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Rollover Caused By Concrete Safety Shaped Barrier

Volume I: Technical Report

Research, Development, and Technology
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FOREWORD

This report documents a study which examined the problem of vehicle rollover on concrete safety shaped barriers. The research included accident analysis and vehicle simulation to identify the extent of the rollover problem and to identify possible contributing factors. The report does identify some possible contributing circumstances, but the reader should be aware of the limitations of the data used to draw these conclusions. The accident data that were used to identify probable causes were very limited in sample size and the conclusions from that data were clinical in nature rather than statistical. Even with these limitations, the report does provide valuable insight into the issue of the performance of concrete safety shaped barriers interacting with smaller cars.

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NOTICE

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16. Abstract

The objectives of this study are to: (1) identify the root causes of rollover of vehicles in impacts with concrete safety shaped barriers, (2) determine the extent and severity of overturn collisions with concrete safety shaped barriers, and (3) identify potential countermeasures to reduce shaped concrete barrier rollovers. The study approach consisted of critical review of literature, statistical and clinical analysis of four accident data files, and computer simulations. The extent of the rollover problem on concrete safety shaped barriers is 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 alternate shapes were evaluated as potential countermeasures: (1) F-shape, (2) single constant sloped barrier, and (3) vertical wall. Results of the evaluation show that the F-shape barrier offers little performance improvement. The vertical wall barrier offers the greatest reduction in rollover potential, but also with the greatest increase in lateral accelerations. The single constant sloped barrier with an 80-degree slope may provide the best compromise solution. A benefit/cost analysis is needed and recommended to properly compare between the various barrier shapes.

This is volume I of a two-volume final report. The other volume, FHWA-RD-88-220, contains appendixes that are too bulky for inclusion in this technical report. It is only available from the National Technical Information Service.

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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
in	inches	25.4	millimetres	mm
ft	feet	0.305	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.093	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometres squared	km^2

VOLUME

Symbol	When You Know	Multiply By	To Find	Symbol
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.028	metres cubed	m^3
yd^3	cubic yards	0.765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°F	Fahrenheit temperature	5(F-32)/9	Celcius temperature	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

LENGTH

Symbol	When You Know	Multiply By	To Find	Symbol
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi

AREA

Symbol	When You Know	Multiply By	To Find	Symbol
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
ha	hectares	2.47	acres	ac
km^2	kilometres squared	0.386	square miles	mi^2

VOLUME

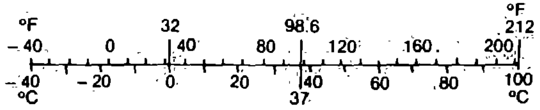
Symbol	When You Know	Multiply By	To Find	Symbol
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

MASS

Symbol	When You Know	Multiply By	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T

TEMPERATURE (exact)

Symbol	When You Know	Multiply By	To Find	Symbol
°C	Celcius temperature	1.8C + 32	Fahrenheit temperature	°F



* SI is the symbol for the International System of Measurement

(Revised April 1989)

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I. INTRODUCTION

1. Problem Statement

Concrete safety shaped barriers have been one of the most popular barriers since their introduction in the early 1960's and there are hundreds of miles of such barriers currently in use on the nation's highways. While the degree to which the concrete safety shaped barriers have 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 and development of the concrete safety shaped barrier was begun in the 1950's at the General Motors Proving Grounds in Milford, Michigan. In the intervening years, further research sponsored by the Federal Highway Administration (FHWA) has continued the development and improvement of this barrier to provide a low cost, low maintenance barrier capable of safely redirecting errant vehicles, particularly passenger cars in the 2,250 to 4,500 lb range. The 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 damages to vehicles impacting the barrier at low impact angles, as demonstrated in various full-scale crash tests.
- The concrete safety shaped barrier is a rigid barrier that does not deflect to any appreciable degree, even at high dynamic loads. For this reason, the concrete safety shaped barrier is often the barrier of choice for use at locations where barrier deflections are unacceptable, such as along narrow medians, as bridge rails, and in construction zones.
- Compared to flexible longitudinal barriers, e.g., W-beam guardrails, the maintenance costs for the concrete safety shaped barrier are negligible. Thus, this barrier is the barrier of choice at locations with heavy traffic, wherein the probability of a barrier impact is high and maintenance is a problem, e.g., along medians of urban freeways.

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

Past research has provided some insights into the various aspects of this rollover problem, in general, and with regard to concrete safety shaped barriers, namely:

- Smaller and lighter passenger cars, with the corresponding reduction in the roll and yaw moments of inertia, are more prone to overturn than larger and heavier passenger cars. This is of grave concern in light of the downsizing trend of the passenger car fleet that began in the mid-1970's.
- The relative severity of single-vehicle rollover accidents is much higher than that of nonrollover single-vehicle accidents, especially in terms of fatalities.
- The potential of overturning for the concrete safety shaped barrier is affected by variations in the profile of the barrier. The approach geometrics of the roadside and the friction coefficients of the barrier may also play important roles in the propensity for rollover.
- The concrete safety shaped barrier was not designed to restrain large trucks, intercity buses, or school buses; and such impacts frequently result in rollovers.

There has not been, however, a concerted effort to study this rollover problem in a comprehensive manner. A clear understanding of the root causes and relative severities of rollover collisions with concrete safety shaped barriers is needed in order to assess the effect of potential design and/or location changes of these barriers and to assist in the selection of barrier types for various applications.

2. Study Objectives

The objectives of this study are as follows:

- To identify the root causes of rollover of vehicles in impacts with concrete safety shaped barriers.
- To determine the extent and severity of overturn collisions with concrete safety shaped barriers.
- To identify potential countermeasures to reduce shaped concrete barrier rollovers.

3. Scope of Study

The scope of the study included a review and analysis of available literature, statistical and clinical analysis of existing accident data files, computer simulation of concrete safety shaped barrier impacts, laboratory testing, and full-scale crash testing. In addition, potential countermeasures to reduce rollovers in concrete safety shaped barrier collisions were identified and evaluated in the study.

Chapter II outlines the research approach used in the study. A summary of the literature review is presented in chapter III. Results of the accident studies are summarized in chapter IV and those of the simulation studies are discussed in chapter V. The study findings, conclusions and recommendations are presented in chapter VI. Materials too bulky for inclusion in the technical report are presented as appendixes in volume II of the final report.

II. RESEARCH APPROACH

The research approach for the study, as outlined in the original Statement of Work, consisted of five major activities: (1) literature review, (2) accident studies, (3) simulation studies, (4) laboratory testing, and (5) full-scale crash testing. The scope of work for laboratory and full-scale crash testing was reduced during the course of the study and the efforts redirected to accident and simulation studies to better suit the needs of the study. Brief descriptions on each of the five activities conducted during the study are presented in this chapter.

1. Literature Review

Available literature relating to rollover accidents on concrete safety shaped barriers as well as rollover and small car safety in general were critically reviewed to obtain insights into the problem being studied. In addition to pertinent literature already known to the project staff through related work, a computerized literature search was conducted through the Transportation Research Information Service (TRIS) and the National Technical Information Service (NTIS) to identify other pertinent literature.

Abstracts from the literature search were screened using a three-point rating scale: (1) definite review, (2) possible review, and (3) no review. References identified as possible review were further screened for their pertinency. The pertinent references were then reviewed critically and the results summarized using a standardized format consisting of five major headings: citation, study purpose, research approach, findings, and critique. The critical review examined and evaluated the appropriateness and validity of such factors as the study design, research approach, data file used, sample size, statistical and other analytical techniques used, as well as the findings and conclusions.

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 the present study. A summary of pertinent information gathered from the literature review is presented in chapter III of this report. Critical review of the individual references is provided as appendix A in volume II of the final report.

2. Accident Studies

A number of available accident data files were considered for use in the accident studies and the following four data files were eventually selected for use in the analyses:

- Texas barrier accident data file.

- Texas CMB accident data file.
- New York Department of Transportation (NYDOT) barrier accident data file.
- National Accident Sampling System (NASS) Longitudinal Barrier Special Study (LBSS) data file.

Other accident data files that were also considered, but not used, included the NASS Continuous Sampling Subsystem (CSS) data file, the Fatal Accident Reporting System (FARS) data file and the California accident data file. The FARS data file does not identify concrete safety shaped barrier in its list of objects struck. The NASS CSS data base does identify concrete safety shaped barrier accidents, but little benefit is expected from analyzing the data except for national estimates since barrier accidents in the CSS data file are already included in the LBSS data file. The California accident data file was considered due to its earlier study on median barrier accidents. However, no vehicle data is available from the computerized accident data files so that review of hard copies of the police accident reports would be required to obtain the needed vehicle data. With such manual review already planned for the Texas accident data file, there simply was not sufficient time or funding to also review hard copies of police accident reports for the California accident data file.

Brief descriptions of these four accident data files are provided below while the results of the analyses are presented in chapter IV of this report.

a. Texas Barrier Accident Data File

The Texas accident data files for the 3-year period of 1982 to 1984 were first processed to identify all barrier accidents. There were over 27,000 barrier accidents reported on State-maintained highways in Texas during this period, nearly 8,000 of which involved median barriers. A breakdown of these barrier accidents by barrier type and functional classification is shown in table 1. Since the overwhelming majority (86%) of median barrier accidents occurred on urban Interstates and freeways and concrete median barriers are used almost exclusively on urban highways, it was decided to include only barrier accidents occurring on urban Interstates and freeways in the data file (herein referred to as the Texas barrier accident data file).

Extensive analyses were originally planned with this Texas barrier accident data file, including the extent of the rollover problem on concrete safety shaped barriers and the comparison among the various barrier types on rollover experience and potential contributory factors. However, a number of major problems were identified in the preliminary analysis of the data file which greatly limited its utility. Consequently, the Texas barrier accident data file was used only in the preliminary analysis and limited to general descriptive statistics and cursory comparison among the various barrier types on characteristics other than rollover involvement. A separate Texas CMB accident data file was created for the detailed analyses.

One problem encountered was that 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. A manual process was used to identify the locations of these concrete safety shaped barriers. The major urban Districts of the Texas State Department of Highways and Public Transportation (SDHPT) were contacted to identify the locations of concrete safety shaped barriers installed in their Districts prior to 1982.

In discussions with the District personnel, it was found that the concrete safety shaped barriers have mainly been used as median barriers in Texas. There are other isolated applications as roadside barriers and bridge railings, particularly for elevated structures, such as double-decked freeways and ramps at interchanges. However, these applications are too scattered and of lengths too short to be effectively identified. It was therefore decided that, for the purpose of this data file, only concrete median barriers (CMBs) would be included as concrete safety shaped barriers and the other isolated applications would be ignored.

The location information on the CMBs, as provided by the Texas SDHPT Districts, was computerized and merged with the Texas barrier accident data file to identify accidents involving concrete median barriers. Of the total 6,870 median barrier accidents on urban Interstates and freeways, 1,964 were identified as involving concrete median barriers through this location matching process.

Table 1. Distribution of barrier accidents by barrier type and functional classification, Texas data, 1982 to 1984.

	Barrier Type							
Functional	Guardrail		Median Barrier		Bridge Rail		Total	
Classification	No.	%	No.	%	No.	%	No.	%
Urban Interstate/ Freeway	6728	54.6	6870	86.0	2733	40.7	16331	60.4
Urban Arterial	888	7.2	305	3.8	485	7.2	1678	6.2
Urban Collector	12	0.1	0	0	3	0	15	0.1
Urban Subtotal	7628	61.9	7175	89.8	3221	48.0	18024	66.7
Rural Interstate/ Freeway	1515	12.3	581	7.3	1080	16.1	3176	11.8
Rural Arterial	1843	15.0	207	2.6	1527	22.8	3577	13.2
Rural Collector	1333	10.8	23	0.3	880	13.1	2236	8.3
Rural Subtotal	4691	38.1	811	10.2	3487	52.0	8989	33.3
Total	12319	100.0	7986	100.0	6708	100.0	27019	100.0

It should be noted that a small portion of the other median barrier accidents might actually involve concrete median barriers. Over the last few years, there have been many major reconstruction projects on urban Interstates and freeways in Texas in which CMBs were installed. Since only concrete median barriers installed prior to 1982 were included, accidents involving CMBs installed after 1982 would not be identified as such. Nevertheless, it is expected that the number of such accidents is relatively small and would not affect the results of the analysis.

Another problem encountered was on the identification of rollovers using the computerized accident data. Since rollover was not specifically identified in the accident report, damage to the top of the vehicle was initially used as a surrogate for rollover. However, of the 1,964 CMB accidents on urban Interstates and freeways, only 46 (2.3%) were identified as rollovers using this surrogate measure. This low number and percent of rollovers for concrete median barrier accidents was totally different from the rollover rates reported in previous studies. An effort was therefore undertaken to double check the data for possible explanations of this discrepancy, including a manual check of hard copies of police accident reports on selected highway sections with concrete median barriers.

The San Antonio District of the Texas State Department of Highways and Public Transportation, which maintained a file of police accident reports on all accidents occurring on Interstates and freeways within the City of San Antonio, was contacted for their assistance. Hard copies of all accident reports on urban Interstates and freeways for the year 1982 were borrowed from the District. Two sections of highways with concrete median barriers, one on an Interstate highway and the other on a US-numbered freeway, were randomly selected for the manual check. The two selected highway sections totaled 22.5 miles in length.

The accident reports were first screened by matching their locations to those of the two selected highway sections. Each accident report with matched location was then reviewed manually by reading through the narrative and checking the sketch to determine if the accident involved the concrete median barrier. The CMB accidents identified from the manual check were compared to those from the computerized accident data file for accuracy and validity, especially on the correct identification of rollover involvement.

The results from the manual check are detailed in appendix B in volume II of the final report and only a summary is presented herein. Basically, two major problems with the data file were identified from the manual check. The first problem was that less than half of the CMB accidents were correctly identified in the computerized data file. This would preclude the determination of the frequencies or rates of CMB accidents, such as the number of CMB accidents per mile of barrier or the number of CMB accidents per 100 million vehicle miles of travel. Fortunately, there was no apparent bias in which median barriers accidents were identified in the computerized accident data file. In other words, using the computerized accident data file to identify CMB accidents is similar to taking a random sample of CMB accidents. Analyses using percent rollover or comparison between the characteristics and severity of rollover versus no rollover accidents would still be valid.

The second problem concerned the accurate identification of rollovers. Less than half of the rollover accidents were correctly identified using top damage to the vehicle as a surrogate measure. This clearly indicated that manual review of police accident reports would be required to accurately determine rollover involvement. Since the review of hard copies of police accident reports is a tedious and time-consuming process, it was decided that only CMB accidents would be manually reviewed to identify rollovers and not all barrier accidents.

This caused a major change in the original analysis plan. First, the analysis of the Texas barrier accident data file was limited to general descriptive statistics and comparisons among barrier types on accident characteristics other than the rollover experience. Second, a separate data file, herein referred to as the Texas CMB accident data file, was created for the more detailed analysis, including the determination of the extent of the rollover problem for CMBs and the identification of accident characteristics that may have contributed to the rollover problem.

b. Texas CMB Accident Data File

As discussed above, a separate Texas CMB accident data file was created for the detailed analysis. This data file contains 1,964 concrete median barrier accidents that occurred on urban Interstates and freeways. Hard copies of police accident reports on these CMB accidents were requested and purchased from the Texas Department of Public Safety. The police accident reports were reviewed manually to:

- Determine if the involved barrier was indeed a concrete median barrier.
- Determine whether the vehicle rolled over after impact with the concrete median barrier.
- Make sure that the police accident reports actually match with the computerized accident data by comparing selected identification data elements between the police accident reports and a listing from the computerized data file. The identification data elements used for the comparison included the accident report number, county where the accident occurred, the year, month, day and time of the accident.
- Collect supplemental data not available from the computerized accident data file, including impacts with the end or near the end of the median barrier, the impact sequence and whether the vehicle was spinning or skidding sideways prior to impact with the concrete median barrier.

The coding form and accompanying instructions used for this manual review are shown as appendix C in volume II of the final report.

The supplemental data were then computerized and merged with the data file. Of the total of 1,964 accidents in the data file, 125 were eliminated for one or more of the following reasons: the involved barrier was not a concrete median barrier, the accident was self-reported by the involved drivers, or the information in the police accident report did not agree with that of the computerized data file. The usable number of accidents in the Texas CMB accident data file was therefore 1,839 accidents.

c. NYDOT Barrier Accident Data File

The NYDOT data file was created as part of a recently completed research study by NYDOT, in which data on approximately 4,700 barrier accidents on State highways in New York State were gathered over a 1-year period from July 1982 to July 1983. The data file provided to the researchers contains only barrier accidents that occurred in upstate New York and Long Island, amounting to some 3,302 accidents. As shown in table 2, nearly 80 percent of the barrier accidents occurred on State highways with another 17.5 percent occurring on Interstate highways. Note that accidents on the Thruway were supposedly excluded from the data set. However, four of the accidents were coded as occurring on the Thruway.

Table 2. Distribution of accidents by roadway system.

Roadway System	Frequency	Percent
State Highway	2,631	79.7
Thruway	4	0.1
Northway	88	2.7
Interstate	579	17.5
Total	3,302	100.0

According to the NYDOT, the accidents in the data file were all single vehicle accidents (excluding parked vehicles) wherein the first harmful event was coded as a collision with a "guardrail" or "median barrier". On closer inspection of the data, seven of the accidents in the data set showed collisions with objects other than barriers as the first harmful event.

Rollover was not identified as a specific data item. In order to determine if a vehicle overturned following collision with a barrier, the only suitable data item available for analysis was the second harmful event. Of the 3,302 accidents in the data file, 2,429 (73.6%) did not have a second harmful event and 258 (7.8%) were coded as overturns in the second harmful event. It should be pointed out, however, that some of the remaining 3,044 accidents may also have resulted in vehicle overturn. For example, if a vehicle struck a guardrail two times and then overturned, both the first and second harmful events would be coded as impact with a guardrail. No mention of the fact that the vehicle overturned would be made in the coded data. The percentage of rollovers contained in this data set is therefore likely to be conservative.

There are 32 different types of longitudinal barriers in the data set. These were grouped under three major headings of guardrail, median barrier, and post only - no rail. The majority of the accidents (79.6%) involved guardrails and only 90 of the 3,302 accidents involved concrete safety shaped barriers.

For analysis purposes, a different breakdown of the barrier types was used: concrete safety shaped barrier, other median barrier, and other barrier. The concrete safety shaped barrier was separated out since it is the subject of this study. For comparison purposes, other types of median barriers were grouped together and referred to as "Other Median Barrier" while all remaining barrier types were grouped together and referred to as "Other Barrier".

Also, the data file was derived from both accident reports filed by investigating police officers and self-reports from involved motorists. The self reports are typically reports of less severe accidents and are likely to be less reliable, e.g., missing or inaccurate data due to unfamiliarity with reporting form or proper definitions, built-in biases over concern for liability, etc. Of the 3,302 accidents in the data file, 846 (25.6%) were motorist generated and 2,456 (74.4%) were from police officer's reports. For the purpose of analysis, it was felt that self reports by motorists are simply too unreliable and should not be included. Thus, only data from police accident reports were used.

d. NASS LBSS Data File

The NASS LBSS data file is perhaps the best data source available for in-depth evaluation of barrier accidents. The data collection system was specifically designed to address the accident severity of impacts with various barrier systems. The data file contains very detailed information on the environmental, vehicular and human factors associated with the accidents plus specific information on the barrier and roadside characteristics. The only missing data element is impact speed which is not available since the accidents have not been reconstructed.

The key drawbacks to the NASS LBSS data file are the nonrepresentative nature of the sampling scheme and the very small sample size. The LBSS cases were basically samples of convenience, based loosely on a stratified random sampling scheme. The accidents included in the LBSS data file are generally more severe in nature as a result of both the case selection criteria and the acceptance criteria. When two or more barrier accidents were eligible for sampling, the most severe accident would be selected according to the case selection criteria. Also, only complete cases were accepted for inclusion in the data file. This favored the more severe accidents since the involved barriers and vehicles were less likely to be repaired and thus not available for inspection. Since the LBSS cases were samples of convenience, the analysis would have to be either comparative or clinical in nature.

The study included 3 years of LBSS cases, from 1982 to 1984. There were a total of 771 barrier accidents in the LBSS data file during this period, 130 of which involved shaped concrete barriers. The sample size is clearly too small for any form of statistical analysis, even for comparative type of evaluation. Thus, the analysis of the LBSS data file was mainly clinical in nature.

Hard copies of the 130 LBSS cases involving shaped concrete barriers were requested and received from the National Highway Traffic Safety Administration (NHTSA) through FHWA. The hard copies of each case consisted of four CSS field data forms: accident, vehicle, driver, and occupant, the LBSS supplemental data form, a scaled collision diagram, and slides with accompanying slide indices. As mentioned above, the only missing information was the impact speed which required reconstruction of the accidents.

A simplified reconstruction procedure specifically for impacts involving shaped concrete barriers was developed and validated. Detailed descriptions of this procedure and the validation effort are presented in appendix D in volume II of the final report and only a brief summary is presented herein.

The simplified reconstruction procedure is based on the principle of conservation of energy, utilizing empirical relationships derived from full-scale crash test results. The procedure uses some of the subroutines from the CRASH3 (Calspan Reconstruction of Accident Speeds on the Highway, version 3) program to reduce the developmental effort. In fact, the CRASH3 program was used as the starting point for coding of the simplified reconstruction procedure.

The accident sequence is first divided into two phases: impact and post-impact. The impact phase goes from the point of initial contact with the barrier to the point where the vehicle separates from the barrier. The post-impact phase goes from the point of separation to the point of final rest. A closed form, backward stepping process is used. In other words, the reconstruction starts at the point of final rest. The separation speed is first estimated from the post-impact trajectory and the impact speed is then estimated based on the separation speed and the energy loss during the impact phase.

There are two components to the post-impact phase: trajectory and roll. If no rollover occurs during the post-impact phase, the energy loss is strictly from the tire/pavement interface and is estimated using the SPIN2 subroutine from the CRASH3 program. Factors such as coefficient of friction between the tires and pavement surface, distance traveled during the post-impact phase, percent braking, and amount of vehicle rotation are included in the calculation. The separation speed is then estimated by summing the total energy loss after impact and dividing it among rotational and translational velocity.

If rollover occurs during the post-impact phase, the speed at the initiation of rollover is estimated using empirical curves relating roll distance to roll speed. Such empirical relationships were developed previously by using the HVOSM (Highway Vehicle Object Simulation Program) program to simulate vehicle rollover accidents. The energy loss from the point of separation to the initiation of rollover is estimated using the SPIN2 subroutine. The roll speed and the trajectory energy loss are then combined to estimate the separation speed.

During the impact phase, the energy loss is broken down into two components: vehicle crushing and frictional loss. It is assumed that no energy is absorbed by the rigid barrier and that the energy loss due to friction between the tires and pavement surface during the impact phase is negligible. The amount of energy dissipated due to crushing of the vehicle sheet metal and structure is estimated using the DAMAGE subroutine of the CRASH3 program. This takes into account the size, weight, and stiffness of the vehicle and the damage dimensions sustained by the vehicle. The estimate should be reasonably accurate for most impacts since the damages tend to be in a vertical plane, i.e., relatively uniform crush.

The barrier/sheet metal frictional energy loss is a function of the normal force and the length of contact between the barrier and the vehicle. In turn, the normal force is a function of the impact speed and angle. Since impact speed is not known, an iterative process using empirical relationships is used. Energy loss during the impact phase is first assumed to be solely a function of vehicle sheet metal crushing. An initial estimate of vehicle kinetic energy at impact is then obtained by summing the vehicle's kinetic energy at separation with crush energy. Impact speed can then be estimated by assuming that most of the kinetic energy at impact is associated with translational velocity.

Frictional energy loss is then estimated by first calculating the average lateral acceleration during impact based on initial impact conditions and then multiplying it by the weight of the impacting vehicle and the length of barrier contact. To account for the coefficient of friction between the barrier and the vehicle sheet metal, the frictional energy loss estimate is adjusted using an empirical equation developed from full-scale crash test results. A revised estimate of impact energy dissipation is obtained by summing the calculated frictional energy and vehicle crush energy and a new impact speed estimate is calculated in the same manner as before. The revised impact speed is then used to calculate new frictional energy dissipation and the process is iterated until the impact velocity converges.

After coding and debugging of the computer program, the reconstruction procedures were validated using data from four full-scale crash tests. Results of the validation are also summarized in appendix D in volume II of the final report. Overall, the validation results were satisfactory given the simplified nature of the reconstruction procedure. The average percent difference in delta V between the crash test and reconstruction results was roughly 13 percent, with a range from 2.9 to 24.8 percent. However, if one looks at the difference in the actual delta V, the difference ranged from 0.2 to 3.3 mi/h, which was rather small considering an impact speed of 60 mi/h. The trajectory portion of the reconstruction procedure, which is unchanged from the CRASH3 program, plays a much more critical role in the accuracy of the impact speed estimation than the portion pertaining to the impact with the CMB.

The reconstruction procedure was also pilot tested by reconstructing a small number of NASS LBSS CMB accidents using the procedure. Subjective assessments were made by the project staff on how well the procedure worked in actual reconstructions and to identify any problems not found during the validation process. Minor changes were made to the procedure as a result of this pilot test.

As mentioned above, analysis of the NASS LBSS was mainly clinical in nature. The rollover accident cases (a total of 31 cases) were reviewed and clinically analyzed by the project staff to determine potential causative factors and conditions contributing to the likelihood of vehicle rollovers after impacts with the shaped concrete barriers. The results of the clinical analysis are presented in chapter IV of this report.

In the course of reconstructing the accidents and clinically analyzing the rollover accidents, it was found that the quality of some of the cases was rather poor and there was considerable inaccuracy in the data, especially with regard to the vehicle impact and post-impact trajectory. Details of the quality assessment on the NASS LBSS cases are presented in appendix E in volume II of the final report.

The poor quality found with some of the NASS LBSS cases raised concern by FHWA and, at its request, a quality review was conducted on the remaining nonrollover cases. A coding form and accompanying instructions were developed for this quality review process, copies of which are shown in appendix E in volume II of the final report. The results of the quality review were also compiled and entered into a Lotus data file for analysis on microcomputers.

3. Simulation Studies

A careful review of available 3-D rigid barrier computer programs including GUARD, HVOSM-Tire Side Force, and HVOSM-RD2, revealed that existing simulation models were not capable of accurately simulating concrete barrier impacts. The GUARD simulation model has had only limited validation for rigid barrier simulation and results of these efforts were not promising.(1,2) A modified HVOSM simulation model incorporating an improved side force tire model was also evaluated and found to no longer contain rigid barrier simulation routines.(3) Finally, a careful review of the HVOSM-RD2 simulation model indicated that, although the program had been successfully validated for concrete safety shaped barrier impacts, it contained severe limitations that would likely invalidate simulations involving major barrier shape modifications.(4,5)

Of the various limitations identified for the HVOSM-RD2 simulation program for modeling rigid barrier impacts, the most significant limitation is linked to sheet metal and barrier contact force calculations. For purposes of sheet metal contact force calculations, the HVOSM-RD2 program models all rigid barriers as a vertical wall. Although tire contact forces are calculated from the actual barrier shape, sheet metal crush forces are assumed to be generated by a vertical wall and must therefore be perpendicular to a vertical plane, i.e. in a plane parallel to the ground. This limitation has been overcome in the past by extensive validation with full-scale crash testing. The location of the vertical wall within the safety shape configuration is then carefully calibrated to yield good correlation between crash test and simulation results. However, when attempting to simulate major changes in barrier design, this limitation can become a major problem.

A major effort was undertaken to modify the HVOSM-RD2 program to resolve some of the limitation associated with rigid barrier impact simulations. Most of the original modifications were accomplished under NCHRP (National Cooperative Highway Research Program) Project 22-6 while some of the refinements to handle unusual impact conditions were accomplished under this study. Modification to the simulation program included improvements to the sheet metal/barrier interaction model, the suspension damping model, and tire normal force model. An extensive validation effort was then undertaken to verify the correlation between the revised simulation model and crash test results. The validation effort involved three phases:

1. A theoretical stage involving solving sample problems with known solutions.

2. Simulation of two full-scale crash tests involving an instrumented vertical wall.

3. Simulation of seven full-scale concrete safety shaped barrier crash tests.

Primary emphasis in the validation process was placed on accurate predictions of overall vehicle trajectory and accelerations. A detailed description of program modifications and validation is presented in appendix F in volume II of this report.

The revised simulation model was then used to evaluate the potential for concrete safety shaped barriers to cause vehicle rollovers and to assess potential barrier improvements to eliminate the identified rollover problems. The simulation effort was divided into three phases, 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 eliminate problems identified with the standard concrete safety shaped barrier. Objectives of each phase of the simulation effort are described below.

a. Baseline Simulations

The first step in the simulation effort involved simulation of 27 impact conditions involving the standard concrete safety shaped barriers that were believed to be representative of a majority of concrete barrier impacts. The purpose of this effort was to: examine the modified simulation program for reasonable results; identify any potential problems with the standard shape under normal impact conditions, i.e., tracking; and establish a measure of the performance of the standard barrier for later evaluation with proposed alternatives.

Crash tests of standard concrete safety shaped barriers have indicated that this barrier can be expected to perform well for impact speeds near 60 mi/h and impact angles of up to 25 degrees for large cars and 20 degrees for small automobiles. Therefore, it is reasonable to expect that the concrete safety shaped barrier would perform well at most speeds and angles less than those used in crash testing and the simulation program should predict this behavior. Further, simulations of impacts over the range of expected conditions could be examined qualitatively to identify any irregularities in the simulation predictions.

If the simulation program predicted rollover for any of the baseline conditions and the simulation results seemed reasonable for all other impacts, the possibility that a problem area had been identified would be considered. Further validation efforts would be undertaken and some means of determining the accuracy of the program, such as additional full-scale crash testing, would be identified. Finally, if no rollovers were predicted in the baseline runs as anticipated, results of these simulations would provide a basis of comparison of the existing shape with any recommended shape modifications. Table 3 shows the matrix of baseline simulations selected for this phase of the study. Results of the baseline simulation runs are presented in chapter V of this report.

Table 3. Baseline simulation matrix.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)
1,800	30	5
3,800	45	15
4,500	60	25

b. Simulation of Contributory Factors

The objective of this phase of the simulation effort was to verify accident data analysis findings regarding factors that were identified as causative or contributory to vehicle rollover during impacts with concrete safety shaped barriers. Accident data findings should identify impact conditions, such as speed, angle, and vehicle orientation, that might increase the propensity for vehicle rollovers. These impact conditions were simulated for a variety of vehicle sizes in an effort to better understand the nature of concrete barrier impacts, especially those impact conditions resulting in rollovers. Further, careful review of those simulations resulting in vehicle rollovers could yield valuable information regarding possible countermeasures for eliminating these rollover problems. Details of the contributory factors simulated and the results are presented in chapter V of this report.

c. Simulation of Potential Countermeasures

After analyzing the results of accident data analysis and the foregoing simulation efforts, countermeasures designed to reduce the significance of the rollover problem were identified. This phase of the simulation effort was designed to evaluate the effectiveness of each of these potential countermeasures. All impact conditions that were 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 in terms of 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 standard concrete safety shaped barrier and countermeasure baseline runs were then conducted to assess changes, if any, on the potential for occupant injury and vehicle damage, such as lateral acceleration levels and extent of vehicle crush. The potential countermeasures evaluated in this simulation effort and the results are presented in chapter V of this report.

4. Laboratory Testing

The purpose of the laboratory testing was to obtain information currently unavailable on selected barrier or vehicle properties in support of the study effort, particularly for the simulation studies. A number of candidate topics were identified, two of which were considered for laboratory testing: (1) to determine the damping rate of various shock absorbers, and (2) to measure the coefficients of friction of concrete barrier surfaces.

In the course of validating the new rigid barrier subroutine for the HVOSM computer simulation model, it was found that the dynamics of the impacting vehicle were very sensitive to the damping rate of the shock absorbers, but there was very little information currently available on this subject. Upon further investigation, it was decided that the testing of shock absorbers under high dynamic loading to determine the damping rates would require the construction of a special test apparatus and the associated costs would be too high for the budgeted effort under this task. Also, the project staff obtained some testing data on damping rates of shock absorbers under low dynamic loading from the University of Michigan Transportation Research Institute (UMTRI) that are considered adequate for the simulation effort.

The other topic for laboratory testing was to determine the coefficients of friction for various concrete barrier surfaces. Surface friction on concrete safety shaped barriers has been reported to have a significant influence on the stability of impacting vehicles.(6) While the conclusions were based on only a couple of crash tests and there were other extenuating circumstances that could also have affected the test results, it did raise the question on the effect of surface friction on the performance of concrete safety shaped barriers.

The most important effect of high barrier surface friction is believed to be the increase in the lifting force imparted to an impacting vehicle through tire sidewall scrubbing. Another factor related to barrier surface friction is the longitudinal retarding of frictional forces acting on the sheet metal of the impacting vehicle as it slides along the barrier.

Other than the study mentioned above, there has been little effort to date to determine the importance of barrier surface friction to the performance of shaped concrete barriers. In fact, there is little information even on the extent of variation in friction from a smooth barrier surface to an extremely rough surface. In support of simulation efforts to examine the importance of barrier friction to its performance, limited laboratory testing was undertaken to estimate the sliding coefficients of friction found on concrete barrier surfaces.

Two concrete barrier surfaces were selected for testing in this study. The first concrete barrier surface, believed to represent a low friction surface, was a recently manufactured precast concrete safety shaped barrier segment with a smoothly finished surface. The second concrete barrier surface, selected for its extremely rough surface, was a 20-year old weathered concrete safety shaped barrier.

Surface friction was measured using a block, which consisted of a 20-lb weight on either a rubber tire pad or a sheet metal pad, on a horizontal barrier surface. The block was dragged slowly across the surface and the force required to maintain a constant sliding speed was measured using a spring scale. Four sets of tests were conducted for combinations of smooth or rough barrier surface and rubber tire or sheet metal pad. Each set of tests included three or more repetitions to ensure accurate and consistent results. Results of the tests on the coefficients of friction for concrete barrier surfaces are presented in appendix G in volume II of the final report. The results were used in support of the simulation efforts, as described earlier.

5. Full-Scale Crash Testing

Two full-scale crash tests were originally planned for evaluation of selected countermeasures to the rollover problems on concrete safety shaped barriers. However, as the work progressed in the study, it became apparent that two crash tests would not be sufficient to evaluate the various countermeasures identified and the evaluation could be better done with computer simulation. With the approval of FHWA, the two crash tests were deleted from the study, and the effort budgeted for this task was redirected to the accident and simulation studies.

One full-scale crash test on a portable concrete safety shaped barrier, commonly used in Pennsylvania as a temporary barrier in construction zones, was later added to the project at the request of FHWA and the Pennsylvania Department of Transportation. The barrier tested consisted of five 20-ft segments connected by slotted plates and was 34 in high with a 5-in reveal (lower vertical face). There was concern that this higher than normal reveal might increase the propensity of rollover for errant vehicles impacting barriers of this design.

The barrier installation was impacted by an 1,800-lb passenger car (1980 Honda Civic) at a speed of 60 mi/h and at an angle of 15 degrees. The vehicle remained upright during and after the impact, although the maximum roll angle of 30.3 degrees was considerably higher than the maximum roll angle observed in other crash tests with the standard New Jersey shaped concrete barrier. Also, the test results met all requirements outlined in NCHRP Report 230, "Recommended Procedures for the Safety Performance of Highway Appurtenances".(7) Details of the crash test and results are provided in Test Report 7051-1, included as appendix H in volume II of the final report.

III. LITERATURE REVIEW

A summary of pertinent information gathered from the literature review is presented in this chapter and is divided into two major subject areas: (1) accident studies, and (2) simulation studies and full-scale crash tests. Synthesis of the available literature is presented in the following sections.

1. Accident Studies

The information from accident studies is further divided into two major topics: (1) extent of the rollover problem for shaped concrete barriers, and (2) rollover and small car safety problem in general.

a. Extent of Rollover Problem for Shaped Concrete Barriers

A number of studies have reported on accident data pertaining to concrete safety shaped barriers used as median barriers, but no specific information is available for their use as roadside barriers or bridge railings. This is to be expected since the concrete safety shaped barriers have mainly been used as median barriers, although their use as roadside barriers or bridge rails is gaining popularity. The information presented in this section is thus limited to concrete median barriers (CMBs).

The rollover experience was compared for three types of median barriers: concrete, cable, and metal beam, using 1979 accident data on freeways in California.(8,9) A summary of the data is shown in table 4. The percentage of passenger car rollovers on CMBs (6.8%) is 1.9 times that of cable median barriers (3.6%) and 3.8 times that of metal beam median barriers (1.8%). For nonpassenger car rollovers, the percentages still follow the same order (3.0% vs. 2.6% vs. 2.0%), but the differences are much smaller. This suggests that the propensity for rollovers is more sensitive to barrier types for passenger cars than for other vehicle types.

A study comparing the rollover experience of imported versus domestic passenger cars as the surrogate for small versus large cars concluded that small cars are significantly overrepresented in rollover accidents for all three barrier types. However, there is no significant difference in the proportions of imported passenger cars between the three barrier types.

The cumulative weight distribution of the 123 passenger vehicles that overturned in collisions were compared with the CMBs to that of passenger cars registered in California in 1979. Vehicles weighing less than 2,250 pounds accounted for 51 percent of the overturned vehicles, but only 24 percent of the passenger car registration. The data indicate that rollovers are overrepresented up to a curb weight of about 2,700 lb. The cable median barrier also shows a vehicle size effect with 50 percent of the vehicles that rolled over weighing less than 2,250 lb. The vehicle size effect is the smallest for metal beam median barriers.

Table 4. Summary of reported median barrier accident data for freeways in California, 1979.(8)

	Barrier Type					
	Concrete		Cable		Metal Beam	
	No.	%	No.	%	No.	%
Total Number of Accidents	1796	100.0	2305	100.0	2005	100.0
Number of Rollover Accidents						
Imported Passenger Car	73	4.1	46	2.0	17	0.9
Domestic Passenger Car	50	2.8	37	1.6	20	1.0
Passenger Car Subtotal	123	6.9	83	3.6	37	1.9
Other Vehicle Types	54	3.0	60	2.6	41	2.0
Total	177	9.9	143	6.2	78	3.9

A Michigan study reported that rollovers accounted for 6-1/2 percent of injury and fatal accidents involving CMBs.(10) Small cars of under 2,500 lb appeared to be overrepresented in the injury and fatal rollover accidents. Median barrier accidents were found to constitute a relatively constant percentage of total freeway accidents, regardless of the type of barrier in place. The severity of CMB accidents was greater than that for left-side guardrail accidents, but lower than that of multivehicle head-on and sideswipe-opposite direction accidents.

The accident experience was monitored on an 8 3/4 mile stretch of Interstate Highway 95 in Florida during a 6-month period from September 1983 to March 1984.(11) The installation included 1 mile of a new median barrier design developed by International Barrier Corporation (I.B.C.) and the remaining 7 3/4 miles are CMBs of the New Jersey design. There were 48 CMB accidents involving 53 vehicles during the study period, five of which (9.4%) resulted in rollovers. In comparison, none of the 10 accidents involving the I.B.C. median barrier resulted in rollover.

In a major research study on concrete median barriers, CMB accident data were obtained from 15 State highway agencies, a summary of which is shown in table 5.(12) The modified New Jersey shape has a reveal (lower vertical face) of 4 to 5 in instead of the standard 3 in. The authors concluded that the performance of the three shapes is comparable except for the occurrence of vehicle rollovers. The New Jersey shape (MB5) shows a definite advantage over the other shapes in preventing vehicle rollover. They also reported that the CMBs have been effective in containing and redirecting heavy vehicles, i.e., buses and large trucks, with only two of 49 heavy vehicle accidents resulting in penetration of the barrier and one rollover.

Table 5. Summary of accident data from 15 States.(12)

Barrier Type	Total Number of Accidents	Vehicle Rollovers Number	Vehicle Rollovers %
New Jersey	180	6	3.3
Modified New Jersey	73	9	12.3
General Motors	299	19	6.4
Total	552	34	6.2

An inservice performance evaluation was conducted on concrete median barriers (General Motors design) installed in Milwaukee County, Wisconsin.(13) For the 12-month period from December 1972 to November 1973, 170 CMB accidents were reported. There were 13 automobiles (7.6%) that rolled over after impacting the barrier, 9 of which were small cars. Two of the rollover accidents resulted in fatalities, one of which also mounted and crossed the barrier. In addition, 11 cars mounted the barrier, 4 of which were on right curves.

The extent of rollovers on concrete median barriers reported herein pertains to only reported accidents. An unknown, but probably significant, portion of accidents involving CMBs are not reported to law enforcement agencies for various reasons. It is reasonable to assume that these unreported accidents are relatively minor in nature and unlikely to involve rollovers. The inclusion of such unreported accidents would certainly change the extent of the rollover problem for concrete median barriers. However, since very little information is available on unreported accidents, the assessment of the rollover problem for CMBs will have to be limited to reported accidents only.

An Indiana study provided an indication of the frequency of unreported to reported accidents on concrete median barriers.(14) On one roadway section, 12 accidents were reported with an estimated 47 incidences based on marks on the barrier (a ratio of 3.9 to 1). On another section, 53 marks resulted in 20 reported accidents (a ratio of 2.7 to 1). The authors concluded that less than half of the incidences involving CMBs were reported to law enforcement agencies.

A study by the Los Angeles District office of the California Department of Transportation reported that some 40 percent of the contact marks on an approximately 3-mile long concrete median barrier were not accounted for by police accident reports.(15) Another study on box-beam median barrier accidents found that only 33 accidents involving the median barrier were reported compared to 204 damages recorded (a ratio of 6.2 to 1).(16)

The ratio of total incidences to reported accidents is even higher for temporary barriers.(17) Precast concrete traffic barriers of the New Jersey design were used in two construction zones in Virginia. For one 2.37-mile long section, there was evidence of 154 vehicle involvements above the 3-in reveal over a 3-month period, but only 3 accidents were reported involving the barrier (a ratio of 51 to 1). A second section 2.28 miles in length had evidence of 89 vehicle involvements above the 3-in reveal over a period of slightly less than 1 month, but only two reported accidents (a ratio of 45 to 1).

b. Rollover and Small-Car Safety Problem In General

The rollover potential of vehicles on embankments, sideslopes, and other roadside features is the topic of a recently completed FHWA study.(3) A detailed review of 13 references, supplemented by limited analysis of 1979-1981 NASS (National Accident Sampling System) data, was conducted as part of that study to determine the general state of knowledge of rollover accidents. Most of the data pertain to rollovers as the first harmful event with no specific reference to rollover involvements subsequent to prior impacts with longitudinal barriers. Nevertheless, the information provides some insights into the rollover problem in general.

In another recently completed FHWA study accident problems associated with mini-cars are defined and evaluated for potential safety countermeasures.(18) The study included a critical review of literature, supplemented by analyses of accident data from three States: North Carolina, Texas and Washington. Safety problems posed by mini-cars in impacts with longitudinal barriers is one of the topics specifically addressed in the study. Other topics studied included general mini-car problems, rollover potential, geometric and roadside design, and safety problems posed by mini-cars in impacts with various roadside objects and features.

Comprehensive review of literature on rollover and small car safety problems in general is well covered in these two studies. Only findings of specific interest to the problem of rollovers on shaped concrete barriers are to be included in this report. For more general information on rollovers and small car safety, the reports from these two studies are recommended.

The first study concluded that rollover is a relatively frequent occurrence, particularly for single vehicle accidents.(3) Also, the rollover rates vary greatly by vehicle type and size. Table 6 shows the percentage of rollover for single vehicle accidents, both as the first harmful event and overall, based on the 1979-1981 NASS data.

Table 6. Percentage of rollover for single vehicle accidents, 1979-1981 NASS data.(3)

Vehicle Type	Number of Single Vehicle Accidents	Percent Rollover	
		First Harmful Event	All Rollovers*
Utility Vehicles	86	38.4	65.2
Pickup Truck	503	19.3	39.7
Van	119	13.5	30.3
Station Wagon	811	7.9	20.2
Passenger Cars	1637	7.1	21.5
All Vehicle Types	3156	10.3	25.6

* 59 percent of the rollovers were not first harmful event.

Utility vehicles have the highest rollover rate (38.4% as the first harmful event and 65.2% overall), followed by pickup trucks and vans. Station wagons and passenger cars have similar rollover rates and are the lowest among the various vehicle types. Utility vehicles are about three to five times more likely to overturn than passenger cars and station wagons. The results are consistent among the various studies reviewed with regard to the rank ordering of the different vehicle classes by rollover rate.

For passenger cars, the relative rollover involvement rate (i.e., the ratio of percentage of all rollovers to percentage of all accidents) increases with decreasing vehicle weight, as shown in table 7. Vehicles weighing 3,000 lb or less are overrepresented in rollover involvement (i.e., a ratio of greater than 1.0). The relationship appears to be curvilinear with the highest relative rollover involvement rate for vehicles weighing 2,000 lb or less. The rate decreases rapidly with increasing vehicle weight up to 3,500 lb and then levels off.

A major problem with mini-cars is their propensity for overturning, citing the literature and analyses conducted in the study.(18) All three accident data bases indicated that mini-cars overturn more frequently than larger cars for all highways types. For rural highways in North Carolina, the lowest mini-car rollover percentage is found on Interstates (28%), which increases progressively on US (35%), State (39%) and secondary routes (46%). Different mini-car rollover percentages are found on Texas highways with rural Interstates having the highest mini-car rollover percentage, as shown in table 8.

Table 7. Comparison of passenger car relative rollover involvement rates in single vehicle accidents, 1979-1981 NASS data.(3)

Vehicle Weight (Pounds)	All Accidents No.	All Accidents %	All Rollovers No.	All Rollovers %	Relative Rollover Involvement Rate
<= 2000	138	8.4	60	16.9	2.01
2100-2500	235	14.2	79	22.3	1.57
2600-3000	257	15.6	74	20.9	1.34
3100-3500	392	23.8	70	19.8	0.83
3600-4000	331	20.1	42	11.9	0.59
4100-4500	218	13.2	21	5.9	0.45
>= 4600	77	4.7	8	2.3	0.49
Total	1648	100.0	354	100.0	1.00

Table 8. Mini-car rollover percentages by location and highway type, Texas data.(18)

Highway Type	Percent Rollover Urban	Percent Rollover Rural
Interstate	15.9	50.5
US/State	16.6	39.1
Farm-to-Market	19.7	40.4
Local		
City Street	10.3	N/A
County Road	N/A	32.4

An analysis of 1980 Texas accident data using logistic regression techniques found that smaller cars are much more likely to roll over than larger cars on all highway classes.(19) Compared to larger cars, mini-cars are found to be eight times more likely to overturn on county roads, 12 times on Interstates, and 37 times on city streets.

The second FHWA study also examined the rollover rate subsequent to impact with a fixed object.(18) Mini-cars are found to have an elevated rollover rate after striking any fixed object when compared to larger vehicles. Table 9 shows the percentage of rollovers after impact with fixed object for three vehicle sizes, using the North Carolina accident data. After impact with a median barrier, 28 percent of mini-cars rolled over, as compared to only 4 percent for big cars and 7 percent for mid-size cars.

Table 9. Percentage of rollovers after impact with fixed objects, North Carolina data.(18)

Object Struck	Vehicle Size Big	 Midi	 Mini
Median Barrier (US, State and Secondary Highways)	4	7	28
Traffic Islands			
Rural Highways	7	32	33
Urban Highways	3	16	18
Catch Basins (Rural Primary)	18	26	30
Ditch Banks			
Rural Interstate	9	28	36
Other Rural Highways	18	30	38
City Streets	6	13	16
Guardrail Ends (Rural Highways)	7	13	18
Bridge Piers (Rural Highways)	0	23	33
All Objects	7.5	15.0	20.8

In a study using Texas accident data, it was reported that median barrier accidents resulted in 9.4 percent incapacitating (A) and fatal (K) injuries, as compared to 10.3 percent for guardrail accidents, 11.2 percent for bridge rail accidents, and 11.9 percent for all single-vehicle fixed-object accidents over all highway types.(20) Median barrier accidents are found to be slightly more severe on rural highways, especially on rural US and State highways.

Rollover accidents are consistently found to be more severe than other types of accidents in all the studies reviewed. Overturn was reported to be the leading cause of roadside fatalities in 1981, accounting for 33.8 percent of the fatalities on all roads and 44.7 percent of those on the Interstate system.(9) The first FHWA study noted that ejection is the leading cause of serious and fatal injuries in rollover accidents, with 40 percent of the occupants being ejected in rollovers and 50 to 70 percent of those killed in rollover crashes being ejected.(3)

Similarly, severity of accidents involving smaller cars is found to be higher than that of larger cars in various studies. For example, the driver of a 2,000-lb vehicle is 2.6 times as likely to be killed as the driver of a 4,000-lb vehicle in similar crashes.(21) The rates for incapacitating and fatal (A + K) driver injuries in single vehicle rollover crashes per 10,000 registered vehicles decreased with increasing car size with a five-fold difference (4.1 vs. 0.8) between subcompact and full-size cars.(22)

However, given a rollover accident had occurred, no difference was found in driver injury by car size, and the increase in injury from rollovers may reflect the increase in overturn rate for smaller cars and not an increase in injury severity.(9) If only rollover accidents are examined, mini-car drivers experience consistently lower, though not significant, serious and fatal injury rates than do the drivers of larger cars.(18) They theorized that this can be partially explained by the fact that: (1) mini-car drivers are belted more often than larger car drivers, and (2) mini-cars overturn at lower speeds.

Car size is found to have no effect on frequency of accidents involving longitudinal barriers other than a higher rollover rate for median barrier accidents as noted earlier.(18) In terms of accident severity, an increase in minor and moderate injury was reported for the smaller cars in guardrail accidents, but not in serious or fatal injury.(23) No difference was found in any level of injury between smaller and large vehicles in bridge rail accidents.

In most of the rollover accidents, the vehicles were skidding out of control at a large sideslip angle prior to overturning.(3) It is hypothesized that smaller vehicles may "trip" more easily than larger vehicles, or roll over more abruptly when striking fixed objects.(18) Research shows that 30.7 percent of all single vehicle accidents on rural two-lane highways involved nontracking vehicles, i.e., skidding sideways or spinning.(24) Nontracking vehicles are two to three times more likely to experience rollovers than tracking vehicles.

An analysis of the National Crash Severity Study (NCSS) data file revealed while vehicles skidding sideways were found in less than 30 percent of all single vehicle accidents, they accounted for over half of the rollover accidents.(25) On the other hand, vehicle spinning was found in only 3.9 percent of all single vehicle accidents and 4.3 percent of rollover accidents. Similar results were found for light trucks and vans.

Analysis of Texas accident data found that mini-cars were overrepresented in single vehicle accidents on wet pavement.(18) Similar results were also reported in other studies.(26,27) However, the Texas data indicated that the rollover rate on wet pavement is much lower than the rollover rate on dry pavement for all vehicle sizes. This may result from the fact that there is less tripping and more sliding on wet pavement due to the lower coefficient of friction, or simply that single vehicle accidents occur at lower speeds which would result in fewer rollovers.

The likelihood of rollover increases with increasing speed prior to impact.(3) The rollover involvement rate for various impact speeds based on the Collision Performance and Injury Report (CPIR) data file is shown in table 10. The data indicated that about one-quarter of the rollovers occurred at speeds below 40 mi/h and over half of the rollovers involved vehicles traveling 50 mi/h or less. The relative rollover involvement rate, i.e., the ratio of percent rollover to percent of accident, increases with higher speed. Rollovers are underrepresented for speeds below 40 mi/h and overrepresented for higher speeds.

Table 10. Impact speed and rollover involvement, CPIR data file.(28)

Impact Speed (mi/h)	All Accidents No.	All Accidents %	Rollovers No.	Rollovers %	% of Rollovers %	% of Rollovers Cum.	Relative Rollover Involvement
1-10	178	9.5	4	2.2	1.9	1.9	0.20
11-20	157	8.4	2	1.1	1.0	2.9	0.11
21-30	341	18.3	9	2.6	4.4	7.3	0.24
31-40	405	21.7	37	9.1	18.0	25.3	0.83
41-50	361	19.3	55	15.2	26.7	52.0	1.38
51-60	195	10.4	41	21.0	19.9	71.9	1.91
61-70	157	8.4	33	21.0	16.0	87.9	1.90
71-80	38	2.0	9	23.7	4.4	92.3	2.20
81-90	25	1.3	10	40.0	4.9	97.2	3.77
91-100	10	0.5	6	60.0	2.9	100.0	5.80
Total	1867	100.0	206	11.0	100.0		

2. Simulation Studies and Full-Scale Crash Tests

Discussions on information gathered from simulation studies and full-scale crash tests are combined into a single section since most studies utilized both approaches in their efforts to develop and evaluate barrier designs and performance. Results of simulation studies are usually presented in summary form without specific details while results of full-scale crash tests are generally provided in considerable detail, a summary of which is shown in table 11. The information gathered from the literature review is presented under two major topics: (1) important barrier properties, and (2) simulation programs.

a. Important Barrier Properties

A number of studies have shown that the New Jersey shaped concrete barrier performs well under normal crash test conditions, i.e., passenger cars approaching the barrier in a tracking mode on hard flat surfaces. Among these are references 5, 12, 29, 30, and 31. These crash test results have led to the widespread use of the NJ shaped concrete barrier, both as median barriers and bridge railings. However, more recent research findings appear to indicate that the concrete safety shaped barrier may not perform

TABLE 11. Summary of results from selection studies and full-scale crash tests.

Ref. No.	Test No.	Shape	Anchoring	Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Approx. Height of Climb (in)	50 MS Average Acceleration			Contact Distance (ft)	Roll	Pitch	Yaw	Remarks
								Longitudinal	Lateral	Vertical					
33	1	8 ft Portable N.J. Shape	PCB	4300	64.9	25.0	-	7.2	8.6	-	80.0	-59	23	90	Redirected, rollover towards barrier. Reached top of barrier.
	2	"	"	2175	65.5	15.0	-	5.6	6.8	-	22.0	-64	8	0	Redirected, near rollover. Reached top of barrier.
	3	"	"	4350	61.1	25.0	-	5.6	6.1	-	70.0	-42	10	270	Redirected, near rollover.
	4	"	"	2175	61.4	15.0	-	3.5	7.5	-	29.0	-11	3	0	Redirected, reached halfway to top of barrier.
39	1	N.J. Shape	PCB	4700	61.0	26.0	66	-	-	-	16.0	48	-	-	Redirected. Rollover towards barrier.
40	1	N.J. Shape	PCB	4860	65.0	7.0	28	3.6	-	11.4	30.5	18	-	-	Smooth redirection.
	2	"	"	"	68.0	23.0	84	4.8	-	28.9	-	61	-	-	Redirected, near rollover.
	3	"	"	"	66.0	40.0	85	13.6	-	31.8	-	33	-	-	Penetrated, vehicle override. Rollover after override.
	4	"	"	4700	39.0	25.0	32	2.4	-	10.0	36.5	33	-	-	Smooth redirection. Reached top of barrier.
41	9	Portable N.J. Shape	PCB	4250	10.0	25.0	-		-		34.0				Redirection, climbed to top.
	10	"	"	4230	54.8	25.0	-				26.0				"
42	1	Concrete safety shape barrier half section & box beam	PCB	4450	55.7	25.0	-	3.2	5.5	-	27.0	10	2	-	Smooth redirection.
	2	"	"	1600	59.0	14.0	-	4.6	8.2	-	-	5	0	0	"
	3	"	"	4150	54.3	29.0	-	11.1	9.7	-	-	-9	4	117	"
	4	"	"	4730	57.1	26.0	-	12.9	7.7	-	-	46	-	70	Penetrated barrier. Rollover towards barrier.
	5	"	"	1800	58.3	20.0	-	10.4	14.0	-	-	3	4	0	Smooth redirection.
	10	"	"	4650	61.2	29.0	-	5.9	10.9	-	-	5	2	-	"
				4500	63.7	30.0	-	9.0	9.9	-	-	-90	-	-	Rollover away from barrier.
29	1	N.J. Shape	2 in. Asphalt	40020	54.0	16.2	-				70.0		4	16	Redirected.
	2	"	"	40030	53.0	15.0	-				58.5		-	10	Mounted barrier.
	3	"	"	"	54.0	14.0	-				61.0		-4	14	Redirected.
	4	"	"	20270	61.6	15.0	-				-		-	-	Rollover.
	5	"	"	19990	60.9	16.0	-				90.0		4	-	"
	6	"	Backed by Concrete Blocks	1970	60.4	15.0	33				10.5		5	15	Redirected.
	7	"	"	1968	61.3	20.0	33				11.0		-10	20	"

TABLE 11. Summary of results from selection studies and full-scale crash tests (continued).

Ref. No.	Test No.	Shape	Anchoring	Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Approx. Height of Climb (in)	50 MS Average Acceleration			Contact Distance (ft)	Roll	Pitch	Yaw	Remarks
								Longitudinal	Lateral	Vertical					
10	1	N.J.		4370	60.3	7.5		-1.7	- 5.0	14.0	-		-	-	Smooth redirection.
	2	G.M.		"	61.6	7.5		-1.5	- 3.5	11.0	-		-	-	"
	3	"		"	56.4	15.5		-3.5	-10.1	28.0	-		-	-	"
	4	N.J.		"	55.9	15.9		-5.0	-10.1	32.0	-		-	-	"
	5	G.M.		2250	53.2	7.0		-2.4	- 4.3	18.0	-		-	-	"
	6	"		"	55.1	7.0		-2.7	- 5.3	21.0	-		-	-	"
	7	"		"	54.2	15.0		-5.3	- 8.3	19.0	-		-	-	Rollover.
	8	N.J.		"	55.9	8.0		-	-	22.0	-		-	-	Smooth redirection.
	9	"		"	58.9	15.5		-3.6	- 5.1	27.6	-		-	-	"
	10	Config. F		"	56.9	6.7		-2.1	- 2.9	-	-		-	-	"
	11	"		4370	58.6	8.3		-1.4	- 3.4	-	-		-	-	"
	12	"		"	60.6	15.7		-5.1	- 6.6	-	-		-	-	"
	13	"		2290	56.4	14.3		-3.8	- 4.6	-	-		-	-	"
	14	"		4500	59.6	24.0		-7.1	-11.3	-	-		-	-	Redirected.
	15	N.J.		"	60.1	25.2		-6.2	-14.1	-	-		-	-	"
	16	"		"	55.8	23.9		-5.4	- 6.4	-	-	-	-	-	"
	17A	"		"	59.6	7.0		-	-	-	-	-	-	-	Straddled barrier.
	17B	"		"	64.1	10.0		-	-	-	-	-	-	-	Launched over barrier into opposing lane.
	18	Config. F		"	62.0	25.0		-	-	-	-	-	-	-	Barrier failed.
	20	"		"	63.0	24.8		-6.1	- 9.8	-	14.7		-	-	Redirected.
	21	N.J.		40000	41.6	11.5		-0.9	- 0.7	-	25.9		-	-	Smoothly redirected.
	22	"		"	51.6	6.6		-0.9	- 0.8	-	28.0		-	-	"
	23	"		"	52.9	16.0		-0.8	- 1.0	-	65.1		-	-	Redirected.
	24	Config. F		4500	56.4	24.1		-3.5	- 4.9	-	44.5		-	-	"
35	1	Nebraska	7/8-in dia. threaded rods	1640	55.0	15.0	-	2.3	8.5	4.1	15.0	11	-	-	Smooth redirection.
	2	"	"	2460	59.0	15.0	-	1.5	8.5	3.0	19.0	12	-	-	"
43	5	PCMB	-	4500	60.7	25.0	34	-6.2	- 7.5	8.2	52.0				Redirected.
	6	"	-	"	60.1	24.0	34	-5.6	- 7.9	7.8	75.0				Redirected after exiting end of barrier.
	7	"	-	"	59.2	25.0	36	-5.7	- 7.1	-7.8	60.0				Redirected.
	8	"	-	20000	57.7	15.0	-	-1.1	5.3	-1.9	180.0				Redirected, came to rest on its side.
	9	PCMB + W-Beam	-	4510	63.4	25.0	-	-8.8	9.9	-2.2	35.0				Redirected.

TABLE 11. Summary of results from selection studies and full-scale crash tests (continued).

Ref. No.	Test No.	Shape	Anchoring	Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Approx. Height of Climb (in)	50 MS Average Acceleration			Contact Distance (ft)	Roll	Pitch	Yaw	Remarks
								Longitudinal	Lateral	Vertical					
5	CMB-1	CMB-70	7/8-in dia. threaded rods	4000	62.4	25.0		3.2	4.4	-	15.3				Redirected.
	CMB-2	"	"	4230	55.7	25.0	32	1.8	2.8	-	-				"
	CMB-3	"	"	4210	60.9	7.0	18	0.5	1.8	-	17.6				"
	CMB-4	"	"	"	60.7	15.0	34	1.4	3.0	-	23.0				"
30	CMB-1	N.J. Type	1-in ACP Base	4500	60.5	23.5	-	1.6	7.5	-	-				Smoothly redirected.
	CMB-2	"	"	4540	59.8	24.2	-	1.1	6.3	-	-				"
44	1	N.J. Precast	-	4500	60.9	15.0	-	3.9	4.9	5.6	60.0				Smoothly redirected.
	2	"	-	"	56.0	25.0	-	7.4	7.7	4.3					"
28	1	42-in N.J. Shape	Permanent	1783	59.9	14.5	12	4.6	10.0	3.0	25.0	10	7	18	Smooth redirection, L.F. tire blown.
	3	"	"	4520	58.6	16.5	7	4.2	7.9	1.8	30.0	9	5	25	Smooth redirection.
	13	"	"	80180	52.1	16.5	0	6.5	3.1	9.3	150.0	52	27	10	Redirected (near rollover).
31	1	N.J./16-in curb 3 in. Reveal	Permanent	3315	72.0	20.0	-	8.4	7.3*	-	16.0	50	-	-	Redirected (near roll away from barrier
	2	"	"	1674	72.0	20.0	-	9.1	12.8*	-	12.0	180+	-	-	Redirected, rollover away from barrier
	3	N.J./16-in curb 6-in Reveal	"	"	71.0	20.0	-	9.1	12.6*	-	12.0	180+	-	-	"
	4	"	"	"	53.0	20.0	-	2.3	7.8*	-	14.0	45	-	-	Redirected, near roll away from barrier
	5	"	"	3315	50.0	20.0	-	2.7	4.9*	-	15.0	20	-	-	Redirected, left tires blown
	6	"	"	1674	60.0	20.0	-	5.5	7.8*	-	11.0	90+	-	-	Redirected, rollover away from barrier.
	7	N.J./3-in knee at top of curb 3-in Reveal	"	"	63.0	20.0	-	6.8	9.2*	-	-	90+	-	-	"
	8		"	"	59.0	20.0	-	4.7	8.2*	-	-	29	-	-	Rollover toward barrier due to damaged suspension & rough ground.
	9	"	"	24450	45.0	20.0	-	1.9	1.2*	-	-	13	-	-	Smooth redirection.
	10	"	"	1674	56.0	23.0	-	6.6	6.6*	-	13.0	25	-	-	Redirected (damaged suspension).
	11	"	"	"	70.0	20.0	-	9.7	9.7*	-	15.0	90+	-	-	Rollover toward barrier due to damaged suspension & rough ground.

*Computed Average Accelerations

TABLE 11. Summary of results from selection studies and full-scale crash tests (continued).

Ref. No.	Test No.	Shape	Anchoring	Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Approx. Height of Climb (in)	50 MS Average Acceleration			Contact Distance (ft)	Roll	Pitch	Yaw	Remarks
								Longitudinal	Lateral	Vertical					
31	12	59-in N.J. 6-in Reveal	Permanent	1674	70.0	20.0	-	8.8	8.8*	-	14.0	5	-	-	Rollover toward barrier due to damaged suspension & rough ground.
	13	"	"	"	59.0	20.0	-	7.6	7.6*	-	19.0	low	-	-	Smooth redirection.
	14	"	"	"	68.0	20.0	-	10.0	10.0*	-	16.0	45°	-	-	Redirected, near rollover due to damaged suspension.
	15	"	"	"	70.0	20.0	-	12.0	12.0*	-	15.4	35	-	-	Rollover toward barrier due to damaged suspension.
45	1	42-in N.J. Shape	Permanent	1860	62.6	15.0	20	4.6	8.3	-	-	90+	6	22	Rollover toward barrier due to damaged suspension.
	2	"	"	80420	52.8	16.0	-	2.3	11.4	-	165.0	90	12	17	Rollover onto barrier.
32	3	32-in F-Shape Bridge Rail	Permanent	1800	60.1	21.4	-	-8.0	12.8	-	-	-	-	-	Smooth redirection.
	4	"	"	5440	65.4	20.4	-	-4.7	13.1	-	-	-	-	-	"
	8	"	"	13050	46.7	15.0	-	-2.2	3.4	-	-	-	-	-	Redirected, near rollover.
	9	"	"	"	47.3	15.3	-	-2.0	2.9	-	-	-	-	-	"
	11	"	"	18000	52.1	14.8	-	-1.4	3.9	-	-	-	-	-	"
	7	42-in F-Shape Bridge Rail	"	29840	55.7	15.7	-	-1.5	6.5	-	-	-	-	-	Smooth redirection.
	10	"	"	29900	52.2	14.0	-	-2.2	4.7	-	-	-	-	-	Redirected, near rollover.
	12	N.J. Shape	"	10900	51.6	15.5	-	-3.2	2.5	-	-	-	-	-	Rollover behind barrier.
47	1	Mod. Reverse Lap Splice Connection	PCB	4600	57.1	25.9	-	-	-	-	-	-	-	-	Redirected, reached top of barrier.
48	1	Lap Splice CMB	PCB	4480	63.2	24.0	-	-5.3	-8.2	-	-	-	-	-	Redirected, reached top of barrier.
	2	"	"	4500	59.2	25.0	-	-5.5	-9.7	-	-	-	-	-	"
34	1	N.J. Shape	Permanent	1560	58.4	15.0	17.0	-4.2	9.0	4.6	9.0	7	10	14	Smooth redirection.
	2	"	"	"	59.9	21.9	20.0	-7.1	13.8	4.5	9.3	8	15	35	"
	3	"	"	1280	60.0	16.0	-	-6.0	7.4	3.6	8.0	13	17	25	"
	4	"	"	1610	61.6	16.0	-	-4.5	7.6	3.7	13.0	4.5	4.5	17	"
	12	"	"	1530	61.6	20.1	-	-6.0	12.1	4.0	12.0	18	8	15	"

*Computed Average Accelerations

as well for unusual impact conditions, and minor changes in the shape can greatly influence its performance. A number of barrier properties have been identified in the literature as important to the propensity of rollover for shaped concrete barrier impacts, especially for smaller vehicles, including:

- Height of reveal.
- Height of first sloped face.
- Offset of the upper sloped face from the edge of the barrier.
- Slope of the upper sloped face.
- Coefficient of friction of barrier surface.
- Approach terrain.
- Lateral barrier movement.

Brief discussions on these important barrier properties as reported in the literature are presented as follows.

Full-scale crash testing and computer simulation were used to evaluate the impact performance of the General Motors (GM) and New Jersey (NJ) shaped concrete barriers as well as six new variations on the safety shaped barrier.(12) These efforts led to the conclusion that even minor changes in the slope of the upper sloped face of the barrier can significantly change the maximum roll angles observed during high-speed impacts. Poor performance of the GM shape during crash testing was attributed largely to the 80-degree slope of the upper sloped face compared to the 84-degree slope on the NJ shaped barrier. HVOSM simulation findings indicated that this increase of four degrees to the slope of the upper sloped face could reduce the maximum roll angle of subcompact vehicles by as much as 10 degrees.

A simulation study of six new barrier shapes led to the development of the so called "F-shape" barrier.(12) This simulation effort identified other important barrier properties including; the height of the vertical reveal, the height of the lower curb face (which includes the vertical reveal and the lower sloped face of the barrier), and the offset of the upper sloped face from the edge of the barrier. Maximum vehicle roll angle and climb were found to be reduced for barriers having shorter vertical reveals and lower curb faces and when the upper sloped face of the barrier was placed closer to the edge of the barrier. All of these general findings were verified by crash testing conducted in England.(32)

Recent crash tests of NJ and F-shaped barriers with single unit trucks indicated that the higher curb face on the NJ shape might have caused these trucks to roll over.(33) Three tests of an F-shaped barrier indicated excellent barrier performance for this class of vehicle. In these tests, the test vehicles' front tires showed no tendency to climb the barrier. As the vehicles were redirected, they began to roll until the bottom of the box van contacted the top of the concrete barrier. The stabilizing forces applied to the bottom of the box prevented vehicle rollover even though roll angles as large as 45 degrees were observed. However, results of a single test of a NJ shape indicated that this barrier would allow a truck's front tire to climb the lower curb face resulting in subsequent rollover. These results indicate that, although the height of the lower curb face of the NJ shape is not found to be a problem for most conventional crash test vehicles, it may de-stabilize other vehicles such as single unit trucks and utility vehicles.

The coefficient of friction of the barrier surface may also contribute to the performance of safety shaped barriers. In two similar crash tests with temporary safety shaped concrete barriers, the test vehicle overturned in a test with a rough barrier surface, but remained upright in a test with a smooth barrier surface.(34) It is not possible to ascertain if the change in the coefficient of friction was the sole cause for the difference in barrier performance between the two tests or if there were other contributing factors, such as differences in the displacement of the barrier. Nevertheless, results of this study point to the possibility that the coefficient of friction may affect the propensity for rollover on concrete safety shaped barriers.

Findings from a recent NCHRP study of the performance of roadside hardware during impacts with micro-size vehicles seemed to contradict the above findings.(35) Five crash tests were conducted on a very rough, high-friction concrete barrier with micro-size vehicles. The concrete safety shaped barrier successfully redirected each of the test vehicles with very low roll angles. Therefore, it may be concluded that the importance of the coefficient of friction of the barrier surface may not be as significant on the performance of the barrier as the first test results might indicate.

Another important factor is the effect of approach terrain on barrier performance. Testing of a modified New Jersey shaped concrete barrier placed in a depressed median showed that relatively minor changes in the approach geometry could significantly affect tire and suspension loadings and the possibility for suspension damage.(29) A simulation study indicated that this problem could be avoided by designing the approach terrain in such a way as to prevent severe suspension loading at the time a vehicle's tires first contact the barrier.(4) Other terrain related problems were reported where test vehicles rolled over while spinning out on soft soil after relatively successful crash tests.(32)

Vehicle rollovers in some of the mini-car tests were attributed to damages to the front suspensions of the vehicles sustained during initial wheel contact with the concrete barriers.(32) The vehicles, which were successfully redirected by the barriers, tripped over the damaged wheels upon returning to the ground and overturned. The rollovers would probably not have occurred had the suspensions not been damaged. The same outcome was observed in other crash tests.(29)

Simulation of a crash test involving suspension failure correlated well with test results until the vehicle separated from the barrier and returned to the ground.(4) The Highway-Vehicle-Object-Simulation Model (HVOSM) cannot predict suspension failure and thus failed to predict the subsequent vehicle overturning. These findings point to the importance of monitoring tire and suspension loads when using simulation programs to accurately predict vehicle behavior for shaped concrete barrier impacts.

High impact angle may also increase the propensity for rollover during impact with concrete safety shaped barriers. A crash test found that a mini-size vehicle would roll over when striking a concrete safety shaped barrier at an impact angle of 52 degrees and an impact speed of 27 mi/h.(36) When the vehicle impacted the barrier, it did not redirect significantly, but instead began to ride up the face of the barrier until it rolled over. The lateral and longitudinal forces on the front of the vehicle apparently combined to form a resultant that was directed at the vehicle's center of gravity. There was, therefore, little or no yaw moment applied to redirect the test vehicle. The vehicle continued to move into the barrier until the vertical forces were sufficient to cause it to roll over.

Another crash test involved a 3,600-lb full-size passenger car impacting a concrete safety shaped barrier at an impact angle of 45 degrees and an impact speed of 40 mi/h.(37) The vehicle was safely redirected and remained upright throughout the impact sequence. This would suggest that, in addition to impact angle, vehicle weight is also a key factor in rollover propensity. Nevertheless, there appears to be a critical window of impact angles for most sizes of vehicles that would prevent redirection and thus increase the propensity for rollover.

Review of crash test films provides further insights into the rollover problem associated with shaped concrete barriers. When a vehicle first impacts a shaped concrete barrier, the side of the vehicle adjacent to the barrier begins to climb the lower sloped face and the vehicle begins to roll away from the barrier. When the tires reach the top of the lower sloped face and the sides of the vehicle's tires begin to interact with the upper sloped face, the vehicle roll angle will usually stabilize and may even begin to decrease. Thus, if the upper sloped face is recessed or the lower curb face is too high, the vehicle roll angle will reach unacceptable levels before the roll angle begins to stabilize.

This behavior is also observed in the testing of temporary barriers where barrier movement increases the effective offset of the upper sloped face. Poor performance is generally observed during crash tests if the barrier moves more than a few inches during the first stages of the impact. For mini-sized vehicles, crash testing has shown that the front of the vehicle tends to contact the lower sloped face, thereby increasing roll impulses imparted on the vehicle. Further, review of the important barrier properties discussed above reveals that each of these items can lead to increases in the height vehicle climb. Thus, height of climb may be an important indicator of the performance of safety shaped barriers during crash testing.

A modified shaped concrete barrier design was developed in an attempt to reduce the propensity for rollover.(38) An upper surface with a reversed slope was added to the top of the barrier to limit the height of vehicle climb. Crash test results indicated that the modified design reduced maximum roll angles and height of climb of the vehicle with only minor increases to vehicle acceleration for small car impacts at 60 mi/h and 15 degrees. This effort points to the potential for reducing the propensity of rollover by making minor changes to the top of the existing safety shape.

b. Simulation Programs

The Highway-Vehicle-Object-Simulation Model (HVOSM) or variations of the basic model was used in most of the simulation efforts and is considered as the best available program for analysis of rigid barrier impacts. The program was found to give reasonably good predictions of barrier performance for most impact conditions. However, there are some limitations associated with the program, brief discussions of which are presented as follows.

First, the program does not adequately simulate low angle impacts (< 10 degrees) and its use has been limited to analysis of relatively high angle impacts. This limitation arises from the program's thin disk tire model. The model cannot properly handle the simulation of tire-barrier interaction for curb impacts which is particularly important for low angle impacts. A better tire model, developed by McHenry, was designed to alleviate this problem.(39) However, when incorporating the new tire model for analysis of curb impacts, barrier simulation routines were removed. While this improved program may in fact solve the thin disk tire model problems discussed above, it cannot be used to simulate barrier impacts.

Further, the HVOSM program cannot predict suspension damage or failure which could cause the vehicle to overturn upon return to the ground, as shown in some of the crash tests. However, the model can predict suspension and tire loadings which should be used as surrogates for predicting suspension damage.

Until recently, the HVOSM model could not model vehicle sheet metal interaction with a sloped barrier face. A recent modification of HVOSM has been completed.(40) Modifications to the HVOSM program included development of a sophisticated vehicle crush model that can interact with virtually any barrier shape, improvements to the suspension model, improvements to the curb simulation routines, and provisions for half-track changes resulting from barrier impacts. Validation of the new model indicated that the program was capable of accurately predicting overall vehicle trajectory, peak accelerations, and height of barrier climb.

The GUARD simulation program has also been used to study rigid barrier impacts. This program has had only limited application due to its simplistic tire and suspension models. Accurate predictions of tire and suspension forces are believed to be critical to the simulation of rigid barrier impacts where much of the redirecting and de-stabilizing forces are applied to the vehicle through its tires. The GUARD program was used to simulate six full-scale crash tests of New Jersey and General Motors shaped concrete barriers.(1,2) Four tests involved subcompact vehicles at 60 mi/h and impact angles ranging from 7.5 to 16 degrees. The two remaining tests involved full-size vehicles impacting a New Jersey shaped concrete barrier at angles of 7.5 and 16 degrees.

The predicted heading angle time histories and exit angles correlated relatively well with measured data, although the results again appeared to be much better for low impact angles. Correlation between predicted and measured roll angle time histories was poor, while that for the maximum roll angle was only marginally better. No information was provided regarding height of vehicle climb or pitch angles during testing. The GUARD program gave unreliable predictions for 50 ms average accelerations. Relatively good correlation between measured average accelerations and simulation predictions was obtained for low impact angles, but correlation for impact angles above 14 degrees was very poor. There appeared to be no correlation between measured peak accelerations and simulation predictions. This poor simulation correlation was not unexpected due to the simplistic tire and suspension models mentioned previously.

A major improvement to the GUARD program is nearing completion that should correct most of the above mentioned problems. The new program is now called NARD and has reportedly incorporated a relatively sophisticated tire/suspension model. Little information is now available regarding the performance of this program for rigid barrier impacts.

IV. RESULTS OF ACCIDENT STUDIES

Four accident data files were included in the accident studies, as described earlier under the "Research Approach" in chapter II:

- Texas barrier accident data file.
- Texas CMB accident data file.
- NYDOT barrier accident data file.
- NASS LBSS data file.

Summary of results from analysis of each of these four data files are presented in this chapter.

1. Texas Barrier Accident Data File

The extent of analysis for the Texas barrier accident data file was limited to general descriptive statistics and comparisons among the various barrier types on characteristics other than rollover involvement. Highlights of the more interesting results are summarized as follows:

- The number of median barrier accidents increased considerably from 1,796 in 1982 to 2,511 in 1983 and leveled off to 2,563 in 1984 while the opposite happened to the number of guardrail and bridge rail accidents (see table 12). The median barrier code was added to the list of objects struck in 1981. This variation from year to year may simply reflect the effect of the learning curve, i.e., the time required for the reporting officers to correctly identify median barrier accidents.

- Median barrier accidents were more frequent during the daytime, especially during lunch hours from noon to 3 p.m., and the afternoon rush hours from 3 to 6 p.m., than guardrail and bridge rail accidents (see table 13). This higher incidence of median barrier accidents during periods of high traffic volume was also reflected in the action of the other motor vehicle which precipitated the accidents (see table 14). A much higher percentage of median barrier accidents involved another vehicle changing lanes, slowing or stopping than did guardrail or bridge rail accidents.

- Bridge rail accidents were most affected by snowy and icy surface conditions, as might be expected. On the other hand, wet surface conditions were most often associated with median barrier accidents (see table 15).

- Median barrier accidents were more frequent than guardrail or bridge rail accidents on straight alignment, as reported by the police officers. No significant difference was noted, however, when the degree of curve, coded from roadway inventory data, was used (see table 16). There is no apparent explanation for this discrepancy.

Table 12. Distribution of barrier accidents by barrier type and year.

Accident Year	Guardrail		Median Barrier		Bridge Rail		Total	
	No.	%	No.	%	No.	%	No.	%
1982	2527	37.6	1796	26.1	1079	39.5	5402	33.1
1983	2174	32.3	2511	36.6	899	32.9	5584	34.2
1984	2027	30.1	2563	37.3	755	27.6	5345	32.7
Total	6728	100.0	6870	100.0	2733	100.0	16331	100.0

Table 13. Distribution of barrier accidents by barrier type, time of day, and light condition.

Time of Day/Light Condition	Guardrail	Median Barrier	Bridge Rail
Daylight	42.7	51.5	45.5
Noon - 3 p.m.	9.7	11.7	10.1
3 p.m. - 6 p.m.	12.2	15.2	11.9

Table 14. Distribution of barrier accidents by barrier type, and action of other motor vehicle.

Action of Other Vehicle	Guardrail	Median Barrier	Bridge Rail
Changing Lane	10.7	14.2	9.3
Stopped or Slowing	4.9	8.9	6.0

Table 15. Distribution of barrier accidents by barrier type, and weather/surface condition.

Surface Condition	Guardrail	Median Barrier	Bridge Rail
Dry	68.8	65.7	56.1
Wet/Muddy	26.2	29.4	23.0
Snowy/Icy	5.3	4.9	20.7

Table 16. Distribution of barrier accidents by barrier type and horizontal alignment.

Horizontal Alignment	Guardrail	Median Barrier	Bridge Rail
	Police Reported		
Straight	84.5	93.3	85.4
Curve	15.5	6.7	14.6
	Roadway Inventory (Degree of Curve)		
No Curve	71.8	72.8	75.3
0.1 - 3.9	22.5	23.0	18.5
>= 4.0	5.7	4.2	6.2

- Median barrier accidents were more frequent on highways with six or more lanes, higher ADT, and lower percentage of trucks, than those involving guardrails and bridge rails. Also, median barrier accidents were more frequently related to construction zones than were guardrail or bridge rail accidents (6.0% versus 4.5% and 3.1%, respectively).
- The incidence of subsequent impact with another vehicle was higher for median barrier accidents than for guardrail or bridge rail accidents (21.1% versus 14.5% and 16.1%, respectively) due, at least in part, to higher traffic volumes associated with median barrier accidents.
- Median barrier accidents had the highest percentage of overall injury, but the lowest percentage of fatal and incapacitating injuries, as shown in table 17. However, the differences were relatively minor to be of much significance.

Table 17. Distribution of barrier accident severity by barrier type.

Severity	Guardrail	Median Barrier	Bridge Rail
	Highest Injury Severity		
% Injured	42.3	46.0	45.5
% (A+K) Injury	8.1	7.7	8.4
	Driver Injury Severity		
% Injured	38.2	40.7	39.8
% (A+K) Injury	6.8	6.3	6.8

- No apparent difference was noted in the distributions of accidents between barrier types for vehicle type, vehicle curb weight, driver age and sex, and contributing factors.

It should be borne in mind, however, that comparisons among barrier types may not necessarily be fair due to inherent differences in the design, placement, and application of the various barrier types. Even comparisons between concrete median barriers and other median barriers may not necessarily be valid for a number of reasons:

- There has been a major effort to reconstruct many of the urban Interstates and freeways in Texas since 1982, so that a considerable portion of the other median barrier accidents may be related to construction zones. This is less of a problem for those highway sections with concrete median barriers.

- Concrete median barriers installed after 1982 are lumped under other median barriers so that the comparison is not really as clear cut as shaped concrete versus metal-beam median barriers.

- The roadside and approach conditions are very different between concrete median barriers and other median barriers.

Despite the problem with the proper identification of rollovers, it may be interesting to compare the rollover rates for the various barrier types as determined from the computerized accident data base. If it is assumed that the error rates are similar for the various barrier types and there is no reason to believe that such is not the case, the comparison of rollover rates among the barrier types may be meaningful when viewed in relative terms while the absolute percentages are totally meaningless and inaccurate.

The percentage of rollovers subsequent to impacts with barriers on rural highways is 2.6 times that for urban highways, probably reflecting differences in traffic speed and roadside conditions. Urban Interstates and freeways have the lowest rollover rate while rural collectors have the highest. Overall, median barriers have the lowest rollover rate, followed by bridge rails (1.6 times that of median barriers) and highest for guardrails (2.7 times that of median barriers). For barrier accidents on urban Interstates and freeways, the rollover rate is similar for median barriers and bridge railings, and highest for guardrails (two times that of median barriers).

However, it should be cautioned that an unknown, but perhaps significant, portion of the rollovers for guardrails, and less so for bridge rails, are the result of impacts with barrier ends. Unfortunately, it is not possible to differentiate between barrier end impacts and those with the barrier length of need. Furthermore, the roadside or approach conditions are very different for the various barrier types which may have contributed to the differences in the rollover rates.

Again, it should be stressed that rollovers are not accurately identified in this data file. They are included only for comparative purposes and should be viewed only in relative terms.

2. Texas CMB Accident Data File

The Texas CMB accident data file contains information on 1,839 accidents involving concrete safety shaped barriers on urban Interstates and freeways. Analysis of the Texas CMB accident data file was centered on the comparison between rollover and nonrollover accidents in efforts to identify accident characteristics that may have contributed to the propensity of rollover in accidents involving concrete safety shaped barriers.

Rollover occurred in 8.5 percent of the accidents involving concrete safety shaped barriers. This is somewhat lower than the 9.9 percent rollover rate reported in the California study.(8,9) Much of the difference could be attributed to the difference in vehicle population between the two study States, California and Texas. California has a much higher proportion of small cars than Texas. As will be discussed later in this section, smaller and lighter cars are found to have a much higher propensity for rollover than their larger and heavier counterparts.

The majority (1,321 or 71.8%) of the 1,839 accidents in the data file occurred on urban Interstate highways, as shown in table 18. The remaining accidents occurred on U.S. highways (409 or 22.2%) and State highways (109 or 5.9%). The rollover involvement rate was highest on U.S. highways (13.2%), 1.8 times that of Interstate highways (7.5%), and 3.6 times that of State highways (3.7%).

Table 18. Rollover involvement by highway type.

	Total Accidents		Rollover Involvement	
Highway Type	No.	%	No.	%
Interstate	1321	71.8	99	7.5
U. S. Highway	409	22.2	54	13.2
State Highway	109	5.9	4	3.7
Total	1839	100.0	157	8.5

Over 90 percent of the accidents occurred on highways with average daily traffic (ADT) of above 50,000 vehicles per day and over half of the accidents were on highways with ADTs in excess of 100,000 vehicles per day, as shown in table 19. The percentage of rollover involvement varied in the narrow range of 6.5 to 7.9 percent up to 150,000 ADT. The rollover rate increased slightly to 9.3 percent for ADTs of between 150,000 to 175,000 vehicles per day, then jumped drastically to 19.2 percent for ADTs between 175,000 and 200,000 vehicles per day and 13.6 percent for ADTs of above 200,000 vehicles per day.

It is evident from the data that the rollover rates varied by highway type and traffic volume. In turn, highway type and traffic volume were interrelated. However, there is no apparent explanation for the rollover rate to increase with higher traffic volume or for the rollover rate to vary with highway type. Attempts were made to further define the relationships by examining the rollover rates broken down by highway type, number of lanes, and traffic volume, but were not successful. The number of rollover accidents was too small for this detailed breakdown, resulting in wide fluctuations in the rollover rates.

Table 19. Rollover involvement by average daily traffic.

Average Daily Traffic	Total Accidents No.	Total Accidents %	Rollover Involvement No.	Rollover Involvement %
< 50,000	145	7.9	10	6.9
50,000 - 74,999	126	6.9	10	7.9
75,000 - 99,999	434	23.6	28	6.5
100,000 - 124,999	369	20.1	28	7.6
125,000 - 149,999	275	15.0	21	7.6
150,000 - 174,999	236	12.8	22	9.3
175,000 - 199,999	73	4.0	14	19.2
>= 200,000	147	8.0	20	13.6
Unknown	34	2.0	4	11.8
Total	1839	100.0	157	8.5

Table 20 shows that the rollover involvement rate was lower on curved (4.3%) than straight (8.9%) horizontal alignment, as reported by the police officers. According to roadway inventory, the rollover rates were similar between straight (8.3%) and curved (9.0%) horizontal alignment. However, when the rollover involvement rate is broken down by degree of curvature, curves with very slight curvature, i.e., less than two degrees, and high degree of curvature, i.e., between 6.0 and 8.0 degrees, showed higher than average rollover rates (11.9% and 10.0%, respectively) while curves with medium degrees of curvatures showed lower than average rollover rates. There is no clear indication that the roadway horizontal alignment has any significant effect on the rollover involvement of CMB accidents.

A number of other roadway or barrier related variables were also examined, including part of the roadway the accident occurred on, type of shoulder, temporary versus permanent barrier, and involvement of barrier end. Of the 1,839 CMB accidents, 11 accidents were reported to have occurred on frontage roads with one rollover. Another four CMB accidents were reported to have occurred on ramps with one rollover. Unpaved shoulders in front of the CMBs were reported in 10 of the accidents, one of which resulted in rollover. Only two of the accidents involved barrier ends with no rollover. Seven of the involved CMBs were temporary installations, one of which resulted in rollover. The sample sizes with these variables are too small for any meaningful analysis.

Table 20. Rollover involvement by horizontal alignment.

Horizontal Alignment	Total Accidents No.	Total Accidents %	Rollover Involvement No.	Rollover Involvement %
	Police Reported			
Straight	1700	92.4	151	8.9
Curve	139	7.6	6	4.3
	Roadway Inventory (Degree of Curve)			
Straight	1307	71.1	108	8.3
Curve	520	28.3	47	9.0
0.1 - 1.9	268	14.6	32	11.9
2.0 - 3.9	151	8.2	10	6.6
4.0 - 5.9	81	4.4	3	3.7
6.0 - 7.9	20	1.1	2	10.0
Total	1839	100.0	157	8.5

As explained previously under the Texas accident data file, the number of CMB accidents was lower in 1982 (451) than for 1983 (617) or 1984 (610), as shown in table 21. The rollover rates varied only slightly among the years.

Table 21. Rollover involvement by year.

Year	Total Accidents No.	Total Accidents %	Rollover Involvement No.	Rollover Involvement %
1982	494	26.9	43	8.7
1983	671	36.5	51	7.6
1984	674	36.7	63	9.4
Total	1839	100.0	157	8.5

The accidents were fairly evenly distributed over the months, as shown in table 22. The rollover rates, however, varied considerably among the months from a low of 4.7 percent in July to a high of 13.7 percent in August. Similar to overall single-vehicle accidents, the proportion of CMB accidents (see table 23) was highest on Fridays (18.2%), followed by Saturdays (17.0%), and lowest on Tuesdays (12.2%) and Wednesdays (12,7%). The rollover rates varied only slightly among the days of the week, within the narrow range of 7.3 to 10.1 percent.

Table 22. Rollover involvement by month of year.

Month	Total Accidents No.	Total Accidents %	Rollover Involvement No.	Rollover Involvement %
January	152	8.3	10	6.6
February	142	7.7	12	8.5
March	165	9.0	12	7.3
April	144	7.8	9	6.3
May	182	9.9	15	8.2
June	170	9.2	14	8.2
July	129	7.0	6	4.7
August	146	7.9	20	13.7
September	120	6.5	11	9.2
October	164	8.9	19	11.6
November	157	8.5	16	10.2
December	168	9.1	13	7.7
Total	1839	100.0	157	8.5

Table 23. Rollover involvement by day of week.

Day of Week	Total Accidents No.	Total Accidents %	Rollover Involvement No.	Rollover Involvement %
Sunday	246	13.4	22	8.9
Monday	248	13.5	25	10.1
Tuesday	224	12.2	19	8.5
Wednesday	233	12.7	17	7.3
Thursday	242	13.2	24	9.9
Friday	334	18.2	25	7.5
Saturday	312	17.0	25	8.0
Total	1839	100.0	157	8.5

Overall, 43.7 percent of the accidents occurred during hours of darkness, as shown in Table 24. A breakdown of the accidents by time of day is shown in table 25. The proportion of CMB accidents was highest during the evening rush hours from 3:00 to 6:00 p.m. (17.0%), followed by the time period from 9:00 p.m. to midnight (14.5%), and lowest during the time period of 3:00 to 6:00 a.m. (5.8%). The rollover rates were slightly higher during hours of darkness, particularly during the time period of midnight to

6:00 a.m. However, the time period of 3:00 to 6:00 p.m. also showed higher than average rollover rate while the lowest rollover rate was during the time period of noon to 3:00 p.m. (6.0%).

Table 24. Rollover involvement by light condition.

	Total Accidents		Rollover Involvement	
Light Condition	No.	%	No.	%
Daylight	1008	54.8	81	8.0
Dawn/Dusk	27	1.5	2	7.4
Dark - No Lights	436	23.7	43	9.9
Dark - Lights	368	20.0	31	8.4
Total	1839	100.0	157	8.5

Table 25. Rollover involvement by time of day.

	Total Accidents		Rollover Involvement	
Time of Day	No.	%	No.	%
Midnight - 2:59 am	281	15.3	28	10.0
3:00 - 5:59 am	106	5.8	13	12.3
6:00 - 8:59 am	227	12.3	16	7.1
9:00 - 11:59 am	202	11.0	14	6.9
Noon - 2:59 pm	233	12.7	14	6.0
3:00 - 5:59 pm	312	17.0	28	9.0
6:00 - 8:59 pm	211	11.5	25	11.9
9:00 - 11:59 pm	267	14.5	19	7.1
Total	1839	100.0	157	8.5

An adverse weather condition, i.e., rain, fog, snow or sleet, was present in nearly 30 percent of the accidents, as shown in table 26. An adverse surface condition, i.e., wet, snowy or icy, was present in one-third of the accidents, slightly higher than that indicated by the weather condition (see table 27). The rate of rollover involvement was significantly lower under adverse weather or surface conditions. For instance, the rollover rate was 3.0 percent for a wet surface condition and 2.5 percent for a snowy/icy surface condition, as compared to 11.3 percent for a dry surface condition. The lower rollover rate can be partially attributed to the lower coefficient of friction under wet and snowy/icy surface conditions. Also, it is likely that drivers tend to drive more slowly and prudently under adverse surface conditions.

A significant proportion (37.1%) of vehicles was skidding sideways or rotating/spinning prior to impact with the CMBs, as shown in table 28. The rollover rate was lower for vehicles that were skidding sideways or rotating

(5.4%) than vehicles that were tracking (10.5%). This is true even when surface condition was taken into account, as shown in table 29. Under dry surface conditions, only over one-quarter (26.9%) of the vehicles were skidding sideways or spinning prior to impact, as compared to 57.1 percent under wet surface conditions and 65 percent under snowy/icy surface condition. However, the rollover rates were lower for skidding/rotating vehicles than tracking vehicles under all three surface conditions.

Table 26. Rollover involvement by weather condition.

	Total Accidents		Rollover Involvement	
Weather Condition	No.	%	No.	%
Clear/Cloudy	1298	70.6	141	10.9
Rain	510	27.7	13	2.6
Fog	17	0.9	2	11.8
Snow/Sleet	14	0.8	1	7.1
Total	1839	100.0	157	8.5

Table 27. Rollover involvement by surface condition.

	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 28. Rollover involvement by vehicle attitude.

	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

This finding of lower rollover rates for skidding/rotating vehicles is somewhat surprising and seemingly contrary to results reported in other studies, as previously presented in chapter II. Intuitively, a vehicle skidding sideways or rotating is more likely to result in rollover due to large side forces on the tires. However, as will be discussed under clinical analysis of the NASS LBSS data file, it is found that vehicles that are principally rotating (i.e., high yaw rates) are less likely to result in rollovers after impact with CMBs while vehicles that are principally skidding sideways (i.e., high slip angles but low to moderate yaw rates) are more likely to result in rollovers. The police reported data are not detailed enough to make this distinction between skidding sideways and rotating.

It should also be borne in mind that the skidding or rotating of the vehicle relates to the attitude of the vehicle prior to impact with the concrete safety shaped barrier. It is found that the attitude of the vehicle after separating from the barrier is probably more important than that prior to impact with the barrier as far as rollover is concerned. For example, a vehicle that is tracking prior to impact may be skidding sideways after separation from the barrier and roll over subsequently.

Table 29. Rollover involvement by vehicle attitude and surface condition.

		Total Accidents		Rollover Involvement	
Surface Condition	Vehicle Attitude	No.	%	No.	%
Dry	Skidding Sideways/ Rotating	330	26.9	29	8.8
	Tracking	772	63.0	92	11.9
	Unknown/Unsure	124	10.1	18	14.5
	Subtotal	1226	66.7	139	11.3
Wet	Skidding Sideways/ Rotating	327	57.1	8	2.5
	Tracking	185	32.3	8	4.3
	Unknown/Unsure	61	10.7	1	1.6
	Subtotal	573	31.2	17	3.0
Snowy/Icy	Skidding Sideways/ Rotating	26	65.0	0	0.0
	Tracking	8	20.0	1	*
	Unknown/Unsure	6	15.0	0	*
	Subtotal	40	2.2	1	2.5
Total		1839	100.0	157	8.5

Prior studies cited in the literature review found that non-tracking vehicles, i.e., skidding sideways or spinning, are overrepresented in rollovers.(24,25) It should be borne in mind, however, that these studies pertain to ran-off-the-road accidents and are not directly comparable to this study which only looks at the vehicle attitude prior to impact with concrete safety shaped barriers. The approach terrain could also play a major part in explaining this difference. Concrete safety shaped barriers are mostly installed in paved medians with little surface irregularities to trip the vehicles. In comparison, ran-off-road accidents usually involved unpaved surfaces which are more likely to have surface irregularities.

Another consideration is that vehicle skidding or rotating is more likely to occur under wet or icy/snowy surface conditions. The coefficient of friction under such conditions is much lower than that under dry surface condition which in turn reduces the side forces acting on the tires of a skidding/rotating vehicle. Also, as will be discussed under clinical analysis of the NASS LBSS data file, the impact speeds of vehicles resulting in rollovers are found to be much higher than those of nonrollover vehicles. The effect of vehicle speed is another important factor to be considered in evaluating the effect of vehicle skidding or rotating on rollover propensity.

This observation of lower rollover rate under adverse surface conditions and vehicle skidding/rotating is also apparent from other related variables. For example, the rollover rate for accidents wherein police reported slick surfaces was only 4.5 percent as compared to 8.9 percent for other accidents, as shown in table 30. The rollover rate for accidents in which the vehicle action was reported as skidding by the police was only 1.1 percent (see table 31). Other vehicle actions that may result in vehicles skidding or spinning out of control, e.g., passing or changing lanes, or swerving, also had slightly lower than average rollover rate (5.7% and 7.9%, respectively).

Table 30. Rollover involvement by road condition.

Road Condition	Total Accidents No.	Total Accidents %	Rollover Involvement No.	Rollover Involvement %
None Reported	1670	90.8	149	8.9
Slick Surface	112	6.1	5	4.5
Construction	57	3.1	3	5.3
Total	1839	100.0	157	8.5

Three-quarters of the vehicles involved in CMB accidents were passenger cars and another 16.5 percent were pickup trucks, vans or utility vehicles (see table 32). Trucks accounted for 7.3 percent of the CMB accidents, slightly over half of which involved tractor-trailers. Pickup trucks, vans and utility vehicles had the highest proportion of rollovers (10.6%), followed by single unit trucks (9.7%) and passenger cars (8.2%) while tractor-trailers had the lowest incidence of rollover (4.2%). The rollover rate for other vehicles is not too meaningful since most of the accidents involved motorcycles.

Table 31. Rollover involvement by vehicle action.

Vehicle Action	Total Accidents		Rollover Involvement	
	No.	%	No.	%
None	1001	54.4	101	10.1
Skidding	95	5.2	1	1.1
Passing/Lane Change	53	2.9	3	5.7
Vehicle Swerved	507	27.6	40	7.9
Vehicle Slowing	111	6.0	9	8.1
Other	72	3.9	3	4.2
Total	1839	100.0	157	8.5

Table 32. Rollover involvement by vehicle type.

Vehicle Type	Total Accidents		Rollover Involvement	
	No.	%	No.	%
Passenger Car	1385	75.3	113	8.2
Pickup Truck/Van	303	16.5	32	10.6
Single Unit Truck	62	3.4	6	9.7
Tractor Trailer	71	3.9	3	4.2
Other	18	1.0	3	16.7
Total	1839	100.0	157	8.5

The higher rollover involvement rates of pickup trucks, vans, utility vehicles, and single unit trucks are expected given the higher center of gravity of these vehicles as compared to the barrier rail height. Indeed, except for a few specialty barriers, all existing barriers are designed for impacts by passenger cars. Even for those few specialty barriers where consideration was given to the larger and heavier vehicles, containment is the major concern and not overturning. The low rollover rate of tractor-trailers is very surprising for the same reasons mentioned above. There is no apparent explanation for this discrepancy and the sample size is too small (there are only three rollover accidents involving tractor-trailers) for any further analysis of the data.

It is interesting to note that the majority (59.2%) of tractor-trailers involved in CMB accidents were skidding sideways or rotating, as compared to roughly one-third for other vehicle types (see table 33). Given the lower incidence of rollovers for vehicles skidding sideways or rotating, this may account partially for the lower incidence of rollover involvement for tractor-trailers.

Table 33. Skidding sideways/rotating by vehicle type.

Vehicle Type	Total Accidents No.	Total Accidents %	Skidding Sideways/ Rotating No.	Skidding Sideways/ Rotating %
Passenger Car	1385	75.3	518	37.4
Pickup Truck/Van	303	16.5	101	33.3
Single Unit Truck	62	3.4	18	29.0
Tractor Trailer	71	3.9	42	59.2
Other	18	1.0	4	22.2
Total	1839	100.0	683	37.1

While the overall rollover rate of passenger cars was slightly below average, smaller and lighter cars showed a much higher propensity for rollover than their larger and heavier counterparts, as shown in table 34. For example, passenger cars with curb weights of 1,800 lb or less had a rollover rate of 17.7 percent, as compared to only 2.9 percent for cars with curb weight above 4,400 lb and an average of 7.9 percent for all passenger cars.

This relationship between vehicle curb weight and rollover rate is well defined, as shown in figure 1. A logarithm model, weighted by the square root of the sample size, was found to provide the best fit to the data, as follows:

$$\text{Rollover Rate} = 106.39 - 12.31 \ln(\text{Vehicle Curb Weight})$$

The rollover rate is expressed in percent and the vehicle curb weight is in pounds. The R square value of the regression equation is 0.73, which is considered a good fit, given the small sample size in some of the cells.

A number of driver characteristics, including driver age, speeding, and driving while intoxicated or under the influence of drugs (DWI/Drugs), on rollover involvement were examined, as shown in tables 35 through 37. Except for drivers age above 60, who had a higher than average rollover rate (13.6%), the other age groups had similar rollover rates. While speeding was cited in nearly two-thirds of the CMB accidents, it had no apparent effect on the rollover rate. Driving under the influence of alcohol or drugs was found in 13.3 percent of the accidents, but it also had very little effect on the rollover rate.

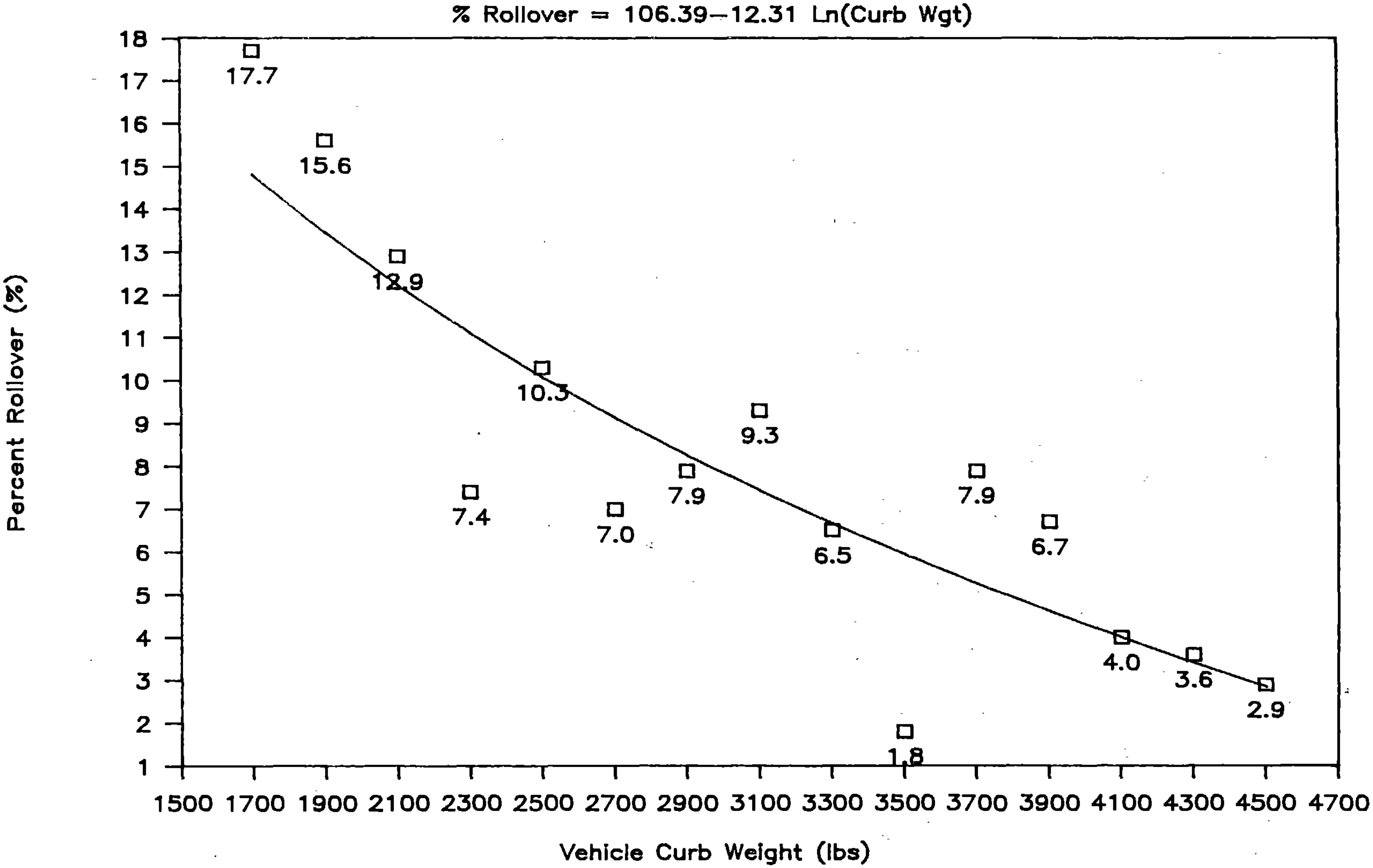

Figure 1. Relationship between vehicle curb weight and rollover rate.

Table 34. Rollover involvement by vehicle curb weight (passenger cars only).

Vehicle Curb Weight (lbs)*	Total Accidents No.	Total Accidents %	Rollover Involvement No.	Rollover Involvement %
<= 1800	17	1.6	3	17.7
1801 - 2000	32	3.0	5	15.6
2001 - 2200	101	9.5	13	12.9
2201 - 2400	68	6.4	5	7.4
2401 - 2600	117	11.0	12	10.3
2601 - 2800	114	10.7	8	7.0
2801 - 3000	76	7.2	6	7.9
3001 - 3200	75	7.1	7	9.3
3201 - 3400	185	17.4	12	6.5
3401 - 3600	56	5.3	1	1.8
3601 - 3800	63	5.9	5	7.9
3801 - 4000	45	2.7	3	6.7
4001 - 4200	50	4.7	2	4.0
4201 - 4400	28	2.6	1	3.6
> 4400	34	3.2	1	2.9
Total	1062	100.0	84	7.9

* 323 of the passenger cars did not have known curb weight.

Table 35. Rollover involvement by driver age.

Driver Age	Total Accidents No.	Total Accidents %	Rollover Involvement No.	Rollover Involvement %
<= 21	316	17.2	29	9.2
22 - 30	723	39.3	65	9.0
31 - 40	420	22.8	31	7.4
41 - 50	162	8.8	14	8.6
51 - 60	89	4.8	8	9.0
> 60	44	2.4	6	13.6
Total	1839	100.0	157	8.5

The severity of injury for CMB accidents resulting in rollover was much higher than that of accidents not resulting in rollover, as shown in tables 38 and 39. The percentage of drivers sustaining some form of injury in rollover CMB accidents was 68.8 percent compared to only 40.5 percent for nonrollover CMB accidents. The differences increased with 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 while that for rollover CMB accidents was 1.3 percent. Similar results were also found when the highest injury sustained in an accident was considered instead of driver injury.

Table 36. Rollover involvement by speeding.

Speeding	Total Accidents No.	Total Accidents %	Rollover Involvement No.	Rollover Involvement %
Yes	1203	65.4	102	8.5
No	636	34.6	55	8.6
Total	1839	100.0	157	8.5

Table 37. Rollover involvement by DWI/drugs.

DWI/Drugs	Total Accidents No.	Total Accidents %	Rollover Involvement No.	Rollover Involvement %
Yes	244	13.3	22	9.0
No	1595	86.7	135	8.5
Total	1839	100.0	157	8.5

Table 38. Driver injury severity by rollover involvement.

Driver Injury Severity	Non-Rollover No.	Non-Rollover %	Rollover No.	Rollover %
No Injury	988	59.5	49	31.2
Possible Injury	182	10.8	18	11.5
Nonincapacitating Injury	406	24.2	70	44.6
Incapacitating Injury	100	6.0	18	11.5
Fatal	2	0.1	2	1.3
Total	1678	100.0	157	100.0

These differences in injury severity between rollover and nonrollover CMB accidents are statistically significant with chi-square values of 58.1 and 43.9 for driver and highest injury severity, respectively. However, it should be cautioned that injury severity is affected by not only rollover involvement, but also other factors, such as impact speed and angle, vehicle size and weight, restraint usage, occupant age, etc., that are not controlled for in this comparison.

Table 39. Highest injury severity by rollover involvement.

Highest Injury Severity	Non-Rollover No.	Non-Rollover %	Rollover No.	Rollover %
No Injury	890	53.0	44	28.0
Possible Injury	209	12.5	19	12.1
Nonincapacitating Injury	456	27.2	71	45.2
Incapacitating Injury	115	6.9	21	13.4
Fatal	8	0.5	2	1.3
Total	1678	100.0	157	100.0

3. NYDOT Barrier Accident Data File

There are only 64 police reported concrete safety shaped (CSS) barrier accidents in the data file, five (7.8%) of which resulted in overturns. This small number of CSS barrier accidents and overturns renders it useless for any meaningful analysis on the performance of CSS barriers. The results presented herein are thus mostly descriptive in nature.

Table 40 shows the frequency and percentage of overturns for the three barrier types. Overturns occurred in 7.8 percent of CSS barrier accidents, compared to only 3.4 percent for other median barrier accidents and 11.9 percent of guardrail accidents. This higher rate of overturn for guardrail accidents may appear significant at first glance. However, there are several factors that could account for such differences and are briefly discussed below. Unfortunately, the data set is not sufficiently detailed to test this hypothesis.

Table 40. Percentage of overturns by barrier type.

Barrier Type	Number of Overturn Accidents	Total Number of Accidents	Percent
CSS Barrier	5	64	7.8
Other Median Barrier	13	382	3.4
Other Barrier	239	2,010	11.9
Total	257	2,456	10.5

First, vehicles impacting with barrier ends have a much higher probability of overturning than those impacting with the length of need. Because median barriers are continuous over long distances, barrier ends have extremely low exposure. Secondly, median barriers are found almost exclusively in urban areas while guardrails are used in both urban and rural areas. Rollovers are reported to be more frequent for rural accidents, probably reflecting the higher incidence of single vehicle ran-off-road accidents and higher travel speed. Thirdly, guardrails are more likely to be installed on steeper slopes which have been shown to have a considerable effect on barrier performance and vehicle stability.

Table 41 depicts the percentage of overturn accidents by barrier type and vehicle type. It is evident from the table that vans, light and heavy trucks, and buses are much more likely to overturn in impacts with barriers than are passenger cars, regardless of barrier type. This is to be expected given the higher center of gravity of these vehicles as compared to the barrier rail height. Indeed, except for a few specialty barriers, all existing barriers are designed for impacts by passenger cars. Even for those few specialty barriers where consideration was given to the larger and heavier vehicles, containment is the major concern and not overturning.

Table 41. Percentage of overturns by vehicle type and barrier type.

Barrier Type	Vehicle Type	Number of Overturn Accidents	Total Number of Accidents	Percent
CSS Barrier	Passenger Car	3	55	5.5
	Van/Light Truck	2	7	28.6
	Bus/Heavy Truck	0	1	0.0
	Other/Unknown	0	1	0.0
	Subtotal	5	64	7.8
Other Median Barrier	Passenger Car	9	341	2.6
	Van/Light Truck	3	25	12.0
	Bus/Heavy Truck	1	4	25.0
	Other/Unknown	0	11	0.0
	Subtotal	13	382	3.4
Other Barrier	Passenger Car	159	1,640	9.7
	Van/Light Truck	47	233	20.2
	Bus/Heavy Truck	20	64	31.3
	Other/Unknown	13	73	17.8
	Subtotal	239	2,010	11.9
All Barriers	Passenger Car	171	2,036	8.4
	Van/Light Truck	52	265	19.6
	Bus/Heavy Truck	21	70	30.0
	Other/Unknown	13	85	15.3
	Total	257	2,456	10.5

It would appear that passengers cars are most apt to overturn on impacts with guardrails (9.7%), followed by CSS barriers (5.5%), and least likely for other median barriers (2.6%). Again, this higher rate of overturn for guardrails may result from factors such as barrier end impacts, urban/rural bias, and nonlevel terrain, as discussed previously. Also, the sample size for CSS barrier accidents is too small for any significance to be attached to the results.

Table 42 shows the percentage of overturns by vehicle curb weight for passenger cars by barrier type. The vehicle curb weight is based on the Vehicle Identification Number (VIN). There are only 47 CSS barrier accidents with known vehicle weights, three (6.4%) of which resulted in overturning. The three passenger cars that overturned weighed 2,035, 2,975 and 3,608 pounds. For other median barriers, there are only six accidents involving overturns. The sample sizes for both CSS barriers and other median barriers are too small for any meaningful analysis.

For all barriers combined, vehicle curb weight appears to have only minor effect on the percentage of overturning. Vehicles with curb weights less than 2,000 lb do show a considerably higher than average (12.7% vs. 7.8%) percentage of overturning while vehicles with curb weights over 3,950 lb have a much lower than average rate (2.6% vs. 7.8%). Otherwise, the percentage of overturning is very similar for vehicles between 2,000 and 3,950 lb.

The NYDOT Barrier Accident data file contained relatively few collisions with concrete safety shaped barriers. The small sample size, particularly for accidents resulting in overturns, severely limits the extent of analysis that can be conducted with this data file. Nevertheless, a number of observations can be made from the analysis:

- Vehicle overturning is more often associated with guardrails than median barriers. This phenomenon may result from factors such as barrier end impacts, urban/rural bias, and nonlevel terrain, as discussed previously. However, the data set is not sufficiently detailed to test this hypothesis.

- The percentage of overturning for impacts involving concrete safety shaped barriers appears to be higher than that for other median barriers. However, the sample size is simply too small for any definitive conclusion to be drawn from the data.

- Vans, straight trucks, and tractor semitrailers are more apt to overturn from impacts with longitudinal barriers than are passenger cars. This is probably due to the higher center of gravity for these vehicles in relation to the barrier rail height. Also, except for a few specialty barriers, the current barriers are designed for passenger cars with little or no consideration given to these larger and heavier vehicles. Even for those specialty barriers, containment is the major concern and not overturning.

- For passenger cars, vehicle curb weight appears to have only a slight effect on the proportion of vehicle overturning from barrier impacts. However, the sample size was too small for meaningful analysis for concrete safety shaped barriers or other median barriers.

Table 42. Percentage of overturns by vehicle curb weight and barrier type

Barrier Type	Vehicle Curb Weight (lb)	Number of Overturn Accidents	Total Number of Accidents	Percent
CSS Barrier	< 2,000	0	4	0.0
	2,000 - 2,449	1	7	14.3
	2,450 - 2,949	0	10	0.0
	2,950 - 3,449	1	14	7.1
	3,450 - 3,949	1	7	14.3
	> 3,950	0	5	0.0
	Subtotal	3	47	6.4
Other Median Barrier	< 2,000	3	33	9.1
	2,000 - 2,449	3	61	4.9
	2,450 - 2,949	0	74	0.0
	2,950 - 3,449	0	73	0.0
	3,450 - 3,949	0	26	0.0
	> 3,950	0	26	0.0
	Subtotal	6	293	1.9
Other Barrier	< 2,000	18	128	14.1
	2,000 - 2,449	27	296	9.1
	2,450 - 2,949	22	277	7.9
	2,950 - 3,449	33	357	9.2
	3,450 - 3,949	21	190	11.1
	> 3,950	4	122	3.3
	Subtotal	125	1,370	9.1
All Barriers	< 2,000	21	165	12.7
	2,000 - 2,449	31	364	8.5
	2,450 - 2,949	22	361	6.1
	2,950 - 3,449	34	444	7.7
	3,450 - 3,949	22	223	9.9
	> 3,950	4	153	2.6
	Total	134	1,710	7.8

4. NASS LBSS Data File

The emphasis in the analysis of the NASS LBSS data file was to identify factors that are causative or contributory to rollovers subsequent to impacts with concrete safety shaped barriers, as opposed to problem identification which was already addressed in the analyses of the other three accident data files described earlier in the chapter. Also, with a total of only 130 CMB accident cases in the data file, the analysis was strictly clinical in nature, using hard copies of the accident cases, including the various field data collection forms, scaled collision diagrams, and slides. No attempt was made to compile any statistics from the computerized data file.

As outlined previously in chapter II, the accidents were first reconstructed, if possible, using a simplified procedure, details of which are presented in appendix D in volume II of the final report. A quality assessment of the accident cases was also made at the request of FHWA, details of which are described in appendix E in volume II of the final report.

Accident cases resulting in rollovers were reviewed and analyzed clinically by the project staff in efforts to identify factors that are causative or contributory to the propensity for rollover subsequent to impact with the concrete safety shaped barrier. Each rollover accident was analyzed in detail and a summary of the key data elements and an assessment of how the rollover occurred were prepared, as shown in appendix I in volume II of the final report. The nonrollover accidents were quality reviewed, but not clinically analyzed on a case-by-case basis and no case summary was prepared for the nonrollover accidents.

Of the total of 130 CMB accidents analyzed, 31 cases involved rollovers. However, only 22 of the rollover accidents were considered applicable for the purpose of identifying factors that are causative or contributory to rollovers. The remaining nine rollover accidents were of little use for this purpose for a variety of reasons, including involvement of tractor-trailers (3 cases), rollover prior to impact with barrier (1 case), rollover resulting from impact with the end of the barrier (1 case), or rollover caused by factors other than and subsequent to the barrier impact, such as impact with curb (1 case), utility pole (1 case) and steep embankment (1 case) or severe driver steering input (1 case).

The fact that a portion of the rollovers on concrete safety shaped barriers was found to be unrelated to the barrier is a significant finding in itself. This in effect reduces the extent of the rollover problem associated with concrete safety shaped barriers since these rollovers would have occurred regardless of the barrier type. While it is recognized that the LBSS accident cases are not a representative sample of all barrier accidents and the proportion of unrelated rollovers may not be accurate in absolute terms, it nonetheless points out that the extent of the rollover problem on concrete safety shaped barriers may actually be less than that indicated by accident data.

Although the number of rollover accidents in the data file was too small for any firm conclusions to be drawn, a number of potential causative or contributory factors for rollovers involving safety shaped barriers were identified through the clinical analysis. Discussions on these identified potential factors will be presented later in the section. First, it is necessary to define some of the common terms used in the discussions. It should be noted that there are actually two sets of common definitions in use, one in accident investigation and the other in vehicle dynamics and simulation, that are slightly different from each other. To facilitate uniformity throughout the report, the vehicle dynamics and simulation definitions are used and are defined as follows.

- Tracking - A vehicle is tracking when the vehicle heading and the velocity vector of the vehicle are the same.
- Yawing - A vehicle is yawing when the vehicle heading is different from that of the velocity vector.
- Slip Angle - The angle between the vehicle heading and the velocity vector, expressed in degrees.
- Yaw Angle - The angle between the vehicle heading and the barrier, expressed in degrees.
- Yaw Rate - The rate at which the yaw angle is changing, expressed as degrees per second.
- Impact Angle - The angle between the velocity vector of the vehicle and the barrier at the point of initial contact with the barrier.
- Impact Speed - The velocity of the vehicle at the point of initial contact with the barrier.

Table 43 lists the key factors pertaining to impact conditions and vehicle curb weight for each of the 22 rollover CMB accident cases analyzed. The actual yaw rates were not available from the data and are subjectively categorized as: low (< 20 degrees per second), moderate (20 - 40 degrees per second), and high (> 40 degrees per second). Also, for cases that were not reconstructed and the impact speeds were unknown, a subjective judgement was made by the project staff to categorize the impact speed into three levels: low (< 25 mi/h), moderate (25 - 50 mi/h), and high (> 50 mi/h). These categorizations are arbitrary in nature and are determined subjectively by the project staff.

Discussions on a number of potential causative or contributory factors identified from the clinical analysis are presented as follows. The analysis, as mentioned previously, was strictly clinical in nature based on observations made by the project staff. Comparisons with nonrollover accidents are provided whenever possible. It should be borne in mind, however, that the nonrollover accidents were not clinically analyzed on a case-by-case basis and subjective determination on some data elements, such as yaw rate and impact speed, are not available for comparison purposes.

Table 43. List of the key data elements pertaining to impact conditions for applicable LBSS rollover accidents.

Case Number	Impact Angle (Deg)	Slip Angle (Deg)	Yaw Angle (Deg)	Yaw Rate	Impact Speed (mph)	Curb Weight (Lbs)
82 30 131 V	14	86	100	high	27	2,000
82 30 228 V	07	00	07	none	high	2,200
82 79 514 W	02	00	02	none	65	3,200
82 80 516 R	29	00	29	none	high	2,500
82 82 534 V	38	12	50	low	high	4,000
82 82 559 W	04	00	04	none	40-55	2,700
82 82 561 R	41	09	50	low	high	2,700
82 82 574 T	12	01	13	none	58	2,100
83 03 040 V	18	00	18	low	high	2,100
83 03 066 V	54	27	81	moderate	high	2,000
83 11 508 W	06	00	06	none	high	3,300
83 30 164 V	19	00	19	none	39	2,200
83 36 099 W	02	00	02	none	high	2,100
83 76 066 W	25	01	26	none	high	3,400
83 79 509 W	10	00	10	none	high	2,600
83 82 503 T	28	07	35	low	moderate	1,900
83 82 515 N	20	220	240	high	high	3,300
83 82 530 V	41	00	41	low	high	2,000
83 82 532 V	06	41	47	high	44	3,500
83 82 539 T	17	44	61	high	41	2,500
84 39 099 R	40	15	55	moderate	high	3,500
84 59 512 V	30	60	90	high	57	2,800

Three impact conditions commonly observed for the rollover accidents studied are as follows:

1. Vehicles impacting the barriers at high impact angles (>= 25 degrees) and moderate to high impact speeds (>= 25 mi/h).
2. Vehicles yawing into the barriers with high slip angles (>= 30 degrees) at moderate to high impact speeds (>= 25 mi/h).
3. Vehicles impacting the barriers in a tracking mode (slip angle <= 15 degrees) at high impact speeds (> 50 mi/h) and low impact angles (<= 10 degrees).

A breakdown of the rollover and nonrollover accident cases by these three impact conditions is shown in table 44.

Table 44. Breakdown of rollover and nonrollover accident cases by impact conditions

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.

Eight of the 22 (36.3%) rollover accidents involved high impact angles compared to only 10.3 percent for nonrollover accidents. The impacting vehicle would typically climb up the lower sloped face of the barrier and continue to climb up 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 subsequent rollover.

This finding is consistent with the results of a full-scale crash test of a Honda Civic impacting a safety shaped barrier at 27 mi/h and 52 degrees which rolled over subsequently.(36) However, another test with a 3,600-lb full-size passenger car impacting the barrier at 40 mi/h and 45 degrees did not result in rollover.(37) 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 of the 22 (18.2%) rollover accidents involved vehicles yawing into the barriers with high slip angles (>= 30 degrees) at moderate to high impact speeds (>= 25 mi/h). In comparison, 20 of the 58 (34.5%) 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 pertain to the yaw rate or the rate the vehicle was rotating or spinning.

For the rollover accidents, the yaw rates were usually low to moderate and the vehicles were principally skidding sideways. The impacting vehicle would already be leaning toward the side of the vehicle leading the skid as the vehicle impacted the barrier. The roll angle would continue to increase as the vehicle crashed into the barrier, leading to subsequent rollover. On the other hand, review of nonrollover accidents indicated that most of the vehicles were principally rotating with high yaw rates as the vehicles impacted with the barriers. The impacting vehicle would typically continue to rotate after the initial impact with the barrier and then impact with 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 not resulting in rollovers.

Results from the analysis of the Texas CMB accident data file, as discussed previously, indicate that vehicle skidding sideways or rotating prior to impact with the barrier is a fairly common impact condition, found in 37 percent of the accidents involving shaped concrete barriers. Vehicles skidding or rotating at impact were found to have lower rollover rates than tracking vehicles. This would suggest that only a small proportion of the vehicles were skidding sideways at impact, i.e., with high yaw angles and low yaw rates, while most of the vehicles were rotating at impact, i.e., with high yaw rates.

Five of the 22 (22.7%) rollover accidents involved vehicles impacting the barriers in a tracking mode at high impact speeds and low impact angles, compared to only 1.7 percent of the nonrollover accidents. The impacting vehicle would typically climb up quickly over the lower sloped face of the safety shape and continue climbing onto the upper sloped face. The vehicle would climb higher and stay on the barrier longer than normal and eventually roll on the side away from the barrier as the vehicle separated from the barrier, sometimes even prior to separating from the barrier.

The presence of 18-in high concrete glare screens on top of the concrete safety shaped barrier was found 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 impacting 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 subsequent rollover.

In some of the rollover accidents, the vehicles actually separated from the barriers in a relatively stable fashion and then began to rotate after separation and subsequently rolled over. The rotation to the vehicle is probably the result of braking and steering inputs from the drivers and damages to the front suspension from impact with the barrier. It is arguable whether the subsequent rollover is actually related to the shape of the barrier or independent of the barrier type.

Lateral displacement of the barrier segments was found in one rollover accident. Crash tests have shown that lateral displacement of the barrier during impact allowed the barrier to rotate in the direction of the impact, thus allowing the vehicle to climb higher on the barrier and could lead to subsequent rollover. Lateral displacement of the barrier is usually not a problem for permanent barrier installations, but certainly an area of concern for temporary installations, such as in construction zones.

The majority of the rollover accidents occurred under dry surface conditions. This is consistent with accident analysis results which indicate that the propensity for rollover after impact with a concrete safety shaped barrier is actually lower under a wet or snowy/icy surface condition than under a dry surface condition. The reduced coefficient of friction under a wet or snowy/icy surface condition prevents critical side forces from building up and tripping the vehicle.

Figure 2 shows a comparison of impact speed between rollover and nonrollover accidents. It is evident from the figure that rollover accidents are associated with much higher impact speeds than nonrollover accidents. None of the rollover accidents has impact speeds of less than 25 mi/h compared to 30 percent of the nonrollover accidents. On the other hand, 73 percent of the rollover accidents has impact speeds of over 50 mi/h compared to only 14 of the nonrollover accidents.

A comparison of impact angle between rollover and nonrollover accidents is shown in figure 3. Rollover accidents are slightly overrepresented at both high (>= 25 degrees) and low (<= 10 degrees) impact angles. This is consistent with the first (high impact angle) and third (low impact angle) sets of conditions associated with rollover accidents.

Figure 4 shows the cumulative distributions of slip angles for both rollover and nonrollover accidents. Nearly three-quarters (73%) of the rollover accidents were in a tracking mode with slip angles of 15 degrees or less, compared to only 45 percent for nonrollover accidents. Only 23 percent of the rollover accidents had slip angles of greater than 30 degrees compared to 42 percent of the nonrollover accidents. However, it should be borne in mind that the yaw rate must also be taken into consideration with the slip angle in assessing the rollover propensity, as discussed previously under the second set of conditions (high slip angle and low to moderate yaw rate) associated with rollover accidents.

Smaller and lighter vehicles were found to be disproportionally involved in rollovers, as illustrated in figure 5 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 is 2,500 lb while that for nonrollover accidents is 3,150 lb. It is interesting to note that the size and weight of the vehicle have less of an effect on rollovers in high-angle impacts with a higher median vehicle curb weight of 2,700 lb.

It should be noted that some of the characteristics identified in previous studies as affecting the propensity of rollover, e.g., height of reveal and lower curb face, slope and offset of upper sloped face, barrier surface friction, and approach terrain, did not appear to play any part in any of the rollover accident cases studied. There was very little variation in the barrier shape and dimensions among the barriers involved in the accidents for their effects to be assessed. As to the effect of the approach terrain, all except one of the barriers involved in the rollover

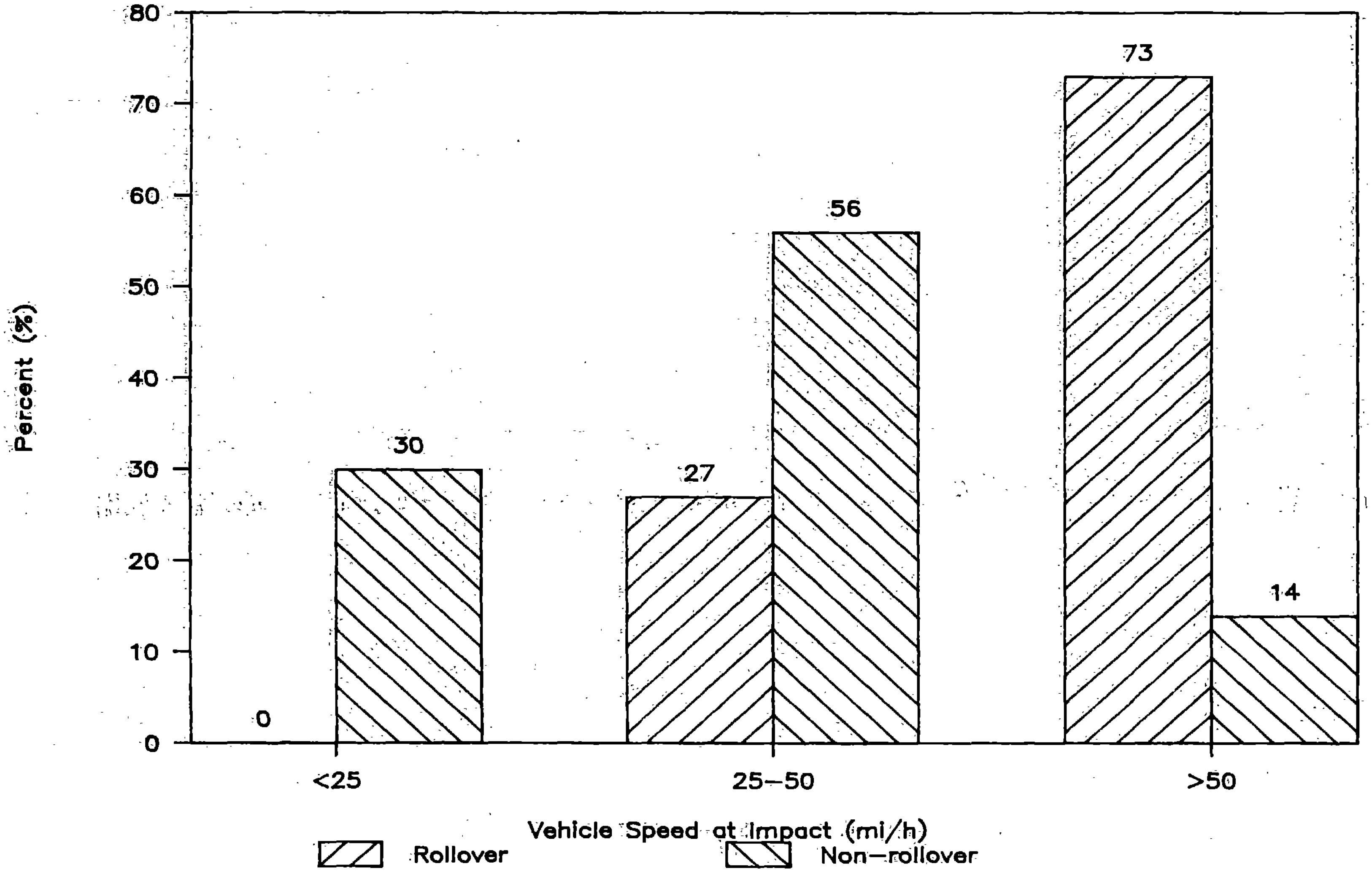

Figure 2. Comparison of impact speed between rollover and nonrollover accidents.

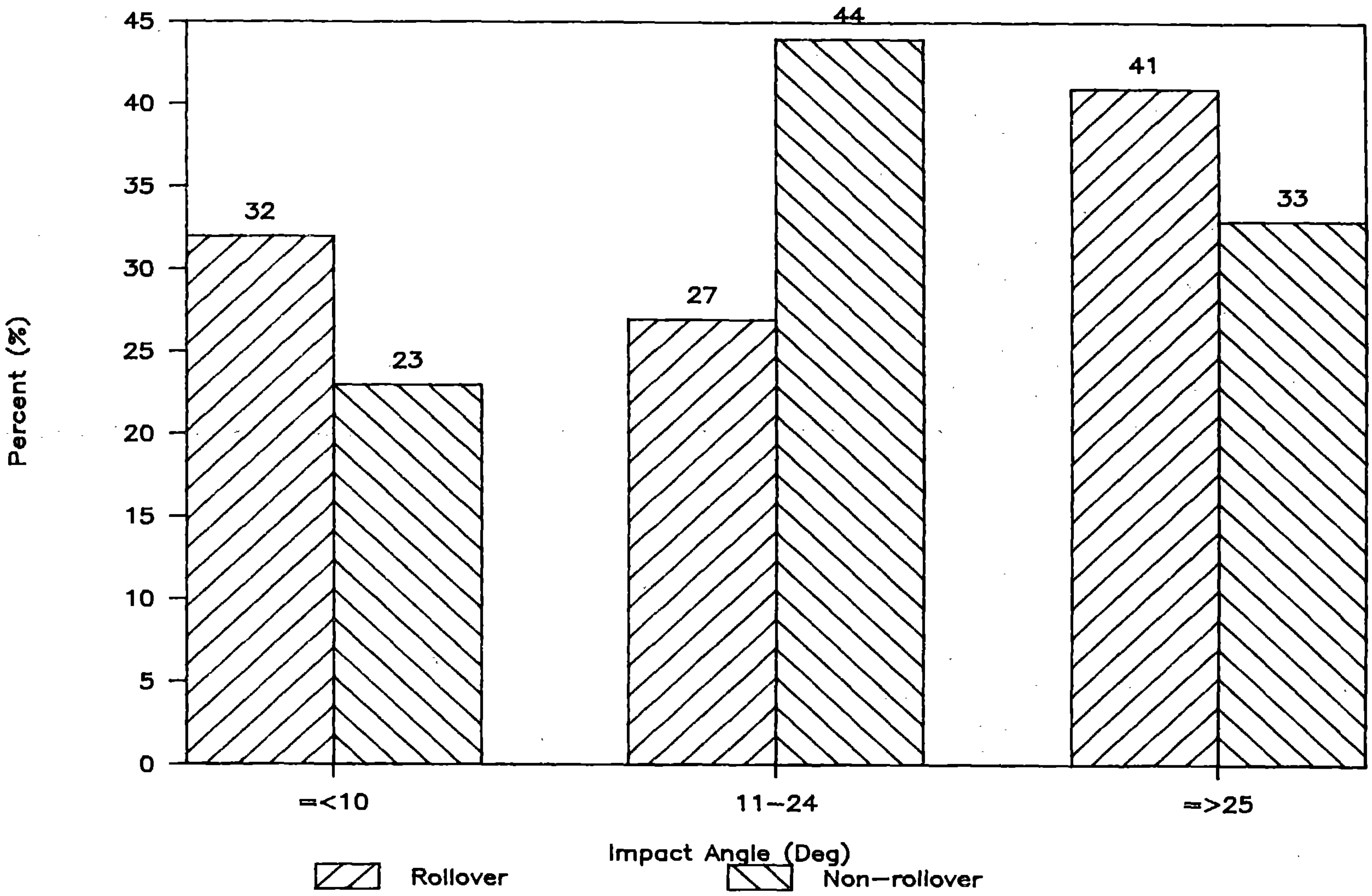

Figure 3. Comparison of impact angle between rollover and nonrollover accidents.

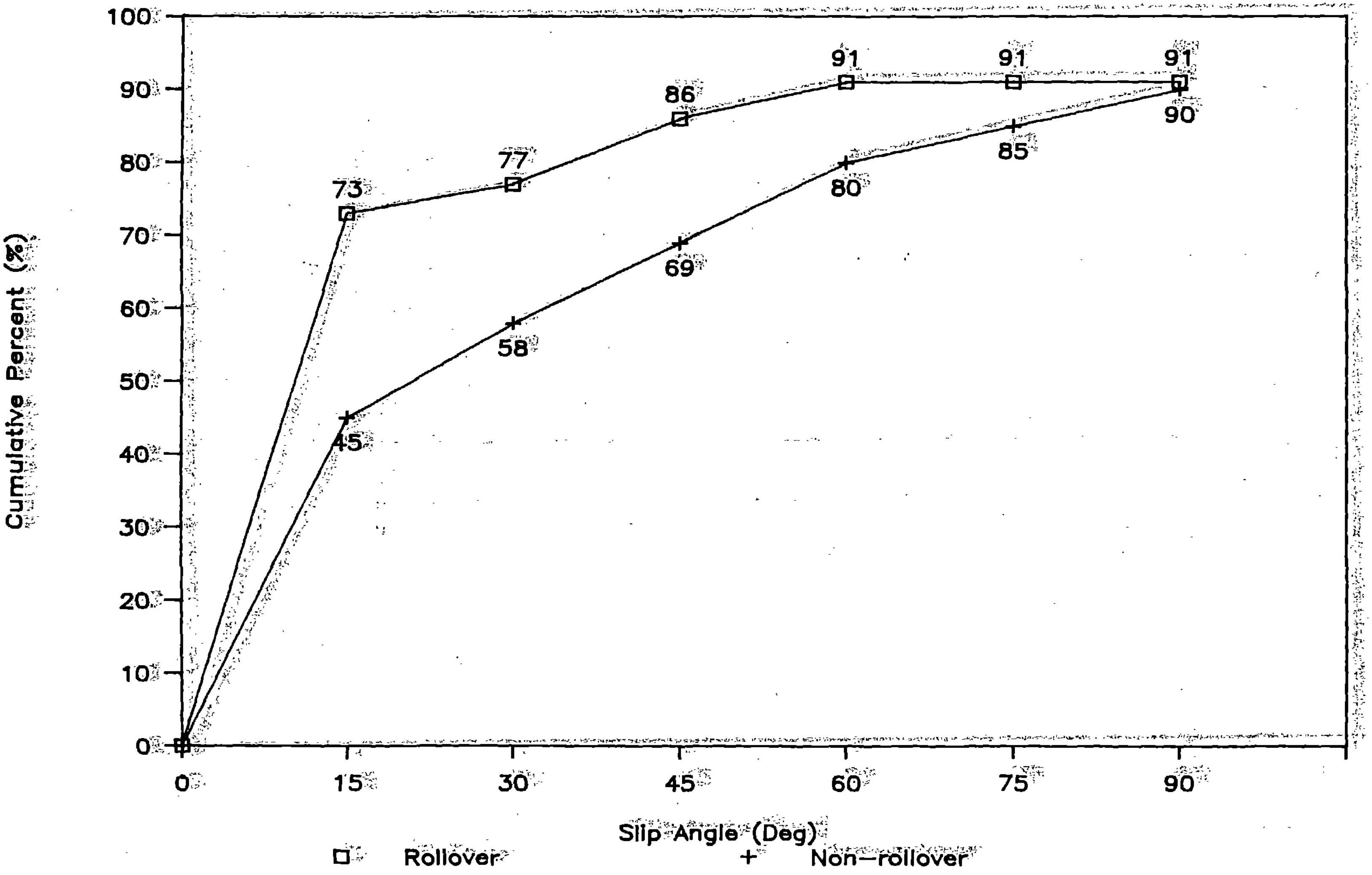

Figure 4. Cumulative distributions of slip angles for both rollover and nonrollover accidents.

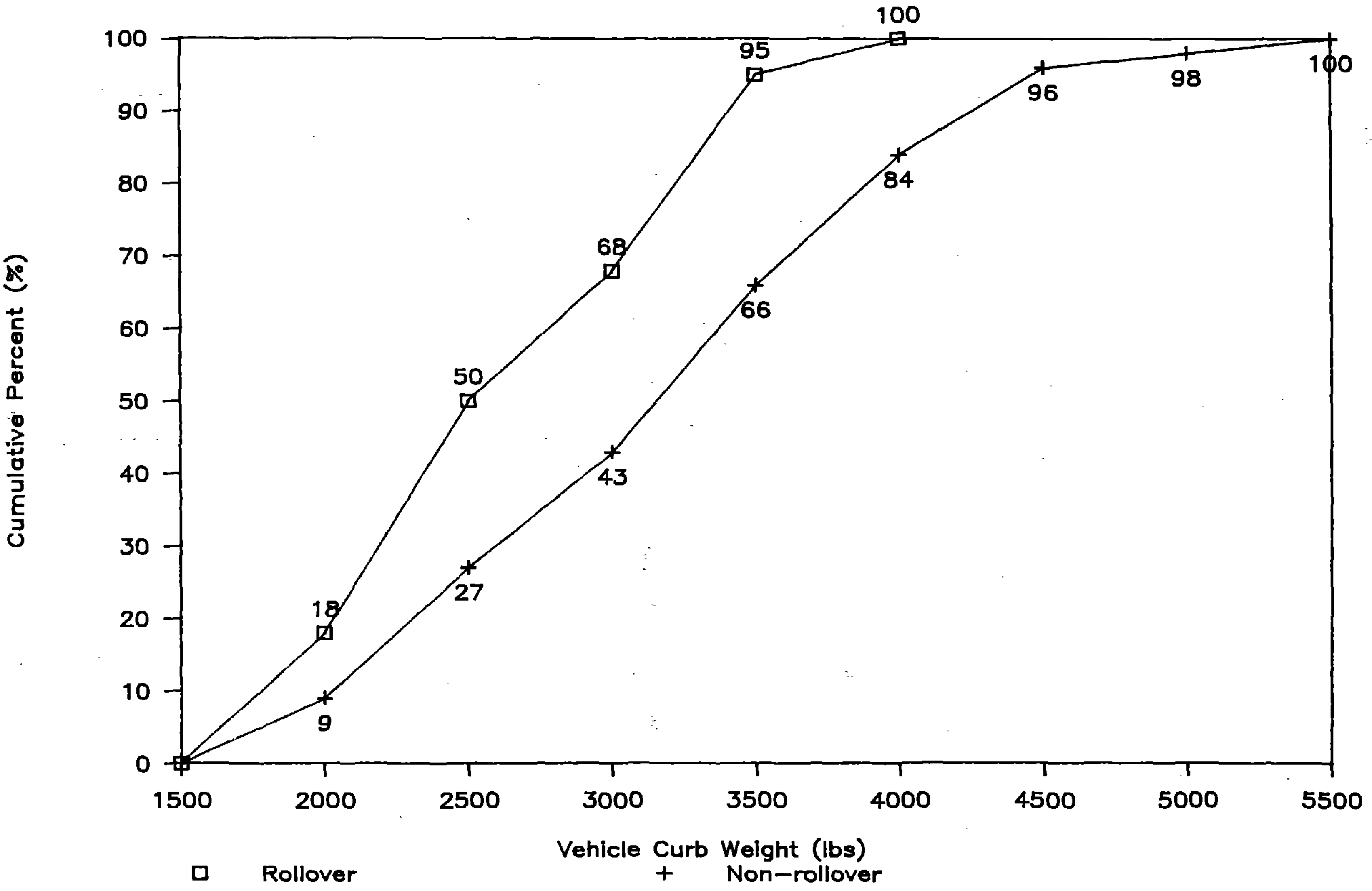

Figure 5. Cumulative distributions of vehicle curb weights for rollover and nonrollover accidents.

accidents had paved shoulders and none with nonlevel terrain in the approach.

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

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

5. Summary

The results from analysis of the four accident data files are presented in this chapter. Highlights of the findings and conclusions are summarized as follows:

- Rollover occurred in 8.5 percent of the accidents involving concrete safety shaped barriers. This is somewhat lower than the 9.9 percent rollover rate reported in the California study.(8,9) Much of the difference could be attributed to the higher proportion of smaller cars in California than in Texas since smaller and lighter cars are found to have a much higher propensity for rollover than their larger and heavier counterparts.
- A significant proportion of the rollovers are found to be unrelated to the barrier properties. This in effect reduces the extent of the rollover problem specifically associated with concrete safety shaped barriers since these rollover accidents would have occurred independent of the barrier type under similar conditions.
- The rollover rate is lower under adverse weather and surface conditions. The lower coefficient of friction under wet or snowy/icy surface conditions prevents buildup of large side forces or tripping of the vehicles.
- The rollover rate of smaller and lighter vehicles is much higher than their heavier and larger counterparts. However, much of problem can be attributed to the inherent nature of the smaller vehicles, which is further aggravated by the shape of the concrete safety shaped barrier.
- The following three impact conditions are identified from the clinical analysis as potential causative or contributory factors for rollover:

  - High impact angle and moderate to high impact speed.
  - High slip angle and low to moderate yaw rate. (Note that vehicles that are rotating at impact, i.e., with a high yaw rate, are less likely to result in rollovers).
  - High impact speed and low impact angle for vehicles in a tracking mode.

  These three impact conditions were selected for further evaluation in the simulation studies. Impacts with CMBs with glare screens was also added to the simulation studies, although only two of the rollover accidents involved CMBs with glare screens and both accidents involved high speed, low angle impacts.

- The extent of the rollover problem on concrete safety shaped barriers is not considered a serious enough problem to warrant retrofitting of existing concrete safety shaped barriers. Thus, only potential countermeasures that are applicable to new barrier constructions were included in the evaluation.

V. RESULTS OF SIMULATION STUDIES

As discussed in chapter II, a major modification to HVOSM-RD2 was undertaken to improve its capability for accurately modeling vehicle sheet metal/rigid barrier contact forces.(35) Upon completion of these modifications, the revised program was validated through simulation of nine full-scale crash tests as discussed in appendix F in volume II of the final report. Limitations of HVOSM's thin disk tire model became apparent during this validation effort. As reported in chapter III, the inability of the tire model to accurately simulate tire scrubbing forces prevent its use for simulation of barrier impacts at angles of less than 10 degrees.

A similar problem proved to present major difficulties during the validation effort. As a vehicle is redirected by a safety shaped barrier, its tires often ride up onto the near vertical surface. The tire is pushed down by the suspension until the vertical component of barrier normal force is sufficient to counter-balance suspension forces. However, since the barrier surface is nearly vertical and the tire is approximately parallel to the surface, barrier normal forces are virtually lateral to the bottom of the tire. Therefore, lateral tire forces reach unreasonably high values before vertical forces are sufficient to counterbalance suspension forces.

In an effort to eliminate problems associated with HVOSM's tire model, the tire/curb interaction surface for concrete safety shaped barrier impacts was idealized as shown in figure 6. Unreasonably high lateral tire forces were eliminated by removing the upper slope of the barrier cross section from the tire contact region. As reported in appendix F in volume II of the final report, this change allowed HVOSM simulation results to correlate very well with the seven full-scale concrete safety shaped barrier crash tests studied. All concrete safety shaped barrier simulations conducted thereafter incorporated the modified tire/curb interaction surface shown in figure 6. However, the modified tire/curb interaction surface significantly limited the usefulness of the modified program for simulation of low angle impacts.

After completion of the validation effort, the revised simulation model was then used to study rollover problems associated with concrete safety shaped barriers and potential countermeasures. The simulation effort was divided into three phases, a baseline evaluation of the concrete safety shaped barrier, an evaluation of potential contributory factors identified in the accident analysis, and a study of potential countermeasures to eliminate problems identified with the standard concrete safety shaped barrier. Each phase of the simulation effort is described in greater detail below.

1. Baseline Simulations

The primary objectives of this phase of the simulation effort were to check the revised simulation program for reasonableness and establish a measure of the performance for the concrete safety shaped barriers over the range of impact conditions believed to represent the majority of concrete barrier accidents. The simulation effort was originally planned to investigate three different vehicle sizes impacting a concrete safety shaped barrier at three different impact angles and speeds as shown in table 3 (see chapter II). However, a careful review of simulations involving a 5-degree impact angle revealed that predicted tire side forces were unreasonably high. Therefore, results of these simulations were not reported and the baseline simulation effort was reduced from 27 to 18 simulation runs, as shown in table 45.

Table 45. Revised baseline simulation matrix.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)
1,800	30	15
3,800	45	25
4,500	60	

Results of the revised 18 baseline simulations are reported in table 46. Note that the simulation did not predict vehicle rollover for any of the baseline impact conditions. However, there are some apparent inconsistencies in reported maximum roll angles. For example, as shown in table 46, maximum roll angles for mini-car simulations involving high impact speeds are lower than those reported for lower impact speeds at the same impact angle. These apparent inconsistencies can be explained when the behavior of mini-size vehicles during impacts with concrete safety shaped barriers are carefully examined.

When a mini-car first impacts a shaped concrete barrier, the tires on the impact side of the vehicle begin to ride up the barrier and the vehicle rolls away from the barrier. As these tires mount the lower curb surface, high forces distort the tire to the point that wheel rims contact the concrete barrier and high lateral forces are generated. These high lateral forces are applied below the vehicle center of gravity and therefore create a moment that tends to right the vehicle. Tires on the side of the vehicle away from the barrier then quickly lift off of the ground and the maximum roll angle during impact can thus be quite low.

When the same vehicle impacts the barrier at a lower speed, tire distortion is greatly reduced and wheel rim contact is delayed until tires reach the upper sloped surface. By this time the vehicle has reached such a roll angle that lateral wheel rim forces are not significantly below the center of gravity of the vehicle and therefore the righting moment is never generated. As a result, maximum roll angles for low impact speeds can be markedly higher than for high impact speeds. Simulation results of mid-size and full-size vehicle impacts do not exhibit this discrepancy in maximum roll angles. Larger automobiles have much higher roll inertia and larger tires that prevent such behavior. These findings are supported by a large number of high-speed, concrete safety shaped barrier crash tests with larger automobiles wherein the vehicle's off side tires remained on the ground.

Note that maximum pitch angles predicted by the program for some impact conditions do not follow a discernable pattern. These findings are not significant, since all predicted pitch angles are very small and the minor differences shown in table 46 are not considered to be significant. In other words, the minor differences in predicted maximum pitch angles are not believed to be within the accuracy of the simulation program.

All other important measures of barrier performance follow reasonable patterns and seem to be consistent with available crash test results. Findings reported in table 46 represent a baseline of concrete safety shaped barrier performance for most common impact conditions that will be used to compare performance of the safety shaped barrier and proposed alternatives described in section 3 below.

2. Simulation of Contributory Factors

As presented in chapter IV, findings from analysis of police level accident data were inconclusive regarding factors contributing to rollover during impacts with concrete safety shaped barriers. However, a number of potential factors that may be causative or contributory to rollover were gleaned from clinical review of rollover accidents from the NASS LBSS data file as presented in chapter 4. These findings indicate that the probability of rollover during impacts with concrete safety shaped barriers may be increased by: (1) high impact angle, (2) high yaw angle at impact coupled with a low yaw rate, (3) very high impact speed coupled with low impact angle, and (4) a glare screen extension on top of the safety shaped barrier. Due to the aforementioned limitations of HVOSM's thin disk tire model and its inability to accurately simulate low angle impacts, the program's capacity for accurately evaluating the impact conditions under cases 3 and 4 is somewhat questionable. Therefore, most of the effort in this phase of the study was concentrated on further evaluation of impact conditions under cases 1 and 2, regarding their effects on causing rollover during impacts with concrete safety shaped barriers.

a. High Angle Impacts

The accuracy of the HVOSM program for simulation of impact angles larger than 25 degrees has never been determined. Therefore, in an effort to further validate the program for high-angle impacts, the HVOSM program was used to simulate a crash test involving a Honda Civic impacting a concrete safety shaped barrier at 27 mph and 52 degrees.(36) As reported in Appendix F, the simulation program correctly predicted the vehicle rollover observed during the test.

TABLE 46. Simulation of baseline impacts with New Jersey shape.

	Simulation No.	Impact Conditions		Exit Conditions		Vehicle Parallel to Barrier						Max. 50 MS Average Accelerations (g)		
		Angle (Deg)	Speed (mi/h)	Angle (Deg)	Speed (mi/h)	Time (Sec) Required	Distance Traveled (ft)	Max. Roll (Deg)	Max. Pitch (Deg)	Max. Height of Climb (ft)	Max. Vehicle Crush (in)	Long.	Lat.	Vert.
Honda Civic	1	15	60	9.59	54.59	0.192	15.88	18.23	11.56	1.63	10.1	-2.70	- 6.45	-4.04
	2		45	6.02	41.20	0.217	13.47	17.40	7.55	1.25	9.2	-1.86	- 4.19	-2.77
	3		30	5.47	27.56	0.299	12.39	15.14	7.12	0.94	7.9	-1.17	- 2.36	-1.77
	4	25	60	1.75	46.68	0.232	17.41	20.27	15.67	2.10	16.5	-8.46	-13.29	-6.07
	5		45	0.81	35.68	0.193	11.01	20.36	12.11	1.69	15.0	-5.73	- 8.92	-4.87
	6		30	1.96	23.69	0.270	10.26	21.86	7.77	1.20	13.2	-3.15	- 4.63	-3.17
Dodge Coronet	1	15	60	4.45	54.88	0.253	21.00	22.71	4.67	1.15	12.8	-2.32	- 5.66	-2.27
	2		45	2.50	41.82	0.329	20.50	6.85	3.71	0.71	11.4	-1.62	- 4.01	-1.48
	3		30	0.00	28.29	0.393	16.42	6.32	2.77	0.30	9.8	-1.02	- 2.39	-0.81
	4	25	60	5.90	47.48	0.200	15.26	22.71	18.53	1.48	19.9	-6.02	- 9.45	-3.67
	5		45	8.48	35.23	0.257	14.76	6.85	14.49	1.12	17.6	-4.23	- 6.62	-2.27
	6		30	3.07	25.25	0.394	15.08	6.32	10.38	0.51	15.0	-2.59	- 3.94	1.12
Plymouth Fury	1	15	60	4.35	55.28	0.228	18.88	13.58	3.00	0.96	12.8	-2.39	- 5.52	-1.74
	2		45	1.22	41.64	0.259	16.13	7.24	2.99	0.67	11.4	-1.69	- 3.85	-1.11
	3		30	0.07	28.06	0.327	13.63	4.36	2.82	0.33	9.7	-1.06	- 2.32	1.01
	4	25	60	7.37	48.62	0.207	15.73	22.64	4.55	1.09	20.3	-6.14	- 9.42	-2.16
	5		45	8.11	36.40	0.253	14.46	15.04	4.65	0.86	17.9	-4.28	- 6.45	-1.73
	6		30	1.60	25.21	0.326	12.46	9.49	4.30	0.48	15.0	-2.62	- 3.81	0.97

There was the only source of information with which to validate the HVOSM program for impacts outside the range of normal crash test conditions at the time of validation. However, since the HVOSM program has been adequately validated under normal crash test conditions and no other simulation model has been validated to this extent, it is still the best available method for analyzing rigid barrier performance for high angle impacts.

In an effort to determine the significance of vehicle rollover during high-angle impacts, the HVOSM program was used to simulate a wide range of high impact angles and speeds for each of three different sizes of automobiles. Table 47 shows the matrix of high impact angle simulations conducted for this phase of the research. Barrier performance for these simulations was measured in terms of maximum roll and pitch angles, maximum height of climb, and maximum 50 ms average accelerations. Table 48 summarizes findings of high impact angle simulations and tables 49 through 51 show more detailed results. Note that the mini-size vehicle was the only vehicle that exhibited a propensity for rollover under these impact conditions. The mini-size vehicle was predicted to be in danger of rolling over at speeds as low as 30 mi/h and an impact angle of 45 degrees. Such impact conditions may well be within the range of real-world accidents and therefore the findings are considered to be significant.

Table 47. High-angle impact simulation matrix.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)
1,800	30	35
3,800	45	45
4,500	60	60
		75

b. High Yaw Angle, Low Yaw Rate Impacts

Accidents involving high yaw angle or nontracking barrier impacts have always been considered to be less severe than those involving tracking impacts. Therefore, little research has been focused on the study of the nontracking or high yaw angle barrier impacts. Consequently, there is no crash test data available with which to evaluate the effectiveness of the modified HVOSM program for simulating high yaw angle impacts. Even though there is no measure of the HVOSM program's accuracy for simulation of these impacts, the program is still the only effective method for analyzing these impact conditions, short of full-scale crash testing.

Rollover problems associated with high yaw angle concrete safety shaped barrier impacts were investigated by simulating a wide variety of impact conditions for each of three different vehicle sizes. Table 52 shows the

Table 48. Stability study for high-speed/angle tracking impacts with New Jersey shape.

(a) Honda Civic

Angle (Deg) \ Speed (mi/h)	30	45	60
35	Spinout	Stable	Stable
45	Marginal	Overturn	Overturn
60	Overturn	Overturn	Overturn

(b) Dodge Coronet

Angle (Deg) \ Speed (mi/h)	30	45	60
35	Stable	Stable	Stable
45	Sideslip	Sideslip	Sideslip
60	Sideslip	Sideslip	Sideslip
75	Sideslip	Sideslip	Sideslip

(c) Plymouth Fury

Angle (Deg) \ Speed (mi/h)	30	45	60
35	Stable	Stable	Stable
45	Sideslip	Sideslip	Sideslip
60	Sideslip	Sideslip	Sideslip
75	Sideslip	Sideslip	Sideslip

Table 49. Simulation results for high-angle mini-size vehicle impacts with New Jersey shape.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
1800	30	35	35	35.3	14.8	1.4	6.8	7.3	6.3
1800	30	45	45	58.1	6.1	1.4	12.0	9.1	5.1
1800	30	60	60		4.6	1.5	20.0	8.1	5.3
1800	45	35	35	29.7	13.1	1.9	12.2	13.3	6.2
1800	45	45	45	90.2	13.8	1.6	20.9	15.3	7.1
1800	45	60	60	88.0	5.8	1.7	33.0	12.5	6.5
1800	60	35	35	35.8	12.8	2.2	17.3	18.5	7.3
1800	60	45	45	90.1	12.9	2.6	28.6	20.8	9.0
1800	60	60	60	90.1	25.8	3.2	44.2	16.8	9.7

Table 50. Simulation results for high-angle mid-size vehicle impacts with New Jersey shape.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
3800	30	35	35	18.7	5.5	0.7	5.0	5.4	1.4
3800	30	45	45	20.8	5.5	0.7	8.6	6.4	1.7
3800	30	60	60	16.2	4.9	0.7	15.9	5.4	1.6
3800	30	75	75	3.1	0.9	0.2	24.1	1.8	0.6
3800	45	35	35	31.4	6.1	1.3	8.3	9.0	2.6
3800	45	45	45	23.0	6.3	1.2	4.5	10.9	3.1
3800	45	60	60	20.0	6.0	1.2	21.9	16.5	6.9
3800	45	75	75	19.2	3.7	0.7	36.9	2.9	1.5
3800	60	35	35	25.1	6.0	1.7	12.5	13.6	3.9
3800	60	45	45	39.3	7.2	1.8	26.2	9.4	3.1
3800	60	60	60	29.8	8.0	1.9	39.3	14.5	5.5
3800	60	75	75	28.3	5.1	1.2	51.2	4.1	2.4

Table 51. Simulation results for high-angle full-size vehicle impacts with New Jersey shape.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
4500	30	35	35	13.6	5.1	0.5	5.2	5.5	1.1
4500	30	45	45	14.6	5.5	0.6	9.1	6.4	1.3
4500	30	60	60	20.5	4.1	0.8	16.4	5.3	1.2
4500	30	75	75	2.4	1.4	0.2	24.1	1.4	0.5
4500	45	35	35	15.7	5.5	0.9	8.5	9.0	2.0
4500	45	45	45	17.9	6.8	0.9	15.0	10.9	2.5
4500	45	60	60	23.9	5.5	0.8	27.2	9.4	2.6
4500	45	75	75	11.6	1.5	0.5	37.4	2.4	1.3
4500	60	35	35	26.3	5.5	1.3	11.9	12.8	3.1
4500	60	45	45	18.9	6.7	1.3	20.7	15.4	3.4
4500	60	60	60	22.8	7.5	1.2	37.6	13.4	3.8
4500	60	75	75	24.7	2.3	0.8	50.7	3.4	2.0

simulation matrix selected for evaluation of nontracking impacts. Terms and symbols used in table 52 are defined in figure 7. Note that, as shown in this figure, a 15-degrees-per-second yaw rate was assumed for all of the simulations. HVOSM simulations of run-off-road accidents has indicated that most automobiles can attain yaw rates as high as 45 degrees per second during steering maneuvers. Thus, the 15-degrees-per-second yaw rate used in the high yaw angle simulations was chosen as representative of a relatively low yaw rate for a nontracking vehicle.

Table 52. Nontracking impact simulation matrix.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Yaw Rate (deg/sec)
1,800	30	35	45	15
3,800	45	45	60	
4,500	60	60	75	

The results of the high yaw angle simulations are summarized in tables 53 through 56. Barrier performance was again measured in terms of maximum roll and pitch angles, maximum height of climb, and maximum 50 ms average accelerations. As shown in table 53, the HVOSM program predicted that New Jersey shaped concrete barriers have the potential for causing rollovers in mini-size vehicles under all of the impact conditions evaluated. Further, the program predicted that the concrete safety shaped barrier could produce rollovers for mid- and full-size vehicles under certain high yaw angle impact conditions.

As reported previously in chapter IV, nontracking barrier impacts are fairly common, accounting for approximately 37 percent of all concrete safety shaped barrier accidents. While it is unknown what proportion of these nontracking barrier impacts involved high yaw angles coupled with low yaw rate, such impacts may comprise a significant proportion of all concrete safety shaped barrier impacts. Furthermore, if the HVOSM predictions regarding the rollover propensity for these impact conditions are correct, such impacts may comprise a significant fraction of all concrete safety shaped barrier rollovers. Thus, even though overall rollover rates for safety shaped barriers have been found to be lower than previously reported and lower than other barrier types, an opportunity for improving its performance may still exist.

c. Glare Screen Impacts

Successful crash tests of safety shaped barrier with a 10-in extension to the upper sloped surface tend to indicate that glare screens would have little effect on automobiles impacting under normal crash test conditions.(29,32) These findings were supported by a review of crash test

Table 53. Stability study for nontracking impacts with New Jersey shape.

(a) Honda Civic

Speed (mi/h) / Imp. Angle (Deg) / Yaw Angle (Deg)	30		45		60	
	15	25	15	25	15	25
45	Overturn	Overturn	Overturn	Overturn	Overturn	Overturn
60	Overturn	Overturn	Overturn	Overturn	Overturn	Overturn
75	Overturn	Marginal	Overturn	Overturn	Overturn	Overturn

(b) Dodge Coronet

Speed (mi/h) / Imp. Angle (Deg) / Yaw Angle (Deg)	30		45		60	
	15	25	15	25	15	25
45	Stable	Stable	Stable	Stable	Stable	Stable
60	Sideslip	Sideslip	Sideslip	Overturn	Overturn	Overturn
75	Spinout	Spinout	Spinout	Spinout	Spinout	Spinout

(c) Plymouth Fury

Speed (mi/h) / Imp. Angle (Deg) / Yaw Angle (Deg)	30		45		60	
	15	25	15	25	15	25
45	Stable	Stable	Stable	Stable	Stable	Stable
60	Sideslip	Sideslip	Sideslip	Sideslip	Sideslip	Overturn
75	Spinout	Spinout	Spinout	Spinout	Spinout	Spinout

Table 54. Simulation results for high yaw angle mini-size vehicle impacts with New Jersey shape.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
1800	30	15	45	90.0	8.0	1.3	3.3	1.2	1.4
1800	30	15	60	90.2	5.3	1.3	4.7	1.2	1.3
1800	30	15	75	24.9	10.0	0.7	5.5	1.2	0.8
1800	45	15	45	90.2	10.3	1.4	5.7	2.8	2.4
1800	45	15	60	90.3	6.8	1.5	7.2	1.3	2.0
1800	45	15	75	90.0	5.5	1.5	8.6	1.6	1.4
1800	60	15	45	90.1	9.8	1.4	9.2	5.3	3.8
1800	60	15	60	90.2	7.6	1.5	9.9	2.1	3.3
1800	60	15	75	90.0	11.6	1.3	11.7	1.3	2.0
1800	30	25	45	90.1	7.3	1.2	6.3	3.5	2.6
1800	30	25	60	90.1	7.0	1.4	7.7	1.5	2.2
1800	30	25	75	84.6	5.2	1.3	9.5	1.2	1.4
1800	45	25	45	90.2	10.2	1.4	11.8	7.6	4.7
1800	45	25	60	90.3	7.1	1.5	14.4	4.0	4.7
1800	45	25	75	90.1	14.8	1.3	14.6	0.1	2.8
1800	60	25	45	90.2	11.2	1.5	17.2	11.4	5.8
1800	60	25	60	90.0	5.6	2.2	21.3	6.4	7.3
1800	60	25	75	90.1	28.3	3.0	22.1	17.6	9.1

Table 55. Simulation results for high yaw angle mid-size vehicle impacts with the New Jersey shape.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
3800	30	15	45	10.1	2.2	0.2	2.7	1.5	.7
3800	30	15	60	8.8	2.5	0.2	3.6	0.5	.5
3800	30	15	75	5.8	2.1	0.2	4.9	0.8	.6
3800	45	15	45	16.4	4.2	0.8	4.5	3.3	1.2
3800	45	15	60	11.3	3.6	0.4	5.8	1.2	.7
3800	45	15	75	5.6	3.0	0.3	8.1	0.9	0.9
3800	60	15	45	20.1	5.3	1.1	6.4	3.6	1.6
3800	60	15	60	86.9	4.4	1.4	8.4	2.0	1.4
3800	60	15	75	6.36	3.7	0.4	11.7	1.1	1.26
3800	30	25	45	15.8	3.3	0.7	5.0	3.0	1.6
3800	30	25	60	10.2	3.3	0.3	6.5	1.4	0.6
3800	30	25	75	4.7	2.7	0.3	9.0	0.1	0.9
3800	45	25	45	20.1	6.4	1.1	8.1	5.0	1.8
3800	45	25	60	90.1	4.8	1.4	11.0	2.8	1.4
3800	45	25	75	6.0	4.2	0.4	14.5	1.2	1.5
3800	60	25	45	23.7	12.4	1.7	11.3	7.3	3.3
3800	60	25	60	90.0	5.9	1.3	15.9	4.4	2.3
3800	60	25	75	9.5	6.8	0.7	20.1	1.8	2.2

Table 56. Simulation results for high yaw angle full-size vehicle impacts with the New Jersey shape.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
4500	30	15	45	12.3	3.2	0.4	2.8	1.4	0.5
4500	30	15	60	6.3	2.0	0.2	3.3	0.6	0.4
4500	30	15	75	6.5	1.7	0.2	4.3	0.7	0.4
4500	45	15	45	19.2	3.7	0.7	4.6	3.1	0.7
4500	45	15	60	7.8	1.7	0.3	5.7	1.1	0.6
4500	45	15	75	6.6	1.9	0.3	7.7	0.7	0.8
4500	60	15	45	20.3	3.9	0.8	6.6	3.8	1.0
4500	60	15	60	21.8	2.7	0.6	8.5	1.9	0.9
4500	60	15	75	7.0	2.7	0.4	11.4	0.7	1.1
4500	30	25	45	18.1	3.7	0.7	5.1	2.8	1.0
4500	30	25	60	7.9	1.3	0.3	6.4	1.3	0.7
4500	30	25	75	6.0	1.9	0.3	8.8	0.7	0.8
4500	45	25	45	19.8	5.2	0.8	8.4	5.3	1.3
4500	45	25	60	36.3	3.0	1.2	11.0	2.9	1.3
4500	45	25	75	6.8	3.0	0.4	14.7	0.8	1.4
4500	60	25	45	22.7	6.5	1.0	11.8	7.8	2.2
4500	60	25	60	63.1	3.2	1.4	15.2	4.5	2.2
4500	60	25	75	17.7	4.5	0.6	20.7	0.9	2.0

films which indicated that many test vehicles would not even contact the glare screen extension to the safety shape. Therefore, if glare screens do increase the potential for rollover, the effect is likely to involve only impacts with low impact angles. However, the HVOSM program's inability to properly simulate tire contact with the upper sloped surface of the concrete safety shaped barrier severely limits the usefulness of the program for simulating low-angle glare screen impacts. Therefore, only a limited simulation effort was devoted to the investigation of the importance of glare screens on the performance of concrete safety shaped barriers under crash test conditions as shown in table 57.

Table 57. Glare screen impact simulation matrix.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)
1,800	30	7
3,800	45	15
4,500	60	25

Simulation findings from glare screen evaluation runs are shown in tables 58 through 61. The HVOSM program predicted good performance for all impact conditions evaluated, as shown in table 58. Based on these simulation findings, there is no reason to believe that vehicle sheet metal contact with glare screens adversely affects 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.

d. High-Speed, Low-Angle Impacts

HVOSM simulations of high-speed, low-angle impacts to the concrete safety shaped barrier suffer from severe limitations associated with its thin disk tire model. Since the program is unable to accurately model low-angle curb impacts, it is unreasonable to expect it to model low-angle impacts with safety shaped barriers. However, reported problems with the tire model have been shown to destabilize the vehicle and predict excessive maximum roll and pitch angles for low-angle concrete safety shaped barrier impacts. Thus, the HVOSM program may overstate the significance of low-angle impacts on concrete safety shaped barrier rollovers.

A limited simulation study was undertaken to estimate the effects of high-speed, low-angle impacts on the performance of concrete safety shaped barrier, as shown in table 62. Note that the modified tire/curb interaction surface was used for these simulations and therefore a vehicle's tires could not climb to the top of the safety shaped barrier. Simulation results are summarized in table 63 and detailed results are

Table 58. Stability study for impacts on New Jersey shape with a 20-in glare screen.

(a) Honda Civic

Speed (mi/h) / Angle (Deg)	30	45	60
7	Stable	Stable	Stable
15	Stable	Stable	Stable
25	Stable	Stable	Stable

(b) Dodge Coronet

Speed (mi/h) / Angle (Deg)	30	45	60
7	Stable	Stable	Stable
15	Stable	Stable	Stable
25	Stable	Stable	Stable

(c) Plymouth Fury

Speed (mi/h) / Angle (Deg)	30	45	60
7	Stable	Stable	Stable
15	Stable	Stable	Stable
25	Stable	Stable	Stable

Table 59. Simulation results for mini-size vehicle impacts on New Jersey shape with a 20-in glare screen.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
1800	30	7	7	6.9	3.7	0.4	0.4	1.2	0.8
1800	45	7	7	18.2	3.7	0.8	0.5	2.0	1.3
1800	60	7	7	4.3	4.3	1.1	0.6	3.1	2.4
1800	30	15	15	15.1	7.1	0.9	1.2	2.4	1.8
1800	45	15	15	17.1	7.8	1.2	1.9	4.2	2.8
1800	60	15	15	17.6	11.5	1.6	2.7	6.5	4.0
1800	30	25	25	21.9	7.7	1.2	3.2	4.6	3.2
1800	45	25	25	20.5	12.3	1.7	5.7	8.9	4.9
1800	60	25	25	16.7	15.9	2.1	8.5	13.3	6.0

Table 60. Simulation results for mid-size vehicle impacts on New Jersey shape with a 20-in glare screen.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
3800	30	7	7	6.5	1.1	0.1	0.3	1.5	0.3
3800	45	7	7	3.6	1.8	0.3	0.4	2.2	1.0
3800	60	7	7	8.2	1.9	0.6	0.6	2.8	1.0
3800	30	15	15	3.0	3.0	0.3	1.0	2.4	0.9
3800	45	15	15	7.9	4.5	0.7	1.6	3.9	1.3
3800	60	15	15	29.3	3.5	1.2	2.3	5.7	2.1
3800	30	25	25	11.7	4.6	0.5	2.6	4.0	1.2
3800	45	25	25	15.3	5.4	1.1	4.2	6.6	2.2
3800	60	25	25	17.5	6.6	1.5	6.1	9.6	3.8

Table 61. Simulation results for full-size vehicle impacts on New Jersey shape with a 20-in glare screen.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
4500	30	7	7	3.4	1.2	0.1	0.3	1.3	0.3
4500	45	7	7	1.3	1.8	0.3	0.5	2.0	0.7
4500	60	7	7	4.1	1.6	0.5	0.7	3.0	0.7
4500	30	15	15	4.9	2.8	0.3	1.1	2.4	1.0
4500	45	15	15	8.1	3.3	0.6	1.7	3.7	0.9
4500	60	15	15	14.8	3.5	0.9	2.5	5.7	1.6
4500	30	25	25	10.6	4.2	0.5	2.8	4.0	0.9
4500	45	25	25	16.7	4.5	0.9	4.5	6.8	2.4
4500	60	25	25	28.3	4.5	1.3	6.2	9.5	3.3

presented in table 64. The HVOSM program predicted stable vehicle performance in all cases except an 85-mi/h, 10-degree impact with a small car. Based on these findings, it was concluded that if high-speed, low-angle impacts are a significant source of rollovers in accidents involving concrete safety shaped barrier, evaluation of the problem is outside the capabilities of existing versions of the HVOSM program. However, based on the infrequency of high-speed impacts in real-world accidents, these impact conditions are not believed to be a major source of concrete safety shaped barrier rollover accidents.(41)

Table 62. High-speed, low-angle impact simulation matrix.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)
1,800	60	5
3,800	85	10
4,500		

3. Simulation of Potential Countermeasures

HVOSM simulations of concrete safety shaped barrier impacts identified two impact conditions, high-angle impacts and high yaw angle coupled with low yaw rate impacts, that may contribute to rollover in accidents involving concrete safety shaped barriers. As reported in chapter IV, rollover rates for concrete safety shaped barrier accidents are lower than previously reported and lower than the rollover rates associated with other types of barriers. Consequently, retrofitting of existing safety shaped barriers to reduce the propensity for rollover is not believed to be cost beneficial. However, for new constructions or reconstructions, there still may be room to improve the basic shape of the shaped concrete barrier to reduce the propensity for rollover in the future. Therefore, only potential countermeasures applicable for new construction or reconstruction were considered and retrofit concepts were excluded.

The F-shape barrier was developed as a potential improvement to the New Jersey shape that would reduce the rollover potential of the safety shaped barrier.(12) The lower and upper sloped faces of the F-shape have the same slope as those of the New Jersey shape. However, the curb portion of the F-shape barrier is only 10 in high compared to 13 in for the New Jersey shape. As discussed in chapter III, lowering the curb face has been shown to have the potential for reducing rollovers under normal crash test conditions. Therefore, the F-shape was selected as a potential improvement that may reduce the propensity for rollovers during high-angle and high yaw angle impacts.

Table 63. Stability study for high-speed low angle impacts on New Jersey shape.

(a) Honda Civic

Angle (Deg) \ Speed (mi/h)	60	85
05	Stable	Stable
10	Stable	Marginal

(b) Dodge Coronet

Angle (Deg) \ Speed (mi/h)	60	85
05	Stable	Stable
10	Stable	Stable

(c) Plymouth Fury

Angle (Deg) \ Speed (mi/h)	60	85
05	Stable	Stable
10	Stable	Stable

Table 64. Simulation results for high-speed/low-angle mini-size vehicle impacts with New Jersey shape.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
1800	60	05	05	20.6	3.0	0.8	0.3	2.2	1.6
1800	60	10	10	35.8	3.9	1.3	1.2	4.1	3.1
1800	85	05	05	36.8	4.8	1.2	0.6	3.5	2.5
1800	85	10	10	47.7	8.6	2.2	2.2	7.8	5.5
3800	60	05	05	8.1	1.4	0.4	0.3	2.7	0.8
3800	60	10	10	12.9	2.7	0.8	1.1	3.8	1.6
3800	85	05	05	14.2	3.7	0.7	0.6	3.6	1.7
3800	85	10	10	39.3	3.3	1.4	1.8	6.8	3.5
4500	60	05	05	2.2	1.6	0.3	0.4	2.3	0.7
4500	60	10	10	8.2	2.2	0.7	1.2	4.0	1.3
4500	85	05	05	2.5	1.4	0.5	0.7	3.5	0.9
4500	85	10	10	18.3	2.1	1.0	1.9	6.6	2.2

Another potential improvement to the New Jersey shape concrete barrier is to totally eliminate the lower curb and have a single constant slope barrier. This barrier would represent somewhat of a midpoint in the natural progression between a safety shaped barrier and a vertical wall. Elimination of the lower curb face will greatly reduce the vertical forces on the tires, which in turn should reduce the vertical forces applied to the vehicle's body structure. As a result, this modification can be expected to reduce the number of rollovers associated with concrete safety shaped barriers and it was therefore selected for evaluation in this phase of the study. However, the slope to be used in this single constant slope barrier was yet to be determined.

The safety shaped barrier with its lower curb face was designed to redirect automobiles impacting at low angles without damage to the vehicle. This barrier performance is possible because a vehicle's tires contact the lower curb surface of the barrier first before the body of the vehicle contacts the recessed upper sloped barrier surface. Removal of the lower curb would likely eliminate such behavior except under extremely low-angle impacts. Sloping the barrier away from the roadway should reduce the degree of sheet metal contact with the barrier and likewise reduce vehicle damage.

Another advantage of the shaped concrete barrier is that lateral accelerations imparted to vehicles impacting a safety barrier have been shown to be lower than those involving a rigid vertical wall. Elimination of the lower curb surface would increase these lateral accelerations. The extent of increases in lateral vehicle accelerations should be controlled to some degree by the barrier slope incorporated.

A limited simulation effort was undertaken to determine the effects of barrier slope on the maximum roll angle and lateral vehicle accelerations under normal crash test conditions. Findings from this effort indicated that maximum roll angle was minimized for a slope of approximately 81 degrees. However, in the interest of reducing lateral accelerations, a barrier slope of 80 degrees was selected for use in the remainder of the simulation study. Finally, it was believed that a barrier that did not apply normal forces with a vertical component to impacting automobiles would offer the best method of minimizing rollovers associated with rigid barriers. A rigid vertical wall was therefore selected for inclusion in the simulation study of potential countermeasures.

Each of the three proposed shape modifications was then simulated for all high-angle and high yaw angle impact conditions used to evaluate the concrete safety shaped barrier. Simulation findings are presented in tables 65 through 84 and summarized below.

a. F-Shape Barrier

As shown in tables 65 and 66, the HVOSM program predicted that F-shape barriers would exhibit performance very similar to the New Jersey shape

Table 65. Stability study for high-speed/angle tracking impacts with F-shape.

(a) Honda Civic

Speed (mi/h) Angle (Deg)	30	45	60
35	Stable	Stable	Overturn
45	Stable	Sideslip	Overturn
60	Overturn	Overturn	Overturn
75	Marginal	Spinout	Overturn

(b) Dodge Coronet

Speed (mi/h) Angle (Deg)	30	45	60
35	Stable	Stable	Stable
45	Stable	Stable	Stable
60	Sideslip	Stable	Stable
75	Stopped	Stopped	Stopped

(c) Plymouth Fury

Speed (mi/h) Angle (Deg)	30	45	60
35	Stable	Stable	Stable
45	Stable	Stable	Stable
60	Sideslip	Stable	Stable
75	Stopped	Stopped	Stopped

Table 66. Stability study for nontracking impacts with F-shape.

(a) Honda Civic

Speed (mi/h)	30		45		60	
Yaw Angle (Deg) \ Imp. Angle (Deg)	15	25	15	25	15	25
45	Overturn	Overturn	Overturn	Marginal	Overturn	Marginal
60	Overturn	Overturn	Overturn	Overturn	Overturn	Overturn
75	Overturn	Overturn	Overturn	Overturn	Overturn	Overturn

(b) Dodge Coronet

Speed (mi/h)	30		45		60	
Yaw Angle (Deg) \ Imp. Angle (Deg)	15	25	15	25	15	25
45	Stable	Stable	Stable	Stable	Stable	Stable
60	Sideslip	Sideslip	Sideslip	Sideslip	Sideslip	Overturn
75	Spinout	Spinout	Spinout	Spinout	Spinout	Spinout

(c) Plymouth Fury

Speed (mi/h)	30		45		60	
Yaw Angle (Deg) \ Imp. Angle (Deg)	15	25	15	25	15	25
45	Stable	Stable	Stable	Stable	Stable	Stable
60	Sideslip	Sideslip	Sideslip	Sideslip	Sideslip	Marginal
75	Spinout	Spinout	Spinout	Spinout	Spinout	Spinout

Table 67. Simulation results of high-angle mini-size vehicle impacts with F-shape.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's) Long.	Lat.	Vert.
1800	30	35	35	14.9	4.5	0.7	7.8	8.0	3.0
1800	30	45	45	24.1	2.6	0.8	13.2	9.3	3.3
1800	30	60	60	90.2	2.2	1.3	21.0	7.1	4.6
1800	30	75	75	56.1	1.2	0.9	24.0	2.6	2.2
1800	45	35	35	22.9	4.5	1.1	12.0	13.3	4.5
1800	45	45	45	32.7	19.2	1.1	21.9	15.0	5.3
1800	45	60	60	90.0	24.4	2.1	34.4	11.7	6.0
1800	45	75	75	30.9	8.7	1.3	40.1	5.1	3.8
1800	60	35	35	90.1	5.0	1.5	18.0	18.3	6.0
1800	60	45	45	90.7	32.0	2.0	29.0	20.2	7.5
1800	60	60	60	90.0	63.7	3.5	45.5	16.1	9.4
1800	60	75	75	49.9	22.9	2.7	54.0	7.5	7.0

Table 68. Simulation results for high-angle mid-size vehicle impacts with F-shape.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms Average Acceleration (g's)		
							Long.	Lat.	Vert.
3800	30	35	35	12.5	4.4	0.4	5.2	5.3	1.0
3800	30	45	45	10.8	4.5	0.4	9.0	6.4	1.1
3800	30	60	60	13.1	2.7	0.5	16.7	5.5	1.1
3800	30	75	75	2.1	1.2	0.2	24.0	1.3	0.6
3800	45	35	35	22.7	4.6	0.7	8.5	9.1	1.9
3800	45	45	45	18.7	5.2	0.7	15.0	11.1	2.3
3800	45	60	60	17.0	3.8	0.7	27.2	9.5	2.4
3800	45	75	75	8.3	1.1	0.4	38.1	2.3	1.2
3800	60	35	35	24.1	4.4	1.1	11.8	12.6	3.3
3800	60	45	45	27.5	5.4	1.2	20.3	15.2	3.1
3800	60	60	60	18.9	5.9	1.0	37.2	13.5	3.6
3800	60	75	75	27.6	1.5	0.9	51.9	3.3	1.9

Table 69. Simulation results for high-angle full-size vehicle impacts with F-shape.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's) Long.	Lat.	Vert.
4500	30	35	35	11.0	4.0	0.4	5.2	5.3	0.8
4500	30	45	45	12.1	4.5	0.4	9.0	6.3	0.9
4500	30	60	60	16.3	4.5	0.5	16.5	5.3	1.0
4500	30	75	75	2.6	1.5	0.2	24.4	1.4	0.6
4500	45	35	35	11.2	3.8	0.6	8.6	9.0	1.5
4500	45	45	45	11.7	4.5	0.6	15.1	11.0	1.9
4500	45	60	60	15.2	3.7	0.6	27.4	9.3	2.0
4500	45	75	75	6.5	1.0	0.3	37.8	2.1	0.9
4500	60	35	35	9.9	5.4	0.8	12.5	13.4	2.3
4500	60	45	45	11.1	4.4	0.8	21.9	16.3	2.9
4500	60	60	60	14.7	3.6	0.7	39.7	14.5	3.3
4500	60	75	75	17.0	1.4	0.6	51.3	3.1	1.5

Table 70. Simulation results for high yaw angle mini-size vehicle impacts with F-shape.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's) Long.	Lat.	Vert.
1800	30	15	45	90.1	2.0	1.1	3.5	1.4	1.1
1800	30	15	60	90.2	4.1	1.2	4.0	1.3	0.8
1800	30	15	75	77.9	13.6	2.8	5.4	2.1	6.9
1800	45	15	45	90.1	7.4	1.2	5.9	3.0	1.8
1800	45	15	60	90.2	6.6	1.3	6.1	1.3	1.5
1800	45	15	75	90.1	3.4	1.4	8.9	1.5	0.9
1800	60	15	45	90.0	7.7	1.3	9.7	5.6	2.7
1800	60	15	60	90.2	5.0	1.3	11.0	2.4	2.3
1800	60	15	75	90.1	5.0	1.3	12.2	1.6	1.3
1800	30	25	45	88.1	1.9	1.1	6.8	3.8	2.0
1800	30	25	60	90.1	3.1	1.2	6.7	1.2	1.6
1800	30	25	75	17.2	5.9	0.4	9.8	3.5	9.5
1800	45	25	45	67.7	1.7	1.1	12.6	7.8	3.4
1800	45	25	60	90.2	1.3	1.1	14.5	3.7	3.4
1800	45	25	75	90.0	7.8	1.3	15.3	1.5	1.8
1800	60	25	45	54.9	4.2	1.0	18.0	11.5	4.6
1800	60	25	60	90.1	5.5	1.2	21.7	6.1	4.0
1800	60	25	75	90.1	6.8	1.2	21.0	1.0	3.0

Table 71. Simulation results for high yaw angle mid-size vehicle impacts with F-shape.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
3800	30	15	45	8.4	1.3	0.1	2.7	1.5	0.3
3800	30	15	60	4.7	1.2	0.1	3.4	0.5	0.4
3800	30	15	75	5.7	0.9	0.1	4.8	0.7	0.4
3800	30	25	45	11.9	2.3	0.4	4.9	2.8	0.7
3800	30	25	60	4.8	2.1	0.2	6.3	1.4	0.6
3800	30	25	75	5.9	1.2	0.2	9.1	0.8	0.7
3800	45	15	45	10.7	1.9	0.3	4.4	3.2	1.0
3800	45	15	60	6.2	1.7	0.2	5.7	1.1	0.6
3800	45	15	75	5.7	1.3	0.2	8.2	0.8	0.7
3800	45	25	45	16.8	3.2	0.6	8.6	5.2	1.4
3800	45	25	60	23.6	3.5	0.8	11.5	3.1	1.1
3800	45	25	75	4.7	2.1	0.2	15.1	1.0	1.2
3800	60	15	45	16.5	4.7	0.7	6.5	3.8	1.6
3800	60	15	60	11.0	2.9	0.3	8.7	2.1	0.8
3800	60	15	75	5.2	1.8	0.3	11.9	0.9	1.0
3800	60	25	45	19.4	4.3	0.9	11.8	7.7	2.0
3800	60	25	60	90.0	6.5	1.7	16.5	9.7	1.7
3800	60	25	75	5.9	2.5	0.4	20.8	1.2	1.6

Table 72. Simulation results for high yaw angle full-size vehicle impacts with F-shape.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
4500	30	15	45	10.2	2.0	0.2	2.7	1.4	0.3
4500	30	15	60	5.8	1.6	0.2	3.3	0.6	0.4
4500	30	15	75	6.8	13.6	0.2	3.9	0.7	0.3
4500	45	15	45	16.0	3.0	0.5	4.4	2.4	1.1
4500	45	15	60	4.9	2.1	0.3	5.6	1.1	0.5
4500	45	15	75	6.7	1.8	0.3	7.7	0.7	0.6
4500	60	15	45	18.1	3.4	0.6	6.5	3.8	1.3
4500	60	15	60	15.8	3.6	0.5	8.4	2.1	0.8
4500	60	15	75	6.7	1.9	0.3	11.5	0.7	1.0
4500	30	25	45	15.0	3.3	0.5	4.9	2.8	0.7
4500	30	25	60	4.5	2.3	0.3	6.3	1.3	0.6
4500	30	25	75	6.2	1.9	0.3	8.8	0.7	0.7
4500	45	25	45	16.4	3.2	0.5	8.4	5.2	1.0
4500	45	25	60	19.0	2.3	0.5	10.8	2.8	1.0
4500	45	25	75	5.8	2.1	0.3	14.9	0.8	1.2
4500	60	25	45	17.8	4.6	0.7	11.9	7.8	1.6
4500	60	25	60	60.9	5.3	1.3	16.4	4.6	1.6
4500	60	25	75	8.4	2.8	0.5	20.7	0.9	1.7

Table 73. Stability study for high-speed/angle tracking impacts with constant sloped barrier.

(a) Honda Civic

Speed (mi/h) / Angle (Deg)	30	45	60
35	Sideslip	Spinout	Spinout
45	Sideslip	Spinout	Marginal
60	Sideslip	Spinout	Spinout
75	Spinout	Spinout	Spinout

(b) Dodge Coronet

Speed (mi/h) / Angle (Deg)	30	45	60
35	Stable	Stable	Overturn
45	Stable	Stable	Marginal
60	Stable	Sideslip	Marginal
75	Stopped	Near Stop	Near Stop

(c) Plymouth Fury

Speed (mi/h) / Angle (Deg)	30	45	60
35	Stable	Stable	Marginal
45	Stable	Sideslip	Stable
60	Sideslip	Sideslip	Stable
75	Stopped	Stopped	Stopped

Table 74. Stability study for nontracking impacts with constant sloped barrier.

(a) Honda Civic

Speed (mi/h)	30		45		60	
Imp. Angle (Deg) Yaw Angle (Deg)	15	25	15	25	15	25
45	Overturn	Overturn	Overturn	Overturn	Overturn	Overturn
60	Marginal	Overturn	Overturn	Overturn	Spinout	Spinout
75	Overturn	Spinout	Overturn	Overturn	Spinout	Spinout

(b) Dodge Coronet

Speed (mi/h)	30		45		60	
Imp. Angle (Deg) Yaw Angle (Deg)	15	25	15	25	15	25
45	Stable	Stable	Stable	Stable	Stable	Stable
60	Sideslip	Sideslip	Stable	Overturn	Stable	Marginal
75	Spinout	Spinout	Sideslip	Spinout	Spinout	Sideslip

(c) Plymouth Fury

Speed (mi/h)	30		45		60	
Imp. Angle (Deg) Yaw Angle (Deg)	15	25	15	25	15	25
45	Stable	Stable	Stable	Stable	Sideslip	Sideslip
60	Sideslip	Sideslip	Sideslip	Sideslip	Sideslip	Marginal
75	Spinout	Spinout	Spinout	Sideslip	Sideslip	Sideslip

Table 75. Simulation results for high-angle mini-size vehicle impacts with constant-slope barriers.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
1800	30	35	35	14.3	5.7	0.7	10.2	12.5	3.7
1800	30	45	45	52.7	4.7	1.3	18.2	16.2	4.9
1800	30	60	60	35.0	12.2	1.4	24.8	10.7	4.5
1800	30	75	75	15.2	3.3	0.7	26.9	3.9	2.8
1800	45	35	35	31.5	18.2	1.9	24.8	10.7	4.5
1800	45	45	45	28.1	14.5	2.1	24.2	19.8	5.4
1800	45	60	60	13.2	22.8	3.0	37.5	13.9	5.8
1800	45	75	75	15.3	9.9	1.5	43.7	15.3	5.4
1800	60	35	35	6.6	30.0	2.2	22.4	27.6	6.2
1800	60	45	45	90.1	26.9	3.0	33.0	25.6	6.5
1800	60	60	60	24.0	2.3	3.5	50.0	17.0	7.5
1800	60	75	75	12.8	22.9	2.0	58.4	9.1	8.8

Table 76. Simulation results for high-angle mid-size vehicle impacts with constant-slope barriers.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
3800	30	35	35	11.2	4.7	0.4	5.1	5.3	1.2
3800	30	45	45	17.1	6.1	0.7	8.9	6.6	1.7
3800	30	60	60	15.3	6.6	1.0	16.4	6.0	2.5
3800	30	75	75	4.1	2.7	0.2	23.5	2.7	1.0
3800	45	35	35	23.9	9.6	1.0	13.8	6.1	2.0
3800	45	45	45	40.1	8.0	1.9	15.2	11.7	3.3
3800	45	60	60	22.7	9.7	2.4	26.7	10.2	4.5
3800	45	75	75	11.2	6.2	0.6	37.0	4.2	2.0
3800	60	35	35	90.1	7.2	2.0	13.0	14.8	4.2
3800	60	45	45	45.2	9.6	3.0	22.5	16.9	5.0
3800	60	60	60	42.1	12.4	3.4	39.1	14.9	6.0
3800	60	75	75	15.8	10.7	1.8	49.6	5.7	3.1

Table 77. Simulation results for high-angle full-size vehicle impacts with constant-slope barriers.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's) Long.	Lat.	Vert.
4500	30	35	35	14.0	5.9	0.7	5.4	5.5	1.3
4500	30	45	45	19.3	7.3	1.2	9.4	6.6	1.9
4500	30	60	60	18.3	8.2	1.3	16.9	5.9	2.0
4500	30	75	75	5.7	4.0	0.2	23.9	3.1	0.8
4500	45	35	35	21.6	14.5	1.8	9.3	9.7	2.5
4500	45	45	45	28.4	21.5	2.8	15.6	11.3	3.2
4500	45	60	60	18.6	8.2	1.3	16.9	5.9	2.0
4500	45	75	75	11.4	7.7	0.7	37.4	4.6	1.7
4500	60	35	35	25.8	18.0	2.9	13.3	14.0	4.9
4500	60	45	45	70.2	28.0	3.8	22.3	16.2	4.7
4500	60	60	60	25.8	15.4	3.7	38.7	14.2	5.5
4500	60	75	75	11.3	12.1	1.7	50.1	6.0	3.1

Table 78. Simulation results for high yaw angle mini-size vehicle impacts with constant-slope barriers

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
1800	30	15	45	88.1	4.7	1.3	4.9	2.2	1.3
1800	30	15	60	52.9	6.3	1.6	4.8	1.2	4.4
1800	30	15	75	48.6	6.6	1.3	4.9	1.0	3.8
1800	45	15	45	90.1	14.5	1.3	8.1	5.2	2.7
1800	45	15	60	85.8	1.9	1.3	9.4	2.5	2.0
1800	45	15	75	90.0	4.2	1.5	8.7	1.7	1.3
1800	60	15	45	90.2	13.4	1.4	13.0	9.6	4.0
1800	60	15	60	57.9	2.0	1.0	14.7	5.0	3.1
1800	60	15	75	44.9	6.3	0.7	12.2	1.5	2.0
1800	60	25	45	90.0	3.2	1.1	9.0	6.3	3.0
1800	30	25	60	34.9	5.3	0.8	10.6	3.4	4.7
1800	30	25	75	24.7	8.0	0.6	9.5	1.1	4.6
1800	30	25	45	90.0	7.9	1.4	16.8	13.7	5.0
1800	45	25	60	71.9	5.1	1.6	18.2	7.0	7.0
1800	45	25	75	69.5	9.1	1.1	16.6	1.8	2.4
1800	45	25	45	90.1	4.9	2.0	23.6	19.8	6.7
1800	60	25	60	12.0	10.5	2.1	25.5	9.4	4.8
1800	60	25	75	31.1	16.5	1.5	24.1	1.1	4.5

Table 79. Simulation results for high yaw angle mid-size vehicle impacts with constant-slope barrier.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
3800	30	15	45	17.0	4.5	1.0	5.0	2.8	2.2
3800	30	15	60	13.1	4.3	0.6	3.6	0.8	0.9
3800	30	15	75	7.5	2.7	0.3	4.2	1.0	0.9
3800	45	15	45	23.1	6.4	1.2	4.3	3.4	1.5
3800	45	15	60	35.6	5.5	1.2	6.0	1.3	1.0
3800	45	15	75	9.4	6.1	0.6	7.1	0.7	1.1
3800	60	15	45	25.8	10.0	1.5	6.2	3.7	1.7
3800	60	15	60	36.3	6.7	1.3	8.5	2.1	1.5
3800	60	15	75	9.7	8.3	0.9	10.4	2.0	2.6
3800	30	25	45	13.8	3.5	0.6	2.7	2.4	1.6
3800	30	25	60	15.6	5.4	0.9	6.9	1.5	1.0
3800	30	25	75	6.9	4.5	0.4	8.7	1.4	1.3
3800	45	25	45	20.2	6.6	1.2	8.6	5.2	1.7
3800	45	25	60	90.0	7.4	1.8	11.4	3.0	1.9
3800	45	25	75	23.9	9.6	1.0	13.8	6.1	2.0
3800	60	25	45	11.3	2.7	0.3	1.7	3.0	1.0
3800	60	25	60	62.9	9.4	2.8	16.6	4.6	3.0
3800	60	25	75	7.7	15.3	1.8	19.5	1.9	3.0

Table 80. Simulation results for high yaw angle full-size vehicle impacts with constant-slope barrier.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's) Long.	Lat.	Vert.
4500	30	15	45	15.7	4.4	0.8	2.8	1.8	1.7
4500	30	15	60	10.6	3.3	0.4	3.4	0.5	0.6
4500	30	15	75	8.2	3.3	0.4	3.9	0.6	0.7
4500	45	15	45	31.7	6.3	1.4	4.5	2.9	1.0
4500	45	15	60	14.2	3.7	0.5	5.6	1.2	1.1
4500	45	15	75	10.4	4.9	0.5	7.1	0.8	1.2
4500	60	15	45	33.1	12.9	1.6	6.4	3.8	2.0
4500	60	15	60	31.6	4.2	0.8	8.3	2.0	1.6
4500	60	15	75	12.2	7.6	0.7	10.8	0.7	1.9
4500	30	25	45	17.2	5.2	0.9	5.0	2.9	1.7
4500	30	25	60	10.7	3.3	0.5	6.4	1.4	1.1
4500	30	25	75	9.2	4.7	0.5	8.1	0.8	1.3
4500	45	25	45	26.6	16.5	1.6	8.5	5.2	1.8
4500	45	25	60	33.7	4.6	1.2	11.3	2.9	2.0
4500	45	25	75	12.0	9.1	0.9	14.2	0.4	2.3
4500	60	25	45	37.5	26.5	2.5	12.1	7.9	2.7
4500	60	25	60	77.5	6.9	1.4	16.6	4.8	3.0
4500	60	25	75	8.8	14.6	1.7	20.2	0.4	3.3

TABLE 81. Stability study for high-speed/angle tracking impacts with vertical wall.

(a) Honda Civic

Angle (Deg) \ Speed (mi/h)	30	45	60
35	Stable	Stable	Stable
45	Sideslip	Sideslip	Marginal
60	Sideslip	Overturn	Overturn

(b) Dodge Coronet

Angle (Deg) \ Speed (mi/h)	30	45	60
35	Stable	Stable	Stable
45	Sideslip	Stable	Stable
60	Sideslip	Sideslip	Stable
75	Sideslip	Sideslip	Sideslip

(c) Plymouth Fury

Angle (Deg) \ Speed (mi/h)	30	45	60
35	Stable	Stable	Stable
45	Sideslip	Sideslip	Sideslip
60	Sideslip	Sideslip	Sideslip
75	Sideslip	Sideslip	Sideslip

Table 82. Stability study for nontracking impacts with vertical wall.

(a) Honda Civic

Speed (mi/h) / Imp. Angle (Deg) / Yaw Angle (Deg)	30		45		60	
	15	25	15	25	15	25
45	Stable	Stable	Stable	Stable	Stable	Stable
60	Sideslip	Sideslip	Sideslip	Marginal	Sideslip	Overturn
75	Spinout	Overturn	Marginal	Marginal	Marginal	Overturn

(b) Dodge Coronet

Speed (mi/h) / Imp. Angle (Deg) / Yaw Angle (Deg)	30		45		60	
	15	25	15	25	15	25
45	Stable	Stable	Stable	Stable	Stable	Stable
60	Sideslip	Sideslip	Sideslip	Sideslip	Sideslip	Sideslip
75	Spinout	Spinout	Spinout	Spinout	Spinout	Spinout

(c) Plymouth Fury

Speed (mi/h) / Imp. Angle (Deg) / Yaw Angle (Deg)	30		45		60	
	15	25	15	25	15	25
45	Stable	Stable	Stable	Stable	Stable	Stable
60	Sideslip	Sideslip	Sideslip	Sideslip	Sideslip	Sideslip
75	Spinout	Spinout	Sideslip	Spinout	Spinout	Spinout

Table 83. Simulation results for high-angle mini-size vehicle impacts with vertical barrier.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
1800	30	35	35	26.9	7.4	0.7	16.8	16.2	1.8
1800	45	35	35	10.2	4.8	0.2	12.3	12.0	1.1
1800	60	35	35	26.9	7.4	0.7	16.8	16.2	1.8
1800	30	45	45	5.6	4.4	0.0	12.7	8.5	0.3
1800	45	45	45	16.8	9.9	0.7	20.0	13.2	2.0
1800	60	45	45	53.8	0.7	1.3	27.2	18.4	2.5
1800	30	60	60	8.2	5.0	0.1	20.5	6.5	0.4
1800	45	60	60	90.1	16.3	1.5	32.7	10.6	1.0
1800	60	60	60			0.1			

Table 84. Simulation results for high-angle mid-size vehicle impacts with vertical barrier.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's) Long.	Lat.	Vert.
3800	30	35	35	6.1	0.3	0.0	5.3	5.5	0.1
3800	45	35	35	7.6	0.2	0.1	8.7	9.2	0.2
3800	60	35	35	9.0	1.5	0.1	12.7	13.8	0.2
3800	30	45	45	6.0	0.8	0.0	22.9	43.1	0.5
3800	45	45	45	5.6	0.5	0.1	15.4	11.4	0.2
3800	60	45	45	3.3	2.5	0.2	22.3	16.8	0.2
3800	30	60	60	6.1	0.7	0.0	17.9	5.7	0.6
3800	45	60	60	6.9	1.1	0.1	28.9	9.9	0.6
3800	60	60	60	5.0	2.3	0.1	40.4	14.3	0.2
3800	30	75	75	3.1	0.3	0.1	26.8	1.3	0.1
3800	45	75	75	4.5	0.2	0.1	40.7	2.1	0.3
3800	60	75	75	5.8	0.5	0.1	52.7	2.8	0.3

Table 85. Simulation results for high-angle full-size vehicle impacts with vertical barrier.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
4500	30	35	35						
4500	45	35	35	9.0	1.0	0.3	9.2	9.7	1.1
4500	60	35	35	9.2	0.6	0.1	12.9	13.8	1.6
4500	30	45	45	8.7	1.7	0.1	10.1	7.0	0.1
4500	45	45	45	9.8	1.5	0.1	16.3	11.8	0.4
4500	60	45	45	10.1	0.9	0.1	22.9	16.9	1.1
4500	30	60	60	7.2	1.6	0.1	18.9	5.9	0.2
4500	45	60	60	8.4	2.5	0.1	30.5	10.1	0.3
4500	60	60	60	7.4	2.5	0.1	41.7	14.2	0.3
4500	30	75	75	3.8	0.8	0.0	25.5	1.3	0.9
4500	45	75	75	4.0	0.6	0.0	39.7	1.9	0.8
4500	60	75	75	4.6	0.8	0.0	53.3	2.5	0.6

Table 86. Simulation results for high yaw angle mini-size vehicle impacts with vertical barrier.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's) Long.	Lat.	Vert.
1800	30	15	45	7.1	7.8	0.1	3.2	1.5	0.3
1800	30	15	60	5.4	1.8	0.0	3.3	0.8	0.2
1800	30	15	75	21.3	5.8	0.4	5.6	1.4	6.0
1800	45	15	45	8.1	2.5	0.1	5.3	3.0	0.3
1800	45	15	60	5.4	2.5	0.0	6.5	1.4	0.3
1800	45	15	75	76.5	5.9	1.5	9.2	1.0	2.7
1800	60	15	45	8.8	3.7	0.1	8.8	5.4	0.4
1800	60	15	60	0.3	3.5	0.1	11.1	2.8	0.4
1800	60	15	75	88.6	7.8	2.4	12.8	1.7	5.5
1800	30	25	45	5.6	2.5	0.1	6.9	3.7	2.7
1800	30	25	60	5.5	2.4	0.0	7.9	1.8	0.21
1800	30	25	75	75.8	5.8	1.5	10.2	1.1	2.9
1800	45	25	45	8.9	6.6	0.1	11.7	7.3	0.3
1800	45	25	60	39.6	6.2	0.9	16.4	3.9	0.4
1800	45	25	75	71.6	7.0	1.8	16.4	1.2	3.6
1800	60	25	45	10.0	7.4	0.3	16.3	10.4	0.7
1800	60	25	60	90.3	2.0	1.1	21.2	6.0	1.7
1800	60	25	75	90.1	8.6	2.6	21.9	1.84	6.0

Table 87. Simulation results for high yaw angle mid-size vehicle impacts with vertical barrier.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
3800	30	15	45	7.2	0.9	0.0	3.0	1.6	0.2
3800	30	15	60	5.7	1.4	0.0	3.5	0.6	0.3
3800	30	15	75	6.1	0.8	0.0	4.2	0.7	0.2
3800	45	15	45	7.6	0.9	0.1	4.3	2.4	0.2
3800	45	15	60	5.5	1.7	0.1	4.8	0.9	0.3
3800	45	15	75	6.3	0.9	0.0	8.5	0.7	0.2
3800	60	15	45	8.2	0.8	0.0	6.9	4.2	0.5
3800	60	15	60	6.2	0.9	0.0	9.8	2.5	0.1
3800	60	15	75	6.8	1.1	0.0	12.5	0.8	0.2
3800	30	25	45	7.5	1.2	0.1	5.4	3.1	0.2
3800	30	25	60	5.5	1.6	0.1	4.9	1.0	0.3
3800	30	25	75	6.1	0.8	0.0	9.8	0.7	0.2
3800	45	25	45	9.0	0.8	0.0	8.7	5.6	0.5
3800	45	25	60	6.1	0.9	0.0	12.6	3.5	0.1
3800	45	25	75	6.4	0.8	0.0	16.4	0.7	0.2
3800	60	25	45	11.2	0.9	0.1	12.3	8.3	0.6
3800	60	25	60	2.1	1.1	0.0	18.0	5.3	0.1
3800	60	25	75	6.5	0.9	0.0	22.3	0.7	0.2

Table 88. Simulation results for high yaw angle full-size vehicle impacts with vertical barrier.

Vehicle Weight (lb)	Impact Speed (mi/h)	Impact Angle (deg)	Yaw Angle (deg)	Max. Roll Angle (deg)	Max. Pitch Angle (deg)	Max. H. of Climb (in)	Max. 50 ms. Average Acceleration (g's)		
							Long.	Lat.	Vert.
4500	30	15	45	8.6	1.1	0.1	3.2	1.6	0.2
4500	30	15	60	6.5	1.3	0.1	3.6	0.6	0.2
4500	30	15	75	6.8	1.4	0.1	4.0	0.7	0.2
4500	45	15	45	10.9	1.2	0.1	5.2	3.0	0.4
4500	45	15	60	6.1	1.7	0.1	6.1	1.3	0.2
4500	45	15	75	7.0	2.0	0.1	7.9	0.7	0.2
4500	60	15	45	12.1	1.2	0.1	7.3	4.5	0.5
4500	60	15	60	6.7	1.6	0.1	7.1	1.7	0.2
4500	60	15	75	7.3	2.0	0.1	12.3	0.7	0.2
4500	30	25	45	10.8	1.2	0.1	5.7	3.4	0.2
4500	30	25	60	6.1	1.6	0.1	6.5	1.4	0.2
4500	30	25	75	6.7	1.9	0.1	9.2	0.7	0.2
4500	45	25	45	12.0	1.4	0.1	9.3	6.0	0.4
4500	45	25	60	6.0	1.5	0.1	9.3	2.4	0.2
4500	45	25	75	7.0	1.6	0.1	16.1	0.7	0.2
4500	60	25	45	11.9	1.2	0.1	13.1	8.7	0.3
4500	60	25	60	6.2	1.6	0.1	14.3	4.2	0.2
4500	60	25	75	7.2	1.5	0.1	22.7	0.8	0.2

barriers for high impact angle and high yaw angle impacts. Although predicted maximum roll angles and climb heights for the F-shape simulations are somewhat lower than those for the New Jersey shape, these differences do not appear to be significant, as shown in tables 67 through 72. Furthermore, the predicted maximum 50 ms average accelerations appear to be very similar for the two barriers. Based on these simulation findings, it was concluded that the F-shape would not greatly reduce the propensity for rollover arising from high-angle and high yaw angle impacts.

b. Constant Slope Barrier

Findings from the HVOSM simulations show that the single constant sloped barrier appears to offer some improvement in barrier performance for the impact conditions simulated. As shown in tables 73 and 74, the HVOSM program predicted 14 overturn conditions for the constant sloped barrier compared to the 25 predicted for the concrete safety shape, as shown in tables 48 and 53. However, as shown in tables 75 through 80, the simulation predicted high roll angles for several of the constant sloped barrier impact conditions that did not result in rollover. Furthermore, maximum accelerations from constant sloped barrier simulations were generally higher than those from concrete safety shaped barrier simulations. Therefore, although the constant sloped barrier appears to offer some potential advantages over the safety shape, there appears to be room for further improvement in the barrier performance.

c. Vertical Wall

Simulations of vertical wall impacts showed further reductions in the rollover potential when compared to constant slope barrier simulation findings. The HVOSM program predicted only 7 rollover impact conditions as shown in tables 81 and 82. Furthermore, these impact conditions where rollover occurred appeared to be clustered about extreme yaw angle and high-speed impact conditions that may not be common among roadside barrier impacts. For most impact conditions studied, maximum roll angles and height of climb predicted for vertical wall impacts were significantly reduced from levels predicted for the concrete safety shaped barrier impacts as shown in tables 83 through 88. The predicted maximum lateral accelerations were somewhat higher for the vertical wall barrier than the concrete safety shaped barrier, as may be expected. The vertical wall barrier appeared to offer the most effective method for reducing rollovers associated with shaped concrete barriers.

The fact that HVOSM simulations predicted rollover in seven vertical wall impacts serves to emphasize the destabilizing effect of tire side forces when a vehicle is yawing prior to impact. This effect is most pronounced for mini-size vehicles where tire side forces can represent as much as 70 percent of the roll moment required to initiate rollover. Further, the vertical wall rollover predictions reemphasize the fact that the HVOSM program has never been properly validated for these impact conditions. While the HVOSM program is certainly the best available method for analyzing these impacts and it should give reasonably accurate results, there is little evidence with which to validate the program for such unusual impact conditions.

In the interest of comparing the performance of the vertical wall to that of the concrete safety shaped barrier under normal crash test conditions, the baseline simulation runs were repeated with the vertical wall. As shown in table 89, the simulation predicted that the maximum roll angles, pitch angles, and climb heights would be much lower for vertical wall impacts while the maximum lateral accelerations are lower for the concrete safety shaped barrier impacts.

4. Summary

A large simulation effort was undertaken to better define the nature of the concrete safety shaped barrier rollover problem and to evaluate potential improvements to the safety shape. The simulation efforts included:

- Identification of concrete safety shaped barrier performance under common impact conditions.
- Investigation of the importance of factors identified during accident data analysis as potentially causative or contributory to rollover.
- Evaluation of the effectiveness of potential countermeasures to reduce rollover propensity.

Major modifications were made to the HVOSM program in an effort to improve its capability for modeling rigid barrier impacts. Even though the simulation's sheet metal crush and suspension models were significantly improved, its thin disk tire model still limits its usefulness for modeling low-angle impacts. Furthermore, due to a lack of available crash test information, the modified program could not be adequately validated for some important impact conditions, including high-angle and nontracking impacts. However HVOSM is still the best available method for evaluating these impacts and can give potentially valuable insight into problems associated with rigid barrier impacts.

Highlights of the major findings from the simulation studies are summarized as follows:

- A series of 18 baseline simulation runs indicated that safety shaped barriers perform relatively well for moderate angle, tracking impacts.
- A limited simulation study involving 39 computer runs revealed that the HVOSM program is unable to accurately simulate high-speed, low-angle impacts or impacts involving glare screens.

Table 89. Simulation of baseline impacts with vertical wall.

		Impact Conditions		Exit Conditions		Vehicle Parallel to Barrier						Max. 50 MS Average Accelerations (g)		
	Simulation No.	Angle (Deg)	Speed (mi/h)	Angle (Deg)	Speed (mi/h)	Time (Sec) Required	Distance Traveled (ft)	Max. Roll (Deg)	Max. Pitch (Deg)	Max. Height of Climb (ft)	Max. Vehicle Crush (in)	Long.	Lat.	Vert.
Honda Civic	1	15	60	3.66	54.21	0.152	12.52	10.12	1.24	0.06	11.0	-3.59	- 7.49	0.42
	2		45	3.17	40.64	0.186	11.49	6.07	0.85	0.04	10.0	-2.54	- 5.29	0.25
	3		30	1.96	27.09	0.293	12.02	3.14	0.35	0.02	8.6	-1.40	- 2.91	0.10
	4	25	60	6.68	48.27	0.154	11.58	19.52	3.30	0.55	16.6	-8.84	-12.39	-1.47
	5		45	5.08	36.08	0.191	10.75	9.85	2.29	0.08	15.2	-6.45	- 8.99	0.46
	6		30	3.71	23.88	0.292	5.81	4.75	1.31	0.03	13.4	-3.82	- 5.30	0.20
Dodge Coronet	1	15	60	4.53	54.65	0.149	12.41	4.76	0.17	0.03	10.6	-2.41	- 6.42	-0.58
	2		45	- - -	- - - -	- - - -	- - - -	- - - -	- NC* -	- - - - - -	- - - - - -	- - - -	- - - -	- - - -
	3		30	1.15	27.36	0.305	12.65	5.02	0.40	0.03	7.7	-1.02	- 2.20	0.18
	4	25	60	0.27	48.98	0.150	11.50	7.42	0.69	0.07	16.9	-6.20	- 9.51	-1.08
	5		45	2.20	36.62	0.196	11.25	6.89	0.22	0.03	14.7	-4.37	- 6.60	-0.67
	6		30	0.00	25.07	0.308	11.87	7.63	1.43	0.11	12.2	-2.67	- 3.92	-0.51
Plymouth Fury	1	15	60	1.47	54.67	0.155	12.90	5.51	0.47	0.04	10.9	-2.45	- 6.16	-0.58
	2		45	1.79	40.95	0.203	12.66	5.05	0.52	0.03	9.6	-1.71	- 4.28	-0.39
	3		30	2.33	27.28	0.327	13.64	5.28	0.57	0.02	8.0	-1.03	- 2.18	-0.09
	4	25	60	1.98	48.95	0.154	11.79	7.55	0.55	0.05	17.3	-6.35	- 9.65	-1.21
	5		45	2.40	36.59	0.203	11.63	7.76	0.71	0.03	15.1	-4.47	- 6.68	-0.88
	6		30	3.63	24.25	0.327	12.41	7.40	0.94	0.03	12.5	-2.71	- 3.95	-0.31

*Nonconvergence

- High angle impacts and high yaw angle, low yaw rate impacts were shown to be potential contributors to the rollover propensity of concrete safety shaped barriers with a more extensive effort involving 87 computer simulations.

- Three alternate shapes were evaluated as potential countermeasures to reduce rigid barrier rollover rates. A series of 300 simulation runs indicated that:

    - The F-shape barrier offers little performance improvement over concrete safety shaped barrier for these impact conditions.

    - A single constant slope barrier with an 80 degree slope offers some rollover reductions while increasing lateral vehicle accelerations.

    - A vertical wall barrier offers the greatest reduction in rollover potential, but also 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 in most cases while increasing lateral accelerations.

VI. CONCLUSIONS AND RECOMMENDATIONS

An extensive and comprehensive effort was undertaken in this study to: (1) determine the extent of the rollover problem associated with concrete safety shaped barriers, (2) identify causative or contributory factors associated with rollovers in concrete safety shaped barrier impacts, and (3) identify and evaluate potential countermeasures to reduce shaped concrete barrier rollovers. The study consisted of a critical review of available literature; statistical and clinical analysis of four accident data files; and computer simulations. Some limited laboratory testing and one full-scale crash test were also conducted in the study. The major findings and conclusions of the study are summarized in section 1 and discussed in section 2 together with recommendations.

1. Findings and Conclusions

The findings and conclusions are divided into three major headings in accordance with the study objectives:

- Extent of rollover problem.
- Causative or contributory factors.
- Potential countermeasures.

a. Extent of Rollover Problem

Rollover occurred in 8.5 percent of the accidents involving concrete safety shaped barriers. This is somewhat lower than the rollover rate reported previously. However, much of the difference could be attributed to the difference in the proportion of smaller cars between the study areas.

A significant proportion of the rollovers was found to be unrelated to the barrier properties in the clinical analysis of NASS LBSS accident cases. While the LBSS accident cases were not sampled on a representative basis so that the proportion is not meaningful in an absolute term, it nonetheless points out that some of the rollover accidents associated with concrete safety shaped barriers are actually not related to the barrier itself and would have occurred independently of the barrier type under similar accident conditions. This in effect reduces the extent of the rollover problem for concrete safety shaped barriers that can be treated by countermeasures.

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

b. Causative or Contributory Factors

Police level accident data, even with manual review of hard copies of the police accident reports, are not detailed enough for identification of factors that are causative or contributory to rollovers on concrete safety shaped barriers. Analysis of police level accident data identified only a few factors that are correlated with rollover involvement.

- The rollover rate is found to be lower under adverse weather and surface conditions. This may be attributed to the lower coefficient of friction under wet or snowy/icy surface conditions which reduces the buildup of large side forces or tripping of the vehicles.
- The rollover rate is found to be lower for vehicles that are skidding or rotating prior to impact with the barriers. Clinical review of the NASS LBSS accident cases confirmed this finding.
- There is a definite relationship between vehicle size and weight and rollover involvement. The rollover rate of smaller and lighter vehicles is much higher than their heavier and larger counterparts. Much of the problem can be attributed to the less stable nature inherent in the smaller vehicles, such as narrower track width and lower roll moment of inertia. However, the less stable nature of the smaller vehicles is further aggravated by the shape of the concrete safety shaped barrier, particularly the lower sloped surface which gives the impacting vehicle a large upward force upon impact.

Clinical analysis of the NASS LBSS accident cases provided much more information and insights into potential causative or contributory factors for rollover, despite the small sample size. The following three impact conditions were identified as potential factors:

- High impact angle and moderate to high impact speed.
- High slip angle, low to moderate yaw rate and moderate to high impact speed. (Note that vehicles that are rotating at impact, i.e., with a high yaw rate, are less likely to result in rollovers).
- High impact speed and low impact angle for vehicles in a tracking mode.

Results from the simulation studies support the findings from the accident studies that high angle impacts and high slip angle, low to moderate yaw rate impacts are potential contributors to rollover propensity. However, the simulation program cannot accurately simulate high-speed, low-angle impacts and the effect of this impact condition on rollover propensity was not evaluated in the simulation study. It should be noted that safety shaped barriers perform relatively well for the majority of impact conditions, i.e., moderate angle, tracking impacts, as indicated by a series of baseline runs.

c. Potential Countermeasures

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

Three alternate shapes were selected for evaluation as potential countermeasures to reduce rigid barrier rollover rates: (1) F-shape, (2) constant slope barrier, and (3) vertical wall. Each of these alternate shapes were evaluated through simulation of impact conditions that have been identified as potential contributors to rollover for the standard concrete safety shaped barrier. Results of the evaluation indicated that:

- The F-shape barrier offers little performance improvement over concrete safety shaped barrier for these impact conditions.
- The constant slope 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 also 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 in most cases, but also the higher lateral accelerations than the standard concrete safety shaped barrier under these impact conditions.

2. Discussions and Recommendations

While 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 other factors, such as damages to impacting vehicles and potential for injuries to the vehicle occupants as well as operational factors, such as cost and maintenance requirements.

The constant slope surface barrier may provide the best compromise solution. It reduces the propensity for rollover when compared to the standard safety shaped barrier while showing less increase in the lateral accelerations, a surrogate for damages to the impacting vehicles and injury potential for vehicle occupants, than the vertical wall barrier. The initial construction cost should be the same or less than the standard safety shaped barrier, but substantially less in terms of maintenance costs.

In order to maintain the shape and height of the barrier for the standard safety shaped barrier, the pavement surface has to be first lowered before any overlay can be applied to provide a new wearing surface. This is an expensive outlay over the life of the pavement and the barrier. On the other hand, a constant slope surface barrier can be built to a greater height initially, e.g., 42 in, than the standard 32-in height for standard safety shaped barrier. Up to 10 in of overlay, e.g., five overlays of 2 in each, can be applied over the years without affecting the shape or the minimum height of the barrier. A study is currently underway to develop such a constant slope surface barrier for use by the Texas State Department of Highways and Public Transportation.

However, in order to properly compare the overall effectiveness between various barrier shapes, a benefit/cost analysis taking into account all the various factors as discussed above is needed. Baseline, high angle, and high yaw rate simulation runs should provide a basis for determining 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 of barrier impact conditions that can be expected along various highway types.

Police level accident data are found to be inadequate for addressing such specific issues as impact conditions and factors causative or contributory to rollovers on concrete safety shaped barriers due to lack of detailed information. Despite the small sample size, clinical analysis of in-depth accident cases provided much more insight and information into this rollover problem. Considerations should be given to further analysis of the NASS LBSS data file for similar information on other barrier types and perhaps a similar data collection effort to gather such data for future evaluations and studies.

Computer simulation is the best available method for analyzing rigid barrier performance under unusual impact conditions and potential countermeasures. Although major improvements were made to the HVOSM simulation program under this and other studies, the program has one remaining major modeling limitation. The thin disk tire model severely limits the usefulness of the program to evaluate high-speed, low-angle impacts and those involving shaped concrete barriers with glare screens. Additional research is needed to improve this portion of the HVOSM simulation program. Full-scale crash testing should be conducted to verify the simulation findings reported above and provide a means of validating the HVOSM model itself.

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