USE OF THE HEAD INJURY CRITERION AS A MEASURE OF VEHICLE OCCUPANT PROTECTION PERFORMANCE

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ABSTRACT

For the past 20 years or so, performance requirements intended to protect motor vehicle occupants against head injury have invariably been based on the use of the Head Injury Criterion (HIC). The most evident difficulty with the Criterion is simply that the assumed inverse relationship between the tolerable level of head acceleration and its duration leads to predictions that contradict practical experience.

The data and analysis most widely cited in support of the continued use of HIC (with a time limit of 15 ms) are reviewed. The assumed equivalence of HIC values from cadaver and ATD head impacts is discussed and several difficulties identified. The validity of the derived "threshold risk curve" is tested against the data by numerically simulating the original experiments. The curve is found substantially to misrepresent the experimental data on which it is based. Extensive data from tests by Transport Canada and other agencies are presented which show that, regardless of either the time duration of the calculation or the criterion level, HIC is incapable of distinguishing potentially injurious events from those that are known to be harmless. For the protection of motor vehicle occupants in frontal collisions, the same data show that an 80 g limit on ATD head acceleration constitutes a rational, attainable and effective performance requirement.

1 INTRODUCTION

The Head Injury Criterion (HIC) has been used for more than twenty years, in North American motor vehicle safety regulations, as a predictor of head injury risk in frontal impacts. In such applications, HIC is calculated from the resultant linear acceleration observed at the centre of mass of the head of an ATD[1], seated in a vehicle that collides with a fixed, rigid barrier. The basic form of the criterion[1][2] is well known and its evolution from the Wayne State Tolerance Curve (WSTC) has been thoroughly reviewed elsewhere.[2]

Despite a number of proposals to change the way HIC is calculated, it has become increasingly clear that the assumed time-dependence of the tolerable average acceleration, which is fundamental to both the WSTC and HIC, inevitably leads to predictions of the risk of

[1]Anthropomorphic Test Device, i.e., an instrumented test dummy

[2]Numbers in square brackets denote references listed at the end of this paper.

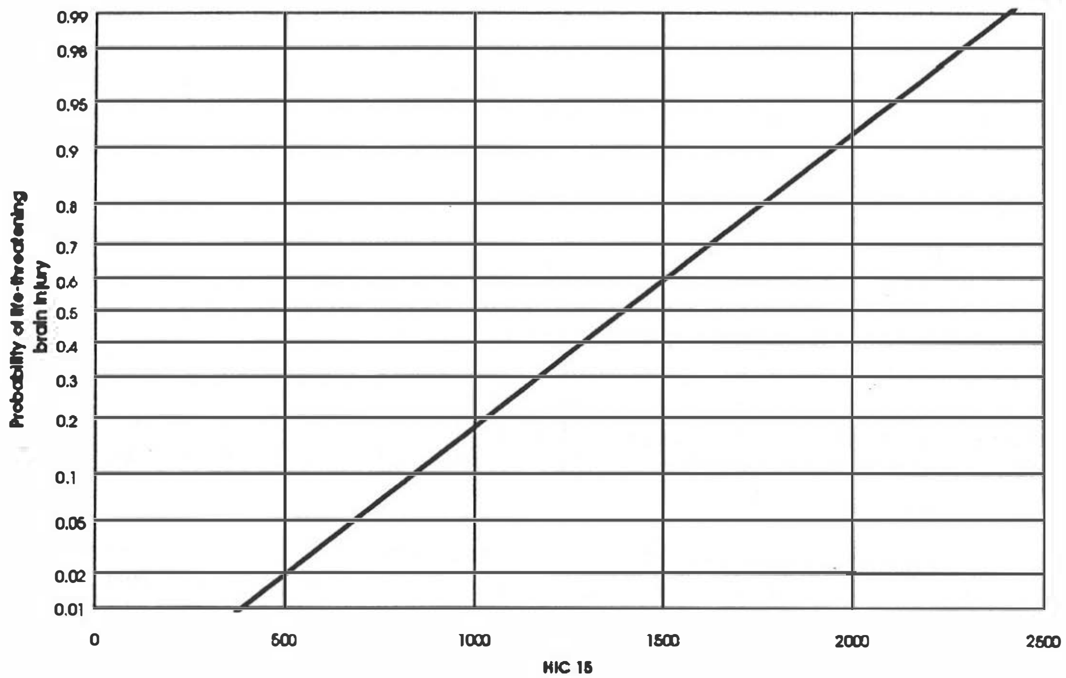
head injury that contradict experience. The assumed time-dependence says that short-duration, high-acceleration events and long-duration, low-acceleration events entail equal risks of closed head injury. Thus, for example, the same risk of head injury is associated with a HIC value of, say, 700, whether it results from an impact to a correctly functioning airbag or to a rigid steering wheel hub. That prediction clearly contradicts common experience, which says unequivocally that the risk of head injury is much greater in the latter case than in the former. (It also denies the basic rationale for the development and use of the airbag.) A HIC value of about 700 may also be observed in a non-contact event, which entails no measurable risk of head injury. However, because of the obvious conflict between the predicted and actual risks in such events, for regulatory purposes, HIC is now deemed to apply only to contact events.

2 THE HEAD INJURY RISK CURVE

2.1 Development

Proponents of the continued use of HIC in regulation commonly cite, as their justification, the existence of the "Head Injury Risk Curve"[3], shown in Figure 1. The curve has its origin in the work of the U.S. Delegation to WG6/SC12/TC22, of the International

Figure 1: The Head Injury Risk Curve



[3]In the interests of brevity, "Head Injury Risk Curve" is abbreviated as "HIRC" in the balance of the paper.

Standards Organization[3]. Given its provenance, and the absence of any more recent work on the subject, it is fair to assume that the paper presents the best case that can be made for the continued use of HIC in motor vehicle safety regulation.

According to the HIRC, a value of HIC of 1400 is associated with a 50 percent probability of life-threatening brain injury, while the regulated limit of 1000 entails a risk of about 18 percent. Those predictions are limited to contact events for which the HIC integration time does not exceed 15 ms.

The development and application of the HIRC may be summarized as follows:

(1) Previously available experimental data on cadaver head impacts were reviewed and those considered acceptable were reanalysed as necessary. Acceleration measurements had been made at two or three locations on the skull of each cadaver. A value of HIC for each subject was extracted from the acceleration data by means that were not described in detail.

(2) The occurrence or otherwise of skull fracture and brain damage in each subject was determined by autopsy and associated with the value of HIC for that subject.

(3) It was then <u>assumed</u> that there existed some underlying normal distribution of "HIC tolerance" in the general population. The parameters of that distribution were determined from the (censored) injury response data by the empirical Mertz-Weber method.[4]

(4) To apply the curve, it is further assumed that a value of HIC 15, <u>determined from an ATD in a frontal collision test</u>, may be used to estimate the probability of life-threatening brain injury to a real vehicle occupant.

2.2 Biomechanical considerations

Newman[2] identified a number of reasons for which the existence of any direct relationship between the value of HIC determined from the response of an ATD head and the risk of injury to a human occupant is, at best, highly improbable. The reasons that bear most directly on the validity of the data and analysis underlying the Head Injury Risk Curve may briefly be recalled.

The head of the Hybrid III ATD consists of an effectively rigid aluminium shell, covered with an elastic, slightly viscous "flesh", and containing a rigidly mounted triaxial accelerometer. The human head is evidently very much more complex. Its mechanical response to impact is, however, determined principally by a skull which behaves essentially as a thin, elastic shell, loosely coupled to the viscoelastic mass of brain tissue that it protects.

An impact to the head of an ATD, such as the General Motors Hybrid III, produces essentially a rigid-body response of the aluminium skull. In contrast, an impact to a human head typically excites an oscillation of the brain within the skull and a damped vibration of the skull itself. Thus, the impact response of a human head differs fundamentally from that of the ATD; it commonly exhibits at least two of the countless non-rigid responses of which it is capable, while the ATD is designed to exhibit none.

It is not, therefore, possible to infer the acceleration of the centre of mass of a cadaver head from two or three accelerometers attached to the skull. Whether or not the skull itself is deforming (or even fracturing), determining the acceleration of the centre of mass of a deforming body requires knowledge of the instantaneous acceleration of every element of the body, not just of several arbitrary points on the skull. Even if the skull does not deform, or skull vibration can be eliminated by filtering, its gross motion is still affected by that of the brain. The biofidelity of the impact response of the Hybrid III head[5] depends largely on the same assumption, i.e., that a useful measure of the resultant acceleration of the centre of mass of the human head can be extracted from accelerometers mounted on a deforming or fracturing skull. Hence, the entire basis of the assumed equivalence between HIC values for cadavers and ATDs is questionable.

A second problem with the HIRC is that the accelerations and the derived value of HIC (however defined and estimated) are _not_ measures of the mechanical input to the cadaver head. The accelerations, the HIC values, and any observed injury, are all _responses_ to an undefined mechanical input, mediated by the characteristics of the individual subject. Any resulting association between the value of HIC and injury is at best an association between two responses of the subject, not between an independently defined input and a corresponding output. Quite independently of the dynamical considerations discussed above, the nature of that association calls in question the relevance of ATD impact response to any possible use of the experimental data.

2.3. Statistical considerations

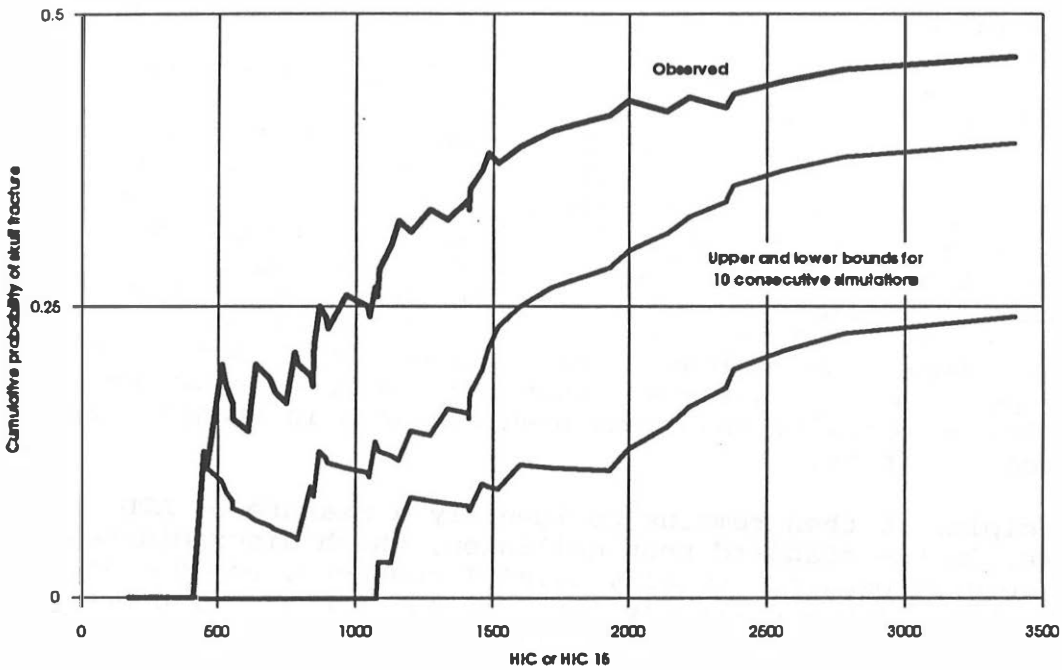
Notwithstanding the immediately preceding point, when, as proposed, a value of HIC measured on an ATD is used to estimate the corresponding probability of injury, it is clearly implied that HIC _is_ considered an independent measure of the mechanical input to the head. Hence, it is of some interest to ask whether the threshold risk curve (HIRC) inferred from the censored experimental data correctly represents those data. Welbourne[6] has addressed that issue in detail elsewhere. Space limitations here allow only a brief account of the approach used and of the principal results.

To test the validity of the HIRC, one may create a hypothetical, ordered sample of n subjects, having the same distribution of "HIC tolerance" as the population represented by the HIRC. The n values of HIC observed in the experiments may then be randomly associated with (i.e.,"applied to") the n subjects in the ordered sample representing the HIRC. If the observed HIC equals or exceeds the "HIC tolerance" of the subject in the sample, that subject is deemed have been injured. Otherwise, it is not.

The simulated experiment can, of course, be repeated indefinitely, with different random ordering of the experimentally determined HIC values. If the proportions of injured and uninjured subjects in the simulations are essentially the same as observed in the original data, then the HIRC fairly represents the original experimental data; if the simulation consistently produces more or fewer injured subjects, it does not.

In Figure 2, the range of results from ten consecutive simulations, with different random ordering of the experimentally observed HIC values, is compared with the experimental data for skull fracture, from which the mean and standard deviation of the HIRC were determined. The cumulative probability of fracture, i.e., the proportion of subjects experiencing skull fracture at less than or equal to the stated value of HIC 15, for the original data, is represented by the heavy line. The range of results from the ten consecutive random simulations falls between the two lighter lines shown in the figure. It can be seen that the overall fracture rate

Figure 2: Experimental skull fracture data and results predicted by the Head Injury Risk Curve



in the simulated experiments is between about 50 and 85 percent of that observed experimentally. Thus, the HIRC of Figure 1 consistently underestimates the probability of skull fracture in the data from which it was inferred. A median HIC value for the Head Injury Risk Curve in the 1200 range would probably represent the data more accurately than the value of 1400 obtained by the Mertz-Weber procedure.

2.4 Validity of the Head Injury Criterion

The foregoing discussion should leave little doubt that presumptively the best experimental evidence for the use of HIC depends on questionable interpretations of experimental data, flawed logic and unsubstantiated assumptions. Most importantly however, as observed in the Introduction, HIC fails the most basic scientific test of all: experience directly contradicts its predictions of the risk of head injury.

As a measure of the risk of head injury to motor vehicle occupants, HIC has no predictive value. Accordingly, if that risk is to be reduced, it is essential that future regulations be based on performance measures that, unlike HIC, are demonstrably correlated with the risk of head injury.

3 A VEHICLE PERFORMANCE REQUIREMENT TO REDUCE HEAD INJURY

3.1 Motor vehicle accident data

The single most important observation about head injury in real automobile collisions is the strong association of head injury with head contact, particularly contact with stiff surfaces or structures. It follows that if frontal crash performance requirements precluded such contacts, a marked reduction might be expected in the incidence of head injury in real collisions.

While reviewing the risk of neck and cervical spinal injuries to occupants restrained by seatbelts, Huelke and collaborators[7] incidentally provided a convincing review of the association between head contact and head injury. From a comprehensive review of both clinical studies and accident data from a wide range of sources, they concluded that: "Head injuries of restrained occupants in frontal collisions in which head contact does not occur are extremely rare". Moreover, in the few cases where non-contact head injury apparently occurred, it was always of minor severity. Such observations provide the essential basis for a vehicle performance requirement that reduces head injury by precluding potentially injurious head contacts in standard vehicle certification tests.

In principle, it then remains to identify a measure of ATD response, in the standard test collision, which discriminates effectively between potentially harmful contacts, and contacts, such as those with a correctly functioning airbag, which are associated with essentially the same low risk of head injury as non-contact events.

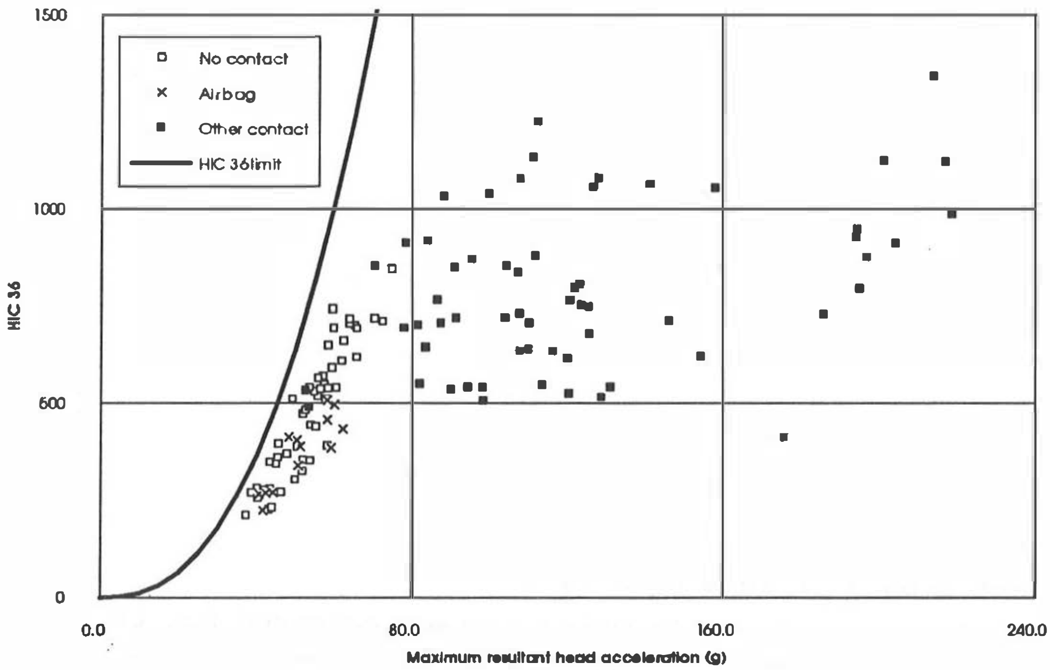
3.2 ATD head response in frontal barrier collisions

Figure 3 shows the results of more than 60 frontal impact tests, conducted by Transport Canada, at 48 km/h into a full-width rigid barrier. All measurements were made on restrained Hybrid III ATDs, seated in the front outboard seating positions of the passenger vehicles tested.

For each ATD, the figure shows the value of HIC, calculated for a maximum time interval of 36 ms or less, plotted against the corresponding value of the maximum resultant head acceleration. Three classes of head acceleration event are identified by the symbols. The **open squares** (□) denote **non-contact events**, in which the head of the ATD did not strike anything in the vehicle interior. It can be seen that all 51 such events produced maximum accelerations of less than 80 g, and, incidentally, HIC values of less than 1000. All the non-contact events pertain to passenger ATDs restrained by three-point seat belts.

Crosses (x) denote **contacts with airbags**. At the time of writing, ten vehicles equipped with airbags had been tested in the standard frontal barrier collision, three with dual airbags. Again, it can be seen that in all 13 cases, the maximum resultant head acceleration was less than 80 g and HIC less than 1000.

Figure 3: Restrained occupants in frontal barrier collisions at 48 km/h (n=135)

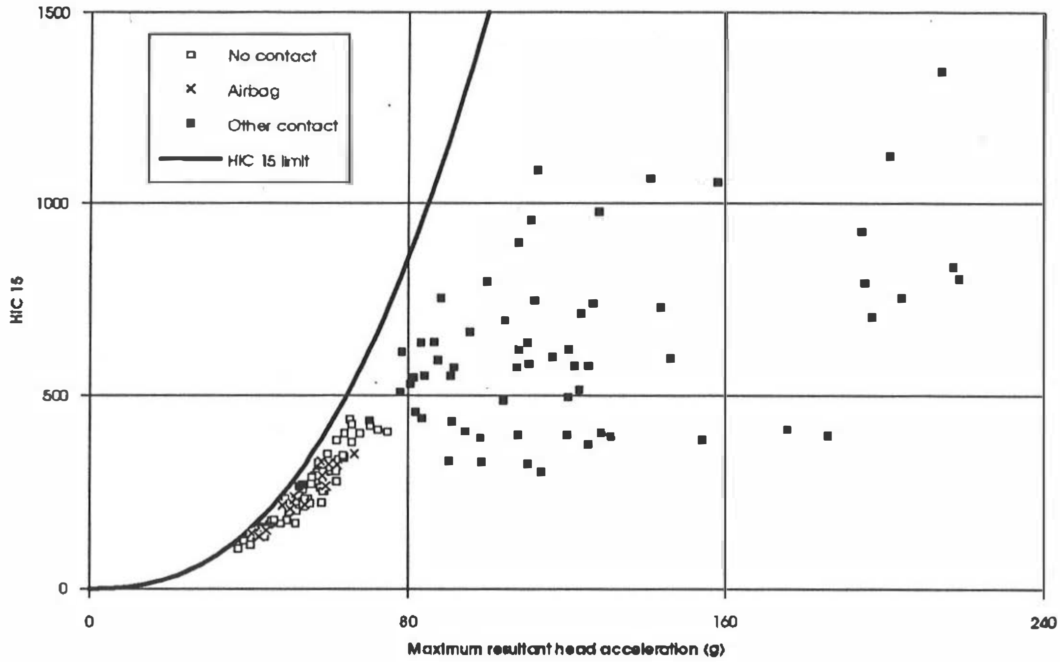


Finally, the **solid squares** (■) denote **other head contacts**. It will be observed that all but five such contacts resulted in maximum head accelerations exceeding 80 g. However, the majority of those contacts also resulted in "acceptable" values of HIC, i.e., values of less than 1000.

These data suggest that a limit of 80 g on the maximum resultant head acceleration of a Hybrid III ATD distinguishes harmful from essentially harmless head acceleration events. Transport Canada therefore proposes to adopt such a requirement, in the final version of CMVSS 208, to protect vehicle occupants against head injury in frontal collisions.

It is important to note that if the HIC integration interval is limited to 15 ms instead of 36 ms, it has no effect whatever on the measure's ability to distinguish soft or non-contact events from hard, short duration events associated with a high probability of closed head injury. The sole effect of reducing the integration time is to reduce the numerical value of HIC for those events for which the interval was previously between 15 and 36 ms. In Figure 4, the results of the same tests as shown in Figure 3 are reproduced using HIC 15 as ordinate.

Figure 4: Restrained occupants in frontal barrier collisions at 48 km/h



3.3 Contact events of less than 80 g

In considering those cases in which contact occurred but the maximum acceleration was less than 80 g, two points should be noted. Firstly, it will be seen that the maximum non-contact head acceleration resulting from restraint of the torso by the three-point belt falls typically in the range from 40 to 70 g. Head contact with the vehicle interior is most likely to occur within a few milliseconds of the maximum acceleration induced by the restraint system, when the ATD head excursion is also near its maximum. The magnitude of the external force input to the ATD head that can occur without exceeding the 80 g limit is therefore quite modest. Where such contact events can be identified on the resultant head acceleration trace, they typically have a duration of about 3 ms and produce an acceleration increment of about 20 g. Often however, though paint transfer between the ATD head and the vehicle has occurred, the contact event can not be identified on the acceleration trace.

The second, and perhaps more important, point is that none of the vehicles in which such events occurred were designed to meet an 80 g head acceleration limit. The intent, and the expected result, of such a requirement is that head contact with anything but an airbag will be avoided entirely. The expected incidence of such events in vehicles designed to comply is very low. Most, if not all, will be equipped with airbags. Those that are not, may be expected to combine improvements in the performance of the primary restraint system with sufficient free head excursion to assure repeatable non-contact head response.

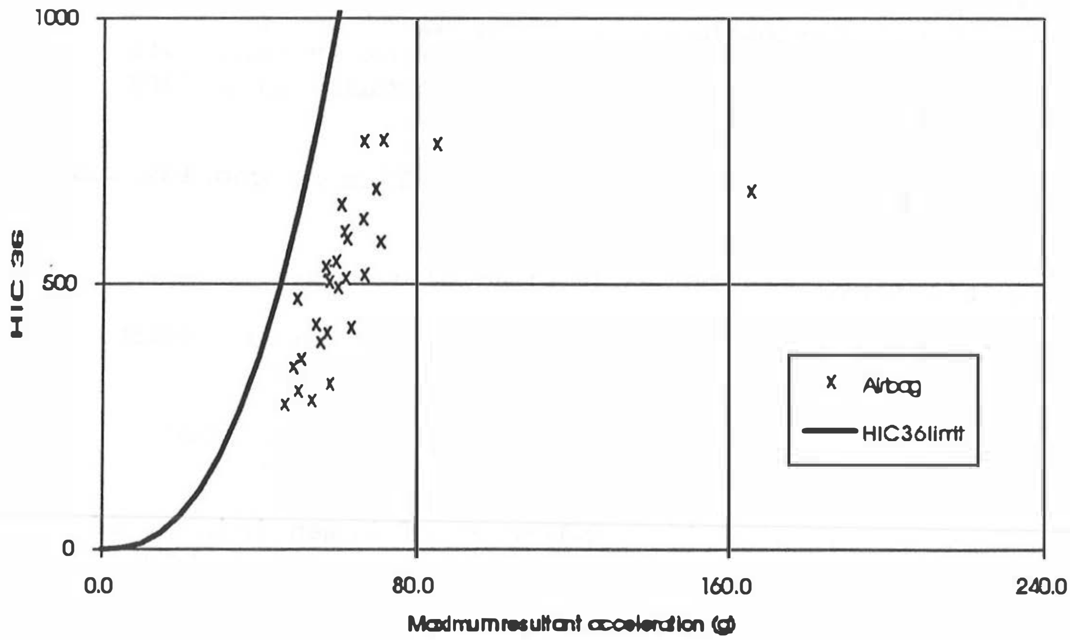
3.4 Non-contact events exceeding 80 g

The principal reason for maintaining the 80 g limit when no head contact occurs, is to limit the risk of neck injury associated with seatbelts that promote the development of high neck forces. As noted by Dalmotas and Welbourne[8], a resultant head acceleration of 80 g is consistent with the limit of 3.3 kN, suggested by Mertz[9], for the tolerable tensile force in the neck.

3.5 Relevance of the requirement to vehicles equipped with airbags.

The data presented above suggest that, if all vehicles were equipped with airbags, the advantages of the 80 g limit with respect to HIC would be moot. Although all vehicles for the North American market will very probably be fitted with airbags, itremains to be seen whether the rest of the world follows North America in that respect. In particular, it is difficult to justify

Figure 5: Restrained occupants with airbags in frontal collisions at 56 km/h (n=28)



the cost of mandating passenger airbags where seatbelt usage exceeds 90 percent or so. A more modest investment in improving lateral impact protection would provide greater benefits. Where a passenger bag is not present, the considerations of Section 3.3 would apply.

However, the 80 g limit distinguishes airbag malfunctions that HIC can not. The data shown in Figure 5 derive from the U.S. New Car Assessment Program (NCAP) of frontal barrier collisions at 56 km/h.

Two cases in which the maximum head acceleration exceeded 80 g will be noted. In the more serious event of the two, the ATD head struck the hardware behind the deployed airbag, producing an "acceptable" HIC of 674, but a head acceleration of 165.7 g. The acceleration limit is also sensitive to high airbag deployment speeds, which may be associated with an increased risk of concussion or facial injury. In such a case, also shown in Figure 5, HIC was 762 and the maximum acceleration, 85.2 g.

3.6 Rebounds

In about six percent of Transport Canada tests, the maximum resultant head acceleration occurred as the ATD rebounded, striking the B-pillar, the side glass or the seat. About half such rebounds resulted in maximum accelerations exceeding 80 g. The indeterminate biofidelity of the ATD in impacts to other than the frontal region of the head effectively precludes the regulation of such events. Moreover the motion of the ATD, some 100 ms or more after initial vehicle-to-barrier contact, is likely to be quite unpredictable. No rebounds are represented in Figures 3,4 or 5.

4 CONCLUDING NOTE

The proposed limit of 80 g on resultant head acceleration is arguably founded on a much firmer base of biomechanical data than the Head Injury Criterion has ever been, since it is consistent with a large body of evidence from live humans in real collisions. However, it should not be considered a biomechanical injury criterion in the conventional sense.

Specifically, the use of the 80 g limit implies no conclusions as to:

(1) human tolerance for linear head acceleration;

(2) the relevance of either angular acceleration or impact duration to human head injury;

(3) desirable or attainable levels of ATD or human head accelerations in other collision environments; or

(4) the general validity, as predictors of human injury, of kinetic (rather than dynamic) measures of ATD response.

The 80 g limit is to be regarded simply as a practical means of distinguishing acceleration events entailing a very small risk of human head injury from those associated with a much higher (though still indeterminate) risk in frontal crash tests.

The only assumption implicit in the use of the 80 g limit is that the ATD kinetic response to the vehicle crash pulse and restraint forces is sufficiently humanlike for regulatory purposes. That assumption underlies any use of an ATD to measure vehicle performance in a crash test.

Finally, the 80 g limit does not eliminate the need for a reliable means of predicting head injury risk in the many practical circumstances where head contact can not be prevented.

5 ACKNOWLEDGMENTS AND DISCLAIMER

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6 REFERENCES

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