K. Theoretical Head Impact Velocity Concept

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A method of quantifying the severity of impact is described for occupants in vehicles that are in collisions with roadside barriers. Analysis of the movement of the vehicle can lead to the prediction of occupant trajectory, and the magnitude of impact velocity with the interior of the vehicle.

The concept of assessing occupant injury as a result of vehicle acceleration or velocity change is used as a guideline for acceptable dynamic performance when a vehicle is in collision with a highway roadside safety feature. Accelerations measured at the center of mass lead to the computation of the forward and lateral components of displacement and velocity for an unrestrained front seat occupant.

In a redirection collision, in which, for example, the vehicle strikes a median barrier or parapet at an acute angle and is deflected away, even though vertical movement, pitch, and roll may be small, yaw angles and velocities can be large and occur within the same time interval as the principal linear accelerations. The trajectory of the unrestrained occupant is not a straight line and can follow a complex curve defined by the linear and rotational (yaw) motions of the vehicle. The analysis method proposed calculates the movement of an unrestrained occupant within the passenger compartment. During impact with the barrier, the vehicle rotates in yaw and translates longitudinally and laterally. The occupant maintains his initial path and eventually comes in contact with the interior of the vehicle. The relative impact velocity can be determined and is considered as a measure of vehicle impact severity in terms of occupant risk. The resultant contact velocity has been named the "theoretical head impact velocity" (THIV).

Over the years, the Transport and Road Research Laboratory (TRRL) has accumulated data from a large number of redirection collisions involving cars and trucks as part of the TRRL safety fence and bridge parapet research program. Almost all the cars contained instrumentation to measure longitudinal acceleration, lateral acceleration, and yaw velocity, and also had installed calibrated and instrumented Hybrid II dummies. This data base has been analyzed to correlate vehicle dynamics, barrier characteristics (mainly deflection), and other injury criteria measured in dummies, namely "head injury criteria" (HIC), and the "chest severity index" (CSI).

Typical occupant trajectories are given for car and truck collisions with safety fences and rigid parapets. Relationships between the dummy injury indices HIC, CSI, and THIV values are explained.

The THIV Concept

The THIV value is the velocity at which a freely moving body impacts a surface within the passenger compartment of a vehicle involved in a collision with a roadside safety feature, such as a safety fence or a lighting column. To calculate the relative impact velocity between the occupant and vehicle, assumptions have to be made about the motion both of the occupant and the vehicle.

Occupant Motion

The occupant is assumed to be an unrestrained object that continues on its precollision trajectory and velocity until it impacts the interior of the vehicle. Sliding friction between the occupant and seat or trim is neglected.

Vehicle Motion

The motion of the vehicle is derived, under impact conditions, from the results of accelerometers, arranged to measure the longitudinal and lateral direction of the vehicle's center of gravity. Only the horizontal trajectory of the vehicle is considered, that is, its lateral, longitudinal, and angle of yaw motions. The angles of pitch and roll are not considered.

The remaining information required to calculate the THIV value is the relative location of the occupant relative to the vehicle's center of gravity and the relative distance of the occupant from the front and sides of the passenger compartment. In this analysis the occupant is assumed to move from the position of the center of gravity.

The equations used to describe the relative motion of the vehicle and the occupant are as follows:

1. Accelerations of the vehicle relative to the ground

Forward:

$$\ddot{X}_c = \ddot{x}\cos\theta + \ddot{y}\cos\theta \qquad (1)$$

Lateral:

$$\ddot{Y}_c = \ddot{y}\cos\theta - \ddot{x}\sin\theta \qquad (2)$$

where x and y are the forward and lateral accelerations of the vehicle as measured by accelerometers (x positive forwards, y positive to vehicle left-hand side, and θ is the angle of yaw (positive clockwise looking from above).

2. Velocity of the vehicle relative to the ground.

$$\dot{X}_c(t+\delta t) = \frac{\ddot{X}_c(t) + \ddot{X}_c(t+\delta t)}{2}\cdot\delta t + \dot{X}_c(t)$$

$$\dot{Y}_c(t+\delta t) = \frac{\ddot{Y}_c(t) + \ddot{Y}_c(t+\delta t)}{2}\cdot\delta t + \dot{Y}_c(t) \qquad (3)$$

where δt is the time interval for calculation.

Velocity of the body relative to the ground.

$$\dot{X}_B = V_0$$

$$\dot{Y}_B = 0 \qquad (4)$$

where V_0 is the vehicle impact velocity with the barrier.

3. Displacement of the vehicle relative to the impact point.

$$X_c(t+\delta t) = \frac{\dot{X}_c(t) + \dot{X}_c(t+\delta t)}{2}\cdot\delta t + X_c(t)$$

$$Y_c(t+\delta t) = \frac{\dot{Y}_c(t) + \dot{Y}_c(t+\delta t)}{2}\cdot\delta t + Y_c(t) \qquad (5)$$

Displacement of the body relative to the impact point.

$$X_B = V_0 t + X_o$$

$$Y_B = Y_0 \qquad (6)$$

4. Displacement of the body relative to the car coordinates.

$$x = X\cos\theta - Y\sin\theta$$

$$y = X\sin\theta + Y\cos\theta \qquad (7)$$

where

$$X = X_B - X_C$$

$$Y = Y_B + Y_C \qquad (8)$$

5. Velocity of the body relative to the car.

$$\dot{x} - (\dot{X}_B - \dot{X}_C)\cos\theta + \dot{Y}_C\sin\theta \qquad (9)$$

6. Theoretical head impact velocity (THIV).

$$THIV = (\dot{x}^2 - \dot{y}^2)^{1/2} \qquad (10)$$

The basic nomenclature is described in Figure 18.

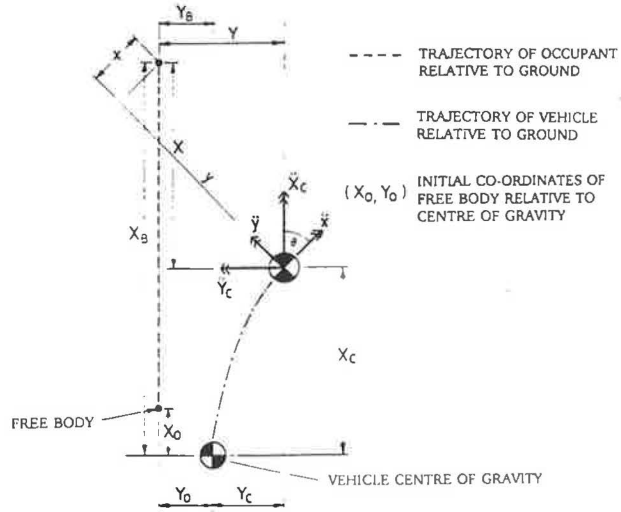

FIGURE 18 THIV diagram showing vehicle and body trajectories relative to ground.

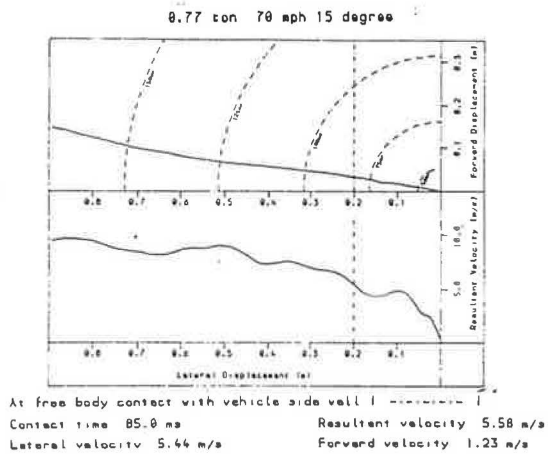

FIGURE 19 THIV program graphical output.

The output from the longitudinal and lateral accelerometers plus the yaw rate transducer first undergo signal conditioning before being filtered and digitized. An analysis of the present signal and signal conditioning is given in Appendix F.

The average acceleration and yaw rate of the vehicle for each time step are calculated. The computation uses time steps of nominally 0.001 sec. The average acceleration and yaw rate of the vehicle for each time step are calculated. The equations of motion are then integrated and the appropriate transformation is made to find the trajectory of the occupant relative to the vehicle as described above.

Having calculated both the relative displacement and velocity trajectories of the occupant, the relative impact velocity of the occupant when the occupant has traveled to the side or front of the passenger compartment is easily found. The resultant velocity at impact is the THIV value.

The results can be presented both in tabulated and graphical form as shown in Figure 19. The graphical format is divided into two parts. The upper part contains the relative displacement of the freely moving head with respect to the center of gravity of the vehicle. This is a plan view with longitudinal (or forward) displacement on the *Y*-axis and lateral displacement on the *X*-axis. The head moves from its rest position at the origin of the forward and lateral displacement axis, and is shown to contact a surface 200 mm to the left of the origin. This may be considered to be the interior surface of a small car. Contact is shown to take place 85 msec after the vehicle impacts the barrier. The head hs moved forward about 40 mm.

The lower part of the graph contains a plot of the occupant's velocity relative to the vehicle. The intersection of the velocity trajectory with the side of the vehicle gives the occupant contact velocity at 5.58 msec. Other impact values are displayed in the lower part of the graph. The resultant impact velocity, being the THIV value, is taken as a measure of impact severity.

Comparison with other Injury Severity Indices for Collisions with Roadside Barriers

Two other concepts for assessing injury severity of occupants in vehicles involved in collisions with roadside appurtenances are currently in use. The flail space model has been developed and used in the United States, and the acceleration severity index, originally conceived in the United States, is now used in Holland, Germany, and France. These models are compared with THIV in Table 16.

As does the THIV concept, the flail space concept uses the impact velocity of an unrestrained passenger impacting the interior passenger compartment. The flail space method has been extensively reported in NCHRP Report 230. However, the impact velocities in the lateral and longitudinal directions are calculated separately without reference to yaw rotations or resultant velocity. Separate limits of impact velocity are given, 12 m/sec in the longitudinal direction and 9 m/sec in the lateral direction. The nomenclature and terminology used in the flail space concept are shown in Figure 20.

Ray and Carney analyzed the methods associated with the flail space model as given in NCHRP Report 230 and have developed a computer model for coupling the equations of motion and also evaluating the effect of

TABLE 16 COMPARISON OF THE THEORETICAL HEAD IMPACT VELOCITY, FLAIL SPACE, AND ACCELERATION SEVERITY INDEX MODELS

Model/Concept	Input	Severity Parameter	Severity Parameter Limits
Theoretical Head Impact Velocity	Longitudinal and lateral acceleration at vehicle centre of gravity Angle of yaw (from yaw rate)	Resultant impact velocity of occupant relative to the vehicle at impact with the side or front of passenger compartment	Maximum resultant impact velocity To be agreed
Flail Space	Longitudinal and lateral acceleration at vehicle centre of gravity	Impact velocity of occupant with the side of passenger compartment. Impact velocity of occupant with the front of passenger compartment Acceleration level of occupant in lateral direction after impact Acceleration level of occupant in longitudinal direction after impact	Maximum lateral velocity 9 m/s Maximum longitudinal velocity 12 m/s Maximum lateral deceleration 20g Maximum longitudinal deceleration 20g
Acceleration Severity Index	Longitudinal, lateral and vertical acceleration of vehicle	Comparison of acceleration level of the vehicle with maximum G levels allowed for restrained occupant	$ASI=\left(\frac{Gx}{Gxd}^2+\frac{Gy}{Gyd}^2+\frac{Gz}{Gzd}^2\right)^{1/2}$ *Gxd* = Longitudinal = 12g *Gyd* = Lateral = 9g *Gzd* = Vertical = 10g

deformation in the passenger compartment. After the occupant makes contact with the interior of the vehicle, he is assumed to remain in contact and experience the same acceleration patterns as the vehicle. This acceleration is called "ride down acceleration." The flail space model evaluates the "ride down" acceleration,

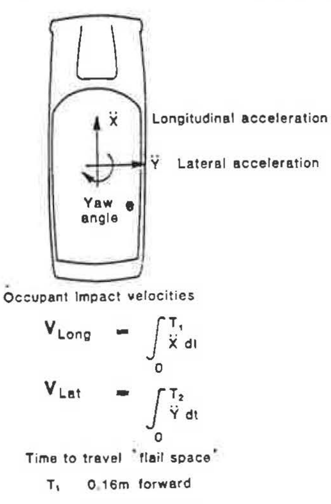

FIGURE 20 Terminology and equations used in the flail space model of NCHRP Report 230.

which is determined separately in the longitudinal and lateral directions from the accelerometer signals. Maximum acceleration limits of 20 gravities are used both for longitudinal and lateral directions.

The THIV model uses the same input parameters as the flail space model with the addition of yaw rotation. This signal filterings used in each model are compared in Appendix F.

The acceleration severity index (ASI) concept was originally derived for applications in space and aero flight. Deceleration to rest was not necessarily considered. This differs both from the THIV and flail space concepts in that it considers both an unrestrained and restrained occupant, the injury being caused by rapid deceleration within the passenger compartment. The ASI value is the root mean square of the signals from accelerometers in longitudinal, lateral, and vertical directions averaged over 0.050-sec intervals taken relative to the given set of maximum acceptable accelerations, as follows:

$$ASI = \left(\frac{G_x^2}{G_xd} + \frac{G_y^2}{G_yd} + \frac{G_z^2}{G_zd}\right)^{1/2} \qquad (11)$$

where

$G_x d$ = maximum tolerable longitudinal acceleration,
$G_y d$ = maximum tolerable lateral acceleration, and
$G_z d$ = maximum tolerable vertical acceleration.

For occupants wearing a seat belt, Germany, Holland, and France use the following limiting values:

$G_x d$ = 12 gravities,
$G_y d$ = 9 gravities, and
$G_z d$ = 10 gravities.

THIV Compared with Other Injury Criteria

The THIV concept has been developed as a criterion for assessing occupant injury in vehicles involved in collisions with roadside barriers or appurtenances. Because most collisions with roadside barriers occur at small angles (0 to 25 degrees), these collisions invariably result in a redirection of the vehicle with lateral acceleration and some angular rotation. This lateral acceleration causes the occupant to initially impact the side, instead of the front, of the passenger compartment. Figure 21 shows the average lateral accelerations during contact produced in cars from full-scale testing of high-containment rigid to flexible barriers against the THIV evaluated for each impact. The lateral accelerations and THIV values are generally higher for smaller cars.

In evaluating vehicle crashworthiness, several injury criteria have been developed using the analysis of output from electronic transducers located inside anthropomorphic test devices (dummies). The HIC and CSI scales are more relevant. In several of the full-scale crash tests on roadside barriers, instrumented test dummies have been installed in the vehicles and the HIC and CSI values have been evaluated. Figure 22 shows these plotted against the THIV evaluated for the same impact tests. A clear correlation is indicated between the THIV values and these injury criteria. This correlation is important, first because it indicates that THIV can be used as a procedure for assessing occupant injury from roadside barrier impacts without the need for using expensive dummies and their associated data recording and analysis systems. Second, the correlation will also assist in determining limiting THIV values from the large amount of data and experience gained from tests on a wide range of safety barriers.

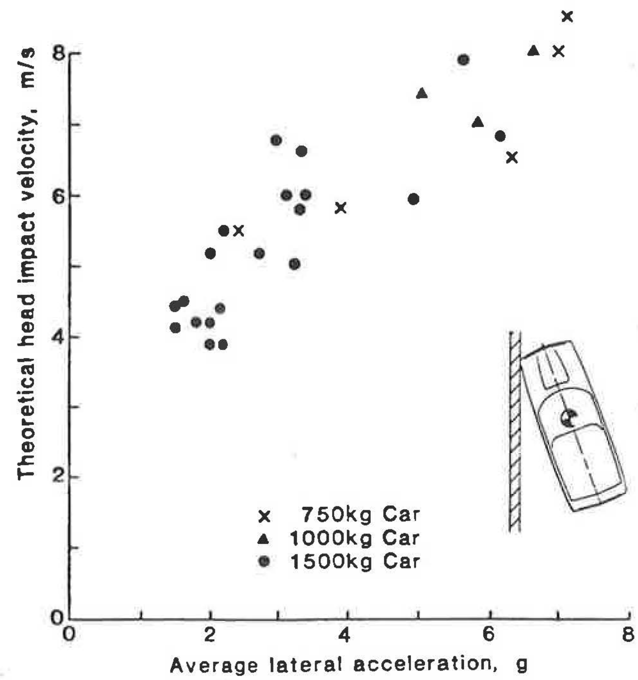

FIGURE 21 THIV versus lateral acceleration for cars impacting with barriers ranging from concrete to flexible steel.

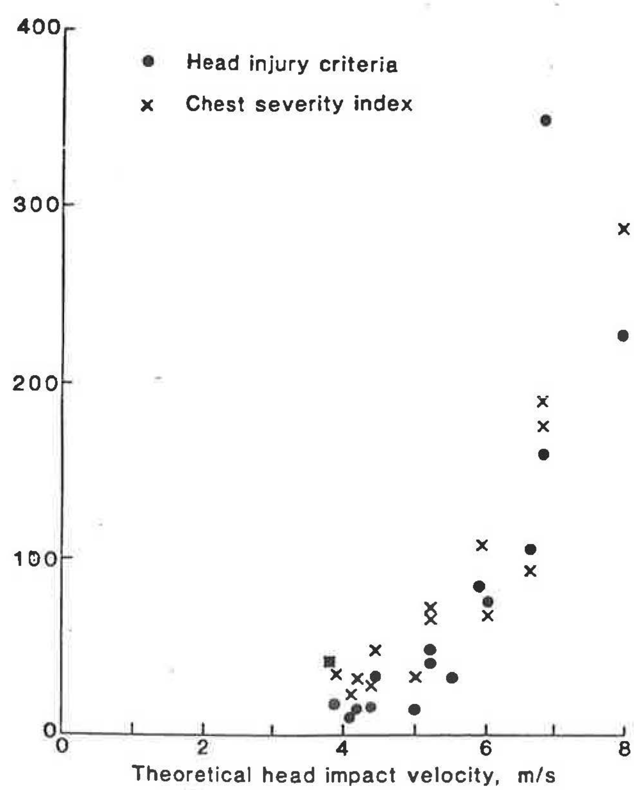

FIGURE 22 Head injury criteria and chest severity index versus THIV for cars impacting with barriers ranging from concrete to flexible steel.

Effects of Vehicle Size

Two major factors that determine THIV values are affected by vehicle size. First, mass and stiffness properties vary with size, affecting the trajectory and velocity of the vehicle after collision with the roadside barrier. Second, internal passenger compartment dimensions will generally increase with the size of the vehicle, altering the occupant position relative to the side and front of the passenger compartment.

In the full-scale roadside barrier testing conducted at Motor Industry Research Association (MIRA), a range of car models was used. For purposes of comparison, the extremes of size are indicated by a small and a large car as shown in Table 17. Both vehicles impacted a rigid barrier at 70 mph at an impact angle of 20 degrees. Figure 23 shows the results of the THIV analysis for both vehicles. The larger car experienced lower deceleration and slower rate of angular rotation. The THIV value is lower at 5.0 m/sec compared to 7.2 m/sec for the smaller car.

THIV analysis has also been conducted for heavier vehicles. Figure 24 shows the THIV results for full-scale crash tests of a 16-ton rigid truck and a 14-ton coach impacting different barriers. The larger and heavier vehicles tend to have lower THIV values (2.8 m/sec both for the truck and the coach). However, care must be taken in evaluating the distance from the occupant to the side of the passenger compartment and in determining whether the occupant will impact the front or side of the passenger compartment first. In these vehicles, the occupants were in the same positions in relation to the passenger compartment. The analysis is capable of calculating a THIV value for any position within the passenger compartment, making it particularly applicable to the different seating positions in coaches and large vehicles.

A large number of full-scale crash tests has been conducted against a variety of different barriers with vehicles of different masses at different speeds and angles. Figure 25 shows the THIV values for cars, 16-ton trucks, and 30-ton trucks impacting rigid barriers.

TABLE 17 RANGE OF VEHICLE PARAMETERS

Vehicle	Mass kg	Nominal Lateral Distance from Occupant to Inside of Passenger Compartment mm
Small car	750	200
Medium/ Large car	1,000-1,500	250
HGV	16,000-38,000	300

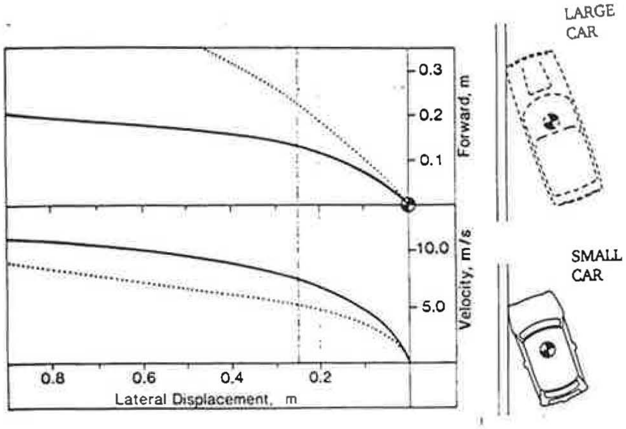

FIGURE 23 Effect of car size on THIV.

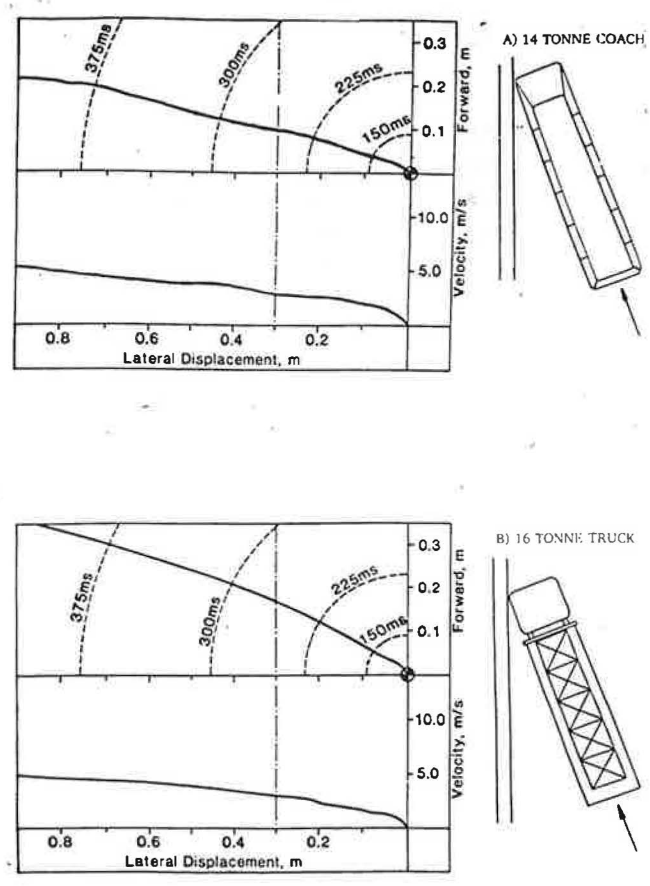

FIGURE 24 Effects of large vehicles on THIV.

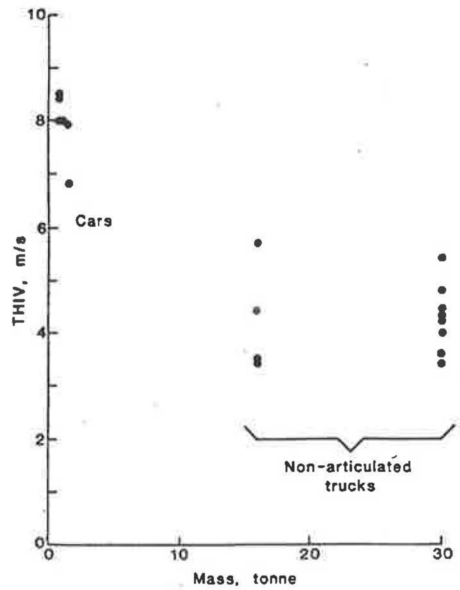

FIGURE 25 THIV versus vehicle mass for vehicles impacting concrete barriers.

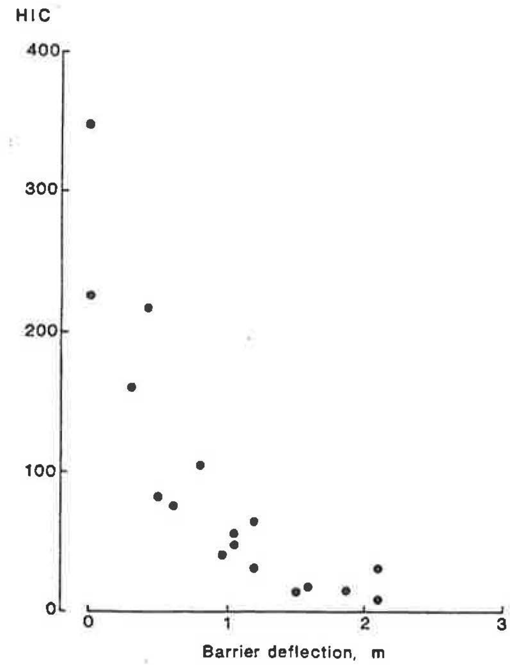

FIGURE 27 Barrier deflection versus HIC of 1500-kg car impacting with barriers ranging from concrete to flexible steel.

Effects of Barrieer Stiffness

Roadside barriers of a variety of stiffnesses have been designed to contain vehicles. With a decrease in barrier stiffness, the vehicle has both a slower rate of deceleration and initially a lower rate of angular rotation. A comparison between rigid and deflecting barriers on THIV is shown in Figure 26. With the deflecting barrier, the THIV is reduced.

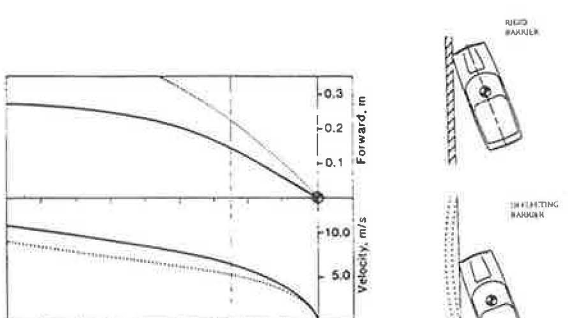

FIGURE 26 Effect of barrier stiffness on THIV.

The effect of increasing barrier deflection can also be seen in Figure 27, which shows head injury versus barrier deflection for a number of full-scale crash tests conducted using large cars against barriers of different stresses. The graph clearly shows a large reduction in the HIC for barrier deflections in the range of 0 to 1 m, with a smaller reduction from 1 to 2 m.

Conclusions

The THIV system has been developed to assess impact severity in vehicles involved in collisions with roadside barriers from full-scale impact tests using a minimal amount of instrumentation. Using filtered outputs from longitudinal and lateral accelerometers and a yaw rate sensor located at the vehicle's center of gravity, the trajectory and velocity of the vehicle can be calculated in relation to that of an unrestrained occupant. The resultant differential velocity of the occupant at impact with the interior of the passenger compartment is the THIV.

The trajectory and resultant velocity of the occupant is displayed in a graphical format that allows the occupant to be positioned anywhere within the passenger compartment.

In evaluating the application of THIV as an occupant injury criterion, the THIV values calculated from crash tests have been compared with the HIC and CSI values measured in instrumented dummies. The good resulting correlation not only indicates that THIV can be used for vehicle occupant impact severity, but the dummy measurement also could be used in determining limiting values of THIV when assessing vehicle and barrier performance. A maximum value of 9 m/sec seems appropriate for roadside barriers.

The effects of varying vehicle mass and size and barrier stiffness have also been investigated. A reduction in THIV value was most noticeable with the increase in mass and size from small to medium or large cars.

THIV has been demonstrated to be a relatively simple parameter to evaluate, yet an effective way of assessing occupant injury in collisions with roadside barriers.