

Pedestrian Impact Testing: Modelling the Effect of Head-form Mass and Speed

D. Searson, R.W.G. Anderson
Centre for Automotive Safety Research, University of Adelaide, AUSTRALIA, 5005
Email: daniel@casr.adelaide.edu.au

Abstract

Pedestrian impact testing is used to assess the relative level of protection from a vehicle to a pedestrian in the event of a collision. Testing is conducted as part of new car assessment programs (Euro NCAP, ANCAP), and for compliance with regulations in Europe and Japan. A key component of pedestrian impact testing is the head-form test, in which a dummy head-form is fired into the front of the vehicle in free flight, at specific locations typically on the bonnet or windscreen. The acceleration of the head-form is measured and is used to assess the relative level of protection at that location through calculation of the Head Injury Criterion (HIC). Alternative protocols specify different test head-form masses and speeds.

This paper presents a model of the acceleration response of the head-form in any given test condition. Given a test with a known result, the model can be used to estimate the outcome of a test on the same structure using a different head-form mass and/or speed. The model is a non-linear damped Hertz model of contact. Validation data showed that the model estimates the HIC to within 10% of that obtained from test results. Simulation of a series of generic impact scenarios was conducted under the conditions of the Australasian New Car Assessment Program (ANCAP) and the draft Global Technical Regulation (GTR) on pedestrian protection, which stipulates a different head-form mass and speed. The results indicate a large discrepancy exists between performance in an ANCAP test and performance under the GTR, such that a structure that would pass the GTR may be rated very poorly under the ANCAP test.

Keywords

Pedestrian Testing, Contact Modelling

Introduction

Pedestrian impact testing simulates contact between the pedestrian and the front of the vehicle using subsystem impactors, each of which represents a different part of the body: the head, tibia and knee joint and the upper leg. During testing, the vehicle remains stationary, and the impactor is fired into the vehicle at a given speed and angle. Head-form testing is typically conducted on the bonnet surface and windscreen.

Testing is conducted as part of new car assessment programs, including the Australasian New Car Assessment Program (ANCAP), the European New Car Assessment Programme (Euro NCAP), and for compliance with regulations in Europe and Japan [1]. Similar tests are also the basis for a proposed Global Technical Regulation (GTR) on pedestrian protection, which is currently being drafted by Working Party 29 of the United Nations Economic Commission for Europe (UNECE) [2]. Australia is a signatory to the UNECE 1958 Agreement concerning the Adoption of Uniform Technical Prescriptions for Vehicle Safety and expects to sign the 1998 Agreement on Global Technical Regulations [3]. As such, it is expected that a final GTR will be considered in Australia with a view to creating a harmonised Australian Design Rule.

The head-form consists of an aluminium base plate and sphere, which is covered in a thick rubber skin. Depending on the wrap-around distance to the location being tested, either a 'child' head-form or a heavier 'adult' head-form are used. The wrap-around distance is measured from the ground along the surface of the car to the location being tested. During the test, data is recorded from a triaxial accelerometer mounted at the centre of gravity of the head-form. The resultant total acceleration of the head-form is used to calculate the Head Injury Criterion (HIC), which determines the score in the case of a Euro NCAP/ANCAP test, or whether the test passes or fails in the case of a regulation test.

Testing for Euro NCAP/ANCAP is conducted according to the Euro NCAP pedestrian testing protocol [4]. The head-form impactors used in Euro NCAP/ANCAP testing are a 4.8 kg adult head-form, and a 2.5 kg child head-form, and tests are conducted at 40 km/h. The locations tested with the child head-form lie within a region bordered by wrap-around distances of 1000 mm and 1500 mm. The locations tested with the adult head-form lie further up the vehicle, between wrap-around distances of 1500 mm and 2100 mm. Any type of structure that lies within these wrap-around distances may be tested, including the bonnet and the windscreen. Maximum points are received for a HIC of 1000 or less, and zero points are received if the HIC exceeds 1350. Between these two values, a linear sliding scale is used. For example, a HIC of 1175 receives half of maximum points [5].

The current draft of the GTR [2] specifies a 4.5 kg adult head-form and a 3.5 kg child head-form, and tests are conducted at 35 km/h. Under the GTR, only the bonnet is tested. Locations that lie between wrap-around distances of 1000 mm and 1700 mm are tested with the child head-form, and locations that lie between wrap-around distances of 1700 mm and 2100 mm are tested with the adult head-form. To pass the regulation, 2/3 of the tested area must have a HIC of less than 1000, and the remaining area must have a HIC of less than 1700. Additionally, half of all of the child head-form tests must have a HIC of less than 1000.

Consequently, vehicles designed to meet the GTR may not necessarily perform well under Euro NCAP/ANCAP testing, where the lighter mass of the child head-form and increased test speed increase the impact acceleration. Additionally, points that lie between wrap-around distances of 1500 mm and 1700 mm would be tested with an ANCAP adult head-form, while under the GTR a child head-form will be used.

Regulations are often considered as minimum benchmark standards, while consumer tests often seek to encourage performance beyond that which the regulation requires. And so some differential in the Euro NCAP/ANCAP performance and performance under the proposed GTR might be expected. Nevertheless, with some experience of consumer testing, it is of interest to see how performance under the Euro NCAP protocol corresponds with performance under the proposed GTR.

It is possible to characterise the force on the head-form throughout an impact using a mathematical model. The model can then be used to simulate the outcome of a test on the same structure under different impact conditions. That is, the force on the head-form in a Euro NCAP/ANCAP test can be used to estimate the force on the head-form in a GTR test on the same structure. One such model is a Hertz-damped model, which has been successfully used to model upper leg-form to bumper impacts [6]. For certain classes of head-form impact, this model may also be applicable.

Once a suitable model has been generated for a particular test location, the influence of the initial speed and mass of the head-form can be examined by numerically simulating the impact under any condition. Thus, it is possible to take an appropriate test conducted under the ANCAP protocol, develop a model that fits the data, and give an approximate result if the test was conducted under the conditions of the GTR.

Method

Estimating the normal acceleration in a head-form test

A schematic of the head-form impacting a flat surface is shown in Figure 1.

If the angle θ is known, then the normal acceleration a_n and the tangential acceleration a_t can be calculated, as the orientation of each accelerometer relative to θ is known. Thus, the goal is to know θ throughout the impact. The initial angle θ_0 is known from measurements, and so the initial acceleration components $a_{n,0}$ and $a_{t,0}$ are known also.

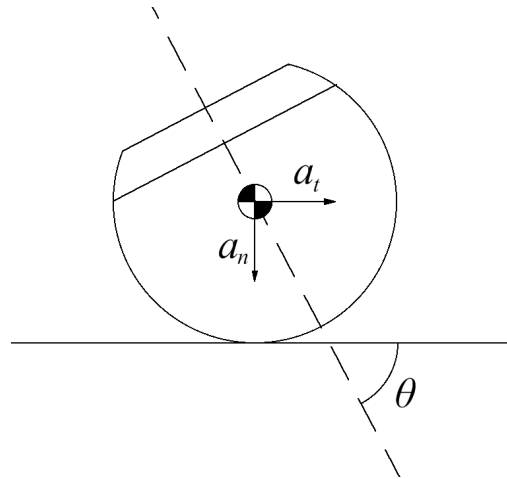


Figure 1 - Schematic of head-form impacting the vehicle surface

We assume that the head-form rolls along the surface of the bonnet with no slippage. Thus, for the i th time-step, including $i = 0$, the angular acceleration $\dot{\omega}_i$ can be calculated as:

$$\dot{\omega}_i = \frac{a_{t,i}}{r}$$

Where r is the radius of the head-form. The resulting angular velocity ω_i and the angle θ_i can be calculated as follows for time-steps $i > 0$ with time difference Δt :

$$\omega_i = \omega_{i-1} + \dot{\omega}_i \Delta t$$

$$\theta_i = \theta_{i-1} + \omega_i \Delta t$$

At the end of this process, the normal acceleration a_n is known at each time-step. Numerical integration can be used to obtain the normal displacement and normal velocity.

Validation of the estimate of the normal acceleration

This method of extracting the normal component was validated using a MADYMO simulation. MADYMO is a multi-body simulation software package developed by TNO Automotive Safety Solutions (TASS). In the MADYMO simulation, a sphere with the same moment of inertia, mass and diameter as a child head-form was impacted into a flat plate at an angle. The normal force-deflection response of the plate was set using a typical model. The conditions of the simulation are summarised below.

Table 1 - MADYMO validation model conditions

Condition	Value	Comments
Diameter	130 mm	As for Euro NCAP child head-form
Mass	2.5 kg	As for Euro NCAP child head-form
Moment of inertia	$3.6 \times 10^{-3} \text{ kg.m}^2$	As for Euro NCAP child head-form
Velocity	11.1 m/s	Euro NCAP head test velocity (40 km/h)
Angle to horizontal	65°	As for Euro NCAP adult head test
Surface angle	10.6°	Typical bonnet angle

The acceleration of the centre of the head-form was measured in the simulation, with the three measurement axes fixed relative to the orientation of the head-form. The head-form rolled during the simulated impact as would be expected in a physical head-form test. This acceleration data was then processed to derive the normal components using the method described earlier. The actual normal component of acceleration was also stored as an output from the simulation. The results were compared, as shown in Figure 2. Although the results diverge slightly towards the end of the impact, the results indicate that the method for extracting the normal component is appropriate.

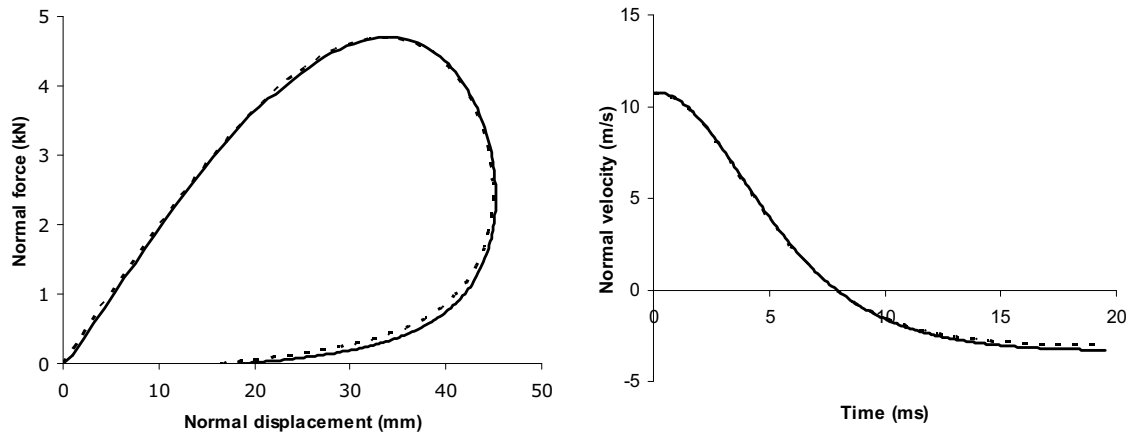


Figure 2 - Derived normal data (dashed line) compared with data from a MADYMO simulation (solid line)

Contact model description and applicability

The Hertz-damped model is presented in Anderson et al. [6]. The model gives the contact force F as a function of the penetration δ and penetration velocity $\dot{\delta}$. The model is based on the Hertz contact law for undamped elastic contacts:

$$F = K\delta^n \quad (1)$$

where K is a stiffness constant and n depends on the geometry of the impact. Hunt & Crossley [7] extended the law to include a damping term that is dependent on the penetration velocity $\dot{\delta}$:

$$F = K\delta^n + b\delta^p \dot{\delta}^q$$

where b is a damping constant, and it is usual to set $p = n$ and $q = 1$ [7]. Introducing a new constant $c = b/K$, the equation reduces to:

$$F = K\delta^n (1 + c\dot{\delta}) \quad (2)$$

However, the above equation does not account for permanent deformation – as the force will only be zero when the penetration is zero. Lankarani & Nikravesh [8] used the maximum penetration δ_m and permanent deformation δ_p to describe the unloading phase of undamped contact. Their equation for unloading can be reduced to:

$$F = K \left[\frac{\delta_m (\delta - \delta_p)}{\delta_m - \delta_p} \right]^n \quad (3)$$

Which has the same form as (1), and as such damping can be added in an analogous way to (2). As a result, the model has two forms, one for the loading phase, when the penetration velocity is positive, and one of the unloading phase, when the penetration velocity is negative.

To summarize, during the load phase, when $\dot{\delta} \geq 0$:

$$F(\delta, \dot{\delta}) = K\delta^n (1 + c\dot{\delta})$$

And, during the unloading (rebound) phase, when $\dot{\delta} \leq 0$:

$$F(\delta, \dot{\delta}) = K \left[\frac{\delta_m(\delta - \delta_p)}{\delta_m - \delta_p} \right]^n (1 + c\dot{\delta})$$

From the test data, δ_p and δ_m can be found. The parameter n is related to the geometry of the impact and should be equal to 1.5 for a sphere impacting a flat plate [7]. Two additional parameters, the stiffness K and damping parameter c depend upon the characteristics of the structure being impacted.

At the time of maximum penetration, the penetration velocity will be zero, and as such we can rearrange to find K from the maximum penetration value δ_m and the force at maximum penetration F_m :

$$K = \frac{F_m}{\delta_m^n} \quad (4)$$

Through trial and error, the parameter c can be chosen to match experimental data. This is done by calculating an estimate of the elastic force by dividing the actual force by the damping term $(1 + c\dot{\delta})$ and comparing with the theoretical elastic force given by (1) during loading and (3) during unloading.

An additional value J can be introduced to ensure that the average slope of the unloading curve remains constant. J can be calculated from existing test data as follows:

$$J = \frac{F_m}{\delta_m - \delta_p}$$

Once values for K , n , c and J are obtained, it is possible to numerically simulate impacts under any test conditions.

The initial conditions for the numerical simulation are as follows:

$$\begin{aligned} \ddot{\delta}_0 &= 0 \\ \dot{\delta}_0 &= \dot{\delta}_{0,impact} \\ \delta_0 &= 0 \end{aligned}$$

Where $\dot{\delta}_{0,impact}$ is the desired impact speed. If the desired head-form mass is m and $F(\delta, \dot{\delta})$ is as described above, then for each time step i ,

$$\begin{aligned} \delta_i &= \delta_{i-1} + \dot{\delta}_{i-1}\Delta t \\ \dot{\delta}_i &= \dot{\delta}_{i-1} - \ddot{\delta}_{i-1}\Delta t \\ \ddot{\delta}_i &= \frac{F(\delta_i, \dot{\delta}_i)}{m} \end{aligned}$$

During the simulated impact, the value of δ_m is taken at the first time step where the penetration velocity $\dot{\delta}$ is found to be less than zero. The permanent indentation δ_p is calculated from J , which is assumed to be constant across all impact conditions:

$$\delta_p = \delta_m - \frac{F_m}{J}$$

Note that the original impact can be simulated by setting $\dot{\delta}_{0,impact}$ to the actual impact velocity, and using the actual head-form mass for m .

There are several limitations on this model, which do not make it applicable for all head impacts. Namely:

- The model applies to a single contact force interaction, and so cannot be used for impacts involving multiple structures – for example, the bonnet, followed by the engine block.
- Energy losses and the associated forces due to vibration are not accounted for – these are often present in lower severity bonnet impacts.
- Only the normal component of the impact is simulated.

The next section is divided into three parts. In the first part, the model is used to simulate the results of a series of impact tests that were conducted at the same location on the bonnet of a particular vehicle. In the second part, an example is given of how the impact speed and mass of the head-form affect the results of a particular test. In the third, a series of general impact scenarios are modelled, and the results under the Euro NCAP protocol are compared with results under the GTR testing protocol.

Results

Comparison with actual impact data

To validate the model, a location on the bonnet of a particular vehicle was tested under various conditions – varying both the impact speed and the mass of the head-form with each test. A new bonnet was used for each test. Test conditions are given in Table 2. A model was constructed using the same values of the parameters K , n , c and J for all of the impacts. The values of these parameters were selected through trial-and-error to best estimate the HIC calculated from test data, across the range of impacts.

A typical example of the fit of the model to a particular test is shown in Figure 3. Note that the maximum displacement is slightly overestimated in the simulated case. This is most likely due to the small initial spike in the actual impact data not being replicated in the model.

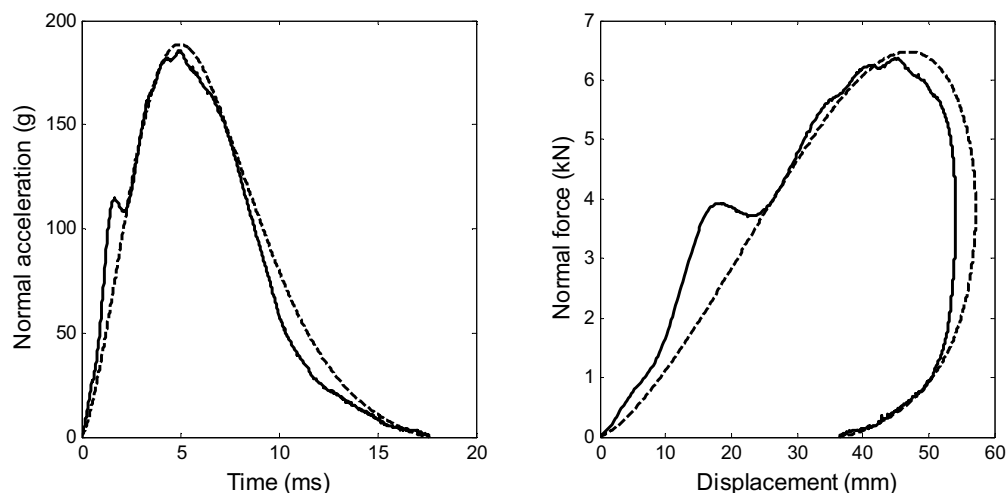


Figure 3 - Actual impact data (solid line) compared with simulated impact data (dashed line)

The HIC was calculated for each test, based on the normal component of acceleration. The reason for this is that the model simulates only the normal component of the impact. The tangential component of acceleration has some effect on the overall HIC, but it is generally small, typically on the order of 5-10%. A comparison between the HIC from the real impact data, and the HIC from the simulated data, is given in Table 2.

Table 2 - HIC in actual vs simulated impacts

Impact speed, m/s	Head-form mass, kg	Actual HIC	Simulated HIC	Error, %
9.46	3.5	1218	1323	+7.9
11.10	3.5	2046	2068	+1.1
12.52	3.5	2935	2907	-1.0
11.10	2.5	2760	2553	-8.1
11.21	4.5	1905	1816	-4.9

The simulated HIC estimates the actual HIC, with an error of up to around 8%. The data in Table 2 are also shown in Table 3, but are stated relative to the test conducted at 11.1 m/s with a 3.5 kg head-form mass. The relative difference in HIC for both the real impacts and the simulated impacts was calculated.

Table 3 - HIC relative to baseline impact, in actual vs simulated impacts

Impact speed, m/s	Head-form mass, kg	Actual HIC, % of reference	Simulated HIC, % of reference
9.46	3.5	59.5	63.9
11.10	3.5	100	100
12.52	3.5	143.5	140.6
11.10	2.5	134.9	123.4
11.21	4.5	93.2	87.8

The data in Table 3 indicates that the model is useful for predicting the general trend in HIC with a variation in mass and/or impact speed, when measured relative to the HIC calculated at a reference set of conditions.

An example of the effect of mass and impact speed on HIC

Using the model as described in the previous section, it is possible to choose a set of parameters and simulate an impact for any impact speed and head-form mass. Thus, the change in HIC under different impact conditions can be estimated.

An example of this can be seen in Figure 4. The parameters used to construct the curves were the same as those used to model the real-world tests in the previous section. Each curve represents a different head-form mass. The impact speed, in km/h, is on the x -axis, and the simulated HIC on the y -axis. The conditions for a Euro NCAP child head-form test (2.5 kg at 40 km/hr) and a GTR child head-form test (3.5 kg at 35 km/hr) are highlighted.

In this case, the HIC for a child head-form test under the Euro NCAP protocol is approximately 2500, while the HIC for a child head-form test conducted under the GTR protocol is approximately 1400. According to the model, this test location would have well exceeded the ANCAP maximum allowable HIC of 1350, while it would have met the maximum HIC requirement of 1700 in the GTR (although a HIC of between 1000 and 1700 is only allowed for 1/3 of the total test area, and 1/2 of the child tests, in the current draft).

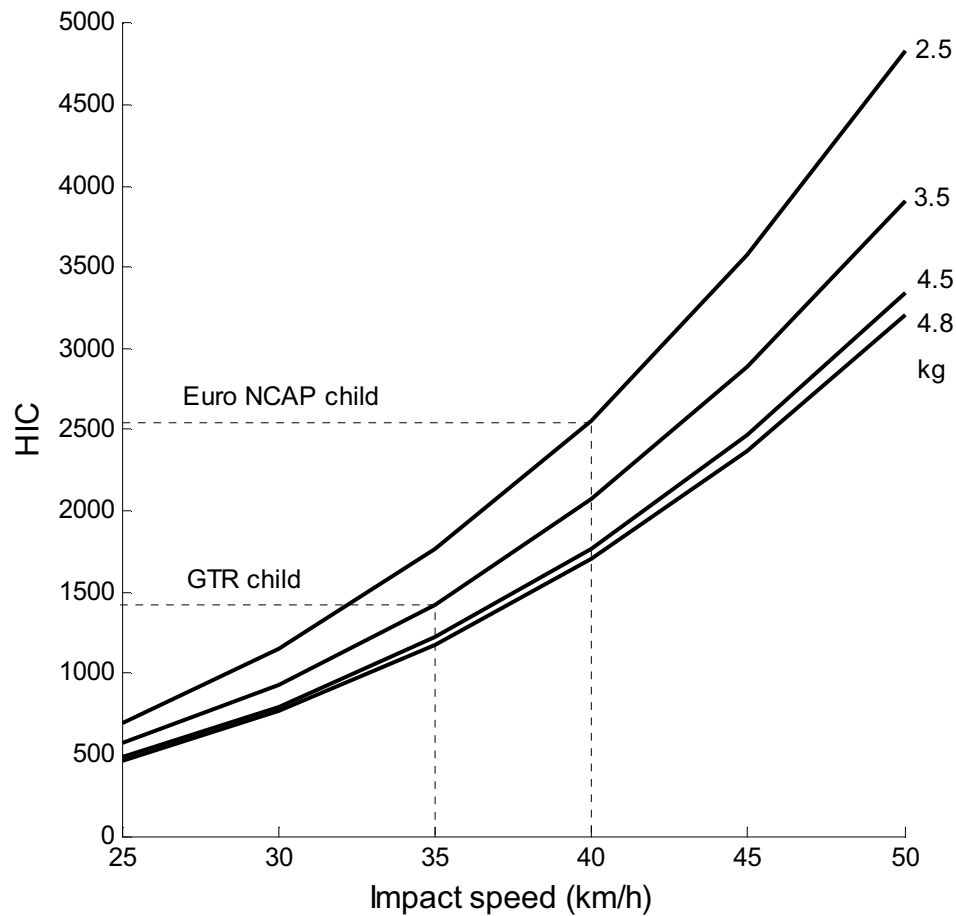


Figure 4 - Effect of impact speed and head-form mass on HIC for a particular test case ($n = 1.4$, $c = 0.21$, $K = 210 \times 10^3$, $J = 241 \times 10^3$)

Correspondence between Euro NCAP performance and GTR performance for a variety of structures

Several sets of parameters were used to compare, more generally, the difference between values of HIC under the Euro NCAP protocol and the GTR protocol. The results of these simulations are shown in Table 4 and Table 5. The parameter n was set to its theoretical value of 1.5, and the parameter c was set to 0.25, which, from our experience, is a typical value for head-form to bonnet impacts. The loading stiffness K affects the HIC the most strongly, and so this was varied to generate specific HIC values under the Euro NCAP test conditions. The unloading slope J was varied also, but had very little influence on the HIC result. After an appropriate value of K was determined, the mass and impact speed were set to the conditions of the GTR and the impact was simulated again, and the HIC recalculated.

Table 4 - Simulated HIC in a child head test under the Euro NCAP protocol and the GTR (with $n = 1.5$, $c = 0.25$)

HIC, Euro NCAP child head test (2.5 kg, 40 km/h)	HIC, GTR child head test (3.5 kg, 35 km/h)	<i>K</i>	<i>J</i>
1000	557	56400	150000
1350	753	92900	150000
1500	836	110700	200000
2000	1115	178500	200000

Table 5 - Simulated HIC in an adult head test under the Euro NCAP protocol and the GTR (with $n = 1.5$, $c = 0.25$)

HIC, Euro NCAP adult head test (4.8 kg, 40 km/h)	HIC, GTR adult head test (4.5 kg, 35 km/h)	<i>K</i>	<i>J</i>
1000	710	108400	200000
1350	958	178400	300000
1500	1064	212600	400000
2000	1419	342800	500000

Note that every simulated test conducted under the GTR protocol fell under the allowable HIC of 1700. (Note though that 2/3 of the total test area must receive HICs of less than 1000, and 1/2 of the child head tests must also have HICs of less than 1000.) In the case of the simulated child head-form tests, 1000 was only exceeded under the GTR conditions when the Euro NCAP HIC was 2000. In the case of the simulated adult head-form tests, 1000 was exceeded under the GTR conditions when the Euro NCAP HIC was 1500.

The data in Table 4 and Table 5 implies that the HIC under the Euro NCAP protocol is linearly related to the HIC under the GTR protocol. Under this set of conditions, the HIC under the GTR is 56% of the Euro NCAP HIC for a child head test, and 71% of the Euro NCAP HIC for an adult head test.

Discussion

This paper detailed preliminary findings of a study on the correspondence between the performance of head-form tests under the Euro NCAP pedestrian protection protocol and the proposed GTR protocol.

Pedestrian head-form impact testing is a core component of Euro NCAP and ANCAP pedestrian testing, and also for regulations, such as the proposed GTR on pedestrian protection. Due to the differences in test conditions between the different protocols, a method of scaling results to different test conditions may be useful. This paper has presented such a method, which utilises a Hertz-damped contact model to model the normal component of a head-form impact. A method of extracting the normal component of acceleration from existing test data has also been presented. When compared with data from a real test, the model estimated the HIC with an error of within 10%.

A series of generic impacts were constructed by choosing appropriate parameters for the model. The impacts were simulated under the conditions stipulated by the Euro NCAP testing protocol, as well as the conditions specified in the most recent draft of the GTR. The HIC under the GTR test conditions was found to be significantly less than the HIC for the equivalent Euro NCAP test. In both child and adult head-form tests, locations that scored zero points under the Euro NCAP protocol were found to pass the equivalent GTR test. Thus, the results of the simulation imply that it is possible that a vehicle that scores zero head test points under the Euro NCAP protocol may pass the GTR requirements. Furthermore, the results indicate that for a fixed set of conditions, the HIC under the Euro NCAP protocol has a linear relationship to the HIC under the GTR.

There are, however, limitations to this study. The model can only be used to reliably simulate a certain class of impacts that involve a single structure and no vibration effects. This type of impact is relatively rare.

It is also worth noting again that only the normal component of the impact is being simulated. As such, only the normal component of the original test data has been used to calculate the HIC in this report. This is valid only if the head-form is contacting the vehicle surface at 90 degrees, for example, a child head-form impact on the leading edge of the vehicle. In many, if not most, impacts, the impact angle is less than 90 degrees, and as such there is an additional tangential and rotational acceleration of the head-form which is not being considered. A preliminary look at the data indicates that this may account for an increase of up to 10% of the HIC value. However, it would be expected that similar trends in the data would still be present, as the tangential component would be expected to rise with the normal component.

Future work in this area will involve developing a more universal model that accounts for multiple structures in an impact, and for vibration effects. Test data for validating such a model has been collected. A more universal model will be able to be used to characterise any new or existing head impacts, and therefore compare performance under alternative test regimes. This will allow for a more comprehensive comparison of results under different protocols, and may generate further insight into the dominant mechanisms that affect the test results.

Conclusions

This preliminary study indicates large potential discrepancies between the results of headform impact tests under the proposed GTR and tests conducted according to the Euro NCAP protocol. If confirmed, it indicates that some cars that perform poorly in Euro NCAP/ANCAP assessments may need no modification to pass the proposed GTR. This tentative conclusion will be tested in a future analysis.

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