The Global Technical Regulation on pedestrian safety: Likely effects on vehicle design

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Abstract

In the future, the Global Technical Regulation (GTR) on pedestrian safety may be adopted as an Australian Design Rule. Eventually, this would require all new vehicles to meet a certain level of performance in pedestrian impact tests. This paper discusses the likely effects of such an ADR on vehicle design, and estimates the effect of the requirements on real world crash performance. This is done by analysing vehicles whose GTR performance could be estimated from prior testing conducted by the Australasian New Car Assessment Program (ANCAP). The resulting performance estimates give an indication of what proportion of vehicles would be likely to pass the GTR, and what characteristics might cause them to fail the requirements. A method is presented for relating headform test requirements to real world performance, taking into account the distribution of speeds in real crashes. The results show that compulsory compliance with the GTR would improve the current situation, but ideally the requirements of the GTR would become stricter in the future.

1. Background

The Global Technical Regulation (GTR) on pedestrian safety provides a means of regulating the level of protection provided from a vehicle to a struck pedestrian. The regulation specifies a series of impact tests, conducted with two different sized dummy headforms, and an adult sized dummy legform. The headform impact tests are conducted by firing the headform into the bonnet of the vehicle and measuring the level of deceleration. This deceleration is used to calculate the Head Injury Criterion (HIC).

This style of testing was originally developed in the 1970s (Harris, 1976), but it was not until the late 1980s that efforts began by the European Enhanced Vehicle-safety Committee (EEVC) to develop a documented test protocol (Harris, 1989). The procedures developed by the EEVC were eventually adopted by the European New Car Assessment Programme (EuroNCAP) in the late 1990s (Hobbs and McDonough, 1998). The EuroNCAP test procedure has been used since then to rate new vehicles with respect to pedestrian safety. The EuroNCAP test procedures have also been used by the Australasian New Car Assessment Program (ANCAP) since 1999.

More recently, Working Party 29 of the United Nations Economic Commission for Europe (UNECE) has developed a GTR on pedestrian safety. The GTR specifies similar tests to those developed by the EEVC and EuroNCAP, but with differences in the speed of the test, and the areas of the vehicle that are tested. Countries that are signatories to the UNECE 1998 Agreement, including Australia, are compelled to submit the GTR to the regulatory processes that would result in the GTR becoming law in their jurisdiction.

Australia does not currently have any compulsory pedestrian safety testing requirements for new vehicles. Previous research by CASR has shown that the adoption of the GTR as an ADR would have a beneficial effect on road safety, with associated monetary savings in crash costs (Anderson et al., 2008). Additionally, countries that have adopted pedestrian safety regulations have been shown to have a safer vehicle fleet for pedestrians (Ponte et al., 2007). In late 2010, Vehicle Safety Standards Australia issued a Regulation Impact Statement on the adoption of the GTR as an Australian Design Rule (ADR). However, the regulatory impact process was halted by the Parliamentary Secretary for Infrastructure and Transport (King, 2011), after sectional backlash over the effect that the regulation might have on bull bar fitment. At this stage it is unclear whether a regulatory process will be restarted.

This paper discusses the changes that may have to occur to existing vehicle designs if the GTR were implemented as an ADR. Although the GTR procedure contains headform and legform tests, the focus of this paper is on the headform testing component only. It is likely that many of these changes are already occurring, in an effort to comply with the GTR overseas, and to improve ANCAP ratings (given that, in the near future, a minimum level of performance will be required for a vehicle to be awarded the maximum five stars). However, for vehicle models that are predominantly sold in Australia and other non-regulated jurisdictions, mandatory compliance with an ADR (based on the GTR) would be expected to spur on these changes.

In section 2, the requirements of the GTR testing protocol and the EuroNCAP test protocol are summarised, with particular attention being paid to the differences between the two. In section 3, results from vehicles tested by ANCAP are used to predict GTR test performance. Section 4 explores the relationship between test results and real crash speeds, and Section 5 contains a discussion of the results.

2. Head testing requirements of the GTR and EuroNCAP/ANCAP

As described above, a major component of the GTR and EuroNCAP test procedures are a series of headform tests on defined areas of the upper surface of the vehicle. In these tests, the deceleration of the headform is used to calculate the Head Injury Criterion (HIC), a measure of the relative risk of head injury in an impact. The HIC is proportional to the magnitude of the deceleration experienced by the headform, and also to the duration of the impact. A maximum HIC value of 1000 is commonly used to demarcate a ‘safe’ impact from an ‘unsafe’ one. Previous examinations of head impact data imply that a HIC of 1000 corresponds to a 15% risk of skull fracture (Mertz, 2003).

Under the GTR, head impact tests are performed on the bonnet of the vehicle, but not the windscreen or A-pillar. The side borders of the testable area are defined by drawing reference lines, based on the angle of the vehicle surface. The testable area generally includes the bonnet top, but may also partially include the top of the front wheel guards.

The testable area is divided into two sections, based on a specified ‘wrap-around distance’. The wrap-around distance is measured from the ground at the front of the vehicle, with a flexible measuring tape along the vehicle surface. The area that lies between wrap-around distances of 1000 and 1700 mm is tested with a 3.5 kg ‘child’ headform at an angle of 50º to the horizontal. The area between 1700 and 2100 mm is tested with a 4.5 kg ‘adult’ headform at an angle of 65º to the horizontal. These wrap-around distances define the areas that the head of a pedestrian is likely to strike in a typical collision.

The most potentially harmful locations are selected within the testable area, and are tested with the appropriate headform. A minimum of nine headform tests are performed in each of the child and adult test areas. Any test that results in a HIC of less than 1000 is considered to pass the GTR requirements. Before testing begins, the manufacturer may nominate up to one third of the testable area to be defined as a so-called ‘relaxation zone’. The relaxation zone may include any part of the testable area and does not need to be contiguous. The relaxation zone cannot consist of more than one half of the child testing area. For tests in the relaxation zone, the HIC may be up to 1700 and still pass the GTR requirements. In the remainder of the testable area, the HIC may not exceed 1000.

The headform impact speed specified by the GTR is 35 km/h, which differs from the speed of 40 km/h specified in the EuroNCAP protocol. In all other respects, the test conditions specified in the current EuroNCAP procedure are similar to the GTR. In the previous version of the EuroNCAP procedure, which was used up until the end of 2009, the child headform was 2.5 kg and the adult headform was 4.8 kg, which differ from the GTR headform masses. In this previous version, the dividing line between child and adult was 1500 mm, not the 1700 mm used in the GTR and the current EuroNCAP procedure.

Some further differences exist between the EuroNCAP and GTR test procedures. Instead of simply passing or failing the vehicle, EuroNCAP (or ANCAP) will assemble the individual test results into an overall assessment of the vehicle. This is based on a system of zones – the child test area and adult test area are each split into six zones, which are in turn split into four quadrants.

The most potentially dangerous location is selected for testing in each zone (the ‘ANCAP test’). This location will lie in one of the four quadrants in that zone. The manufacturer may then choose to nominate one or more of the remaining three quadrants to be tested. Out of these nominated quadrants, the most potentially dangerous location is selected by ANCAP for a second test (the ‘manufacturer test’).

The results from both of these tests, in each zone, are assembled to give an overall point score for the vehicle. For each individual test, the maximum score is awarded for a HIC of less than 1000, and a score of zero is received for HIC values greater than 1350. For HIC values in between those, the points are linearly scaled – e.g. a HIC of 1100 will score 5/7ths of the maximum points available.

3. Estimated GTR performance of vehicles previously tested by ANCAP

3.1 Data

The analysis used the results of sixty vehicles tested by ANCAP before the end of 2009. These vehicles were analysed to estimate whether or not they would pass the GTR test requirements.

There were 523 impact tests conducted across the sixty vehicles. Some of these were conducted on the windscreen, and these were excluded as they were not relevant to the GTR. For the remaining tests, an estimate was made of the HIC value that would have been obtained under the GTR test procedure, taking account of differences in head impact speed and headform mass. These individual results were then compiled to form an overall prediction of each vehicle’s performance. These two steps are discussed in separate sections below.

3.2 Estimation of HIC values

Since the ANCAP tests were conducted at a higher speed and with different mass headforms, a method was needed to convert each HIC value obtained in the ANCAP test to an equivalent HIC value for the GTR test. This conversion method was developed by assuming that the vehicle structure behaved like a simple linear spring, with the stiffness of the spring determining the relative danger of a particular test location.

Under the assumption of a linear spring the HIC values from two tests performed on a structure of constant stiffness can be related via the following:

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

In this equation, the value HIC_1 corresponds to an impact speed of v_1 and headform mass m_1, and similarly for HIC_2. The full derivation of Equation 1 can be found in Searson et al. (2009). This relationship has been shown to be adequate to describe the empirical scaling of HIC with changes of mass and speed in impact tests with vehicle structures typically tested with pedestrian headforms (Searson et al., 2009).

For each test performed on the bonnet by ANCAP, this formula was used to estimate the HIC value that would have been obtained had the test been performed under GTR test conditions. The values of m_1 and v_1 were taken from the GTR headform that would be used at that particular location (based on the wrap-around-distance), and the GTR test speed of 35 km/h. The values of m_2 and v_2 were taken from the headform mass and test speed in the original ANCAP test.

The linear spring assumption is based on the kinematics of the headform that are normal, or perpendicular to the surface of the vehicle; as such, the values of v_1 and v_2 were taken from the component of the headform velocity that was normal to the vehicle surface. For example, if the headform struck the bonnet at 40 km/h, with an angle of 60º between its trajectory and the bonnet surface, then trigonometry was used to calculate the normal component of the velocity: $v = 40 \sin(60º) = 34.6$ km/h. In cases where the impact angle was the same in both the ANCAP and GTR tests, this calculation was not relevant. However, for tests lying between wrap-around distances of 1500 and 1700 mm, the impact angle would be different for each protocol, so the normal component of the impact speed was calculated.

3.3 Estimation of vehicle performance

The estimated HIC values for each individual test location were assembled to form an overall estimate of each vehicle's performance in the headform component of the GTR. This estimate was given in terms of the best possible result that the vehicle could obtain, and the worst possible result that the vehicle could obtain, based on the estimated HIC values. Best and worst case estimates were made because, while many tests are performed in an ANCAP assessment, the tests are an incomplete survey of the vehicle. The main implication of the uncertainty arising is whether or not the requirements regarding the size of the relaxation zone are met or not.

Best case and worst case compliance with the GTR was estimated by making the following assumptions:

- That the ANCAP test represented what was truly the most dangerous location in that zone, unless the manufacturer test happened to produce a higher HIC value (unlikely, but may occur).
- That the manufacturer test, if performed, represented what was truly the most dangerous location of the nominated quadrants.
- That any quadrants not nominated by the manufacturer would perform, at worst, the same as the ANCAP test, and at best, the same as the manufacturer test. If no manufacturer test was specified, then at best they would score a very low HIC and pass any requirements.
- That any manufacturer nominated quadrants would perform, at worst, the same as the manufacturer test, and at best, would score a very low HIC and pass any requirements.
- Each quadrant counted for one unit of area, and the best and worst-case HIC values for that quadrant apply to that amount of area.
- That any area with an estimated HIC value greater than 1000 would be part of the relaxation zone nominated by the manufacturer.

Using these assumptions, a best-case and worst-case estimate of each vehicle's performance could be made against the three headform testing criteria of the GTR:

1. Out of the total testable area, at least two thirds of the area must score a HIC of less than or equal to 1000.
2. Out of the area tested with a child headform, at least half of this area must score a HIC of less than or equal to 1000.
3. No test may score a HIC greater than 1700.

If any of these criteria were not met, then the vehicle would be estimated to fail the requirements of the GTR. In some cases, the vehicle may have passed a particular criterion under its best-case estimate, but would fail that criterion under its worst-case estimate.

3.4 Results

Of the sixty vehicles considered, seven were estimated to pass all of the GTR requirements in both their best and worst-case scenarios.

The second criterion (that a maximum of half of the child area may produce HIC values between 1000 and 1700) was found to be redundant when the first criterion was considered (that a maximum of 1/3 of the total area may exceed a HIC of 1000). For all vehicles in which the second criterion was not satisfied, the first criterion was also not satisfied. Thus, the second criterion was not a limiting factor in a vehicle's ability to pass the GTR – a vehicle was only estimated to fail this criterion in cases where the first criterion was not satisfied anyway.

Thus, the following discussion refers only to the first and third criteria – we will refer to the first criterion as the 'HIC1000' criterion, and the third criterion as the 'HIC1700' criterion.

Table 1 groups the vehicles by their performance, according to the HIC1000 and HIC1700 criteria. The row and column that are labelled 'Uncertain' indicate when a vehicle passed that criterion under its best case, but failed the criterion in its worst case.

The upper left box indicates the seven vehicles that were estimated to pass both criteria, in their best and worst cases. Additionally, there were 11 vehicles that were estimated to pass the HIC1000 criterion and possibly pass the HIC 1700 criterion. Except for one, all of these vehicles had a maximum of four ANCAP quadrants that might fail the HIC1700 criterion. For these vehicles, it would be reasonable to expect that only minor modifications would be needed in order to make them pass both criteria. In fact, many of these vehicles might pass the HIC1700 criterion without any modification, if their best case estimate was proved correct.

Of those vehicles for which it was uncertain whether they would pass the HIC1000 criterion, 26 vehicles were estimated to fail the HIC1700 criteria. There were only two vehicles in total that were estimated to fail both criteria under their best and worst cases.

Table 1: Performance in the HIC1000 criterion compared with performance in the HIC1700 criterion, by number of vehicles.

HIC 1700: A requirement that no tests produce a HIC > 1700	HIC1000: A requirement that max 1/3 of test area produces a HIC > 1000		
	Estimated pass	Uncertain	Estimated fail
Estimated pass	7	1	0
Uncertain	11	9	0
Estimated fail	4	26	2

The performance of vehicles against the HIC1000 and HIC1700 criteria can also be seen in the light of the vehicles' ANCAP assessment. Table 2 shows the mean ANCAP head testing score (out of 24) for each category of vehicle.

Table 2: Mean ANCAP head score (out of 24). Performance against the HIC1000 criterion compared with performance against the HIC1700 criterion.

HIC 1700: A requirement that no tests produce a HIC > 1700	HIC1000: A requirement that max 1/3 of test area produces a HIC > 1000		
	Estimated pass	Uncertain	Estimated fail
Estimated pass	10.6	1.2	-
Uncertain	12.6	7.7	-
Estimated fail	8.7	5.1	3.9

In general, the vehicles that scored the highest under ANCAP were those that passed the HIC1000 criterion, regardless of their performance against the HIC1700 criterion. This suggests that the performance in the HIC1000 criterion is most closely related to the ANCAP performance of a vehicle. This makes sense: the ANCAP score is based on performance across the entire upper surface of vehicle (to a wrap-around distance of 2100 mm); similarly the HIC1000 criterion requires good performance across the majority of the hood. The HIC1700 criterion of the GTR may fail if just one test yields a poor result – if the rest of the bonnet is designed well then the same vehicle may still score relatively well under ANCAP.

4. Real crash speeds and HIC

Using Equation 1, if we know that a structure will give a certain HIC value at a certain speed, we can predict what HIC values the structure will yield at other impact speeds. Therefore, if we assume that the test HIC produced for a given impact speed is the same as the HIC experienced in an actual collision at an equivalent speed, then HIC levels produced by a vehicle can be estimated across speeds typical in collisions. Furthermore, if the distribution of head impact speeds in real collisions is known, then this distribution can be used to estimate the distribution of HIC levels likely in actual collisions, given a particular test HIC.

This process was performed using a distribution of vehicle impact speeds estimated from real pedestrian crashes. The speed distribution was taken from the IHRA dataset presented by Mizuno (2003). This dataset was a compilation of just over 1600 pedestrian crash cases investigated in Australia, Japan, Germany, and the USA. The Australian data was a relatively small portion of the overall dataset, and consisted of 64 crashes that were investigated in-depth in Adelaide.

For the present purpose, 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 a 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. It was assumed that the head impact speed distribution of these cases was the same as the vehicle impact speed distribution.

To simplify the analysis, a Weibull statistical distribution was fitted to the impact 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 1 shows the cumulative distribution of crash speeds for the data and for the fitted Weibull distribution.

The speed distribution described by the Weibull distribution was used to calculate an equivalent distribution of HIC values, using Equation 1, for two different theoretical structures. The first theoretical structure is one which gives a HIC of 1000 when tested at the GTR test speed of 35 km/h. The second theoretical structure gives a HIC of 1700 at the same speed. The resulting HIC value distributions are shown in Figure 2, and are labeled as ‘HIC1000’ and ‘HIC1700’. A third distribution is also shown in this figure, which is an overall HIC distribution. The overall distribution assumes that one third of tests at 35 km/h result in the head striking the relaxation zone, which gives a HIC of 1700, and the remaining two thirds of tests result in a HIC of 1000. This is essentially the worst possible case for a vehicle that still meets the requirements of the GTR, and represents the upper limit of HIC levels likely to be experienced in collisions with a fleet of vehicles that comply with the requirements of the GTR.

The vertical line in Figure 2 can be used to read off the proportion of crashes that result in a HIC of less than 1000 (the commonly used ‘safe’ limit). For the HIC1000 structure, 39% of crashes might result in a HIC of less than 1000 (this aligns with the 39% of crashes having an impact speed of 35 km/h or less in Figure 1). For the HIC1700 structure, 26% of crashes might result in a HIC of less than 1700. For vehicles just meeting all of the minimum requirements of the GTR, 33% of crashes result in a HIC of less than 1000.

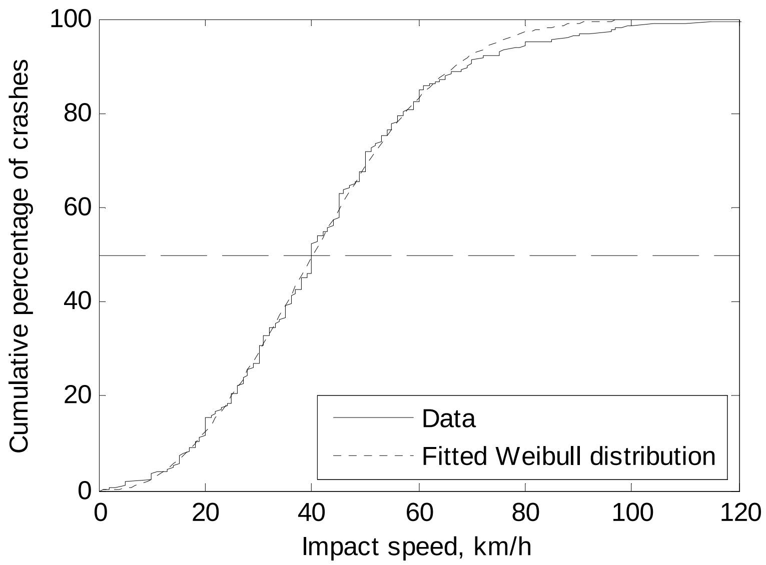

Figure 1: Cumulative impact speed distribution of IHRA pedestrian data (Head AIS >1; from Mizuno 2003) and the fitted Weibull distribution.

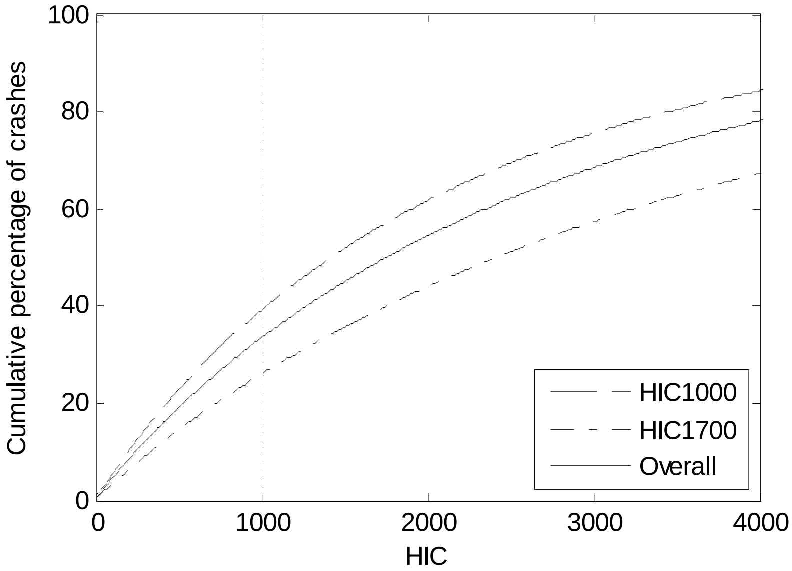

Figure 2: Cumulative distribution of HIC values for real crash speeds, for two structures that meet the criteria of the GTR, as well as the combined distribution.

Figure 2 is based on several assumptions, and hence has limitations.

- It assumes that the relationship in Equation 1 holds for all crash speeds. This implies that the structure will behave like a linear spring at any speed. One obvious exception to this is that in reality, the outer structure of the vehicle may deform sufficiently that it comes into contact with a harder structure beneath (e.g. the engine). This will break the assumption of the linear spring, and hence the cumulative distributions in Figure 2 may be overestimated.
- It assumes that the head impact speed is equal to the speed of impact of the vehicle. Previous studies have shown that this may be true, but the ratio may also be slightly higher or lower than one (Lawrence et al., 2006). The distribution of impact speeds used is based on crash reconstruction and hence may suffer from overdispersion. As a result, the dependence of HIC upon speed, as applied to the distribution, may not be as strong as given by the theoretical spring model (i.e., the spring model applies to the true distribution of speeds that may have a smaller variance than the one shown here).
- It assumes that the impact test conditions are representative of a real pedestrian crash – namely that the impact angle and headform mass are representative of the angle and effective mass of the head in a real crash.

5. Discussion

The GTR on pedestrian safety has been implemented as part of vehicle design regulations in Europe, but it remains to be seen whether it will become part of an ADR in Australia. Nevertheless, the requirements of the GTR are likely to affect vehicle designs from overseas, and also those produced locally.

An examination of existing test results from ANCAP pedestrian testing was conducted, to see how many vehicles would be likely to pass the requirements of the GTR, and what would cause them to fail the requirements. It was only possible to make a best-case and worst-case estimate of each vehicle's performance from its

ANCAP results. Sixty vehicles were evaluated, and a relatively small number – seven – were estimated to pass in both the best and worst cases. A greater number may pass if their true performance is closer to their best case estimate. One potential reason for the relatively low number of passes is that the vehicles were all manufactured prior to the end of 2009.

Of the three headform testing criteria of the GTR, the requirement that no test exceeds a HIC of 1700 was the criterion that was least likely to be satisfied, in both the best and worst cases of the vehicles' performance. In many cases, this criterion may be addressed by relocating a dangerous structure that lies beneath the bonnet surface, or by redesigning one particular area of the vehicle. Many vehicles that failed this requirement still performed relatively well in ANCAP pedestrian testing, suggesting that the HIC1700 criterion was not an indicator of the vehicle's overall safety.

The results were ambiguous in relation to the vehicles' compliance with the criterion that a minimum of two thirds of the testable surface must not exceed a HIC of 1000. Vehicles that were estimated to fail this criterion had typically performed worse in ANCAP tests. Without more testing, it is difficult to know how vehicles would perform against this criterion. If we consider the difference in test speeds, scoring a HIC of 1000 in the GTR test is the equivalent of scoring a HIC of 1400 in the current ANCAP test (using Equation 1). Such a test would score zero in the ANCAP test but would just pass the GTR requirements. Thus, even vehicles which perform relatively poorly under ANCAP may pass the GTR requirements. (It is also noteworthy that the GTR HIC1700 criterion is equivalent to a HIC of 2373 produced under equivalent ANCAP conditions).

The minimum performance requirement for a vehicle passing the GTR is one which scores a HIC of 1000 across two thirds of its bonnet surface, and a HIC of 1700 across the remaining third. This scenario was examined in the context of a real crash speed distribution. If it is assumed that the real crash matches the test conditions, then the resulting HIC distribution shows that around a third of crashes would result in HIC values under the commonly used 'safe' limit of 1000. Using this same distribution, around 50% of crashes would result in a HIC in excess of 1700.

These results show that compulsory compliance with the GTR on pedestrian safety would be likely to bring about an improvement in the current situation – many vehicles at present would be likely to fail the requirements of the GTR. However, the minimum standard set by the GTR would still appear to be fairly conservative. There is room for improvement in the future – once vehicles begin to meet this minimum standard, it would be appropriate to tighten the requirements of the GTR. This could occur through an increased test speed, or by reducing the maximum allowable HIC levels.

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