforms are 165 mm in diameter. Additionally, in the WAD range of 1500 mm to 1700 mm, any tests on the bonnet top are performed using the child headform instead of the adult headform. The impact speed remains at 40 km/h, and the impact angles for the child and adult headforms have not changed.

ANCAP award each vehicle a pedestrian star rating (separate to the occupant star rating), between zero and four stars. The HIC obtained from each child or adult headform test is used to determine how many points are awarded for that location. Each test location is worth a maximum of between 0.5 and 2 points, dependent on whether the vehicle manufacturer chooses to nominate their own test locations. For a given location, a HIC of below 1000 scores maximum points, a HIC of above 1350 scores zero points, and any HIC between those two values is linearly scaled – e.g. a HIC of 1175 scores half of the maximum points.

1.3.2 Global Technical Regulation (GTR) on pedestrian safety

A more recent development in pedestrian impact testing is the Global Technical Regulation (GTR) on pedestrian safety (UNECE 2009), developed by the United Nations Economic Commission for Europe (UNECE). This regulation describes a series of tests, similar to those used by ANCAP, that are used to assess whether a vehicle meets an acceptable level of pedestrian protection prior to it being sold. The GTR may be adopted in Australia as an Australian Design Rule (ADR), under the UNECE 1998 Agreement (UNECE 1998).

Under the GTR, headform testing is conducted in a similar manner to ANCAP testing, with some differences. The most significant difference is that the impact speed for GTR tests is 35 km/h. The child headform mass is 3.5 kg, and the adult headform mass is 4.5 kg, as for Version 5 of the EuroNCAP testing protocol (EuroNCAP 2009b). Both headforms are 165mm in diameter. The dividing line between the child and adult headform test areas differs slightly to that used by ANCAP. Under the GTR, the child headform is used for WAD values between 1000 mm and 1700 mm (instead of 1500 mm), and is fired at an angle of 50° to the ground. The adult headform is used for WAD values between 1700 mm and 2100 mm, and is fired at an angle of 65° to the ground.

If the HIC obtained in a GTR test is less than 1000, that test location passes the requirements. However, the vehicle manufacturer may also nominate a ‘relaxation’ area, in which the test HIC may be up to 1700 and still pass. The relaxation area may be defined in any way, and may consist of several non-continuous sections. The relaxation area may consist of up to 1/3 of the total test area, and may be no more than 1/2 of the child test area.

1.3.3 AS 4876.1 Motor vehicle frontal protection systems (bull bars)

Finally, another pedestrian headform testing protocol of relevance in Australia is the test specified as part of AS 4876.1 Motor Vehicle Frontal Protection Systems Part 1: Road User Protection (Standards Australia 2002). The standard specifies a single test, conducted with a 2.5 kg child headform. The test is conducted at what is judged to be the most potentially injurious location, above a height of 1000mm when the bull bar is mounted on a vehicle. The impact speed is 30 km/h, and the standard requires that the HIC from the impact test is less than 1500.

In each of these three testing protocols a decision has been made regarding the impact speed, headform mass and acceptable level of HIC. These three factors determine whether a structure will pass or fail the test in question. An increase in impact speed will lead to a more severe impact, and hence a higher HIC. Conversely, increasing the headform mass will generally reduce the level of acceleration experienced by the headform and hence decrease the HIC. An increase in headform mass may also increase the amount of deformation of the structure being tested, which may cause other stiffer structures to be engaged during the impact. Raising or lowering the acceptable HIC limit determines how ‘safe’ the structure needs to be in order the pass the requirement.

When we consider a structure designed to meet one of these three test protocols, there are four possible criteria that it might be designed in order to meet:

1. The ANCAP pass criteria of HIC < 1000 at 40 km/h
2. The GTR all-pass criteria of HIC < 1000 at 35 km/h
3. The GTR relaxation area pass criteria of HIC < 1700 at 35 km/h
4. The AS 4876.1 pass criteria of HIC < 1500 at 30 km/h

Each of these criteria defines a minimum standard of acceptability under a particular test protocol. By setting this standard, they implicitly define an acceptable level that a structure should be designed to meet. If a structure is designed to meet a particular test standard, then the choice of test criteria and test specifications will have real-world outcomes when those structures interact with the human body in a collision.

1.4 Objectives and outline

The objective of this study was to develop a framework for examining the effect on head injury risk, in terms of the Head Injury Criterion, of changing the test specifications and acceptable HIC limits in pedestrian headform tests. A further objective was to apply this framework to examine the consequences for real-world safety arising from easing requirements in pedestrian head impact testing. This information can be used when designing new pedestrian testing protocols, or modifying existing protocols.

The method used for scaling the HIC from one set of test conditions to another is presented in Section 2, and is based on work presented in Searson et al. (2009). The scaling method was used to compare the expected change in HIC between two test protocols on the same structures. This was done by comparing the current ANCAP protocol with the GTR, and also comparing the Version 4 and Version 5 of the EuroNCAP/ANCAP pedestrian testing protocol.

Section 3 is concerned with how a change in test protocol interacts with actual impact speeds to produce a change in real-world safety. Where the acceptable HIC limit was not 1000, an equivalent ‘safe speed’ corresponding to a HIC of 1000 was calculated. Additionally, a distribution of real pedestrian crash speeds was used to estimate the distribution of HIC values that could be expected for structures that just meet the criteria of each protocol.

Section 4 contains a discussion of the results.

2 Changes in HIC between test protocols

2.1 Method for scaling HIC

Consider two headform impacts on the same structure, the first with impact speed v_1 and headform mass m_1, and the second with impact speed v_2 and headform mass m_2. If the impact speed and/or headform mass are different, then we would expect different HIC values for each test.

In Searson et al. (2009), a method was developed for scaling the HIC obtained under two such tests. The method was validated using test data from 77 impact tests performed across 31 test locations on 4 vehicles.

The method was developed by considering an impact between a mass and a simple spring of constant stiffness. The acceleration of the striking mass over the time of the impact is represented by a 'half-sine' pulse. Chou and Nyquist (1974) derived an analytical expression for the HIC resulting from a half-sine pulse. If the two impacts with conditions (m_1, v_1) and (m_2, v_2) had resulting HIC values of HIC_1 and HIC_2, then the expression relating these two HIC values was found to be:

$$\frac{HIC_1}{HIC_2} = \left(\frac{m_1}{m_2}\right)^{-3/4} \left(\frac{v_1}{v_2}\right)^{5/2} \tag{1}$$

Thus, if we know the HIC under one set of test conditions, Equation (1) gives us an estimate of what it is likely to be under another set of test conditions. Similarly, the equation may be rearranged to calculate the required change in impact speed in order to achieve a certain change in HIC. Equation (1) is derived from Chou and Nyquist's (1974) expression for HIC and the relationship between mass, velocity and the half-sine pulse produced in a mass-spring system.

The value for velocities v_1 and v_2 in Equation (1) are the components of the impact velocity normal to the surface of the vehicle. This can be calculated if we know the actual impact speed, as well as the angle of the vehicle surface and the angle of the impact.

The normal impact velocity is calculated using the following equation:

$$v = v_m \sin(\theta_i + \theta_s) \tag{2}$$

Where the measured, or desired, impact speed is v_m (e.g. 40 km/h in the case of an ANCAP test, 35 km/h for a GTR test, etc), the angle between the direction of the headform and the ground is θ_i, and the angle between the vehicle surface and the ground is θ_s.

If the comparison is between two tests on the same structure, with the same impact angle, then once Equation (2) is substituted into Equation (1), the *sin()* terms will be equal and will cancel each other out. Thus, the ratio between the normal impact velocities is the same as the ratio between the total impact speeds. However, if the impact angle changes between the two tests, then the *sin()* terms will differ and need to be included in the calculation of the HIC ratio.

In Searson et al. (2009), a change in headform diameter was also found to influence the change in HIC between two tests on the same locations. This was not accounted for in the linear-spring model. Two diameters of headform existed in the empirical data, 130 mm and 165 mm. As such, the empirical data was used to calculate HIC scaling factors for moving from one headform diameter to another.

2.2 General effect of easing test conditions

The general effect of impact speed and headform mass on the HIC levels can be seen in Figure 2.1. The figure shows the ratio of HIC values obtained in a pair of tests on the same structure given the ratio of impact speeds and headform masses in the pair of tests. These curves are a graphical representation of Equation (1).

The figure shows that a reduction in impact speed of 25% would be expected to decrease HIC values by around 50%. Similarly, increasing the headform mass by 50% could be expected to decrease HIC values by just over 25%. This demonstrates the high sensitivity of HIC to changes in impact speed, relative to changes in headform mass. For this reason, the relationship of HIC to real world impact speeds is of importance.

The next three sections consider specific comparisons between different test protocols. The first is a comparison of results between tests done under EuroNCAP Version 5 and the GTR. The second is a comparison of results between tests done under Version 4 and Version 5 of the EuroNCAP protocol. The third compares the current AS 4876.1 test conditions with the EuroNCAP/ANCAP test conditions.

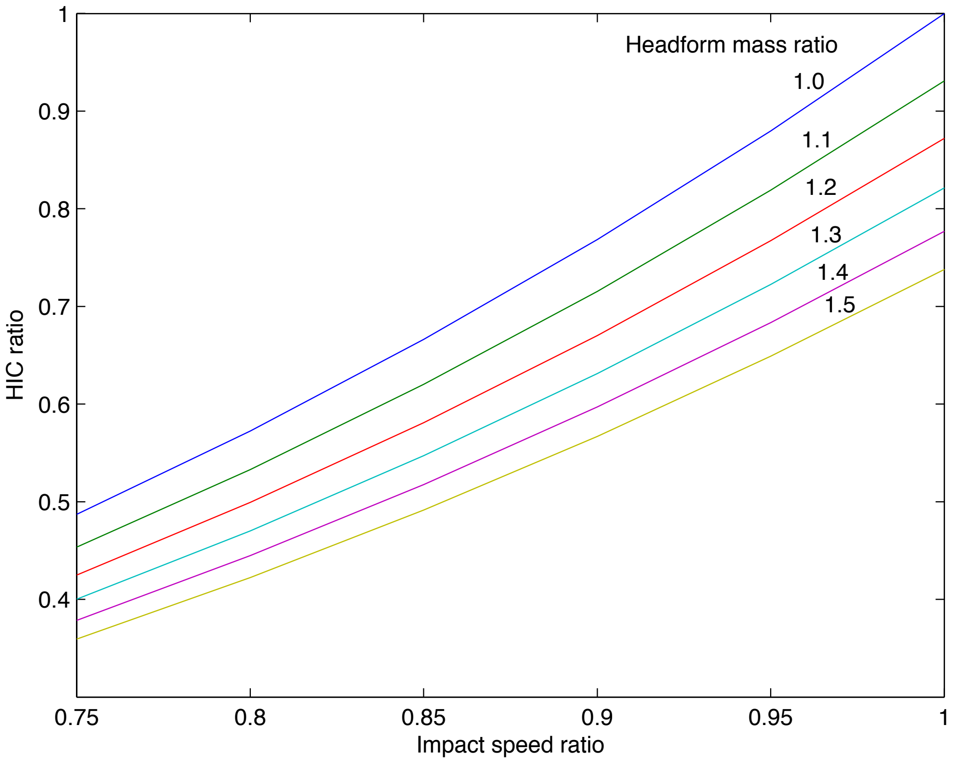

Figure 2.1
General effect on HIC of decreasing impact speed and increasing mass

2.3 Differences in HIC resulting from EuroNCAP/ANCAP and the GTR test protocols

The test protocols for EuroNCAP/ANCAP and the GTR are similar, and similar locations are likely to be tested under both protocols. Using Equation (1), the expected change in HIC was calculated, given the change in impact speed and impact angle between the two protocols, and the potential change in headform mass.

In this section, Version 5 of the EuroNCAP protocol was considered, as it is the current EuroNCAP and ANCAP test protocol.

Three types of test location were considered, based on the wrap-around distance (WAD) and the type of structure being tested. The first type was all locations between WAD 1000 - 1500 mm and those between 1500 – 1700 mm that lie on the bonnet top: for these locations the child headforms are used under both protocols, and are fired at an angle of 50° to the ground. The second type was locations lying between WAD 1500 - 1700 mm on the windscreen: for these locations the adult headform is used under ANCAP and is fired at an angle of 65° to the ground, whereas under the GTR the child headform is used and is fired at an angle of 50° to the ground. The third type was all locations between WAD 1700 - 2100 mm: for these locations the adult headforms are used under both protocols, and are fired at 65° to the ground.

For the second type of location, the change in impact angle meant that the *sin()* term in Equation (2) became relevant. Thus, a vehicle surface angle of 10° was assumed in order to calculate an expected change in HIC for this region.

Table 2.1 shows the predicted difference in HIC for each region, between the ANCAP and GTR headform testing protocols.

Table 2.1
Comparison of HIC levels resulting from ANCAP (Version 5) and the GTR protocols in wrap-around-distance ranges

	Wrap-around-distance range (mm)		
	1000 – 1500 (all) 1500 – 1700 (bonnet)	1500 – 1700 (windscreen)	1700 – 2100
Headform type (ANCAP – GTR)	Child – Child	Adult – Child	Adult – Adult
ANCAP test conditions	3.5 kg, 40 km/h, 50°	4.5 kg, 40 km/h, 65°	4.5 kg, 40 km/h, 65°
GTR test conditions	3.5 kg, 35 km/h, 50°	3.5 kg, 35 km/h, 50°	4.5 kg, 35 km/h, 65°
HIC scaling factor	**0.72**	**0.66**	**0.72**

Thus, an average reduction in HIC of 28% can be expected for most test locations. The exception to this is locations in the WAD range of 1500 – 1700 mm that lie on the windscreen, which would expect a slightly greater HIC reduction of around 34%.

2.4 Differences in HIC resulting from EuroNCAP/ANCAP protocol changes

As described in Section 1.3.1, Version 5 of the EuroNCAP test protocol was introduced in 2010 and was adopted by ANCAP. Version 5 of the test protocol specifies new headforms, which are the same diameter and mass as those used under the GTR. Additionally, the new child headform is used to test locations in the WAD 1500 – 1700 mm region that lie on the bonnet. Locations in this region that are on the windscreen or windscreen base are tested with the adult headform (as they were under the previous protocol, Version 4).

Again, there are three types of test location that were considered. The first type was the child headform test locations in the WAD range 1000 – 1500 mm: these are tested with a heavier and larger headform under the Version 5 protocol. The second type was the locations in the WAD range of 1500 – 1700 mm that lie on the bonnet: these were previously tested with an adult headform fired at 65° to the ground, but are now tested with the child headform under the Version 5 protocol, fired at 50° to the ground. The third type was locations in the WAD range of 1700 – 2100 mm, as well as those in the WAD range 1500 – 1700 mm that lie on the windscreen: these are tested with a slightly lighter adult headform under the Version 5 protocol.

The change in headform diameter for the first type of test location was accounted for using a scaling factor of 0.87 (Searson et al. 2009). The change in impact angle for the second type of locations was accounted for assuming a bonnet angle of 10°. Table 2.2 shows the expected change in HIC for each type of impact location, between Version 4 and Version 5 of the ANCAP/EuroNCAP testing protocols.

Table 2.2
Comparison of HIC levels resulting from ANCAP/EuroNCAP protocols Version 4 and Version 5 in wrap-around-distance ranges

	Wrap-around-distance range (mm)		
	1000 – 1500 (all)	1500 – 1700 (bonnet)	1500 – 1700 (windscreen) 1700 – 2100 (all)
Headform type (Version 4 – Version 5)	Child – Child	Adult – Child	Adult – Adult
Version 4 test conditions	2.5 kg, 40 km/h, 50°	4.8 kg, 40 km/h, 65°	4.8 kg, 40 km/h, 65°
Version 5 test conditions	3.5 kg, 40 km/h, 50°	3.5 kg, 40 km/h, 50°	4.5 kg, 40 km/h, 65°
HIC scaling factor	**0.67**	**0.96**	**1.05**

Thus, for a given structure in the WAD 1000 – 1500 mm region, a reduction in HIC of around 33% can be expected under the new testing protocol. For all other test locations, the HIC will change slightly: locations in the WAD 1500 – 1700 mm region that are on the bonnet type could expect a reduction in HIC of around 5%, while all other current adult test locations may expect an increase in HIC of around 5%.

2.5 Differences in HIC resulting from EuroNCAP/ANCAP and AS 4876.1 test specifications

The Australian Standard on Motor Vehicle Frontal Protection Systems, AS 4876.1, currently specifies a single headform test at 30 km/h using a 2.5 kg child headform with a diameter of 130 mm, as used in the Version 4 EuroNCAP/ANCAP tests. The test is conducted with the headform travelling horizontally into the bull bar, as it would be mounted on the vehicle.

Equation (1) was used to predict the difference in HIC that could be expected if AS 4876.1 used the EuroNCAP/ANCAP test speed of 40 km/h. The difference calculated was 0.48. This value does not account for any differences in headform mass, but it is reasonable to assume that any future versions of AS 4876.1 would be likely to adopt the same 3.5 kg headform used in Version 5 of the EuroNCAP test protocol and the GTR.

Thus, the HIC values obtained under the current AS 4876.1 test protocol are approximately half of what might be expected if the EuroNCAP/ANCAP child test conditions were used.

3 Relationship of test specifications with outcomes at real crash speeds

This section of the report estimates the relative performance of the different test protocols in the real world. This was done by assuming the existence of four structures that exactly meet the requirements of each test protocol. These structures were envisaged to meet each of four test criteria: the ANCAP pass criteria, the GTR full pass criteria, the GTR relaxation area pass criteria, and the AS 4876.1 pass criteria.

For the two test criteria that specify an acceptable HIC limit greater than 1000, an equivalent 'safe speed' was calculated. The safe speed was the speed at which a HIC of 1000 would be expected for the structure that just meets that criteria.

In addition to this, a real crash speed distribution was obtained from previous in-depth crash investigations. This was used to derive a distribution of HIC values for each of the four theoretical structures, across the distribution of real crash speeds. Doing this indicates what proportion of real crash speeds would be likely to meet a certain HIC level, for structures that meet each of the four test criteria.

3.1 Equivalent 'safe speed'

Consider the four pass criteria outlined in Section 1.3.3:

1. The ANCAP pass criteria of HIC = 1000 at 40 km/h
2. The GTR all-pass criteria of HIC = 1000 at 35 km/h
3. The GTR relaxation area pass criteria of HIC = 1700 at 35 km/h
4. The AS 4876.1 pass criteria of HIC = 1500 at 30 km/h

There are two pass criteria which set an acceptable HIC limit of 1000 (1 and 2), and two pass criteria which set an acceptable HIC limit that is greater than 1000 (3 and 4).

Consider a structure that just passes either criteria 3 or 4 at 35 km/h or 30 km/h. Conceptually, there ought to be a lower speed at which that structure would produce a HIC of 1000 for the same headform. This speed is conceptualised as an equivalent 'safe speed'; such a speed may be interpreted as the safe operating speed for the structure.

While headform mass could be considered in the same way as speed, for the present purposes it is assumed that headform choices are appropriate in each protocol. Thus, Equation (1) can be rewritten as:

$$HIC_1 = HIC_2 \left(\frac{v_1}{v_2} \right)^{5/2} \tag{3}$$

A HIC of 1000 is usually regarded as the 'safe' limit for a head impact. In this respect, the two pass criteria with higher limits than 1000 should have a 'safe' impact speed at which a structure designed to meet that criteria will score a HIC of 1000. For the other two criteria, the 'safe speed' would be the speed of the impact test itself – i.e. 40 km/h for the ANCAP test, and 35 km/h for the GTR full pass criteria.

Consider a structure that just passes one of the criteria given in the list above. For each criterion, at least one such structure would exist – these structures may be considered to be ones that just satisfy the design requirements implied by each criterion. For example, for criterion 1, a structure will exist that scores a HIC of exactly 1000 when struck at 40 km/h with the appropriate headform – i.e. with a child headform for WAD 1000 – 1500mm and an adult headform for WAD 1500 – 2100mm.

Equation (3) was used to estimate the HIC over a range of speeds, for each of these four theoretical structures. HIC_2 is the allowable HIC value given by each criterion, and v_2 is the test speed used in each test. v_1, represents a range of impact speeds that might be encountered in actual impact. The values of HIC_1 are the levels of HIC that would result from impacts at the different impact speeds. Figure 3.1 shows the resulting dependence of HIC on impact speed, for each of these four theoretical structures. Table 3.1 lists the 'safe speeds' for each of these structures.

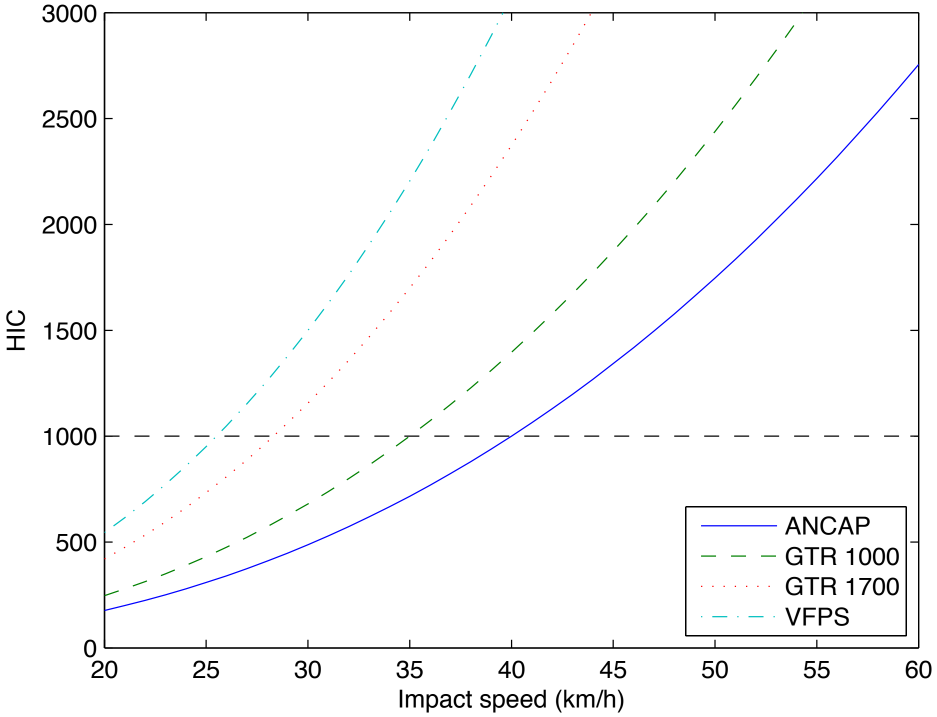

Figure 3.1
Estimated HIC for different impact speeds, for structures designed to meet four different pass criteria

Table 3.1
Maximum 'safe speed' values for structures that comply with four alternate pass criteria

	EuroNCAP/ANCAP pass	GTR full pass	GTR relaxation area (up to 1/3 of the total test area, and 1/2 of child test area)	VFPS Standard AS 4876.1
Test speed (km/h)	40	35	35	30
Required test HIC	1000	1000	1700	1500
'Safe speed' (km/h) (HIC = 1000)	**40**	**35**	**28.3**	**25.5**

Thus, a structure that is designed to exactly meet the GTR relaxation area requirements could be considered ‘safe’ for impact speeds below 28.3 km/h, assuming that ‘safe’ corresponds to a HIC of 1000. Similarly, a VFPS designed to exactly meet the requirements of AS 4876.1 could be considered ‘safe’ for impact speeds below 25.5 km/h, assuming that ‘safe’ corresponds to a HIC of 1000.

3.2 Real crash speed distribution

In the real world, pedestrian crashes occur at a range of vehicle speeds. The distribution of crash speeds tells us what proportions of crashes occur at a given speed, and the proportions of crashes that occur below or above a given speed.

A speed distribution from real world crashes implies a limiting distribution of HIC values for any set of test specifications. For example, if a structure just meets the GTR pass criteria, the expected HIC values for any speed can be calculated using Equation (3). A real crash speed distribution can then be used to calculate the proportion of real crash speeds that would fall beneath certain HIC levels for that structure.

In this section, a distribution of real crash speeds was used to calculate an equivalent distribution of HIC values, for each of the four theoretical structures. An impact speed distribution that was representative of a wide range of injury severities was needed. Mass crash data collected via the Traffic Accident Reporting System (TARS) was not useful for this purpose as it does not contain reliable estimates of impact speed in pedestrian crashes, or much detail of injury severity. Instead a crash speed distribution was obtained from in-depth crash investigation studies.

Mizuno (2003) presented a dataset compiled by the International Harmonised Research Activities (IHRA) working group on pedestrian safety. The dataset consisted of just over 1600 pedestrian crash cases investigated in Australia, Japan, Germany, and the USA. The Australian data consisted of 64 cases investigated by the Centre for Automotive Safety Research (then known as the Road Accident Research Unit) in metropolitan Adelaide between 1999 and 2000, the Japanese data consisted of 240 cases investigated from 1987 to 1988, the German data consisted of 783 cases investigated between 1985 and 1998, and the USA data consisted of 521 cases investigated between 1994 and 1999.

The IHRA dataset was used for this study; however, cases were only included where the list of pedestrian injuries included a head injury with an Abbreviated Injury Scale (AIS) score greater than one. This meant that any cases were excluded where the pedestrian received no head injury, or minor head injury only. These cases were excluded as the headform impact testing requirements would be unlikely to have any effect on the outcome of a crash where no head injury occurred, or only minor head injuries were received.

After these exclusions, a sample of 498 crashes was available, 21 of which were from Australia.

To simplify the analysis, a Weibull statistical distribution was fitted to the crash speed data. The distribution was fitted using least-squares regression on the Weibull cumulative distribution function. The Weibull scale parameter was 46.97 and the shape parameter was 2.37.

Figure 3.2 shows the cumulative distribution of crash speeds for the data and for the fitted Weibull distribution. Figure 3.3 shows the Weibull probability density function – i.e. the percentage of crashes that would be expected to occur at different crash speeds.

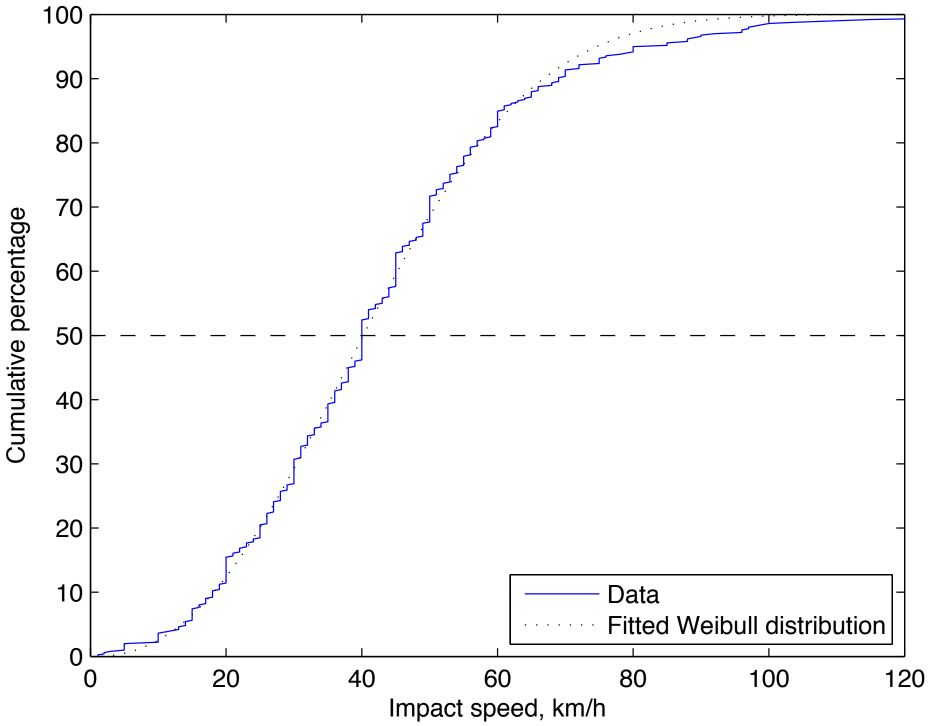

Figure 3.2
Cumulative impact speed distribution of IHRA pedestrian data (Head AIS >1; from Mizuno 2003) and the fitted Weibull distribution

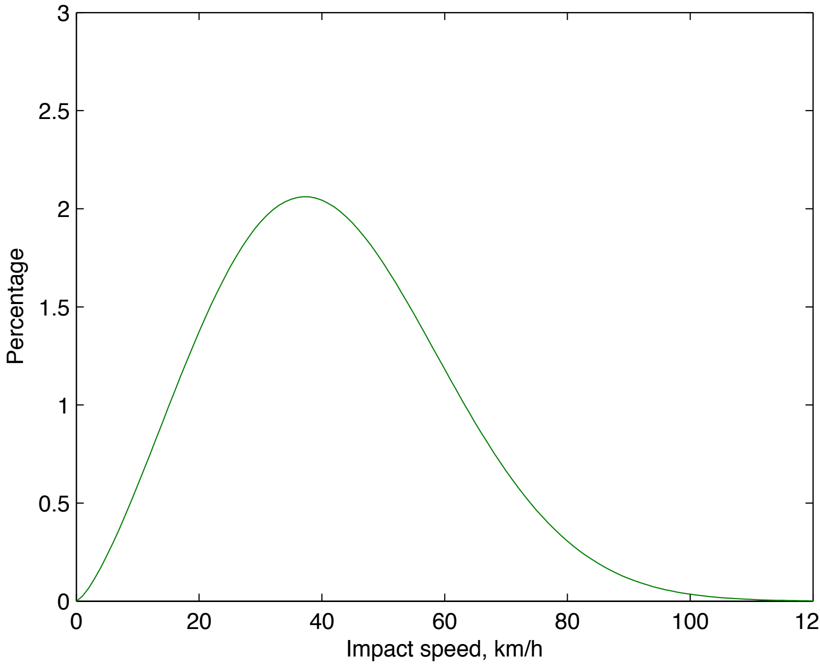

Figure 3.3
Impact speed distribution of the IHRA pedestrian cases (Head AIS >1; from Mizuno 2003) given by the fitted Weibull function

3.3 HIC distribution for real crash speeds

The cumulative distribution shown in Figure 3.2 was used to generate equivalent cumulative HIC distributions corresponding to each of the four theoretical structures discussed in Section 3.1. For the purposes of the analysis, it was assumed that the head impact speed was equal to the vehicle collision speed.

Equation (3) was used to calculate the HIC distribution. HIC_2 was set to the allowable HIC value given by each criterion, and v_2 is the test speed used in each test. The speed distribution in Figure 3.2 described values for v_1. The resulting values of HIC_1 were used to generate a cumulative distribution of HIC values for each theoretical structure. These cumulative distributions are shown in Figure 3.4.

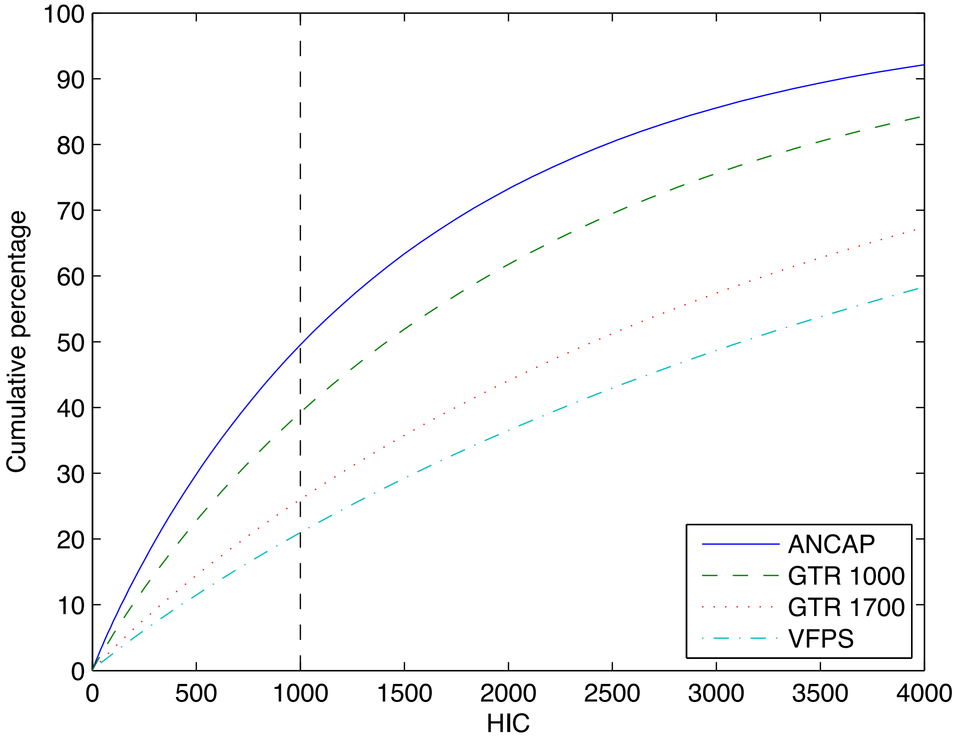

Figure 3.4
Cumulative distributions of HIC values for real crash speeds, for structures that exactly meet the requirements of four different test criteria

As shown in Figure 3.4, a structure that exactly meets the ANCAP requirements could be expected to give a HIC of less than 1000 for 50% of real crash speeds. A structure that meets the GTR base criteria could be expected to give a HIC of less than 1000 for 39% of real crash speeds, while a structure that meets the GTR relaxation criteria could be expected to give a HIC of less than 1000 for 26% of real crash speeds. Finally, a structure that meets the VFPS test criteria could be expected to give a HIC of less than 1000 for 21% of real crash speeds.

3.3.1 Effect of assumption on the results

When the GTR was developed, the goal was to design for a vehicle crash speed of 40 km/h, and the test speed of 35 km/h was chosen to represent the resulting speed of the head (UNECE 2003). This implies a ratio of 0.875 between the crash speed and head impact speed.

The results presented above assume that the head impact speed is equal to the crash speed. However, this assumption may introduce an error if results are sensitive to it. To test the sensitivity of the result, the alternate assumption underpinning the GTR was used and the results recalculated. To do this, the speed distribution used above was scaled by 0.87, and the HIC distribution was recalculated.

Under the modified HIC distribution, a structure that exactly meets the ANCAP requirements could be expected to give a HIC of less than 1000 for 61% of real crash speeds. A structure that exactly meets the GTR base criteria could be expected to give a HIC of less than 1000 for 49% of real crash speeds, while a structure that meets the GTR relaxation criteria could be expected to give a HIC of less than 1000 for 34% of real crash speeds. Finally, a structure that exactly meets the VFPS test criteria could be expected to give a HIC of less than 1000 for 28% of real crash speeds.

This indicates that the quantitative estimates for the proportion of real crash speeds resulting in a HIC of less than 1000 are sensitive to the assumption that the head impact speed is equal to the crash speed. However, the differences in values between the four test protocols are roughly equivalent. For example, if the head impact speed is assumed equal to the crash speed, then the structure that meets the ANCAP requirements will score a HIC of less than 1000 for 2.4 times as many real crash speeds as the structure that meets the VFPS requirements. This proportion is 2.2 when the head impact speed is taken as 0.875 of the crash speed.

One other factor needs to be taken into consideration regarding this result, which is a test phenomenon known as ‘bottoming out’. Bottoming out occurs when a much stiffer structure exists beneath the outer surface of the structure being tested – for example, the engine block underneath the bonnet. If the outer surface deforms sufficiently during the impact that it comes into contact with the much stiffer structure, then the acceleration of the headform rises, and higher HIC values can be expected.

In the model used to predict the change in HIC, it is assumed that the structure can deform as much as necessary without encountering any bottoming out. However, in a real vehicle structure, bottoming out can be expected to occur eventually as the impact energy increases. As the impact speed and headform mass rise, so too does the amount of deformation, and eventually bottoming out will occur.

Generally speaking, if bottoming out does occur, the resulting HIC values are sufficiently high that the structure being tested will not pass whichever test criteria it is being tested against. Thus, for the theoretical structures used to generate Figure 3.4, it was assumed that no bottoming out will occur in tests that pass the test criterion. However, at higher impact energies the possibility of bottoming out remains. Hence, the numerical HIC values above the pass level given in Figure 3.4 should be considered a lower estimate.

4 Discussion

4.1 Summary of findings

The overall goal of this report was to examine the effect of changing test conditions and acceptable HIC limits in pedestrian headform tests. Three test protocols were considered: the ANCAP pedestrian testing protocol, the GTR pedestrian testing protocol, and AS 4876.1 on Motor Vehicle Frontal Protection Systems.

The first two of these protocols can be compared directly, as they are intended to be performed on the same structures on the front of a vehicle. The results show that most test locations would have a HIC around 30% lower under the GTR compared with their result under the current ANCAP protocol (Version 5).

The expected changes in HIC between Version 4 and Version 5 of the EuroNCAP/ANCAP pedestrian testing protocol were also calculated. Locations tested with the child headform under both versions of the protocol could be expected to have HIC values just over 30% lower under Version 5. Locations tested with the adult headform under Version 4 of the protocol would experience little change in HIC values under the new protocol.

In Section 3, the real-world safety effects were estimated for four different structures. These structures were defined to meet each of four different test criteria: (1) the ANCAP pass criteria, (2) the GTR pass criteria, (3) the GTR relaxation area pass criteria and (4) the AS 4876.1 pass criteria. For criteria (3) and (4), the acceptable HIC was higher than 1000, and so an equivalent 'safe' impact speed was calculated, which would correspond to a HIC of 1000. These 'safe' speeds were 28 km/h and 26 km/h, respectively. For criteria (1) and (2), the 'safe' speed would be the actual test speeds, i.e. 40 km/h and 35 km/h, respectively.

Finally, a distribution of real crash speeds was used to derive an equivalent distribution of HIC values for each of these four hypothetical structures. For each of the four structures, it was possible to estimate the percentage of real crash speeds for which the HIC would be less than 1000. These percentages were: (1) 50%, (2) 39%, (3) 26% and (4) 21%. For these estimates, the impact speed was assumed to be equal to the crash speed.

4.2 Limitations

The results presented in this report were derived using the HIC scaling method presented in Searson et al. (2009). This scaling method was derived from a theoretical linear mass-spring model, which was used to derive an equation relating the HIC under two sets of test conditions, on the same test location.

The linear mass-spring model may not be representative of a real impact. In a real impact, there are additional forces due to damping and friction, and so the impact is not purely elastic as in the case of a linear spring. Additionally, the model does not account for bottoming out, as discussed in Section 3.3. However, despite the absence of these factors, the model was found to agree well with experimental data (Searson et al. 2009), and can be considered a reasonable estimate of the change in HIC.

In Section 3, four theoretical structures were considered that conformed exactly to four different pass criteria. The HIC distribution for a range of speeds was calculated, which was then used to construct a cumulative distribution of HIC values across real crash speeds. While real crash speeds were used, care must be taken in extrapolating these results to apply to the ‘real world’. If these results were to apply to real crashes, then the headform mass and impact angle must be assumed to be biofidelic.

For example, the distribution of HIC values for the structure that meets the ANCAP requirements only applies to the ‘real world’ if in a real crash the effective head mass of the struck pedestrian was the same as the applicable ANCAP headform mass, and if their head strikes at the same speed and impact angle as the test. This may not always be the case. So, while the ANCAP structure may score a HIC of less than 1000 for 50% of the real crash speeds considered, it may be faulty reasoning to extrapolate this result to suggest, for example, that such a structure was ‘safe for 50% of struck pedestrians’. Instead, the results may be best interpreted as a further comparison between the requirements of different testing protocols, in a real world context. Additionally, the results provide a qualitative estimate of the distribution of HIC values that might be expected for each of the four theoretical structures, but for the reasons just outlined, the true quantitative distributions may vary from these. This is evident in that when the head impact speed was assumed to be less than the crash speed, the proportion of crashes deemed ‘safe’ differed. However, the relative performance of test protocols was less affected.

The speed distribution in Section 3 was based on predominantly international data. It is possible that that the true Australian distribution of pedestrian crash speeds may differ from this distribution. As such, the values produced by this speed distribution may not be truly indicative of real crash speeds in Australia. Note that the crash speeds in the Australian contribution to this data were not markedly different from the overall distribution of crash speeds. The method could be easily applied to a more comprehensive set of Australian crash speed data, if it were obtained in the future.

4.3 Conclusions

The results presented in this report suggest that care must be taken when decisions are made regarding the test conditions, and acceptable HIC limits, in pedestrian headform tests. For relatively small changes in impact speeds and headform mass, a large change in HIC may be expected, with a concomitant change in the proportion of real-world impacts that are made safe by marginal compliance with the applicable standard. This is illustrated by the change in impact speed between ANCAP and the GTR: for a change in impact speed from 40 km/h to 35 km/h, a 28% reduction in HIC can be expected. This is the most extreme case considered in this report, but illustrates how sensitive HIC is, particularly to impact speed. Coupled with relaxed criteria, these changes in HIC may see a large reduction in the proportion of head impacts that are made safe by marginal compliance with the test criteria. As an example, if we compare a structure designed to meet the GTR full pass criteria with a bull bar designed to meet AS 4876.1, the GTR structure could be expected to score a HIC of less than 1000 for twice as many real crash speeds compared to the bull bar.

In general, care should be taken if a HIC of higher than 1000 is selected as an acceptable limit. If a structure is designed to meet that limit, then the ‘safe’ speed at which the structure would achieve a HIC of less than 1000 may be considerably less than the test impact speed.

More specifically, the pedestrian testing protocols considered in this report have relevance for the Australian vehicle fleet. At present, ANCAP testing is conducted on selected new vehicles, for consumer information purposes. The bull bar standard, AS 4876.1, is a non-compulsory test. The GTR test is part of a draft proposed regulation, and is yet to be adopted in Australia as part of an ADR on pedestrian safety. As such, there is no compulsory standard for pedestrian protection in Australia at present, and so the ‘safe speed’ for pedestrians, in the context used for this report, may be quite low. The implementation of any compulsory standard would increase the ‘safe speed’ of vehicles and bull bars being used on the road.

While any compulsory standard should constitute an improvement, some consideration should still be given to the minimum level of performance specified by such a standard. The GTR and ANCAP tests are both aimed at vehicles; however, the GTR specifies a minimum standard of performance, while ANCAP specifies a level for vehicles to aspire to. In this sense, it might be expected that the GTR minimum standard would be lower than the standard set by ANCAP.

The bull bar standard, AS 4876.1, is not aimed at vehicles, but attachments to vehicles. If an ADR based on the GTR was implemented, then bull bars which comply with AS 4876.1 could still perform worse than the vehicle front itself: the ‘safe speed’ of the VFPS standard is 26 km/h, compared with 28 km/h for the GTR relaxation criteria. Consequently, it is the opinion of the authors that if an ADR based on the GTR was implemented, then compliance with AS 4876.1 should be made compulsory for all bull bars, and AS 4876.1 should be modified to raise the ‘safe speed’ to at least 28 km/h. This could be done by using equivalent test conditions, for example, by matching the GTR relaxation criteria of a 35 km/h test with a maximum allowable HIC of 1700.

These are specific recommendations; however the information and methodology used in this report can also be used to help guide future decisions on headform testing as part of pedestrian safety standards. When a test protocol or standard is introduced, a minimum standard is set for vehicle manufacturers to work towards. Because there would appear to be little market driven demand for pedestrian safety features, manufacturers are likely to be driven only by standards and consumer testing programs such as ANCAP. Given this, it is important to fully consider the implications of how test criteria are set in such test protocols.

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References

Chou CC, Nyquist GW (1974). Analytical Studies of the Head Injury Criterion. SAE Paper #740082. Warrendale: Society of Automotive Engineers.

European New Car Assessment Programme (EuroNCAP) (2009a). EuroNCAP Pedestrian Testing Protocol Version 4.3.

European New Car Assessment Programme (EuroNCAP) (2009b). EuroNCAP Pedestrian Testing Protocol Version 5.0.

McLean AJ (2005). Vehicle design for pedestrian protection. CASR Report #037. Adelaide: Centre for Automotive Safety Research.

Mizuno Y (2003). 'Summary of IHRA Pedestrian Safety WG Activities', in Proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles', Nagoya, Japan, 19-22 May 2003.

Searson DJ, Anderson RWG, Ponte G, van den Berg AL (2009). Headform impact test performance of vehicles under the GTR on pedestrian safety. CASR Report #072. Adelaide: Centre for Automotive Safety Research.

Standards Australia (2007). Methods of testing protective helmets – determination of impact energy attenuation – helmet drop test. AS/NZS 2512.3.1:2007

Standards Australia (2002). Motor vehicle frontal protection systems – Part 1: Road user protection. AS 4876.1-2002.

Standards Australia (1996). Playground surfacing – Specifications, requirements and test method. AS/NZS 4422:1996.

United Nations Economic Commission for Europe (UNECE) (2009). Draft Regulation on Pedestrian Safety. Document ECE/TRANS/WP.29/GRSP/2009/10.

United Nations Economic Commission for Europe (UNECE) (2003). GRSP informal group on pedestrian safety – 6th meeting – draft detailed meeting minutes. Document GR/PS/64 (Sec 6.5). Available from <http://www.unece.org/trans/doc/2003/wp29grsp/ps-64.pdf>

United Nations Economic Commission for Europe (UNECE) (1998). Agreement Concerning The Establishing Of Global Technical Regulations For Wheeled Vehicles, Equipment And Parts Which Can Be Fitted And/Or Be Used On Wheeled Vehicles.

Versace J (1971). 'A Review of the Severity Index', in Proceedings of the 15th Stapp Car Crash Conference, Coronado, California, 17-19 November 1971.