Integrating the assessment of pedestrian safety in vehicles with collision detection and mitigation systems

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Abstract This paper presents an integrated model to assess pedestrian protection of vehicles that are equipped with collision detection and mitigation systems. Traditionally, impact injury risk is assessed at a single speed, whereas actual pedestrian collisions occur at many speeds. Therefore, the test result is used to represent risk across all crashes even though no information about the speeds of actual crashes is used explicitly in the assessment. When the impact speed of a vehicle is likely to be affected by technology that reduces impact speeds, the average risk must be less than for equivalent vehicles without such a system. A model is presented in this paper that takes such effects into account by using information on how the test result varies with impact speed, and the relationship between the test result and injury risk, to calculate average injury risk. If the effect of a collision detection system on impact speeds is known, then the model can assess the reduction in average risk for any given impact test result. The model is also used to adjust Euro NCAP and GTR assessment criteria for pedestrian head impact protection when vehicles are equipped with effective pedestrian collision avoidance technologies.

Keywords Pedestrian, Injury risk assessment, Testing, Injury risk, Autonomous braking

I. INTRODUCTION

In Euro NCAP pedestrian testing, vehicle performance is characterized on a scale of 'poor' to 'good' [1], and by inference the HIC value produced by the Head Injury Criterion (HIC) function is used to characterize a particular headform test result as being on a similar scale of 'poor' to 'good'.

By implication, the performance of individual impact tests are used to represent the performance of the vehicle over all likely impact conditions in the field – a good result in a test conducted at 40 km/h is taken to be good on average. What is important here is that an assumption of constant distribution of impact conditions is necessary in order for this implication to be approximately correct, and hence this assumption is also necessary in order to be able to make meaningful comparisons between individual test results and between vehicle assessments. The variation in impact conditions is usually considered explicitly during the development of any crash test methodology, but not further in the assessment of the test result, where the focus is on acceptable risk at the test speed. The implicit assumption that the distribution of impact speeds is constant underlies current approaches to testing, but this assumption may break down when vehicles are equipped with technology that assists in mitigating or avoiding collisions.

The desirability of extending assessment to take account of either test performance or risk over the range of impact conditions likely to exist in the field has been recognized in the past [2]-[4], but the ideas expressed in previous publications have not extended to practical means of interpreting impact test results to assess average risk.

In a recent publication [5] we presented a method for assessing the result of an impact test (or tests) given information on real-world impact conditions. The features of the method are presented below: information on how the result of an impact test responds to a change in the impact conditions, the risk associated with any level of impact severity, and the likelihood that any specific impact condition will be encountered in the field are combined to estimate the average risk associated with the result of an impact test.

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Once a method for calculating average risk from the result of a test has been established, the effect on that risk of a systematic change to the field impact conditions, as might occur with a system that detects an imminent pedestrian collision and applies the vehicle's brakes, can be estimated.

Objectives

The first objective of the present paper is to examine how the average head injury risk that is associated with performance in an impact test changes in response to reduced impact speeds in collisions. The second objective is to examine what implications the reduced average risk might have for current protocols for the assessment of headform impact test results.

II. BACKGROUND

An expression for average injury risk/cost

For the purposes of this analysis, the severity of an impact refers to a quantity that measures some physical aspect of the impact to which the risk of injury can be related. Let the function that describes how the severity of an impact varies with impact conditions be $h(x,i)$ where x refers to the impact condition and i refers to the location or structure involved being tested or struck in a collision. (In the present context, $h(x,i)$ might refer to the relationship between the level of the Head Injury Criterion obtained in a headform impact test at location i on a vehicle, and the impact speed of the test, x.) The probability (or alternatively the cost) of the injury is a function of h and is $p(h(x,i))$. The function p therefore also describes the risk of injury (or cost) at the location or structure as a function of the impact condition x. Next, consider a function that describes the likelihood of any impact condition, $f(x)$. The proportion of all impacts that are injurious, or the costs that are incurred at the condition x is then $f(x).p\big(h(x,i)\big)$. Finally, the proportion of all impacts that are injurious, or the average injuriousness of all impacts, or the average cost, across all conditions is given by the integral expression

$$\text{Average}(p_i) = \int f(x).p\big(h(x,i)\big)dx \qquad (1)$$

This equation is a fundamental expression that links the average risk of injury in typical crash conditions with biomechanical risk as indicated by h. A point to note at this stage is that any kind of effective braking enhancement will affect the distribution of test speeds $f(x)$, and efforts to improve the secondary safety of the vehicle will affect the function $h(x,i)$. Hence, Equation 1 provides a means of assessing the joint effects of primary safety technologies and secondary impact protection.

Note that when we use the term 'cost' we do so to imply that injury risk is not the only measure of severity that can be used in Equation 1, not to advocate any particular system of calculating the monetary cost of injury. Any form of monetary or societal cost thought appropriate could be used for the severity measure $p(h(x,i))$.

Typically, test protocols evaluate a vehicle or structure using a single test and a defined set of conditions. In the case of the Euro NCAP headform test, the test condition may be characterized by the speed of the test, and so the evaluation is based on the value of the HIC function, H, in a test conducted at 40 km/h. (The headform mass is also a parameter in the test, although this aspect of the test will not be considered further in this paper.) In the case of the Global Technical Regulation on pedestrian protection the evaluation is based on a test conducted at 35 km/h [6]. In order to transform H into an estimate of average risk, the test result must first be used to estimate how the value of the HIC function varies with impact speed, $h(x,i)$, and subsequently how risk (or cost) varies: $p\big(h(x,i)\big)$.

Baseline assumptions about the components of Equation (1)

Equation 1 was previously presented in [5]. In that analysis, some initial results were given based on estimates for the components of the equation. The baseline assumptions to be used in the present analysis are described below.

The impact speed distribution, $f(x)$ The analysis will consider effects of such systems on an impact speed distribution $f(x)$ based on a distribution developed by the International Harmonised Research Activities

Pedestrian Safety Working Group [7]. Figure 1 shows the distribution of vehicle speeds resulting in AIS2+ head injuries, to which a Weibull distribution has been fitted [8]. The Weibull distribution was chosen as it could be parameterized to fit the data obtained from in-depth crash investigation. The area under the distribution sums to one. The median value of the distribution happens to correspond to the Euro NCAP test speed (40 km/h).

The distribution describes vehicle impact speed rather than head impact speed. Some studies have indicated the head impact speed may be 10-15% lower than the impact speed of the vehicle. How consistent this reduction is across the vehicle impact speed is not clear and, therefore, for the present purpose, the speed distribution was not modified and will be used to represent head impact speeds.

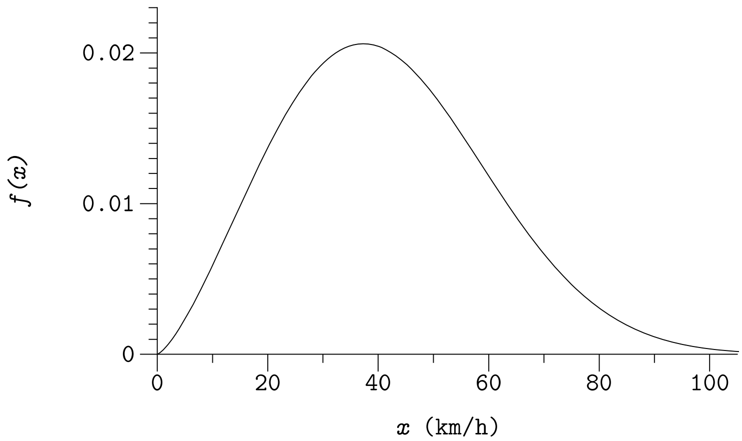

Fig. 1. Weibull distribution fitted to the distribution of impact speeds in pedestrian collisions resulting in AIS2+ head injury (reproduced from [8])

The dependence of impact severity on impact speed, $h(x, i)$ The impact condition x is, in its most general sense, any aspect of the impact that can affect the value of h and, as such, may include impact speed, impact angle and head mass. For the present, only impact speed will be considered, as the focus is on the effect of head impact speed on average head injury risk. Assuming a car's surface can be modelled as a linear spring and the head impact mass is constant, then h is proportional to $x^{2.5}$ where x is the normal velocity of impact [8]. Thus, the logarithm of h is a linear function of the logarithm of x. An approximately linear dependence of h on $x^{2.5}$ has some experimental support for subsystem headform impacts on hoods [9]-[10], and, therefore, this relationship will be used in Equation 1.

Additionally, for many impact locations, the response of the structure changes as bottoming out (i.e. a non-linearity in the response) occurs. This can be incorporated into the expression for $h(x, i)$ and may be important for any given impact location [5]. In the present analysis, the phenomenon of bottoming out is not considered, although it should be considered in any implementation of Equation 1.

The injury risk function, $p(h(x, i))$ The form of the risk (or cost) function p should be chosen to be consistent with the objectives of the testing: if the objective is to minimize monetized crash costs, p would refer to the cost of injury associated with a given value of h. Most commonly the objective is to minimize serious and fatal injury risk; therefore, risk curves such at those published in [11] may be used. In the present analysis, the risk of sustaining a head injury with severity AIS3+ [11] is used as the definition of p.

III. METHODS

In order to estimate benefits of collision detection and autonomous braking systems, modified speed distributions, $f^*(x)$, are introduced to represent the effect of such systems on impact speeds. Estimates of how pedestrian impact speeds would be reduced by such systems were made in [12] using in-depth crash data. The authors of that study estimated that the mean speed of collisions in their data set would have been reduced by approximately 25 per cent, and 15 per cent of collisions would have been avoided completely for a system with a wide field of view.

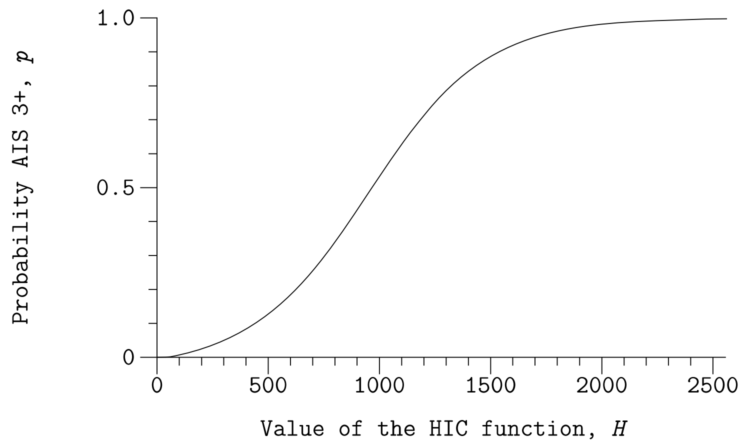

Fig. 2. Risk of AIS 3+ head injury for a given value of the Head Injury Criterion [11]

It is reasonable to assume that the proportion of crashes avoided is related to the reduction in mean impact speed through the effectiveness of the system. For the purposes of this analysis, the reduction in mean impact speed and the proportion of crashes avoided are specified separately. Two systems will be considered: one based on the effect of the wide-angle system analysed in [12] and another that prevents collisions and reduces impact speed at half that rate. These are implemented by adjusting the scale factor of the Weibull distribution and reducing the amplitude such that the median is reduced by the required amount and the area is reduced to reflect the proportion of crashes avoided completely. These speed distributions are shown in Figure 3.

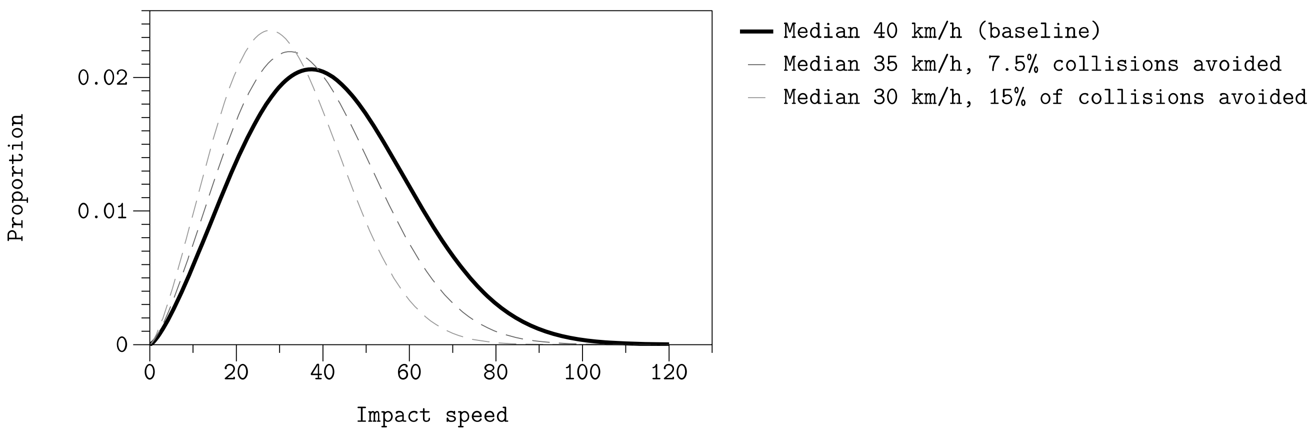

Fig. 3. Speed distribution $f(x)$ and modified distributions, $f^*(x)$, representing two levels of effectiveness of autonomous braking interventions

Equation 1 was evaluated over a wide range of H with parameters as described in the Background. In this application of Equation 1, Average(p_i) is a function of H; H implies $h(x)$, then p and $f(x)$are used to calculate Average(p_i).

The evaluation was then repeated for two modified distributions, $f^*(x)$, as described above. Comparisons were then made between each speed distribution of the average risk associated with an impact test result H. Comparisons were made with respect to the 2013 Euro NCAP assessment protocol [1] and the Global Technical Regulation on pedestrian protection (GTR) [6].

IV. RESULTS

Effect of speed distribution on average risk

Average(p_i) was calculated using Equation 1, with the components of the equation as described above. The result is illustrated in Figure 4. It is notable that Average(p_i) changes over a wide range in H. The change in

Average(p_i) is approximately linear with the logarithm of H over a wide range of values typically obtained in subsystem testing .

Also shown in Figure 4 are the curves for Average(p_i) for the reduced impact speed distributions. It is immediately clear that the average risk is substantially reduced given the speed reductions as described; moreover, values of H that correspond in respect of Average(p_i) are substantially different between the three speed distributions: 50% risk values correspond to H values of approximately 900, 1500 and 2500 for the 40 km/h, 35 km/h and 30 km/h distributions respectively. A value of H = 1000 corresponds to risks 0.52, 0.39 and 0.26. In other words, Average(p_i) is halved in the case of the 30 km/h distribution when H = 1000.

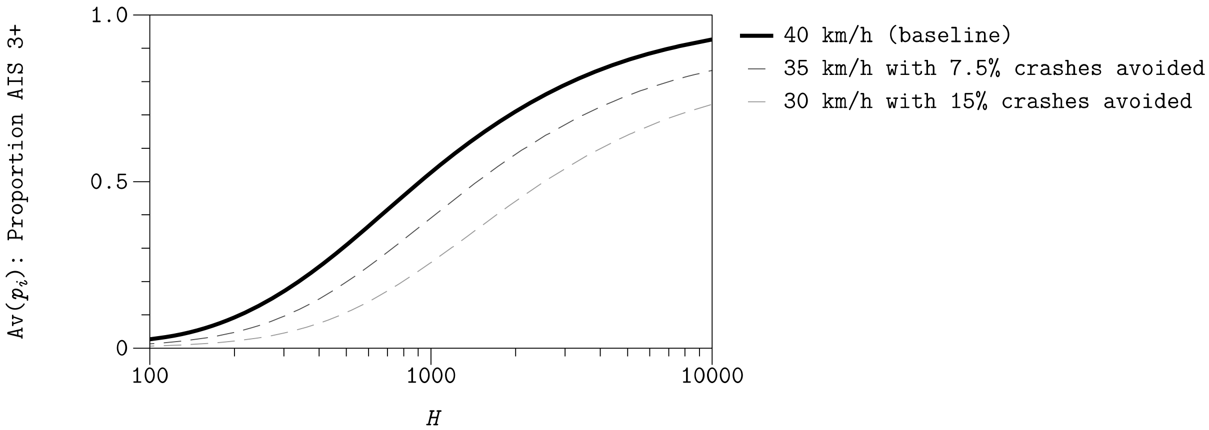

Fig. 4. The effect of modified impact speed distributions of Average(p_i)

Implications for changes in Average(p_i) for Euro NCAP assessment and GTR compliance

The 2013 Euro NCAP pedestrian assessment protocol rewards impact performance on a sliding scale between one and zero for values of H between 650 and 1700, with one point awarded for values less than or equal to 650 [1]. This range is indicated on the graphs in Figure 5 by the shaded band, A. According to the present analysis, this band (650-1700) corresponds to a range in the average risk of 0.39 to 0.67.

The results of Equation 1 might be used to suggest that this range is more limited than it should be given that risk continues to decline below H = 650 and increase above H = 1700. Nevertheless, the band of average risk implied by the Euro NCAP assessment protocol can be used as a reference to examine the ranges of H that would provide the same levels of average risk should the impact speeds of vehicles be reduced. The graphs in Figure 5 indicate these equivalent ranges as A^*: the upper graph shows A^* for the 35 km/h impact speed distribution and the lower graph shows A^* for the 30 km/h distribution. The ranges are approximately H = 1000 to H = 3000 and H = 1660 to H = 6000. The reduction of the speed distribution would appear to greatly improve the safety of locations with values of H that are currently seen as unacceptably dangerous.

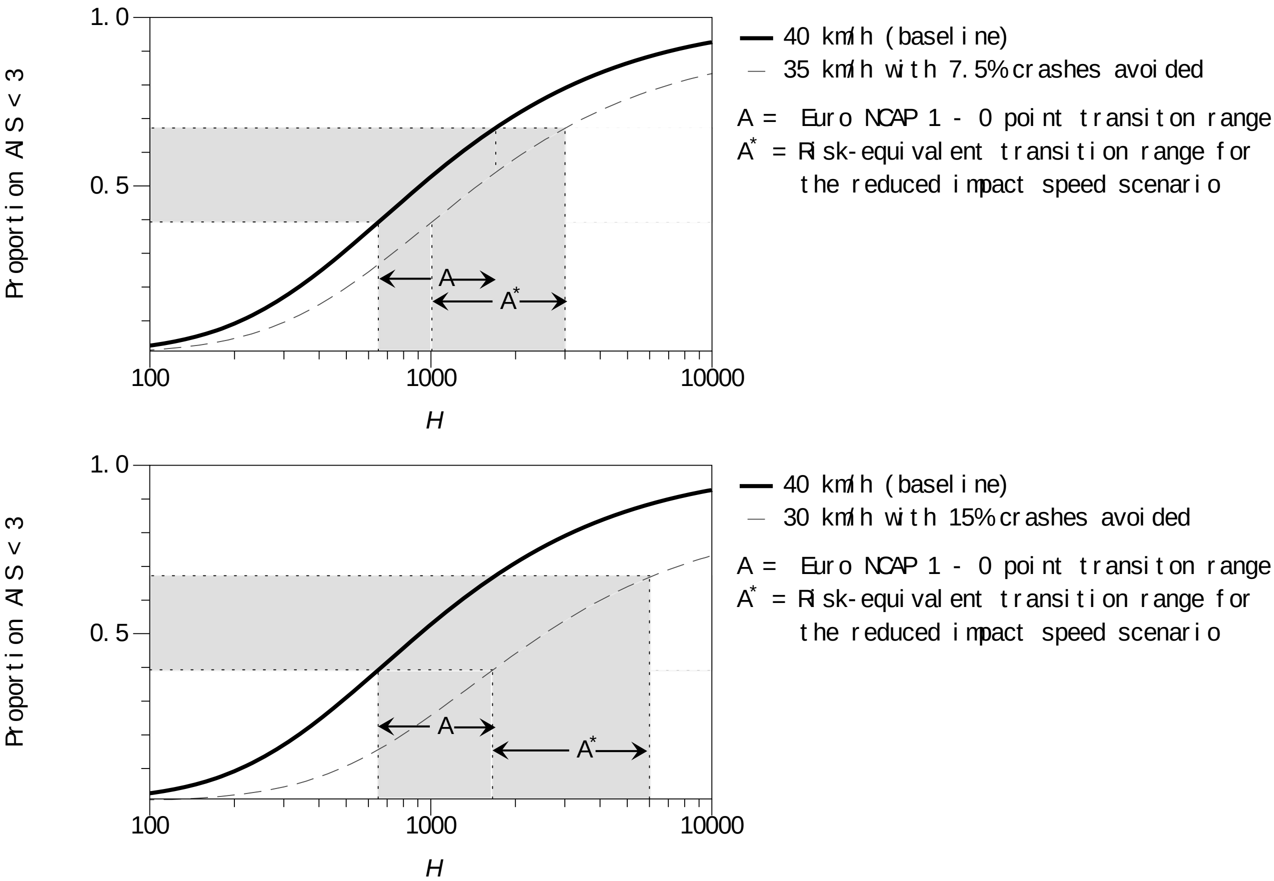

Fig. 5. Risk-equivalent ranges for H where automated emergency braking has been applied. Range A corresponds to the Euro NCAP (2013 assessment protocol) 1-to-0 point transition range. Range A^* is a risk-equivalent range for H given the modified impact speed distribution.

The concept of risk-equivalence may also be applied to GTR compliance. In this case, the assessment of compliance is based on H < 1000 (or < 1700 in the relaxation zone) in a 35 km/h test (see [6] for details). If speeds are according to the 35 km/h $f^*(x)$ speed distribution rather than the baseline $f(x)$, then equivalent risks to H = 1000 and H = 1700 in the baseline case are obtained at H values of 1700 and 3240. Average risks associated with these values of H are 0.62 and 0.75.

Summarising changes in risk brought about through effective autonomous braking

The changes in risk brought about by reducing the mean and amplitude of the impact speed distribution were shown in Figure 4 and are summarized in Figure 6. In this figure, the risk associated with a given value of H in the case of the modified speed distribution $f^*(x)$ is plotted against the risk in the baseline case. This graph is useful for indicating the general reduction in risk brought about by reducing the speed and incidence of impacts. In the case of the 35 km/h distribution, average risk lies about 0.1 below the average risk in the baseline case, over the range in H shown on the secondary x axis. In the case of the 30 km/h distribution, average risk is 0.25 less over the range in H.

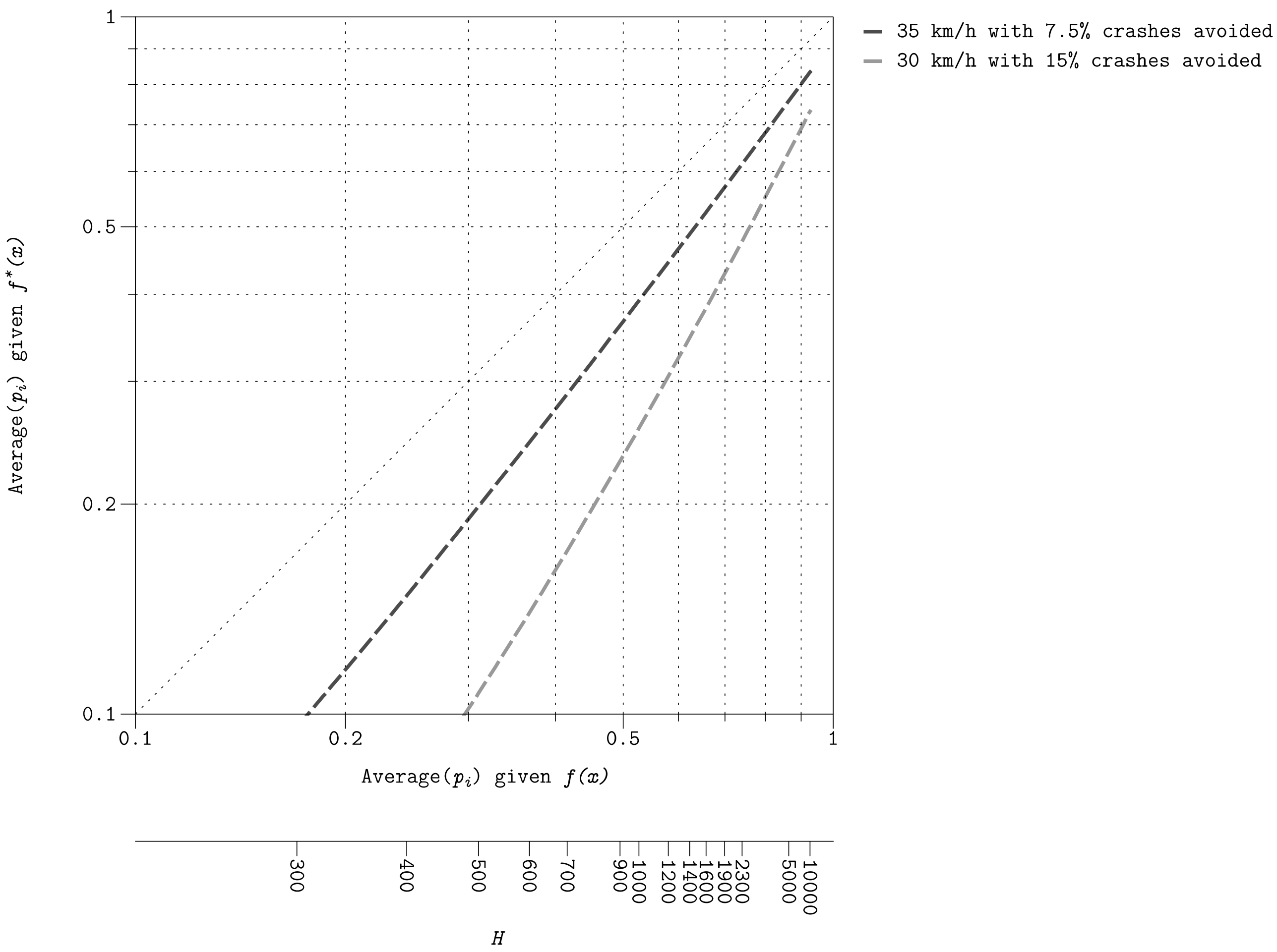

Fig. 6. Average risk associated with modified speed distributions $f^*(x)$ plotted against average risk associated with the baseline impact speed distribution $f(x)$, and against H obtained in the 40 km/h impact test

V. DISCUSSION

Equation 1 may be used to describe the average risk (or cost) associated with the impact severity measured in one test or impact condition. While it may use information from a single test, it approaches the question of injury risk in a different way than is usual: crash testing normally involves assessing risk in one condition, and the implication is that the severity in the test represents average risk in the field. As was mentioned earlier, current methods of assessing risk will need to adapt to incorporate changes in impact conditions that are likely to arise with the installation of collision avoidance or mitigation technology. A given result in an impact test represents potentially a much lower average risk when the average impact speed of that vehicle is reduced, and/or when collisions are avoided.

Equation 1 was applied in this paper to the problem of integrating the assessment of primary and secondary safety systems that affect the risk of head injury in pedestrian collisions. While the results of the analysis are contingent on the appropriateness of the inputs to Equation 1, some general implications for vehicle assessment have been raised:

- Average injury risk varies over quite a large range of H. Certainly, the risk continues to change over values of H where Euro NCAP ratings no longer reward or penalize changes in H. Average risk appears to be approximately linear with the logarithm of H rather than with H over quite a large range, and these findings may have implications for how risk might be assessed in programs such as Euro NCAP.

- A further point is that our results may understate just how wide the range of HIC is important, as Figure 2 refers only to one injury level, rather than a true average cost.
- The range of H considered by Euro NCAP when assessing risk in a headform test might be expanded for the reasons just mentioned, but may also be required solely for properly integrating the assessment of pedestrian safety in vehicles that have pedestrian detection and automated braking systems. Ranges of H for reduced speed distributions were found that are risk-equivalent to the HIC range of 650-1700 used in the 2013 Euro NCAP assessment protocol. This range was 1000 – 3000 for a speed distribution that had a median 5 km/h less than the baseline, and in which 7.5% of crashes were avoided.
- As average risk varies over a wide range of H, it raises the possibility that much stiffer structures such as the A-pillar, that are not currently tested by Euro NCAP, might be included in the area of a vehicle that is tested. For example, two A-pillars that might result in HIC values of 4000 and 2000 are not currently differentiated in the assessment protocol, and both structures would be given no credit if they were tested. However, this analysis suggests that such differences in H are meaningful, and efforts to lessen the severity of impacts with such structures, even if the result is not to produce values of H that are traditionally thought of as safe, would produce benefits in the field.
- The concept embodied by Equation 1 might be extended in several ways. For example, different parts of the vehicle may have different impact speed distributions (for example, collisions with child pedestrians may occur at different speeds to those involving adults, or impacts with A-pillars may have different speed distributions from those involving the hood). Similarly, different vehicles may produce different head impact conditions by virtue of their geometry. It might also be extended to cover a range of head masses, and methods for doing so are outlined in [5]. Equation 1 might also be extended by further averaging it over the surface of the vehicle, with a weighting to reflect the relative incidence of impact with different parts of the vehicle.

Current limitations on the use of the expression for average injury/cost

This paper has presented both a conceptual framework and some quantitative results for the integrated assessment of primary and secondary pedestrian safety in vehicles. However, it is important to note that the quantitative results are specific to the definition of the components of Equation 1. They are also a consequence of assumptions about how impact speed distributions will be affected by collision detection and braking systems, and those assumptions may be in error. Confidence in the numerical results will be improved with careful consideration of the inputs to Equation 1, and with further evaluation of the likely effect that primary safety systems will have on impact speeds.

In introducing Equation 1 we previously noted some other potential obstacles to its use for calculating average injury/cost [5]:

- The dependence of HIC upon speed noted in laboratory testing may not apply to a sample distribution of real-world impact speeds, as the former are measured accurately whereas the latter have a random error included. Most obviously, the distribution of speeds should refer to the head impact and not the vehicle speed, and this might also vary according to test area.
- The form of the risk or cost function needs to apply to the population being described and the specific risk of injury given a test result with the nominated headform.

To elaborate, as distributions of head impact speeds are necessarily currently estimated from in-depth crash investigation, they will include random error. If the effect of this is to inflate the variance in impact speeds, current estimates of $f(x)$ may be 'flatter' than the true distribution, and hence any estimate of the function $h(x,i)$ made using precisely measured impact speeds may be steeper than the function that should apply to a crash-based estimate of $f(x)$.

With regard to the second dot-point, the risk or cost function that is derived from, for example, post-mortem human subject tests may or may not be a suitable risk function to describe head injury risk in a population of struck pedestrians as indicated by the result of a headform test. Current risk curves, based as they are on [13], are based on only limited data. The entire risk curve is used in calculating average risk, whereas such curves have commonly only been used in the past to identify risks associated with specific HIC values (e.g. HIC = 1000). In the present application, the level of H at which risk approaches unity is influential on the quantitative results, and therefore the correctness of the entire risk curve is important.

The form of the function p might describe the risk of a certain injury for a given value of h, but equally a cost function might be preferred that described the average cost of injuries for any value of the function h. Different forms of the cost/risk function will yield a different estimate of Average(p_i) that may also affect the influence of a modified $f(x)$, and hence the estimated contribution of autonomous braking interventions to reduced average cost/risk.

VI. CONCLUSIONS

An expression for the average risk of injury across varying impact conditions has been presented and applied to the problem of integrating the assessment of primary (collision avoidance) and secondary (impact protection) pedestrian safety. In the course of doing so, observations were made regarding current approaches to impact test assessment: for example, average risk continues to change for values of H over ranges where the Euro NCAP assessment does not change.

The model of average risk implies that effects of impact speed reduction technologies will be substantial and this has implications for how impact test assessments are made. Given the average risk implied by current assessment criteria, applying risk-equivalence in the case of reduced impact speeds suggests that substantial credit will need to be applied to the assessment of vehicles that have effective collision detection and autonomous braking systems installed.

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