Rollover Caused by Concrete Safety-Shaped Barrier

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The results of a study sponsored by the Federal Highway Administration and conducted at the Texas Transportation Institute that examined the issue of rollovers caused by concrete safety-shaped barriers are presented. The study objectives were to determine the extent and severity of overturn collisions with concrete safety-shaped barriers, identify the causes of rollover of vehicles in impacts with concrete safety-shaped barriers, and identify potential countermeasures to reduce concrete safety-shaped barrier rollovers. The study approach consisted of a critical review of the literature, clinical and statistical analysis of accident data files, and computer simulation. The extent of the rollover problem on concrete safety-shaped barriers was found to be less than reported in previous literature. A number of impact conditions were identified from accident studies and confirmed by simulation as potential contributory factors to rollovers. Three alternative barrier shapes were evaluated as potential countermeasures: F-shape, constant slope, and vertical wall. Results of the evaluation indicate that the F-shaped barrier offers little performance improvement over the existing safety shape. The vertical wall barrier offers the greatest reduction in rollover potential, but with the greatest increase in lateral accelerations. The constant sloped barrier may provide the best compromise solution.

The concrete safety-shaped barrier has been one of the most popular types of barrier since its introduction in the early 1960s, and hundreds of miles of such barriers are in use on the nation's highways. Although the degree to which the concrete safety-shaped barrier has been successful in reducing deaths and serious injuries is unknown, results from various full-scale crash tests suggest that the benefits are substantial. Hundreds, perhaps thousands, of lives may be saved each year because of the deployment of these barriers.

The original research on and development of the concrete safety-shaped barrier began in the 1950s at the General Motors Proving Grounds in Milford, Michigan. In the intervening years, further research sponsored by the Federal Highway Administration (FHWA) continued the development and improvement of this barrier. Advantages of the concrete safety-shaped barrier are several:

- The design of this barrier, with its inclined lower surface, is intended to minimize or prevent damage to vehicles during low-angle impacts.
- The concrete safety-shaped barrier is a rigid barrier that does not deflect to any appreciable degree, even under severe impact conditions.
- Compared with flexible longitudinal barriers (e.g., W-beam guardrails), the maintenance costs for the concrete safety-shaped barrier are negligible.

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Although the concrete safety-shaped barrier is an important development in the continuing efforts to safely restrain and redirect errant vehicles on the highways, it is not a panacea. One concern regarding the performance of concrete safety-shaped barriers is the increased likelihood of vehicle rollover on impact with this barrier, especially for small cars (i.e., cars weighing less than 2,250 lb) and vehicles with high centers of gravity (e.g., pickup trucks and vans), not to mention large trucks, intercity buses, and school buses.

Past research has provided some insights into the various aspects of the rollover problem in general and with regard to concrete safety-shaped barriers in particular.

- Smaller passenger cars, with reduced roll and yaw moments of inertia, are more prone to overturn than larger passenger cars.
- The relative severity of single-vehicle rollover accidents is much higher than that of nonrollover single-vehicle accidents.
- The potential for overturning during concrete safety-shaped barrier impacts is affected by seemingly small variations in the profile of the barrier. The approach geometrics of the roadside and the friction coefficient of the barrier may also play important roles in the propensity for rollover.
- The concrete safety-shaped barrier was not designed for impacts involving large trucks, intercity buses, or school buses; such impacts frequently result in rollovers.

This paper presents the results of a study sponsored by FHWA and conducted at the Texas Transportation Institute (TTI) that examined the issue of rollovers caused by concrete safety-shaped barriers (*1*). The study objectives were to determine the extent and severity of overturn collisions with concrete safety-shaped barriers, identify the causes of rollover of vehicles in impacts with concrete safety-shaped barriers, and identify potential countermeasures to reduce concrete safety-shaped barrier rollovers.

RESEARCH APPROACH

The research approach for the study consisted of three major activities: literature review, accident studies, and simulation studies.

Literature Review

Available literature relating to rollover accidents on concrete safety-shaped barriers as well as rollover and small car safety

in general was critically reviewed to obtain insights into the problem being studied. In general, a relatively large number of potential information sources relating to concrete safety-shaped barriers and rollover accidents were identified through the literature search. However, many of the references reviewed were found to contain little information useful to this study.

Accident Studies

A number of available accident data files were considered for use in the accident studies. The following three data files were eventually selected for use in the analyses:

- The Texas barrier accident data file,
- The Texas concrete median barrier (CMB) accident data file, and
- The National Accident Sampling System (NASS) Longitudinal Barrier Special Study (LBSS) data file.

Brief descriptions of these accident data files are provided below.

Texas Barrier Accident Data File

This data file contained all police-reported longitudinal barrier accidents on urban Interstates and freeways in Texas for the 3-year period 1982 to 1984 (more than 16,331 barrier accidents, 6,728 of which involved median barriers). This data file was used in the preliminary analysis and limited to general descriptive statistics.

The limited use of this data file was the result of a number of problems identified in the preliminary analysis and a manual check using printed copies of police accident reports for a sample of highway sections. First, concrete safety-shaped barriers were not specifically identified in the accident reports, nor were the locations of these barriers available from any computerized data file. The manual check found that less than half of the CMB accidents were correctly identified in the computerized data file. Second, rollover was not specifically identified in the accident reports. Damage to the top of the vehicle was initially used as a surrogate for rollover, but the manual check found that less than half of the rollover accidents were correctly identified using this approach.

Texas CMB Accident Data File

Because of the problems with computerized accident data files discussed, a second data file was created using a manual process. First, the locations of concrete median barriers were identified through contacts with the major urban districts of the Texas State Department of Highways and Public Transportation (SDHPT). The location information on the CMBs was then computerized and merged with the Texas barrier accident data file. Of the total 6,870 median barrier accidents on urban Interstates and freeways, 1,964 were identified as involving CMBs through this location-matching process.

Printed copies of police accident reports on these CMB accidents were obtained from the Texas Department of Public Safety. The police accident reports were reviewed manually to verify barrier type and rollover involvement. Also, supplemental data that were not available in the computerized accident data file, but that might be gleaned from manual review of the police accident reports, were coded from the reports. The supplemental data included indications as to whether the impact was with or near the end of the median barrier, the impact sequence, and whether the vehicle was spinning or skidding sideways before impact with the concrete median barrier.

The supplemental data were then entered into the computer and merged with the accident data file. Of the 1,964 accidents in the data file, 125 were eliminated for various reasons, such as accidents not involving concrete median barriers or other incorrect codes. The usable number of accidents in the Texas CMB accident data file was therefore 1,839.

The Texas CMB data file was based on police level accident data supplemented by manual review and coding of the accident reports. It did not contain any detailed information on impact conditions. The quality of the data was limited to that of the police accident reports. The Texas CMB data file was therefore used mainly for determining the extent of the rollover problem and for some limited analysis on the causative or contributory factors associated with rollover involvement.

NASS LBSS Data File

The NASS program is a continuing crash data collection effort sponsored by the National Highway Traffic Safety Administration (NHTSA). Teams of trained investigators, under contract to NHTSA, collected data on a statistical sample of accidents at selected locations throughout the nation. The LBSS study was sponsored by FHWA and conducted as a special study under the NASS program. NASS investigators were specifically trained for this data collection effort. The data collection forms and protocol were specifically designed for impacts involving longitudinal barriers. For these reasons, detailed information on impact conditions was collected.

A total of 130 NASS LBSS cases involving concrete safety-shaped barriers were identified for the years 1982 to 1984. The sample size is clearly too small for any form of statistical analysis. Thus, the analysis of the LBSS data file was mainly clinical in nature. Printed copies of these 130 LBSS cases were first reviewed for accuracy and corrected, as appropriate. The accidents were then reconstructed to estimate impact speed using a simplified reconstruction procedure developed specifically for impacts involving concrete safety-shaped barriers.

A total of 31 rollover accident cases were identified from the 130 NASS LBSS cases. After further review, 9 of the 31 cases were excluded from the analysis, including 6 cases in which the rollovers were not related to the barriers and 3 cases involving tractor-trailers. The remaining 22 cases were then clinically analyzed to determine potential causative factors and conditions contributing to the vehicle rollovers.

Simulation Studies

A version of the HVOSM-RD2 program modified specifically for use with rigid barrier impacts was used for the simulation study. Most of the original modifications were accomplished

under NCHRP Project 22-6, whereas some of the refinements to handle unusual impact conditions were accomplished under this study (*1,2*). Modifications to the simulation program included improvements to the sheet metal–barrier interaction model, the suspension damping model, and the tire normal force model. The modified program was validated extensively using data from available crash test results. Because of limitations associated with the program's thin disk tire model, HVOSM could not be adequately validated for very low angle impacts (i.e., 5 degrees or less). Although this limitation restricted the use of the program for simulating some impacts of interest to this study, HVOSM is believed to be the best available tool for analyzing rigid barrier impacts.

The modified simulation model was used to evaluate the potential for concrete safety-shaped barriers to cause vehicle rollovers and to assess potential barrier improvements to minimize the identified rollover problems. The simulation effort was divided into three parts: a baseline evaluation of the concrete safety-shaped barrier, an evaluation of contributory factors identified in the accident analysis, and a study of potential countermeasures to minimize the rollover problem.

Baseline Simulations

The first step in the simulation effort involved simulation of 27 impact conditions that were believed to be representative of a majority of concrete barrier impacts. Results of these simulations provided a basis for comparing the existing shape with any potential modifications.

Simulation of Contributory Factors

Factors identified from accident analysis as causative or contributory to vehicle rollover during impacts with concrete safety-shaped barriers were verified with simulation. The factors evaluated included impact conditions that might increase the propensity for vehicle rollovers, such as impact speed and angle and vehicle orientation. These impact conditions were simulated for a variety of vehicle sizes to better understand the nature of concrete barrier impacts, especially those impact conditions resulting in rollovers.

Simulation of Potential Countermeasures

After analyzing the accident data and the simulation efforts, countermeasures to reduce the significance of the rollover problem were identified. This phase of the simulation effort evaluated the effectiveness of each of these potential countermeasures. All impact conditions identified as potential contributors to vehicle rollover under the second phase of the simulation effort were simulated with each proposed countermeasure.

The effectiveness of each countermeasure was then evaluated by the proportion of rollover conditions that were eliminated. All baseline simulation runs were then conducted for the best countermeasure. Comparisons between the baseline runs on the standard concrete safety-shaped barrier and the best countermeasure were then conducted to assess changes, if any, in measures of the potential for occupant injury and vehicle damage, such as lateral acceleration levels and extent of vehicle crush.

CONCLUSIONS AND RECOMMENDATIONS

Highlights of the major findings and conclusions of the study are summarized and discussed together with recommendations.

Findings and Conclusions

Extent of Rollover Problem

Analysis of the Texas CMB file indicated that rollover occurred in 8.5 percent of the accidents involoving concrete safety-shaped barriers. This is somewhat lower than the rollover rate reported previously [e.g., California reported a rollover rate of 9.9 percent (*3*; K. Sides, unpublished data)]. However, much of the difference could be attributed to the difference in the proportion of smaller cars between Texas and California.

The severity of rollover accidents was much higher than that of nonrollover accidents, as indicated in Table 1, based on the Texas CMB data file. The percentage of drivers sustaining some form of injury in rollover CMB accidents was 68.8 percent compared with only 40.5 percent for nonrollover CMB accidents. Differences were more pronounced for more severe injuries. For incapacitating injuries, the percentages were 11.5 percent for rollover CMB accidents and only 6.0 percent for nonrollover CMB accidents. The driver fatality rate for nonrollover CMB accidents was only 0.1 percent; that for rollover CMB accidents was 1.3 percent. Similar results were found when the highest injury sustained in an accident was considered instead of driver injury.

TABLE 1 INJURY SEVERITY BY ROLLOVER INVOLVEMENT (TEXAS CMB DATA FILE)

	Driver Injury				Highest Injury			
	Nonrollover		Rollover		Nonrollover		Rollover	
Injury Severity	No.	%	No.	%	No.	%	No.	%
No Injury	988	59.5	49	31.2	890	53.0	44	28.0
Possible Injury	182	10.8	18	11.5	209	12.5	19	12.1
Nonincapacitating Injury	406	24.2	70	44.6	456	27.2	71	45.2
Incapacitating Injury	100	6.0	18	11.5	115	6.9	21	13.4
Fatal	2	0.1	2	1.3	8	0.5	2	1.3
Total	1678	100.0	157	100.0	1678	100.0	157	100.0

In the analysis of NASS LBSS accident cases, it was found that 6 of the 31 rollover accidents (19.4 percent) were not related to the barrier itself and would have occurred regardless of the barrier type. Because the LBSS accident cases were not sampled on a representative basis, it is not possible to determine the proportion of rollovers involving concrete safety-shaped barriers that are not attributable to the barrier. However, it is evident that the proportion of the rollover problem for concrete safety-shaped barriers treatable by countermeasures is less than the 8.5 percent indicated.

Though the extent of the rollover problem was found to be less than previously reported, this does not mean that rollover is not a problem for concrete safety-shaped barriers, but only that the problem is less extensive than anticipated. Given the severe nature of rollover accidents, efforts to identify potential improvements to the concrete safety-shaped barrier to reduce the propensity for rollover should continue.

Causative or Contributory Factors

Police level accident data, even with manual review of printed copies of the police accident reports, are not detailed enough to identify factors that cause or contribute to rollovers on concrete safety-shaped barriers. Nonetheless, analysis of the Texas CMB data file identified several factors that are correlated with rollover involvement.

- The rollover rate was found to be lower under adverse weather and surface conditions, as indicated in Table 2. This might be attributed to the lower coefficent of friction, which would reduce the buildup of large side forces for tripping vehicles, under wet or snowy and icy surface conditions. Reduced operating speeds associated with adverse weather conditions could also contribute to the lower rollover rate.
- The rollover rate was found to be lower for vehicles that skid or rotate before impact with the barrier, as indicated in Table 3. Review of the NASS LBSS accident cases confirmed this finding.
- There is a definite relationship between vehicle size and weight and rollover involvement, as illustrated in Figure 1. The rollover rate of lighter vehicles was much higher than that of their heavier counterparts. This problem is inherent in the nature of small vehicles because of their narrow track width and low roll and yaw moments of inertia. However, these basic problems with small vehicles could be further aggravated by the shape of the concrete safety-shaped barrier.

Analysis of the NASS LBSS accident cases provided much more information and insight into potential causative or contributory factors for rollover despite the small sample size. Three impact conditions were identified as potential factors. The descriptors used to define the impact conditions are in accordance with vehicle simulation conventions and are as follows:

1. A vehicle is *tracking* when the vehicle heading and the velocity vector of the vehicle are the same.
2. A vehicle is *yawing* when the vehicle heading is different from that of the velocity vector.
3. The angle between the vehicle heading and the barrier, expressed in degrees, is the *yaw angle*.
4. The rate at which the vehicle heading angle is changing, expressed in degrees per second, is the *yaw rate*.
5. The angle between the vehicle heading angle and its velocity vector, expressed in degrees, is the *slip angle*.
6. The angle between a vehicle's velocity vector and the longitudinal axis of the barrier at the point of initial contact with the barrier, expressed in degrees, is the *impact angle*.
7. The velocity of the vehicle at the point of initial contact with the barrier is the *impact speed*.

TABLE 2 ROLLOVER INVOLVEMENT BY SURFACE CONDITION (TEXAS CMB DATA FILE)

	Total Accidents		Rollover Involvement	
Surface Condition	No.	%	No.	%
Dry	1226	66.7	139	11.3
Wet	573	31.2	17	3.0
Snowy/Icy	40	2.2	1	2.5
Total	1839	100.0	157	8.5

TABLE 3 ROLLOVER INVOLVEMENT BY VEHICLE ATTITUDE (TEXAS CMB DATA FILE)

	Total Accidents		Rollover Involvement	
Vehicle Attitude	No.	%	No.	%
Skidding Sideways/ Rotating	683	37.1	37	5.4
Tracking	965	52.5	101	10.5
Unknown/Unsure	191	10.4	19	10.0
Total	1839	100.0	157	8.5

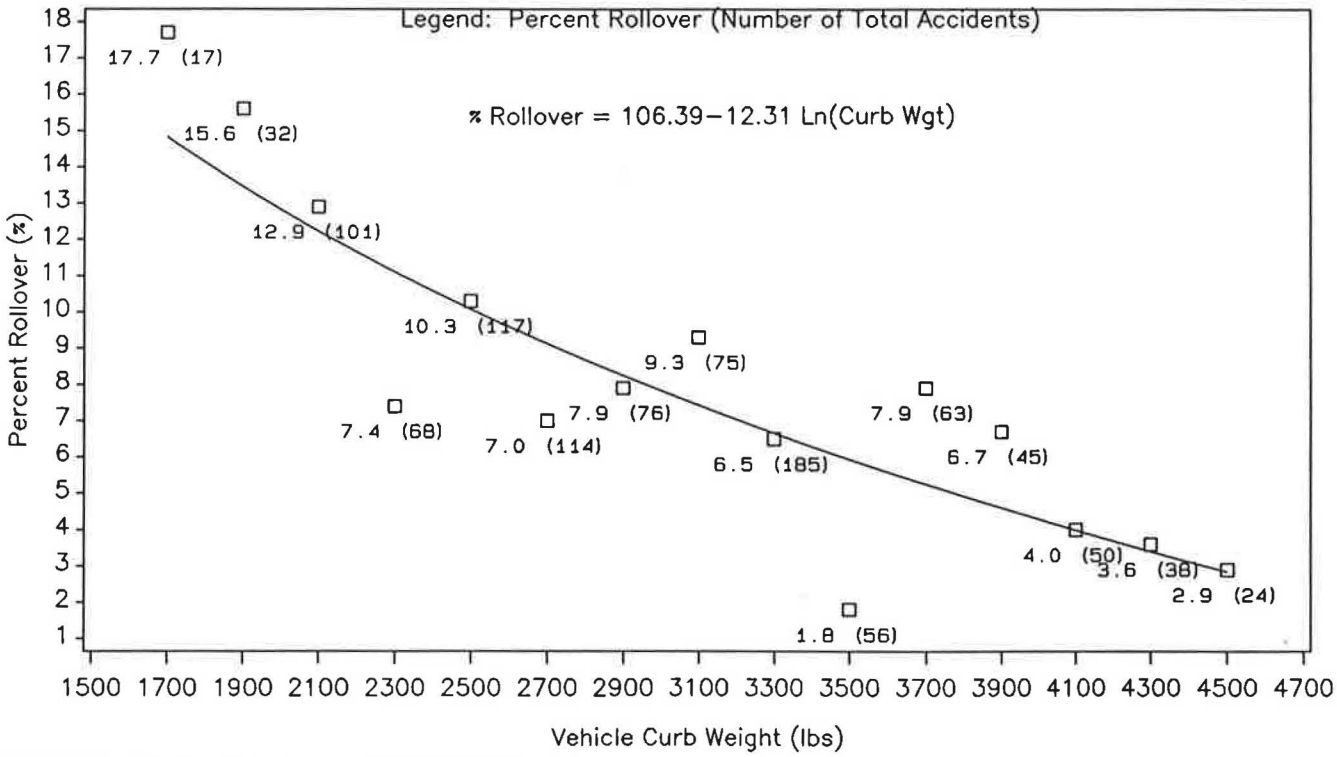

FIGURE 1 Relationship between vehicle curb weight and rollover rate.

The three impact conditions were as follows, where "moderate" impact speed means 25 to 50 mph and "high" impact speed means more than 50 mph:

- High impact angle (at least 25 degrees) and moderate to high impact speed;
- High slip angle (at least 30 degrees), low to moderate yaw rate, and moderate to high impact speed [vehicles that were rotating at impact (i.e., with a high yaw rate) were found to be less likely to result in rollovers]; and
- High impact speed and low impact angle (not more than 10 degrees) for vehicles in a tracking mode (i.e., slip angle not more than 15 degrees).

Table 4 shows a comparison between rollover and nonrollover accidents on these three impact conditions. Eight (36.3 percent) of the 22 rollover accidents involved high impact angles compared with only 10.3 percent for nonrollover accidents. The vehicle would typically climb the lower sloped face of the barrier and continue to climb the upper sloped face of the safety shape without any significant redirection. This would cause the vehicle to attain a high roll angle away from the barrier as the vehicle began to redirect and separate from the barrier, leading to rollover.

This finding is consistent with the results of a full-scale crash test of an 1,800-lb Honda Civic that struck a safety-shaped barrier at 27 mph and 52 degrees and subsequently rolled over (*4*). However, another test with a 3,600-lb full-size passenger car impacting the barrier at 40 mph and 45 degrees did not result in rollover (*5*). These are the only two crash tests available with such high impact angles. The normal impact angles used for crash testing are 15 to 25 degrees, substantially lower than some of the impact angles observed in these accidents.

Four (18.2 percent) of the 22 rollover accidents involved vehicles yawing into the barriers with high slip angles at moderate to high impact speeds. In comparison, 20 (34.5 percent) of the 58 nonrollover accidents had similar impact conditions but did not result in rollovers. The major difference observed between the rollover and the nonrollover accidents under these impact conditions pertained to the yaw rate or the rate at which the vehicle was rotating or spinning.

For the rollover accidents, the yaw rates were usually low to moderate and the vehicles principally skidded sideways. The vehicle would roll slightly into the skid as it struck the barrier. The roll angle would continue to increase as the vehicle crashed into the barrier, leading to rollover. On the other hand, review of nonrollover accidents indicated that most of the vehicles principally rotated with high yaw rates as the vehicles struck the barriers. The vehicle would typically continue to rotate after the initial impact with the barrier and then strike the barrier a second time with the rear corner. The roll angle of the vehicle was usually fairly small and the second impact would generally stabilize the trajectory of the vehicle as it separated from the barrier, thus preventing rollovers.

As discussed previously, results from the analysis of the Texas CMB accident data file indicated that the vehicle skidding sideways or rotating prior to impact with the barrier was a fairly common impact condition, composing 37 percent of the accidents involving concrete safety-shaped barriers. Further, vehicles skidding or rotating at impact were found to have lower rollover rates than tracking vehicles. This suggests

TABLE 4 ROLLOVER AND NONROLLOVER ACCIDENTS BY IMPACT CONDITION (NASS LBSS DATA FILE)

Impact Condition	Rollover No.	Rollover %	Nonrollover* No.	Nonrollover* %
1	8	36.3	6	10.3
2	4	18.2	20	34.5
1 and 2	1	4.5	5	8.6
3	5	22.7	1	1.7
Other	4	18.2	26	44.8
Total	22	100.0	58	100.0

* Only 58 of the 99 nonrollover accident cases have all three data elements (i.e., impact speed, impact angle, and slip angle) available.

Impact Condition	Description
1	High impact angle (>= 25 degrees) and moderate (25-50 mph) to high (> 50 mph) impact speed.
2	High slip angle (>= 30 degrees), low to moderate yaw rate and moderate (25-50 mph) to high (> 50 mph) impact speed.
3	High impact speed (> 50 mph) and low impact angle (<= 10 degrees) for vehicles in a tracking mode (i.e., slip angle <= 15 degrees).

that only a small proportion of the vehicles were skidding sideways at impact (i.e., had high slip angles and low yaw rates) and that most of the vehicles were rotating at impact (i.e., had high yaw rates).

Five (22.7 percent) of the 22 rollover accidents involved vehicles striking the barriers in a tracking mode at high impact speeds and low impact angles, compared with only 1.7 percent of the nonrollover accidents. The vehicle would typically quickly climb to the top of the lower sloped face of the safety shape and then slowly climb the upper sloped face. Because of the high impact speeds, the vehicle would climb higher and stay on the barrier longer than normal. The vehicle would eventually roll away from the barrier as it separated from the barrier.

Concrete glare screens were found on top of the concrete safety-shaped barrier in two of the high-speed, low-angle rollover accidents. It appeared that the glare screen would act as an extension to the top of the safety-shaped barrier, thereby causing the vehicle to climb higher on the barrier than without the glare screen. This allowed the roll angle on the vehicle to go higher than normal, leading to rollover.

In some of the rollover accidents, the vehicles separated from the barriers in a relatively stable fashion and then began to rotate after separation and subsequently rolled over. These rotations were probably the result of driver braking and steering inputs or damage to the front suspension from impact with the barrier or a combination of these factors. It is arguable whether the subsequent rollover was related to the shape of the barrier.

Lateral displacement of the barrier segments was found in one rollover accident. Crash tests have shown that lateral barrier displacement during impact increases the time that a vehicle is in contact with the lower curb surface and reduces the slopes of all surfaces as the barrier leans away from the vehicle. As a result, the vehicle climbs higher on the barrier and the propensity for rollover is increased. Lateral displacement of the barrier is usually not a problem for permanent barrier installations, but is certainly an area of concern for temporary installations, such as construction zones.

The majority of the rollover accidents in the NASS-LBSS file occurred under dry surface conditions. This is consistent with accident analysis results, which indicated that the propensity for rollover after impact with a concrete safety-shaped barrier was actually lower under a wet or snowy and icy surface condition than under a dry surface condition. The reduced coefficient of friction under a wet or snowy and icy surface condition might have prevented critical side forces from building up and tripping the vehicle. Lower operating speeds typical of adverse surface conditions might also have contributed to the reduced incidence of rollover.

Figure 2 compares impact speed in rollover and nonrollover accidents. It is evident from the figure that rollover accidents were associated with much higher impact speeds than nonrollover accidents. None of the rollover accidents had an impact speed of less than 25 mph, compared with 30 percent of the nonrollover accidents. On the other hand, 73 percent of the rollover accidents had impact speeds of over 50 mph compared with only 14 percent of the nonrollover accidents.

Smaller and lighter vehicles were found to be disproportionately involved in rollovers, as illustrated in Figure 3, where the cumulative distributions of vehicle curb weights for rollover and nonrollover accidents are shown. The median (50th percentile) vehicle curb weight for rollover accidents was 2,500 lb, whereas that for nonrollover accidents was 3,150 lb. It is interesting to note that the weight of the vehicle appears to have less of an effect on rollovers in high-angle impacts with a higher median vehicle curb weight of 2,700 lb.

Some of the characteristics identified in previous studies as affecting the propensity for rollover (e.g., height of reveal and lower curb face, slope and offset of upper face, barrier

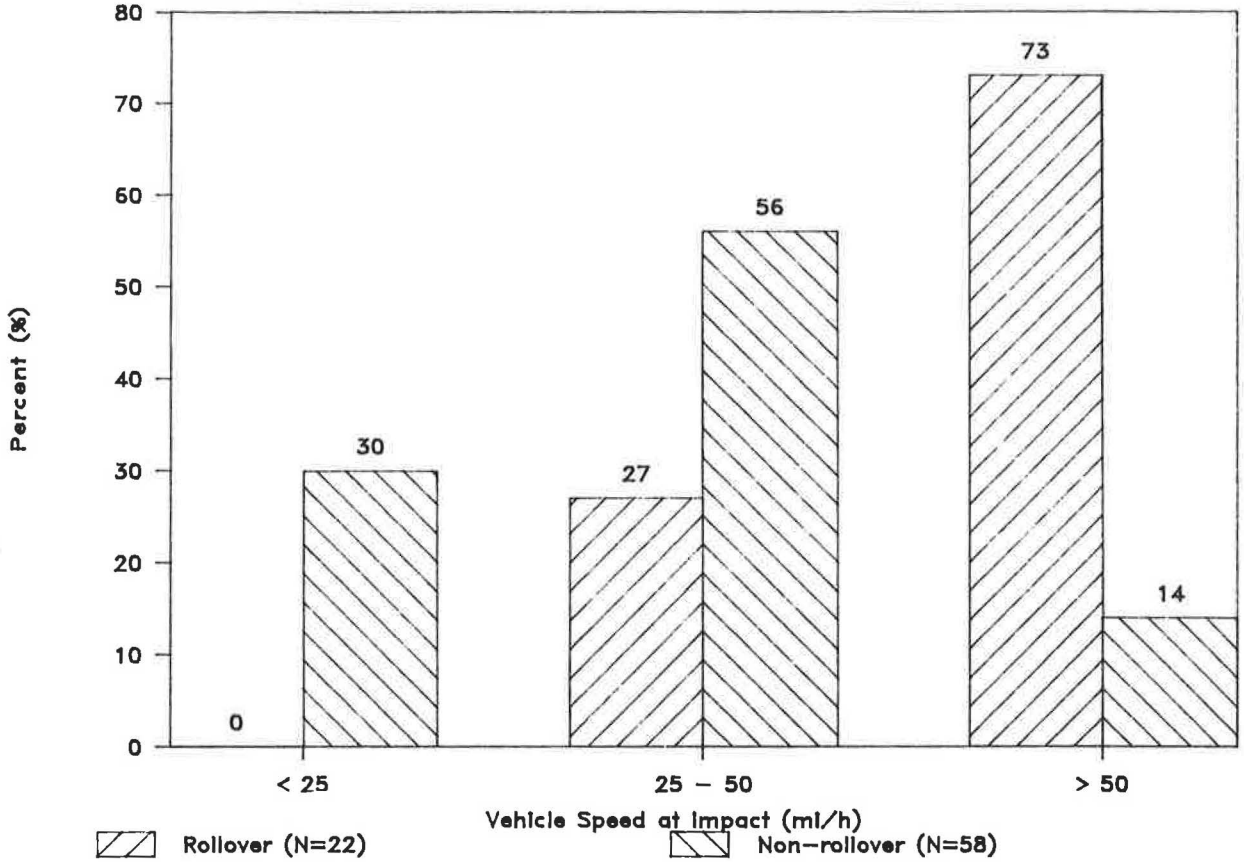

FIGURE 2 Comparison of impact speed for rollover and nonrollover accidents.

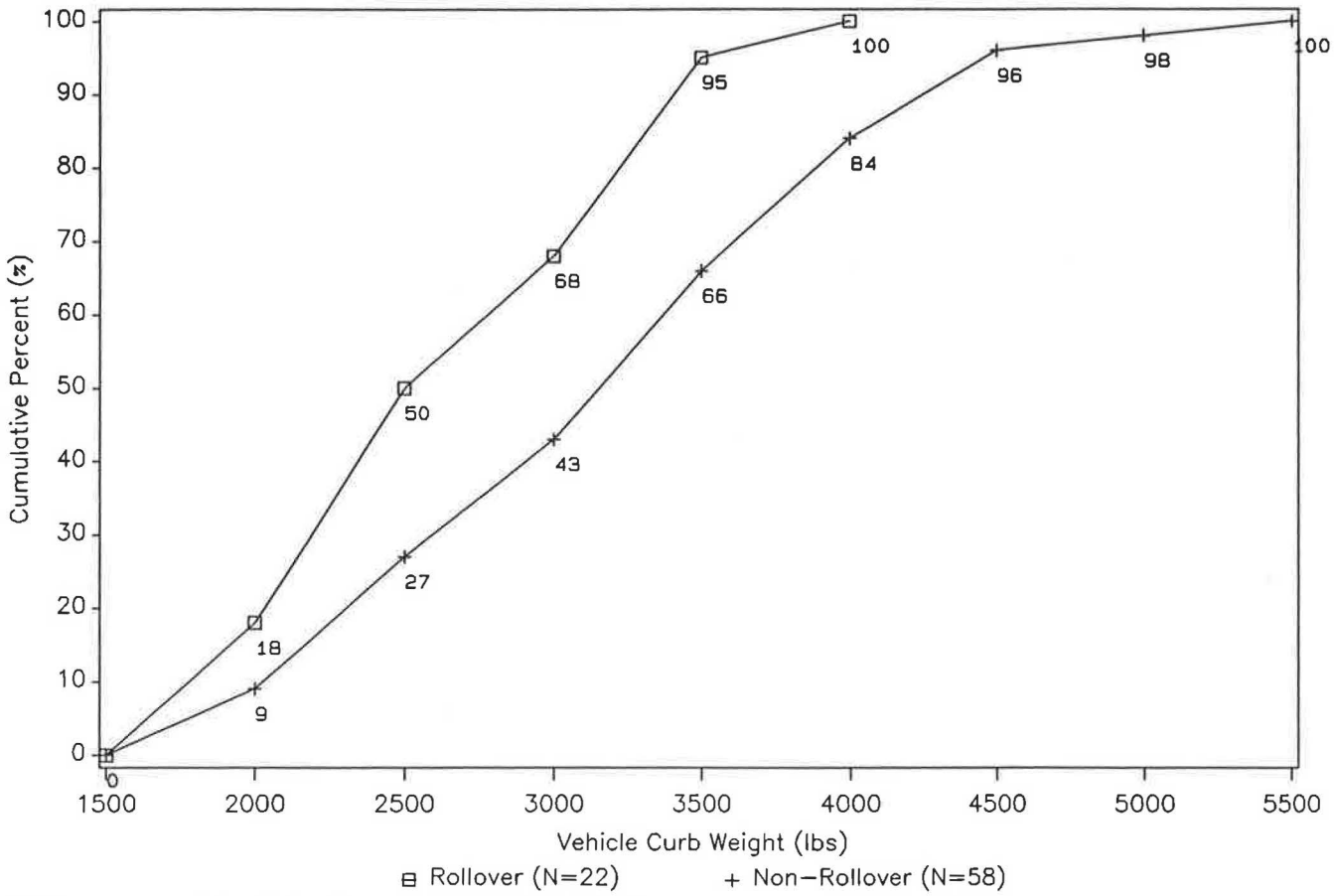

FIGURE 3 Cumulative distributions of vehicle curb weights for rollover and nonrollover accidents.

surface friction, and approach terrain) did not appear to play a part in any of the rollover accident cases studied. This finding apparently reflects the lack of variation in barrier shape and dimensions that would allow their effects to be assessed. Further, all barriers involved in rollover accidents had flat approach terrain and only one had an unpaved shoulder. Consequently, the effects of approach terrain on the propensity for rollover could not be properly assessed.

On the basis of the results of the clinical analysis, the following four factors, or conditions, were selected for further evaluation in the simulation studies:

- High-angle impacts with moderate to high impact speeds;
- Impacts with high slip angles, low yaw rates, and moderate to high impact speeds;
- Impacts with safety-shaped concrete barriers with glare screens; and
- Low-angle impacts with high impact speeds.

As discussed previously, HVOSM was not well validated for very low impact angles. Thus, the final impact condition selected for evaluation in this study, low-angle and high-speed impacts, could not be included in the simulation effort. These limitations notwithstanding, the simulation results generally supported findings from the accident studies, as described below.

The significance of vehicle rollover during high-angle impacts was investigated by conducting 12 HVOSM simulations with each of three classes of vehicles—1,800 lb, 3,800 lb, and 4,500 lb. The 12 combinations of impact speed and impact angle are listed in the first two columns of Table 5. The simulation results indicated that only small cars were significantly susceptible to rollover during high-angle impacts. Rollovers for mini-size vehicles were predicted even for some moderate-speed impacts.

Impacts with high slip angles and low yaw rates were evaluated through the simulation of barrier accidents involving yaw angles ranging from 45 to 75 degrees with a yaw rate of 15 degrees/sec. The 18 combinations of impact speed, impact angle, and yaw angle are listed in the first three columns of Table 6. HVOSM simulations of run-off-road accidents has indicated that most automobiles can attain yaw rates in excess of 45 degrees/sec during steering maneuvers. Thus, the 15-degree/sec yaw rate was chosen as representative of a relatively low yaw rate for a nontracking vehicle.

HVOSM simulation of impacts with safety-shaped barriers with glare screens was limited to moderate-angle impacts as a result of the aforementioned limitations of the program's tire model. The program predicted that glare screens did not significantly destabilize vehicles during impacts at speeds ranging from 30 to 60 mph and angles ranging from 7 to 25 degrees. On the basis of these simulation findings, there is no reason to believe that glare screens adversely affect the performance of concrete safety-shaped barriers under normal crash test conditions. However, the question of the effects of a glare screen for low-angle impacts remains unanswered.

The simulation of concrete safety-shaped barrier impacts involving unusual impact conditions did support findings from the accident data analysis described previously. However, safety-shaped barriers performed relatively well for the majority of impact conditions (moderate-angle, tracking impacts).

Potential Countermeasures

The extent of the rollover problem on concrete safety-shaped barriers is not considered serious enough to warrant retrofitting of existing barriers. Therefore, only potential countermeasures that are applicable to new construction were included in the evaluation. This does not mean that rollover is not a problem for concrete safety-shaped barriers; rather it is believed that retrofitting of existing barriers would not be cost-effective.

Three alternative shapes were selected for evaluation as potential countermeasures to reduce rollover rates: F-shape, constant slope, and vertical wall. The F-shape uses the basic safety-shape configuration with a smaller lower curb face, whereas the constant sloped barrier consists of a single, near-vertical face. Each of these alternate shapes was evaluated through simulation of impact conditions that were identified as potential contributors to rollover for the standard concrete safety-shaped barrier. Results of the evaluation are summa-

TABLE 5 SUMMARY OF HVOSM SIMULATIONS OF IMPACTS WITH MINI-SIZE VEHICLES AT HIGH ANGLES

Impact Speed (mph)	Impact Angle (deg)	Predicted Maximum Roll Angle (deg)			
		Concrete Safety Shaped Barrier	F Shaped Barrier	Constant Sloped Barrier	Vertical Wall
30	35	35	15	14	27
30	45	58	24	53	6
30	60	N/A	> 90	35	8
30	75	N/A	56	15	N/A
45	35	30	23	32	10
45	45	> 90	33	28	17
45	60	> 90	> 90	13	> 90
45	75	N/A	31	15	N/A
60	35	36	> 90	7	27
60	45	> 90	> 90	> 90	54
60	60	> 90	> 90	24	> 90
60	75	N/A	50	13	> 90

TABLE 6 SUMMARY OF HVOSM SIMULATIONS OF IMPACTS WITH MINI-SIZE VEHICLES AT HIGH SLIP ANGLES AND LOW YAW RATES

Impact Speed (mph)	Impact Angle (deg)	Yaw Angle (deg)	Predicted Maximum Roll Angle (deg)			
			Concrete Safety Shaped Barrier	F Shaped Barrier	Constant Sloped Barrier	Vertical Wall
30	15	45	> 90	> 90	> 90	27
30	15	60	> 90	> 90	53	6
30	15	75	25	> 90	49	8
45	15	45	> 90	> 90	> 90	N/A
45	15	60	> 90	> 90	> 90	10
45	15	75	> 90	> 90	> 90	17
60	15	45	> 90	> 90	> 90	> 90
60	15	60	> 90	> 90	56	N/A
60	15	75	> 90	> 90	45	27
30	25	45	> 90	> 90	> 90	54
30	25	60	> 90	> 90	35	> 90
30	25	75	> 90	18	25	> 90
45	25	45	> 90	68	> 90	N/A
45	25	60	> 90	> 90	> 90	10
45	25	75	> 90	> 90	68	17
60	25	45	> 90	45	> 90	> 90
60	25	60	> 90	> 90	12	N/A
60	25	75	> 90	> 90	31	27

TABLE 7 SUMMARY OF HVOSM SIMULATIONS OF IMPACTS WITH MID-SIZE VEHICLES AT HIGH SLIP ANGLES AND LOW YAW RATES

Impact Speed (mph)	Impact Angle (deg)	Yaw Angle (deg)	Predicted Maximum Roll Angle (deg)			
			Concrete Safety Shaped Barrier	F Shaped Barrier	Constant Sloped Barrier	Vertical Wall
30	15	45	10	9	14	27
30	15	60	9	5	53	6
30	15	75	6	6	35	8
45	15	45	16	11	15	N/A
45	15	60	11	6	32	10
45	15	75	6	6	28	17
60	15	45	20	17	13	> 90
60	15	60	> 90	11	15	N/A
60	15	75	7	5	7	27
30	25	45	16	12	> 90	54
30	25	60	10	5	24	> 90
30	25	75	5	6	13	> 90
45	25	45	20	17	15	N/A
45	25	60	> 90	24	32	10
45	25	75	6	5	28	17
60	25	45	24	19	13	> 90
60	25	60	> 90	> 90	15	N/A
60	25	75	10	6	7	27

TABLE 8 SUMMARY OF HVOSM SIMULATIONS OF IMPACTS WITH FULL-SIZE VEHICLES AT HIGH SLIP ANGLES AND LOW YAW RATES

Impact Speed (mph)	Impact Angle (deg)	Yaw Angle (deg)	Predicted Maximum Roll Angle (deg)			
			Concrete Safety Shaped Barrier	F Shaped Barrier	Constant Sloped Barrier	Vertical Wall
30	15	45	12	10	14	27
30	15	60	6	6	53	6
30	15	75	6	7	35	8
45	15	45	19	16	15	N/A
45	15	60	8	5	32	10
45	15	75	7	7	28	17
60	15	45	20	18	13	> 90
60	15	60	22	16	15	N/A
60	15	75	7	7	7	27
30	25	45	18	15	> 90	54
30	25	60	8	5	24	> 90
30	25	75	6	6	13	> 90
45	25	45	20	16	15	N/A
45	25	60	36	19	32	10
45	25	75	7	6	28	17
60	25	45	23	18	13	> 90
60	25	60	63	61	15	N/A
60	25	75	18	8	7	27

rized in Tables 5 through 8. General findings from this simulation effort are as follows.

- The F-shaped barrier offers little performance improvement over the concrete safety-shaped barrier for these impact conditions.
- The constant sloped barrier with an 80-degree slope offers some rollover reductions while slightly increasing lateral vehicle accelerations.
- The vertical wall barrier offers the greatest reduction in rollover potential, but with the greatest increase in lateral accelerations.

Baseline runs were repeated with the vertical wall barrier to generate a basis for comparing its performance with the concrete safety-shaped barrier under the more common impact conditions. As expected, the vertical wall barrier has lower maximum roll angles and climb heights, but also higher lateral accelerations than the standard concrete safety-shaped barrier under these impact conditions. A comparison of the baseline simulations for the concrete safety-shaped and vertical wall barriers is presented in Table 9.

Discussion and Recommendations

Although the vertical wall barrier shows the best potential for reducing the propensity for rollover, it may not be the shape of choice for rigid barriers when all factors are taken into consideration. The propensity for rollover needs to be balanced against factors such as damage to vehicles and potential for injuries to the vehicle occupants, as well as operational factors such as cost and maintenance requirements.

The constant sloped barrier may provide the best compromise solution. It reduces the propensity for rollover compared with the standard safety-shaped barrier and shows less increase in the lateral accelerations, a surrogate for injury potential during nonrollover accidents, than the vertical wall barrier. Construction costs for the constant slope barrier should be only slightly higher than the standard safety-shaped barrier, but the shape can substantially reduce life cycle costs.

In order to maintain safety barrier shape and height during resurfacing operations, the pavement surface has to be planed down before any overlay can be applied. Pavement planing is a costly procedure, and several pavement overlays are normally required during the life of a concrete barrier. On the other hand, a constant sloped barrier can be built to a greater height initially, thereby eliminating the need for removal of the old pavement surface. For example, a 42-in. constant sloped barrier would allow up to 10 in. of overlay before being reduced to the height of a standard 32-in. safety-shaped barrier. These overlay operations would not affect the shape or the minimum height of the constant sloped barrier. A study to develop such a barrier for the Texas SDHPT was recently completed (*6*). Construction bids for constant sloped barriers were not significantly higher than those for safety-shaped barriers. Thus, the reduced costs of pavement overlays associated with the constant sloped barrier should be much greater than the increase in construction costs.

However, to properly compare the overall effectiveness of various barrier shapes, a benefit/cost analysis taking into account all the various factors is needed. The computer simulation runs discussed should provide a basis for determining the relative severity of impact with these barriers for any impact condition. In support of such a benefit/cost analysis, additional research is needed to better identify the distributions

TABLE 9 SUMMARY OF HVOSM SIMULATIONS OF BASELINE IMPACTS

Vehicle Weight (lb)	Impact Speed (mph)	Impact Angle (deg)	Max. 50 ms. Lat. Acc. (g) Concrete Safety Shaped Barrier	Max. 50 ms. Lat. Acc. (g) Vertical Wall	Height of Climb (ft.) Concrete Safety Shaped Barrier	Height of Climb (ft.) Vertical Wall
1800	30	15	2.4	2.9	0.9	0.0
1800	45	15	4.2	5.3	1.3	0.0
1800	60	15	6.5	7.5	1.6	0.1
1800	30	25	4.6	5.3	1.2	0.0
1800	45	25	8.9	9.0	1.7	0.1
1800	60	25	13.3	12.4	2.1	0.5
3800	30	15	1.0	2.2	0.3	0.0
3800	45	15	1.6	N/A	0.7	0.0
3800	60	15	2.3	6.4	1.1	0.0
3800	30	25	2.6	3.9	0.5	0.1
3800	45	25	4.2	6.6	1.1	0.0
3800	60	25	6.0	9.5	1.5	0.1
4500	30	15	1.1	2.2	0.3	0.0
4500	45	15	1.7	4.3	0.7	0.0
4500	60	15	2.4	6.2	1.0	0.0
4500	30	25	2.6	4.0	0.5	0.0
4500	45	25	4.3	6.7	0.9	0.0
4500	60	25	6.1	9.7	1.1	0.1

of barrier impact conditions that can be expected along various highway types.

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