SIMULATION OF VEHICLE IMPACT WITH TEXAS CONCRETE MEDIAN BARRIER: TEST COMPARISONS AND PARAMETER STUDY

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The highway-vehicle-object simulation model, a computer program developed at Cornell Aeronautical Laboratory, has been modified to simulate a vehicle impacting the Texas concrete median barrier at speeds from 50 to 80 mph and angles from 5 to 25 deg. The barrier was impacted by a 4,000-lb sedan for angles of 7, 15, and 25 deg at 60 mph. The results of those full-scale tests were closely approximated by the modified simulation model. Comparisons of simulation and test results are presented in computer-generated drawings of the vehicle during impact, frames from the high-speed film, and plots relating predicted and measured accelerometer readings. After the simulation of the full-scale tests, a parameter study on impact conditions was conducted. The model simulated a 4,780-lb vehicle impacting the barrier at speeds of 50, 70, and 80 mph at angles of 5, 10, and 15 deg for each of those speeds. For speeds less than 70 mph, the results were in line with findings of other researchers. For speeds of 70 mph and greater and impact angles of 15 deg and greater, automobile roll-over can be expected. The results of all simulated impacts with the barrier are presented graphically with regard to a severity index, which quantifies the severity of each crash based on vehicle accelerations.

•EVALUATION of barrier systems usually includes full-scale vehicle crash tests. Those tests are often quite expensive, and many man-hours are required for all phases of the test program. A more ideal method of studying the performance of barriers is by computer simulation.

The original version of the highway-vehicle-object simulation model (HVOSM), which was formerly known as CALSVA (1, 2), was capable of predicting automobile behavior for impact with certain types of barriers, provided the automobile crash was moderate (12 to 18 in.). The types of barrier systems that can be studied with the HVOSM are those whose lateral resistance to vehicle penetration is independent of the longitudinal position of the vehicle contact. The Texas concrete median barrier (CMB) is a rigid barrier and falls within this category. The HVOSM was modified by the Texas Transportation Institute (TTI) to include hard points within the automobile structure. Hard points simulate the effects caused when very stiff automobile members are encountered, such as the engine, a frame member, or a wheel assembly. Basic details of HVOSM (1, 2, 3) and the description of the hard-point modifications (4) are not included in this report.

Comparisons are made between experimental data from full-scale crash tests of the CMB and simulated results from the modified HVOSM (including hard points). The crash test data were obtained from another research program (5) sponsored by the Texas Highway Department. In general, good correlation exists between simulated and experimental results.

A parametric study of the CMB was conducted by using the HVOSM, and the results are described. The parametric study was used to determine the barrier's performance characteristics for a range of vehicle encroachment conditions. Factors used in measuring the performance were the vehicle's exit angle, maximum pitch and roll angle, and a severity index that quantified the impact severity.

COMPARISON OF EXPERIMENTAL DATA WITH PREDICTIONS BY HVOSM

Sponsors and researchers felt that a good correlation between simulation and testing was a prerequisite to conducting parametric studies of the CMB with the HVOSM.

The 3 tests used in the comparisons (5) consisted of passenger cars (roughly 4,000-lb in weight) being towed into a full-scale model of the CMB, model I-70 (designated CMBI-70), at approximately 60 mph for impact angles of 7, 15, and 25 deg. The CMBI-70 designation is used when illumination poles are placed atop the barrier. The exterior dimensions of the barrier are the same, however, whether illumination is used or not. Accelerometers were mounted to the structural framework of the vehicles and were oriented to measure the lateral and the longitudinal components of vehicle acceleration. Vehicle motion was recorded on high-speed film from rear, side, and overhead views. These films were used to determine the automobile's speed and angle at impact and to provide a comparison of the vehicle's simulated and actual motion.

As explained earlier, the computer simulation used was a modified version of the HVOSM (4). Certain limitations dictated the description of the CMB by a combination (or superposition) of the program's "curb impact" and "barrier impact" capabilities. As shown in Figure 1, the sloping face of the barrier was simulated as a curb (line 1-2), and the upright face was simulated as a vertical rigid barrier (line 2-3). In the simulation, tire-curb interaction is accounted for, but tire-rigid barrier interaction is not. However, since good comparisons between simulations and tests were obtained (for both kinematics and accelerometers), it would appear that tire contact with the upright face is of secondary importance. For the same reason, the omission of slope 4-5 (Fig. 1) was apparently not detrimental to the simulation. This is not surprising in view of the relative dimensions of the tires to the length of line 4-5 and the high impact speeds. Likewise, idealizing the upright face as vertical rather than sloped a few degrees proved to be adequate representation. For the shallow angle impact of 7 deg, the whole barrier could have been defined as one high curb (1), but for the sake of uniformity all cases were defined as described above.

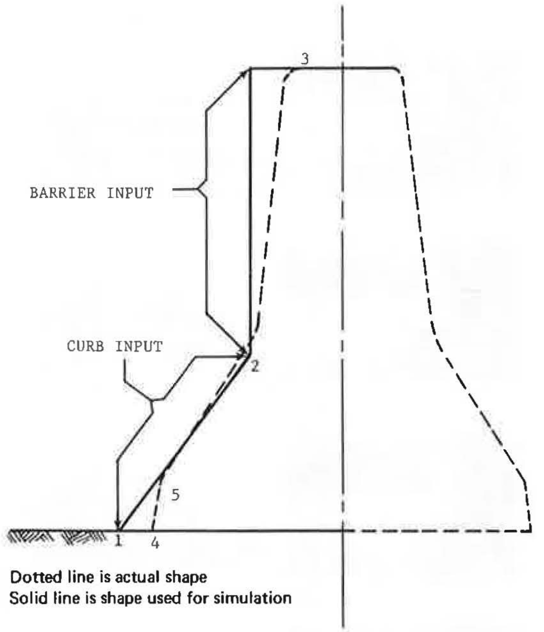
Data corresponding to the CMB and the test vehicles, such as vehicle weight, barrier and vehicle dimensions, and impact speed and angle, were read into the HVOSM program. All computer input data are documented elsewhere (6).

Plots of the predicted and measured acceleration components at points corresponding to the locations of accelerometers in the actual vehicle were made. Drawings of the simulated impacts were generated by a computer program (7). The program produces a perspective drawing of the vehicle and barrier at selected times, using vehicle position as determined from the HVOSM. These line drawings were then compared with corresponding photographs taken from the high-speed photography of the test.

The results of the comparisons are shown in Figures 2 through 7. The test results are for a vehicle impacting on the left (driver) side of the vehicle, while the simulation is on the opposite (passenger) side. For this reason, the accelerometer results are expressed in terms of impact side of the vehicle. Time of initial impact was taken as zero, and the times shown on the figures are with respect to impact time. Comparisons were stopped when the vehicle lost contact with the barrier.

The comparison of test photographs and computer drawings shown in Figures 2, 3, and 4 is very good for all 3 tests. Comparing the wheel positions, height of climb, and relative position of vehicle body to the ground shows that the simulation accurately computed the motions of the test vehicle. The small differences observable between the positions of simulated and actual vehicles is largely attributable to a standard automobile that was used for all the computer drawings and that was not necessarily of the same dimensions as the actual test vehicles. A second noticeable discrepancy is the appearance of the simulated vehicle to penetrate the barrier in a few instances. The program that produces the computer drawing cannot show sheet metal crushing, although it is accounted for in the HVOSM.

Figure 1. Idealization of CMBI-70 for computer simulation.



Dotted line is actual shape
Solid line is shape used for simulation

Figure 2. Simulation and test results for 4,000-lb vehicle impacting CMB at 63 mph and 25 deg.

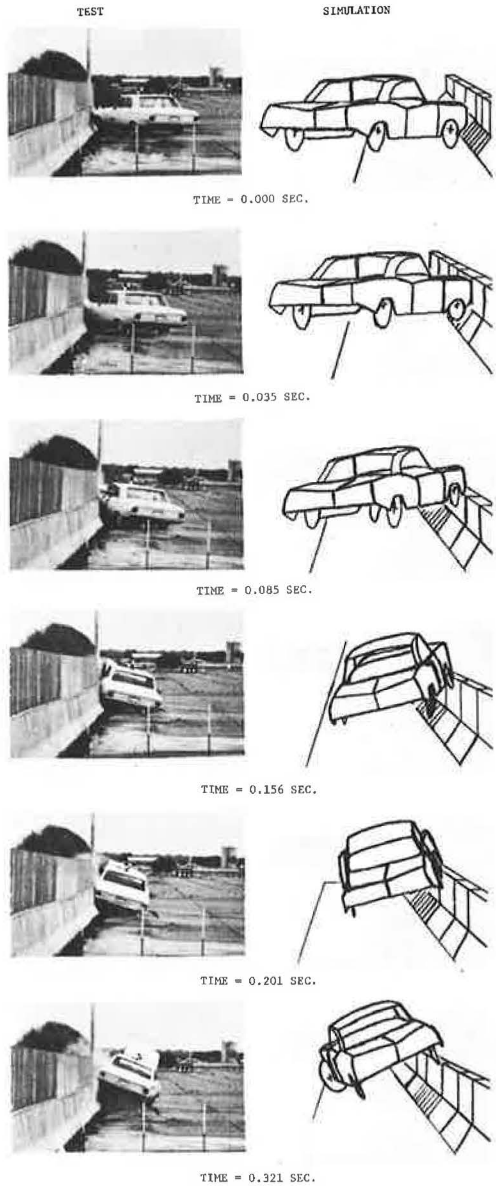


Figure 3. Simulation and test results for 4,210-lb vehicle impacting CMB at 59.6 mph and 15 deg.

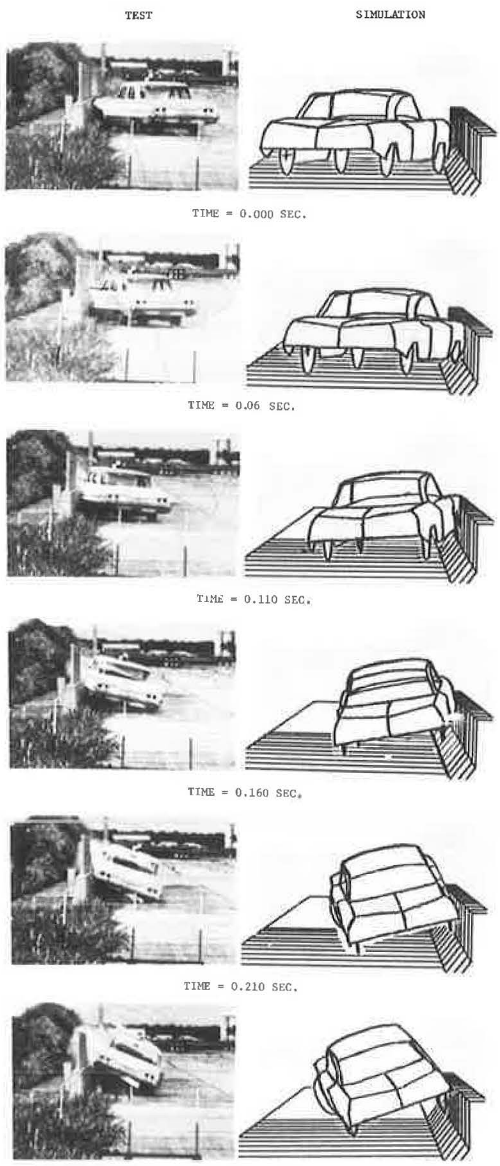


Figure 4. Simulation and test results for 4,210-lb vehicle impacting CMB at 61.9 mph and 7 deg.

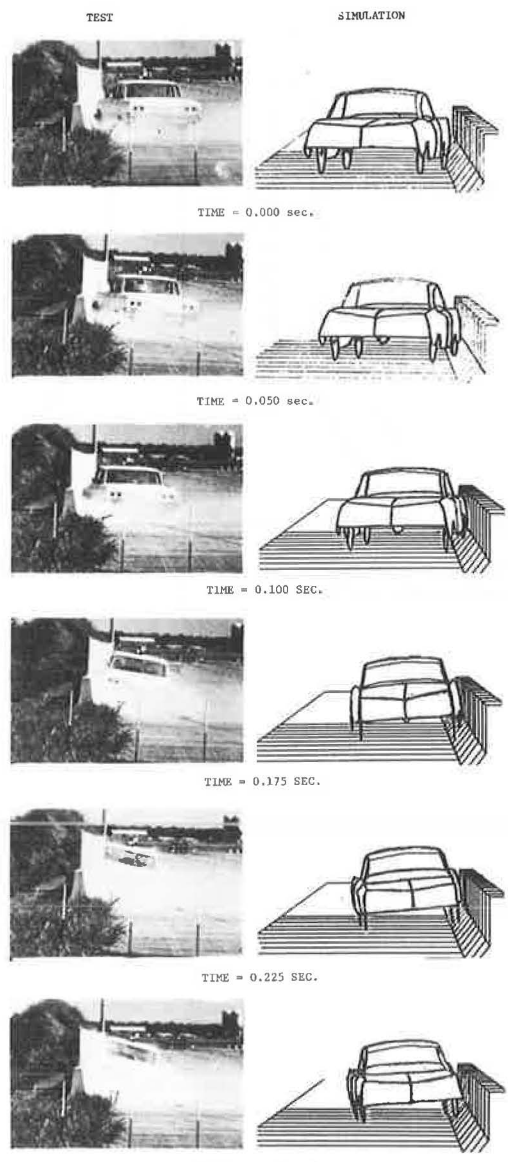


Figure 5. Acceleration on impact side of 4,000-lb vehicle at 63 mph and 25 deg.

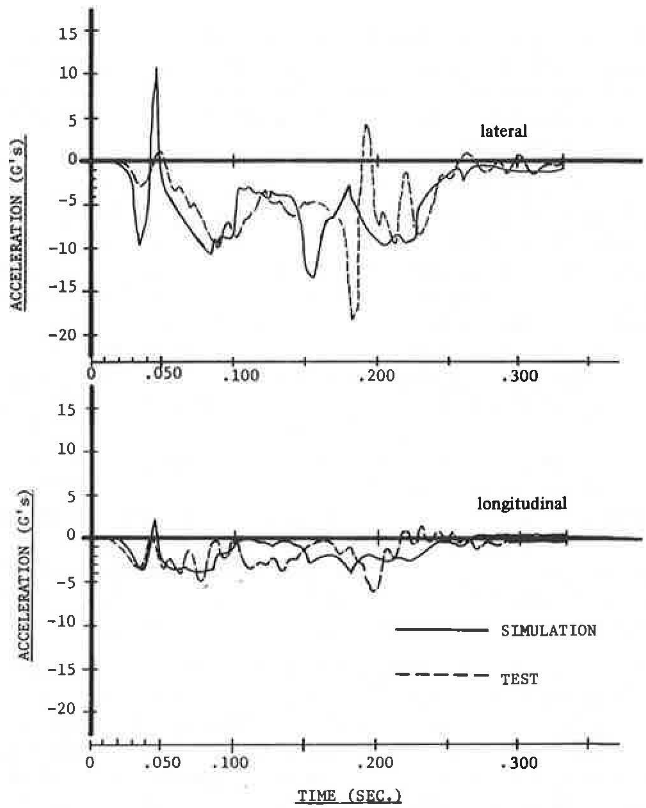
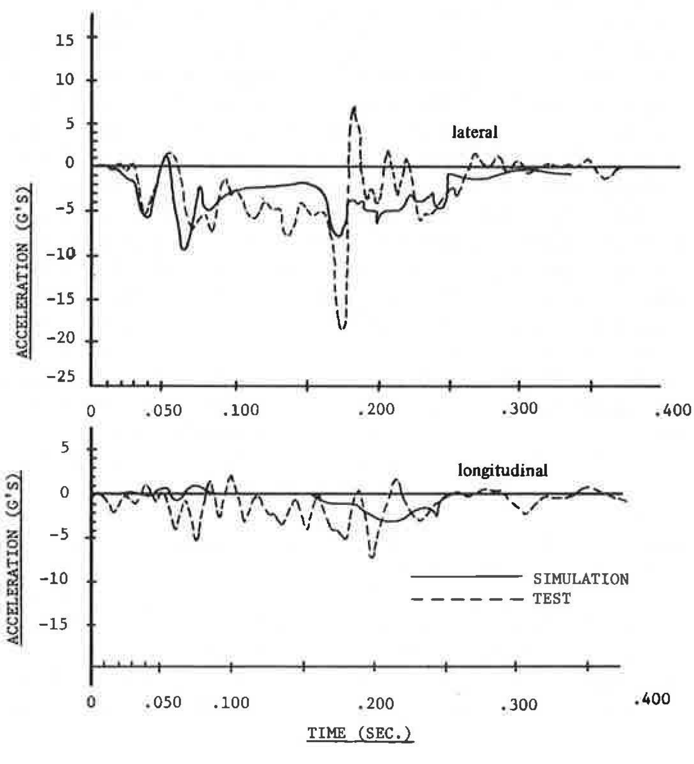


Figure 6. Acceleration on impact side of 4,210-lb vehicle at 59.6 mph and 15 deg.



The comparisons of simulated and measured acceleration components shown in Figures 5 and 6 can be considered good, whereas the comparison shown in Figure 7 can only be considered poor. Fortunately, the discrepancies occurring in all 3 cases, whether slight or major, can be explained in terms of 2 basic differences between the actual and simulated vehicles.

1. The actual vehicle structure comprises structural subassemblies, each possessing its own vibrational characteristics (natural frequencies and damping). However, the simulated vehicle structure (wheels and suspension systems excluded) is a rigid mass that is undamped and free of natural frequencies of vibration. Therefore, the actual accelerometers will respond to those structural vibrations that do not contribute to vehicle redirection and, accordingly, will not be felt by an occupant. Correspondingly, the simulated accelerometers respond only to those actions that cause vehicle redirection or rigid body motion because the simulation is devoid of structural vibrations except those stemming from the wheels and suspension systems.
2. In the actual case, the effect of a force applied to the vehicle structure is diminished or damped before reaching an accelerometer located some distance away from the point of application. In some cases, if the distance is large enough and the force is of short duration, the effect may be damped out completely and, hence, undetected by the accelerometer. However, in the simulated case, all forces applied to the vehicle structure are transferred to the center of gravity of the rigid body as an equivalent force-couple system such that all simulated accelerometers respond instantaneously regardless of their location on the structure.

The simulated lateral accelerometer traces shown in Figure 5 exhibit an oscillation of ±11 g between 30 and 50 msec, which was not recorded by the test accelerometers. That is caused by the front wheel violently engaging the suspension bumper stops as it first hits the barrier at the large impact angle of 25 deg. The same probably occurred in the test, but, because the accelerometers were located about 6.5 ft behind the front wheel (just ahead of the rear wheel mounted to the frame member), the effects of those short-duration forces were largely damped out before reaching the accelerometers.

The test lateral accelerometer traces shown in Figures 5 and 6 reveal oscillations between 175 and 200 msec, which were not predicted by the simulation. Those represent structural vibrations of the frame member, to which the accelerometers were mounted, and were induced by oscillations of the rear axle assembly when the rear wheel encountered the barrier. All of the differences in accelerations explained thus far were vibrational in nature and produced negligible net changes in velocity and, hence, did not contribute to vehicle redirection. This is upheld by the fact that the comparisons of vehicle position are excellent (Figs. 2, 3, and 4).

The huge spike appearing in Figure 7 has 2 possible explanations. First, it is highly probably that this spike is also the result of a structural vibration caused by the rear wheel impacting the barrier. The vibration could have been critically damped, explaining the existence of only 1 spike. Furthermore, the reason that higher levels were recorded for this test, although it was less severe (only slight sheet metal damage), could be a result of the accelerometers being more directly aligned with the blow because of the small pitch and roll motions of the vehicle. If this explanation is accepted, the spike can be disregarded as not contributing to redirection of the vehicle, and the accelerometer comparison can be considered good.

However, as a second explanation, it is conceivable that initial tire contact caused the vehicle to rotate (yaw) parallel to the barrier without appreciably changing the vehicle's velocity vector (magnitude or direction). The vehicle would then have impacted the barrier in this position, causing an abrupt change in lateral velocity. In fact, for 60 mph at 7 deg, the component of velocity normal to the barrier is 10.7 ft/sec, which corresponds to the area under the spike in question. This comparison is justifiable in this case because the car was parallel to the barrier when the spike occurred. If this explanation is accepted, the question remains as to whether this is a reproducible phenomenon or an abnormality. Until this question is answered, the HVOSM accelerometer results cannot be discounted, especially because good accelerometer comparisons were achieved for the 2 higher angles of impact, and good vehicle position comparisons were attained for all 3 tests.

Considering all facets of the comparison, it can be concluded that the HVOSM (with added structural hard points) provides a good simulation of an automobile impacting a rigid barrier of the CMB type. Hence, it follows that the results of the parameter study can be treated with added confidence.

PARAMETER STUDY

The modified version of the HVOSM computer program (4) was used to study the dynamic behavior of an automobile impacting the CMB. The objective of the parametric study was to determine the performance characteristics of the CMB for a range of vehicle encroachment conditions. Factors used to measure barrier performance consisted of the vehicle's exit angle, maximum pitch and roll angle, and an index to quantify the severity.

Severity Index

The automobile acceleration severity index (SI) was used to quantify the relative severity of an automobile impacting a traffic barrier. The severity index takes into consideration the combined effects of the longitudinal, lateral, and vertical accelerations of the automobile at its center of mass. The SI is computed as follows:

$$SI = \sqrt{\left(\frac{G_{LONG}}{G_{XL}}\right)^2 + \left(\frac{G_{LAT}}{G_{YL}}\right)^2 + \left(\frac{G_{VERT}}{G_{ZL}}\right)^2} \quad (1)$$

The terms in the numerator are the computed or measured accelerations of the automobile, and the terms in the denominator are the limit or tolerable accelerations of the automobile.

An in-depth discussion of the background and development of Eq. 1 is given in another report (9). Information relating tolerable accelerations to degree of occupant restraint, rate of onset or rise time, and time duration of accelerations is included in that discussion. In the study presented here, the tolerable accelerations were for an unrestrained occupant, rise times greater than 0.03 sec, and a time duration of 0.050 sec. The limit or tolerable accelerations for these conditions (9) are assumed to be

$$G_{XL} = 7 \text{ g}$$
$$G_{YL} = 5 \text{ g}$$
$$G_{ZL} = 6 \text{ g} \quad (2)$$

There has been much discussion of the relation of the severity index to the probable level of occupant injury. The authors have interpreted an SI of unity to imply that occupants will sustain injuries that border on the serious type. Until more data are available on limit accelerations and the interaction relation itself, there appears to be no other logical way to interpret the index.

In addition, vehicle accelerations have never been translated into expected g levels on the occupant, and until such a correlation becomes available the possible applications of the severity index must be qualified. The index in its present form is intended for comparing the severity of one event to another and can also serve as an aid in making decisions concerning highway modifications that should effect a reduction in occupant injury and loss of life. However, it must be emphasized that the index, as defined by TTI researchers (here or elsewhere), has never been intended for direct assessment of human injury and, therefore, should not be used in that regard.

Simulations

Nine different automobile impacts with the CMB were simulated. The impact speeds were 50, 70, and 80 mph, and for each speed there were 3 impact angles: 5, 10, and 15 deg. The simulated automobile had the properties of a 1963 Ford Galaxie weighing 4,780 lb. Also included in this phase of the study were the 3 impacts simulated in the validation study at angles of 7, 15, and 25 deg and an impact speed of approximately 60 mph. These 12 different impact conditions are representative of the majority of accidents involving traffic barriers. The results of the 12 runs are given in Table 1.

All impact data for the computer runs, including vehicle and barrier information, are reported elsewhere (6). Some of the significant parameters are as follows: hard-point stiffness, 2,500 lb/in.; sheet metal crushing coefficient, 2 lb/in.^{3}; automobile-barrier coefficient of friction, 0.3; and tire-curb coefficient of friction, 0.50.

In some instances, the roll angle of the vehicle was still increasing at the termination of the computer run. Rather than rerun those cases (which would have been uneconomical), a formula was developed to estimate the roll angle beyond the termination point. This relation was used to determine the maximum roll angle and thereby determine whether roll-over would have occurred. Its derivation is shown in Figure 8.

Barrier Performance

Model simulation indicates that the vehicle will roll over during a collision with a CMB at impact speeds of 70 and 80 mph and an impact angle of 15 deg. Also, at 63 mph and 25 deg the vehicle is very near roll-over. The roll angle given in Table 1 is the maximum roll angle of the automobile and may or may not occur when the automobile is in contact with the barrier.

The maximum pitch angle of the automobile appears more sensitive to impact angle than to impact speed (Table 1). In any event, the pitch angle remains small for any angle of impact and appears to be insignificant when the motion of the automobile is considered.

Height of the front tire climb on the face of the CMB is given in Table 1. During a 5-deg collision, the front tire of the automobile climbs roughly 5 to 7 in. on the lower inclined CMB surface; and, during a 10-deg collision, the tire climbs roughly 9 to 12 in. on the lower surface. As indicated, the climb height was not available in some cases because tire-rigid barrier interaction is not accounted for in the HVOSM. However, based on an analysis of the output, it is doubtful that the tire climb would have exceeded the height of the barrier in those cases.

A desirable characteristic of a traffic barrier is that a colliding automobile be redirected at a shallow exit angle in order to minimize the danger to traffic. The exit angles given in Table 1 were determined at the time the vehicle lost contact with the barrier. The exit angle appears to be more sensitive to impact angle than to impact speed. In all cases, however, the exit angles were shallow.

Another criterion used to determine barrier performance was the relative severity of the impact as measured by automobile accelerations. A severity index is given in Table 1 for each of the 12 runs studied. Figure 9 shows the severity index versus impact angle for 4 impact speeds. The apparent inconsistency of the 60-mph case is attributable to the differences in vehicle weight and dimensions. For speeds of 50, 70, and 80 mph the vehicle weighed 4,780 lb; in the 60-mph case, the vehicle weighed 4,210 lb. The hard-point stiffness, sheet metal crushing coefficient, automobile-barrier coefficient of friction, and tire-curb coefficient of friction were the same for all 4 speeds. The results, therefore, suggest that the severity of a lighter vehicle impacting the barrier may be more than that of a heavier vehicle, all other factors being the same.

Figure 10 shows impact speed versus impact angle for a severity index of 1.0. The 4 points on the curve were obtained from the intersection of the SI = 1.0 line with the 4 respective speed curves shown in Figure 9. The data may be useful in selecting roadway locations where the CMB can be safely used. For a given roadway, an upper limit on impact angle can be estimated (8) as a function of the roadway's design speed and surface conditions and the distance from the roadway to the barrier. If the combination of design (or impact) speed and impact angle falls above the curve, it may be advisable to select a more flexible barrier.

Figure 7. Acceleration on impact side of 4,210-lb vehicle at 61.9 mph and 7 deg.

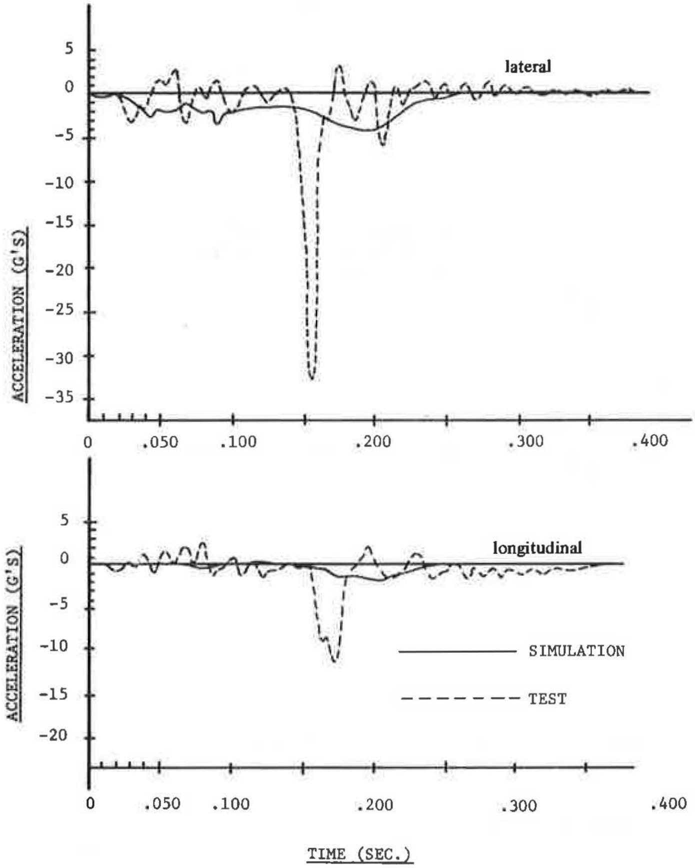
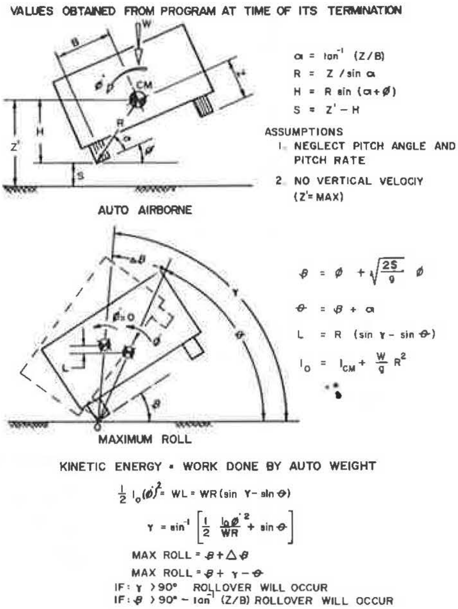


Figure 8. Estimation of maximum roll angle.



$$\vartheta = \phi + \sqrt{\frac{2S}{g}}\,\dot{\phi}$$
$$\theta = \vartheta + \alpha$$
$$L = R\,(\sin\gamma - \sin\theta)$$
$$I_O = I_{CM} + \frac{W}{g}R^2$$
$$\frac{1}{2} I_o(\dot{\phi})^2 = WL = WR(\sin\gamma - \sin\theta)$$
$$\gamma = \sin^{-1}\left[\frac{1}{2}\frac{I_o\dot{\phi}^2}{WR} + \sin\theta\right]$$

Table 1. Results of CMB simulations.

Run	Auto Weight (lb)	Impact Conditions: Speed (mph)	Impact Conditions: Angle (deg)	Automobile Kinematics: Max Roll (deg)	Automobile Kinematics: Max Pitch (deg)	Automobile Kinematics: Front Tire Climb (in.)	Automobile Kinematics: Exit Angle[a] (deg)	Avg Accelerations During Primary Impact: G_{long}	Avg Accelerations During Primary Impact: G_{lat}	Avg Accelerations During Primary Impact: G_{vert}	Severity Index
1	4,780	50.0	5.0	1.3	0.9	4.6	1.1	0.49	1.61	0.12	0.33
2	4,780	70.0	5.0	2.2	1.5	6.5	0.3	0.72	2.53	0.43	0.52
3	4,780	80.0	5.0	3.3	1.8	7.1	0.1	0.21	2.90	0.54	0.58
4	4,780	50.0	10.0	4.2	3.2	8.6	2.5	1.13	2.99	0.94	0.64
5	4,780	70.0	10.0	19.5[b]	5.0	11.2	1.2	0.16	5.06	2.03	1.07
6	4,780	80.0	10.0	34.6[b]	5.8	12.6	1.2	1.92	6.42	2.61	1.38
7	4,780	50.0	15.0	15.0[b]	6.5	11.9	3.6	0.47	4.29	1.38	0.91
8	4,780	70.0	15.0	RO[c]	6.6	NA[d]	2.7	2.81	6.44	3.16	1.45
9	4,780	80.0	15.0	RO[c]	6.1	NA[d]	2.9	3.24	7.49	3.29	1.66
10	4,210	61.9	7.0	4.7	2.3	7.4	2.2	1.07	3.21	0.64	0.67
11	4,210	59.6	15.0	21.0[b]	8.2	13.2	5.5	2.78	6.86	2.92	1.48
12	4,000	63.0	25.0	37.0	8.6	NA[d]	5.1	6.47	11.23	4.38	2.54

[a]When vehicle loses contact with barrier.
[b]Estimated roll obtained by energy expression using initial conditions from computer simulation at the time it was terminated.
[c]Roll-over.
[d]Not available.

Figure 9. Severity index of CMB as related to vehicle encroachment conditions.

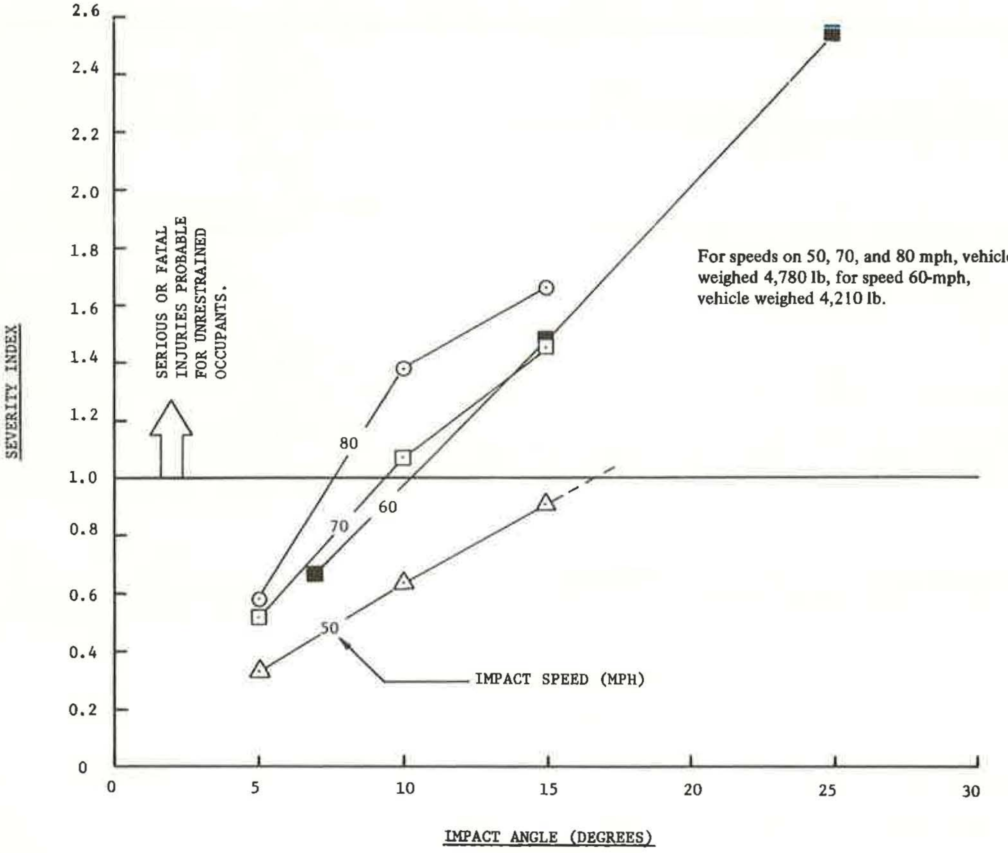
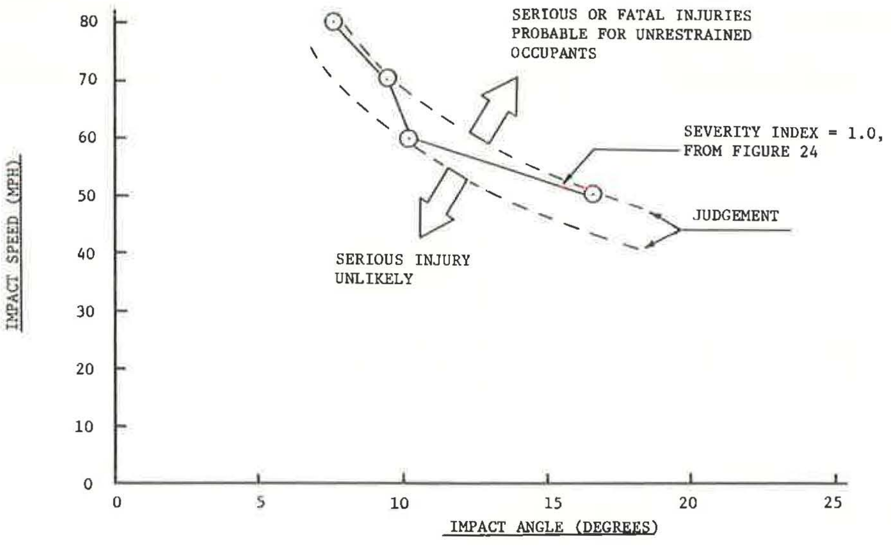


Figure 10. Relation of encroachment conditions at severity index near unity for CMB.



SUMMARY OF RESULTS

1. The impact subroutines of HVOSM were modified by TTI to account for the effects of hard-point contacts (frame members, motor block) that occur when large vehicle deformations occur.

2. The modified HVOSM computer program (with hard points) can accurately predict automobile accelerations, motions, and external forces due to an impact with the CMB. This conclusion is based on a good correlation that was obtained between full-scale test results and simulations by HVOSM.

3. As a result of a parametric study with HVOSM, the following conclusions are made with regard to the CMB performance:

a. For impact speeds of 70 mph and greater and impact angles of 15 deg and greater, automobile roll-over can be expected;

b. For impact speeds of 80 mph and less and impact angles of 15 deg and less, there was no tendency for the automobile to vault or climb over the barrier;

c. In each of the 12 impact conditions studied, the automobile's exit angle was shallow after impact with the barrier; and

d. A graphical presentation was made of the impact angles and speeds for which the barrier can presumably redirect an automobile without serious injuries to the occupants.

ACKNOWLEDGMENTS

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