Dependence of the Head Injury Criterion and Maximum Acceleration on Headform Mass and Initial Velocity in Tests Simulating Pedestrian Impacts With Vehicles

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Impact testing of pedestrian headforms is usually conducted at one velocity and with one mass of headform, but real impacts occur at a range of velocities and masses. A method is proposed to predict the Head Injury Criterion (HIC) and similar quantities at other velocities from their values observed under test conditions. A specific assumption is made about acceleration during the impact as related to displacement, its differential (instantaneous velocity), mass of headform, and initial velocity: namely, that it is the product of a power function of displacement (representing a possibly nonlinear spring) and a term that includes a type of damping. This equation is not solved, but some properties of the solution are obtained: HIC, maximum acceleration, and maximum displacement are found to be power functions of mass of headform and initial velocity. Expressions for the exponents are obtained in terms of the nonlinearity parameter of the spring. Simple formulae are obtained for the dependence of HIC, maximum acceleration, and maximum displacement on velocity and mass. These are relevant to many types of impact. [DOI: 10.1115/1.4025331]

Keywords: impact testing, Head Injury Criterion, maximum acceleration, pedestrian subsystem testing, contact force, nonlinear damped spring

Introduction

To provide the car buyer with safety information, or to satisfy regulatory requirements, instrumented headforms are projected at the fronts of cars in order to check that the vehicle is not excessively injurious if a pedestrian is struck. See Refs. [1,2] for introductions to the tests and Ref. [3] for examples of the protocols. Many different locations on a car's front are tested and results are assembled into a score for the car as a whole. The results in this paper were obtained in this context. These tests measure acceleration of the surrogate head, and use the Head Injury Criterion (HIC) to summarize the acceleration trace and to indicate likely injury severity; HIC and also maximum acceleration are used for this purpose in various other types of impact test, too. Another quantity of interest is maximum displacement, as "bottoming out" (i.e., contact between the underside of the hood or other surface structure and the stiffer structures beneath) would imply a great increase in HIC and maximum acceleration. The conditions of the test, including the velocity and mass of the headform, are specified in the test protocol. Starting from HIC, maximum acceleration, and maximum displacement in the specified test conditions, the aim in the present paper is to say what they would be in different conditions, that is, with different masses or impact velocities. This will be done by assuming a specific differential equation relating force to displacement and velocity. The equation is not solved, but results about HIC and other quantities can nevertheless be obtained.

These results about HIC and other quantities are of obvious interest. Two specific applications are envisaged. Firstly, to predict what will happen if the headform mass or impact velocity specified in a test protocol are changed, and to allow equivalences to be established between protocols requiring different masses and velocities. Secondly, information about (a) the relative frequencies of different real-world conditions (notably, different velocities), and (b) the clinical meaning of different levels of HIC, will permit average safety performance in real-world conditions to be calculated, which would be a great improvement over HIC in test conditions only [4].

Even assuming the specific equation for force in terms of displacement and velocity is valid, there are likely to be two major limitations with the application of the results. The first is that little information is being collected and used: observing HIC in one test is assumed to be sufficient to imply what HIC is over the whole relevant range of v and m. The reason for only a single test is that more tests would imply higher costs, of course. Consequently, appreciable inaccuracy must be expected. The second major problem is that the results will not be valid if there is a qualitative change in what happens—for example, if bottoming out is introduced by increased v and m. Some forms of extra information may be useful in warning about possible qualitative change. Examples might include measuring underhood clearance in order to predict bottoming out, or impact simulation using finite element modeling. Similarly, a high testing velocity might be thought preferable to a low one, as the acceleration trace would show what was happening at velocities less than initial velocity and displacements less than the maximum, and if there is no evidence of qualitative change in behavior, there can be some confidence in predicting HIC at a lower velocity.

The definition of HIC is $[av(a)]^{2.5}(t_2 - t_1)$, where $av(a)$ is the average acceleration over a period from t_1 to t_2, with t_1 and t_2 chosen so that the resulting HIC is maximized (average acceleration is velocity change in the relevant period divided by $(t_2 - t_1)$. In some contexts, it is required that $(t_2 - t_1)$ does not exceed a prespecified length of time, e.g., 15 ms).

Chou and Nyquist [5] obtained a number of algebraic consequences of the definition of HIC, for example, that for some particular shapes of the acceleration pulse, HIC is proportional to $A^{2.5}T$, where $A =$ maximum acceleration and $T =$ total contact time. However, it seems possible that the shape may change if headform mass m and velocity v change. An equation for force as a function of displacement and speed should be a more useful starting point than a pulse shape, but few results of this type are known. For the linear spring with no damping, Searson et al. [6] found HIC to be proportional to $m^{-0.75}v^{2.5}$. For force being a piecewise linear function of displacement (three regimes, the second being the least steep and the third being the steepest), see Deb and Ali [7]. The equation to be used in this paper is one proposed by Hunt and Crossley [8].

This paper is organized in the conventional way as: Methods, Results, Discussion, and Conclusions. Critical comments on the assumptions made will be included in the Discussion.

Methods

It is assumed here that force depends on displacement x and velocity x' via the following proportionality relationship:

$$\text{force} \propto x^c[1 + (b/v)x'] \tag{1}$$

Without the damping term, this represents a nonlinear spring, force $\propto x^c$. The damping term is $x^c(b/v)x'$. This is not an arbitrary assumption. Firstly, it is zero for both $x = 0$ and $x' = 0$, as Hunt and Crossley [8] have argued is realistic. Secondly, the multiplier is b/v. If, instead, force $\propto x^c[1 + bx']$, it can be shown that b is the

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ratio of some function of the coefficient of restitution to v. Thus, if it is thought that the coefficient of restitution itself does not depend strongly on v, the multiplier should be written as b/v (see pp. 212–213 of Ref. [9].)

The differential equation relating acceleration to displacement is

$$mx'' - kx^c[1 + (b/v)x'] = 0 \tag{2}$$

As k is not a variable being studied here, it can be taken as 1 for simplicity (if k were a variable of interest, the results below are still valid, but with m interpreted as the ratio m/k). Initial conditions are $x'(0) = v$ and $x(0) = 0$.

Results

For the particular form of nonlinearity and the particular form of damping being considered, a change of m or v only stretches the time and the height of the acceleration pulse, and does not otherwise change its shape (the "shape" of the pulse refers here to something beyond its length and its height—that is, if it is merely stretched linearly in time or height, its shape is said to remain the same). This will first be proved, and will be used when considering how m and v affect HIC.

Start with $m = 1$ and $v = 1$, and suppose $p(t)$ is a function satisfying the three requirements $x'' - x^c(1 + bx') = 0$, $x'(0) = 1$, and $x[0] = 0$. Velocity is p' and the acceleration pulse is p''. Now consider

$$q(t) = m^{1/(c+1)} v^{2/(c+1)} p(m^{-1/(c+1)} v^{(c-1)/(c+1)} t) \tag{3}$$

Velocity and acceleration are as follows

$$q'(t) = vp'(m^{-1/(c+1)} v^{(c-1)/(c+1)} t) \tag{4}$$

$$q''(t) = m^{-1/(c+1)} v^{2c/(c+1)} p''(m^{-1/(c+1)} v^{(c-1)/(c+1)} t) \tag{5}$$

The function $q(t)$ satisfies

$$mx'' - x^c[1 + (b/v)x'] = 0 \tag{6}$$

$$x'(0) = v \tag{7}$$

$$x(0) = 0 \tag{8}$$

The proof is completed by checking q, q', and q'' against the three requirements, Eqs. (6)–(8). Equation (5) shows that the pulse shape is still described by p'', though in most cases it is changed in height and duration (the exception is that if $c = 1$, it is not changed in duration by a change in v).

Equations (3)–(5) permit conclusions that maximum acceleration, maximum displacement, and HIC are proportional to power functions of m and v, as given in the next three paragraphs.

For maximum acceleration, the dependence on m and v follows immediately: the expression for acceleration q'' includes a multiplier of $m^{-1/(c+1)} v^{2c/(c+1)}$.

Similarly, for maximum displacement, the expression for q includes a multiplier of $m^{1/(c+1)} v^{2/(c+1)}$.

Turning now to HIC, the result is obtained in three steps. The first is to note that provided pulse shape does not change except for linear stretching in time and height, HIC is proportional to $A^{2.5}T$. To demonstrate this, consider the pulse $a(t)$ for which $A = 1$ and $T = 1$, and the stretched pulse $Aa(t/T)$. In the former case, HIC is based on $[\int a(t)dt]^{2.5}$, and in the latter case, HIC is based on $T[\int Aa(t/T)dt/T]^{2.5}$. On substituting $s = t/T$, the result is $T[\int Aa(s)Tds/T]^{2.5} = A^{2.5}T[\int a(s)ds]^{2.5}$, which is $A^{2.5}.T$ times the original result. Second, maximum acceleration includes a multiplier of $m^{-1/(c+1)} v^{2c/(c+1)}$, as already noted, and the time for which the pulse lasts will be inversely proportional to the multiplier of t in the argument of $p(.)$. Finally, as HIC is proportional to $A^{2.5}T$, HIC will be proportional to $[m^{-1/(c+1)}.v^{2c/(c+1)}]^{2.5}$ $[m^{-1/(c+1)} v^{(c-1)/(c+1)}]^{-1}$. That is

$$\text{HIC} \propto m^{-1.5/(c+1)} v^{(4c+1)/(c+1)} \tag{9}$$

The limits of integration are not a source of complications: the shape of the pulse is not changing, so the limits will be particular fractions of T, and their dependence on T will be removed when substituting $s = t/T$. However, if a definition of HIC is being used that requires the time length of the integration to be less than (say) 15 ms, that will limit the validity of this result.

Special Cases. For HIC, some special cases are as follows. If $c = 0$, HIC $\propto m^{-1.5}v$; if $c = 0.5$, HIC $\propto m^{-1}v^2$; for the linear spring, $c = 1$ and thus HIC $\propto m^{-0.75}v^{2.5}$; if $c = 1.5$ (sometimes termed Hertzian impact), HIC $\propto m^{-0.6}v^{2.8}$; if $c = 2$, HIC $\propto m^{-0.5}v^3$; and if c is very large, then (considering the behavior of the expression as $c \to \infty$) HIC is independent of m and proportional to v^4.

Aggregation Impermissible. The above proportionality results were obtained assuming that b and c are constant. These may change from one impact location to another. Consequently, the results refer to a specific impact location, not to a dataset in which there are many impact locations.

Qualitative Effects. The effects of initial velocity v on maximum acceleration, HIC, and maximum displacement are all positive (the exception is that if the spring exponent c is 0, there is no effect of velocity on maximum acceleration). The effects of headform mass m are negative on maximum acceleration and HIC, and positive on maximum displacement.

Quantitative Effects. Some examples of the quantitative effects are given in Table 1. For example, if $c = 1$, then a 15% increase in impact speed will lead to a 15% increase in maximum displacement, a 15% increase in maximum acceleration, and a 42% increase in HIC. A qualitative difference may arise from quantitative differences, as shown in the following example. Maximum acceleration and HIC are both used for the same purpose, to indicate likely injury severity, and qualitatively they are affected in the same direction by a change in v and by a change in m. However, they are affected to different degrees, and when both v and m change, maximum acceleration and HIC may be affected in opposite directions. Table 1 shows that if $c = 1$, multiplying v by 1.15 and m by 1.5 leads to maximum acceleration decreasing (being multiplied by 0.94) and HIC increasing (being multiplied by 1.05).

Discussion

Limitations. In the next three paragraphs, limitations are acknowledged both of impact testing generally and of the present results more specifically.

Table 1 Effects of changing *v* and *m*. The table gives the factors by which maximum acceleration *A*, HIC, and maximum displacement *S* are multiplied when *v* is multiplied by 1.15, or *m* is multiplied by 1.50, or both of these changes occur. Results for three values of the spring exponent c are given.

	$c = 0$			$c = 1$			$c = 2$		
	A	HIC	S	A	HIC	S	A	HIC	S
Multiply v by 1.15	1.00	1.15	1.32	1.15	1.42	1.15	1.20	1.52	1.10
Multiply m by 1.50	0.67	0.54	1.50	0.82	0.74	1.22	0.87	0.82	1.14
Both the above	0.67	0.63	1.98	0.94	1.05	1.41	1.05	1.24	1.26

Firstly, it is assumed that injury depends on (translational) accelerations, not on forces or something else. The discussion in Ommaya et al. [10] supports this, but makes clear that there is uncertainty. Effects on force may be qualitatively different from effects on acceleration, as is familiar from the example of the undamped linear spring: kinetic energy is proportional to m; therefore maximum displacement is proportional to $m^{0.5}$, therefore maximum force is proportional to $m^{0.5}$, therefore maximum acceleration is proportional to $m^{-0.5}$, opposite directions of effect on force and acceleration. Whether translational acceleration is more or less important than rotational acceleration is also controversial.

Secondly, the use of a headform for impact testing is convenient practically, but the absence of a neck and body is thought to change the results somewhat. A linear equation may be used to convert a headform result to an equivalent dummy result; the term HIC(d) is sometimes used in this context. More broadly, a variety of other experimental arrangements are also used for impact testing, including a helmeted headform hitting a rigid anvil, a projected impactor hitting a helmeted headform, and a dummy representing the whole human. The results obtained here for a headform projected against a car's exterior will be relevant in other circumstances, but may need some modification (e.g., if the impact is between two free-to-move bodies, both masses will need to be considered).

Thirdly, the results given in this paper are based on a particular differential equation. References [8,9] were cited in support, and the equation has been used by others (e.g., Refs. [11–14]). However, the criticism could be made that damping being zero for $x=0$ and for $x'=0$ is true not only for the expression chosen but also for many other functions: indeed, the model has been described as an ad hoc one [15]. It should also be noted that although x^c does succeed in representing a spring that stiffens with increasing displacement (if $c>1$), it does not represent one that stiffens so much that force tends to infinity for some finite displacement, as with so-called tangent elasticity. This might be thought more appropriate if bottoming out is a real possibility.

Strength of Damping. It is noteworthy that the strength of damping affects HIC and the other quantities of interest, but not how HIC depends on m and v. Confirmation is given by numerical simulations based on Eq. (1) reported by Searson et al. [16]. That paper confirms how the exponents of m and v depend on c, for HIC and maximum displacement (those for maximum acceleration were not reported). It also gives some illustrations of how damping affects pulse shape and coefficient of restitution. In the model used, the damping coefficient will imply what the coefficient of restitution is. For example, if $b=0$, the coefficient of restitution is 1 (in pedestrian headform tests, the coefficient of restitution is typically about 0.25).

Six Covarying Exponents. Overall, there are six exponents (of m and v, for maximum acceleration, maximum displacement, and HIC) that are determined by c. Thus relationships between the exponents would be expected if different locations of impact have different values of c. Searson et al. [17] noted a negative relationship between the exponents of v for maximum displacement and HIC.

Empirical Results. For seven specific locations on a car, Searson et al. [17] reported on how HIC varied with speed, and found exponents between 1.6 and 3.0, which would imply that c is between 0.25 and 2. For two locations on a car, Fig. 9 of Mizuno et al. [18] implies exponents of about 2.3 and 3.5, which would imply that c is, respectively, 0.8 and 5.

Conclusions

The conclusions of this paper may be stated succinctly. If the dependence of force on displacement and velocity is as in Eq. (1), $\text{HIC} \propto m^{-1.5/(c+1)} v^{(4c+1)/(c+1)}$, maximum acceleration $\propto m^{-1/(c+1)} v^{2c/(c+1)}$, and maximum displacement $\propto m^{1/(c+1)} v^{2/(c+1)}$.

Those relationships are useful in predicting what the result will be if the headform mass or impact velocity change, and as input (along with other information) to the calculation [4] of average real-world safety performance.

If $c=1$ is thought to have special plausibility, then exponents of -0.75 and 2.5 (in the case of HIC), -0.5 and 1 (in the case of maximum acceleration), and 0.5 and 1 (in the case of maximum displacement) will also be thought to be especially plausible. However, if $c=1$ has no special status, then other values will become plausible. It will remain true that all six exponents remain connected by their common dependence on c, and thus evidence about any one of them will carry implications about the others as well.

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Nomenclature

A = maximum acceleration during the impact of headform
T = total contact time of the headform with the vehicle
S = maximum displacement
b = damping constant
c = spring exponent
k = spring stiffness
m = mass of headform
$p(t)$ = a possible solution of the differential equation
$q(t)$ = another possible solution of the differential equation
t = time since the start of impact
v = initial velocity at impact of headform
$x(t)$ = displacement of the headform into the vehicle's hood
$x'(t)$ = first differential, velocity
$x''(t)$ = second differential, acceleration

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