Centre for
Automotive Safety Research

Measuring underbonnet clearances in order to evaluate pedestrian safety performance of vehicles at various impact speeds

DJ Searson

CASR REPORT SERIES
CASR109
July 2012

THE UNIVERSITY of ADELAIDE

Report documentation

REPORT NO.	DATE	PAGES	ISBN	ISSN
CASR109	July 2012	27	978 1 921645 47 1	1449-2237

TITLE

Measuring underbonnet clearances in order to evaluate pedestrian safety performance of vehicles at various impact speeds

AUTHORS

DJ Searson

PERFORMING ORGANISATION

Centre for Automotive Safety Research
The University of Adelaide
South Australia 5005
AUSTRALIA

SPONSORED BY

NRMA - ACT Road Safety Trust
GPO Box 2890
Canberra
ACT 2601
AUSTRALIA

ABSTRACT

The focus of this report is on the head testing component of pedestrian impact testing. Current pedestrian testing protocols evaluate vehicle performance at a single crash speed. Vehicles that perform well at the test speed may perform poorly at a slightly higher test speed if there is minimal clearance between the bonnet and harder structures beneath. Measurement of this clearance may aid in giving the vehicle a more appropriate assessment. In previous work, a method has been developed for evaluating performance across a range of speeds, taking account of underbonnet clearance. In this report, a new practical methodology is presented for measuring underbonnet clearance, by drilling holes in the outer surface of the bonnet. This method was used to measure underbonnet clearance for 64 test locations on five vehicles tested by the Australasian New Car Assessment Program, and the resulting clearance measurements were used to evaluate each vehicle. This evaluation took into account the result from the original test, the clearance measurements, the distribution of speeds in real pedestrian crashes, and a function for predicting fatal head injury risk from Head Injury Criterion values. The resulting evaluations showed that knowledge of the underbonnet clearance measurements affected the evaluation of specific individual test locations and could potentially affect the overall evaluation of each vehicle. The clearance measurements may also be of use in monitoring performance, encouraging safer designs and in other evaluation schemes that were not considered.

KEYWORDS

Pedestrian safety, ANCAP, Impact testing, Head injury

© The University of Adelaide 2012
The views expressed in this report are those of the authors and do not necessarily represent those of the University of Adelaide or the funding organisations.

Summary

Pedestrian headform testing is conducted by firing a dummy headform into different locations on the front of a vehicle, and is used to assess the relative level of protection that the vehicle provides to the head of a struck pedestrian. The headform measures the relative injuriousness of the impact via the Head Injury Criterion (HIC), which is calculated from the recorded acceleration of the headform.

Current pedestrian test protocols evaluate the performance of the vehicle at a single speed. There are good reasons to suggest that performance should be evaluated over the full range of crash speeds encountered in the real world (weighted towards those that are more common). One reason for this is that at higher speeds the bonnet may begin to 'bottom out', by coming into contact with much harder structures just below the surface.

Previous research by the Centre for Automotive Safety Research (CASR) has developed a method for scaling a HIC value obtained at one test speed to equivalent HIC values at any other speed. Thus the results of a single test (e.g. that conducted by the Australasian New Car Assessment Program, ANCAP) can be used to predict performance across a range of speeds. However, if bottoming out occurs above a particular speed the scaling method cannot be used to predict the resulting HIC values, which would likely be much higher than otherwise expected.

The first goal of this project was to develop a practical method for measuring underbonnet clearance between a test location and any harder structures below the bonnet. This can then be used to calculate the speed at which bottoming out will occur. This information has the potential to be used in the vehicle's overall assessment by rewarding high clearances and penalising narrow clearances. The method that was selected was to drill holes in the bonnet at the test locations, and to measure the underbonnet clearance directly using a Vernier gauge. This report gives details of this method such that it can be applied in other laboratories. Using this method, the underbonnet clearances were measured for five different vehicles that had been tested by ANCAP, at a total of 64 test locations. The method proved practicable and showed that such information can be gained for a relatively small investment of time and additional equipment.

The second goal of this project was to use these clearance measurements to evaluate the performance of vehicles across a real crash speed distribution. This was done by using a published crash speed distribution, which was converted to a distribution of HIC values for each test result, using the relationship mentioned above. This HIC distribution was then converted to a calculation of injury risk, using a published fatal head injury risk curve. For each test location (and for each vehicle), an overall 'injury risk value' was calculated using this method, with and without the added clearance information.

For the five vehicles considered, the underbonnet clearances were found to be quite large and thus their overall evaluation was not greatly affected. This is a great improvement on many designs in previous years. However, for one vehicle, the assessment was worse when bottoming out was included in the evaluation. This was due to a series of test locations that did not bottom out at the ANCAP test speed, but were found to bottom out at slightly higher speeds. The limitation of this evaluation method is largely the lack of basic knowledge about the speed distribution and the injury risk curve.

Contents

1 Background 1
2 Scaling HIC with speed 4
2.1 Inclusion of bottoming out into the scaling method 4
2.2 Calculation of *B* when bottoming out occurred in the test 5
3 Method for measuring underbonnet clearance 7
3.1 Method selection 7
3.2 Description of chosen method 7
3.3 Underbonnet geometry considerations 9
3.4 Experience with the measurement method 10
4 Evaluating vehicle performance across all crash speeds 11
4.1 Method for evaluating overall performance 11
4.2 Results for each vehicle 13
5 Discussion 19
Acknowledgements 22
References 23

1 Background

Pedestrians account for around 15% of the national road toll, or about 200 deaths per year. In the ACT, there were 21 fatal pedestrian crashes in the period 2001-2010, which represents 15% of the total road fatalities, in line with the Australian national average (Infrastructure 2012). One measure to address the prevalence and severity of pedestrian injuries is through improving vehicle design. The extent to which a vehicle design provides protection to pedestrians may be evaluated through the use of pedestrian impact testing.

Pedestrian impact testing is used as part of new car assessment programs and for compliance with vehicle design regulations. These tests are conducted as part of the Australasian New Car Assessment Program (ANCAP), and have been conducted at the CASR pedestrian testing laboratory for over a decade. The tests involve firing dummy components into the front of a stationary vehicle. These components include a full legform, an upper legform and two differently sized headforms (child and adult). The focus of this project is on the headform testing components, as it is typically pedestrian head injuries that are life-threatening.

Figure 1.1 illustrates a typical pedestrian headform test. The headform strikes the bonnet, which deforms significantly (typically somewhere in the range of 50-100mm, measured perpendicular to the bonnet surface). During the impact the high speed footage shows that the headform rolls along the surface of the bonnet. Note that in this sequence of stills, the vehicle is facing right and the headform is initially travelling down and to the left.

The headform tests are evaluated using a quantity known as the Head Injury Criterion, or HIC. The headform is equipped with accelerometers, which measure the acceleration, or deceleration, experienced by the headform. The HIC value is calculated using the following relationship:

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

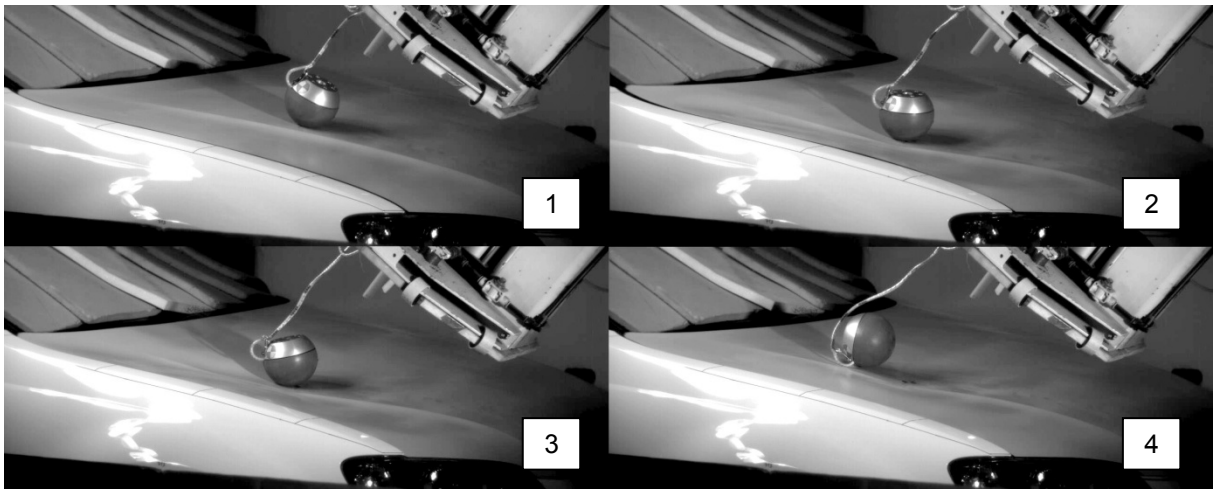

Figure 1.1
High speed video capture of a typical pedestrian headform test.

In Equation (1), the time points t_1 and t_2 are selected to maximise the expression inside the braces, and $a(t)$ is the head acceleration data recorded during the impact. While Equation (1) looks quite complicated, it may be summarised by saying that HIC is positively related to the average acceleration experienced by the headform, and to the duration of the time window over which that average acceleration is taken. The exponent 2.5 penalises the more sharply peaked acceleration pulses.

In ANCAP tests and in many vehicle design regulations, an upper HIC limit of 1000 is used to denote an acceptable level of impact severity. The ANCAP tests use the testing protocol developed by Euro NCAP. The current version of the protocol is Version 5, which awards the maximum available point score to tests that result in a HIC of less than 1000, and zero points to tests that score a HIC in excess of 1350 (Euro NCAP, 2011). In 2013 these limits will be changing to 650 and 1700 respectively. Tests that score in between these two values receive points on a linear scale.

In general, a vehicle will perform well in a pedestrian impact test if the outer surface of the vehicle is relatively soft on impact, but is stiff enough that it does not deform far enough to come into contact with a much harder structure underneath. For example, the bonnet should be able to deform sufficiently to absorb the energy of the headform, without coming into contact with the engine block. If the bonnet does make contact with a harder structure beneath, this is referred to as 'bottoming out'.

Current testing protocols specify impact tests that are performed at a single test speed. For example, the pedestrian testing conducted as part of ANCAP is conducted at a fixed speed of 40 km/h. The new Global Technical Regulation (GTR) on pedestrian safety specifies a fixed impact speed of 35 km/h and as such is generally a less stringent test (Searson and Anderson 2010).

There are downsides to evaluating the performance of a test location at one speed only. One downside is that the design of the vehicle may be optimised to perform well at the test speed, at the expense of performance at other speeds. The previously mentioned example of the bonnet bottoming out on the engine block is a good example of this. If the bonnet does not bottom out at the test speed of 40 km/h, it may perform well in the ANCAP test. However, if it bottoms out at slightly higher impact speeds, its real world performance would be severely compromised. Since a significant proportion of impacts happen above 40 km/h, the result of the single test at 40 km/h would not be representative of the danger posed by that location on the vehicle.

Another downside of a fixed impact speed is that locations that perform poorly at the test speed are not encouraged to improve. Manufacturers may 'write off' these locations as not worth improving, even though there may be benefits to improving the design of these locations for low speed impacts. For example, the A-pillars of vehicles generally perform very poorly at 40 km/h. There is no incentive to improve the design, because it would be very difficult to score a HIC below 1350, let alone 1000. However, at 25 km/h, it might be possible to achieve a HIC of 1000 or less, and this should be encouraged.

It would be possible, but very expensive and time consuming, to test every test location at a wide range of impact speeds. As a faster and cheaper alternative, the performance of a test location across a range of test speeds may be inferred from its performance at a single test speed. Previous research conducted by CASR has demonstrated a method for converting HIC values from one test speed to a range of impact speeds (Searson et al 2009). This method is based on a theoretical model of a linear spring, and has compared well with experimental data. It is described more fully in Section 2.

At present, the HIC scaling method is based on a theoretical model that does not account for bottoming out and the experimental data has not included impacts that bottomed out. However, the presence of bottoming out may be accounted for by simply assuming a much steeper relationship

between HIC and speed (also discussed further in Section 2). With this in mind, all that remains is to distinguish between test speeds that cause bottoming out and those that do not.

In order to make this distinction, the speed of bottoming out must be calculated. Such a calculation is dependent on knowing two quantities:

1. The maximum displacement of the headform during the test.
2. The available clearance between the bonnet and the hard structure that causes bottoming out.

For item 1, the displacement of the headform during the test may be estimated by double-integrating the acceleration measurements (Searson and Anderson 2008).

As for item 2, there is no current procedure for measuring the underbonnet clearance, and that is what this project aims to develop. Using this information, we are able to predict the speed at which contact with the harder structure would occur. The harder structure may then be taken into account in the severity measurement of that test location.

Thus, the primary goal of this project is to develop a usable method for measuring underbonnet clearance. The secondary goal of this project is to demonstrate how this information can be used to assess the performance of a vehicle across a wide range of crash speeds.

2 Scaling HIC with speed

This section describes the method that has been developed by CASR for scaling HIC values with speed, taking into account the possibility of bottoming out. The method, in the absence of bottoming out, is based on a theoretical model of a linear spring: the bonnet structure is represented by a spring, the force on the spring is linearly related to the displacement of the headform. When bottoming out occurs, the method is slightly altered to reflect the higher values of HIC that would be expected.

The linear spring model implies the following: if a test is conducted at a speed of v_1 and results in a HIC value of HIC_1, then the HIC value HIC_2 of a second test conducted at a speed of v_2 can be predicted using the following relationship:

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

The value of b is 2.5 from the theoretical model, and this value is in line with that obtained from experimental data (Searson 2012, Chapter 5). Thus, this equation with b=2.5 can be used to predict HIC values for speeds that have not been tested. However, this relationship assumes that no bottoming out occurs, and has only been validated with data from non-bottomed out impacts.

For this project, Equation (2) was retained but with b=5 for bottomed out impacts. While this has not yet been verified with experimental data, it is a simple method for ensuring that the HIC values are much higher above the bottoming out speed. (Hutchinson et al, 2012, suggested a still higher exponent of b=7.5.)

Using the theoretical linear spring model, a relationship between the maximum displacement of the headform and the test speed can also be derived. In this case, the maximum displacements in each test are labelled s_1 and s_2. The value of s_2 can be predicted as follows:

$$s_2 = s_1\left(\frac{v_2}{v_1}\right) \tag{3}$$

Thus if we can measure the maximum displacement at one test speed (v_1), we can predict what the maximum displacement is at another speed (v_2). Equation (3) has been compared with experimental data (Searson 2012, Chapter 5), and the data suggests that an exponent of 0.8 on the velocity ratio is more appropriate. However, for the purposes of the evaluations in this report, Equation (3) will be used as is.

Equation (2) can be used to scale the HIC result from one test to a wider range of speeds. However, if we are to account for the possibility of bottoming out, then we need a way to distinguish between speeds that do or do not result in bottoming out. This can be achieved by using Equation (3) to calculate the speed of bottoming out, based on the measured clearance and the displacement of the headform in the original test.

2.1 Inclusion of bottoming out into the scaling method

We will begin by assuming a test has been conducted at a speed v_1 resulting in a HIC value of HIC_1 and a maximum displacement of s_1. In the case of an ANCAP test, the speed v_1 would be approximately 40 km/h, and the values of HIC_1 and s_1 would be taken from the measured acceleration of the headform. The measured underbonnet clearance at the test location will be called C.

We then assume that there is a speed *B* at which the headform will bottom out on a stiff structure beneath the surface. In other words, when the test speed is equal to *B*, the peak displacement of the head will be exactly equal to *C*. The value of *B* may be calculated using the linear relationship between peak displacement and impact speed.

$$B = v_1\left(\frac{C}{s_1}\right) \tag{4}$$

This method for calculating *B* only holds when the original impact did not experience any bottoming out. If bottoming out did occur in the original impact, then *B* is lower than v_1 and may be estimated using the acceleration data. See Section 2.2 for a full description of this method.

Thus, we know that at a speed of *B*, bottoming out will occur. We can then calculate the HIC at the bottoming speed, HIC_B, using Equation (2) as follows:

$$HIC_B = HIC_1\left(\frac{B}{v_1}\right)^b \tag{5}$$

In this formula, the value of *b* is 2.5 if bottoming out did not occur in the original test. However, if the original test experienced bottoming out (i.e. $v_1 > B$), then the value of *b* in this calculation is 5.

The HIC is then calculated for other test speeds using Equation (2), using the value of HIC_B and by recognising that the value of *b* is dependent on whether the speed in question is above or below the bottoming out speed. To write this explicitly, the HIC at any speed *x* can be estimated by calculating as follows:

$$HIC(x) = \begin{cases} HIC_B(x/B)^{2.5} & x < B \\ HIC_B(x/B)^5 & x \geq B \end{cases} \tag{6}$$

Using the above formulae, a single test result (described by v_1, HIC_1 and s_1) can be used in conjunction with a clearance measurement (*C*) to give HIC values across all speeds.

2.2 Calculation of *B* when bottoming out occurred in the test

In order to calculate *B* using the above method, it is necessary to use the relationship between peak displacement and impact speed, as expressed in Equation (3). However, this relationship is based on the theoretical linear spring model, which does not account for bottoming out. Thus, if bottoming out occurred in the original test (at speed v_1), then an alternative method is needed to calculate *B.*

The method used to calculate *B* in this situation was to directly measure (from acceleration data), the energy required for bottoming out. The acceleration measurements from the test location in question were used to derive the normal displacement of the headform throughout the impact relative to the bonnet surface (Searson and Anderson 2008). The time step at which bottoming out occurred was estimated by the time point at which the measured normal displacement was higher than or equal to *C*. The normal velocity of the headform at this time in the impact is labelled v_{CN}. The normal component of the test speed is labelled v_N.

The specific energy (i.e. energy per unit mass) required for the headform to bottom out, e_B, was calculated by the change in kinetic energy up until the moment that bottoming out occurred (normal component only):

$$e_B = \tfrac{1}{2} v_N^{\ 2} - \tfrac{1}{2} v_{CN}^2 \quad (7)$$

It was then assumed that the energy loss characteristics of the bonnet would be equal in an impact that occurred at the bottoming out speed, *B*. In such an impact, the headform would bottom out at the exact time that its normal impact speed reaches zero. For this to occur, the initial kinetic energy of the headform (normal component) must be equal to e_B.

Since we only consider the normal component, the test speed in the equation for kinetic energy is $B\sin\theta$, where θ is the angle between the initial trajectory of the headform and the bonnet surface.

$$e_B = \tfrac{1}{2} (B \sin \theta)^2 \quad (8)$$

Equating (7) and (8), and rearranging for *B*, we arrive at the following expression:

$$B = \frac{\sqrt{v_N^2 - v_{CN}^2}}{\sin \theta} \quad (9)$$

To summarise: using Equation (9) the bottoming out speed, *B*, was calculated via the following:

- The initial normal impact speed, v_N.
- The normal impact speed at the time in the original impact where the clearance distance is reached. This was calculated from a double integration of the acceleration data (Searson and Anderson 2008), and is labelled v_{CN}.
- The initial angle between the trajectory of the headform and the bonnet surface, θ.

3 Method for measuring underbonnet clearance

3.1 Method selection

Several methods for measuring under bonnet clearance were considered. They are listed in Table 3.1 along with their pros and cons.

Table 3.1
Pros and cons of different methods.

Method	Pros	Cons
Use a digital surveying tool to obtain coordinates of key features above and below the bonnet. Obtain clearance measurements using analysis software.	* High accuracy of individual measurements.	* Time consuming to take measurements and process in software. * Requires specialised equipment and software.
Place crushable foam beneath the bonnet, and close bonnet. Take clearance measurements using height gauge.	* Direct physical measurement. * Fast, does not require specialised equipment.	* Would consume large amounts of foam (potentially expensive/wasteful). * Low accuracy, hard to determine test location on foam. * Difficult to account for distance between outer and inner bonnet skin.
Drill holes in bonnet at test locations, measure clearance using Vernier depth gauge.	* Direct physical measurement. * Relatively fast, does not require specialised equipment.	* May be difficult to resolve geometry of structures beneath bonnet surface. * An additional undamaged bonnet is required.

The third method listed in Table 3.1 was selected for use in this project. The main benefits of this method were that the measurements were taken directly on the vehicle, and that the only equipment required would be present in most engineering laboratories. The method also does not require any specialised experience or skills of the laboratory engineer.

One downside to this method was the difficulty of accounting for the geometry of structures beneath the bonnet; this problem is discussed in greater detail in Section 3.3.

Another downside was that an additional bonnet is required. For the ANCAP testing conducted at the CASR laboratory, a spare bonnet is usually available that has been ‘marked up’ prior to testing. In other laboratories, this may necessitate the purchase of an extra bonnet.

A Vernier depth gauge was used to measure the distance from the outer surface of the bonnet to the harder structure below. While a Vernier gauge is a very accurate tool, the degree of accuracy it provides was not a requirement. In practice, any tool that provides such a measurement to around ±1 mm will be more than sufficient.

3.2 Description of chosen method

Step one: Bonnet markings

Mark each test location onto the bonnet if they have not already been marked. This should be achieved using an accurate method for reproducing location markings – e.g. measurements from the upper left and right corners of the bonnet.

For each test location, the ‘aiming point’ (AP) should also be marked. This is the location that the headform is aimed at during the test. For the majority of tests, this will be a located further to the rear of the vehicle than the test location, or point of first contact (POFC).

Both of these markings are made as part of ANCAP tests, and should be marked following the procedure in the Euro NCAP test protocol.

Step two: Drill holes in bonnet

For each test location, drill a hole at the AP and another at the POFC. This is easiest to achieve by first drilling a small pilot hole, and then drilling a larger hole to accommodate the Vernier depth gauge. The larger hole should be the smallest hole possible that will accommodate the depth gauge. We would recommend no greater than M6.

When the bonnet has an additional layer of metal under the location being drilled, it might be easier to turn the bonnet over and drill the second layer from the underside. A larger drill bit may be used for the additional layer(s).

Step three: Take measurements

The bonnet should now be mounted onto the vehicle. At each drilled hole (AP and POFC), the Vernier depth gauge is held at 90° to the surface of the bonnet. This can be checked using a square, or by ensuring that the base of the gauge is sitting flush with the surface. The gauge is then extended until the probe strikes an item below the bonnet. Figure 3.1 demonstrates this step.

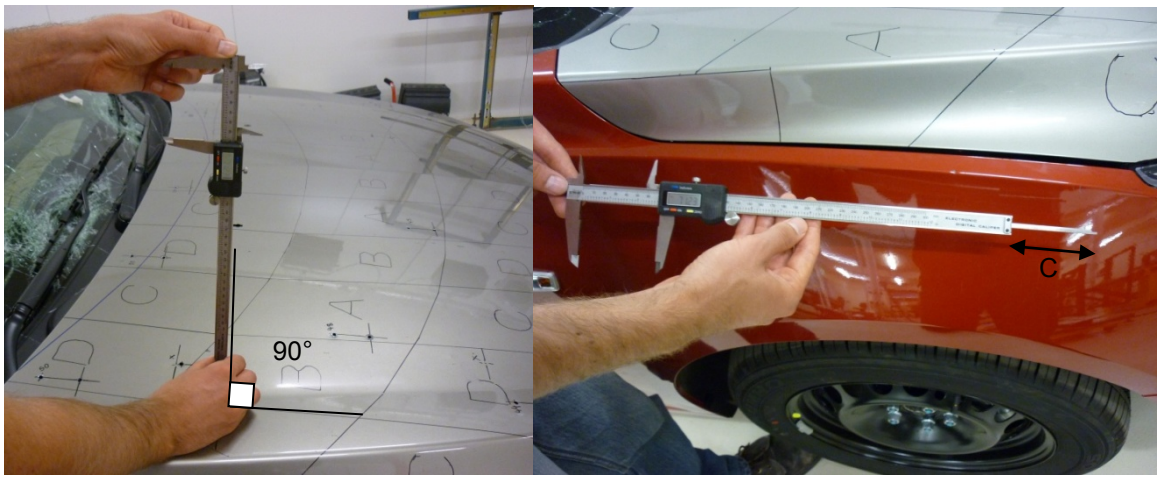

Figure 3.1
Measurement of clearance using Vernier depth gauge. The gauge is held at 90° to the surface and the probe is extended.

In general, the clearance measurement taken at the AP is the relevant clearance for predicting the speed of bottoming out. In some cases the POFC may be used depending on the geometry of the underbonnet structures. Section 3.3 discusses this in more detail.

Step four: Subtract bonnet layer thickness

The measurement of interest is the distance between the underside of the bonnet and the harder structure beneath. When using the Vernier gauge as described above, the resulting measurement will be the distance from the top side of the bonnet to the hard structure. Thus, it is necessary to subtract the thickness of the bonnet layers from the initial measurement.

The thickness of the bonnet layers may be measured using the Vernier calipers. This may require cutting into the bonnet to expose a usable edge. If there are two or more layers then each layer thickness should be measured, if possible. If it is not possible to easily measure a particular layer, then a thickness of 1 mm may be assumed.

3.3 Underbonnet geometry considerations

The two locations that are marked on the bonnet are the point of first contact (POFC) and the aiming point (AP). In the test, the centre of the headform is aimed at the AP, and due to the angle of impact, it makes contact at the POFC. When the test is perpendicular to the surface, these two locations will be the same. Otherwise, the AP is typically further to the rear of the vehicle than the POFC.

So where do we measure our underbonnet clearance from and from what angle? The headform will roll along the surface of the bonnet, and as such, the area where maximum displacement occurs will not necessarily be the POFC or the AP.

The geometry of the structures beneath the surface also makes a difference, as shown in Figure 3.2 and Figure 3.3. The dashed line is the trajectory of the headform, the dotted lines are the measurements taken from the POFC and the AP. The POFC will give a much higher clearance than the AP in Figure 3.2, and the measurement taken from the AP would be more likely to reflect reality. The opposite situation is shown in Figure 3.3.

There is also some dependency on the crush characteristics of the bonnet itself.

The best solution may be to generally take the measurement from the AP on the assumption that the headform rolls along the surface, and thus peak displacement will occur further to the rear of the vehicle than the POFC. In situations such as that illustrated in Figure 3.3, the measurement from the POFC would be more appropriate.

Generally speaking, the discretion of the test laboratory should be used where the correct measurement location is not clear. If neither the AP or POFC are appropriate, then another hole may be drilled and used for the measurement.

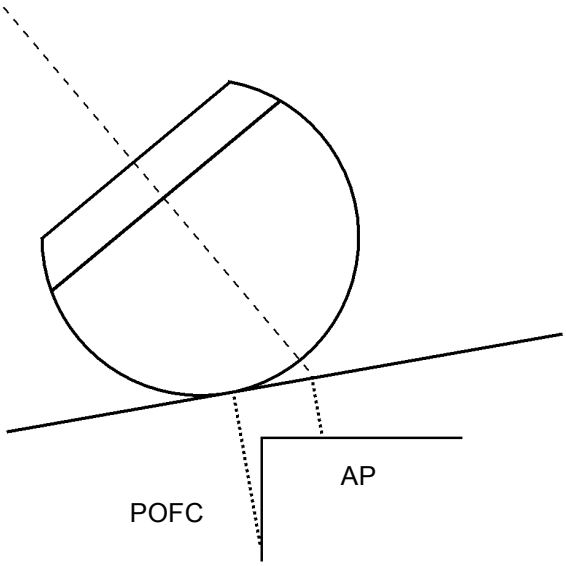

Figure 3.2
Aiming point (AP) is more accurate in this case.

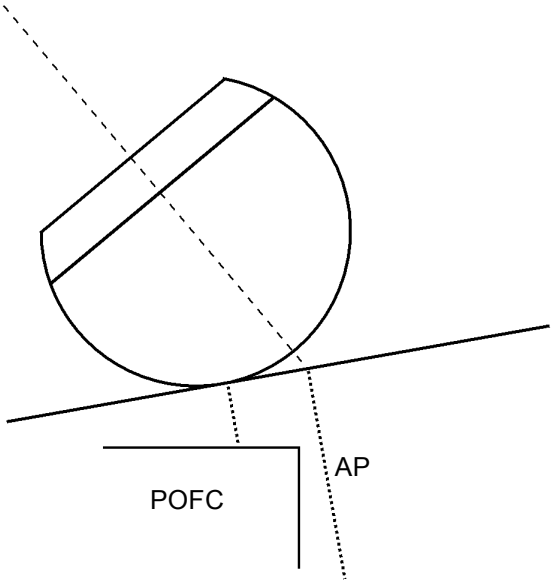

Figure 3.3
Point of first contact (POFC) may be more accurate here.

3.4 Experience with the measurement method

The method described above was used to measure the underbonnet clearance for a total of 64 test locations spread across the bonnets of five ANCAP test vehicles. For each test location, the clearance at the AP and the POFC was measured. In most cases the clearance at the POFC was taken as the relevant measurement, although the AP was used in some cases where it was more appropriate.

In general, the entire process of marking the test locations, drilling holes and taking measurements took approximately one working day per vehicle for a single laboratory engineer. The accuracy of the results seemed reasonable, the direct measurement with the Vernier gauge meant that there was little doubt as to whether the measured value was an accurate reflection of the available clearance. Despite this, the issue outlined in Section 3.3 may be the cause of some inaccuracy.

For the majority of test locations on these vehicles, the clearance was very high, so high that on current bonnet designs, bottoming out would not occur at any reasonable impact speed (say, those under 100 km/h). At such high speeds, the measurement that was made would not necessarily be relevant; with or without bottoming out, the level of head injury sustained would be incredibly high. In these cases, the measurement of clearance was not required and did not have any effect on the severity measurement of the test location. However, in some cases the test location did have a clearance measurement that would result in bottoming out at speeds only slightly higher than the test speed. For these cases, the presence of bottoming out would have an effect on crashes that might otherwise be less injurious.

The generally high clearance measurements may imply that bottoming out is less of an issue on modern vehicles than it has been in the past. In the experience of the laboratory staff, older vehicles generally had more locations that were likely to bottom out during the ANCAP test. With the advent of pedestrian testing regulations in Europe and Japan, and the presence of new car assessment programs around the world, vehicle manufacturers would appear to be designing their vehicles with sufficient underbonnet clearance available.

4 Evaluating vehicle performance across all crash speeds

As described in the Background section, current pedestrian testing protocols evaluate performance at a single test speed. In Section 2, a formula was presented that makes it possible to estimate performance at any given speed, based on the results of a single test. This formula was based on the assumption that no bottoming out occurs. With the addition of an underbonnet clearance measurement, it is possible to make such estimates taking into account bottoming out.

The following method was used to evaulate the performance of the five measured vehicles, over a distribution of real world crash speeds, taking into account bottoming out where necessary.

4.1 Method for evaluating overall performance

The method used to evaluate the performance of each vehicle was based on that developed by Searson (2012) (Chapter 8) and Hutchinson et al (2012), and requires a distribution of crash speeds as well as a relationship between HIC and injury risk. To perform the evaluations, a computer program was written and run using Matlab Version R2011a.

It is worth noting that simpler methods for evaluation may also be developed to account for the range of crash speeds as well as bottoming out. For example, a simple method would be to award points for underbonnet clearance as well as for HIC. The evaluation in this report was used to demonstrate the possibility of integrating a test result with a real world injury risk (although the reality is that this real world injury risk is probably far from correct in an absolute sense, for reasons outlined later on).

4.1.1 Assessing individual test location performance

The test locations on the bonnet of each vehicle were marked and the clearances were measured in accordance with Section 3.2. The measured clearances, along with the results of the original ANCAP test, were used to estimate an injury risk value for each test location.

The injury risk value was calculated using the methodology previously developed by Searson (2012) (Chapter 8). A distribution of impact speeds was taken from the dataset presented by Mizuno (2003), taking only those cases where head injury AIS was 2 or greater. The speed distribution is shown in Figure 4.1, and had a mean speed of 42.7 km/h and a median of 40 km/h. The HIC obtained at the test speed was scaled to the distribution of crash speeds using the method detailed in Section 2.

After the speed distribution had been converted to a HIC distribution, the HIC distribution was converted to a distribution of injury risk values. This was done using the HIC versus fatal head injury risk relationship developed by NHTSA (1995), which was based on the initial work of Prasad and Mertz (1985). The relationship is shown in Figure 4.2, and is derived from the following equation:

$$Risk = \left(1 + \exp(12.24 + \frac{200}{HIC} - 0.00565 \times HIC)\right)^{-1} \quad (10)$$

The mean of the final distribution of injury risk values was calculated to give an overall injury risk value (IRV) for each test location.

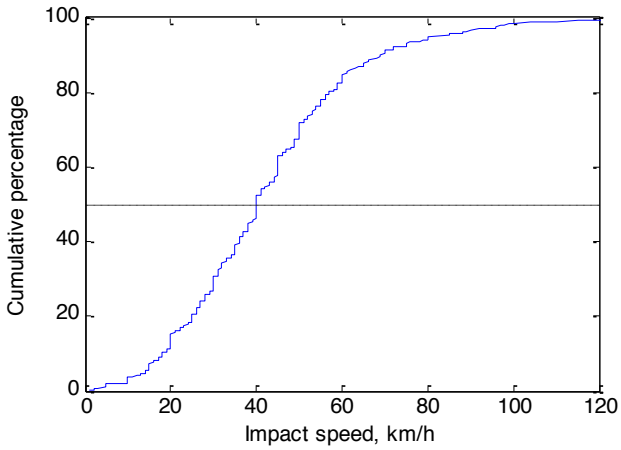

Figure 4.1
Impact speed distribution taken from IHRA data presented by Mizuno (2003), Head AIS 2+.

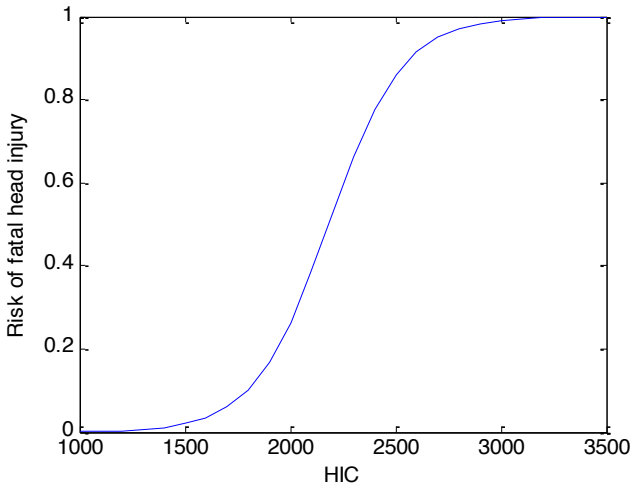

Figure 4.2
Fatal head injury risk versus HIC (NHTSA 1995).

This process for estimating an IRV was performed for each test location, with and without the consideration of the measured value of *C* (as defined in Section 2.1). When *C* was not considered, one of the following two assumptions were made:

1. If bottoming out did not occur in the original test, then the bottoming out speed was assumed to be very high (greater than 100 km/h).

2. If bottoming out occurred in the original test (this can be determined by the test pulse and/or visual inspection of high speed footage and the damaged bonnet), then the bottoming out speed was assumed to be 35 km/h, or 9.7 m/s.

When *C* was included in the evaluation, it was used to calculate the bottoming out speed directly via Equation (4) or using the method described in Section 2.2 when bottoming out occurred in the original test.

By performing the evaluation with and without the knowledge of *C*, it was possible to determine whether the measurement of underbonnet clearance had an effect on the overall evaluation of each test location and vehicle.

4.1.2 Assessing overall vehicle performance

The individual test location results were combined into an overall vehicle performance measure. This was done by calculating the mean of the injury risk values for all of the test locations on each vehicle.

The calculation of the mean was weighted in the same way as the Euro NCAP test protocol weights its points scores. The front of the vehicle is divided into zones (six adult and six child), and these are each divided into four quadrants. Euro NCAP (or ANCAP) select one test location in each zone, based on what is thought to be the most dangerous, or worst, location in that zone. The vehicle manufacturer can nominate one or more of the non-selected quadrants and a single additional test is conducted on what is judged to be the worst location in any one of those quadrants.

The weighting scheme was applied as follows:

- If no quadrants had been nominated by the manufacturer for an additional test in a particular zone, then the ANCAP test had a weighting of one.
- If one quadrant out of four had been nominated by the manufacturer for an additional test, then the ANCAP test had a weighting of 0.75 and the manufacturer test a weighting of 0.25.
- If two quadrants were nominated, then both the ANCAP and manufacturer tests had a weighting of 0.5.
- If three quadrants were nominated, then the ANCAP test had a weighting of 0.25 and the manufacturer test a weighting of 0.75.

These weightings were used as they give an approximation of how ‘representative’ a particular a test result is of the performance of each zone, and are consistent with the method for combining scores in the Euro NCAP protocol.

In limited cases, the weightings as described above are slightly different for the ANCAP assessment. For example, if the manufacturer test performs worse than the ANCAP test, then the manufacturer test has a weighting of 0.25 and the ANCAP test 0.75, regardless of how many quadrants were nominated. In these cases, the modified weightings were used for calculating the mean IRV as well.

4.2 Results for each vehicle

The results for each test location on each vehicle are summarised below in Table 4.1 through to Table 4.5. For some test locations there was a change in the IRV when the measured value of *C* was included in the evaluation. These locations are highlighted in italics.

Bottoming out speeds that are marked with an asterisk (*) are for tests that experienced bottoming out in the original test. Thus, the bottoming out speeds were determined using the method described in Section 2.2. Also note that for these locations, the bottoming out speed was assumed to be 9.7 m/s (35 km/h) when the measured value of *C* was ignored.

Although not particularly important for the contents of this report, the location naming scheme is as follows:

- The first letter indicates a child (C) or adult (A) headform.
- The number indicates the zone (1 to 6).

- The second letter indicates the quadrant that was tested (A, B, C or D).
- If there are lowercase letters in brackets, the test was performed in a manufacturer nominated quadrant. The quadrants selected by the manufacturer are those listed in the brackets.

Only test locations on the bonnet were considered in this evaluation. Although many ANCAP tests are also conducted on the lower front area of the windscreen, the relationship between HIC and impact speed given by Equation (2) has not been verified in windscreen impacts, so they were excluded.

Note that for many locations lying on the same vehicle, the HIC values are identical. In these cases, the same test has been used to represent both locations, due to design symmetry.

The vehicles have been deidentified as the limitations of the method (see Section 5) mean that while it is realistic to consider relative values of the IRV valid, the absolute values may not reflect reality.

Table 4.1
Results for each test location on Vehicle 1.

Location	HIC	C,mm	Weight	ANCAP Score	IRV (ignore C)	IRV (include C)	B, m/s
C1C	1308	128.5	0.75	0.18	0.333	0.333	22.6
C1D(d)	904	221.5	0.25	0.50	0.212	0.212	36.4
C2B	773	298.5	0.50	1.00	0.168	0.168	53.7
C2D(cd)	*542*	*144.5*	*0.50*	*1.00*	*0.099*	*0.107*	*18.8*
C3D	706	141.5	1.00	2.00	0.146	0.146	21.6
C4C	706	140.5	1.00	2.00	0.146	0.146	21.4
C5C(cd)	542	217.5	0.50	1.00	0.099	0.099	28.2
C5A	773	298.5	0.50	1.00	0.168	0.168	53.7
C6C(c)	904	186.5	0.25	0.50	0.212	0.212	30.7
C6D	1308	128.5	0.75	0.18	0.333	0.333	22.6

Table 4.2
Results for each test location on Vehicle 2.

Location	HIC	C,mm	Weight	ANCAP Score	IRV (ignore C)	IRV (include C)	B, m/s
C1A	1470	108.5	0.75	0.00	0.367	0.367	22.8
C1D(d)	940	248.5	0.25	0.50	0.222	0.222	47.8
C2B	1078	298.5	1.00	1.55	0.261	0.261	56.8
C3B	874	298.5	1.00	2.00	0.200	0.200	52.4
C4A	874	298.5	1.00	2.00	0.200	0.200	52.4
C5A	606	298.5	1.00	2.00	0.120	0.120	48.3
C6C(c)	940	98.5	0.25	0.50	0.222	0.222	19.0
C6B	1470	108.5	0.75	0.00	0.367	0.367	22.8

Table 4.3
Results for each test location on Vehicle 3.

Location	HIC	C,mm	Weight	ANCAP Score	IRV (ignore C)	IRV (include C)	B, m/s
C1C	2235	42.5	1.00	0.00	0.524	0.524	10.0*
C2C	1962	107.8	1.00	0.00	0.476	0.476	27.7
C3D	1635	90.0	1.00	0.00	0.413	0.413	23.9
C4C	1635	91.0	1.00	0.00	0.413	0.413	24.2
C5D	1962	107.8	1.00	0.00	0.476	0.476	27.7
C6D	2235	42.5	1.00	0.00	0.524	0.524	10.0*

Table 4.4
Results for each test location on Vehicle 4.

Location	HIC	C,mm	Weight	ANCAP Score	IRV (ignore C)	IRV (include C)	B, m/s
C1B	*1250*	*63.5*	*0.75*	*0.43*	*0.312*	*0.360*	*12.4*
C1D(d)	878	133.5	0.25	0.50	0.201	0.201	21.4
C2C(abc)	1037	248.5	0.25	0.45	0.248	0.248	43.0
C2D	1028	248.5	0.75	1.38	0.244	0.244	43.1
C3A(abc)	*482*	*138.5*	*0.75*	*1.50*	*0.080*	*0.109*	*17.3*
C3D	*938*	*80.5*	*0.25*	*0.50*	*0.214*	*0.267*	*13.5*
C4B(abd)	482	248.5	0.75	1.50	0.080	0.080	31.1
C4C	938	248.5	0.25	0.50	0.214	0.214	41.6
C5C	1028	248.5	0.75	1.38	0.244	0.244	43.1
C5B(abd)	796	65.3	0.25	0.50	0.330	0.330	11.0*
C6A	*1250*	*59.5*	*0.75*	*0.43*	*0.312*	*0.384*	*11.6*
C6C(c)	*878*	*88.5*	*0.25*	*0.50*	*0.201*	*0.242*	*14.2*
A1D(d)	1612	34.5	0.25	0.00	0.454	0.454	8.5*
A2D(cd)	1069	48.5	0.50	0.80	0.375	0.375	9.6
A3D(cd)	*852*	*81.5*	*0.50*	*1.00*	*0.196*	*0.284*	*12.6*
A4C(cd)	*852*	*81.5*	*0.50*	*1.00*	*0.196*	*0.284*	*12.6*
A5C(cd)	1069	51.5	0.50	0.80	0.375	0.375	9.9*
A6C(c)	1612	34.5	0.25	0.00	0.454	0.454	8.5*

Table 4.5
Results for each test location on Vehicle 5.

Location	HIC	C,mm	Weight	ANCAP Score	IRV (ignore C)	IRV (include C)	B, m/s
C1B(b)	*845*	*80.5*	*0.25*	*0.50*	*0.190*	*0.210*	*15.4*
C1C	2841	82.5	0.75	0.00	0.600	0.600	21.4
C2C	933	248.5	0.50	1.00	0.218	0.218	45.6
C2B(ab)	773	248.5	0.50	1.00	0.164	0.164	41.7
C3B(ab)	703	248.5	0.50	1.00	0.148	0.148	38.4
C3D	2059	72.8	0.50	0.00	0.491	0.491	21.3
C4A(ab)	703	248.5	0.50	1.00	0.148	0.148	38.4
C4D	2059	72.8	0.50	0.00	0.491	0.491	21.3
C5A(ab)	586	248.5	0.50	1.00	0.113	0.113	37.6
C5D	933	248.5	0.50	1.00	0.218	0.218	45.6
C6A(a)	845	248.5	0.25	0.50	0.190	0.190	47.5
C6D	2841	82.5	0.75	0.00	0.600	0.600	21.4
A1D(d)	1346	69.8	0.25	0.01	0.435	0.435	10.9*
A2C(cd)	854	112.5	0.50	1.00	0.194	0.194	17.3
A2A	1303	66.5	0.50	0.13	0.424	0.424	10.7*
A3B	1062	58.5	0.50	0.82	0.378	0.378	10.1*
A3D(cd)	415	249.3	0.50	1.00	0.068	0.068	27.2
A4C(cd)	*415*	*186.3*	*0.50*	*1.00*	*0.068*	*0.075*	*20.3*
A4A	1062	54.5	0.50	0.82	0.378	0.378	9.7*
A5B	1303	64.5	0.50	0.13	0.424	0.424	10.5*
A5D(cd)	854	139.5	0.50	1.00	0.194	0.194	21.4
A6C(c)	1346	69.8	0.25	0.01	0.435	0.435	10.9*

In most cases, bottoming out did not occur at the test speed or at any speeds within the distribution. Thus, the IRV values are the same with and without the inclusion of the clearance measurement.

In the cases where the knowledge of clearance had an effect on the IRV (highlighted in italics), an increase in IRV was experienced when the measured value of *C* was used in the evaluation. This is the result we might expect, as the presence of bottoming out leads to much higher HIC values at higher impact speeds.

Figure 4.3 is a plot of the HIC and IRV for each test location. The relationship follows a general curving trend upwards. Locations where bottoming out was a factor are those above the lower curve – the possibility of bottoming out makes their IRV assessment effectively higher than what the HIC alone could be used to predict. For locations that have high clearances and are unaffected by bottoming out, the HIC and the IRV are highly correlated.

The overall results for each vehicle are summarised below in Table 4.6. The ANCAP score for each vehicle is also listed in the table, although note that each vehicle is scored out of a different total, which represents the points available from locations lying on the bonnet only. The overall ANCAP head score is usually out of 24, but this includes locations on the windscreen as well.

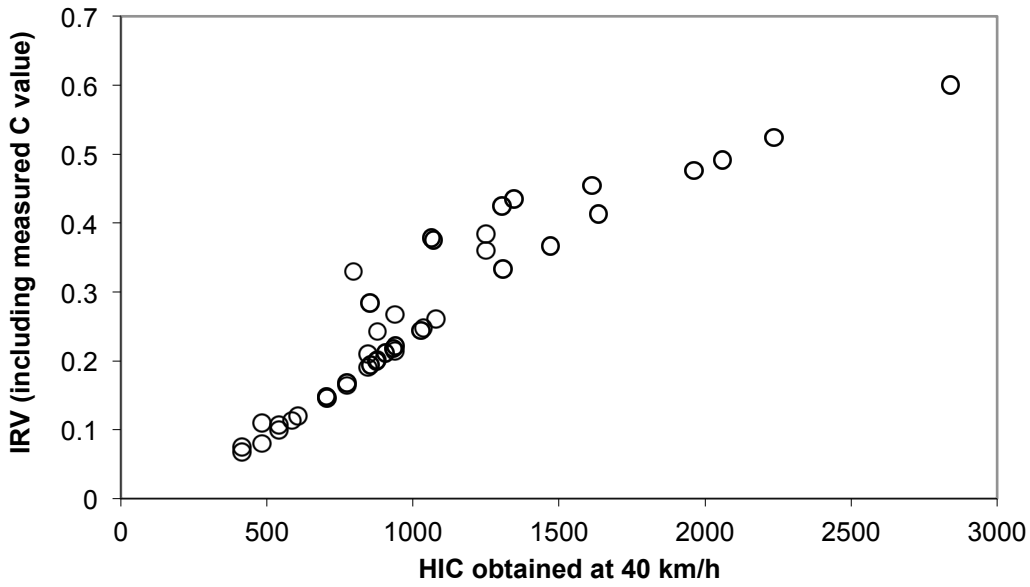

Figure 4.3
HIC versus IRV for all measured test locations.

Table 4.6
Results for each vehicle.

Vehicle	ANCAP bonnet tests score	Weighted Mean IRV (ignore C)	Weighted Mean IRV (include C)
1	9.4 out of 12	0.194	0.195
2	8.6 out of 12	0.240	0.240
3	0 out of 12	0.471	0.471
4	13.2 out of 17	0.248	0.274
5	12.9 out of 21	0.312	0.312

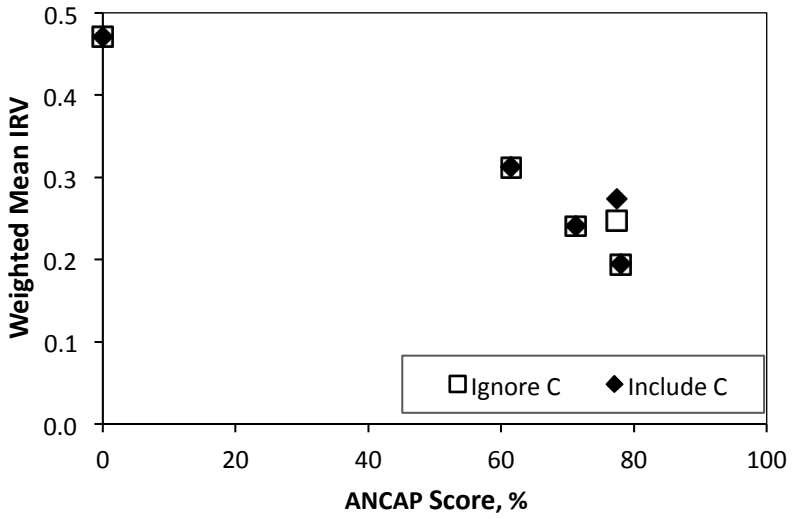

Figure 4.4
Weighted Mean IRV versus ANCAP score, with and without using the measured value of *C*.

Figure 4.4 plots the weighted mean IRV for each vehicle against the ANCAP score as a percentage of the points available on the bonnet. This plot shows that the Weighted Mean IRV and the ANCAP score for each vehicle were generally negatively related to each other. The overlap between the points with and without the inclusion of *C* illustrates that the inclusion of the clearance measurement had very little effect on the IRV measurement, except for one case (Vehicle 4).

Vehicles 1 and 2 were unaffected by the inclusion of *C*, and had the lowest overall injury risk values. The reason these vehicles were unaffected by bottoming out is that they have a large amount of clearance space available between the bonnet and other structures beneath. This factor would also contribute to their relatively good performance in the ANCAP tests.

Vehicle 3 had by far the largest IRV of all the vehicles, and a very poor ANCAP score (zero). It was unaffected by the inclusion of *C* in the IRV evaluation. In the case of C1C and C6D, the estimated true bottoming out speed was close to the assumed bottoming out speed of 9.7 m/s (35 km/h), so there was no effect of including *C*. For the other four test locations on Vehicle 3, the clearance measurements implied bottoming out speeds that were high enough that bottoming out did not affect the result.

Vehicle 4 had a relatively low overall risk value, and this increased by about 10% when the measured value of *C* was included in the evaluation. Vehicle 4 had a number of test locations that bottomed out at speeds just in excess of the test speed of 11.1 m/s (40 km/h). For this reason, when *C* was not included in the evaluation, they had a much lower IRV than when it was taken into account. A number

of locations on Vehicle 4 also had bottoming speeds just lower than the test speed of 11.1 m/s. In these cases, the assumed bottoming out speed of 9.7 m/s (35 km/h) was close to the true bottoming out speed, and so the evaluation was unaffected by the inclusion of *C*.

Vehicle 5 had the second highest IRV and the second lowest ANCAP score. It was unaffected by the inclusion of *C* in the IRV evaluation method, despite a few locations that would experience bottoming out. In this case, the locations either had a bottoming out speed close to the assumed value of 35 km/h leading to no difference between the evaluation with or without *C*, or the bottoming out speed was so high that the possibility of bottoming out did not affect the evaluation.

5 Discussion

The goal of this project was to develop a method for measuring underbonnet clearance for the purpose of improving the assessment of vehicle pedestrian protection, by considering the full range of crash speeds. This has been acheived with a practical, direct method of measuring underbonnet clearance, and an evaluation of vehicle performance that integrates these measurements.

The method that was selected for measuring underbonnet clearance was to drill holes in the bonnet of the vehicle at the test locations selected by ANCAP, and to measure the clearance directly using a Vernier depth gauge. This method was selected for its simplicity, and because it relies only on tools and skills that would be commonly available in most test laboratories. The downsides of this method were the difficulty in determining the geometry of structures below the bonnet (addressed in Section 3.3), and the requirement of an additional undamaged bonnet. The additional bonnet might add an additional cost of around $500-1000 to the testing process, which would typically be less than 5% of the total cost.

Using this method, measurements were taken on the bonnets of five different vehicles that had been tested by ANCAP. Each test location was evaluated for its 'injury risk value' (IRV). The IRV was calculated using the HIC from the original test result, coupled with a distribution of real crash speeds and a relationship between HIC and injury risk. The presence of bottoming out was accounted for by assuming a sharp increase in HIC when the crash speed was above the bottoming out speed. The bottoming out speed was calculated from the underbonnet clearance measurements and the measured displacement of the headform during the original ANCAP test.

Each test location and vehicle was also evaluated for its IRV, without the measurement of underbonnet clearance. In this case it was assumed that bottoming out did not occur, unless it occurred in the original ANCAP test. If bottoming out had occurred in the original test, then the bottoming out speed was assumed to be 35 km/h.

In general, most test locations did not experience any bottoming out across the full range of speeds considered. As such, the IRV was the same whether the clearance distance, *C,* was known or unknown. However, some test locations were found to experience bottoming out at speeds above the test speed, and some test locations experienced bottoming out in the test. For these locations, the IRV was generally higher when bottoming out was taken into consideration.

For this set of five vehicles, the knowledge of *C* in the evaluation of the ANCAP vehicles only had a small effect on the overall IRV. Four of the five vehicles were essentially unaffected by in inclusion of *C*, but one experienced a notable 10% increase in IRV. Thus, although the knowledge of *C* was not required for some vehicles, we have shown that in one case at least it could make a significant difference to the assessment of a vehicle.

We might conclude from these results that the knowledge of underbonnet clearance only has a small potential effect on the evaluation of the vehicle. However, there are a few things worth noting:

1. The sample size (five vehicles) was quite small. Other vehicles could potentially be more affected by the inclusion of *C*. For example, a test that produces a HIC of 1000 at 40 km/h, with no bottoming out possible, would imply an IRV of 0.239. However, if this same test had a clearance that resulted in bottoming out at 45 km/h, then the IRV would be 0.318. This represents a 33% higher risk when bottoming out is included in the evaluation.

2. Even if most evaluations are not overly affected by the knowledge of *C*, it may be worth including in the evaluation of vehicles, simply to discourage manufacturers from designing

vehicles that might bottom out at common crash speeds. Future vehicles may be trying to satisfy new market niches, and some of these may place exceptional constraints on vehicle design (for example, sports cars with particularly low bonnets). Additionally, new manufacturers that enter the market may not have sufficient experience with designing vehicles for pedestrian protection, and may unwittingly design vehicles with particulary low clearances.

3. Older vehicles may be much more susceptible to bottoming out. While older vehicles are not assessed by ANCAP, there might be a case for measuring these vehicles to compare with newer models using this evaluation method. This point also emphasises the potential need for clearance measurements in order to measure progress in vehicle design. One measure of improvement is reduced HIC values, another measure might be increased underbonnet clearance.

Some caution is required when interpreting these results. The method of evaluating vehicles based on the IRV can only be considered as a notional indicator of performance. The evaluation requires an assumption that the headform impact test is representative of an real crash that occurs at that speed, and an assumption that the NHTSA risk curves accurately represent the risk of fatal head injury for a given HIC. The true fatal injury risk for a particular vehicle model may be quite different from the values calculated using this method. It is not claimed that Vehicle 1 truly has a 20% chance of causing a fatal head injury in a random pedestrian accident. In fact, this would be likely to be an overestimate by a factor of 10 or more. Instead, the IRV may be thought of as a fairer comparison between vehicles than what is presently used.

There are several reasons why the IRV does not represent an accurate measure of real world fatal injury risk. Firstly, the Euro NCAP test protocol focuses only on the most dangerous locations on the vehicle. In a real accident, the pedestrian may be struck by other locations that presumably would result in a higher chance of survival. Secondly, the speed distribution is biased towards more dangerous impacts, because it represents a sample of crashes that resulted in AIS 2+ head injuries, and excludes crashes that resulted in no head injury or minor injuries only. This selection was made so that the distribution is representative of crash speeds that would result in a potentially injurious head impact, but means that lower speed crashes that resulted in minimal injury were excluded from the data set. Thirdly, the speed distribution represents the vehicle speed immediately prior to impact, and not necessarily the head impact speed. Previous studies have indicated that the head impact speed is generally lower than the vehicle impact speed in a pedestrian accident (Mizuno 2003). Finally, there is limited empirical evidence to support the NHTSA fatal injury risk curve shown in Figure 4.2 (NHTSA, 1995). The true relationship between HIC and fatal injury risk may differ from this. Despite these inaccuracies, the IRV nevertheless represents an indicator of safety performance that links test results to real world outcomes.

Could such an evaluation form a part of a pedestrian safety assessment such as Euro NCAP? There may be several aspects to this evaluation that might be held against it. Aside from the question of accuracy in the speed distribution and injury risk function, one objection might be that the evaluation requires too many steps. Specific software is required to convert the original test result and measurements into an injury risk value. A simpler system could probably be arranged that uses a combination of lookup tables and/or graphs. An even simpler system might be to deduct a set amount of points when the measured clearance is below a certain value.

The next version of the Euro NCAP test protocol promises more changes that might make such a process more viable. Version 6 of the protocol, to be implemented in 2013, suggests that test results for each location may be supplied by computer simulations conducted by the vehicle manufacturer

(Euro NCAP, 2012). In this instance, obtaining a clearance measurement would be simple, provided that the computer models of the vehicle were available to Euro NCAP and other testing organisations. Such computer models could also be used to evaluate the performance of a test location at many different speeds: if the model is capable of evaluating HIC at 40 km/h, it should be possible to evaluate at other speeds as well. Even if the models were not available, vehicle manufacturers could be asked to supply clearance data.

To summarise, the method developed in this report for measuring underbonnet clearance proved to be a relatively simple way to obtain clearance measurements with minimal equipment or special training required. The knowledge of underbonnet clearance has the potential to add more information to the assessment of new vehicles. A method was presented for estimating a notional injury risk value for each test location and for each vehicle. For one of the five vehicles considered the knowledge of underbonnet clearance had a notable effect on this risk value (increase of 10%). Underbonnet clearance measurements may be of use in monitoring performance, encouraging safer designs and in other evaluation schemes that give points for increased underbonnet clearance.

Acknowledgements

This study was funded by the NRMA ACT Road Safety Trust through a Project Grant to the Centre for Automotive Safety Research. The NRMA Project Manager was Linda Cooke.

The Centre for Automotive Safety Research is supported by both the South Australian Department of Planning, Transport and Infrastructure and the South Australian Motor Accident Commission. CASR also provides testing services for the Australasian New Car Assessment Program, who have kindly allowed us to use their test results in this report.

The author would like to acknowledge the assistance of Andrew van den Berg and Brett Linke in the testing laboratory, Paul Hutchinson for editorial comments and Robert Anderson for his input.

The views expressed in this report are those of the authors and do not necessarily represent those of the University of Adelaide or the funding organisations.

References

Euro NCAP (2012). Pedestrian testing protocol. Version 6.0. Brussels, Belgium: European New Car Assessment Programme.

Euro NCAP (2011). Assessment protocol – pedestrian protection. Version 5.1. Brussels, Belgium: European New Car Assessment Programme.

Hutchinson TP, Anderson RWG, Searson DJ (2012). 'Pedestrian headform testing: Inferring performance at impact speeds and for headform masses not tested, and estimating average performance in a range of real-world conditions'. Traffic Injury Prevention, *In press (available online)*.

Infrastructure (2012). Road fatality statistics, viewed February 2012, <http://www.infrastructure.gov.au/roads/safety/road_fatality_statistics/fatal_road_crash_database.aspx>. Canberra: Department of Infrastructure, Transport, Regional Development and Local Government.

Mizuno Y (2003). 'Summary of IHRA Pedestrian Safety WG Activities', in Proceedings of the 18th International Technical Conference on the Enhanced Safety of Vehicles, Washington DC: National Highway Traffic Safety Administration.

NHTSA (1995). FMVSS No. 201 upper interior head protection. Final economic assessment. Washington DC, USA: National Highway Traffic Safety Administration.

Prasad P, Mertz H (1985). The position of the United States delegation to the ISO Working Group 6 on the use of HIC in the automotive environment. SAE Technical Paper 851246. Warrendale, USA: Society of Automotive Engineers.

Searson DJ, Anderson RWG (2008) 'Pedestrian Impact Testing: Modelling the Effect of Head-form Mass and Speed', Proceedings of 2008 Australasian Road Safety Research, Policing and Education Conference. Adelaide: Department for Transport, Energy and Infrastructure.

Searson DJ, Anderson RWG (2010) Implications of easing head impact criteria in pedestrian crash standards. CASR Report 083. Adelaide: Centre for Automotive Safety Research, University of Adelaide.

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, University of Adelaide.

Searson DJ (2012) The infuence of test conditions on the results of pedestrian headform impact tests. PhD Thesis. The University of Adelaide, Australia.