

ON THE APPLICATION OF THE HIC AS HEAD PROTECTION CRITERION

E. Faerber
Bundesanstalt für Strassenwesen (BAST)
Bergisch Gladbach

and

F. Kramer
Institut für Fahrzeugtechnik
Technische Universität Berlin
Federal Republic of Germany

ABSTRACT

The WSU tolerance curve describes the relationship between effective acceleration and time duration of effective acceleration for brain injury in forehead impacts. This relationship represents impacts against plane, unyielding surfaces. The HIC was developed to rate resultant dummy head accelerations according to the WSU tolerance curve. In the ECE/GRCS draft regulation concerning occupant protection in frontal passenger car impacts, a head protection criterion (HPC) is now being considered which limits the application of HIC in the case of dummy head impact.

In this paper, problems of HIC application in crash testing are discussed.

1. OBJECTIVES

Since the introduction of head loading criteria such as the 3 ms acceleration value, severity index (SI) and in particular the head injury criterion (HIC), the discussion as to the expediency of these injury criteria has not been concluded /1, 2/*.

Based on this literature, the types of injury and the injury mechanism during head loading are described below. In addition, measuring and mathematical problem areas are indicated which must be taken into consideration during practical application of the HIC in evaluating head loadings.

2. The BIOMECHANICAL ASPECT

Efforts have been and are being made worldwide to investigate the mechanisms of head injuries resulting from accidents. These efforts can be traced back to the middle of the 19th century when the development of characteristic values to describe head injuries arising from the effect of force were studied for the first time, see e.g. the literature study /3/.

The difficulties involved in solving this problem are due first and foremost to the fact that direct measurement of mechanical variables cannot be carried out on a living person at a sufficiently high load. For this reason, steps were taken to investigate this phenomenon based on carefully recorded accident data. Tests were carried out with human and animal corpses and with

* Numbers in parentheses designate references at the end of the paper

living animals fitted with transducers, whereby the head was subjected to a specific impact or deceleration. In addition to measuring the accelerations, the motion patterns were analyzed using high-speed film.

2.1 TYPES OF LOADING

The head of the vehicle occupant is subjected to dynamic loadings during an accident. Depending on whether the head makes contact with parts of the vehicle or not, the head is subjected to loading from the impact forces or from the inertia forces via neck forces.

Impact and inertia forces generally induce head movements comprising both translatory and rotatory components, thus resulting in corresponding accelerations. Rotatory acceleration components almost always occur because:

- The freely moving head follows curved paths as a result of restraining forces of the trunk via the neck
- The resulting impact force due to the irregular contours of the skull passes only in the most seldom of cases through the centre of gravity of the head over the entire period of impact.

2.2 TYPES OF INJURY

Injuries to the head are differentiated into skull and brain injuries. If forces and torques are transferred solely through the cervical spine, injuries to the skull can be excluded. Impact forces, on the other hand, can cause both skull and brain injuries.

2.2.1 SKULL INJURIES

With skull injuries, distinction is normally made between indirect fractures and depressed fractures of the skull. Indirect fractures occur where forces are exerted over large areas causing opposite oscillations between the half of the skull on the side of contact and the half of the skull away from the point of contact (anti-resonance at 300 to 360 Hz). Depressed fractures are the result of hard blows to small areas: The part of the skull on the side of contact oscillates at high amplitude whilst the part of the skull away from the point of contact is relatively undisturbed (resonance at approx. 900 Hz) /4/.

2.2.2 BRAIN INJURIES

Studies of road traffic accidents /5/ have shown that brain injuries only occur when the head makes impact with parts of the vehicle. Brain injuries include concussions, haemorrhages, contusions and crushing in the area nearest to the point of contact resulting from compressions, and also ruptures as a result of depressed skull fractures.

A further phenomenon in brain injuries are "contrecoup" injuries. They occur on the opposite side of the brain from the point of contact when the vapour pressure of the tissue fluid is too low, causing gas bubbles dissolved in the brain to expand /6/.

The above-mentioned injuries are observed primarily where translatory loadings predominate. Rotatory loading of the head normally results in widespread brain haemorrhages due to ruptures of the pontine veins induced by inertia-related relative movements between skull and brain /7/.

In more recent studies /8/, serious brain injuries with fatal consequences are differentiated into subdural hematoma (SDH) and diffuse axonal injury (DAI). These two types of injury have different causes. SDH occurs primarily in falls, whilst DAI occurs almost exclusively in vehicle collisions. Both types of injury occur under the same mechanical load, but which differs only in its intensity; quotation from /8/:

"Subdural hematoma is due to vascular injury that is caused by relatively short duration angular acceleration loading at high rates of acceleration. These are the circumstances that occur in falls where the head rapidly decelerates because of impact to firm, unyielding surfaces. DAI is also due to angular acceleration of the head, but occurs most readily when the head moves coronally and it only occurs when the acceleration duration is longer and the rate of acceleration lower than conditions that produce SDH. These conditions are met in vehicle occupants where impact to deformable or padded surfaces lengthen the deceleration and decrease its rate. In DAI the principal mechanical damage is to the brain itself (mainly to axons) while in SDH the primary damage occurs to surface blood vessels."

If one accepts the results of this study, then the translatory acceleration of the head is of lesser importance, at least for the more serious brain injuries. In contrast to this, however, is the fact that nowadays measurements conducted during safety crash tests on dummies are restricted almost exclusively to translatory accelerations. On the other hand, it is concluded in /7/ from a number of studies that local effects of impact clearly reduce the tolerance level of the brain compared with rotational accelerations.

2.3 INJURY-RELEVANT PHYSIOLOGICAL PARAMETERS

Since studies of head injuries were first started, the wide range of influencing factors has caused very great difficulties in relating injuries to mechanical loading factors when determining, for example, the protection criteria. But even if the mechanical influences are held constant, the physiological differences between the victims of road traffic accidents are very wide ranging. Of the parameters: Body size, constitution, sex and age of the vehicle occupants, the size of the body determines the point of contact in the vehicle and, as a result of the close relationship between size and weight, the energy content of the part of the body to be decelerated. For head injuries, age is a dominant factor, whilst the sex of the occupant and the other parameters are of minor importance. The effect of age can be even greater for the seriousness of the injury than the effect of the relative speed /9, 10/. For chest injuries (rib fractures), a factor was developed for age characterization of bones (BCF = bone condition factor) /10/ which, if applied analogously to the bones of the skull, could sharply reduce the age-related variance of injuries under equal load.

2.4 INJURY SEVERITY LEVELS

Whilst determining an acceptable injury severity level for the head, a distinction is drawn on the one hand between dangerous to life and not dangerous to life (WSU curve) and on the other hand, a line is drawn between reversible and irreversible injuries /12/.

With the introduction of the "abbreviated injury scale" (AIS) in 1971 and the revision in 1980, an injury coding system has been established.

However the AIS coding only covers the traumatological assessment of injuries at the scene of an accident. It does not take into consideration the long-term consequences of the injuries, for example succeeding severity increase. This situation is indicated separately by the introduction of the lethality rate in /13/. According to this rating, 16% of those victims with AIS3 injuries and 4% of those with AIS2 injuries died. With a rough classification, the border between reversible and irreversible head injuries lies between AIS2 and AIS3, whilst the border between dangerous to life and not dangerous to life is more likely to lie between AIS3 and AIS4. If one takes into consideration the consequences of the injury severity levels mentioned above, the acceptable limit should be set between AIS2 and AIS3.

2.5 INJURY CRITERIA/PROTECTION CRITERIA

In the following, the terms: Injury criteria, injury criteria levels, human tolerance levels, protection criteria, protection criteria levels and performance criteria limits will be used as defined in /14/. These definitions were developed as part of the EEC biomechanics program. To date, these terms have not been applied uniformly in biomechanical research.

The most important head injury and protection criteria are classified in Table 1 from /15/. SI and HIC use the resulting acceleration of the head as the injury criterion whilst at the same time also using it as the protection criterion.

| SI | HIC | JTI | RBM | EDI | MSC |
|--|--|---|---|--|--|
| SEVERITY INDEX (GADD) | HEAD INJURY CRITERION (VERSACE & NHTSA) | J-TOLERANCE INDEX (SLATTENSCHER) | REVISED BRAIN MODEL (FAN) | EFFECTIVE DISPLACEMENT INDEX (BRINN) | MAXIMUM STRAIN CRITERION (STALNAKER) |
| Weighted Impulse of a(t) $SI = \int_0^T a(t) ^{2.5} dt$ Time in seconds Acc. in g.msec. | Weighted Impulse of a(t) $Let \bar{a}_{11} = \frac{\int_{t_1}^{t_2} a(t) dt}{t_2 - t_1}$ $HIC = \left\{ \max_{t_1, t_2} \left[\bar{a}_{11}^{1.5} (t_2 - t_1) \right] \right\}^2$ $0 < t_1 < t_2 < T$ | $\omega_n = \sqrt{k/m} \quad (rad/sec)$ $\beta = c/c_c$ $\omega_n = 635.$ $\beta = 1.0$ | $\omega_n = 175.$ $\beta = 0.4$ | $\omega_n = 482.$ $\beta = 0.707$ | $m_1 = 0.6 \text{ (lbs)}$ $m_2 = 10.0 \text{ (lbs)}$ $c = 2.0 \text{ (lb-sec/in)}$ $k = 50000. \text{ (lb/in)}$ |
| $S_{1, tot} = 1500$ | $HIC_{1, tot} = 1000$ | $J = \frac{x_{max}}{0.0735} \cdot \frac{in}{in}$ $J_{1, tot} = 10$ | $T < 10ms \quad T > 10ms$ $\dot{x}_{1, tot} = 135.3 \frac{in}{sec} \quad x_{1, tot} = 1.25 \text{ in}$ | $x_{1, tot} = A-P \quad RES.$ HUMAN: 0.15 in 0.18 in DUMMY: 0.17 in 0.2 in | $\epsilon = x_{max}/l$ HUMAN: $\epsilon = 5.75 \text{ in(A-P)}$ $\epsilon_{1, tot} = 0.0061 \text{ in/in}$ |

Table 1:

Summary of some injury criteria and protection criteria levels (mechanical models \approx dummies) from /15/

The value HIC = 1000 is the performance criterion limit of US FMVS standard 208. The other four criteria (JTI, RBM, EDI, MSC) use deformations and deformation speeds as the injury criteria.

2.6 HEAD INJURY CRITERION (HIC)

The HIC (and the other criteria) are based on the "Wayne State University Cerebral Concussion Tolerance Curve", which depicts a limit between dangerous to life and not dangerous to life head loadings, see Figure 1.

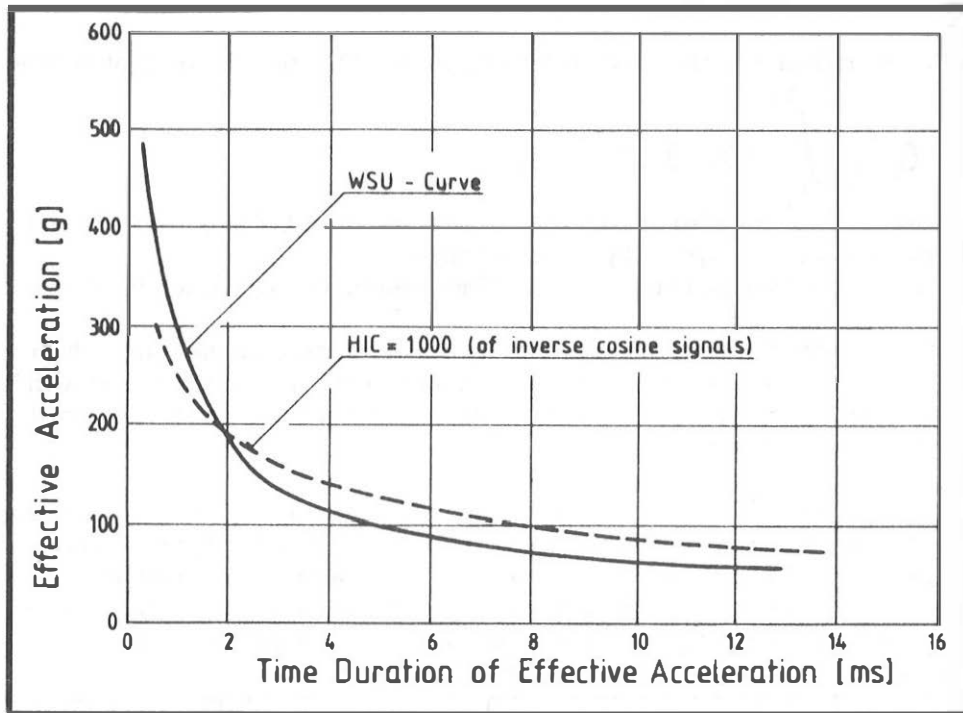


Figure 1:
Comparison WSU tolerance curve-HIC = 1000 calculated for inverse cosine signals, from /16/

The WSU curve thus draws a dividing line for pairs of values for effective translatory head acceleration and pulse duration.

The complete acceleration/time tolerance field for concussions resulting from frontal collisions was obtained by taking into consideration a very wide range of test data. The limit values for brief duration impacts (up to approx. 10 ms) were obtained from skull impact tests of human and animal corpses against a steel plate. The accelerations of longer duration were measured on volunteers below the injury threshold.

The Wayne State Curve was empirically approximated using the formula:

$$\bar{a}^{2.5} \cdot \Delta t = 1000 \quad (\text{where } \bar{a} = \text{effective acceleration and} \\ \Delta t = \text{time duration of the acceleration pulse})$$

From this formula, the HIC was initially defined as follows:

$$\left(\frac{1}{\Delta t} \int_{\Delta t} a dt\right)^{2.5} \Delta t \quad \text{with the limit value 1000.}$$

In /17/, the fact is criticized that for certain acceleration patterns, the HIC values calculated for part intervals could become greater than the values calculated over the entire duration.

For this reason, interval limits t_1 and t_2 were introduced to the complete measured acceleration pattern.

The currently valid version of the HIC introduced by the NHTSA in FMVSS 208 is:

$$\text{HIC} = \text{maximum} \left| \left(\frac{1}{t_2 - t_1} \int_{t_1}^{t_2} a(t) dt\right)^{2.5} (t_2 - t_1) \right|$$

where "a" is the resultant acceleration expressed as a multiple of "g" and "g" is the acceleration due to gravity, and either

(i) " t_1 " and " t_2 " are any two points in the time measured in seconds during the impact, or

(ii) " t_1 " and " t_2 " are any two points in the time measured in seconds during any interval when the head is in continuous contact with a part of the vehicle other than the seat belt system when the anthropomorphic test device is restrained by a seat belt system.

The limit value was set at 1000. Paragraph (ii) is currently not in force; it applied only for a specific time span and specific vehicle types. The limit HIC = 1000 is only a rough approximation of the WSU tolerance curve. Figure 1 is intended to illustrate this fact: In addition to the WSU curve, this figure also shows the HIC = 1000 limit curve for the mathematically simple pulse shape of the inverse cosine, see Table 2.

| Pulse Shape Parameter | Square | Triangle (Isosceles) | Half Sine ($A \cdot \sin \omega \cdot t$) | Inverse Cosine ($-A \cdot \cos \omega \cdot t + A$) |
|--------------------------|---|---|---|---|
| t_1 | 0 | $0,2143 \cdot T$ | $0,1651 \cdot T$ | $0,2462 \cdot T$ |
| t_2 | T | $0,7857 \cdot T$ | $0,8349 \cdot T$ | $0,7538 \cdot T$ |
| HIC | $a_{\max}^{2.5} \cdot T$ | $0,2464 \cdot a_{\max}^{2.5} \cdot T$ | $0,4146 \cdot a_{\max}^{2.5} \cdot T$ | $0,3250 \cdot a_{\max}^{2.5} \cdot T$ |
| HIC = 1000 | $a_{\max} = 15,85 \cdot T^{-0,4}$ $T = 1000 \cdot a_{\max}^{-2,5}$ | $a_{\max} = 27,76 \cdot T^{-0,4}$ $T = 4058 \cdot a_{\max}^{-2,5}$ | $a_{\max} = 22,54 \cdot T^{-0,4}$ $T = 2412 \cdot a_{\max}^{-2,5}$ | $a_{\max} = 24,85 \cdot T^{-0,4}$ $T = 3077 \cdot a_{\max}^{-2,5}$ |

a_{\max} = maximum acceleration in g

T = pulse duration in s

Table 2:

HIC calculation formula for some acceleration pulse shapes

For the other signal shapes shown in Table 2, this applies also in principle.

3. THE MEASURING ASPECT

In the analysis of the effects of the components of the measuring equipment on the HIC values, calibration of the accelerometer and filtering of the recorded signals were expected to exert the greatest influence.

3.1 ACCELERATION MEASUREMENT

Generally, translational acceleration is measured using transducers based on the Piezo effect. A universally applicable special rotation angle transducer is not yet available since in collision tests, the point of rotation of the body to be measured is not known in advance and, furthermore, this position normally changes during the measurement.

The measurement of combined translatory and rotatory accelerations must therefore be carried out using a suitable layout of several translatory acceleration transducers. For minimum requirements, six transducers are sufficient, but where higher demands are made on the measuring accuracy, at least nine transducers must be used.

The application and calibration of acceleration transducers are standardized in SAE J211 and ISO 6487. The ISO standard, in particular, makes high demands on the calibration of the transducers. Normally, shakers and/ or impact pendulums are used to generate acceleration signals. By performing comparisons with reference transducers, the acceleration transducer to be calibrated can normally only be tested at low accelerations - but over a wide frequency band - on the shaker, and at high accelerations on the impact pendulum. With the impact pendulum test the frequency pattern is calculated in a Fourier analysis. Observation of the acceleration transducers has shown that due to their high natural frequency (normally higher than 5 - 7 kHz) problems seldom occur in the frequency pattern. With the increasing use of digital measuring data transmission and storage, errors arising in the modules which perform these functions are now almost negligible.

3.2 EFFECTS OF FILTERING

The separation of the useful signal from possible interference signals is achieved by low-pass filtering. According to recommendation SAE 211 b, the "channel class 1000" is used for head accelerations. Here, the frequency range from 0.1 to 1000 Hz is regarded as the linear range. For higher frequencies, a wide range of signal damping is permitted. In metrology, selection of a suitable filter is a major problem. Particularly with the shapes of crash test acceleration signals with their often relatively high and brief peaks, the recorded signal is seriously affected by the filter characteristics - particularly with analog filters, see Figure 2 for examples.

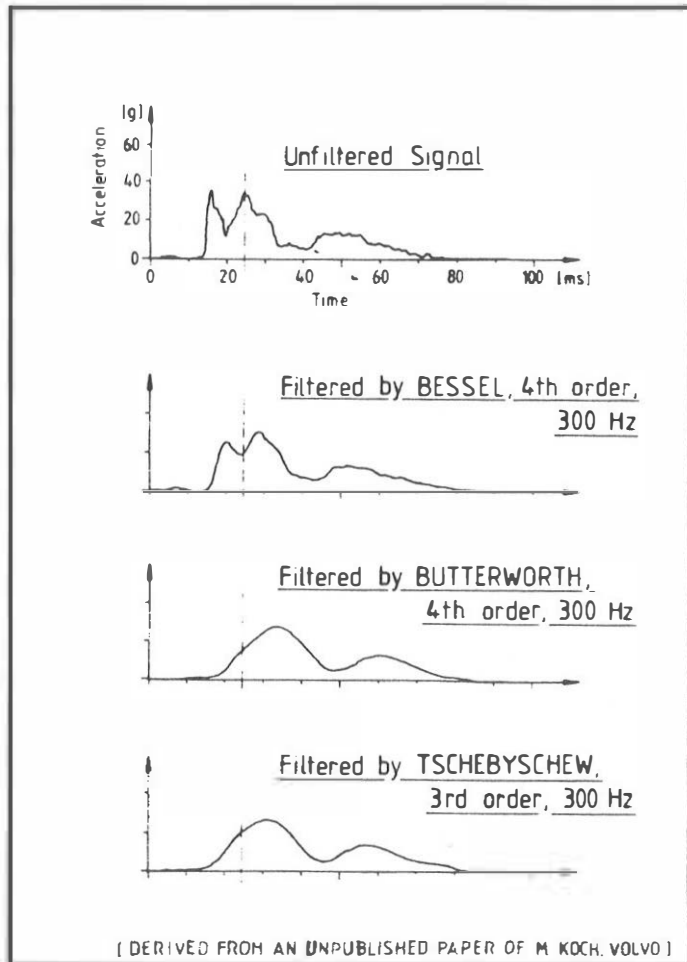


Figure 2:
Influence of analog filter characteristics on pulse shape

In order to further investigate this problem, the HIC formula was applied to a number of mathematically simple pulse shapes. The equations are shown in Table 2. It is apparent that for similar HIC values - e.g. 1000 - the acceleration duration is of greater importance than the maximum acceleration. This fact was a first indication that filter characteristics do not have any great effect on the HIC value. In a first attempt, high frequency acceleration signals were filtered through various filters. This unsystematic investigation proved that the various filters only caused insignificant changes to the HIC values. In the meantime, an unpublished study from Volvo which deals with the same problem has come to our notice. This showed that crash signals are considerably modified by analog filters (with decreasing limit frequency, the maximum values decrease; with differing filter characteristics and filter slopes, the phase shifts of the frequency components of the acceleration signals are changed), but that the HIC values are only insignificantly (3 - 5%) changed down to limit frequencies of 100 to 150 Hz.

The change caused in the HIC values by digital filters was investigated in a thesis from the TU Berlin /16/. With decreasing limit frequencies, digital filters produce decreasing maximum amplitudes but scarcely any phase shift,

see Figure 3.

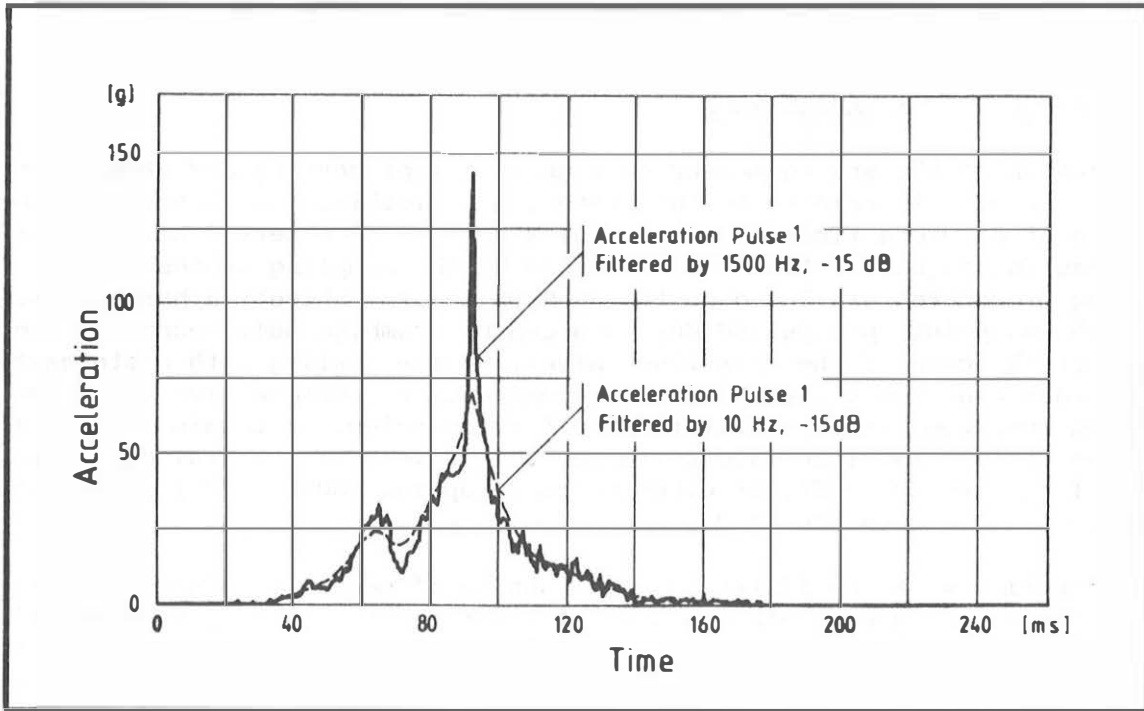


Figure 3:
Influence of digital filtering on pulse shape

Table 3 shows the calculated values for a selected set of digital filters applied on acceleration pulse 1, see Figure 3.

| Cut-off frequency [Hz] | Damping [dB/oct] | Acceleration pulse 1 according to fig. 3 | | | | | | | | |
|---|------------------|--|----------------|----------------|---------------------|----------------|----------------|---------------------|----------------|----------------|
| | | step width 0,1 [ms] | | | step width 0,1 [ms] | | | step width 0,1 [ms] | | |
| | | HIC T | t ₁ | t ₂ | HIC VW | t ₁ | t ₂ | HIC E | t ₁ | t ₂ |
| 1 715 | - 29,2 | 405 | 78,4 | 99,0 | 405 | 67,6 | 106,2 | 405 | 78,3 | 99,1 |
| 1 715 | - 9,0 | 405 | 78,4 | 99,0 | 405 | 67,6 | 106,2 | 405 | 78,3 | 99,1 |
| 1 470 | - 24,0 | 405 | 78,4 | 99,0 | 405 | 67,1 | 105,6 | 405 | 78,3 | 99,1 |
| 1 150 | - 7,7 | 406 | 78,4 | 99,0 | 406 | 67,6 | 106,2 | 405 | 78,3 | 99,1 |
| 100 | - 150,0 | 407 | 79,4 | 98,1 | 407 | 79,4 | 98,1 | 406 | 78,9 | 98,2 |
| 100 | - 999,0 | 408 | 79,1 | 98,5 | 408 | 79,1 | 98,5 | 408 | 78,8 | 98,5 |
| 1 500 | - 15 | 406 | 78,4 | 99,0 | 406 | 67,6 | 106,2 | 405 | 78,3 | 99,1 |
| 1 000 | - 15 | 406 | 78,4 | 99,0 | 405 | 67,0 | 105,6 | 405 | 78,3 | 99,1 |
| 750 | - 15 | 405 | 78,4 | 99,0 | 405 | 67,6 | 106,2 | 405 | 78,3 | 99,1 |
| 500 | - 15 | 405 | 78,4 | 99,0 | 405 | 66,7 | 102,3 | 405 | 78,8 | 99,1 |
| 200 | - 15 | 405 | 78,5 | 99,0 | 405 | 66,7 | 102,3 | 405 | 78,5 | 99,1 |
| 100 | - 15 | 405 | 78,9 | 98,9 | 405 | 78,9 | 98,9 | 405 | 78,8 | 98,9 |
| 10 | - 15 | 379 | 81,5 | 100,9 | 379 | 76,6 | 102,8 | 377 | 74,4 | 103,3 |
| Mean CPU time per HIC calculation [min:sec] | | 15 : 37 | | | 0 : 14 | | | 0 : 10 | | |

Table 3: HIC values of acceleration pulse according to Fig. 3, calculated for different digital filters. Additionally, three different calculation procedures are tested: HIC T: All samples are combined with each other, HIC VW and HIC E: iterative calculation procedure according to /WAGNER/ applied by VW and TUB (quoted from /MORRES/).

At the same time, various methods of calculation which were discussed below were tested. Table 3 shows clearly that digital filters with limit frequencies as low as 100 Hz modify the HIC value only insignificantly.

3.3 EFFECTS OF THE SAMPLE RATE

Digitization of the analog measuring signals for processing and storage in a computer is closely related to the filtering. Digitization is performed by scanning at discrete times. Certain rules have to be observed here, since the measuring signal must not be distorted by the sampling process. The sampling procedures are based on the SHANNON theorem whereby a harmonic signal with two points per period duration can be unambiguously reconstructed. Since, in the case of the measuring values, we are dealing with a stochastic rather than a harmonic signal, it is recommended to perform five times the scanning compared with the filter cut-off frequencies. According to SAE J 211, the minimum sampling rate corresponds to five times the value of the filter frequency at -3 dB, in other words at approx. 8000 Hz during acceleration measurements on the head.

In conjunction with the filtering and scanning of measuring signals, mention should be made of one possible source of error which is normally underestimated and therefore ignored; this is the "aliasing" effect. Errors due to this effect can achieve a magnitude which considerably impairs the measuring accuracy.

The aliasing effect occurs with every sampling process based on a periodical sampling from a continuous process.

This effect can be prevented using anti-aliasing filters; these low-pass filters with a falling flank steepness of 24 or 30 dB per octave (filter of fourth or fifth order) adequately limit the band of the measuring signal.

To return to the effects of digitization rates on the HIC values of crash signals: As with filtering, the effect is low. By reducing the scanning rate from 8000 Hz to 1000 Hz during evaluation of acceleration signals measured during collision tests, the changes in the HIC values were less than 2%.

The deviations for irregular, mathematically formulated signals were higher. Figure 4 shows an example of the evaluation for a synthetic curve with a triangular fundamental oscillation and superimposed triangular peak. The distances between the peaks were generated by a random number generator. The reduction in the sample rate was achieved by stepwise omitting every second value. The spread with the low sample rate was achieved by calculating once with the omitted values and once with the values to be used.

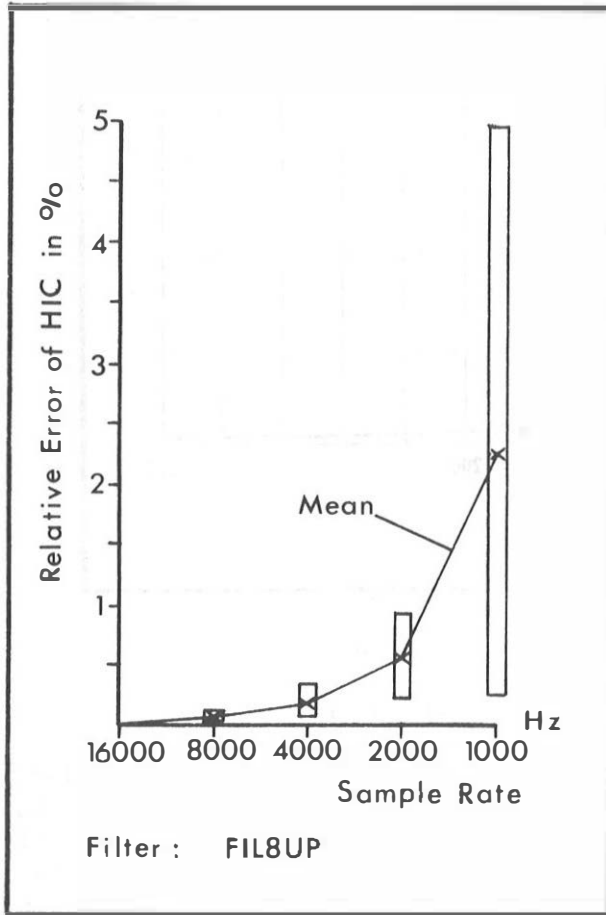


Figure 4:

Relative deviation of HIC values calculated for different sample rates for an irregular synthetic pulse shape: Basic triangle superimposed by triangular peaks, distances between peaks stochastic

The reason for the negligible effect of considerable reductions in filter limit frequencies and sample rates becomes clear when one considers the amplitude spectra of unfiltered crash signals. Figure 5 shows the spectrum of the measuring signal from Figure 3. Above approx. 100 Hz, the measuring signal shown as an example contains only frequency components with low amplitudes.

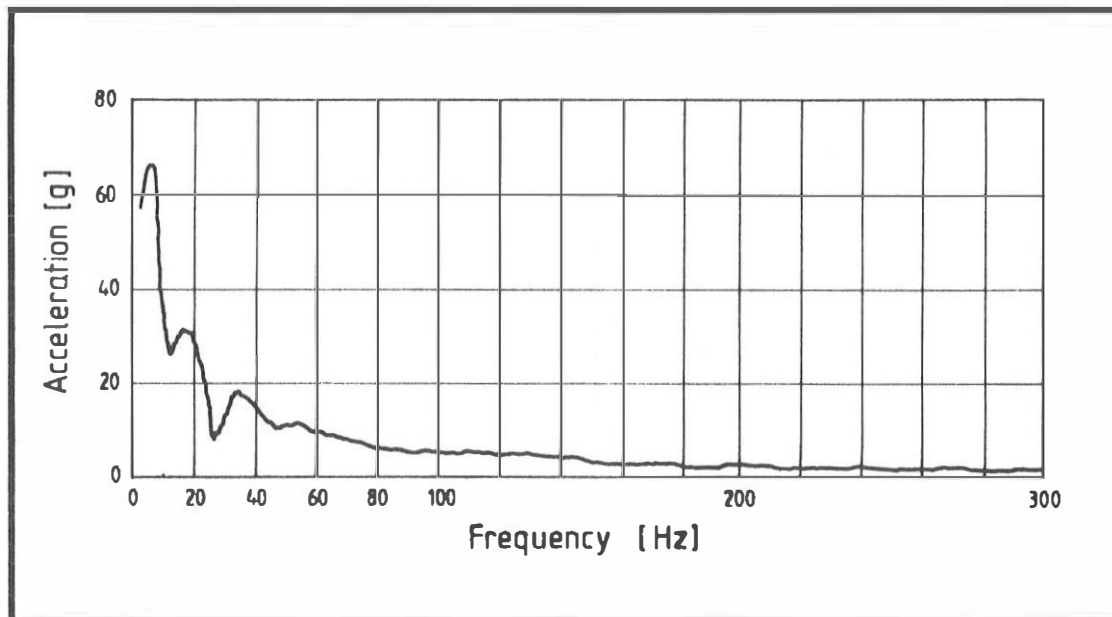


Figure 5:
Amplitude spectrum of "unfiltered" signal of Figure 3

3.4 DETERMINATION OF THE HEAD CONTACT AND ITS DURATION

It was stated above that skull and severe brain injuries only occurred during head impact against parts of the vehicle. Consequently, calculation of the HIC should only be carried out during the impact interval. Measurement of this interval can be performed by evaluation of high-speed film recordings and actuation of electrical contacts. Possible impact points on the vehicle and on the head of the dummy are coated with an electrically conducting material. When the two contact areas touch, an electrical circuit is closed.

Generally, and particularly with weak head impacts, the contact duration can only be determined very inaccurately from film. By using electrical contact areas, it is generally possible to measure the start of contact accurately. High impact forces, however, frequently cause the surfaces to be damaged and thus the electrical circuit to be interrupted so that the end of the contact can only be determined very inaccurately.

Dummy head drop tests in accordance with US PART 572 have shown that the calibration values of the dummy head are only insignificantly affected by the application of contact paints and foils, see Table 4.

| | Maximum resultant acceleration of dummy head (g) | | |
|-----------|--|------------------------|-------------------------|
| | Bare | Aluminium foil covered | Conducting paint coated |
| Head 1 * | 228 | 219 | 229 |
| Head 2 * | 226 | 219 | 227 |
| Head 3 ** | 232 | 215 | 233 |

Specification of PART 572:

$$210 \text{ g} \leq a_{\text{max}} \leq 260 \text{ g}$$

Tests performed at Union Technique de l'Automobile et du Cycle (UTAC)

Tests performed at BAST, mean values of 3 tests

Table 4:
Head drop test results according to PART 572

Whilst the start of contact can be determined electrically with a very high degree of accuracy, the acceleration signal of the head can be distorted and temporally displaced by analog filtering; as a result, parts of the impact forces would lie outside the impact period.

In contrast to the statement made earlier, this results in higher demands being made on analog filtering.

However, since the filtered signals are shifted backwards and only the start of contact can be determined accurately, this problem is, in turn, insignificant if the HIC calculation is allowed to run from the start of contact and the end of contact is ignored.

4. THE NUMERIC-MATHEMATICAL ASPECT

The following section discusses the determination of the resulting head acceleration and its integration. Thereafter, HIC calculation methods are assessed with respect to programming time, memory space requirement and, in particular, CPU time requirement. Finally, the sensitivity of the HIC calculation is examined with respect to the shifting of the interval limits.

4.1 DETERMINATION OF THE RESULTING ACCELERATION

The resulting acceleration is produced by vectorial addition from the acceleration components of the body in x, y and z direction of the centre of gravity of the head: $a_{\text{res}} = \sqrt{a_x^2 + a_y^2 + a_z^2}$. By using the resulting acceleration in the HIC calculation, the relative angle - for example between the acceleration vector and the vertical axis of the head - is ignored.

In view of the missing angle information the temporal sequence of the resulting acceleration $a_{\text{res}}(t)$ is a factor which, from a physical standpoint, must be regarded with some caution. With single or double integration, an incorrect speed or path sequence normally results (e.g. where the sign changes several times within one measuring channel). Oscillating accelerations without sizeable effects on the head speed are added positively by squaring and lead to an increase in the area under $a_{\text{res}}(t)$. On the other hand, the oscil-

lating accelerations must reach a considerable level (e.g. 30%) relative to the main loading in order to have a greater effect on the resultant acceleration (in this example, approx. 10%).

4.2 HIC CALCULATION METHOD

For an initial approximate calculation of the HIC for a given curve $a_{res}(t)$, the formulae in Table 2 can be used. In /18/, a graphic method for determining the HIC is described. Normally, however, the HIC is calculated from digitized measuring value sequences on the computer.

For numeric integration of the expression $\int a_{res}(t) dt$ mathematical approximation methods are used, whereby

- the rectangular formula,
- the trapezoidal formula and
- SIMPSON's (parabolic formula) rule

are the approximation methods most frequently used. All three procedures are more accurate the smaller the step width. With the same step width, the parabolic formula is more accurate than the trapezoidal formula, which in turn is more accurate than the rectangular formula. With the high sampling rate of 8000 Hz demanded in the regulations, the selection of the integration method is of no significance. With reduced scanning rates (down to 1000 Hz), the application of the trapezoidal formula, see Figure 6, for the HIC calculation offers a good compromise between CPU time and cost on the one hand and the demands of accuracy on the other hand.

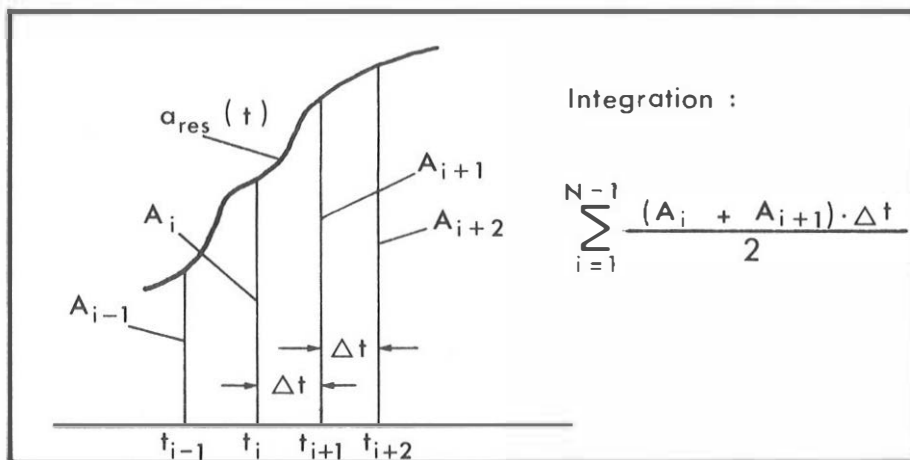


Figure 6:
Integration procedure according to trapezium formula

The simplest, yet most time-consuming method (basic HICT method, see Table 3) of calculating the HIC value for a head acceleration sequence is to perform the integration for every possible combination of digital values and then calculate the HIC value. The maximum value is then the required HIC value.

For the acceleration sequence in Figure 3, a high-power computer system requires more than 15.5 minutes (see Table 3). It is therefore necessary to look for more logical and more rapid methods.

In French-speaking countries, an approximation method is frequently used which starts with large steps and then moves to ever finer steps to pin-point the times t_1 and t_2 of the HIC value. Initially, this method was intended to be included as an exemplary method in the ECE/GRCS draft regulations for the protection of occupants in head-on collisions /19/.

In German-speaking countries, mainly iterative methods are used which are based on mathematical analyses of the HIC equation published in /18/. In this study, it was found that for the HIC value, the accelerations at t_1 and t_2 are on the same level. Furthermore, this acceleration level always lies between 0.6 of the integral mean value and 0.6 of the maximum value of the acceleration sequence.

The study which initially aimed at a graphic determination of the HIC value requires only a single integral of the resulting acceleration function. Furthermore, horizontal lines of constant acceleration are placed through the curve in order to find the interval in which the HIC value is located. Consistent application of the above conditions enables the interval containing the HIC value to be found reliably and rapidly and, also allows an arbitrary level of accuracy to be obtained due to the iterative shift of the acceleration level between $0.6 \times \bar{a}$ and $0.6 a_{\max}$.

Apart from its own computer program (HICE according to /18/), the TU Berlin also has a program from Volkswagen (HICVW) at its disposal. The capabilities of the above-mentioned three programs (HICT, HICE, HICVW) were investigated in a thesis reported in /16/. Table 3 shows an example for the results of the calculations for the acceleration curve from Figure 3.

It can be seen that the iterative methods (HICE and HICVW) have a high degree of accuracy and also require considerably shorter CPU times (10 and 14 seconds respectively).

4.3 EFFECT OF THE CALCULATION INTERVAL ON THE HIC VALUE

As already mentioned above, the HIC should only be calculated during the head contact time of a head impact. If this aspect is examined it becomes apparent that in crash testing the start of contact frequently lies within the interval limits t_1 and t_2 of the HIC calculated over the entire acceleration sequence. If the HIC calculation method is now applied from the start of contact, new interval limits t_1' and t_2' are obtained, whereby t_1' is normally at the start of contact and t_2' is slightly nearer to t_1 or t_1' than is t_2 . Furthermore, the HIC value now determined is considerably lower (normally 10 to 15%, maximum values even up to 50%) than that calculated over the entire acceleration sequence.

It must be taken care whether applied iteration methods still function correctly in limiting the calculation range. With the iteration method according to /18/, for example, it must be noted that there is normally no functional value of the acceleration sequence at the new interval start t_1' .

5. DISCUSSION OF VARIOUS HEAD PROTECTION CRITERIA

In FMVSS 208, the HIC must be calculated over the entire head acceleration period. 1000 is set as the performance criterion limit value. The ECE/GRCS draft regulations stipulate that the head protection criterion is fulfilled if no head impact takes place. In the event of a head impact, the HIC equation should be applied from the start of contact. The filter frequency for the acceleration signals is set at 600 Hz. The value 1000 is set as the limit. As a result of a study /20/ in which the variation between dummy measured values in collision tests (method as in ECE/GRCS draft regulation), a tolerance of +250 is permitted.

Although the significance of rotatory acceleration on the head loading was pointed out during the EEC biomechanics symposium in March 1983 in Brussels, no steps have yet been taken to include this in a head protection criterion (HPC).

Other head protection criteria as shown in Table 1 (except SI) propose the application of head deformation as an injury criteria. If one wished to apply these criteria in dummy tests, the heads of the dummies would have to be manufactured to high mechanical standards. The deformation measurement is very difficult since, as a rule, the point of head impact and the direction of impact is not known in advance. As a result, a dummy head would have to be fitted with a large number of deflection transducers or pairs of acceleration transducers.

Furthermore, the deformation measurements only take indirect and insufficient account of rotatory accelerations since only parts of the mechanical model opposite the point of impact can be taken into consideration and not the rotation itself.

It would be worth considering whether mechanical models which permit such measurements could not be better applied in component tests after the precise impact parameters had been determined in a full scale test.

6. SUMMARY

- Influence of combined loads of longitudinal and rotational acceleration on head injury criteria levels is not well known today
- Rotational head acceleration should be considered in future HPC
- Filter characteristics distort acceleration signals but weakly affect HIC values
- High reduction of sample rate in digital data processing has low influence on HIC value
- Time synchronization of filtered acceleration signal events and undistorted event registration (filming, high frequency event markers) might be difficult
- Beginning of contact time could easily be measured, while end of contact time could not be ascertained

- Conducting materials applied to the dummy head (for the use as contact switch) have little influence on PART 572 head drop test results
- Several numerical procedures for HIC determination gave similar results
- Limiting the time interval for HIC calculation can cause a high reduction in the HIC value.

7. CONCLUSIONS

- In view of the fact that HIC or HPC = 1000 correlates only unsatisfactorily with head injuries, no proof has yet been given that purely translatory loads are not correctly evaluated
- Rotatory loads can be measured by attaching several linear acceleration transducers to the head of the dummy
- If calculation formulae similar to the HIC equation are applied in the evaluation of rotatory accelerations, the increase in the quantity of digital data due to the increased number of measuring channels can be compensated by a reduction in the cut-off frequency of the measuring channels to approx. 600 Hz (even 300 Hz when determining the filter characteristics) and reduction in the sample rate to 2000 per second.

8. REFERENCES

1. NEWMAN, J.A.: Head Injury Criteria in Automotive Crash Testing. SAE Paper No. 801317. Proc. 24th Stapp Car Crash Conference, 1980.
2. GOLDSMITH, W.; OMMAYA, A.K.: Head and Neck Injury Criteria and Tolerance Levels. The Biomechanics of Impact Trauma, pp. 149-187, Amalfi 1983, ICTS 1984.
3. FAERBER, E.; GÜLICH, H.-A.; HEGER, A.; RÜTER, G.: Biomechanische Belastungsgrenzen, Literaturstudie über die Belastbarkeit des Menschen beim Aufprall. "Unfall- und Sicherheitsforschung Straßenverkehr", Volume 3, BAST, Cologne, 1976.
4. HODGSON, V.R.; PATRICK, L.M.: Response of the Human Cadaver Head. SAE Paper 680784. Proc. 12th Stapp Car Crash Conference, 1968.
5. BRUN-CASSAN, F.; FAYON, A.; TARRIERE, C.: Tolerance of the Human Head at Impact: Reconstruction of Head Impacts Observed in True-Life Accidents. Seminar on "The Biomechanics of Impacts in Road Accidents", Brussels 1983
6. SELLIER, K.: Das Schädel-Hirn-Trauma. "Rechtsmedizin" magazine 68. Pp. 239-252, Springer-Verlag, 1971.
7. OMMAYA, A.K.: The Head: Kinematics and Brain Injury Mechanisms. The Biomechanics of Impact Trauma, pp. 127-138, Amalfi 1983, ICTS 1984.
8. GENNARELLI, T.A.: Clinical and Experimental Head Injury. The Biomechanics of Impact Trauma, pp. 103-116, Amalfi 1983, ICTS 1984.

9. SCHMIDT, G.; KALLIERIS, D.; BARZ, J.; MATTERN, R.; SCHULZ, F.: Belastbarkeitsgrenze und Verletzungsmechanik des angegurteten Fahrzeug-Insassen. FAT Schriftenreihe No. 6. Frankfurt, 1978.
10. SACRESTE, J.; BRUN-CASSAN, F.; FAYON, A.; TARRIERE, C.; GOT, C.; PATEL, A.: Evaluation of the Influence Inter-Individual Differences on the Injury Level. Seminar on EEC Biomechanics Research Programme. Brussels, 1983.
11. GURDJIAN, E.S.; ROBERTS, V.L.; THOMAS, L.M.: Tolerance Curves of Acceleration and Intracranial Pressure and Protective Index in Experimental Head Injury. Journal of Trauma, 1964.
12. APPEL, H.; KRAMER, F.; HOFMANN, J.: Protection Criteria for Occupants and Pedestrians. ESV Conference, Paris 1979.
13. KRAMER, F.; HEGER, A.; MELZ, T.: Die Verwendung der Letalitätsrate unter Berücksichtigung der Unfallstatistik. Annual Report TUB 8201 to the BMFT Research Project "Insassenschutz". Berlin, 1982.
14. ALDMAN, B.: Synthesis Report of the EEC Biomechanics Programme. Proc. of the Seminar: "The Biomechanics of Impacts in Road Accidents", Brussels 21-23 March 1983
15. McELHANEY, J.H.; STALNAKER, R.L.; ROBERTS, V.L.: Biomechanical Aspects of Head Injury. Human Impact Response. Proc. of the Symposium on Human Impact Response, GM Research Laboratories, Warren, Michigan, 1972.
16. MORRES, H.: Berechnungsverfahren und Parametereinflüsse bei der Ermittlung von Dummybelastungswerten (Untersuchungen zum HIC). Thesis No. 14/82 (FG 1), Technical University of Berlin 1984.
17. VERSACE, J.: A Review of the Severity Index. SAE Paper No. 710881. Proceedings of the XV Stapp Car Crash Conference, 1971.
18. WAGNER, R.: Ein Verfahren zur iterativen Bestimmung des HIC-Wertes beim Kopfaufprall. Automobiltechnische Zeitschrift ATZ 78, 1976.
19. Economic Commission of Europe:
Draft Regulation: Uniform Provisions Concerning the Approval of Private (Passenger) Cars with Regard to the Protection of the Occupants in the Event of Head-On Collisions, August 1983.
20. FAERBER, E.: Streuung von Schutzkriterien in kontrollierten Aufprall-Versuchen gegen die 30° Barriere. Research Reports of the Federal Highway Research Institute, Accident Research Division, No. 8267, 1983. (Translated into English: Highway Safety Literature, NHTSA 385735).