Prediction of Rollovers Caused by Concrete Safety-Shape Barriers

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Based on five full-scale crash tests and a series of computer simulations, the performance of the concrete safety-shape barrier (CSSB) with the New Jersey profile was found to be acceptable for impact conditions recommended in *NCHRP Report 230* for evaluation of safety appurtenances. Vehicle sizes ranged from minicars weighing 1,250 lb to large cars weighing 4,500 lb. All tests recommended in *NCHRP Report 230* are conducted with the vehicle impacting in a tracking mode; however, it is estimated that approximately 50 percent of inadvertent off-the-road vehicle encroachments occur in a nontracking mode. Hence, a modified version of the Highway-Vehicle-Object-Simulation Model (HVOSM) was used in studying the performance of the CSSB for nontracking and tracking impacts with high angle/speed combinations. The modified HVOSM program was subjected to an extensive calibration effort and found to produce reasonably accurate results. It was determined that overturns can be expected for small cars in nontracking and/or high angle impacts with the CSSB. Performance of potential new shapes of rigid longitudinal barriers were also studied. A barrier with a constant-slope face or a vertical wall will greatly reduce the overturn problem. A retrofit design for the CSSB consisting of a longitudinal member placed on the side of the barrier near the top also showed promise in reducing this problem.

Concrete safety-shape barrier (CSSB) initially appeared on U.S. highways as a median barrier and is now widely used as a roadside barrier, bridge railing, and temporary barrier in construction or work zones. The "New Jersey" shape (see Figure 1) (AASHTO MB5) is the most common CSSB in use. Therefore, this shape was selected for the study described in this paper.

Small car accident data from a variety of studies were examined in a recently completed study by Council et al. (*1*). It was found that small vehicles have an increased propensity to overturn in almost all types of accidents, including impacts with the CSSB. However, a series of computer simulations and five full-scale crash tests conducted in accordance with *NCHRP Report 230* recommendations (*2*) gave no indication of increased overturn propensity for small and minicars (*3*). Therefore, an attempt was made to investigate the disparity between these results and evidence from accident studies. As reported by Deleys and Parada (*4*), a large percentage of single-vehicle accidents involve a skidding or nontracking vehicle. Hence, it was decided to make a series of computer runs to study the impact behavior of small cars as well as large cars for nontracking impacts with CSSB. Tracking impacts at lower speeds and higher impact angles than those recommended in *NCHRP Report 230* were also given attention.

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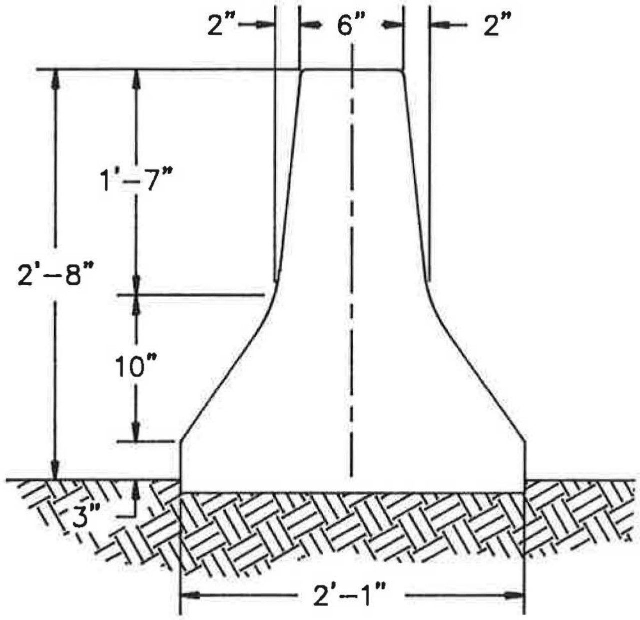
HVOSM COMPUTER PROGRAM, THE SIMULATION TOOL

Two computer programs—Highway-Vehicle-Object-Simulation Model (HVOSM) (*5*) and GUARD (*6*)—were considered as candidates for the simulation of impacts with the CSSB. Both have three-dimensional response capabilities, a necessity for studying the potential for vehicular overturn following impact with the CSSB. Both also have limitations with regard to simulation of the CSSB; neither program can accurately simulate the tire scrubbing forces that occur during impacts. The suspension model used in GUARD is quite limited compared with that used in the HVOSM. In the HVOSM, the vehicle's tire can interact with the sloped face of the CSSB, but the sheet metal can only interact with a vertical wall.

Previous studies with the HVOSM of CSSB impacts have met with reasonably good success (*7, 8*). The version of the HVOSM used in these studies was one modified by the Texas Transportation Institute (TTI) to include "hard points" within the vehicle's structure (*7*). In all of these studies, however, special calibration techniques were used due to inherent limitations of the HVOSM. A major limitation involved the assumption that a barrier with a vertical wall greatly reduces the overturn problem. A key variable in previous calibration efforts was the lateral location of the vertical wall.

Hence, as part of a research project undertaken by TTI to study roadside safety design for small vehicles, the RD2 version of the HVOSM (*5*) was modified to permit the vehicle's structure to interact with the sloped faces of the CSSB or other shaped barriers. Perera (*9*) and Ross et al (*3*) provide complete details of the modifications. A paper in this Record describes the development and validation of the modified HVOSM program.

Even with the above modifications, limitations still remain regarding the simulation of impacts with a rigid barrier, and, in particular, impacts with the CSSB. A major limitation lies with the tire and suspension models and with the data describing their characteristics. During impact, the leading tire and associated suspension system is typically subjected to extremely high loads and loading rates. This results in large displacements and usually structural failure in the form of bent rims and a wheel jammed up and back from its normal position. Little data are available on tire and suspension system damping properties for high loading rates. The models simply are not designed to simulate structural failures. These limitations notwithstanding, the HVOSM program is a useful tool, when properly calibrated, in the analysis of barrier and vehicle parameters as they affect impact performance.



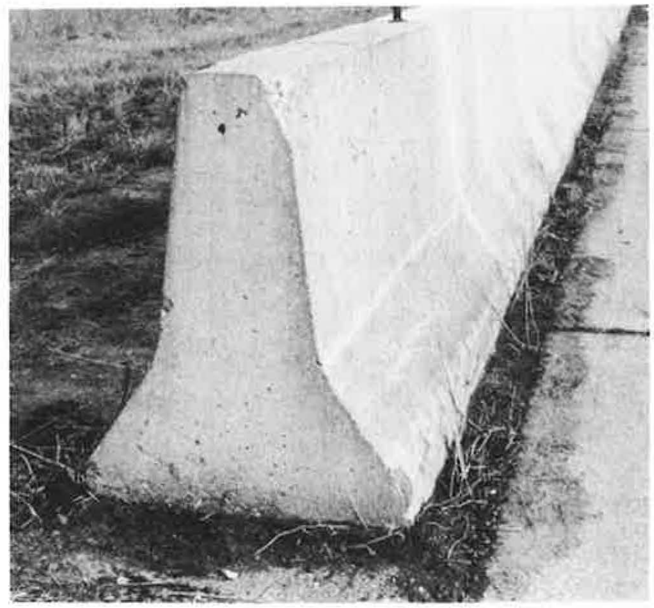


FIGURE 1 Concrete safety-shape barrier with the New Jersey profile.

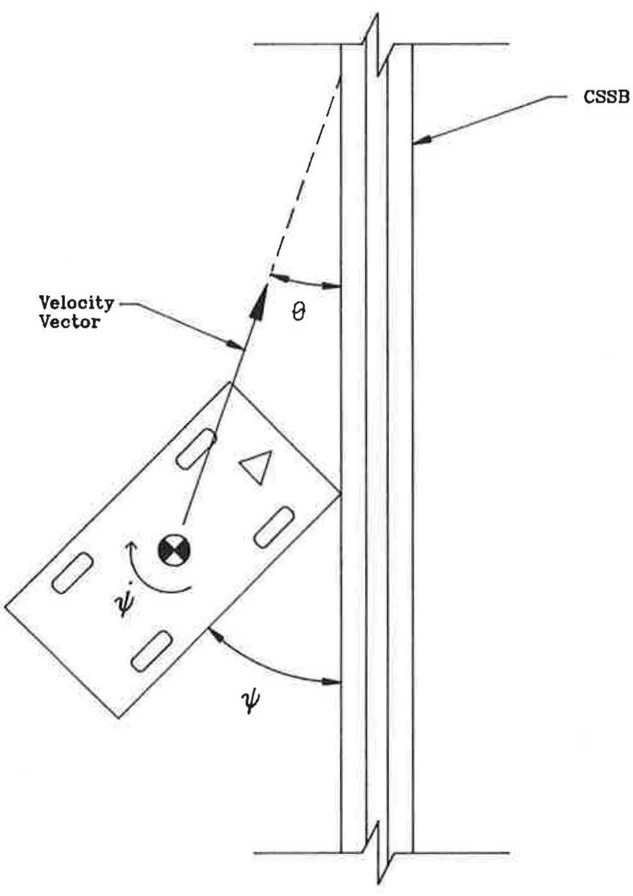


FIGURE 2 Nontracking impact parameters.

Unfortunately, nontracking impacts could not be included in the calibration of the program due to the void in full-scale crash tests involving nontracking conditions. High angle impact tests are also rarely conducted; however, during the validation effort a low speed, high angle test of a Honda Civic on a CSSB (*10*) was simulated and the program accurately predicted the resulted rollover. The impact speed was 27.4 mph and the impact angle was 52°. The test vehicle rode up the barrier and across the face while rolling away from the barrier. It continued to roll over onto its side away from the barrier and stopped, lying on the camera rack hung on the right window, which prevented it from rolling over. The vehicle came to rest with its heading direction making an angle of 69° with the centerline of the barrier, resulting in a net yaw displacement of 17°. The program accurately predicted the rollover away from the barrier, and the predicted yaw dispacement was 11.5° when the roll angle was at 90°.

PREDICTIONS OF ROLLOVER

Vehicles impact barriers at various angle/speed combinations in a tracking condition, but a large percentage of vehicles strike barriers in a nontracking condition. Therefore, a series of HVOSM runs was made to estimate vehicle performance for these atypical conditions. The purpose of these runs was to examine the stability after impact and to predict rollover.

For purposes of analysis and characterization of vehicular stability, six terms are used in the figures that follow. They are defined, somewhat arbitrarily, as follows:

- *Stable.* Vehicle is redirected.
- *Stop.* While still in contact with the barrier, the vehicle almost comes to a stop, with the heading angle ψ (see Figure 2) attaining an approximate constant value close to 90°.
- *Sideslip.* With reference to Figure 3, the vehicle is sideslipping when $\tan^{-1} [|v|/u] > 20°$.
- *Spinout.* With reference to Figures 2 and 3, the vehicle spins out when $u \leq 0$, and the heading angle $\psi > 90°$.
- *Marginal.* Response is marginal when roll and/or pitch displacement exceeds 40° but the vehicle does not overturn. See Figure 4 for definitions of angular displacements.
- *Overturn.* When angular displacement in the roll and/or pitch direction is 90° or more, the vehicle has overturned.

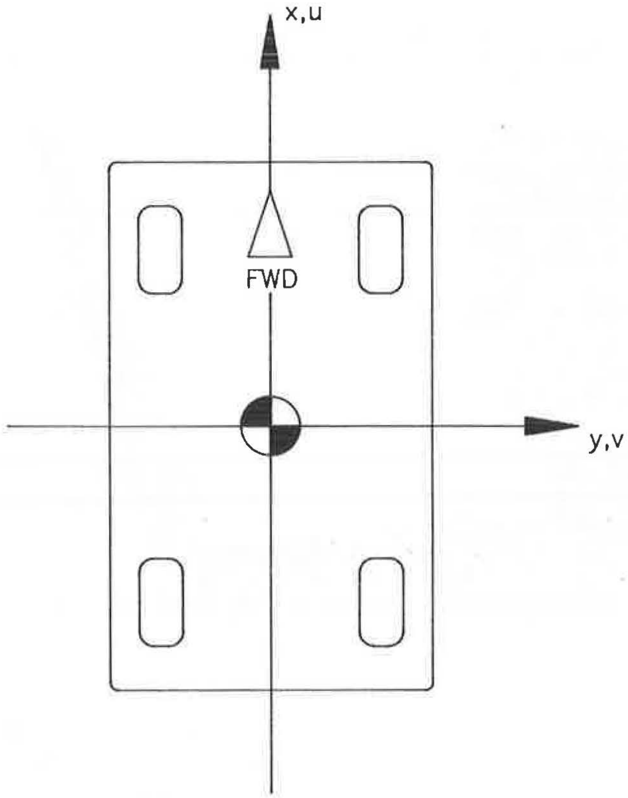


FIGURE 3 Vehicle velocity components: u = vehicle velocity component, x direction; v = vehicle velocity component, y direction; sideslip angle = $\tan^{-1} |v|/u$.

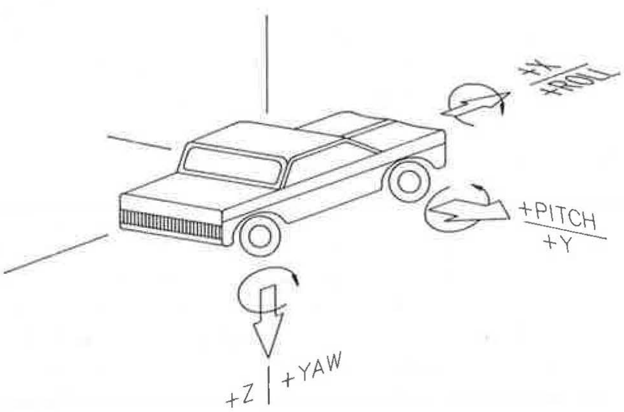


FIGURE 4 Positive sign convention for vehicular displacements.

The rationale for using an angle and the threshold value of 20° in the definition of sideslip is that the angle formed between the longitudinal axis of the vehicle and the vehicle velocity vector at some specified point in the vehicle is known as the "sideslip angle" (*11*). The "slip angle," on the other hand, is defined as the angle formed between direction of wheel travel and the line of intersection of wheel plane with the road surface (*11, 12*). Therefore, the sideslip angle at the wheel becomes the same as the slip angle, for zero wheel steer. The cornering force at the tire-road contact patch is a function of the slip angle; when it reaches a maximum, the tire begins sliding laterally (*12*). Hence, the threshold for sideslip of the tire is the slip angle at which the cornering force becomes a maximum. After a careful review of typical cornering force versus slip angle plots, a conservative value of 20° was chosen for the threshold slip angle. For simplicity and convenience, the threshold value of the sideslip angle at the vehicle center of mass is also considered to be equal to 20°, as stated in the above definition of the sideslip condition.

TABLE 1 STABILITY STUDY FOR HIGH SPEED/ANGLE TRACKING IMPACTS WITH CSSB

Angle	Speed (mph)		
(deg)	30	45	60
Fiat Uno-45 (1,560 lb)			
35	Stable	Stable	Stable
45	Stable	Marginal	Overturn
60	Overturn	Overturn	Overturn
Daihatsu Domino (1,280 lb)			
35	Stable	Stable	Stable
45	Spinout	Spinout	Marginal
60	Overturn	Overturn	Overturn
Chevrolet Sprint (1,530 lb)			
35	Stable	Stable	Stable
45	Sideslip	Marginal	Overturn
60	Overturn	Overturn	Overturn
Honda Civic (1,800 lb)			
35	Stable	Stable	Stable
45	Marginal	Overturn	Overturn
60	Overturn	Overturn	Overturn
Plymouth Fury (4,500 lb)			
35	Stable	Stable	Stable
45	Sideslip	Sideslip	Sideslip
60	Sideslip	Sideslip	Sideslip
75	Stop	Stop	Stop

Results of a series of HVOSM runs of high speed/angle impact combinations with the CSSB for a variety of cars are shown in Table 1. The vehicle sizes range from a micromini Daihatsu Domino with an approximate weight of 1,280 lb to a large Plymouth Fury weighing approximately 4,500 lb. Approximate weights of the Fiat Uno-45, Chevrolet Sprint, and Honda Civic included in Table 1 are 1,560 lb, 1,530 lb, and 1,800 lb, respectively. It can be seen that small cars exhibited a significantly greater overturn propensity for these conditions than did the larger car. Also, the probability of injury would be higher for the large speed/angle combinations, regardless of the vehicle's stability or size.

Shown in Figure 5 is a plot of the yaw, pitch, and roll displacements of the 45 mph/45° Chevrolet Sprint run from Table 1. In analyzing the nature of the angular response, the yaw displacement is measured with respect to the vehicle's position at impact, with a value of zero. In this case, the longitudinal axis of the vehicle was oriented 45° to the longitudinal axis of the barrier at impact, i.e., the heading angle ψ (see Figure 2) was 45°. An increasing negative yaw displacement means that the car rotated toward the barrier after impact.

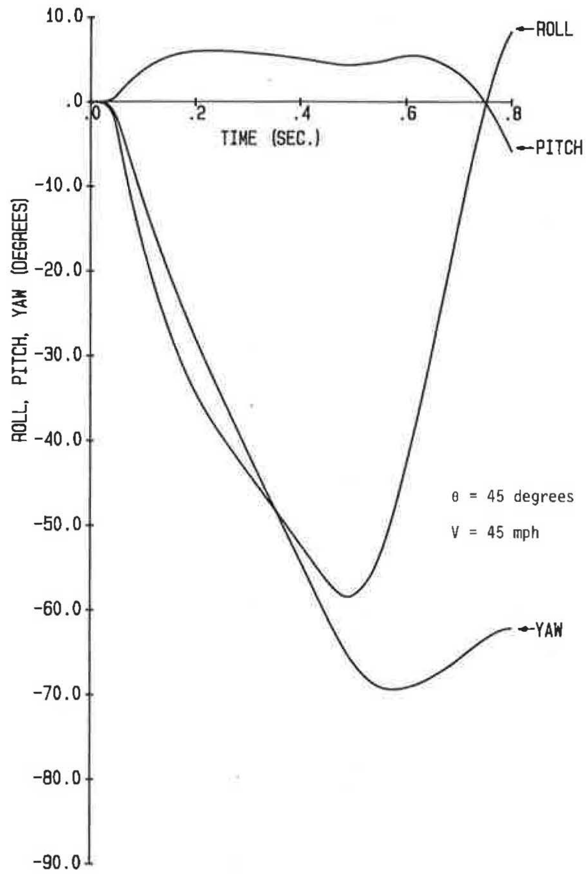


FIGURE 5 Roll, pitch, and yaw displacements for high angle, tracking impact of Chevrolet Sprint with CSSB.

Parameters included in the nontracking impacts are shown in Figure 2. Note that θ is the angle formed by the resultant translational velocity vector of the vehicle and the longitudinal axis of the barrier, ψ is the angle formed by the vehicle and the longitudinal axis of the barrier, and $\dot{\psi}$ is the angular velocity or yaw rate of the vehicle as it strikes the barrier. Yaw rates usually occur when the driver loses control, due to abrupt steering when trying to avoid an obstruction on the lane or to a sudden application of the brakes. If the driver tries to avoid the barrier when losing control, the result is a counterclockwise $\dot{\psi}$. Conversely, a clockwise $\dot{\psi}$ is the outcome if the driver is avoiding the traffic on the adjacent left-hand lane. It is not known which direction, if either, is predominant for barrier impacts. A clockwise $\dot{\psi}$ was arbitrarily selected since it seemed more critical in terms of overturn potential, and the chances of a barrier impact are less when $\dot{\psi}$ is counterclockwise. A value of 15°/sec was used for $\dot{\psi}$. It is known that yaw rates of 20 and 30°/sec can be achieved in an emergency steer maneuver. The rate can be much higher if the vehicle strikes another vehicle or object before impacting the barrier.

Table 2 shows results of HVOSM runs of nontracking impacts with the CSSB for a variety of cars. These results refer to the post-impact behavior. By definition, the vehicle is sideslipping at impact for each run. Again, the results clearly indicate a greater overturn problem for the small cars than for the larger car. Yaw, pitch, and roll displacements, with respect to time, of a Chevrolet Sprint run are shown in Figure 6. The nature of the angular response in this case is similar to that previously described for the 45 mph/45° tracking impact with the Sprint.

ROLLOVER PROPENSITY OF OTHER SHAPES

Studies were made of new shapes for the concrete barrier to mitigate the overturn problem associated with high angle and/or nontracking small car impacts with CSSB. Three designs that show promise in meeting this goal are shown in Figure 7. Slopes (β) of up to approximately 10° for the constant-slope barrier appear satisfactory. The modified CSSB shape of Figure 7 could be a new design, or an existing CSSB could be retrofitted to achieve the shape. This concept was conceived by Ivey et al. (*13*) at TTI. As discussed below, in comparison with CSSB, these shapes showed greatly reduced overturn propensity for small cars.

The Texas State Department of Highways and Public Transportation is currently pursuing a feasibility study of the constant-slope barrier with TTI. In addition to the potential for improved impact performance, the height of the constant-slope barrier can be selected so that several pavement overlays can be accommodated without the necessity of raising the barrier. As opposed to the CSSB, the adding of an overlay does not alter the shape of a constant-slope barrier. Use of the vertical wall or constant-slope barrier shown in Figure 7, in lieu of the CSSB, would not be without some tradeoffs. Certain shallow angle impacts with the CSSB that produce no damage would cause some with new shapes. However, one life saved by preventing an overturn and the associated societal cost will outweigh a very large number of minor scrape hits. The new shapes may also require more concrete than CSSB. All of the above factors should be evaluated in a benefit/cost analysis if further evaluations of the new designs are planned.

Table 3 shows results of nontracking impacts of the Chevrolet Sprint with the constant-slope barrier. No tracking runs were made since the nontracking impacts were assumed to be more critical in terms of overturn. With reference to Figure 7, *H* was set at 32 in. Note that the β equal to zero case represents a vertical wall. A scaled drawing of the sloped wall in comparison with the CSSB is shown in Figure 8. Comparing the results of Table 3 with Table 2 shows that a distinct reduction of the overturn problem is achieved with the new designs. Yaw, pitch, and roll displacements with time of a selected run of the $\beta = 8.9°$ case are shown in Figure 9. Figure 10 shows the same data for the $\beta = 0°$ case. Data in Figures 9 and 10 can be compared with data for the CSSB in Figure 6

Tables 4 and 5 give results of HVOSM runs of high speed/angle impacts and nontracking impacts with the modified CSSB design (see Figure 7). A Chevrolet Sprint was simulated in these runs. A comparison of Table 4 with part c of Table 1 shows that the modified CSSB design does reduce the overturn problem for most impact conditions expected to occur in the field. Even though overturn is still indicated for 45 mph/60° impact conditions for the modified CSSB, the probability of serious injuries or fatalities would be high regardless of the vehicle's post-impact stability. A comparison of Table 5 with part c of Table 2 also shows that the modified CSSB significantly reduced the overturn problem for nontracking impacts.

TABLE 2 STABILITY STUDY FOR NONTRACKING IMPACTS WITH CSSB

Angle ψ (deg)	Speed (mph) 30 θ = 15 deg	30 θ = 25 deg	45 θ = 15 deg	45 θ = 25 deg	60 θ = 15 deg	60 θ = 25 deg
Fiat Uno-45 (1,560 lb)						
45	Overturn	Overturn	Overturn	Overturn	Overturn	Overturn
60	Overturn	Overturn	Overturn	Overturn	Overturn	Overturn
75	Overturn	Marginal	Overturn	Overturn	Overturn	Overturn
Daihatsu Domino (1,280 lb)						
45	Overturn	Overturn	Overturn	Overturn	Overturn	Overturn
60	Overturn	Overturn	Overturn	Overturn	Overturn	Overturn
75	Overturn	Overturn	Overturn	Overturn	Overturn	Overturn
Chevrolet Sprint (1,530 lb)						
45	Overturn	Overturn	Overturn	Overturn	Overturn	Overturn
60	Spinout	Overturn	Overturn	Overturn	Overturn	Overturn
75	Spinout	Spinout	Spinout	Spinout	Spinout	Marginal
Honda Civic (1,800 lb)						
45	Overturn	Overturn	Overturn	Overturn	Overturn	Overturn
60	Overturn	Overturn	Overturn	Overturn	Overturn	Overturn
75	Overturn	Marginal	Overturn	Overturn	Overturn	Overturn
Plymouth Fury (4,500 lb)						
45	Stable	Stable	Stable	Stable	Stable	Stable
60	Sideslip	Sideslip	Sideslip	Sideslip	Sideslip	Overturn
75	Spinout	Spinout	Spinout	Spinout	Spinout	Spinout

NOTE: $\dot{\psi}$ = +15 deg/sec in each run.

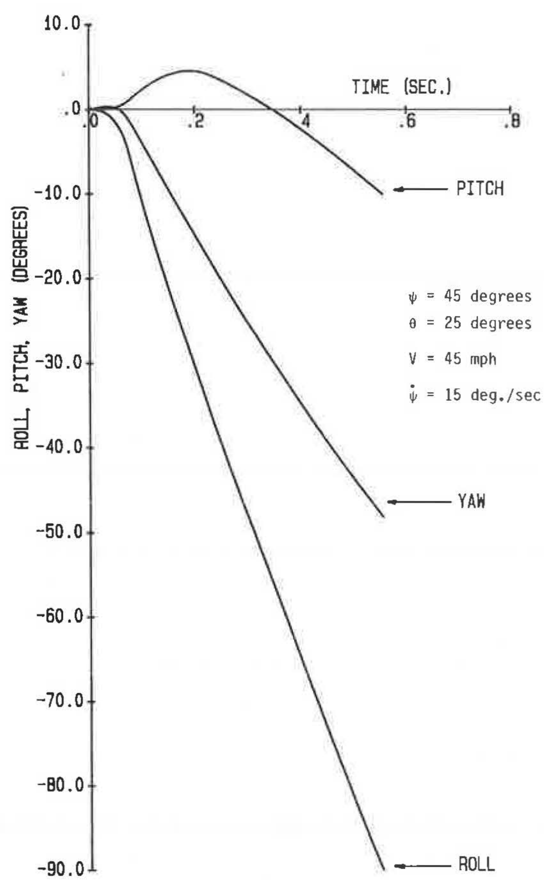


FIGURE 6 Roll, pitch, and yaw displacements for nontracking impact of Chevrolet Sprint with CSSB.

Figures 11 and 12 show the angular response of the Chevrolet Sprint upon impact with the modified CSSB in a high angle tracking and nontracking condition, respectively. Impact conditions are as indicated on the figures. The comparisons of Figure 11 with Figure 5 and of Figure 12 with Figure 6 show the degree to which the modified CSSB reduces the roll response.

The improved performance of the modified CSSB shape over the unmodified shape is due to the resisting action of the overhang on the rolling motion of the vehicle, as the impacting corner rides up the barrier. However, for high values of heading angle ψ the vehicle tends to spin out, and the impacting corner may not come into contact with the overhang. Therefore, a wider overhang would help the performance on high angle tracking or nontracking impacts whereas size and shape of the overhang would have a minimal effect on low angle impacts. Further research is needed to discover more about these factors.

TTI is continuing research on these findings, using a widened set of speed/angle combinations, considering different vehicle sizes, and including other barrier shapes. A research study currently being completed at TTI (*14*) reports the simulation results for the high speed/angle tracking and nontracking impacts of both 1,800-lb and 4,500-lb vehicles on CSSB, F- shape, constant-slope barrier, and vertical wall.

CONCLUSIONS

A modified version of the HVOSM was used to study the rollover propensity of vehicles impacting the concrete safety-shape barrier with the New Jersey profile and potential new

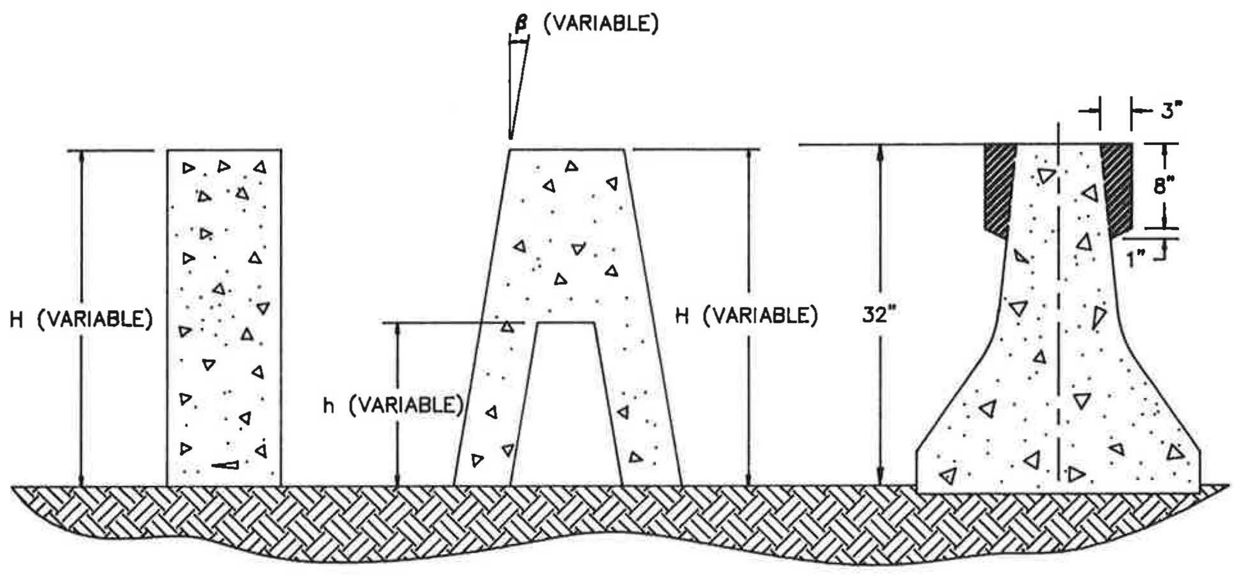


FIGURE 7 Potential rigid barrier shapes.

TABLE 3 STABILITY STUDY FOR NONTRACKING IMPACTS OF CHEVROLET SPRINT (1,530 LB) WITH CONSTANT SLOPE BARRIER

	Speed (mph)					
	30		45		60	
Angle ψ (deg)	θ = 15 deg	θ = 25 deg	θ = 15 deg	θ = 25 deg	θ = 15 deg	θ = 25 deg
Constant Sloped Barrier, β = 8.9 degrees						
45	Stable	Stable	Stable	Stable	Stable	Stable
60	Spinout	Spinout	Spinout	Spinout	Spinout	Overturn
75	Spinout	Spinout	Spinout	Spinout	Spinout	Spinout
Vertical Wall, β = 0.0 degree						
45	Stable	Stable	Stable	Stable	Stable	Stable
60	Stable	Stable	Stable	Stable	Spinout	Spinout
75	Spinout	Spinout	Spinout	Spinout	Spinout	Spinout

NOTE: $\dot{\psi}$ = +15 deg/sec in each run.

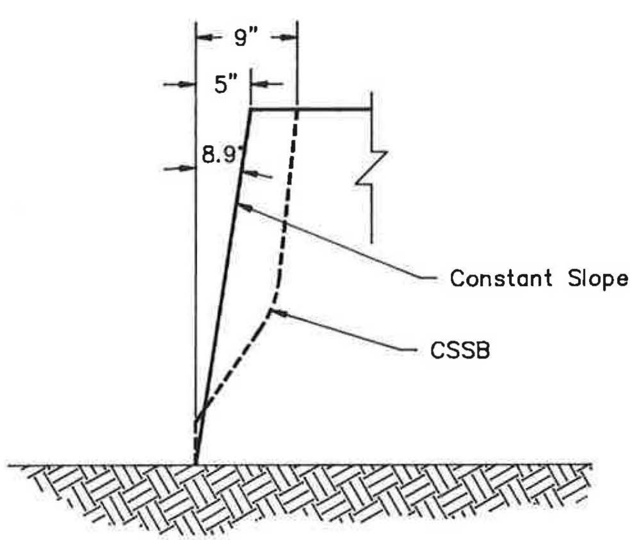


FIGURE 8 Constant slope barrier and CSSB profiles.

designs. Prior to the prediction of rollovers, the program was subjected to an extensive calibration effort and found to produce reasonably accurate results in most cases (*3*, *9*).

The performance of CSSB is acceptable for the tracking impact conditions recommended in *NCHRP Report 230* for the evaluation of safety appurtenances. However, overturns can be expected for nontracking and/or high angle impacts with the CSSB by small cars. A barrier with a constant-slope face or vertical wall will greatly reduce the overturn problem. A retrofit design for the CSSB consisting of a longitudinal member placed on the side of the barrier near the top also shows promise in reducing this problem.

A reevaluation of the crash test parameters in *NCHRP Report 230*, in light of high speed/angle tracking and nontracking impacts, is recommended for the upcoming revision of the report. If subsequent testing verifies the computer simulation, and the evaluation criteria for barrier performance are revised to include the safety in high speed/angle tracking and nontracking impacts, the modification of existing barriers should be seriously considered.

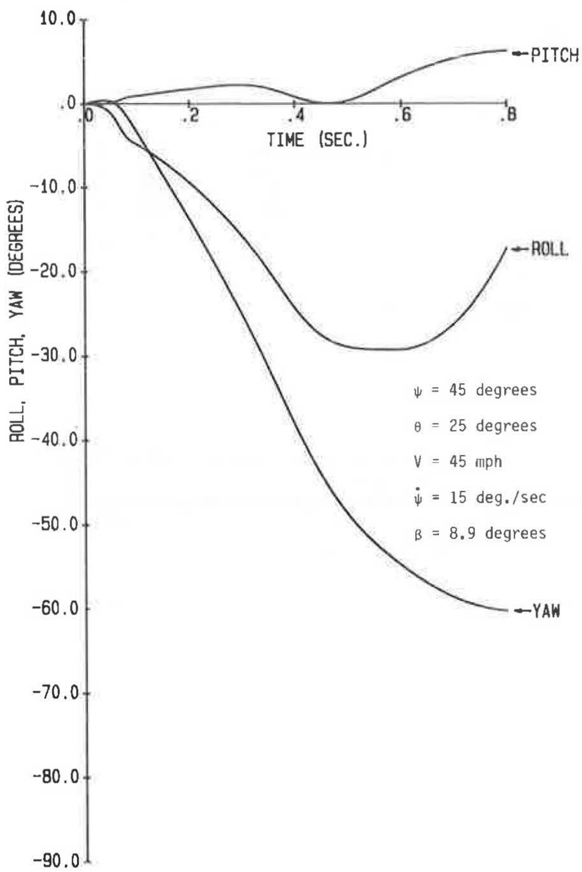


FIGURE 9 Roll, pitch, and yaw displacements for nontracking impact of Chevrolet Sprint with constant slope barrier.

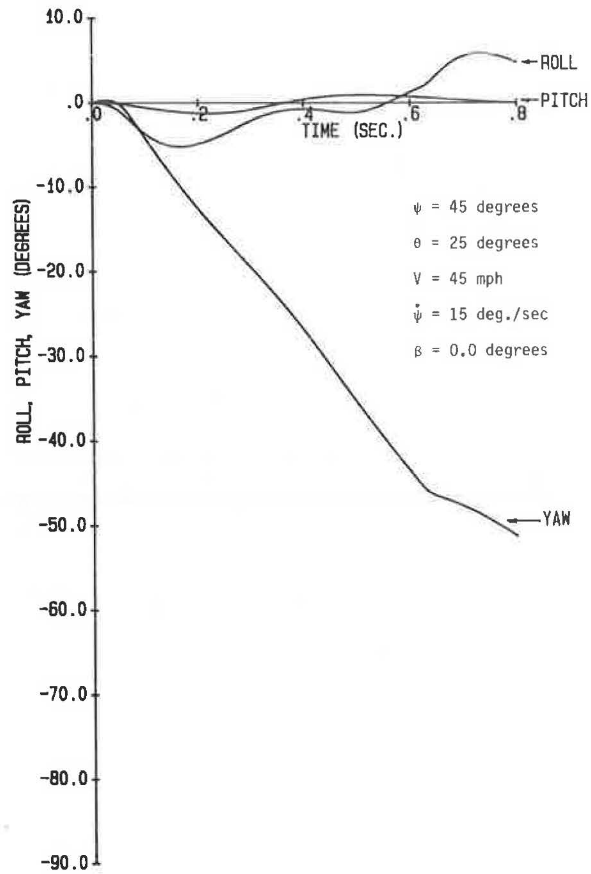


FIGURE 10 Roll, pitch, and yaw displacements for nontracking impact of Chevrolet Sprint with vertical wall.

TABLE 4 STABILITY STUDY FOR HIGH SPEED/ANGLE TRACKING IMPACTS OF CHEVROLET SPRINT (1,530 LB) WITH MODIFIED CSSB

Angle (deg)	Speed (mph) 30	45	60
35	Stable	Stable	Stable
45	Stable	Stable	Stable
60	Spinout	Overturn	Overturn

TABLE 5 STABILITY STUDY FOR NONTRACKING IMPACTS OF CHEVROLET SPRINT (1,530 LB) WITH MODIFIED CSSB

	Speed (mph)					
	30		45		60	
Angle ψ (deg)	θ = 15 deg	θ = 25 deg	θ = 15 deg	θ = 25 deg	θ = 15 deg	θ = 25 deg
45	Stable	Stable	Stable	Stable	Stable	Stable
60	Spinout	Spinout	Spinout	Spinout	Overturn	Overturn
75	Spinout	Spinout	Spinout	Spinout	Spinout	Spinout

NOTE: $\dot{\psi}$ = +15 deg/sec in each run.

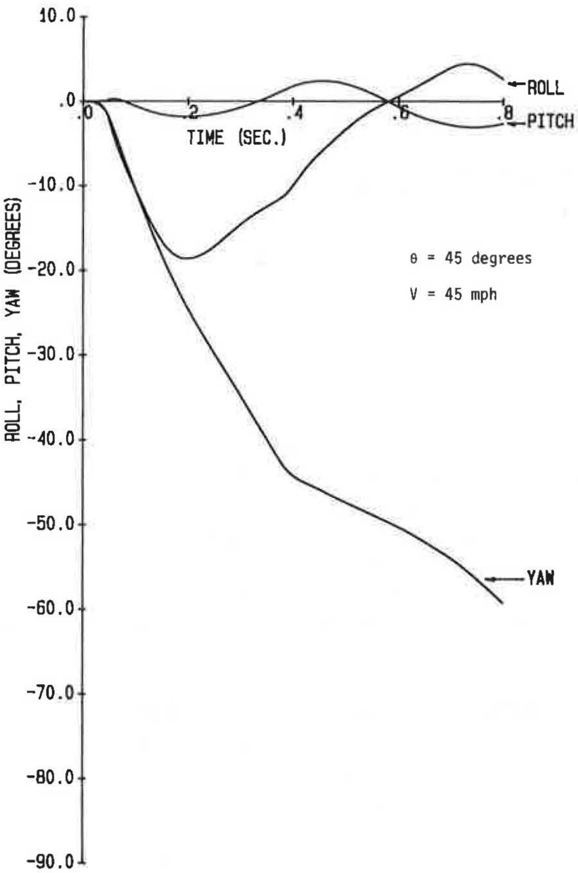


FIGURE 11 Roll, pitch, and yaw displacements for high angle, tracking impact of Chevrolet Sprint with modified CSSB.

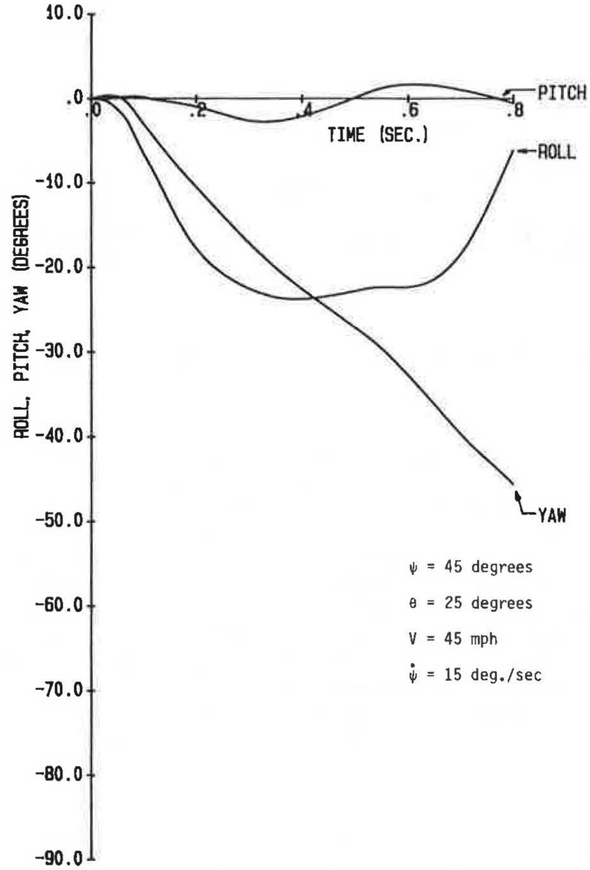


FIGURE 12 Roll, pitch, and yaw displacements for nontracking impact of Chevrolet Sprint with modified CSSB.

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