SENSITIVITY ANALYSIS FOR THE TRANSLATIONAL ENERGY CRITERIA: OVERALL HEAD INJURIES

by

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ABSTRACT:

The recently developed Translational Energy Criteria (TEC) for predicting head injury severity was used to analyze three types of theoretical pulses represented by triangular, half-sine, and trapezoidal pulses as shown in Figure 1. These pulses were used as an input force to a lumped parameter model represented by the Translational Head Injury Model (THIM) of the human head in the TEC analysis. The effects of impact duration, pulse shape and magnitude on the dynamic responses of the THIM model were studied in detail. Pulse durations ranging from 2. to 20. msec were analyzed in order to study the full range of all normally observed human head impacts (rigid or padded). An input force pulse amplitude of 1000. lb_f was used in all analyses except where the effects of impact force magnitude were evaluated. Variations of the peak force, F(t), and acceleration, $A_2(t)$, with respect to pulse duration at two constant energy levels were studied. Energy constants which represent head injury severity equivalent to AIS scale of 2 and 4 were evaluated in detail for impacts in both the A-P and L-R directions.

The analysis of the effects of the impact force duration on the dynamic responses of the head model indicates that for pulse duration between 5. to 20. msec, the energy function of the TEC increases as the pulse duration increases when all other variables are kept constant. This is consistent with the general conclusion that a harder impact (higher magnitude and/or longer duration impact) causes a more severe head injury. For shorter duration impact, the TEC shows that skull fracture is predominant. In addition, the TEC results indicate that the pulse shape with highest input momentum has the highest energy value, thus predicting the most serious head injury. The effects of pulse amplitude on the energy function is determined to be a square relationship. Therefore, a higher magnitude impact will result in a more severe head injury when all other variables are unchanged. The variational studies indicate that results from one TEC energy level may be used at other energy levels through proper parametric adjustments.

INTRODUCTION:

Head injury is considered to be one of the most serious mode of injuries encountered in automobile accidents (1-5). Many studies were involved in the developments of some methods to predict the degree of head injury severity base on measurable parameters (head accelerations, impact forces, etc.) and/or reproducible damages (dents or scratches in automobile parts, hospital and police records, etc.). Unfortunately, the progress was limited because most of the available head injury data from cadaver experiments (6-9) and accident records (10) was inadequate for conducting a detailed empirical study. At the

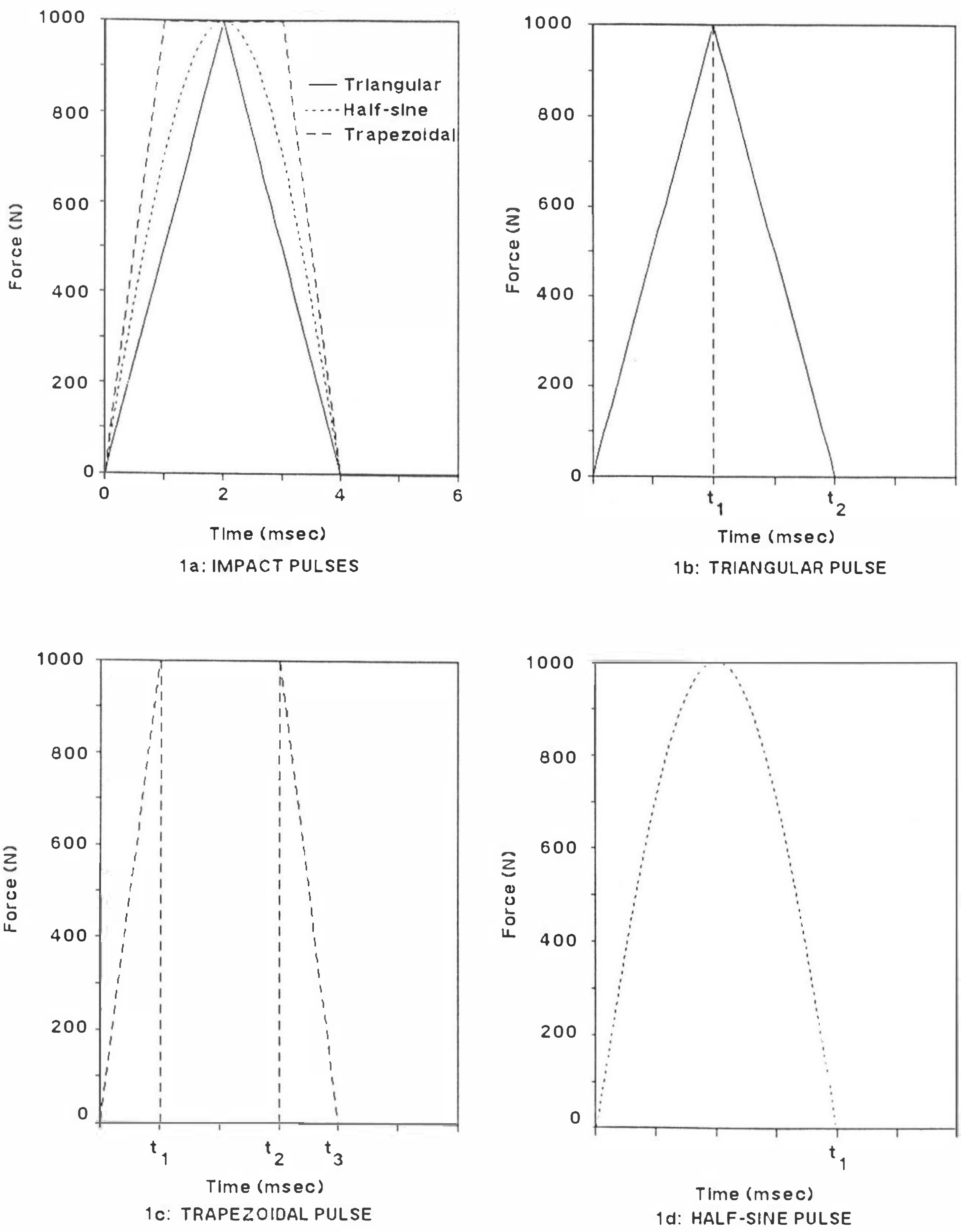


Figure 1: Impact pulses used in the sensitivity studies of the TEC

same time, a new cadaver is hard to obtain. And, the experimental process involved in cadaver testing is very difficult, expensive and time consuming. Consequently, no well-established head injury criterion (HIC, SI, Gadd, TEC, etc.) has been thoroughly studied for the entire range of head impacts encountered in automobile or other industrial accidents. It is also unlikely that much improved head injury data will be available in the near future because drastic technical advancement in head injury experimentation is doubtful with present day technology. Thus, it is improbable that a "complete" investigation base on cadaver or lived human head injury data will be carried out soon.

When actual human or cadaver data was not available, an analysis base on theoretically generated impacts may be conducted as a viable alternative. Theoretical analysis is usually much faster, easier to control and cheaper to perform when the procedure is clearly understood and all the boundary conditions are well defined. For the TEC analysis, accurate theoretical impact analysis may be performed over the full dynamic range of commonly observed head impacts in automobile related accidents. The THIM model used in the TEC analysis is suitable for analysis employing theoretically generated head impact forces of different shapes, durations and/or magnitudes. Thus, a systematic investigation of the head injury severity may be achieved for the whole dynamic range of human head impact using the TEC.

The objective of this paper is to investigate the sensitivity of the recently developed Translational Energy Criteria. In this study, the TEC is subjected to theoretically generated impacts representing different head impact conditions normally observed in automobile accidents (impacts to windshield, A-pillar, steering wheel, etc.). Effects of the variations in impact duration, distribution (pulse shape) and magnitude on head injury severity prediction capability of the TEC are studied in detail.

BACKGROUND:

A. DEVELOPMENT OF THE TRANSLATIONAL ENERGY CRITERIA

Stalnaker, Lin and Guenther (11) first introduced the New Mean Strain Criteria (NMSC) in 1984. This criteria linked head injury severity with the strain, e(t), and strain rate, d(e)/dt, determined from the head impact responses. A lumped parameter model called the Translational Head Injury Model (THIM) was used in the NMSC analysis. In 1986, Stalnaker, Low and Lin (12) upgraded the criteria to the current Translational Energy Criteria (TEC). The THIM model was kept unchanged; however, a better head injury criteria was developed. In the TEC, contusion head injuries were correlated with the energy dissipated by damper C_2, EC_2, and skull fracture were correlated with the rate of energy stored in the spring element, PW. Both EC_2 and PW are defined in later derivations.

The THIM model is a one dimensional, three degrees of freedom semi-definite lumped parameter model composed of two masses, one spring, and two dampers as shown in Figure 2. Several techniques (13,14) may be used to formulate the transfer functions of the THIM model. In our derivation, the driving-point impedance function was developed. This impedance function, F/V (s), may be expressed as

$$F_1/V_1(s) = \frac{s\{C_1M_1M_2s^2+[C_1C_2(M_1+M_2)+KM_1M_2]s+[K(M_1+M_2)(C_1+C_2)]\}}{M_2C_1s^2+(C_1C_2+KM_2)s+K(C_1+C_2)}$$

and in standard frequency response form,

$$I = \left| \frac{F_1}{V_1}(i\omega) \right| = \frac{\omega\sqrt{\{KM_1M_2+C_1C_2(M_1+M_2)\}^2\omega^2+\{K(M_1+M_2)(C_1+C_2)-\omega^2C_1M_1M_2\}^2}}{\sqrt{\{K(C_1+C_2)-\omega^2M_2C_1\}^2+\omega^2(C_1C_2+KM_2)^2}}$$

and,

$$\angle\phi = \angle\frac{F_1}{V_1}(i\omega) = \frac{\pi}{2} - \mathrm{Tan}^{-1}\left[\frac{C_1C_2+KM_2}{K(C_1+C_2)-\omega^2M_2C_1}\right]$$

$$+ \mathrm{Tan}^{-1}\left[\frac{C_1C_2(M_1+M_2)+KM_1M_2}{K(M_1+M_2)(C_1+C_2)-\omega^2C_1M_1M_2}\right]$$

where,

F_1 - Impact force to the head model
K - The THIM model spring
C_1, C_2 - The THIM model dampers
M_1, M_2 - The THIM model masses
I - Magnitude of the impedance function at frequency ω
ϕ - Phase angle of the impedance function at frequency ω

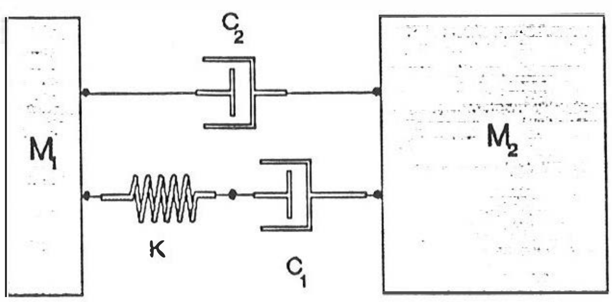


Figure 2: The THIM Model

From these impedance equations, the kinematics of the THIM model may be determined from known impacts. The energy function, EC_2, and the power function, PW, are computed from the relative motions and the parametric values of the elements in the model. These functions may be expressed as,

$$EC_2 = \int_0^t C_2(\dot{X}_1-\dot{X}_2)^2 \, dt$$

and,

$$PW = d/dt \left[\tfrac{1}{2}K(X_1-X_3)^2 \right]$$

where,

d/dt, $\dot{}$ = Notation for time derivative
X_1, X_2, X_3 = Displacements at junctions 1, 2 and 3

The THIM model only refers to translational accelerations and does not address the consequences of angular motion.

B. IMPACT FORCES:

Three different types of impact force pulse shapes were used in this study. They are triangular, half-sine and trapezoidal pulses, as shown in Figure 1a, 1b and 1c. These pulse shapes were selected in this investigation since they represent the general shapes of commonly observed human head impacts in automobile related accidents. The mathematical formulas used in generating these pulses were summarized in the following equations,

For triangular pulse,

$$F(t) = \begin{cases} \dfrac{A_1}{t_1} * t & 0 < t < t_1 \\[2ex] \dfrac{-A_1}{(t_2-t_1)} * t & t_1 < t < t_2 \\[2ex] 0 & t > t_2 \end{cases}$$

For half-sine pulse,

$$F(t) = \begin{cases} A_1 \sin \left[\dfrac{\pi}{t_1} * t \right] & 0 < t < t_1 \\[2ex] 0 & t > t_1 \end{cases}$$

For trapezoidal pulse,

$$
F(t) = \begin{cases} \dfrac{A_1}{t_1} * t & 0 < t < t_1 \\ A & t_2 < t < t_3 \\ \dfrac{-A_1}{(t_3-t_2)} * t & t_2 < t < t_3 \\ 0 & t > t_3 \end{cases}
$$

where,

$F(t)$ - Impact force function
A_1 - Magnitude of impact force
t - Actual time after initial impact
t_1, t_2, t_3 - Constant time values represented in the figures

DISCUSSION OF RESULTS:

The complete results of the sensitivity studies of the TEC are presented in the sections below. Effects of impact duration, distribution and magnitude were considered in the analyses. Variational studies at two constant energy levels representing head injury severity equivalent to AIS scale of 2 and 4 were conducted. Both the A-P and L-R impacts were studied.

A. PULSE DURATION EFFECTS:

The effects of pulse duration on the dynamic responses of the THIM Model are shown in Figures 3 through 7. The effects of the pulse duration on the energy dissipated by the damper C_2, EC_2, is shown in Figure 3. For impact with pulse duration longer than 5. msec, EC_2 increases as the pulse duration increases for all three pulse shapes. This suggests that for pulse durations between 5. and 20. msec, the impact force momentum, or the area under the force-time curve, is directly related to the energy dissipated by C_2 in the THIM model. This seems to be consistent with the general conclusion that a harder impact (higher magnitude and/or longer pulse duration) causes a more severe head injury as predicted by higher EC_2 value. For pulse durations shorter than 5. msec, the trend is not observed which seems to contradict the general conclusion just mentioned. However, for pulse duration less than 5. msec, skull fracture is considered very likely at the peak force amplitude of 1000. lb_f. This mode of head injury is very different from brain contusion and has to be addressed separately. The very short pulse duration represents highly concentrated load which creates high localized stress. This type of loading causes skull fracture and possible bruising of the brain. As the pulse duration increases, given the same load as before, the load concentration will decrease; thus, decreasing the chance of skull fracture. This explains the decreasing EC_2 as pulse duration increases up to approximately 5 msec. In summary, the EC_2 value from the TEC analysis seems to be able to predict the sensitivity of contusion head injury for impacts with pulse duration between 5. to 20. msec. For shorter duration impact pulse, skull fracture should be considered in conjunction with brain contusion.

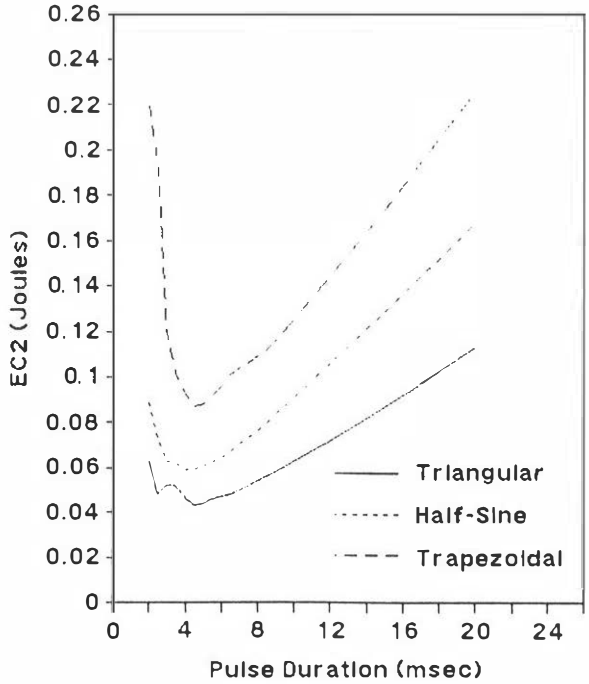


Figure 3: Energy Functions (A-P Impact)

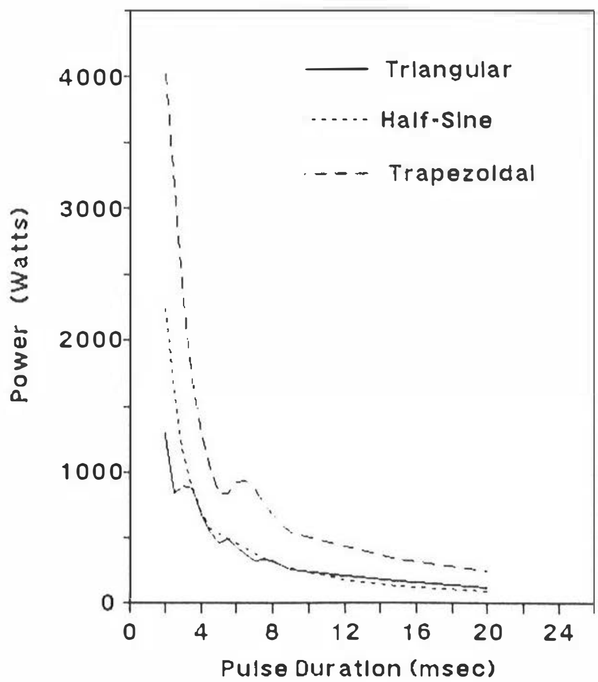


Figure 4: Power Functions (A-P Impact)

The effects of pulse duration on the maximum rate of change of energy stored in the spring element, PW, is shown in Figure 4. For all three pulse shapes, PW decreases as the input force pulse duration increases, except for a small peak between 5. to 7. msec for the trapezoidal pulse. Similar effects are also evidence in the triangular and half-sine pulses. This correlates very well with the relationship between the onset rate and the pulse duration shown in Figure 5. Thus, a higher rate of onset generally corresponds with a higher PW and a shorter pulse duration. Figure 6 illustrates the relationship between PW and the onset rate. Figure 7 shows the relationship between PW and the its corresponding peak time. The small peaks in Figure 4 are minor effects caused by the dynamics of the THIM model. The pulse duration and the model natural frequencies interact to create this small deviation which distorts the graph slightly; however, the general trend of decreasing PW for increasing pulse length is still valid.

B. PULSE SHAPE EFFECTS:

The effects of pulse shape on the dynamic responses of the THIM model are summarized in Figure 3 and 4. From these two figures, it is observed that for the same impact duration the trapezoidal pulse has the highest EC_2 and PW values, while the triangular pulse has the lowest. This is because the trapezoidal has the highest input momentum as evidence in the force-time curve shown in Figure 1. On the other hand, the triangular pulse has the smallest area under the force-time curve; thus, it has the lowest input momentum and EC_2 value. The trapezoidal pulse also has the highest onset rate as illustrated in Figure 5. Therefore, it has the highest PW value as well. On the other hand, the triangular pulse has the lowest onset rate, hence it has the lowest PW value for the same impact condition. The half-sine pulse's input momentum and onset rate are in between those of the trapezoidal and triangular pulses. As a result, the dynamic responses of the half-sine pulse also lie within the range bounded by these two pulses.

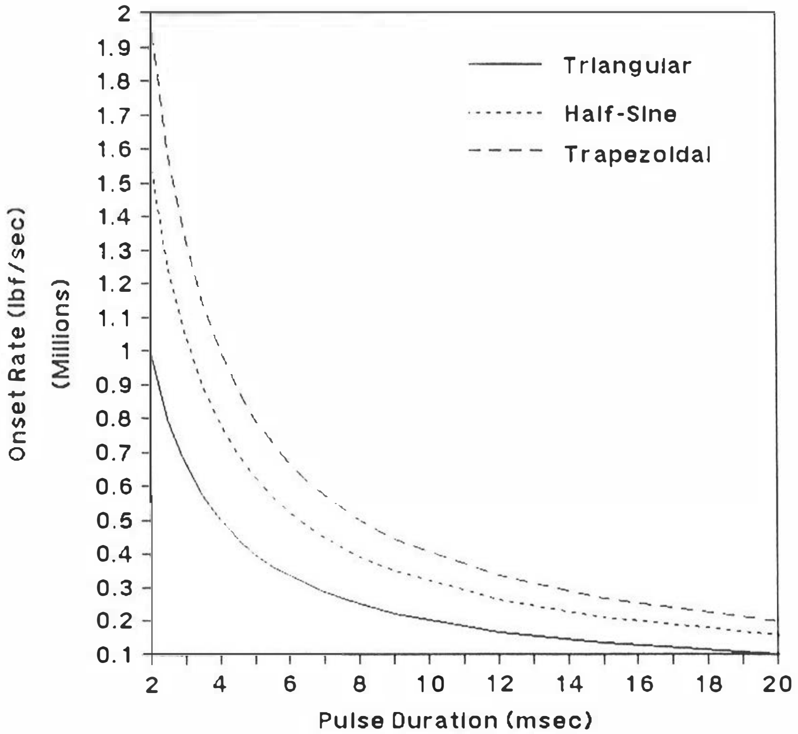


Figure 5: Relationship between impact onset rate and duration

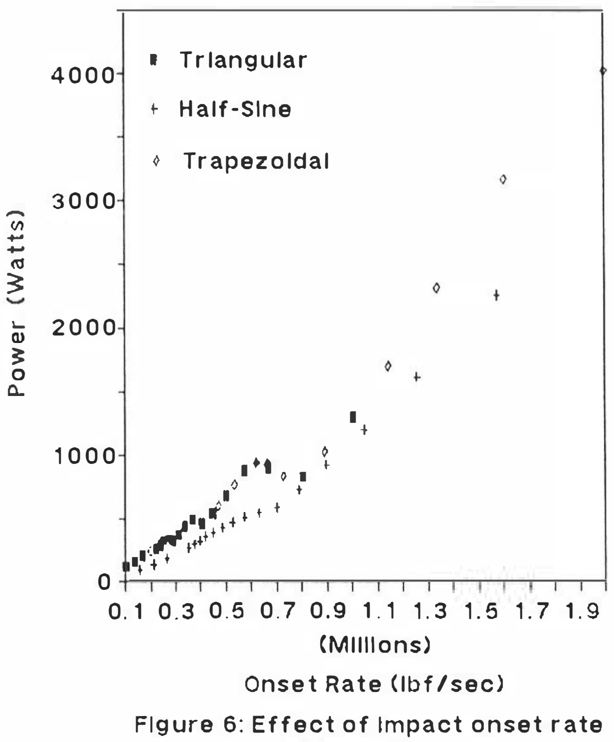


Figure 6: Effect of impact onset rate on power function

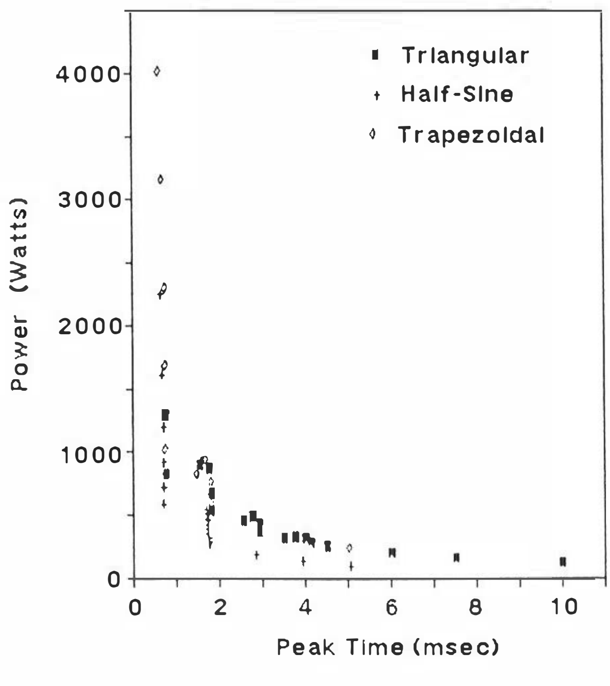


Figure 7: Effect of power peak on power function

C. PULSE AMPLITUDE EFFECTS:

The effects of amplitude variations on the EC_2 and PW of the half-sine pulse are shown in Figures 8 and 9 for impact duration of 6.5 msec. From the TEC analysis, the energy function, EC_2, is proportional to the integral of $(V_1-V_2)^2$. While, the accelerations, velocities and displacements predicted by the TEC are proportional to the magnitude of the input force because the THIM model equations are linear. Therefore, we expect the EC_2/peak F(t) relationship to be a square function. On the other hand, PW is directly proportional to $(V_1-V_3)(X_1-X_3)$. Thus, the PW/peak F(t) relationship is expected to be a square function as well. The results of the study illustrated in Figures 8 and 9 confirm these findings.

D. VARIATION OF PEAK F(t) AND $A_2(t)$ AT CONSTANT ENERGY LEVELS:

Figures 10a and 10b showed the variations of peak F(t) and $A_2(t)$ at two constant energy levels of .23 and .46 Joules for impacts in the A-P direction. These energy numbers are equivalent to AIS head injury scale of 2 and 4. Pulse durations between 2. and 9. msec were used in the analysis. Figures 10c and 10d showed the normalized curves of Figure 10a and 10b (normalized based on the amplitude of the 2. msec signals). From these two normalized curves, we observed that the variations of the force and acceleration ratios are almost the same for the two EC_2 levels under investigations. Thus, it is assumed here that the variation at any other EC_2 level has the same relationship. This allows linear interpolation and/or extrapolation of the

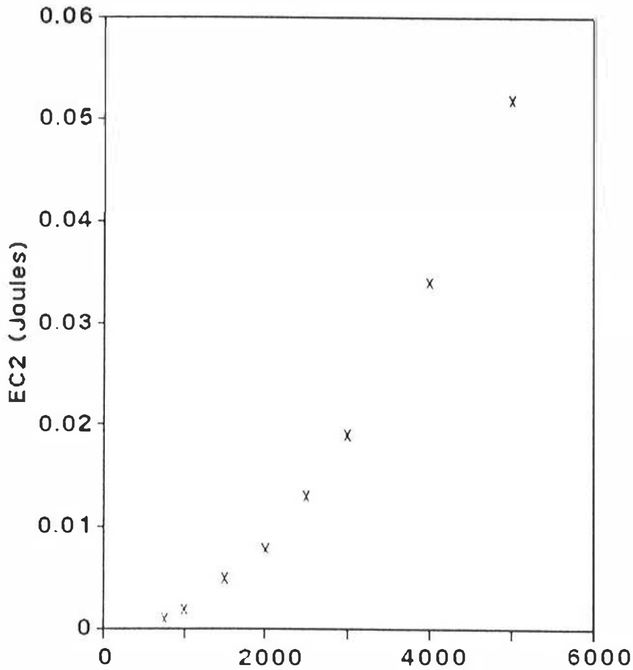


Figure 8: Impact force magnitude effect on energy function

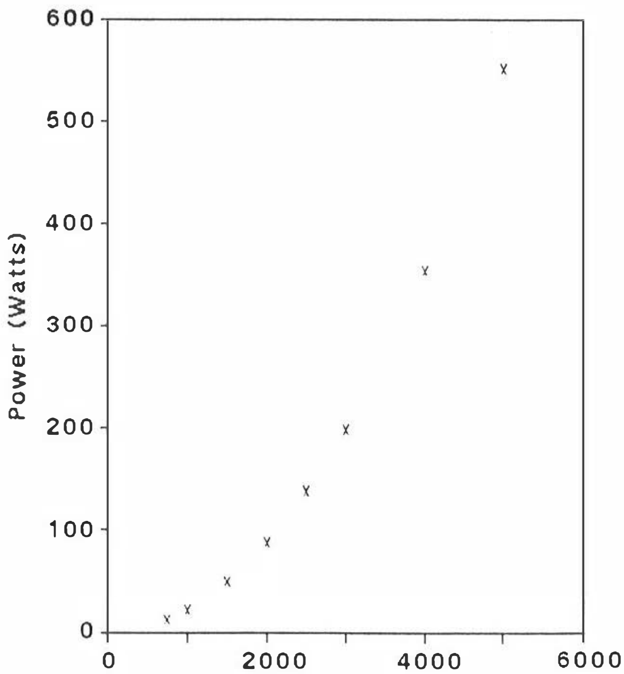


Figure 9: Impact force magnitude effect on power function

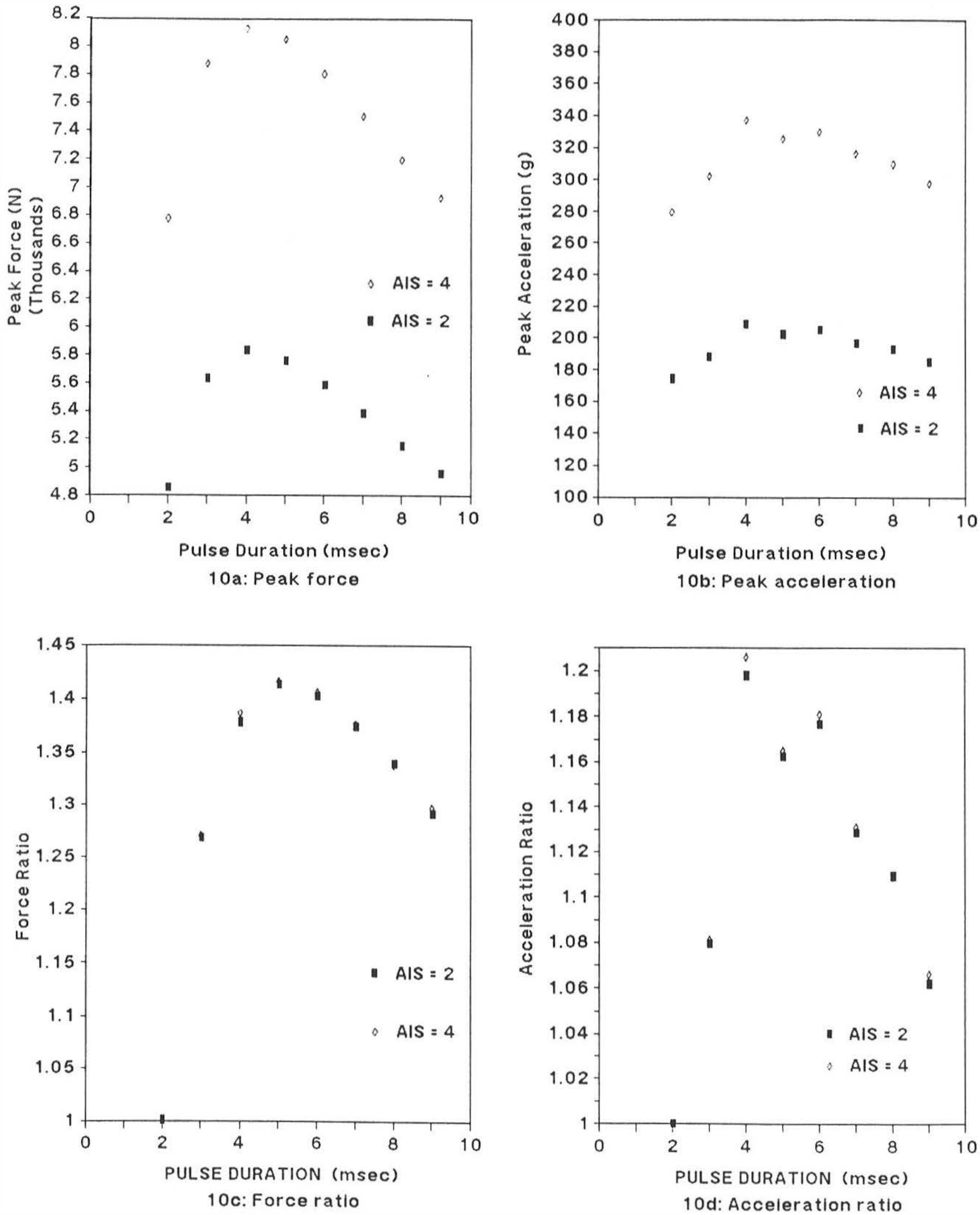
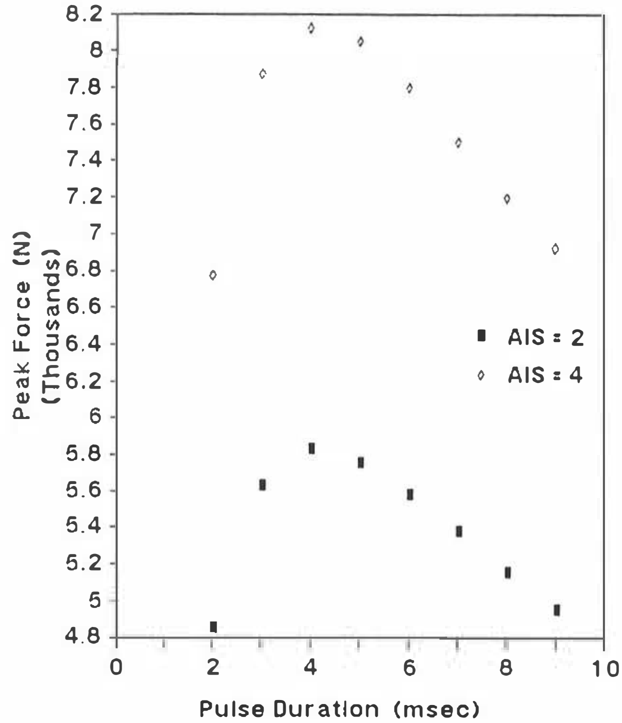
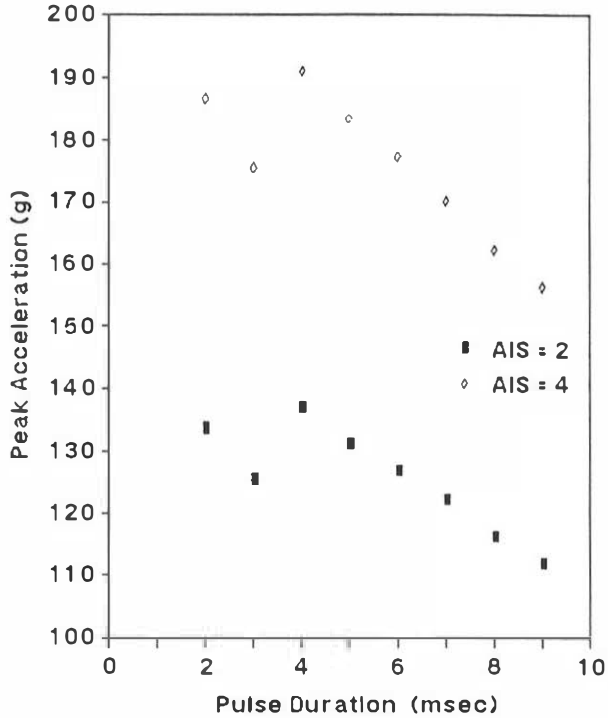


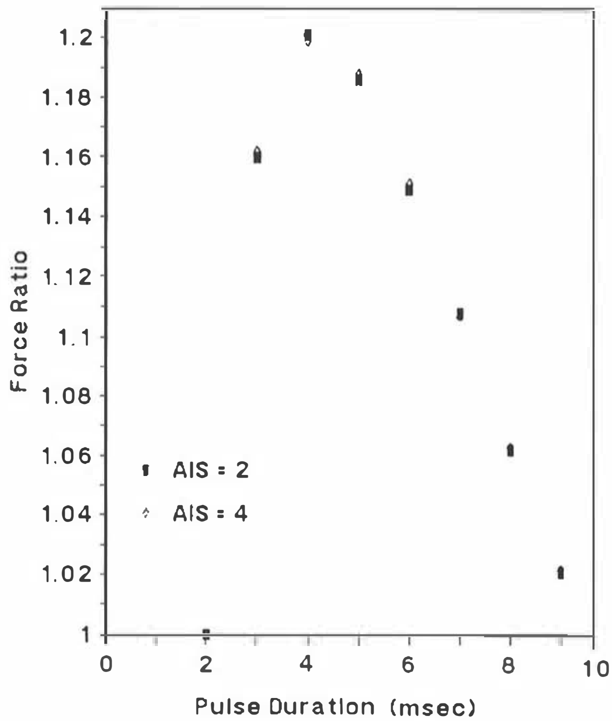
Figure 10: Variational analysis for A-P impact



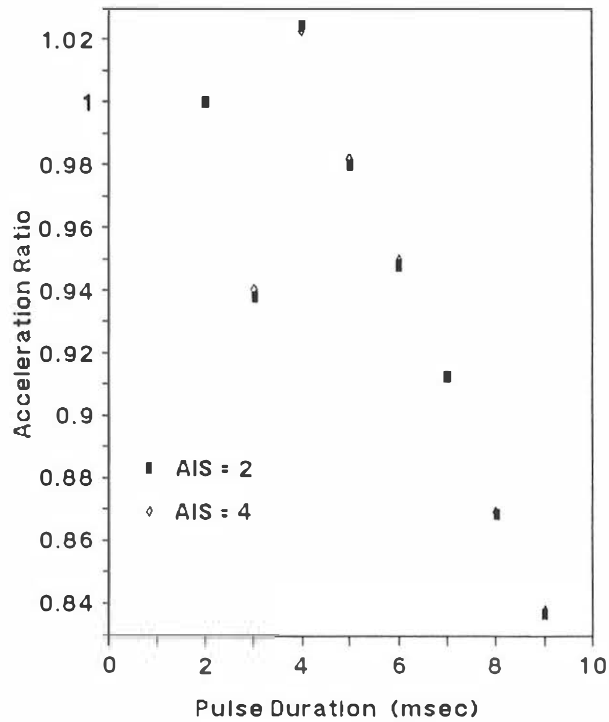
11a: Peak force



11b: Peak acceleration



11c: Force ratio



11d: Acceleration ratio

Figure 11: Variational analysis for LR impact

results in this study to other energy levels. Figures 11a through 11d illustrated the same results for impacts in the L-R direction. Note that sensitivities of the variations are different from those in the A-P direction; however, the normalized curve relationships in the L-R direction are still constant and may be scaled up or down as done previously in the A-P direction.

SUMMARY:

In this paper, a detailed sensitivity study on the recently developed Translational Energy Criteria was accomplished. The results of the study confirmed that the TEC is consistent with the well accepted conclusion implying that a harder head impact causes a more severe head injury. In the TEC analysis, the energy function increases as the impact momentum increases. Thus, a harder hit (higher momentum) causes a more serious head injury and has a higher EC_2 value. The results of the TEC analysis also showed that the power function, the impact onset rate and skull fracture correlate well. As a result, the TEC may also be used to predict the occurrence of skull fracture in impact situations.

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