AN EQUATION FOR GENERALISING FROM IMPACT TEST PERFORMANCE TO REAL-WORLD CRASHES

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ABSTRACT

Research Question / Objective: Instrumented headforms are projected at the fronts of cars to assess pedestrian safety. Better information would be obtained from these and other types of impact tests if performance over the range of expected impact conditions in the field were taken into account. That is, some means is needed to convert from performance in tightly-specified test conditions to what happens in the real-world. *Method:* Pedestrian impact safety performance of a car is affected by speed, head mass, and the distribution of impact locations over the front of the car. The effects are complicated because bottoming out may occur, that is, the hood or other surface structure may fail to absorb sufficient energy to prevent contact with much stiffer structures beneath it. In turn, the locations are affected by the geometry of the car, the impact speed, and the pedestrian's stature. The relative frequencies of different speeds, masses, and so on are important inputs to the calculation of an average. *Results:* The principal result is a theory. This has three steps. The first is to convert the test quantity (e.g., HIC, the Head Injury Criterion) observed in test conditions to what would be observed if (for example) speed or mass were different. The second is to convert the test quantity to something that can be meaningfully averaged --- for example, average dollar cost of HIC or the probability of death corresponding to a given HIC. The third is to obtain the average cost, or average probability of death, by integration over the quantities that vary from crash to crash: speed, head mass, stature, and impact location. *Discussion and Limitations:* The theory that is developed may be used to calculate, for example, the changes that result if test performance is improved, or the probabilities of different conditions change. With appropriate modification, the theory is applicable to many other forms of testing also. The chief limitation is that good information is required on such things as the dependence of HIC on speed and mass, the dependence of cost on HIC, and the relative frequencies of speeds, masses, and so on. Such information is difficult to obtain. *Conclusions:* Better representation of the effect of impact conditions on severity is required if a test regime is to provide appropriate incentives for improvement in vehicle design. This paper identifies what information is needed, and shows how it can be used to estimate average real-world performance starting from what is observed in an impact test.

INTRODUCTION

As part of testing of new cars by consumer organisations, an approximate sphere with an accelerometer inside it is projected at the front of a car. The speed and other conditions of the impact are specified. However, real pedestrian impacts are at a wide range of speeds. We have recently described a method of calculating average performance across a range of impact speeds, and across a range of effective head masses (Hutchinson et al., 2012a). Lubbe et al. (2012) discussed our method and other literature on this, and gave attention to variation in other factors as well as speed. They were most concerned with the distribution of pedestrian impact points over the front of the car. In turn, this distribution is affected by the geometry of the car, the impact speed, and the pedestrian's stature. Lubbe et al. also make passing mention of pedestrian gender and age as factors that vary. Further, a review by Hu and Klinich (2012) particularly emphasised (a) the need to keep in mind the special characteristics of older pedestrians, and (b) bottoming out as a danger to pedestrians (this term refers to the hood deforming so much that very stiff structures underneath it are contacted, with consequent great increase of the severity of the impact). Both of these issues imply the need for information beyond a test result.

This paper proposes an equation that will integrate over the range of pedestrian head masses, the range of pedestrian statures, and the range of impact locations on the car, as well as over the range of speeds. To some extent, then, this paper is a response to Lubbe et al. and to Hu and Klinich. Geometry of the car is not a random variable, and frailty of the pedestrian affects injury and its consequences rather than what is measured in an impact test, and these are discussed separately. Our arguments are made in the context of (and with reference to the specifics of) pedestrian headform

testing, but are of broad applicability in impact testing.

At present, the purpose of impact testing appears to be the measurement of safety in particular conditions of impact. Impact testing will be more valuable if it measures safety averaged over a wide range of real-world impact scenarios. Perhaps "estimation" would be a better word than "measurement", as to the variability in test results is added uncertainty about how to generalise from the particular conditions of the test to real-world crashes. In referring to conditions of impact, we mean the speed of the headform, its mass, the locations on the front of the car that are tested, and so on. The specifics which are laid down in the test protocol seem to be intended to be representative of, or typical of, pedestrian impacts. Performance in other conditions is also important. Performance will be different if conditions change --- the impact will be more severe if the speed is higher --- and the effects are likely to be complicated.

- Low speed impacts are very important numerically. Some authors have argued that the test speeds that are used are consequently unrepresentative.
- If bottoming out did not occur at the test speed, it may do at some higher speed that is still within the realistic range. If bottoming out did occur at the test speed, it may not at some lower speed that is still within the realistic range. In either case, there is a great change from what happens in the test.
- The A pillars are usually not tested. They are typically very stiff and receive a default fail result.
- The windscreen is usually not tested. It is typically sufficiently soft to receive a default pass result.
- Pedestrians of different statures will impact the car in different places: the taller they are, the further from the front of the car will be the impact.
- Speed will affect not only the severity of the impact at a given location, but also the location that is struck.
- A change of the effective head mass is likely to have different results at different speeds and different locations. An increase of effective head mass will lead to acceleration taking place over a longer distance. At low speed and with plenty of clearance distance under the hood, that will mean lower accelerations. But at high speed and with little clearance distance under the hood, the increased distance will make bottoming out more likely, and hence a great increase in severity.
- New technology such as forward-looking radar or improved tyres may substantially reduce impact speeds. Lubbe et al. (2012) note that passive and active safety systems cannot be assessed by a straightforward combination of distinct methods as the benefits "are measured in different units: e.g., impact speed reduction for active safety systems and injury criteria measurements for the passive safety system component test".

As already mentioned, our method was described in Hutchinson et al. (2012a). There is relevant previous literature that we built upon, notably by Searle et al. (1978), Horsch (1987), Viano (1988), and Korner (1989). Other aspects are discussed in Anderson et al. (2012), Hutchinson et al. (2012b), and Searson et al. (2012a,b,c).

DERIVATION OF REAL-WORLD CONSEQUENCES FROM A TEST RESULT

Notation

Notation is given below. It is consistent with that of Hutchinson et al. (2012a).

- x: speed of impact of the car with the pedestrian (it is assumed this is the same as the speed with which the head hits the car)
- m: effective mass of the pedestrian's head
- s: stature of pedestrian
- i: location on the car (this is a categorical variable, a name rather than a number)
- u: distance of the head impact point from the front of the car
- w: distance of the head impact point from the side of the car, laterally across the car
- h: HIC, the Head Injury Criterion
- p(h): cost of h (or, rather, the average cost, as the injuries and outcomes will vary)
- f(x): probability density function of speed x
- g(m, s): joint probability distribution of head mass m and stature s
- z: frailty

In pedestrian headform tests, HIC is used to characterise the test result. This is not essential, though, and h could instead be the maximum acceleration or some other summary.

Overview of Calculation

The calculation has three steps. The first is to convert the test quantity (e.g., HIC, the Head Injury Criterion) observed in test conditions to what would be observed if (for example) speed or mass were different. The second is to convert the test

quantity to something that can be meaningfully averaged --- for example, average dollar cost of HIC or the probability of death corresponding to a given HIC. The third is to obtain the average cost, or average probability of death, by integration over the quantities that vary from crash to crash. Hutchinson et al. (2012a) were chiefly concerned with the effect of speed, and had the expression p(h(x, i)).f(x) for the cost corresponding to speed x and location i. (Notice that it is assumed that h alone determines p: the other variables have their effects on p because they affect h.) Hutchinson et al. obtained the following equation for average cost (their equation 3).

$$Av(p_i) = \int p(h(x, i)).f(x).dx$$

The above equation refers to location i on the car. Locations differ in how safe or unsafe they are. HIC at a location is converted to a number of points at that location, and points are summed to get a score for the car. For these reasons, Hutchinson et al. regarded the location on the car as being the basic unit to analyse. But Lubbe et al. (2012) are quite correct to say that averaging over the whole car is important (this is particularly so because change to the distribution of speeds will change the distribution of impact locations), and so is averaging over pedestrian head mass and stature. A generalised expression of similar form will be obtained below that applies to the car as a whole.

Conditions that Vary

Quantities that vary in the real world, and over which the cost should be averaged, are listed below, with a short description of how they have their effects.

- Speed of impact. Firstly, at any given location on the car, HIC increases with increasing speed. Secondly, the impact location of the head will be further from the front of the car, the higher the speed is.
- Mass of pedestrian's head. HIC depends on mass as well as on speed.
- Stature of pedestrian. The impact location of the head will be further from the front of the car, the taller the pedestrian is.
- Impact location on the car. Each location on the car may be different in respect of both the surface (e.g., the hood) and what is underneath (e.g., the engine). The distance u of the head impact point from the front of the car is not random, being determined by impact speed and pedestrian stature, but the distance w of the head impact point from the side of the car is a random variable. Possibly impact angle should be included also, but this will not be considered below.

These effects are represented in mathematical notation as follows (the symbols are as listed earlier).

- Speed. Firstly, h(x). Secondly, u(x).
- Mass. h depends on m as well as on x: h(x, m).
- Stature. u depends on s as well as on x: u(x, s).
- Impact location. h depends on location: h(x, m, i).

Expression for the Average of p

As already noted, Hutchinson et al. (2012a) wrote p(h(x, i)) to show that x affects h and this in turn affects p, and multiplied this by f(x). To include the extra variables, this may be generalised as below.

Firstly, p(h(x, m, i)) shows that mass affects h and hence p.

Secondly, i is defined by the distances u and w, along and across the car. Thus p becomes p(h(x, m, i(u, w))).

Thirdly, u is determined by x and s. Thus p becomes p(h(x, m, i(u(x, s), w))).

Fourthly, this will need to be multiplied by the probabilities with which x, m, and s occur: p(h(x, m, i(u(x, s), w))).f(x).g(m, s).

Finally, average p is obtained by integrating over the four quantities x, m, s, w. The equation (below), in contrast to our earlier paper, applies to the car as a whole.

$$Av(p) = \int\int\int\int p(h(x, m, i(u(x, s), w))).f(x).g(m, s).dx.dm.ds.dw. \qquad \text{(Equation 1)}$$

Comments

Four comments on Equation (1) are worth making.

- Different probabilities of different w are not shown in Equation (1). It would be necessary to do so if some locations across the width of the car are struck more frequently than others. (In addition, it may be the case that narrow cars miss some pedestrians that wider cars would hit. It is probably more convenient to take account of this via reduced impact frequency rather than by setting h to 0 for impacts that are avoided.)
- The effective head mass m and the pedestrian's stature s may not be independent, in which case g(m, s) will be a complicated bivariate probability density, but lack of information may mean the use of the product of probability densities of m and of s, $g_1(m).g_2(s)$.

- The name of the impact location, i, could be omitted from the equation. The expression would then be p(h(x, m, u(x, s), w)). There is nothing wrong with this, but the disadvantage is that it may mislead us into thinking that h is a simple function of the distances u and w. That is unlikely: h is quite a different function of x and m for all the various locations that might be struck.
- The dependence of cost on h could be split into several stages --- for example, injury at a given h, outcome of a given injury, and cost of a given outcome. But at present this seems unnecessary.

DISCUSSION

Data Requirements

The expression p(h(x, i)).f(x) (Hutchinson et al., 2012a) requires good data on the functions h(x) and p(h) and on the probability density f(x) if the result is to be accurate in absolute terms. What Lubbe et al. (2012) call for, and we have tried to provide in Equation (1), requires in addition good data on the dependence of h on m, the dependence of u on x and s, and the bivariate probability density g(m, s). These are severe demands, but are not out of the question. This is so especially since improvement in the comparability of vehicles and usefulness of impact test results may occur even if the numerical magnitude of Av(p) is not accurate in absolute terms.

Frailty

Injuries, outcomes, and therefore costs vary from person to person, even if they are of the same stature and effective head mass, and strike the same location on the car at the same speed and angle. This may be ascribed to differences in frailty. “Frailty” here may have a limited meaning (bone strength, resistance to infection, and so on), or may be a catch-all term referring to any aspect of a person’s reaction to applied physical force. Frailty is not recorded in road crash statistics, but perhaps age could be used instead. It should also be noted that in the present context, frailty is something other than stature and head mass, as these are already included in the expression given.

Variability in frailty is not treated in Equation (1) in the same way as variability in speed, stature, and head mass. The reason is that variability in frailty is presumed to be taken account of by using an average cost function p(h). That is, frailty does not affect HIC, or whatever other summary of the physical aspects of the impact is being used. Rather, frailty affects the human’s reaction to HIC: with z being frailty, h is still h(x, m, i), not h(x, m, i, z), and frailty would be introduced by writing p(h, z). Expressed in other words, an impact location that is safer than another for one level of frailty is expected to also be safer for all other levels of frailty; the same cannot be said about speed or stature or head mass. Furthermore, if the distributions of x, m, and s are independent of z, it is sufficient to use p(h), with this having been averaged over z. If the distributions of x, m, and s are different for people of different frailties, then the product of cost and its probability should be shown as p(h, z).f(x, z).g(m, s, z). But this is impracticable --- it is far too demanding of data.

Car Geometry

Cars differ in their geometry, including hood height, hood length, hood angle, and various other characteristics. This is not a random variable, and is not treated as x, m, and s are. But car geometry will, with speed and pedestrian stature, affect where on the car the pedestrian will strike, and perhaps also affect the speed and angle of the impact. Referring to Equation (1), either the distance u(x, s) will depend on car geometry or this quantity will need re-interpretation dependent on car geometry (perhaps as a wrap-around distance).

Crash Configuration

The characteristics of the car (that is, the dependence of h on i and other variables) may be relevant to more than one type of crash. For example, some locations on the car may be capable of striking a pedestrian who was in front of the car or a pedestrian who walks into the side of the car. This would require separate equations of the form of Equation (1) for the different crash types.

Overview

Equation (3) of Hutchinson et al. (2012a) and Equation (1) of the present paper show the principles of the necessary calculation.

Benefits from the calculation will include estimation of the effects of making changes --- changing the design or material of the hood so as to reduce the HIC observed in the test, increasing the underhood clearance distance, reducing the speeds at impact (e.g., by use of active safety systems, or improved brakes and tyres), and so on.

The considerable obstacles to using Equation (1) should be recognised. These include inferring the dependence of h on x and m from HIC measured at specific x and m, knowing the empirical dependence of p on h, and knowing the empirical relative frequencies of different speeds, effective

head masses, and pedestrian statures (i.e., f(x) and g(m, s)).

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