NCHRP

REPORT 794

NATIONAL
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PROGRAM

Median Cross-Section Design for Rural Divided Highways

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By B. Ray Derr
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This report presents guidelines for designing typical cross-sections for medians on new and existing rural freeways and divided highways. The report examines the interrelationships between median width, median slope, and the use of median barrier on crash risk and severity. The report should be useful to designers and safety analysts, particularly those responsible for agency standards.

The AASHTO *Policy on Geometric Design of Highways and Streets* contains general median width and median side-slope design guidance that has remained unchanged for many years. However, changes have occurred in the vehicle fleet, travel speeds, and traffic volumes that warrant further examination of this guidance. Concern with rollover crashes has caused many state departments of transportation (DOTs) to flatten their depressed medians. More recently, highly visible cross-median crashes have caused many state DOTs to increase their use of median barrier beyond the recommendations in the AASHTO *Roadside Design Guide*. There is speculation that flatter medians have contributed to the cross-median problem, but the data do not present a clear picture. Installation of median barrier reduces the number of cross-median crashes but increases the number of fixed-object crashes. Understanding how different median cross-section designs influence different types of crashes is vital in making safe and cost-effective decisions for state design standards and for project design.

In NCHRP Project 22-21, MRIGlobal, in association with the Pennsylvania State University, updated the survey of state practice developed in NCHRP Project 17-14, including the types of barrier being installed and the policies for their installation. The research team also compiled information on typical median cross-sections for new construction and reconstruction projects. Based on the literature, the researchers identified design, traffic, and human factors that influence median and roadside safety. The research team then collected field data to assess the safety and cost-effectiveness of various median cross-section designs. Simulations of median encroachments were also made to evaluate the contributions of the various factors to cross-median crashes.

C O N T E N T S

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

SUMMARY

Median Cross-Section Design for Rural Divided Highways

The AASHTO *Policy on Geometric Design of Highways and Streets*, commonly known as the Green Book, contains general median width and median side slope design guidance that has remained unchanged for many years. Crashes where a vehicle crosses the median and continues into the opposing lanes are often very severe. Concern with rollover crashes has caused many state highway agencies to flatten their depressed medians. More recently, Chapter 6 of the AASHTO *Roadside Design Guide* was revised in 2006 to increase the range of situations in which use of median barrier is considered. There is speculation that flatter medians have contributed to cross-median crashes, but the data do not present a clear picture. Understanding how different median cross-section designs influence different types of median-related crashes is vital in making safe and cost-effective decisions for state design standards.

The objective of this research was to develop improved guidelines for designing median typical cross sections (i.e., width, slope, and barrier) on new and existing rural divided highways. The scope of the research focused on the medians of rural freeways (i.e., facilities with full access control), but rural nonfreeway facilities also were considered. The research included review of current literature on median design guidelines and studies of the safety of various median designs and median barrier effectiveness. A survey on state practices in median design also was conducted. Crash analysis and simulation of vehicle incursions into medians of various design were conducted. Consideration of the results of both the crash analysis and the simulation of vehicle incursions provided a complete picture of the effects of each design variable on overall median safety and cost-effectiveness.

Median Width

The crash analysis results for fatalities and injuries on rural four-lane freeways generally indicate that cross-median crashes (CMCs)—crashes that involve a vehicle crossing the median, entering opposing traffic, and colliding with an opposing-direction vehicle—decrease with wider medians, while rollover crashes generally increase with wider medians. These two effects are of almost equal magnitude, but in opposite directions.

The crash analysis shows a monotonic relationship between crashes and median width, suggesting that CMCs would keep decreasing and rollover crashes would keep increasing continuously as the median width increases. The results of the vehicle dynamics simulation show a more subtle interpretation of this relationship. Specifically, the vehicle dynamics simulation results indicate that, at a median width in the range from 15 to 18 m (50 to 60 ft), there is a boundary at which the probability of a CMC becomes less than the probability of a rollover crash. This suggests that when the lower severity of rollover crashes is taken into account, there are diminishing returns in continuing to make the median wider.

Median Slope

The crash analysis indicates that the median slope ratio also has opposing effects for CMC and rollover crashes, but that these opposing effects for median slopes are opposite to the effects for median width. Crash prediction models for rural four-lane freeways show that flatter slopes are associated with more CMCs and fewer rollover crashes. The models indicate that flatter slopes on rural four-lane freeways also are associated with fewer fixed-object crashes.

The vehicle dynamics simulation analysis again provides a more complete understanding of the subtleties of median slope effects, as it did for median width effects. In this case, the vehicle dynamics simulation results show an interaction between median slope and median width not evident in the crash analysis results. For median slopes in the range from 1V:4H to 1V:7H, the boundary between medians for which CMCs are most prevalent, and those for which rollover crashes are most prevalent, falls in the median width range from 15 to 17 m (50 to 55 ft). For median slopes of 1V:8H or flatter, that boundary falls at 18 m (60 ft). Thus, the vehicle dynamics simulation results indicate that the concerns about high-severity CMCs are of greatest concern for median widths less than 18 m (60 ft) and for median slopes steeper than 1V:8H. Furthermore, the vehicle dynamics simulation results suggest that the likelihood of CMCs does not continue increasing as the median slope becomes flatter than 1V:8H.

Median Barriers

Crash prediction models developed for traversable and barrier medians can be used to estimate the safety differences between these median types with various geometric characteristics and barrier types. In addition, a before/after evaluation of median barrier installation estimated crash modification factors (CMFs) for flexible, semi-rigid, and rigid median barriers. The analysis results show that flexible barriers (i.e., cables), semi-rigid barriers (i.e., steel guardrail), and rigid barriers (i.e., concrete) can all be cost-effective in reducing crashes under appropriate conditions. A benefit-cost analysis shows that all of these barrier types can be cost-effective under appropriate conditions in reducing severe CMCs, while increasing less severe crashes of other types.

Flexible median barriers may be cost-effective even at lower traffic volumes than shown in current AASHTO median barrier warrants.

CHAPTER 1

Introduction

1.1 Background

The AASHTO *Policy on Geometric Design of Highways and Streets* (*1*) contains general median width and median side slope design guidance that has remained unchanged for many years, not recognizing the dramatic changes that have occurred in vehicle fleet, travel speeds, and traffic volumes. Concern with rollover crashes has caused many state highway agencies to flatten their depressed medians. Recently, Chapter 6 of the AASHTO *Roadside Design Guide* (*2*) has been revised to increase the range of situations in which use of median barrier is considered. There is speculation that flatter medians have contributed to the cross-median problem, but the data do not present a clear picture. Certainly, installation of median barrier reduces the number of cross-median crashes but increases the number of fixed-object crashes. Understanding how different median cross-section designs influence different types of crashes is vital in making safe and cost-effective decisions for state design standards and project design.

NCHRP Project 17-14, Improved Guidelines for Median Safety, attempted to develop guidelines for using median barrier and selecting median widths and slopes. Unfortunately, collection of data needed for Project 17-14 proved to be very expensive, and the data limitations hampered the strength of the recommendations.

To avoid some of the obstacles that Project 17-14 faced, Project 22-21, Median Cross-Section Design for Rural Divided Highways, focused on typical cross-section designs selected for a construction or reconstruction project rather than the exact cross-section design at a particular point. The typical cross-section designs are determined fairly early in the design process before adjustments are made to account for variations that occur along the alignment (e.g., horizontal and vertical curves, interchanges and intersections, and special drainage requirements).

A related project, NCHRP Project 22-22, Placement of Traffic Barriers on Roadside and Median Slopes, will furnish additional guidance on the placement of median barriers.

1.2 Research Objectives and Scope

The objective of this research was to develop improved guidelines for designing median typical cross sections (i.e., width, slope, and barrier) on new and existing rural divided highways. Traffic volumes, clear zones, and drainage were considered. The guidelines are suitable for inclusion in the AASHTO *Roadside Design Guide* (*2*) and the AASHTO *Policy on Geometric Design of Highways and Streets* (*1*).

The scope of the research addressed the design of medians on rural divided highways. The research focused on the medians of rural freeways (i.e., facilities with full access control), but rural nonfreeway facilities also were considered. However, intersection areas on nonfreeway facilities were not considered, because such intersections are being addressed in a separate research effort in NCHRP Project 15-30, Median Intersection Design for Rural High-Speed Divided Highways. The issue of barrier end treatments at divided highway intersections was considered outside the scope of the research.

The primary focus of the research was on documenting the safety performance of, and developing design guidelines for, traversable medians with no barrier and nontraversable medians with barriers because they appear to present the greatest design challenges and the greatest need for re-examination of current design policies. Nontraversable medians with no barriers (e.g., medians with trees or natural obstructions) were not considered in the research.

1.3 Organization of This Report

This report presents an overview of the work conducted in the project. The subsequent chapters of this report are organized as follows. Chapter 2 describes the review of current median design guidelines, review of studies on the safety of median designs, state highway agency median safety research, and median barrier effectiveness evaluations. Chapter 3 summarizes the survey of state practice on median design and safety. Chapter 4 discusses the safety analysis of traversable medians and the safety analysis of medians with barrier. Chapter 5 details the simulation of vehicle encroachments on medians. Chapter 6 discusses a benefit-cost comparison of median design alternatives. Chapter 7 presents the guidelines for median cross-section design and the conclusions and recommendations of the research.

Appendixes to this report are not published herein, but are available on the project webpage and can be found by searching the TRB website for NCHRP Report 794. The 2003 state-of-the-practice survey questionnaire used in NCHRP Project 17-14 is presented in Appendix A. The 2006 survey questionnaire used in this project is presented in Appendix B. Appendix C presents the logic used in each state to categorize median-related crashes. Appendix D discusses an approach to digital terrain mapping developed by MRIGlobal's subcontractor, Pennsylvania Transportation Institute (PTI); this approach was used in the field to collect data on median side slopes and offset of median barriers. Appendix E details the benefit-cost analysis.

CHAPTER 2

Literature Review

2.1 AASHTO Median Design Guidelines

The AASHTO *Roadside Design Guide* (*2*) and the AASHTO *Policy on Geometric Design of Highways and Streets* (commonly referred to as the Green Book) (*1*) contain guidelines for the design of medians on divided highways. Included are guidelines related to median width, median cross-slopes, and median barrier warrant and placement criteria. This literature review examines and synthesizes existing median design policies and research related to them.

The most recent update to the AASHTO *Roadside Design Guide* (*2*) was made in 2006. This update references the performance requirements for median barriers and contains guidelines for selecting and installing an appropriate barrier system. Characteristics of median barrier systems are included in this update.

This section describes the guidance outlined by AASHTO policies regarding median width, median side slopes, approved median barriers, and median barrier placement guidelines.

2.1.1 Median Width

The median width is a linear dimension between the edges of the traveled way on divided highways, including the left shoulders. Functionally, medians are intended to separate opposing traffic, provide a space for emergency stopping, provide a recovery area for out-of-control vehicles, allow space for speed changes and storage of left-turning and U-turning vehicles, minimize headlight glare, and provide width for future lanes (*1*). General guidance suggests that median widths should range between 1.2 to 24 m (4 to 80 ft). Depressed medians are generally suggested on freeways. Widths greater than 12 m (40 ft) are intended to provide drivers with a sense of separation from traffic traveling in the opposing lanes.

Median widths between 15 to 31 m (50 to 100 ft) are common on rural freeways. Such a dimension is easily achievable in areas with level terrain with no right-of-way restrictions and where alignments are often parallel. In rural areas with rolling terrain, independent vertical profiles commonly are used to blend the freeway into the environment. Again, wide median widths are achievable. Narrow median widths (3 to 9.1 m [10 to 30 ft]) may be needed in mountainous terrain or where right-of-way restrictions dictate.

In certain instances, the median width guidelines set forth in the AASHTO Green Book (*1*) may not be obtainable. Alternatively, cross-median crashes may occur frequently although the design guidelines are adhered to closely. In either case, median barriers are used to prevent cross-median crashes at narrow median sites. Median barrier warrant criteria are provided in the previous edition of the *Roadside Design Guide* (*3*) and are considered for application based on combinations of median width and average daily traffic volumes. Figure 2-1 shows these criteria. For median widths up to 9 m (30 ft) and traffic volumes greater than 20,000 vehicles per day, median barrier is typically evaluated. Between 9 to 15 m (30 to 50 ft), regardless of average daily traffic (ADT) volumes, median barrier is considered optional. For medians greater than 15 m (50 ft), median barrier is not normally considered (*2*).

The median barrier warrant criteria shown in Figure 2-1 are for high-speed, controlled-access highways that have traversable median slopes. In the "Barrier Optional" region of Figure 2-1, a cross-median crash problem may dictate the need for median barrier.

The guidelines for median barriers for high-speed, fully controlled-access roadways were updated in the new edition of the AASHTO *Roadside Design Guide* (*2*) in 2006 and are shown in Figure 2-2. These revised guidelines recommend median barrier on high-speed, fully controlled-access roadways when the median is 9 m (30 ft) in width or less and the average daily traffic is greater than 20,000 vehicles per day. For locations with median widths less than 15 m (50 ft) and where the ADT is less than 20,000 vehicles per day, a median barrier is optional. For locations where median widths are

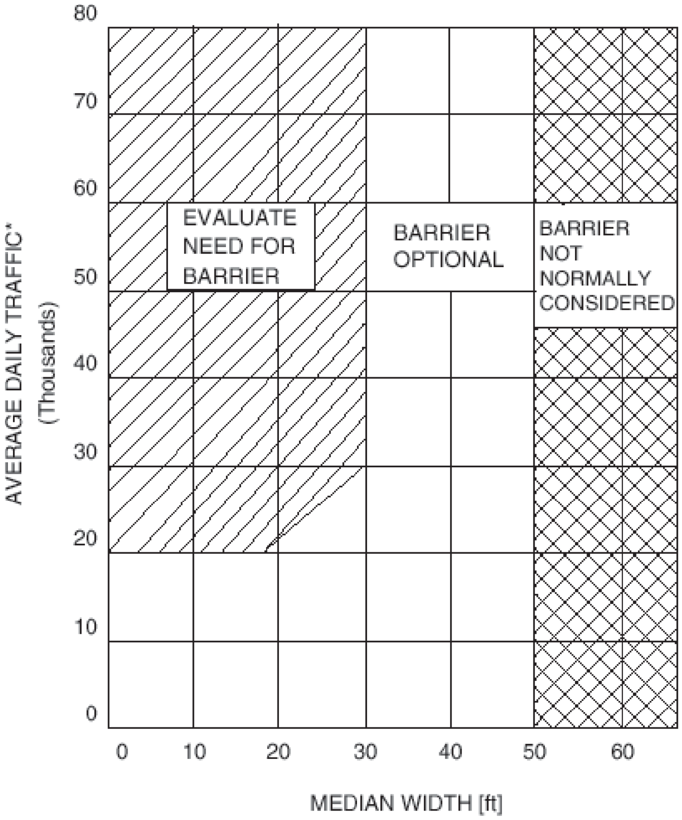


Figure 2-1. Median barrier warrant criteria from 2002 AASHTO* Roadside Design Guide *(3).

greater than 9 m (30 ft) but less than 15 m (50 ft) and where ADT is greater than 20,000 vehicles per day, a median barrier should be considered. Studies in determining a need for median barrier in these circumstances can include cost/benefit analysis or an engineering study evaluation considering such factors as traffic volumes, vehicle classifications, median crossover history, crash incidents, vertical and horizontal alignment relationships, and median/terrain configurations. Where median widths are greater than 15 m (50 ft) a barrier is not normally considered except in special circumstances such as a location with significant history of cross-median crashes.

2.1.2 Median Side Slopes

Median slopes are designed to provide adequate drainage channels to convey storm run-off between opposing directions of travel, and to provide a traversable recovery area for errant vehicles that leave the roadway to the left of the travel lanes. To accomplish these objectives, the Green Book (*1*) recommends 1V:6H side slopes. Steeper slopes (e.g., 1V:4H) may be adequate. Slopes flatter than 1V:6H are often required when placing longitudinal median barrier on a slope. The cable median barrier, however, is effective on 1V:6H slopes and, some manufacturers claim, even on slopes steeper than 1V:6H.

2.1.3 Median Barrier Types

Longitudinal median barriers may be rigid, semi-rigid, or flexible. Rigidity is measured in terms of the barrier's design deflection distance as determined in a standardized vehicle impact test. Longitudinal median barrier systems approved in the AASHTO *Roadside Design Guide*, Chapter 6—Update (*2*), and their test levels, are shown below:

- Weak-post, W-beam guardrail — TL-3
- 3-strand cable, weak post — TL-4
- High-tension cable barrier — TL-3 or TL-4
- Box-beam barrier — TL-3
- Blocked-out W-beam (strong post) — TL-3 or TL-2
- Blocked-out thrie-beam (strong post) — TL-3
- Modified thrie-beam — TL-4
- Concrete barrier — TL-4 or TL-5
- Quickchange moveable barrier — TL-3

Generally, flexible median barrier systems have lower installation costs than semi-rigid or rigid systems. Flexible systems usually require greater maintenance costs than more rigid systems. Also, the impact forces associated with rigid barriers are much greater on the impacting vehicle than those associated with flexible barriers.

The 2006 edition of the AASHTO *Roadside Design Guide* (*2*) reports that there are currently five high-tension cable barrier systems. Characteristics of these barriers systems are shown in Table 2-1. Each of these systems is proprietary and utilizes a unique post design.

2.1.4 Median Barrier Placement Guidelines

In level terrain, symmetric medians are commonplace. In rolling or mountainous terrain, however, asymmetric medians may be constructed due to topography or environmental constraints. Guidelines for placing median barrier in these cross sections are provided in the AASHTO *Roadside Design Guide* (*2*) and shown in Figure 2-3.

The dimensions in Figure 2-3 are as follows:

- W = median width (ft or m)
- W/2 = one-half the median width (ft or m)
- S2 = left median side slope
- S3 = right median side slope
- a, b, c, d, e = median barrier placement locations

Section I of Figure 2-3 shows guidelines for depressed medians; Section II shows placement illustrations for medians with significant traveled way elevation differences; Section III illustrates raised median barrier applications.

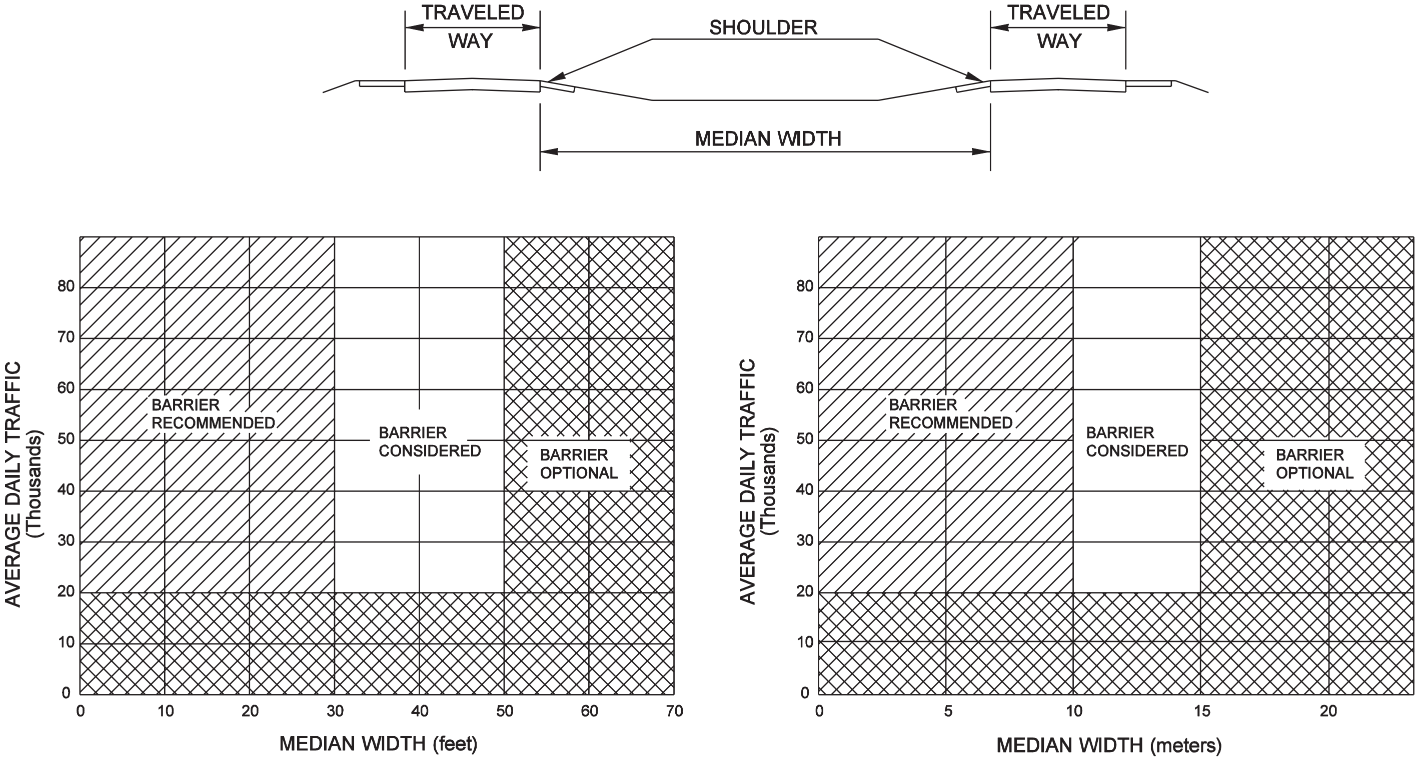


Figure 2-2. Guidelines for median barriers on high-speed, fully controlled-access roadways from 2006 AASHTO **Roadside Design Guide** ***(2).***

Table 2-1. Characteristics of high-tension cable barrier systems.

Cable Barrier Characteristics						
Cable barrier name	**No. of cables**	**Cable heights**	**Date of earliest installation**	**Crash tests**	**Dynamic deflection**	**Slope requirement***
Standard[a]	3	Top: 30 in Middle: 26 in Bottom: 21 in		TL-4	11.5 ft	up to 1V:6H
Brifen[b]	4	Top: 36.5 in 3rd: 30.5 in 2nd: 25.0 in 1st: 19.0 in	2000	TL-4	Small car: 4.25 ft Pickup: 7.25 ft	up to 1V:6H
Trinity CASS	3	Top: 29.5 in Middle: 25.0 in Bottom: 21.0 in	2003	TL-4	Pickup: 7.7 ft	up to 1V:6H
Gibraltar	3	Top: 39 in Middle: 30 in Bottom: 20 in	2005	TL-4	Car (Geo Metro): 2.5 ft Truck (GMC Sierra): 8.6 ft	up to 1V:6H
Safence	4	Top: 36.5 in 3rd: 30.5 in 2nd: 25.0 in 1st: 19.0 in		TL-3	Small car: 3.7 ft Pickup: 5.9 ft	up to 1V:6H
U.S. High-Tension Cable System	3	Top of post: 33.0 in Top cable: 29.5 in Middle cable: 25.5 in Bottom cable: 21.5 in	2002	TL-3	Pickup: 6.5 ft	up to 1V:6H

[a] As in the *Roadside Design Guide*.
[b] Measurements only found for TL-4 traffic barrier.
*Note: No documentation on 1V:4H slope.

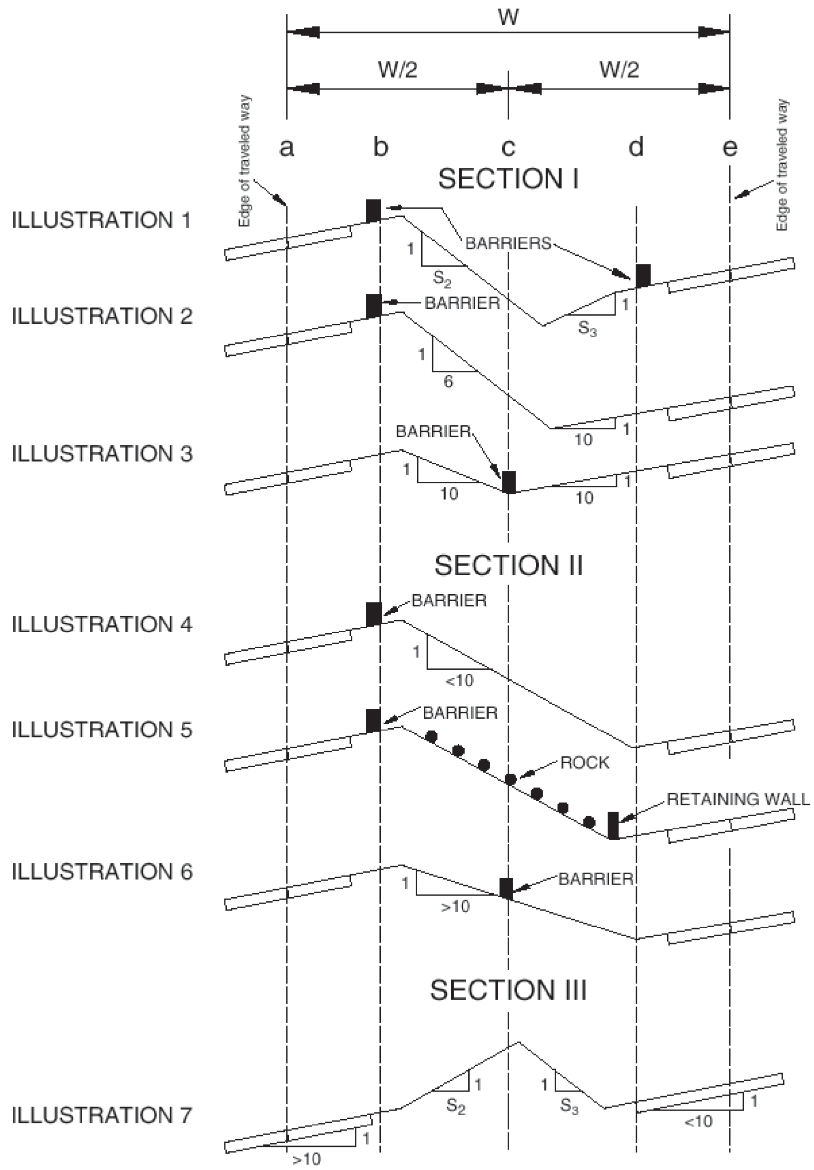


Figure 2-3. Median barrier placement guidelines (2).

A roadside barrier may be required either to prevent errant vehicles from colliding with a fixed object in the median or to prevent vehicles from overturning when traversing the slope. Placement locations "b" and "d" in Figure 2-3 are at the edge of the inside (or median) shoulder and are intended to prevent errant vehicles from encroaching onto the median slope. Reasons for placing barriers at such locations vary; however, the most common reasons are that fixed objects are located on the slope or the median slope(s) are not traversable. Placement location "a" is at or near the center of the median—barriers can be placed at such a location when the risk of a vehicle overturning is low. Median barriers perform best when the impacting vehicle has all wheels on the ground.

2.2 Review of Median Safety Studies

Past research on median safety has investigated either the factors that caused vehicle encroachments or median crash frequency or severity. Additionally, early cross-median crash analysis was performed using simulation models. The following sections summarize the history of median safety research by reviewing past encroachment and crash studies, as well as simulation studies. Research related to median barrier type and side slope design also is included in the following sections. Last, several state transportation agencies use median barrier warrants that are not the same as those recommended in the AASHTO *Roadside Design Guide* (*2*). The research or engineering studies used to establish the warrants are presented.

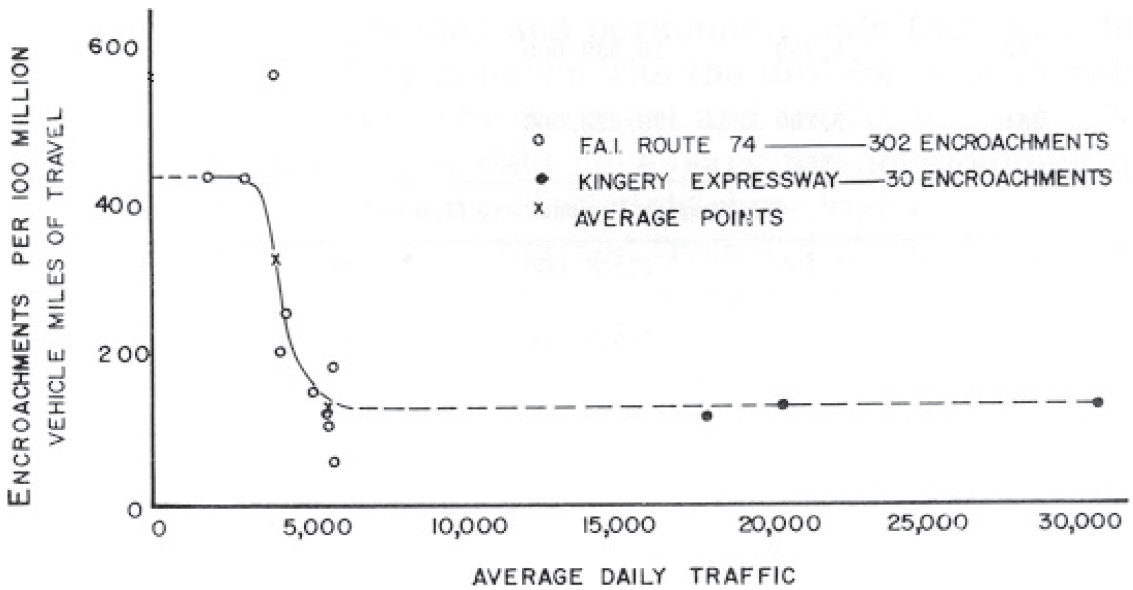


Figure 2-4. Encroachment rate for Interstate 74 and Kingery Expressway (4).

2.2.1 Encroachment Studies

Early median safety studies sought to determine and quantify factors that caused vehicle encroachments into the median area on divided highways. In the early 1960s, Hutchinson and Kennedy (*4*) studied vehicle encroachments along I-74 and the Kingery Expressway (I-57) in Illinois. Each facility was a four-lane divided highway. I-74 had a depressed median width of 12 m (40 ft) while the Kingery Expressway had a depressed median width of only 5.5 m (18 ft). After 6 years of data collection, four relationships were observed, each containing ADT as one-half of the relation. One of the relationships examined was ADT versus encroachment rate, which is based on encroachments per 100 million vehicle-miles traveled. It was shown that for ADT volumes of 4,000 vehicles per day and less, the encroachment rate was stable and slightly above 400 per 100 million vehicle-miles traveled. As the ADT increased from 4,000 to 5,000 vehicles per day, there was a sharp decline in the encroachment rate to approximately 150 encroachments per 100 million vehicle-miles traveled. As the ADT volume continued to increase, the encroachment rate then stayed relatively constant at 150 encroachments per 100 million vehicle-miles traveled. Figure 2-4 shows the relationship between ADT and encroachment rates.

The driving environment was considered a primary reason for the fluctuation in encroachment rates in relation to traffic volumes. At low traffic volumes, drivers are less attentive. There is more freedom of movement within the travel lanes and the only restrictions are the physical features of the roadway (*4*). Therefore, it is likely that vehicles tend to sway off the traveled way and eventually into the median area. As traffic volumes increase, driver alertness also increases and the percentage of "lateral veering" vehicles is greatly reduced because of the decreased vehicle spacing within the traffic stream. In addition, with the presence of other vehicles, a "follow-the-leader" phenomenon results in which vehicles farther back in the traffic stream tend to position in the same vehicle path as those farther downstream.

Another relationship studied by Hutchinson and Kennedy related ADT to the average encroachment angle. As ADT increased from 2,000 to 6,000 vehicles per day, the encroachment angle also increased from 9 to 14 degrees. Figure 2-5 shows the relation between ADT and average encroachment angle. The theory behind these observations is that there is an increase in vehicle conflict as traffic volumes increase. As a result, a driver may suddenly leave the traveled way and

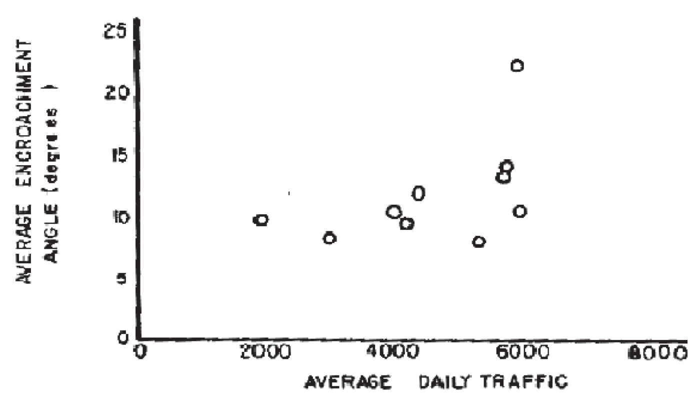


Figure 2-5. Relationship between ADT and average encroachment angle (4).

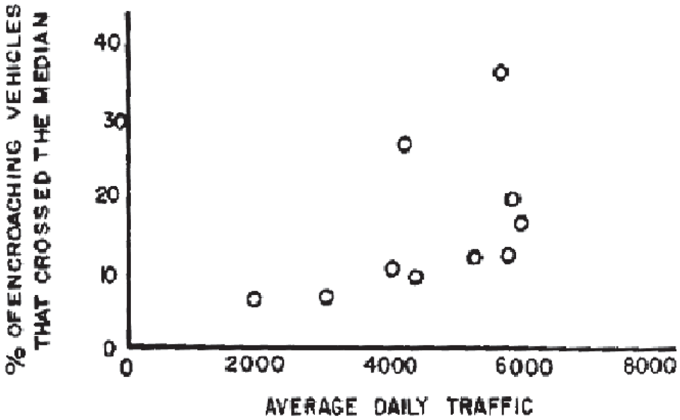


Figure 2-6. Relationship between ADT and percent vehicles crossing into median (4).

enter the median area because another vehicle unexpectedly merges into the occupied lane.

Hutchinson and Kennedy also examined the relationship between ADT and the percent of vehicles that crossed into the median. As shown in Figure 2-6, as ADT increased from 4,000 to 6,000 vehicles per day, the percentage of vehicles crossing into the median increased.

The final relationship studied by Hutchinson and Kennedy was that between ADT and lateral distance traveled by encroaching vehicles on I-74. The ADT volumes range from 2,000 to 6,000 vehicles per day. These vehicles traveled an average of 5.8 to 8.2 m (19 to 27 ft) into the median area over this range of ADTs. This relationship is shown in Figure 2-7.

Beginning in 1976, single-vehicle run-off-the-road accidents on both multilane divided and undivided rural highways were studied in Canada (*5*). Through 1978, a 9-km (5.6-mi) section of an urban freeway in Ottawa was studied that had ADT volumes ranging from 50,000 to 100,000 vehicles per day. With the exception of a 1-m (3-ft) paved shoulder, the median was grass. Over the 2-year study period, 140 encroachments were observed and the results were very similar to those in other studies. The following is a list of the study results obtained by Sanderson:

- Average roadway departure angle for both median and right-side encroachments was 14 degrees.
- Median encroachments were twice as many as right-side encroachments.
- There was a significant disparity between the numbers of encroachments reported to those observed. The ratio between observed and reported median encroachments was 3 to 1, while the ratio for right-side encroachments was 4 to 1.

In 1978, data from several Canadian provinces were collected to investigate single-vehicle run-off-the-road accidents on divided and undivided rural highways. A multiple regression analysis of 1,937 encroachments explained only 30 percent of the variance between accidents and traffic volumes (*5*). Factors such as alcohol, weather, and driver variables were considered to have a significant effect on the models developed. This study showed no significant correlation between ADT volumes and encroachment rates; however, when the data were forced into 2,000 vehicle per day groupings and averaged over a set of ranges, the results were nearly identical to the Hutchinson and Kennedy (*4*) study discussed previously. This study also showed that, on average, the ratio of observed-to-reported accidents was 3.75 to 1 for two-lane undivided highways and 5 to 1 for multilane divided highways.

2.2.2 Crash Studies

Crosby (*6*) evaluated the cross-median crash experience on the New Jersey Turnpike over a 7-year period (1952 through 1958, inclusive). The accident data were from the original 190-km (118-mi) New Jersey Turnpike before the installation of median guardrails. In 1958, 29 km (18 mi) of median guardrail were installed on sections with variable median widths (1.8 to 7.9 m [6 to 26 ft]). The data used for the research were limited to the through travel lanes (excluding those within service areas), interchanges, and their interconnecting roadways and ramps. During the analysis period, 48 of 158 (30.4 percent) fatal crashes were considered cross-median crashes. During the analysis period, there were a total of 455 cross-median crashes. They constituted approximately 8.3 percent of all crashes on the New Jersey Turnpike during the analysis period (455 of 5,473 total collisions). The cross-median crash rate was higher when the medians were narrower.

Garner and Deen (*7*) compared various median types on divided, four-lane Interstate highways with similar geometric features in the state of Kentucky. The two variables that

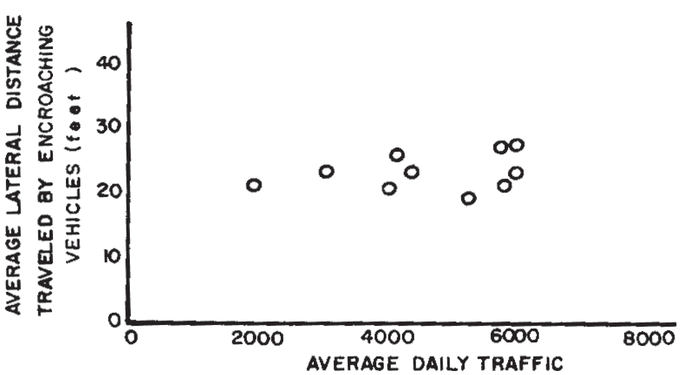


Figure 2-7. Relationship between ADT and encroachment distance (4).

were the primary focus in the study were median width and median cross section. For the routes studied, variables such as pavement width and shoulder width remained constant. The types of medians analyzed in the study were raised, depressed, deeply depressed, and irregular medians.

The results of the Garner and Deen study verified previous conclusions from other researchers that wider medians are safer. Their data indicated that the percentage of vehicles crossing the median decreases as the median width increases. Their data also indicated that the relationship between accident rate and median width was not clear. However, deeply depressed medians had a higher accident rate than raised medians. Garner and Deen suggested that the beneficial effects of wide medians can be offset by steep median side slopes. As such, they recommended slopes of 1V:6H or flatter when the median is 18 m (60 ft) wide. Additionally, median widths of 9 to 12 m (30 to 40 ft) were recommended on high-speed divided highways. However, Garner and Deen also stated that other median elements, such as cross slopes, and the presence of obstructions can have a greater effect on median safety than the width.

Median cross-slopes play a major role in the safety aspects of a median. Deeply depressed medians that have cross slopes of 1V:4H and 1V:3H for an 11-m (36-ft) wide median have been shown to have a significantly higher accident rate than the raised medians for widths of 6, 9, and 18 m (20, 30, and 60 ft). Medians with steep slopes do not provide reasonable recovery areas and are often hazards in themselves (*7*). In addition, steep slopes also increase the likelihood of vehicle rollover. It was shown that the alignments studied with cross slopes of 1V:4H and 1V:3H had 10.3 and 16.5 accidents per 100 million vehicle-kilometers (6.4 and 10.3 accidents per 100 million vehicle-miles) of travel, respectively, but the average accident rates for the alignments with other types of medians were averaged to be 2.08 accidents per 100 million vehicle-kilometers (3.35 accidents per 100 million miles).

The raised median design analyzed in the Garner and Deen study also was shown to have some downfalls. This design seemed to have a higher number of crossover crashes. It was concluded that when drivers hit the median, they tend to overreact, which causes them to lose control of the vehicle. There also are disadvantages associated with raised medians. Raised medians do not provide an adequate storage area for snow removal. Also, water tends to migrate onto the roadway, which allows icy spots to form during cold weather. Garner and Deen also concluded that irregular medians, which have a varying median width and nature, have higher median accident rates, total accident rates, and severity rates.

Foody and Culp (*8*) studied the safety aspects between raised and depressed medians, each having a 2.6-m (84-ft) design width. They observed the accident frequency and severity of single-vehicle accidents of four-lane divided Interstates in Ohio from 1969 to 1971 for each median type. They observed 201 km (125 mi) of highway with the raised median design and 166 km (103 mi) of highway with the depressed median design. The depressed median had side slopes that are 1V:8H. The raised median had 1V:8H foreslopes and 1V:3H backslopes. The study detailed single-vehicle median accidents, accident severity, vehicle path encroachments, and median rollover accidents. The following summarizes the study results obtained by Foody and Culp:

- The accident rate was slightly higher for the raised median than for the depressed median section.
- There was no difference in injury-related accidents between the two median types.
- There was no difference between the two types of medians in the number of median encroachments.
- There was no significance in the difference of rollover frequency between the two median designs.

A study by Kniuman et al. (*9*) investigated median safety using Highway Safety Information System (HSIS) data from Utah and Illinois. In Utah, the total accident rate was found to decline from 404 accidents per 100 million vehicle-kilometers (650 accidents per 100 million vehicle-miles) for medians with zero width to 69 accidents per 100 million vehicle-kilometers (111 accidents per 100 million vehicle-miles) for median widths in the range of 26 to 34 m (85 to 110 ft). In Illinois, the data suggest a similar trend, with an accident rate of 430 accidents per 100 million vehicle-kilometers (692 accidents per 100 million vehicle-miles) for medians with zero width and 33 accidents per 100 million vehicle-kilometers (53 accidents per 100 million vehicle-miles) where the median is 26 to 34 m (85 to 110 ft) in width. It was also reported that the average rate of head-on collisions for median widths greater than 17 m (55 ft) was 0.6 and 1.9 accidents per 100 million vehicle-kilometers (1 and 3 accidents per 100 million vehicle-miles) for the Utah and Illinois data, respectively. For the Utah data, single-vehicle accidents do not decline as the median width is increased from a range between 0.3 to 7 m (1 to 24 ft) to a range between 26 and 34 m (85 and 110 ft). For the Illinois data, single-vehicle accidents were found to decline by almost half as the median width increased from a range of 0.3 to 7 m (1 to 24 ft) to a range of 26 to 34 m (85 to 110 ft). It was also shown that little reduction in accident rate was obtained for median widths in the range of from 0 to 8 m (0 to 25 ft). The most apparent decline in total accident rate was found to occur roughly between 6 and 9 m (20 and 30 ft). For medians between 18 and 24 m (60 and 80 ft), the decline in accident rates seems to level off. All of the previously discussed results can be found in Table 2-2, which is an excerpt from the study results.

Table 2-2. Relationship between median width and accident rate in Utah and Illinois (*9*).

Median width (ft)			Average crash rate (crashes per 100 veh-mi traveled)			
Category	Mean	N	Single vehicle	Head-on	Rollover	Total
			Utah			
0	0.0	176	127	10	14	650
1 to 10	9.4	257	97	10	5	618
11 to 29	14.9	213	89	8	7	462
30 to 54	46.3	52	109	1	29	159
55 to 84	71.7	179	106	1	22	137
85 to 110	101.0	105	93	0	29	111
All	32.0	982	103	6	14	424
			Illinois			
0	0.0	567	86	21	5	692
1 to 24	12.8	199	69	12	8	647
25 to 34	29.8	176	92	3	15	292
35 to 44	39.7	479	51	2	6	129
45 to 54	49.2	200	61	2	7	127
55 to 64	63.8	450	27	1	3	45
65 to 84	71.9	239	40	1	5	59
85 to 110	88.9	171	36	1	6	53
All	39.4	2481	58	7	6	283

Relationships were developed between the type of collision and the relative effects of the median width. The type of accident most affected by the increase in median width was head-on collisions. For the Utah data, the relative effects were fairly linear. There was an approximate 17 percent decrease in the relative effect of increasing the median width in 3-m (10-ft) increments. For the Illinois data, there was a sharp decline in the relative effect between median widths in the range from 3 to 12 m (10 to 40 ft). The largest decline was in the interval from 3 to 6 m (10 to 20 ft), in which there was a 45 percent decrease in the relative effect of increasing the median width. From 6 to 12 m (20 to 40 ft), the average decline in relative effect of median width was 42 percent. For median widths greater than 12 m (40 ft), the relative effect of increasing the median width for head-on collisions stayed fairly constant around 0.10, equivalent to a 10 percent reduction in the total accident rate.

The validity of the Kniuman results observed from the Illinois and Utah HSIS study is controlled by the variables used. Other variables were either not measured by the database or not used in the final model simply because of the need to limit the model to as few variables as possible (*9*). Other variables that could have been included in the model were median slope, type of traffic, environmental factors, and other geometric factors. The general results of this study indicate that crash rates decrease as the median width increases. It also is apparent from the data that there is little decrease in crash rate for medians less than 6 to 9 m (20 to 30 ft). Therefore, increases in safety effects are not seen until the median reaches at least 6 to 9 m (20 to 30 ft) in width. Even larger safety benefits can be seen for median widths up to 20 to 24 m (65 to 80 ft), at which point the safety effects of increasing median width begin to level off.

Mason et al. (*10*) recently used crash and roadway inventory data to characterize CMCs on Pennsylvania Interstates and expressways. In 5 years, 267 of these crashes occurred where 15 percent resulted in fatalities and 72 percent resulted in injury-type crashes. When compared to all crash types on Interstates and expressways, the severity level of CMC collisions is significantly more severe. Additionally, nearly 63 percent of CMCs occurred during daylight conditions, 58 percent occurred during wet or snow and icy conditions, and 12 percent involved drugs or alcohol usage. Limited field data collection found that median shoulder width, roadway grade, median cross-slopes, the presence and degree of horizontal curvature, presence of roadside obstacles, and vehicle type did not statistically influence CMCs. However, there was preliminary evidence to conclude that the presence of interchange entrance ramps does increase the likelihood of CMCs.

Using the CMC data from Pennsylvania, Donnell et al. (*11*) estimated models of crash frequency for Interstate highways. The model took the form shown in Equation 1.

$$N_{CMC} = 0.2 \cdot e^{-18.203} L \cdot ADT^{1.770} \cdot e^{-0.0165MW} \qquad (1)$$

where

N_{CMC} = number of CMCs per year for one direction of travel

L = segment length (mi)

ADT = average daily traffic (veh/day)

MW = median width (ft)

All of the parameters were statistically significant ($p < 0.0001$). However, the model explained only a relatively low proportion of the variation in CMC frequency. Interpretation of the ADT parameter (1.77) suggests that CMCs are a two-stage process. First, the likelihood that a vehicle loses control and enters the median when traveling in one direction of travel is roughly proportional to the traffic volume (ADT) in that direction. The out-of-control vehicle must than traverse the median, enter the opposing traveled way, and collide with a vehicle traveling in the opposite direction. The likelihood of this occurring should be roughly proportional to the one-way traffic volume (ADT) in the opposing travel lanes. Because the traffic volumes on opposing roadways are typically quite similar on Interstate highways, it seems logical that the likelihood of a CMC be roughly proportional to the square of the one-way ADT. A one unit increase in the median width decreases CMC frequency by approximately 1.7 percent.

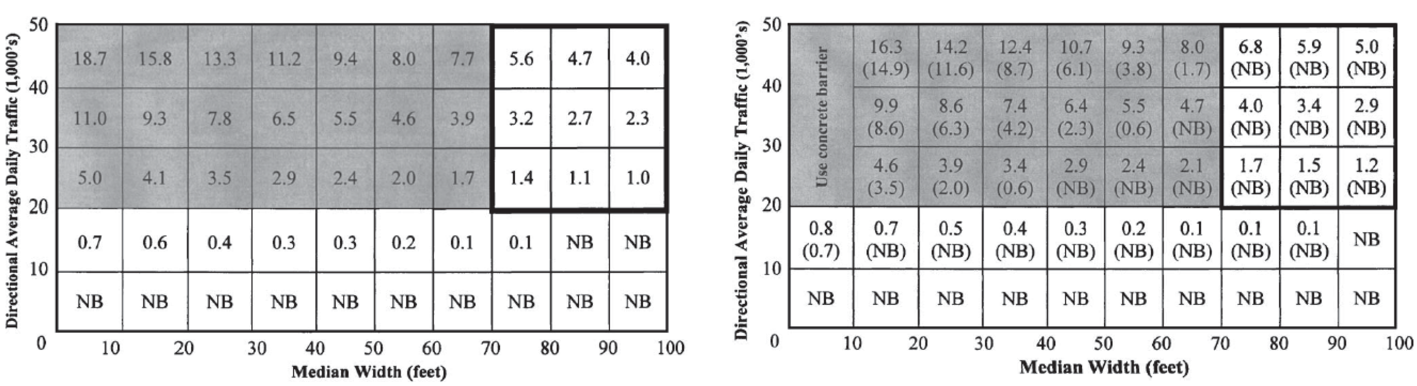
Donnell and Mason (*12*) used negative binomial regression to predict the frequency of median barrier crashes on Pennsylvania Interstate highways. There were a total of 4,416 median barrier collisions that occurred during the 5-year study period (1994 through 1998) on 1,188 km (738 mi) of divided highway protected with a longitudinal barrier. The ADT, presence of an interchange entrance ramp, posted speed limit, horizontal curve indicator, and median barrier offset from the left-edge of the traveled way were all statistically significant predictors of median barrier crash frequency. Curved roadway sections were expected to increase the median barrier crash frequency, holding all other variables constant. A unit increase in the median barrier offset was expected to decrease the median barrier crash frequency by 3.5 percent, holding all other variables constant. A lower posted speed limit was expected to decrease the median barrier crash frequency while the absence of interchange entrance ramp also was expected to decrease the expected median barrier crash frequency, holding all other variables constant.

Donnell and Mason (*13*) predicted the severity of both CMCs and median barrier crashes using crash event and roadway inventory data from Pennsylvania Interstate highways. Three severity levels (fatal, injury, and property damage only [PDO]) were considered. In the CMC severity model, an ordered response was used while multinomial logistic regression was used to estimate median barrier crash severity. In the CMC severity model, the use of drugs or alcohol and the direction of the horizontal curve influenced severity. The predicted probabilities of a fatal CMC were between 9.8 and 24.3 percent when considering the various categories of independent variables. The predicted probabilities of an injury CMC were between 68.1 and 70.5 percent when considering the various categories of the independent variables. The assumption of parallel regression lines was violated when predicting the severity of median barrier crashes. As such, a nominal response was considered. The independent variables that influenced crash severity included pavement surface condition, drug or alcohol use, the presence of an interchange ramp, and ADT. The predicted severity probabilities were as follows:

- Fatal: 0.5 to 0.8 percent;
- Injury: 53.5 to 60.2 percent; and
- PDO: 39.0 to 46.0 percent.

Donnell and Mason (*14*) used both CMC and median barrier crash frequency and severity models to evaluate existing median barrier warrant criteria in Pennsylvania. Interstate highways with and without median barrier were compared using roadway inventory and crash data. The economic evaluation consisted of benefits derived from changes in crash costs and the costs were derived from barrier installation, maintenance, and user costs. The benefit-cost analysis results are shown in Figure 2-8.

In Figure 2-8(a), the concrete barrier was assumed to be installed only in the center of a median. The gray-shaded area represents benefit-cost (B/C) ratios that exceed 1.0 and where the data used in the analysis represent most CMCs and



(a) Concrete Median Barrier

(b) W-Beam Guiderail Median Barrier

NB = No barrier

Figure 2-8. Benefit-cost ratios for median barrier installation (**14*****).***

median barrier crashes. The outlined region also contains B/C ratios that exceed 1.0. The frequency of crashes was very low in the outlined region and, therefore, a site-specific evaluation, using the methodology described, was recommended. In Figure 2-8(b), two numerical values are shown in each cell. The value on top represents the B/C ratio for center placement location, while the value on the bottom represents a 1.2-m (4-ft) offset from the edge of the traveled way. Because the strong post W-beam guiderail used along medians in Pennsylvania has design deflection ranging from 0.6 to 1.2 m (2 to 4 ft), they are not used when the median is less than 3 m (10 ft) wide. The "note" in Figure 2-8(b) represents a condition where no benefits were found by considering a longitudinal barrier. Either the crash severity or frequency did not change enough when comparing the with-without median barrier scenario to show a net benefit in crash cost.

Ulfarsson and Shankar (*15*) estimated a predictive model of median crossover crash frequencies with a multiyear panel of cross-sectional roadway data using data for the State of Washington. The study compared three different count regression models, including: negative multinomial (NM), negative binomial (NB), and random-effects negative binomial (RENB). The results showed that the negative multinomial model outperformed the other two due to the existence of section-specific correlation in the panel. Variables considered in the model included indicator variables for the following conditions:

- ADT less than 5,000 vehicles per day;
- ADT between 5,000 and 10,000 vehicles per day per lane;
- Median width between 9 to 12 m (30 to 40 ft);
- Number of horizontal curves per km;
- Length of section (km) if median width is less than 12 m (40 ft);
- Length of section (km) if median width is between 12 and 18 m (40 ft to 60 ft);
- Length of section (km) if median width is greater than 18 m (60 ft);
- Difference between maximum and minimum shoulder width is greater than 1.2 m (4 ft) and the number of horizontal curves is greater than two per section;
- Roadway friction factor if number of horizontal curves is greater than 0.67 per km (1.08 per mi); and
- Section located (either Interstate Route 90, Interstate Route 205, US Route 2, or State Route 16).

These indicator variables had the value of 0 when the condition specified was not present or not applicable, and had the value of 1 (or a specified length, width, or number of curves) if the condition specified was present or applicable.

A comparison of the model output for NM, NB, and RENB is shown in Table 2-3. The results of the negative multinomial regression model indicate that crash frequencies are lower along road sections with lower traffic volumes. The predicted median crossover crash frequency decreases as the number of horizontal curves per km increases. However, the indicator for the difference between the maximum and minimum shoulder width (greater than 1.2 m [4 ft]) and number of horizontal curves is greater than two per section, suggesting that the crash frequency increases as the curve frequency and shoulder width difference increases. The section length variables were all positive in the negative multinomial model.

Miaou et al. (*16*) presented predictive models of crash frequency and severity as well as B/C analysis results for a cross-sectional with-without median barrier study in Texas. Two years of data (1998 and 1999) were collected from Interstates, freeways, and expressways with four or more lanes and a posted speed limit of 88 km/h (55 mph) or greater.

Only divided highway sections with ADT less than 150,001 vehicles per day were considered in the analysis as were sections with medians between 4.6 to 45.7 m (15 to 150 ft) wide. There were 346 cross-median crashes in 52 Texas counties during the 2-year analysis period. An additional 3,064 median-related crashes were identified on sections with no longitudinal median barrier. There were 3,672 median-related crashes included in the analysis time period along sections with longitudinal median barrier. Of these 3,672 crashes, 2,714 crashes (74 percent) were defined as hit-median-barrier crashes.

The following four median crash types were considered in the frequency and severity models: cross-median crashes on sections with no barrier, other median-related crashes on sections with no barrier, all median-related crashes on sections with a barrier, and hit-median-barrier-only crashes on sections with a barrier. A Poisson-gamma model, using a full Bayes approach, was used to specify and estimate the crash frequency prediction model. The advantage of using such a modeling technique is that it accounts for the uncertainty associated with the model parameter estimates. The roadway inventory and traffic volume variables included in the models were as follows:

- Median width (ft);
- Logarithm of ADT;
- Number of lanes;
- Posted speed limit (dummy variable for 96 km/h [60 mph], dummy variable for 105 km/h [65 mph], dummy variable for 113 km/h [70 mph]); and
- A dummy variable for the year 1999.

Results of the crash frequency modeling effort are shown in Table 2-4. As shown, the median width is negatively

Table 2-3. NM model coefficient estimation results for median crossover accident frequency (*15*).

Variable	NB	RENB	NM
Constant	–1.551 (0.181)†	–0.118 (0.391)	–1.500 (0.251)†
ADT less than 5,000 veh per lane daily, indicator	–1.398 (0.186)†	–1.373 (0.190)†	–1.381 (0.312)†
ADT between 5,000 and 10,000 veh per lane daily, indicator	–0.233 (0.158)	–0.266 (0.157)‡	–0.298 (0.290)
Median width between 30 and 40 ft, indicator	0.463 (0.206)†	0.368 (0.215)‡	0.432 (0.309)
Number of horizontal curves per kilometer	–0.309 (0.128)†	–0.325 (0.141)†	–0.502 (0.262)‡
Length of section (km) if median width is less than 40 ft, 0 otherwise	0.281 (0.047)†	0.278 (0.062)†	0.175 (0.052)†
Length of section (km) if median width is between 40 and 60 ft, 0 otherwise	0.526 (0.065)†	0.502 (0.070)†	0.292 (0.068)†
Length of section (km) if median width is greater than 60 ft, 0 otherwise	–0.358 (0.060)†	–0.343 (0.065)†	0.105 (0.026)†
Difference between maximum and minimum shoulder width is greater than 4 ft and the number of horizontal curves is greater than two per section, indicator	0.542 (0.321)‡	0.489 (0.285)‡	0.486 (0.580)
Roadway friction factor if number of horizontal curves is greater than 1.08 per mi, 0 otherwise	0.011 (0.004)†	0.010 (0.005)†	0.009 (0.006)
Washington State Route 2, indicator	–2.093 (1.098)‡	–1.973 (1.371)	0.271 (0.587)
Washington State Route 16, indicator	–1.338 (0.581)†	–1.290 (0.792)	–1.188 (0.746)
Washington State Route 90, indicator	–0.722 (0.199)†	–0.732 (0.195)†	–0.560 (0.341)
Washington State Route 205, indicator	–1.814 (1.055)‡	–1.756 (1.150)	–8.815 (0.533)†
α	0.447 (0.172)†		0.258 (1.074)
a		128.780 (312.380)	
b		34.514 (90.241)	
ln *L*(□=0, α=1), naïve model	**	**	–827.556
ln *L* at NB values	—	—	–883.746
ln *L* at convergence	–711.931	–715.801	–613.078

Notes: Standard errors are given in parentheses. An “indicator” variable is 1 or a specified quantity if the condition holds and 0 otherwise. The NB and RENB model results presented elsewhere (6) are presented here for comparison with the NM model results.
† = Significance at the 95% level by the two-tailed s-test: ‡ = significance at the 90% level by the two-tailed test.
a,b = parameters of the beta distribution used in the RENB model: ** = information not available.

correlated with crash frequency in all models. This indicates that as the median width increases, the crash frequency decreases.

Ordered multinomial logistic regression models were used to develop crash severity models for all four crash types described previously. The variables considered in these models included the following:

- Five levels of crash severity (K: fatal injury, A: incapacitating injury, B: nonincapacitating injury, C: possible injury, O: property damage only);
- Dummy variable for year 1999;
- Median width (ft);
- Logarithm of ADT;
- Number of lanes; and
- Posted speed limit (dummy variable for 96 km/h [60 mph], dummy variable for 105 km/h [65 mph], dummy variable for 113 km/h (70 mph]).

None of the explanatory variables used in the crash severity models were found to be statistically significant, therefore, the observed crash severity distributions were used in

Table 2-4. Posterior mean and standard error of estimated parameters of Texas median safety crash frequency models (*16*).

Covariate (coefficient)	Crash frequency model: No barrier — Cross-median crashes	No barrier — Other median-related crashes	With barrier — All median-related crashes	With barrier — Hit-median-barrier crashes
Offset = exposure (in MVMT) = v_1 (= 365 * AADT * Segment Length / 1,000,000)	—*	—	—	—
Intercept term				
Overall intercept (β_0)	–3.779 (±0.48)	–2.239 (±0.07)	–1.771 (±0.07)	–1.740 (±0.99)
Dummy variable for 1999: 1 if 1999 and 0 if 1998 (β_1)	1.163 (±0.14)	–0.068 (±0.05)	–0.031 (±0.001)	–0.018 (±0.06)
Median width (in ft) (β_2)	–0.011 (±0.003)	–0.002 (±0.001)	–0.006 (±0.001)	–0.013 (±0.002)
Log (AADT) (β_3) (AADT in 1,000s)	—	—	—	—
Number of lanes (= β_4)	–0.293 (±0.09)	—	—	—
Posted speed limit (mph)				
Dummy variable for 60 mph (= 1 if 60 mph; = 0 if otherwise) (β_5)	–0.139 (±0.54)	–0.342 (±0.17)	–0.575 (±0.08)	–0.063 (±0.10)
Dummy variable for 65 mph (= 1 if 65 mph; = 0 if otherwise) (β_6)	0.500 (±0.16)	–0.126 (±0.06)	–0.075 (±0.07)	–0.188 (±0.09)
Dummy variable for 70 mph (= 1 if 70 mph; = 0 if otherwise) (β_7)	0.284 (±0.18)	–0.079 (±0.07)	–0.007 (±0.07)	0.004 (±0.09)
Inverse dispersion parameter				
Inverse dispersion parameter for this model (Ψ)	0.727 (±0.17)	1.388 (±0.12)	1.956 (±0.16)	1.464 (±0.13)
Inverse dispersion parameter for worst possible model of crash frequency (Ψ_0^{freq})	0.158 (±0.02)	0.429 (±0.02)	(0.466 (±0.02)	0.367 (±0.02)
Goodness-of-fit measures				
Deviance information criterion/sample size (DIC/n)	0.39	1.71	2.54	2.14
$R_{\frac{1}{\Psi freq}} = 1-(1/\Psi)(1/\Psi_0^{freq})$	0.78	0.69	0.76	0.75

Notes: All models were structured using the full Bayes framework with noninformative priors (or hyperpriors). Parameters (β and Ψ) were estimated by using Markov Chain Monte Carlo techniques, and the values shown in the table are their posterior means. Values in parentheses are the estimated one standard error of parameters to their left based on the posterior density of the parameter.
—* indicates not statistically significant at a 10% significance level.

the economic analysis. The severity distributions for each of the four crash types are shown in Table 2-5.

The crash frequency models and severity data were used to estimate B/C ratios for both concrete and high-tension cable median barrier in Texas. Figure 2-9 shows a potential guideline for concrete median barrier based on B/C ratios. As shown, the B/C ratios increase from lower left to upper right. Zone No. 4 includes divided, limited-access roadways with low traffic volumes and the entire range of median widths considered in the study. The B/C ratios in Zone No. 4 were less than 2.0, thus the combination of traffic volume and median width was considered a lower priority for longitudinal barrier consideration than the other zones. Zone No. 1 includes average annual daily traffic volumes between 70,000 and 125,000 vehicles per day and median widths between 0 and 60 ft. In Zone No. 1, various median width–traffic volume combinations

Table 2-5. Texas median crash severity distribution (*16*).

Barrier and crash type	N	K	%	A	%	B	%	C	%	PDO	%
No Median Barrier											
Cross-median	346	73	21.1	73	21.1	82	23.7	58	16.8	60	17.3
Other Median-related	3,046	71	2.3	272	8.9	639	20.9	734	23.9	1,348	44.0
With Median Barrier											
All Median-related	3,672	36	1.0	190	5.2	681	18.5	1,098	29.9	1,667	45.4
Hit-Median-Barrier	2,714	13	0.5	128	4.7	490	18.0	835	30.8	1,248	46.0

(Columns K through % under PDO: Number and percentage of crashes by severity type)

N = total number of crashes
K = fatal
A = Incapacitating injury
B = Nonincapacitating injury
C = Possible injury
PDO = Property damage only

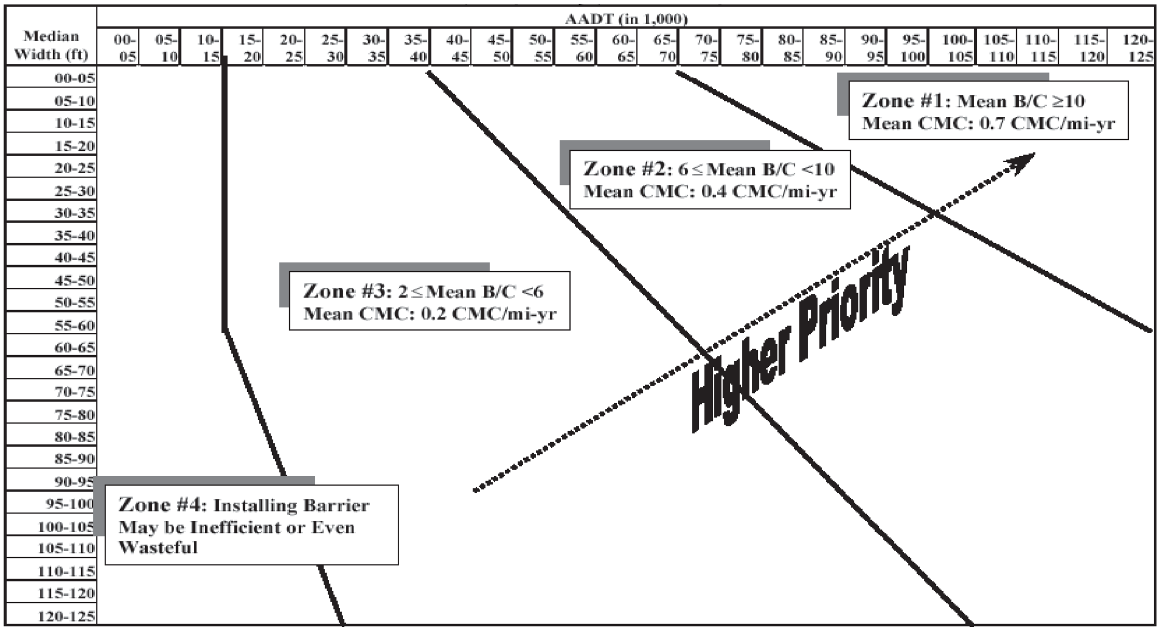


Figure 2-9. Benefit-cost ratios based on Texas study (16).

produced B/C ratios greater than 10.0. As such, divided highways in Zone No. 1 without longitudinal median barrier were considered the highest priority for median barrier installation. Further, it was recommended that road sections with a mean B/C ratio greater than 10 be given the highest priority when installing concrete median barriers.

To develop a potential guideline for the installation of high-tension cable barriers, a favorability ratio was developed. A favorability ratio was defined as the ratio of the high-tension cable barrier's mean B/C ratio over the concrete barrier's mean B/C ratio. Table 2-6 shows the calculated favorability ratios for various median widths and traffic volumes. A favorability ratio of 1 indicated that concrete and high-tension cable barriers had the same mean B/C ratio and higher ratios suggested increased favorability of using the high-tension cable barrier over the concrete barrier in terms of the mean B/C ratios.

Table 2-6. Favorability ratios from Texas study (*16*).

Median Width (ft)	AADT (in 1,000s) 5**	10	15	20	25	30	35	40	45	50	55	60	65	70	75	80	85	90	95	100	105	110	115	120	125
25*	2.3	2.1	2.0	1.9	1.8	1.8	1.7	1.6	1.6	1.5	1.5	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.2	1.1	1.1	1.1	1.1	1.0	1.0
30	2.3	2.2	2.1	2.0	1.9	1.9	1.8	1.7	1.7	1.6	1.6	1.5	1.5	1.4	1.4	1.4	1.3	1.3	1.3	1.2	1.2	1.2	1.2	1.1	1.1
35	2.4	2.3	2.2	2.1	2.1	2.0	1.9	1.8	1.8	1.7	1.7	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.4	1.3	1.3	1.3	1.3	1.2	1.2
40	2.6	2.4	2.3	2.2	2.2	2.1	2.0	2.0	1.9	1.8	1.8	1.7	1.7	1.7	1.6	1.6	1.5	1.5	1.5	1.4	1.4	1.4	1.4	1.3	1.3
45	2.7	2.5	2.4	2.4	2.3	2.2	2.1	2.1	2.0	2.0	1.9	1.9	1.8	1.8	1.7	1.7	1.6	1.6	1.6	1.5	1.5	1.5	1.5	1.4	1.4
50	2.8	2.6	2.5	2.5	2.4	2.3	2.2	2.2	2.1	2.1	2.0	2.0	1.9	1.9	1.8	1.8	1.8	1.7	1.7	1.7	1.6	1.6	1.6	1.5	1.5
55	2.9	2.7	2.7	2.6	2.5	2.4	2.4	2.3	2.2	2.2	2.1	2.1	2.0	2.0	1.9	1.9	1.9	1.8	1.8	1.8	1.7	1.7	1.7	1.6	1.6
60	3.0	2.9	2.8	2.7	2.6	2.5	2.5	2.4	2.4	2.3	2.2	2.2	2.2	2.1	2.1	2.0	2.0	1.9	1.9	1.9	1.8	1.8	1.8	1.8	1.7
65	3.1	3.0	2.9	2.8	2.7	2.7	2.6	2.5	2.5	2.4	2.4	2.3	2.3	2.2	2.2	2.1	2.1	2.1	2.0	2.0	2.0	1.9	1.9	1.9	1.8
70	3.2	3.1	3.0	2.9	2.8	2.8	2.7	2.7	2.6	2.5	2.5	2.4	2.4	2.3	2.3	2.3	2.2	2.2	2.2	2.1	2.1	2.1	2.0	2.0	2.0
75	3.3	3.2	3.1	3.0	3.0	2.9	2.8	2.8	2.7	2.7	2.6	2.6	2.5	2.5	2.4	2.4	2.3	2.3	2.3	2.2	2.2	2.2	2.1	2.1	2.1
80	3.4	3.3	3.2	3.1	3.1	3.0	3.0	2.9	2.8	2.8	2.7	2.7	2.6	2.6	2.6	2.5	2.5	2.4	2.4	2.4	2.3	2.3	2.3	2.2	2.2
85	3.5	3.4	3.3	3.3	3.2	3.1	3.1	3.0	3.0	2.9	2.9	2.8	2.8	2.7	2.7	2.6	2.6	2.6	2.5	2.5	2.5	2.4	2.4	2.4	2.3
90	3.6	3.5	3.4	3.4	3.3	3.3	3.2	3.1	3.1	3.0	3.0	2.9	2.9	2.8	2.8	2.8	2.7	2.7	2.7	2.6	2.6	2.6	2.5	2.5	2.5
95	3.7	3.6	3.6	3.5	3.4	3.4	3.3	3.3	3.2	3.2	3.1	3.1	3.0	3.0	2.9	2.9	2.9	2.8	2.8	2.7	2.7	2.7	2.6	2.6	2.6
100	3.8	3.7	3.7	3.6	3.5	3.5	3.4	3.4	3.3	3.3	3.2	3.2	3.1	3.1	3.1	3.0	3.0	2.9	2.9	2.9	2.8	2.8	2.8	2.7	2.7
105	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4	3.3	3.3	3.2	3.2	3.2	3.1	3.1	3.0	3.0	3.0	2.9	2.9	2.9	2.8
110	4.0	4.0	3.9	3.8	3.8	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4	3.4	3.3	3.3	3.2	3.2	3.2	3.1	3.1	3.1	3.0	3.0	3.0
115	4.1	4.1	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.7	3.6	3.6	3.5	3.5	3.4	3.4	3.4	3.3	3.3	3.3	3.2	3.2	3.2	3.1	3.1
120	4.2	4.2	4.1	4.1	4.0	4.0	3.9	3.9	3.8	3.8	3.7	3.7	3.7	3.6	3.6	3.5	3.5	3.5	3.4	3.4	3.4	3.3	3.3	3.3	3.2
125	4.3	4.3	4.2	4.2	4.1	4.1	4.0	4.0	3.9	3.9	3.9	3.8	3.8	3.7	3.7	3.7	3.6	3.6	3.6	3.5	3.5	3.5	3.4	3.4	3.4

Based on a 4-lane highway with a posted speed limit of 65 mph (104 km/hr) scenario.
*Due to the deflection characteristic of cable barriers upon impact, installing on medians with a width less than 25 ft is usually not recommended.
**Low estimates of the B/C ratios for high-tension cable barriers are less than 1 when AADT is less than 5,000.

Miaou et al. (*16*) recommended considering high-tension cable barriers only when the favorability ratio exceeded 2.

Noyce and McKendry (*17*) investigated the magnitude of and factors affecting median crossover crashes in Wisconsin using data from freeways and expressways. In 3 years (2001 through 2003), there were 631 median crossover crashes on four Interstates and 17 other freeways and expressways in Wisconsin. Of these, 81 percent (511 of 631) were single-vehicle crashes. In such instances, single-vehicle crashes involve motorists running off the road to the left and entering the median; however, a collision with a vehicle traveling in the opposing travel lanes did not result. The crossover crash severity distribution was as follows:

- 6.5 percent fatal (41 of 631);
- 53.2 percent injury (336 of 631); and
- 40.3 percent property damage only (254 of 631).

The most common initial cause of median crossover crashes was lost control due to weather (44.0 percent), lost control on dry pavement (41.7 percent), and vehicle collision (11.1 percent).

2.3 Other State Highway Agency Median Safety Research

2.3.1 North Carolina

Population growth in North Carolina has spawned an increase in the number of vehicle-miles traveled. This increase in travel is also associated with an increase in cross-median crashes on the Interstate and freeway system. The *Across Median Safety Study* (*18*) identified and investigated over 800 cross-median crashes along nearly 2,212 km (1,375 mi) of Interstate and non Interstate freeway facilities in North Carolina from January 1, 1994 through June 30, 1997. The study showed that although cross-median crashes make-up less than 5 percent of the injuries on the entire Interstate system, these crashes comprise nearly 23 percent of all fatal injuries and 13 percent of all severe injuries (*18*). Only 27 percent of all cross-median crashes on North Carolina freeways occurred where a barrier is warranted according to AASHTO criteria; 58 percent occur where barrier is optional; 15 percent occur where barrier is not normally considered. The cross-median crash data are shown in Figure 2-10 with the AASHTO warrants indicated.

In 1998, the Traffic Engineering and Safety Systems Branch initiated a three-pronged proactive approach to prevent cross-median crashes in North Carolina. The result of the first phase of the plan showed 23 high-priority locations along 386 km (240 mi) of freeway where cross-median crashes represented an unusually high concentration of accidents. It was recommended that some type of positive barrier protection be installed immediately in these locations to prevent further accidents. The second phase of the plan consisted of prioritizing and systematically protecting all freeway sections with median widths less than 21 m (70 ft). A hazard index that linked ADT, speed limit, and median widths was developed to help create a priority ranking system. In all, over 100 additional sections were identified as potential protection locations. The final phase of the plan consisted of revising the

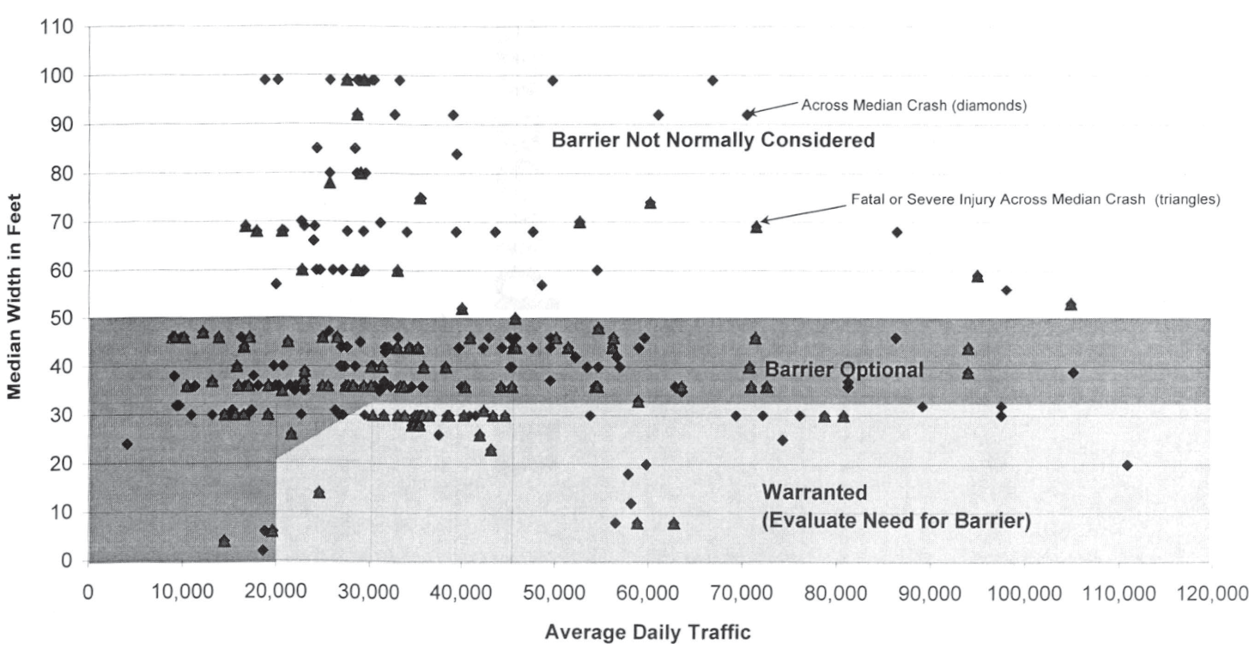


Figure 2-10. Cross-median crashes on North Carolina divided freeways (18).

state's median design policy so that no more freeways could be built with median widths less than 21 m (70 ft) (*18*).

Of the 23 locations identified in the first phase of the plan, the total estimated cost of installing some type of positive barrier was nearly $16 million; the 100 locations subsequently identified for protection in the second phase of the plan could cost an additional $65 million based on an estimated unit cost of $49,720 per km ($80,000 per mi) (*18*).

2.3.2 California

Beginning in 1947, the California Department of Transportation (Caltrans) has been constantly reviewing median installations and the effect that they have on accident frequency and severity. A major study performed in 1958 related traffic volumes to median widths, thus establishing a barrier warrant policy. This 1958 study called for barrier consideration on roadways carrying volumes in excess of 60,000 vehicles per day and having median widths less than 11 m (36 ft) (*19*). Cable barriers were considered positive protection for median widths between 5 and 11 m (16 and 36 ft) while metal beam barriers were used in medians less than 5 m (16 ft) in width. Subsequent evaluations took place, which only confirmed that the barriers were successful in reducing fatal cross-median crashes.

In 1968, the California Department of Transportation used a diminishing-return analysis and concluded that the placement of barrier would be concentrated at locations with medians up to and including 14 m (45 ft) in width (*19*). A diminishing-return analysis estimates the greatest return in reduced median-related crashes for the barrier investment cost. In California, the total cross-median fatal-and-injury crashes eliminated were compared to the miles of median barrier required on high-speed, divided highways. Based on comparing the cumulative crashes to cumulative miles of barrier required to prevent such crashes, a point of diminishing return is reached where barrier installation costs would outweigh the cost in crash cost benefits. The median width/volume criteria developed by Caltrans were later adopted by AASHTO with some modifications. This policy has gone relatively unchanged in California since the late 1960s.

In 1997, Caltrans again conducted a study to investigate the benefits of their median barrier warrant criteria. The study evaluated the traffic volume/median width warrant as well as an accident study warrant of 0.3 cross-median accidents of any severity per km per year (0.50 cross-median accidents of any severity per mile per year) or 0.07 fatal cross-median accidents per km per year (0.12 fatal cross-median accidents per mile per year) (*19*). The volume/median width warrant was evaluated based on a diminishing-return analysis, as well as a benefit-cost analysis that accounted for the increased number of accidents that occurred when installing barrier to decrease the severity of an accident. This particular study analyzed data over a 5-year period beginning in 1991.

The benefit-cost analysis used in the study was based on a human capital method where fatal accidents were valued at $850,000 per accident, injury accidents were valued at $17,200 per accident, and property-damage-only accidents were valued at $3,700 per accident. In addition, the cost of installing median barrier on California freeways was valued at $270,000 per mile. To complete the benefit/cost analysis, the severity of hit-barrier accidents versus cross-median accidents was determined. The data collected for the study contained sites where barrier was present (after condition) and where barrier was not present (before condition). Many combinations of median width and average daily traffic were studied, and the results are shown in Figure 2-11. Ultimately, the benefit/cost ratio determined in relation to extending the volume/width warrant from 14 m (45 ft) up to 23 m (75 ft) was 1.10. In all, this modified warrant required 628 km (390 mi) of newly installed barrier estimated to provide a reduction of 15 fatal accidents per year, an increase of 320 injury accidents per year, and an increase of 550 property-damage-only accidents per year. The diminishing-return analysis served to verify that a combination of median width and average daily traffic produces the best results for the study type.

2.3.3 Florida Turnpike

In February 1999, the Florida Turnpike Traffic Operations Center performed a study to investigate cross-median collisions along the Florida Turnpike (SR 91) and the Homestead Extension of the Florida Turnpike (SR 821). The study evaluated fatal cross-median collisions along 502 km (312 mi) of the turnpike for the years 1995 to 1997. As a result of the study, the Turnpike Authority contracted HNTB in March 1999 to perform a comprehensive study so that a median safety improvement program could be created.

The data collection effort consisted of identifying and reviewing crash reports, interviewing individuals from various organizations, conducting detailed field reviews, and retrieving physical, geometric, and operational characteristics of the Florida Turnpike (*20*).

An interview questionnaire was sent to 22 individuals representing traffic engineering organizations in Florida. From the responses received, the following statements best summarize the findings (*20*):

- Standing water on the turnpike shoulders could result in an increased number of cross-median collisions or injury-type accidents as a result of impacting a barrier wall.
- Illegal U-turns are a concern on the Florida Turnpike as motorists seek to avoid the toll.

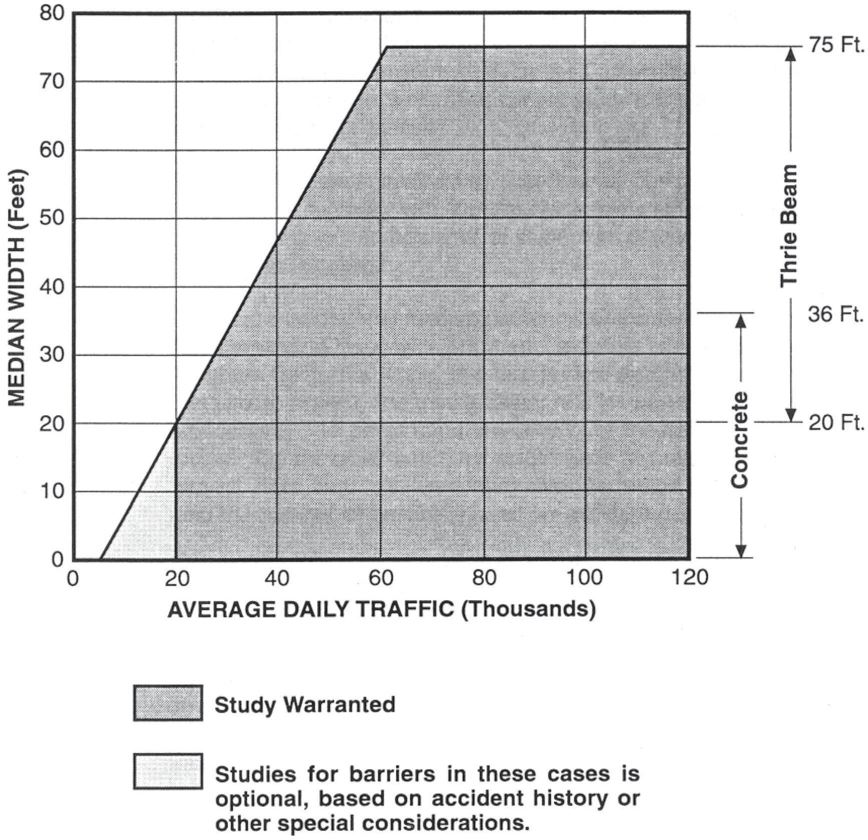


Figure 2-11. California freeway median barrier warrant (19).

- The Florida Highway Patrol should have a line item on their accident report forms that clearly indicates a cross-median crash.
- The benefit of using shoulder rumble strips along shoulders adjacent to median barrier walls should be evaluated.
- Concrete median barrier should be used to protect narrow medians with paved or hard-surfaced shoulders, and guardrail should be used when there is a wider grass median.

A typical cross section of the Florida Turnpike contains two basic median types as well as two basic lane configurations that consist of either four or six through lanes. The depressed median configuration consists of sections that are 12, 16, 20, and 27 m (40, 52, 64, and 88 ft) in width. The continuous median barrier section is typically 6 m (20 ft) wide (*20*). In both the depressed and barrier median sections of the turnpike, the frequency of crashes steadily rose during the study period. The number of cross-median collisions had risen from 17 in 1995 to 93 in 1998. Similarly, the number of median barrier crashes increased significantly from 151 in 1995 to 380 in 1998. In the case of both the crossover and barrier crashes, both the fatality and injury rates increased. To identify the highest crash locations, the turnpike was divided into 1-mile increments, and the number of crashes, cross-median collisions, cross-median fatal collisions, and median barrier crashes were plotted and analyzed for each 1-mile segment (*20*). From the analysis, five priority locations were pinpointed as high crash locations where median barrier could be expected to reduce median-related fatal accidents by nearly 75 percent.

The final phase of the study included a benefit/cost analysis to determine the most economical implementation program for improving median safety along the Florida Turnpike. In all, 10 different combinations were considered and analyzed. They considered barrier placement locations, barrier type, and median width and cross-slopes. The benefit/cost ratios ranged from 3.3 to 37.5 for various treatment combinations. The breakeven analysis showed that it would take 15 to 25 years, depending on the treatment type, to begin realizing a benefit from a median safety improvement program. Finally, 55 to 107 fatal crashes could be prevented when reaching the cost breakeven point (*20*).

In addition to the Florida Turnpike Commission, the Florida Department of Transportation evaluated median-related crashes in the late 1990s. In 1991, the Florida Department of Transportation adopted the policy of installing longitudinal median barrier on all divided Florida highways if the median width were less than 20 m (64 ft). An examination of cross-median crashes based on 5 years of crash data (1995 through 1999) was undertaken to determine the typical characteristics of these crashes and to recommend methods to reduce their frequency and severity. During the data collection period, it was estimated that between 300 and 750 cross-median collisions occurred on Florida highways. The following characteristics of cross-median crashes were identified by review of hardcopy police accident reports (*21*):

- Approximately 19 percent involved, or were suspected to involve, alcohol.
- About 2 percent of crashes involved a truck as the crossing vehicle.
- Nearly 78 percent of crashes occurred when the crossing vehicle's speed was within 5 mph of the posted speed limit.
- Prevailing weather conditions were good in 75 percent of crashes—83 percent of these crashes were the result of driver error and avoidance maneuvers.
- About half of the crashes that occurred during adverse weather conditions involved hydroplaning and the other half were the result of driver error and avoidance maneuvers.
- Approximately 62 percent of all cross-median crashes occurred within one-half mile of interchange ramp termini, and approximately 82 percent occurred within 1 mile of ramp termini.

A cost-effectiveness analysis revealed that median barriers should reduce the fatality rate and societal costs due to cross-median crashes by about 50 percent; however, the overall crash frequency and injury rates will increase by 600 and 28 percent, respectively. When installed in areas without a crash history, the barrier may not offer any cost benefit over the no-barrier alternative. It was recommended that the 20-m (64-ft) median barrier warrant be retained and the barrier is evaluated based on crash history. Also, crash locations within 1 mile of ramp termini were investigated and locations with a crash history are being considered for barrier installation.

2.3.4 Georgia

In the summer of 2000, a panel of experts on median design and safety at the Georgia Department of Transportation met to revise the department's median guidelines. They concluded that several factors would be used to address the applicability of median treatments. These factors are classification of roadway, number of lanes, base year traffic, design year traffic, posted speed limit, design speed, and accident/crash data. Highways were grouped into functional classifications. Georgia median guidelines for each classification considered are stated in the following subsections (*22*).

2.3.4.1 Urban Interstates

The panel determined that all urban Interstates will have positive barrier separation. In addition, all urban multilane roadways that interchange with an Interstate will have a raised median for a distance of 300 m (1,000 ft) from the ramp termini or to the first major intersection.

2.3.4.2 Rural Interstates

For rural Interstates, the panel concluded that all would require a depressed median as specified in the AASHTO Green Book. In areas where right-of-way restrictions exist, the guidelines suggest positive barrier separation to be incorporated. In addition, all rural multilane roadways interchanging with the Interstate will have a raised median for a 300-m (1,000-ft) distance from the ramp termini or to the first major intersection.

2.3.4.3 Arterials

The panel derived several guidelines to be incorporated for median treatment of arterial highways. These median policies are as follows:

- All arterial highways with design speeds or posted speed limits less than or equal to 72 km/h (45 mph), and having base year traffic volumes less than 18,000 vehicles per day, and design year traffic volumes equal to 24,000 vehicles per day will require a five-lane cross-section that includes a flush median. For new alignments, an additional 6 m (20 ft) of right-of-way will be purchased to incorporate a future 6-m (20-ft) raised median. The need for implementing a 6-m (20-ft) raised median will be determined by monitoring accidents and traffic volumes over a 5-year cycle.
- A 6-m (20-ft) raised median will be constructed on all urban arterials with base year traffic volumes greater than or equal to 18,000 and design year traffic volumes greater than or equal to 24,000 with a design speed less than or equal to 72 km/h (45 mph).
- All arterial highways with posted speed limits greater than or equal to 88 km/h (55 mph) or design speeds greater than or equal to 80 km/h (50 mph) will require the incorporation of a 13-m (44-ft) depressed median. If this is not feasible, a positive barrier system must be implemented.
- All multilane facilities with three or more lanes in one direction of travel must include positive separation of opposing traffic using a median. The type of median to implement shall be determined from the guidelines stated above.

2.3.5 Washington

The purpose of a Washington State Department of Transportation study (*23*) was to evaluate the frequency and severity of cross-median crashes on divided highways. A benefit-cost analysis was used to develop revised median barrier installation guidelines and to rank or prioritize median barrier improvement projects. In all, 1,089 km (677 mi) of Washington State highways were studied. Each section examined was a multilane, divided highway with full control of access and with a depressed or unprotected median. Additionally, posted speed limits were greater than 72 km/h (45 mph) and average daily traffic volumes were greater than 5,000 vehicles per day. Five (5) years of crash data (1996 through 2000) were examined and a total of 642 cross-median crashes identified. Prior to the research, the AASHTO median barrier warrant criteria were used to evaluate the need for median barrier. Crash analyses showed the following crash frequencies (*23*):

- At highway locations with 0- to 9-m (0- to 30-ft) medians, three cross-median crashes in 5 years;
- At locations with 9- to 12-m (31- to 40-ft) medians, 273 crashes;
- At locations with 12- to 15-m (41- to 50-ft) medians, 100 crashes;
- At locations with 15- to 18-m (51- to 60-ft) medians, 9 crashes;
- At locations with 19- to 21-m (61- to 70-ft) medians, 16 crashes;
- At locations with 22- to 24-m (71- to 80-ft) medians, 153 crashes; and
- At sites with medians wider than 24 m (80 ft), 88 crashes.

Based on the analysis, there was a clear indication that the installation of median barrier offered benefits that exceeded costs for medians up to 15 m (50 ft) in width, regardless of the barrier type being installed. Currently, median barrier is recommended on all access-controlled, multilane highways with posted speeds greater than 45 mph if the median is less than 15 m (50 ft) wide. The barrier type is determined on a project basis and medians with lower posted speeds or with widths greater than 15 m (50 ft) are considered as candidate median barrier locations based on crash histories. Shankar et al. (*24*) validated the results using count regression and societal cost modeling methods.

2.4 Median Barrier Effectiveness Evaluations

As previously discussed, there are nine general median barrier types commonly recognized for installation on access-controlled, high-speed, divided highways. The concrete median barrier has several variations, including the New Jersey shape, F-shape, and single-slope (or vertical wall). Also, other forms of high-tension cable barrier (e.g., Brifen Wire Rope Safety Fence) are now being used by state transportation agencies. The results of a survey of state transportation agency median barrier type use are shown in Figure 2-12 (*25*), which shows the number of responding agencies that approve the various median barrier types on high-speed, divided highways.

Published research related to the median barrier types used by various agencies is described in the remainder of this section.

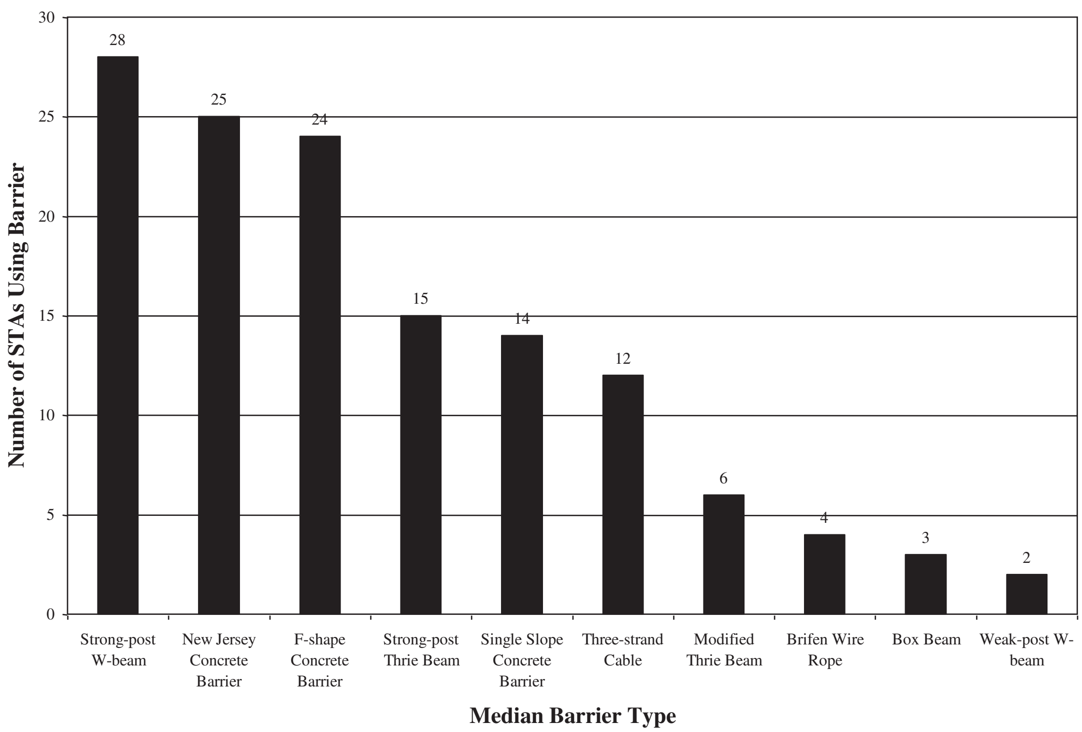


Figure 2-12. Approved median barrier use by state transportation agencies (25).

2.4.1 Cable Barrier

In December 1996, the Oregon Department of Transportation installed two sections of cable barrier along I-5 between Salem and Portland to reduce cross-median collisions. Sposito and Johnston (*26*) evaluated the effects of cable median barrier on I-5 in Oregon using historical crash data. The total length of two separate evaluation sections was 14.5 km (9.0 mi). The average median width was 15 m (50 ft). The posted speed limit was 105 km/h (65 mph) and the average daily traffic (ADT) for 1997 varied from 71,900 to 74,700 vehicles per day on the two sections. A simple before-after crash analysis was performed. The data before the installation of median barriers was from 1987 to 1996 while the after-period data was from December 1996 through March 1998. By comparing the crash rates before and after the installation of barrier, it was concluded that the fatality rate dropped (from 0.6 per year to 0) but the injury crash rate increased (from 0.7 per year to 3.8 per year). Also, by investigating the barrier impact accidents from December 1996 to March 1998 using maintenance records and police crash reports, it was concluded that the cable median barrier system was effective in preventing crossover accidents at the researched sites because 21 potential crossovers (40 percent of the total barrier impacts) were prevented by the barriers. The annual cost of a cable median barrier system would be less than that of a concrete barrier system.

Monsere et al. (*27*) performed a subsequent evaluation of median-related crashes before and after installation of cable median barrier on freeway facilities in Oregon. The evaluation section was 35.2 km (21.9 mi) long on I-5. The average median width was 15 m (50 ft) and the average width of the inside paved shoulder was 3 m (10 ft). The posted speed limit was 105 km/h (65 mph) and the ADT for the analysis period varied from 66,000 to 82,600 vehicles per day. The data before the installation of median barriers were from December 1993 to December 1996 and the data after the installation of median barriers were from May 1998 through May 2001. Target crash types included: (1) median crossover crash; (2) striking barrier crash, and (3) crashes unrelated to barrier. Types (1) and (2) were considered in the analysis and were summarized by severity using the KABCO scale. By comparing the number of crashes for each severity level before and after installation of the cable barrier system, it was concluded that the cable median barrier was effective in preventing median crossover crashes. It was estimated that 105 potential crossovers (45 percent of the total barrier impacts) were prevented by the longitudinal cable median barrier.

Hunter et al. (*28*) studied crash rates and crash types for three-strand cable median barrier installed on I-40 in North Carolina. Crash data used to develop the model contained crash counts along with associated roadway characteristics from 1990 to 1997 involving 6,111 crashes. Three-strand cable median barrier was not installed on high hazard sections until after 1994. Therefore, researchers were able to compare the before and after effects of the cable barrier installment.

Three-strand cable barrier was installed on a 13.7-km (8.5-mi) section of I-40 between Raleigh and Durham. The median width along this segment of highway ranged from 13 to 20 m (44 to 64 ft). Approximately 80 percent of the cable was installed as the double-run type except in the eastern section where the median width was 20 m (64 ft). In the placement of the single-run cable at the median center, the North Carolina Department of Transportation (NCDOT) recommends that it should not be used on narrow medians or on medians with slopes greater than 1V:6H.

In developing the model, two populations were identified. One population consisted of sections treated with guiderail, while the other population consisted of the entire North Carolina Interstate system not treated with cable barrier, known as the reference population. Analyses were conducted for several different crash types.

For total crashes, the reference group had a higher expected crash per mile rate than the pre-treatment group even though the reference group had lower crashes per mile than the treatment sites. In addition, a significant increase in total crashes was realized from pre-treatment years to post-treatment years, but only at a level equivalent to the rest of the Interstate system (*28*).

For serious injury and fatal accidents, the analysis showed that these types of crashes started to decrease during the transition year (1994), and continued in the post-treatment period. The analysis also revealed lower post-treatment rates when compared to sections in the reference population.

Run-off-road-left-hit-fixed-object accident models revealed that there was a significant increase in 1994 (transition year), which continued through the post-treatment period. This confirmed expectations because installing cable barrier into the median reduces the effective clear recovery width. These types of crashes stayed relatively the same between the reference population and the pre-treatment period.

Rear-end crashes were revealed to significantly increase from the pre-treatment years to the post-treatment years. The modeling also exhibited that there were not significant changes in ran-off-road-left overturn crashes from the transition period to the post-treatment period.

A severity index was calculated for crash types during each of the study years. NCDOT developed the mathematical formula used to calculate the severity index for this study (*28*). Severity indexes can fall into one of five categories: low, average, moderate, high, and very high. Severity index values for the pre-treatment years fall into the moderate severity category. For the transition year and post-treatment years, the severity index fell into the average severity index category. In other words, this states that the severity index of a crash decreased after cable barrier was installed in the median.

Davis and Pei (*29*) reconstructed two cross-median crashes using Markov Chain Monte Carlo (MCMC) and Bayesian methods to verify that simulation could be used to produce estimates of impact severity if cable barrier had been in use at the time of the crash event. The impact severity estimates were computed for a barrier located at the edge of the shoulder and at the center of the median. Once the crashes were verified using the reconstruction method, six cross-median and three rollover crashes were considered in the impact severity analysis. The median widths for the nine cases ranged from 13.1 to 21.8 m (43.0 to 71.4 ft). The posted speed limit ranged from 80 to 113 km/h (50 to 70 mph) and the ADT ranged from 8,900 to 42,000 vehicles per day. In all cases, the AASHTO *Roadside Design Guide* (*2*) would consider median barrier optional or not normally considered. The results indicated that had a barrier been present, the impact severity of the crossing vehicle would have been below the maximum set forth in NCHRP Report 350 (*30*).

Bergh et al. (*31*) described the Swedish National Road Administration's program to improve traffic safety on existing 13-m (42-ft) wide two-lane roads. The program consisted of converting roadways with two travel lanes (3.75 m or 12.3 ft each) and two paved shoulders (2.75 m or 9.0 ft each) to a three-lane roadway with 3.75-m (12.3-ft) wide outside travel lanes and a 3.5-m (11.5-ft) wide middle lane with 1.0-m (3.1-ft) paved shoulders. Traffic flows changed direction every 1.0 to 2.5 km (0.6 to 1.6 mi) in the middle lane and the opposing travel lanes were separated using a cable median barrier (known as 2+1 roads with a cable barrier). Speed performance, traffic safety, driver attitudes, and maintenance issues were all included in the evaluation. The findings were as follows:

- The average travel speed increased by 2 km/h (1.2 mph) after converting to a 2+1 road with cable median barrier when the posted speed was 90 km/h (55 mph).
- On roads with a posted speed limit of 110 km/h (68 mph), the average travel speed on the two-lane sections was 111 km/h (69 mph) and the average travel speed in the single lane sections was 106 km/h (66 mph).
- Capacity was estimated to be 1,500 to 1,550 vehicles per hour per lane after the conversion; the capacity for the previous cross-section was approximately 1,800 vehicles per hour per lane.
- The reduction in severe injury crashes was estimated to be 40 to 55 percent.
- The reduction in fatal crashes was estimated to be 65 to 70 percent.
- The median cable barrier crash rate was 0.6 crashes per million axle-pair km (0.97 crashes per million axle-pair mi).
- After 2 years, drivers began to prefer the 2+1 cable median barrier design over other road conversion types (e.g., 2+1 with pavement markings).
- Maintenance costs increased after installation of the cable median barrier.

2.4.2 Concrete Safety Shape Barriers

McNally and Yaksich (*32*) showed that New Jersey barrier installation decreased the frequency of fatal accidents by 31 percent while the frequency of nonfatal and non-injury accidents increased by 9.2 and 2.4 percent, respectively.

Elvik (*33*) summarized 32 previous studies using meta-analysis to evaluate the effects of median barriers, guardrails, and crash cushions on crash rate and crash severity. The results showed that median barriers increased crash rate but reduced crash severity, while guardrails reduced both the crash rate and crash severity. The effects of crash cushions were not conclusive. The best estimate of the safety effects of median barriers was a 30 percent increase in crash rate, a 20 percent reduction in fatalities given a crash has occurred, and a 10 percent reduction in nonfatal injuries given a crash has occurred. The safety effects of guardrails were a 45 percent reduction in fatalities and a 50 percent reduction in nonfatal injuries, given a crash has occurred.

CHAPTER 3

State Survey Results

3.1 Survey Method

A survey of state highway agencies concerning their median design practices was conducted in 2003 as part of NCHRP Project 17-14. This previous survey was updated by a survey conducted as part of the current research. The survey conducted as part of the current research, referred to here as the 2006 survey, was not identical to the earlier survey, but did contain several of the same questions relating to typical median cross sections and use of median barriers. Copies of the survey questionnaires for the 2003 and 2006 surveys are presented in Appendices A and B, respectively, which are not provided herein but are available on the TRB website and can be found there by searching for NCHRP Report 794.

Both the 2003 and 2006 surveys were sent to the design engineers of the 50 state highway agencies. The 2006 survey used a Web-based approach that allowed the questions asked to be based on the responses to earlier questions. To avoid duplication of effort, survey respondents were first asked whether their median design policies had changed since 2003. If the agency had responded to the 2003 survey and their response to this first question in the 2006 survey indicated that the agency's median design policies had not changed since 2003, many of the subsequent questions that had already been answered in the previous survey were omitted.

The summary of survey results that follows is based on the combined results of the 2003 and 2006 surveys for all cases in which common questions were asked.

3.2 Response Rate

The 2003 survey received responses from 35 of the 50 states, or 70 percent. The 2006 survey also received responses from 35 of the 50 states, or 70 percent. There were 28 states that responded to both surveys. There were nine states that responded to the 2003 survey, but not to the 2006 survey. There were six states that responded to the 2006 survey, but not the 2003 survey. Thus, the combination of both surveys includes responses from 43 states (or 86 percent). Table 3-1 summarizes the states that responded to one or both of the surveys.

Table 3-2 summarizes the responses concerning changes in median design policies from the 28 states that responded to both surveys. The table indicates that approximately half of the highway agencies changed their median design policies since the 2003 survey and half did not. Table 3-3 summarizes the responses from all states to the question in the 2006 survey about changes in design policies since 2003.

3.3 Survey Summary

3.3.1 Typical Cross Sections

Agencies were asked to identify their design criteria for median width and median side slope. They could also indicate other information about their typical design elements. There were 18 responses to this question in the 2006 survey and 9 responses from the 2003 survey were added. All responses to this question are summarized in Table 3-4. The responses for specific design elements are summarized in the following subsections.

3.3.1.1 Median Widths

Table 3-5 shows the distribution of minimum or typical median widths currently used by state highway agencies in freeway design. The minimum median widths in current use range from 8 m (26 ft) (used only for flush medians with median barrier) to 23 m (76 ft). Throughout this report, median width is defined as the distance from the inside edge of the traveled way to inside edge of the traveled way for the opposing roadways of a divided highway.

Table 3-6 shows that nine state highway agencies specify desirable median widths for freeways greater than the minimum median width used by the same agency. The desirable median widths range from 18 to 38 m (60 to 126 ft).

Table 3-1. State highway agencies that responded to one or both surveys.

Agencies responding to both 2003 and 2006 surveys	Agencies responding to the 2003 survey only	Agencies responding to the 2006 survey only
Alabama	Alaska	Idaho
Arkansas	Arizona	Kentucky
California	Colorado	New Mexico
Connecticut	Hawaii	Oregon
Delaware	Kansas	Tennessee
Florida	Massachusetts	Texas
Indiana	Michigan	
Iowa	New Hampshire	
Maine	North Dakota	
Maryland		
Minnesota		
Mississippi		
Missouri		
Montana		
Nebraska		
Nevada		
New Jersey		
New York		
North Carolina		
Ohio		
Pennsylvania		
South Carolina		
South Dakota		
Virginia		
Washington		
West Virginia		
Wisconsin		
Wyoming		

Table 3-7 shows that four state agencies specify minimum median widths for nonfreeways less than the minimum widths used by the same agency for freeways. The minimum median widths for nonfreeways range from 12 to 15 m (40 to 50 ft).

3.3.1.2 Median Side Slopes

Table 3-8 shows that the minimum median side slopes range from 1V:4H to 1V:6H, with 17 of the 19 state highway agencies who responded indicating that they use minimum median side slopes of 1V:6H. Two states stated specifically that they use slopes flatter than 1V:6H in medians with barriers.

Table 3-9 shows that four states specify desirable median side slopes flatter than the minimum median side slopes. The desirable median side slopes ranged from 1V:6H to 1V:12H. In addition, two states specified that median side slopes flatter than their minimum value of 1V:6H are preferred. Only one state uses different values of desirable median side slope for freeways and nonfreeways. Texas uses a desirable side slope of 1V:8H for nonfreeways while the desirable side slope for freeways is 1V:12H; the minimum side slope for both freeways and nonfreeways in Texas is 1V:6H.

3.3.2 Median Barrier Warrant Criteria

Highway agencies were asked in both the 2003 and 2006 surveys if they used the median barrier warrants in the 2002 AASHTO *Roadside Design Guide* (see Figure 2-3). Table 3-10 indicates that 20 of the 30 states (66.7 percent) that responded to the question in at least one of the two surveys indicate that

Table 3-2. Changes in median design policies between 2003 and 2006 indicated by agencies that responded to both surveys.

Response	Number (percentage) of highway agencies[a]
No change in policy since 2003	14 (50.0)
Policies have changed since 2003	12 (42.8)
No response	2[b] (7.1)
Total	28

[a] Percentage based on 28 agencies that responded to both the 2003 and 2006 surveys.
[b] Although these two agencies did not respond to the question about policy changes since 2003, they included copies of their current policies with their response.

Table 3-3. Response from specific agencies about changes in median cross-section design policies since 2003.

Agency	Response
Alabama	No change. The 2003 responses are still current.
Arkansas	Did not respond to this question.
California	No change. The 2003 responses are still current.
Connecticut	No change. The 2003 responses are still current.
Delaware	Policies or practices have changed since 2003.
Florida	Did not respond to this question.
Idaho	Did not respond to the 2003 survey.
Indiana	Policies or practices have changed since 2003.
Iowa	Policies or practices have changed since 2003.
Kentucky	Did not respond to the 2003 survey.
Maine	No change. The 2003 responses are still current.
Maryland	Did not respond to the 2003 survey.
Michigan	No change. The 2003 responses are still current.
Minnesota	Policies or practices have changed since 2003.
Mississippi	No change. The 2003 responses are still current.
Missouri	Policies or practices have changed since 2003.
Montana	No change. The 2003 responses are still current.
Nebraska	Policies or practices have changed since 2003.
Nevada	No change. The 2003 responses are still current.
New Jersey	Policies or practices have changed since 2003.
New Mexico	No change. The 2003 responses are still current.
New York	Policies or practices have changed since 2003.
North Carolina	No change. The 2003 responses are still current.
Ohio	No change. The 2003 responses are still current.
Oregon	Did not respond to the 2003 survey.
Pennsylvania	No change. The 2003 responses are still current.
South Carolina	No change. The 2003 responses are still current.
South Dakota	Policies or practices have changed since 2003.
Tennessee	No change. The 2003 responses are still current.
Texas	Did not respond to the 2003 survey.
Virginia	Did not respond to the 2003 survey.
Washington	Did not respond to the 2003 survey.
West Virginia	Policies or practices have changed since 2003.
Wisconsin	Policies or practices have changed since 2003.
Wyoming	Policies or practices have changed since 2003.

they use the AASHTO median barrier warrants. Ten of the 30 responding states (33.3 percent) indicate that they did not use the AASHTO median barrier warrants. The responses are shown in Table 3-11. All responses shown in Table 3-11 are from the 2006 survey, except where responses to the 2003 survey are specifically noted. At the time of the survey, the revised 2006 AASHTO median barrier warrants had just been published, so highway agencies had not yet had time to decide whether to adopt these warrants.

Table 3-12 summarizes the median barrier warrant criteria of the 10 states that indicated that they do not use the 2002 AASHTO criteria. Where more than one criterion is used by an agency, multiple columns appear in Table 3-12. Factors other than median width considered in these criteria included ADT, posted speed limit, cross-median crash rates, location within 1 mile of entrance/exit ramp gore areas, and roadway type (freeway versus nonfreeway).

For criteria based on median width alone, minimum median widths where barriers are not required ranged from 5 to 20 m (18 to 64 ft). One state (Maryland) stated that they do not install barrier if the median is more than 23 m (75 ft) wide.

Five agencies specified median widths in conjunction with ADT. In Maryland, medians up to 23 m (75 ft) in width would require barriers if the ADT was greater than 80,000 vehicles per day. One agency considers both median width and speed and requires barrier if the median width is less than 15 m (50 ft) and the posted speed limit is greater than 72 km/h (45 mph). Another agency stated specifically that median barrier is not placed on collectors or other highways without access control.

All of these 10 state highway agencies that have median barrier warrants that differ from the 2002 AASHTO warrants require barrier in more situations than AASHTO, and most require median barrier in more situations than the updated 2006 AASHTO warrants.

3.3.3 Approved Median Barriers

Both surveys asked highway agencies which median barrier types are approved for use and in what situations each barrier type was used. A total of 28 responses were received to this question, 19 responses in the 2006 survey, and 9 responses in the 2003 survey.

Table 3-13 summarizes the number of states that approve use of specific median barrier types. Table 3-14 shows the median barrier types approved for use in specific states. Some agencies have as many as six approved median barrier types. The barrier type used by the most agencies was the W-beam guardrail (23 of 29 responding agencies). The F-shaped and New Jersey concrete barrier are approved for use by 15 agencies; the single-slope concrete barrier is approved for use by 12 agencies; and high-tension cable barrier is approved for use by 13 agencies. High-tension cable barrier use is much higher in 2006 than reported in 2003.

The survey also asked each state highway agency whether they had any approved median barrier types other than those listed in the survey. Only one state (New York) identified an additional approved median barrier type. In New York, steel-backed timber rail is approved for use as a median barrier.

3.3.4 Minimum Median Widths for Use of Median Barriers

Each responding agency was asked to state the minimum medium width in which each barrier type is used. The range of minimum median widths for each barrier type is shown

Table 3-4. Survey responses concerning median cross-section elements.

Agency	Response		
	Median width	Median side slopes	Other
Alabama (2003)	Use AASHTO Guidelines		
California (2003)	60 ft desirable	1V:10H desirable, 1V:6H min	
Delaware	40-ft min; wider is desirable where r/w permits	1V:6H or flatter	
Florida	Non-limited-access rural: 40 ft; Interstate: 64 ft; other freeways: 50 ft; limited access with barrier: 26 ft	1V:6H	
Idaho	100 ft between roadway center lines, typically 38 ft from edge travel way to median center w/ 4-ft paved shoulder.	1V:6H	
Indiana	26 ft in paved flush median; 60 ft typical, or 80 ft in some new construction where site conditions allow in graded earth medians	1V:5H max	Where median barriers are present, median side slopes should be 1V:10H or flatter in graded median, 1V:24H in paved median
Iowa	64 ft	1V:6H	
Kentucky	40 ft	1V:6H	
Maine (2003)		1V:6H	
Minnesota	40 ft	1V:4H to 1V:6H	
Mississippi (2003)	Use AASHTO Guidelines		
Missouri	60 ft	1V:6H	
Montana (2003)	36 ft min to 75 ft desirable		
Nebraska	64 ft to 76 ft	1V:6H	12-ft left shoulders on 6-lane facilities
Nevada (2003)	Use AASHTO Guidelines		
New Jersey	4 ft min to 84 ft desirable	1V:12H most common; 1V:6H max	Use Concrete Barrier Curb (CBC) for median width up to 12 ft. Prefer CBC for medians 13 to 26 ft, but may also use dual faced beam guide rail (DFBGR). Use DFBGR for 26 to 60 ft median.
New York	No typical sections	No typical sections	No typical sections
North Carolina (2003)	Use AASHTO Guidelines		
Ohio (2003)	Use AASHTO Guidelines		
Oregon	Rural 76 ft, 126 ft preferred; nonfreeway: 76 ft; 46 ft min in constrained area	No steeper than 1V:6H, slope values dependent on fill height	
Pennsylvania (2003)	Use AASHTO Guidelines		
South Carolina	48-ft min	1V:6H	
South Dakota	Variable as it depends on project conditions; 80-ft preferred and 42-ft min	1V:6H, toe at 30 ft clear zone	1V:20H from toe of 1V:6H slope to centerline of median
Texas	Freeways: 76 ft; multilane divided: 76 ft desirable	Freeways: 1V:12H des; 1V:6H min. Multilane divided: 1V:8H des; 1V:6H	Concrete median barrier not to be placed on slopes steeper than 1V:10H. High-tensioned cable barrier not to be placed on slopes steeper than 1V:6H.
Washington	40 ft to 60 ft (width is influenced by the number of lanes and the type of access control)	Not steeper than 1V:6H	
West Virginia	46 ft	1V:6H	
Wisconsin	60 ft for 65 mph posted speed, 50 ft for 55 mph posted speed	1V:6H	
Wyoming	76 ft preferred	1V:6H or flatter preferred	

Table 3-5. Minimum or typical median widths used in freeway design.

Minimum median width (ft)	Number of state highway agencies
26	1[a]
36	1
40	4
42	2
46	2
48	1
60	3
64	3[b]
76	3
	20

[a] Minimum 26-ft width used only for flush median with median barrier.
[b] One state with a minimum 64-ft median for the Interstate system permits 50-ft medians on non Interstate freeways and 26-ft flush medians with median barriers.

Table 3-6. Desirable median widths used in freeway design.

Desirable median width (ft)	Number of state highway agencies
60	2
65	1
76	2
80	2
84	1
126	1
	9

Table 3-7. Minimum median widths for nonfreeways less than minimum median widths for freeways.

Minimum median width (ft)		Number of state highway agencies
Nonfreeways	Freeways	
40	64[a]	1
46	76	1
48	76	1
50	60[b]	1
		4

[a] Minimum 50-ft median width permitted for noninterstate freeways.
[b] Minimum 60-ft median width for 65-mph freeways; 50-ft medians used for 55-mph freeways and nonfreeways

Table 3-8. Minimum median side slopes used in freeway design.

Minimum median side slope	Number of state highway agencies
1V:4H	1
1V:5H	1
1V:6H	18[a,b]
	20

[a] One state uses minimum median slope of 1V:10H in graded median where barrier is present and 1V:24H in paved median.
[b] One state uses minimum median slope of 1V:10H in median with concrete median barrier.

Table 3-9. Desirable median side slope use in freeway design.

Median side slope		Number of state highway agencies
Desirable	Minimum	
1V:6H	1V:4H	1
1V:10H	1V:6H	1
1V:12H	1V:6H	2[a, b]
Flatter than 1V:6H preferred		2
		6

[a] One state most commonly uses 1V:12H median slopes, but permits use of minimum 1V:6H slopes.
[b] One state uses 1V:8H desirable median slopes on nonfreeways.

Table 3-10. Highway agency usage of the 2002 AASHTO median barrier warrants.

Does your agency use the 2002 AASHTO median barrier warrants?	Number (percentage) of state highway agencies
Yes	20 (66.7)
No	10 (33.3)
	30

Table 3-11. Response from specific agencies on whether they use the 2002 AASHTO median barrier warrants.

Agency	Does your agency use the 2002 AASHTO median barrier warrants?
Alabama (2003)	Yes
California (2003)	No
Delaware	Yes
Florida	No
Idaho	Yes
Indiana	Yes
Iowa	Yes
Kentucky	Yes
Maine (2003)	No
Maryland	No
Minnesota	Yes
Mississippi (2003)	Yes
Missouri	Yes
Montana (2003)	Yes
Nebraska	Yes
Nevada (2003)	Yes
New Jersey	No
New York	No
North Carolina (2003)	No
Ohio (2003)	Yes
Oregon	No
Pennsylvania	Yes
South Carolina	Yes
South Dakota	Yes
Texas	Yes
Virginia	Yes
Washington	No
West Virginia	Yes
Wisconsin	No
Wyoming	Yes

in Table 3-15 and the specific responses from each state highway agency are shown in Table 3-16. Table 3-16 also shows the barrier types for which responding agencies did not identify a specific minimum median width. The minimum median widths for use of different barrier types varied with the barrier system's rigidity. For concrete barriers, minimum medium widths of 0.6 to 8 m (2 to 26 ft) were required; for metal guardrails, the minimum median widths ranged from 1.2 to 13 m (4 to 41 ft). For high-tension cable barriers, minimum median widths ranged from 5 to 15 m (15 to 50 ft) and for three-strand cable barriers, the minimum median width ranged from 7 to 14 m (22 to 46 ft).

3.3.5 Median Barrier Placement Criteria

Highway agency responses concerning the placement of median barriers are presented in Table 3-17. Median barriers are generally placed either in the center of the median or along the median shoulder. Concrete barrier is typically placed in the center of the median. Guardrail is typically placed in the center of the median if slopes are flat and on the shoulder otherwise. Cable barriers are typically placed in the center of the median or upslope from the low point of the median cross section. Cable barriers can be used on steeper side slopes than other barriers (see next section); however, vehicles can go under the cable barriers if they approach the barrier when their suspension is fully compressed, as when the vehicle crosses the low spot in the median.

3.3.6 Maximum Side Slope for Use of Median Barrier

Highway agency responses concerning the maximum side slopes where approved barriers may be installed are shown in Table 3-18. The responses indicate that guardrail and concrete barrier are not normally used where side slopes are steeper than 1V:10H. Where steeper slopes are present, barriers are typically placed near the shoulder of the roadway. A few agencies indicated that guardrail or concrete barriers could be used on slopes as steep as 1V:6H. Most of the responding agencies indicated that they would use either of the cable barriers on 1V:6H slopes and two agencies indicated that they would use high-tension cable barrier on slopes as steep as 1V:4H.

3.3.7 Distribution of Barrier Usage by Barrier Type

Highway agencies were asked to estimate their current usage of each median barrier type only in the 2006 survey. Usage estimates are presented in Table 3-19. F-shaped and New-Jersey-shaped concrete barriers have the greatest reported usage in agencies where they are approved. W-beam guardrail also has heavy usage in some agencies. Although the use of high-tension cable barrier is increasing, it is only used extensively by two agencies according to the survey responses. Three-strand cable barriers have generally had little usage except in one state among the states that responded to the question.

3.3.8 Ditch Cross Sections

The 2006 survey asked about ditch cross sections used by state highway agencies in divided highway medians. There were 19 responses to this question; 12 agencies indicated typical cross sections for ditches in medians, and responses are shown in Table 3-20. Responses to this question varied, because some agencies indicated the total median widths they use and others indicated dimensions for ditches with the median. The typical widths identified for ditches within the median were 1.2, 1.8, and 3.0 m (4, 6, and 10 ft); other responses indicated variable ditch widths. Ditch slopes were mainly listed as 1V:6H, and others listed were as steep as 1V:4H. The ditch depths listed varied from 0.2 to 1.4 m (0.5 to 4.6 ft).

Table 3-12. Median barrier criteria.

Agency	Response Median barrier criteria			
California (2003)	Conduct study if median width is 0 to 20 ft and ADT exceeds 20,000 veh/day	Conduct study if median width is less than 75 ft and ADT exceeds 60,000 veh/day	Study any median with 0.5 cross-median crashes per mile per year or 0.12 fatal crashes per mi per year	
Florida	On Interstate, install barrier if median width less than 64 ft; 50 ft on other freeways	On Interstates and expressways, median barrier is required within 1 mi of exit/entrance gore with one or more cross-median crashes within 5 years		
Maine (2003)	Install barrier if the median width is < 20 ft and ADT > 20,000	Install barrier if median width is < 30 ft and ADT > 30,000 veh/day	Barrier optional if width is < 20 ft and ADT is 5,000 to 20,000 veh/day	Barrier optional if median width is 30 ft to 50 ft and ADT > 40,000 veh/day
Maryland	Install median barrier if width <= 30 ft	Install median barrier if width > 30 ft but < 50 ft and ADT > 40,000 veh/day	Install median barrier if width > 50 ft but < 75 ft and ADT > 80,000 veh/day	Do not install barrier if median width > 75 ft
New York	Install barrier if median width < 36 ft and ADT > 20,000 veh/day	Barrier encouraged if median width < 72 ft	Barrier is optional if median width is < 45 ft and ADT >10,000 veh/day	
North Carolina (2003)	Install barrier if median width < 70 ft			
Oregon	Install barrier if median width less than or equal to 60 ft; over 60 ft, base warrant on cross-median collision statistics			
Virginia	18 ft			
Washington	Provide median barrier on multilane highways with full access control with median widths of 50 ft or less and posted speeds of 45 mph or more	Consider median barrier on highways with wider medians or lower posted speeds when there is a history of cross-median accidents	Median barrier is not normally placed on collectors or other state highways that do not have limited-access control	
Wisconsin	On new freeway construction: range (median width, ADT) from (< = 20 ft, > = 20,000 veh/day) to (< 60-ft, > = 50,000 veh/day)	No retrofit warrant		

Table 3-13. State highway agency usage of specific median barrier types.

Median barrier type	Number (percentage) of state highway agencies that currently approve each median barrier type for use on rural divided highways[a]
Weak-post W-beam guardrail	4 (13.8)
Box-beam barrier	3 (10.3)
Blocked-out W-beam guardrail (strong post)	23 (79.3)
Blocked-out Thrie-beam guardrail	10 (34.5)
Modified Thrie-beam guardrail	4 (13.8)
New-Jersey-shaped concrete barrier	15 (51.7)
Single-slope concrete barrier	12 (41.4)
F-shape concrete barrier	15 (51.7)
Three-strand cable barrier (weak post)	8 (27.6)
High-tension cable barrier	13 (44.8)

[a] Based on response from 29 state highway agencies; responses sum to more than 100 percent because most states use more than one barrier type.

Table 3-14. Approved median barrier types for specific state highway agencies.

	Median barrier types currently approved for use on rural divided highways									
	Weak-post W-beam guardrail	Box-beam barrier	Blocked-out W-beam guardrail (strong post)	Blocked-out Thrie-beam guardrail (strong post)	Modified Thrie-beam guardrail	New-Jersey-shaped concrete barrier	Single-slope concrete barrier	F-shaped concrete barrier	Three-strand cable (weak post)	High-tension cable barrier
Alabama (2003)			X			X	X		X	
Arkansas			X			X	X	X		X
California (2003)				X			X			
Delaware			X							
Florida			X		X			X		
Idaho			X	X		X				
Indiana			X		X			X		
Iowa			X	X				X		X
Kentucky	X					X				X
Maine (2003)			X	X		X				
Maryland			X	X		X		X		
Minnesota		X	X				X	X		X
Mississippi (2003)			X	X	X	X				
Missouri			X	X		X	X		X	X
Montana (2003)						X				
Nebraska										X
Nevada (2003)			X	X				X	X	
New York	X	X	X				X	X	X	
North Carolina (2003)	X		X			X			X	
Ohio (2003)			X			X	X			X
Oregon			X		X		X	X		X
Pennsylvania (2003)			X				X	X		
South Carolina			x						x	
South Dakota				X		X	X	X		X
Texas						X	X	X		X
Virginia	X		X					X		
Washington			X			X	X		X	X
Wisconsin			X					X	X	X
Wyoming		X	X	X		X		X		X

Table 3-15. Range of minimum median widths for use of specific median barrier types.

Median barrier type	Range of minimum median widths (ft) for use of specific median barrier types
Weak-post W-beam guardrail	18
Box-beam barrier	10 to 14
Blocked-out W-beam guardrail (strong post)	5.5 to 41
Blocked-out Thrie-beam guardrail (strong post)	4 to 26
Modified Thrie-beam guardrail	8 to 30
New-Jersey-shaped concrete barrier	2 to 24
Single-slope concrete barrier	2 to 18
F-shaped concrete barrier	2 to 26
Three-strand cable barrier (weak post)	22 to 46
High-tension cable barrier	15 to 50

3.3.9 Typical Median Cross Sections

Highway agencies responding to the 2006 survey were asked to provide typical cross sections for divided highways. This question was not asked in the 2003 survey. Typical cross sections provide useful information because they show the entire set of dimensions used in median cross-section design. There were 16 responses to this question, as indicated in Table 3-21. The median widths for these typical cross sections range from 12 to 38 m (38 to 126 ft); median shoulder widths vary from 1.2 to 5 m (4 to 15 ft); side slopes range from 1V:4H to 1V:12H; ditch widths vary from 0 to 9 m (0 to 28 ft); and ditch depths range from 0.3 to 1.4 m (1 to 4.6 ft).

3.3.10 Safety Performance Evaluations

Responding agencies were asked if they had conducted any safety performance evaluations of median cross-section features and were asked to provide copies of any evaluations they had completed. Information was received from four agencies, as follows:

- Iowa: High-tension cable barrier study;
- Missouri: Comprehensive guard cable study;
- Oregon: Sent proposed policy for Interstate median closures; and
- Washington: Sent information on comparison of barrier collisions.

The results of these studies are reviewed in Section 3.4.

3.3.11 Additional Materials

The following seven highway agencies sent other materials on design such as policies, procedures, or published materials:

- California: Two reports on median barrier warrants;
- Indiana: Design manual excerpts;
- Kentucky: Draft guidelines on median barrier applications on fully controlled-access highways;
- New York: Highway design manual link;
- South Dakota: Information on median barrier use and link to design manual;
- Virginia: Referred to AASHTO *Roadside Design Guide*; and
- Wyoming: Standards engineer contact information.

3.3.12 State Highway Agencies Willing to Furnish Data

Respondents were asked whether they would be willing to furnish crash and roadway inventory data for the research, if asked. Twenty of the 29 responding agencies indicated that they would be willing to furnish data. The agencies that indicated that they would be willing to furnish data for the research were as follows:

1. Alabama,
2. Nevada,
3. California,
4. New Mexico,
5. Iowa,
6. North Carolina,
7. Kentucky,
8. Ohio,
9. Maine,
10. Oregon,
11. Maryland,
12. Pennsylvania,
13. Minnesota,
14. Texas,
15. Missouri,
16. Washington,
17. Montana,
18. Wisconsin,
19. Nebraska, and
20. Wyoming.

(*text continued on page 43*)

Table 3-16. Minimum median width for use of specific median barrier types.

Agency	Minimum median width (ft) for use of specific barrier types									
	Weak-post W-beam guardrail	Box-beam barrier	Blocked-out W-beam guardrail (strong post)	Blocked-out Thrie-beam guardrail (strong post)	Modified Thrie-beam	New-Jersey-shaped concrete barrier	Single-slope concrete barrier	F-shaped concrete barrier	Three-strand cable (weak post)	High-tension cable barrier
Alabama (2003)			8			6.5	6.5		32	
Arkansas			30			18	18	18		16
California (2003)				20			[a]			
Delaware			10							
Idaho			10	10		5				
Indiana			30		30			26		
Iowa			14	14				[a]		
Kentucky	18					18				30
Maine (2003)			26	26		22				
Maryland			6	6		2		2		
Minnesota		10	10				10	10		15
Mississippi (2003)			24	24	24	24				
Missouri			8	4		2	2		24	16
Montana (2003)						9				
Nebraska										50
Nevada (2003)			[b]	[b]				[a]	24	
New York							2	2	22	
North Carolina (2003)	[a]		36			[a]			46	
Ohio (2003)			5.5			[a]	[a]			15
Oregon			10		8		8	8		20
Pennsylvania (2003)			[a]				[a]	[a]		
Texas						10	10	10		25
Virginia	18		18					6		
Washington			14			14	14		25	
Wisconsin			41					[a]	41	41
Wyoming		14	12	12		10		10		16

[a] No formal minimum median width specified.
[b] Minimum median width based on dynamic deflection distance for specific barrier type.

Table 3-17. Median barrier placement criteria.

Agency	Most common placement location for each barrier type									
	Weak-post, W-beam guardrail	Box-beam barrier	Blocked-out W-beam guardrail (strong post)	Blocked-out Thrie-beam guardrail (strong post)	Modified Thrie-beam guardrail	New-Jersey-shaped concrete barrier	Single-slope concrete barrier	F-shaped concrete barrier	Three-strand cable (weak post)	High-tension cable barrier
Alabama (2003)			Shoulder break			Center of median	Center of median		4 ft upslope from ditch	
Arkansas			Face of guardrail 2 ft from outside edge of shoulder			Face of barrier 2 ft from outside edge of shoulder	Face of barrier 2 ft from outside edge of shoulder	Face of barrier 2 ft from outside edge of shoulder		Center of median
California (2003)				Center of median				Center of median		
Delaware			Center of median							
Idaho			2 ft from face of rail to roadway normal shoulder	2 ft from face of rail to roadway normal shoulder		1.33 ft from face of rail to roadway normal shoulder				
Indiana			Center of median or offset for drainage considerations		Center of median or offset for drainage considerations			Center of median		
Iowa			Center of median	Center of median				Center of median		Placed 2 ft off edge of shoulder
Kentucky	Edge of shoulder					Center of median				10 ft from edge of shoulder on slopes flatter than 1V:6H
Maine (2003)			Center of median	Center of median		Center of median				
Maryland			On slopes 1V:10H or flatter, as far away from the travel lane as possible. For slopes steeper than 1V:10H, either 2 ft from shoulder or 12 ft from shoulder	At the edge of the shoulder; used when approaching bridge parapets		Center of median		Center of median		
Minnesota		Variable depending on	Vary depending on shoulder and/or SSD				Vary depending on shoulder	Vary depending on shoulder		Either 2 ft from paved shoulder edge or just

(continued on next page)

Table 3-17. (Continued).

Agency	Most common placement location for each barrier type: Weak-post, W-beam guardrail	Box-beam barrier	Blocked-out W-beam guardrail (strong post)	Blocked-out Thrie-beam guardrail (strong post)	Modified Thrie-beam guardrail	New-Jersey-shaped concrete barrier	Single-slope concrete barrier	F-shaped concrete barrier	Three-strand cable (weak post)	High-tension cable barrier
		shoulder and/or SSD needs	needs				and/or SSD needs	and/or SSD needs		above ditch bottom on one or the other side slope
Mississippi (2003)			Center of median	Center of median	Center of median	Center of median				
Missouri			Center of median	Center of median		Center of median	Center of median		Center of ditch, vertex of ditch, or 10 ft upslope	Center of ditch, vertex of ditch, or 10 ft upslope
Montana (2003)						Center of median				
Nebraska										12 ft from driving lane
Nevada (2003)			2 ft from paved shoulder	2 ft from paved shoulder				Center of narrow medians and 2 ft from paved shoulder on wider medians > 26 ft	Center of median	
New York	Middle	Middle	Middle				Middle	Middle	Middle	
North Carolina (2003)	Shoulder		Shoulder			Center of median			4 ft from ditch center	
Ohio (2003)			Center of median			Center of median	Center of median			Center of median
Oregon			Center of median on slopes flatter than 1V:10H		Center of median on slopes flatter than 1V:10H		Center of median on slopes flatter than 1V:10H	Center of median on slopes flatter than 1V:10H, at edge of shoulder high side in a split elevation		Prefer center of median on slopes flatter than 1V:10H, may be used on 1:6 slopes if needed
Pennsylvania (2003)			Center of median				Center of median	Center of median		
South Carolina									4 ft from ditch center	
South Dakota				Center of median (used with flush		Center of median (used with	Center of median (used with	Center of median (used with flush		1 ft from center of median on 1V:6H slope;

Table 3-17. (Continued).

Agency	Most common placement location for each barrier type: Weak-post, W-beam guardrail	Box-beam barrier	Blocked-out W-beam guardrail (strong post)	Blocked-out Thrie-beam guardrail (strong post)	Modified Thrie-beam guardrail	New-Jersey-shaped concrete barrier	Single-slope concrete barrier	F-shaped concrete barrier	Three-strand cable (weak post)	High-tension cable barrier
				medians)		flush medians)	flush medians)	medians)		preferred at center of median on 1V:10H and flatter slope;
Texas						Center of median	Center of median	Center of median		8 to 12 ft from travel lane on slopes 1V:6H or flatter
Virginia	Center of median		Center of median					Center of median		
Washington			Alongside shoulder			Alongside shoulder or in the center of flatter paved medians	In the center of flatter paved medians		In the low point, or at least barrier deflection distance away from closest lane edge	In the low point, or at least barrier deflection distance away from closest lane edge
Wisconsin			Edge of shoulder					Edge of shoulder	Has been center of median but are re-considering	At least 8 to 10 ft from ditch; and beyond edge of shoulder far enough to (1) allow vehicles to pull completely off the travel lane and (2) prevent design deflection from encroaching into travel lanes
Wyoming		Center of median with slopes 1V:10H or flatter	Center of median with slopes 1V:10H or flatter	Center of median if median slope 1V:10H		Center of median with flat slope or normal crown		Center of median with flat slope or normal crown		Minimum of 8 ft off edge of traveled way or 8 ft from center of V-shaped median with 1V:6H or flatter median slope

Table 3-18. Maximum side slopes for median barrier use.

Agency	Maximum median side slope on which the specified barrier is installed									
	Weak-post W-beam guardrail	Box-beam barrier	Blocked-out W-beam guardrail (strong post)	Blocked-out Thrie-beam guardrail (strong post)	Modified Thrie-beam guardrail	New-Jersey-shaped concrete barrier	Single-slope concrete barrier	F-shaped concrete barrier	Three-strand cable (weak post)	High-tension cable barrier
Arkansas			1V:25H			1V:25H	1V:25H	1V:25H		1V:6H
Delaware			1V:10H							
Idaho			Barrier placed off shoulder with the paving surface extended to the barrier; cross-slope matches slope of roadway, end terminals may have slope of 1V:10H for flares	Barrier is placed off shoulder with the paving surface extended to the barrier; cross-slope matches slope of roadway; end terminals may have slope of 1V:10H for flares		Barrier is placed off shoulder with the paving surface extended to the barrier; cross-slope matches slope of roadway; end terminals may have slope of 1V:10H for flares				
Indiana			1V:6H max; 1V:10H or flatter desirable		1V:6H max; 1V:10H or flatter desirable			Barrier is plumb with adjacent shoulder slope; typically 1V:24H except in curves where shoulder slope might be 1V:12H.		
Iowa			1V:10H	1V:10H				1V:33H (3%)		1V:6H
Kentucky	1V:10H					1V:10H				1V:4H
Maryland			N/A; where the slope is steeper than 1V:6H, barrier is placed at edge of shoulder	N/A; when the slope is steeper than 1V:6H barrier is placed at edge of shoulder		1V:10H		1V:10H		
Minnesota		1:10 (but typically curbed application)	N/A; typically curbed application				N/A; typically curbed application	N/A; typically curbed application		1V:6H or steeper if allowed by manufacturer's recommendation
Missouri			1V:6H	1V:6H		1V:6H	1V:6H		1V:6H	1V:4H
Nebraska										1V:10H
New York	1V:8H	1V:8H	1V:8H				1V:10H	1V:10H	1V:6H	

Table 3-18. (Continued).

Agency	Weak-post W-beam guardrail	Box-beam barrier	Blocked-out W-beam guardrail (strong post)	Blocked-out Thrie-beam guardrail (strong post)	Modified Thrie-beam guardrail	New-Jersey-shaped concrete barrier	Single-slope concrete barrier	F-shaped concrete barrier	Three-strand cable (weak post)	High-tension cable barrier
	Maximum median side slope on which the specified barrier is installed									
Oregon			1V:10H		1V:10H		1V:10H	1V:10H		1V:6H
South Carolina			1V:10H						1V:6H	
South Dakota				Prefer 1V:50H; max 1V:10H		Prefer 1V:50H; max 1V:10H	Prefer 1V:50H; max 1V:10H	Prefer 1V:50H; max 1V:10H		Prefer 1V:10H or flatter; Max 1V:6H
Texas						1V:10H	1V:10H	1V:10H		1V:6H
Virginia	1V:6H		1V:6H					1V:6H		
Washington			1V:10H or flatter, or placed at least 12 ft from shoulder edge with a slope between 1V:6H and 1V:10H			1V:10H or flatter, or placed at least 12 ft from shoulder edge with a slope between 1V:6H and 1V:10H	1V:10H or flatter, or placed at least 12 ft from shoulder edge with a slope between 1V:6H and 1V:10H		Not steeper than 1V:6H	Not steeper than 1V:6H
Wisconsin			Shoulder slope					Shoulder slope	1V:6H	1V:6H
Wyoming		1V:10H	1V:10H	1V:10H		Flat or normal crown		Flat or normal crown		1V:6H min; 1V:8H or flatter preferred

Table 3-19. Distribution of barrier usage by barrier type.

Agency	Current agency usage (percent) of each of the approved barrier types									
	Weak-post W-beam guardrail	Box-beam barrier	Blocked-out W-beam guardrail (strong post)	Blocked-out Thrie-beam guardrail (strong post)	Modified Thrie-beam guardrail	New-Jersey-shaped concrete barrier	Single-slope concrete barrier	F-shaped concrete barrier	Three-strand cable (weak post)	High-tension cable barrier
Arkansas			Less than 5%			20%	30%	Less than 5%		Less than 5%
Delaware			100% where barriers are placed in rural medians, which is very seldom							
Idaho			~ 30%	~ 10% (mostly across structures that do not use a concrete barrier system)		~ 60%				
Indiana			19%		1%			80%		
Iowa			1%	0%				60%		40%
Kentucky	19%					80%				1%
Maryland			75%	5%		10%		10%		
Minnesota		5%	5%				5%	5%		80%
Nebraska										1%
New York	15%	25%	25%				25%	10%	0	
Oregon			5%		0% (to date)		5%	85%		5%
South Carolina									Majority	
South Dakota				3%		92%	5%	0%		0%
Texas						50%	30%	5%		15%
Virginia	20%		20%					10%		
Wyoming		40%	40%	5%		5%		5%		5%

Table 3-20. Responses from specific agencies about ditch cross sections used in medians.

Agency	Response		
	Width (ft)	Slopes	Depth (ft)
Delaware	60 ft preferred	1V:6H or flatter	
Indiana	V-shaped ditch is typical; 4-ft wide flat bottom ditch with 1V:5H side slopes	1V:6H or flatter typical; 1V:5H w/ flat bottom ditch	4.2 ft max typical; 4.6 ft max (w/flat bottom ditch)
Iowa		1V:50H	4 ft
Kentucky	Varies	1V:6H	2.8 ft for earth shoulder, 2.58 ft for paved shoulder
Minnesota	Varies	1V:4H to 1V:6H	3 ft typical
Missouri	8 ft	1V:5.5H	4 ft
Nebraska	10 ft min	1V:6H	3 ft
Oregon	6 ft, one on each side of median	1V:6H	0.5 ft
South Carolina	28 ft	1V:6H	2.3 ft
Washington	Varies	1V:6H	2 ft
Wisconsin	0	1V:6H max	1 ft below subgrade shoulder
Wyoming	76 ft preferred for new projects	1V:6H min; 1V:8H or flatter preferred	2 ft min

Table 3-21. Responses from specific agencies about typical cross sections for divided highway medians.

Agency	Dimensions used in typical median cross sections				
	Median width (ft)	Median shoulder width (ft)	Median side slope	Ditch width (if specified)	Ditch depth (if specified)
Arkansas	60	6	1V:6H	NA	1.5 ft below subgrade
Delaware	60	4	1V:6H		
Idaho	38	4	1V:6H		At least 0.5 ft below roadway ballast section
Indiana	60	4	1V:5H[a]	4 ft for flat bottom ditch[b]	Approx. 4.2 ft[c]
Iowa	64	6	1V:6H		4 ft
Kentucky	40	6	1V:6H	Varies	2.8 ft for earth shoulder; 2.58 ft for paved shoulder
Minnesota	60	4	1V:4H to 1V:6H	8 ft	3 ft
Missouri	60	4	1V:6H	8 ft	4 ft
Nebraska	64	6	1V:6H	10 ft min	3 ft
South Carolina	48	10	1V:6H	28 ft	2.3 ft
South Dakota	26	4	1V:6H		
Texas	76	4	1V:12H		
Virginia	60	15	1V:10H	Based on hydrology	Based on hydrology
Washington	40	4	1V:6H		2 ft
Wisconsin	60	6	1V:6H	0	1 ft below shoulder subgrade
Wyoming	76	4	1V:6H or flatter	Not specified—use normal rounding	2 ft min; 3 ft or greater preferred

[a] Applicable to graded median; 1V:24H side slope used in flush paved median.
[b] No ditch width given for graded median with V-shaped ditch.
[c] Applicable to graded median with V-shaped ditch; approximately 4.6-ft width used for graded median with flat bottom ditch.

3.4 In-Service Performance Evaluations and Unpublished Reports

The Iowa Department of Transportation and the Ohio Department of Transportation submitted reports of the use of the Brifen Wire Rope Safety Fence (WRSF). Tabulations of median-related crashes were received from the Oregon Department of Transportation and the Washington State Department of Transportation. These studies are summarized in the remainder of this section.

3.4.1 Iowa Department of Transportation

Iowa DOT installed Brifen Wire Rope Safety Fence on I-35 north of Des Moines in December 2003. The barrier was installed just inside the southbound shoulder of the freeway. Posts were set in socketed sleeves to enable easy replacement of posts damaged in crashes. In the period from December 2003 to August 2005, there were 20 reported accidents involving the cable barrier system. There were no fatalities or cross-median crashes. There was one injury crash where a vehicle impacted a semi-tractor trailer and then rolled over the barrier. The barrier was impacted by both northbound and southbound vehicles, although southbound crashes were more frequent due to the location of the barrier near the southbound shoulder.

Iowa DOT was pleased with the performance of the barrier and installed a second system on a non-controlled-access highway in Cedar Falls. Issues raised in the report included:

1. Difficulty of replacing posts in winter conditions,
2. Bidding of four-strand and three-strand systems under one item, and
3. Ease of snow removal with cable barrier as opposed to concrete barriers.

3.4.2 Ohio Department of Transportation

Ohio DOT evaluated the Brifen Wire Rope Safety Fence (WRSF) and has provided in-service performance reports for the first 2 years of a 3-year evaluation period. A presentation was obtained that reported on all 3 years of the evaluation. ODOT installed the Brifen WRSF on I-75 north of Cincinnati. The roadway is a 23.3-km (14.5-mi) section of six-lane rural Interstate with an 18-m (60-ft) depressed median with 1V:10H side slopes. The median shoulder width is 1.2 m (4 ft) and the barrier was installed 5 m (15 ft) from the edge of traveled way. The roadway has an ADT of 92,000 vehicles per day with 22 percent trucks.

ODOT developed a special form for reporting crashes with the barrier system. This form was supplemented with photo and crash report forms. Maintenance reports of repairs to damaged barrier sections also were made.

The analysis of median crashes showed a total of 233 crashes in 2 years. No serious injuries or fatalities were experienced in these crashes. The total number of crashes in the 2 years since the cable was installed did increase by 26 percent. ODOT maintenance did experience difficulty in replacing nonsocketed posts and recommended that driven posts be replaced with the socketed type.

A summary of crashes over 3 years revealed 13 penetration hits with only 3 from the opposing roadway. Many of the vehicles were spinning when they hit the barrier and at least one vehicle overturned on the barrier. Several trucks hit the barrier with only one recorded penetration.

There were no fatal cross-median crashes in the 3-year period after the cable installation.

3.4.3 Washington State Department of Transportation

The Washington State DOT has published several reports on median safety. At the time of this writing, they were conducting a comparison of barrier collisions with various types of barriers. This data is still being analyzed by WSDOT.

3.4.4 Oregon Department of Transportation

The Oregon DOT studied the safety performance of open medians and drafted a revised policy on warrants for median barriers. A plot of accidents occurring on medians without barriers (open medians) is shown in Figure 3-1. The crash data used in Figure 3-1 was furnished to the project team.

3.5 Analysis of Trends in the State of Median Design

Only about one-third of the responding agencies have not changed their median design practices in some way since 2003. This in itself is evidence that median design practice and use of median barriers is changing rapidly. If the 2006 survey results are contrasted with those of the 2003 survey, several specific changes are evident.

First, agencies are now placing median barriers on wider medians than in the past. For example, Maryland now installs median barriers in 23-m (75-ft) medians if the ADT of the roadway is 80,000 vehicles per day or greater. In other states, the median widths used for median barrier warrants on high-ADT routes were 20, 18, and 15 m (64, 60, and 50 ft). The direction of this trend is generally consistent with Chapter 6 of the AASHTO *Roadside Design Guide*, which calls for median barrier to be considered on controlled-access roadways

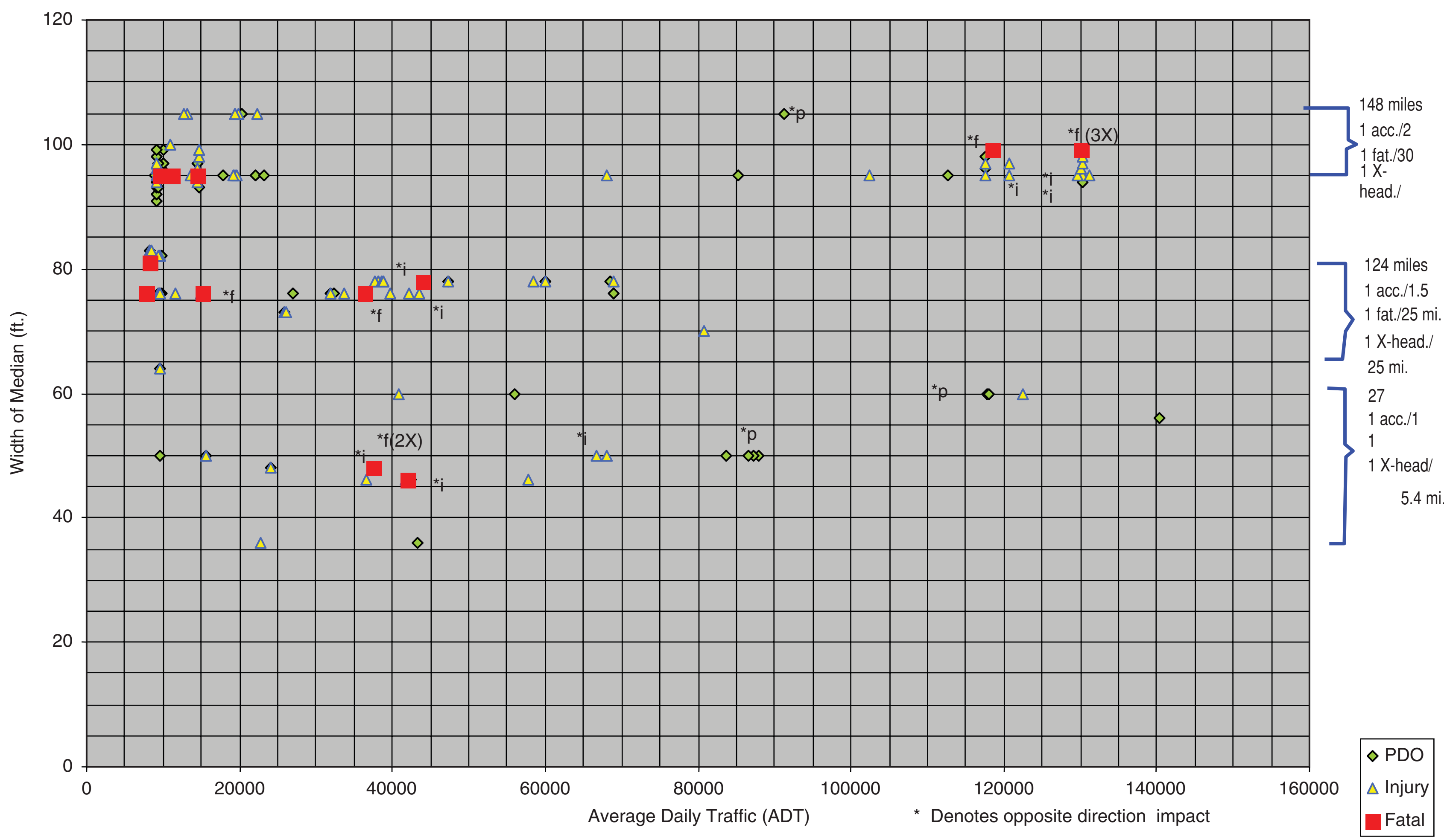


Figure 3-1. Summary of traversable median crashes on Oregon divided highways (2002–2005) (Oregon DOT).

when medians are 15 m (50 ft) or less and ADTs are over 20,000 vehicles per day.

Second, it is evident that many more agencies have approved the use of high-tension cable median barrier. Five manufacturers of this type of barrier are now listed in the AASHTO *Roadside Design Guide* and its use is approved in 13 of the highway agencies that responded to the 2006 survey. According to the survey, there is less use of three-strand cable barrier than in 2003. This may be due to more competition in high-tension cable barriers, or to the high cost of maintenance for the three-strand cable barriers. There have been some changes in the placement criteria for both types of cable barrier. Some agencies are now specifying placement 2.4 to 3 m (8 to 10 ft) upslope from the low point of the median. This placement is meant to minimize crashes that may go under some cable barrier designs. However, various policies on barrier placement indicate that many agencies are still unsure of how to best use the new cable barrier designs.

There were no major changes in typical median cross sections. Median width and median side slopes dimensions in the 2006 survey were in about the same range as in the 2003 survey. Side slopes seem to be changing only in relation to median barrier usage.

CHAPTER 4

Safety Analysis of Median Cross-Section Design

The safety analysis involved consideration of roadway and crash data for two types of medians on rural divided highways. These median types were traversable medians and medians with barriers.

A traversable median is defined as a median in which there is no median barrier and few fixed objects or steep slopes that would hinder an out-of-control vehicle from crossing the entire median and entering the opposing travel lanes. A traversable median may have short lengths of roadside barrier at individual fixed objects or terrain features, but does not have a continuous median barrier. If an out-of-control vehicle enters a traversable median, three outcomes are possible; the vehicle will either return to the original traveled way, come to rest in the median due to the driver's action or of its own accord, or cross the median and enter the opposing lanes. The objective of the safety analysis of traversable medians is to develop a methodology to predict the safety performance of traversable medians, specifically expected crash frequency, and severity, as a function of key median cross-section design variables including median width and median slopes.

The definition of a barrier median is self-evident; such medians contain a barrier placed by the highway agency to minimize the possibility that out-of-control vehicles will cross the median. A barrier median is one with a continuous median barrier for an extended section. A traversable median with short lengths of barrier at individual fixed objects and terrain features is not considered a barrier median.

4.1 Target Crashes

The safety performance measures used in the statistical modeling for median cross sections included total crashes and crash severity levels. The primary safety analysis considered median-related crashes and included crashes in traversable medians, and crashes in medians with barriers.

4.1.1 Median-Related Crashes

Median-related crashes are defined as crashes in which one or more of the involved vehicles departs from the left side of one of the divided roadways and enters the median. Median-related crashes were classified into specific crash types by the crash outcome. The basic crash types that can occur in any median type include

- Rollover crashes in the median,
- Fixed-object crashes in which one or more vehicles strike a fixed-object (other than median barrier),
- Crash-involved vehicle comes to a rest in the median, and
- Vehicle departs from, and then returns to, the original traveled way.

In addition, there are median-related crash types that can occur in only specific median types. These include

- Cross-median crashes that can only occur in traversable medians or in barrier medians where a vehicle crosses or penetrates the barrier and
- Barrier crashes in which one or more of the involved vehicles strike the median barrier.

Each of these crash types is addressed in the following discussion of the median types in which they may occur.

4.1.2 Crashes in Traversable Medians

All of the four basic crash types that can occur in any median type are possible on traversable medians. In addition, the following specific crash types that will primarily occur on roadways with traversable medians include

- Crossed median, entered opposing traveled way and collided with an opposing vehicle; and
- Crossed median, entered opposing traveled way, but did not collide with an opposing vehicle.

The first of these crash types, which involves a collision with an opposing vehicle, is often referred to as a cross-median crash (CMC) or a crossover crash. The second of these crash types, which involves a vehicle that enters or crosses the opposing roadway but does not collide with an opposing vehicle, has been referred to as noncollision cross-median crashes (NCMC). CMCs have high severity because they involve a collision between vehicles traveling in opposite directions. Concern about the frequency of CMCs has led to the addition of barriers to traversable medians.

The four basic crash types listed in Section 4.1.1 can be readily identified from computerized crash records. CMCs and NCMCs are difficult to identify without a review of hardcopy police crash reports. Most state accident data do not include a code that indicates explicitly whether a vehicle entered an opposing roadway or collided with an opposing vehicle. Procedures were developed to use computerized crash data in identifying candidate crashes, but review of hardcopy police crash reports was done for some crashes to ensure that CMCs and NCMCs were correctly identified.

4.1.3 Crashes in Medians with Barriers

Specific median-related crash types that primarily occur on roadways that have a median barrier include the following:

- Hit barrier;
- Went over or through barrier, hit opposing vehicle (CMC);
- Went over or through barrier, entered opposing roadway but did not collide with opposing vehicle (NCMC);
- Rollover;
- Fixed object crash; and
- Other median-related crash.

The research team assigned crashes to these categories based primarily on computerized crash data, but a limited review of hardcopy police crash reports from Ohio and Pennsylvania was used to test the methodology for properly classifying some crashes. A review of hardcopy police crash reports was conducted to verify that all barrier-involved crashes could be classified with computerized crash data.

4.1.4 Crash Sorting Sequence

Electronic crash databases vary by state, but the general procedure for identifying median-related crashes had the following steps:

1. Obtain all crashes for a rural divided highway segment.
2. Sort crashes to distinguish median-related crashes from on-roadway crashes and run-off-road crashes involving the right side of the roadway. Fields such as first harmful event, most harmful event, and sequence of events, as well as the overall crash classification, were used to identify crashes in which a vehicle did run off the road into the median. The median-related crashes were then culled to remove ramp, backing, and wrong-way crashes, and crashes in which vehicles purposefully entered or crossed the median.
3. Sort the median-related crashes to identify overturn, struck-barrier, vaulted-, or broke-through-barrier, CMCs, and NCMCs.
4. Determine the proportion of severe crashes in each crash category.

(The sorting sequences for each state are shown in Appendix C which is available on the TRB website.)

4.2 Analysis of Traversable Medians

The objective of the analysis was to determine the effects of key median cross-section design features and roadway characteristics on the safety performance of traversable medians. The key median cross-section design features of interest are median width and median slopes. The key roadway characteristic of interest is traffic volume. Other roadway characteristics considered are median shoulder types and widths, locations of interchange ramps, particularly entrance ramps, locations of horizontal curves, and presence of median shoulder rumble strips.

Past studies of the safety performance of geometric design features of roadways have used two fundamentally different approaches: before-after evaluation and statistical model development. Before-after evaluation was not a feasible approach to analysis of traversable medians in this research because highway agencies seldom implement projects that change the width or slope of a traversable median without making other more extensive changes as part of the same project. Therefore, a statistical modeling approach based on negative binomial regression was used in the analysis of traversable medians. A commonly used term for the type of analysis in highway research is cross-sectional analysis. However, this term may be confusing in the context of this project, because it refers to a statistical cross-sectional approach, rather than to analysis of the highway median cross section; therefore, the term *cross-sectional analysis* is not used in this research.

On many rural divided highways, median widths are consistent over extended sections of roadway, although median widths for some roadways with curvilinear alignment are designed to vary continuously. In contrast, on many divided roadways median slopes may vary along the roadway as the cross-section design is adapted to specific terrain features.

Roadway sections used to assess the safety performance of traversable medians are defined on the basis of their median cross-section design policies. Median cross-section designs for traversable medians are characterized by median width (measured from edge of traveled way to edge of traveled way) and the steepness of the median slopes (1V:4H, 1V:6H, 1V:8H, 1V:10H, etc.). Specific combinations of median width and median slope can be referred to either as a typical cross-section or a median cross-section design policy.

The objective of the analysis of traversable medians was to determine and compare the expected crash frequency and crash severity distribution for specific median cross-section designs. The remainder of this section presents the safety measures (dependent variables), median cross-section and roadway characteristics (independent variables), data collected, and data analyses performed.

4.2.1 Safety Measures (Dependent Variables)

The safety measures for the analysis of traversable medians are the crash frequencies (overall and by crash severity level) for specific median typical cross sections. Specific crash severity levels of interest include the following:

- All crash severity levels combined,
- Fatal-and-injury crashes, and
- Property-damage-only crashes.

Decisions concerning appropriate median cross-section designs are driven primarily by the frequencies of fatal-and-injury crashes. However, the frequency of less severe injury crashes must be considered because of their importance in comparison of the differences in safety performance between traversable and barrier medians. Property-damage-only crashes were considered, particularly because placement of a barrier would be expected to increase property-damage-only crashes.

Specific crash types of interest are as follows:

- Median-related crashes,
- CMCs,
- NCMCs,
- Rollover crashes,
- Fixed-object crashes, and
- Other median-related crashes.

4.2.2 Median Cross-Section and Roadway Characteristics (Independent Variables)

The median cross-section and roadway characteristics of interest are as follows:

- Traffic volume (ADT) for mainline roadways;
- Median width (edge of traveled way to edge of traveled way);
- Typical median slope category (e.g., 1V:4H, 1V:6H, 1V:10H, etc.);
- Number of lanes by direction of travel;
- Inside shoulder type and width;
- Presence of entrance and exit ramps;
- Presence of horizontal curves; and
- Presence of rumble strips.

Independent variables in addition to ADT and median width were incorporated in models where they are found to significantly affect median crash frequencies or severities.

4.2.3 Data Collection

Steps in collecting the data for analysis of traversable medians included choosing cooperating states that could furnish crash and roadway data needed, selecting sites for each agency, and collecting field and other supplementary data needed to ensure a credible study.

Participating States

Several state highway agencies agreed to furnish data for this research. Of those who were willing to furnish data the researchers identified six states (California, Missouri, North Carolina, Ohio, Pennsylvania, and Washington) with reliable roadway and crash data and appropriate sites for the research. These states were selected for the following reasons:

- California, North Carolina, Ohio, and Washington are participants in FHWA's Highway Safety Information System (HSIS). Their data are, therefore, readily accessible to the research team and known to be of high quality.
- Missouri was selected because of MoDOT's extensive recent installation of cable barrier in freeway medians and because of their extensive mileage of rural divided nonfreeways. In addition, the research team has worked extensively with MoDOT data in past studies, and has an established agreement with MoDOT for online access to their roadway, crash, and video log data.

- Pennsylvania was selected because their existing computerized roadway data files already classify divided highway medians into traversable, nontraversable, or barrier categories. The research team has used Pennsylvania data extensively in previous median cross-section safety research for PennDOT.

These states had sufficient mileage sites available to furnish the required sample sizes and had medians with various typical cross sections.

Data Set Collected from Computerized Files

The following list identifies the variables collected from existing computerized data files provided by state highway agencies (or obtained from HSIS to save state highway agency labor):

- Median width,
- Presence/absence of barrier,
- Type of barrier,
- Barrier location relative to traveled way,
- Number of lanes by direction of travel,
- Median shoulder width (ft),
- Presence of rumble strips on median shoulder,
- Segment length (mi),
- Posted speed limit,
- ADT (veh/day),
- Ramp locations,
- Mileposts or other location reference data that ties to crash locations, and
- Electronic crash records.

Note, some data was obtained or verified from state highway agency videologs or verified during field data collection.

Median widths were available from existing computerized roadway inventory databases, but review of typical cross sections on as-built plans was not a good source of median slope data. Median slope data had to be determined from field data collection as described in this subsection.

Data collection for the basic data set for traversable medians was conducted jointly with similar activities for the basic data set for barrier medians. Medians with barriers were categorized by the type of barrier and the location of the barrier within the median, usually near the edge of the shoulder, in the center of the median, or 2.4 m (8 ft) upslope from the median ditch line.

At least 5 years of crash data were obtained as well as yearly ADT data corresponding to the crash data. For the states of California, North Carolina, Ohio, and Washington, crash data was obtained from the FHWA HSIS system. The research team had on-line access to Missouri crash data. Pennsylvania crash data was obtained through arrangements with PennDOT. The crash data period varied from state to state. The years of crash data used from each state are as follows:

- California—2001 to 2005,
- Missouri—2002 to 2007,
- North Carolina—2000 to 2004,
- Ohio—2001 to 2005,
- Pennsylvania—2002 to 2006, and
- Washington—2001 to 2005.

Field Data Collection

The following two methods were used to collect field data:

- Use of Penn State's scanning laser system developed during this research. Penn State's system, described in more detail in Appendix D of this report (available on the TRB website), consists of a scanning laser mounted on the rear of a vehicle. This system has the capability to create a digital terrain map of the median. This system was used to collect detailed field data in California, North Carolina, Ohio, Pennsylvania, and Washington State. In all participating states except Pennsylvania, data sections coincided with mile markers and were 1.6 km (1 mi) in length. In Pennsylvania, reference markers are placed every 0.8 km (0.5 mi), so study sections were 0.8 km (0.5 mi) in length.
- Manual measurements of median cross-section features including median slopes. In Missouri, manual measurement of median cross-section features was made by a team of two trained field personnel. Slope measurements were made with an electronic level and dimensions of cross-section features were measured with a measuring wheel or tape. Point or continuous objects in the median, other than median barrier, were measured over a 60-m (200-ft) section, 30 m (100 ft) either side of the sample measurement point. Field data collectors also categorized the horizontal or vertical curves at each measurement point. Presence of shoulder rumble strips was verified. A pilot test was conducted as part of the research to estimate field data collection costs. Measurements of the median cross section for a 3.2-km (2-mi) section required approximately 3 hours for a two-person team.

The manual field measurement method was very labor intensive and the scanning laser system was used in five of the six participating states to minimize the cost of collecting a detailed data set. Automated data collection was shown to

Table 4-1. Total roadway mileage for project database.

State	Area type	Road type	Traversable median (mi)	Barrier median (mi)	Combined (mi)
CA	Rural	Freeway	263.17	52.00	315.17
		Nonfreeway	37.12	3.86	40.98
	Urban	Freeway	14.00	12.00	26.00
MO	Rural	Freeway	55.00	65.50	120.50
		Nonfreeway	150.50	0.00	150.50
	Urban	Freeway	0.00	3.00	3.00
		Nonfreeway	6.00	0.00	6.00
NC	Rural	Freeway	17.00	385.81	402.81
		Nonfreeway	0.00	16.55	16.55
	Urban	Freeway	20.79	92.85	113.64
		Nonfreeway	0.00	5.00	5.00
OH	Rural	Freeway	126.81	45.08	171.89
	Urban	Freeway	37.87	22.72	60.59
PA	Rural	Freeway	254.59	32.47	287.06
WA	Rural	Freeway	181.33	43.24	224.57
		Nonfreeway	33.02	0.00	33.02
	Urban	Freeway	31.14	11.97	43.11
Total			1,228.34	792.05	2,020.39

be both accurate and less expensive than manual field data collection.

4.2.4 Crash Statistics for Traversable Medians

The mileage of freeway and nonfreeway sites is shown in Table 4-1. The total roadway length considered was 3,250.8 km (2,020.4 mi). There were 1,976.4 km (1,228.3 mi) with traversable medians. The sample of rural freeways totaled 1,444.7 km (897.9 mi) in length, while rural nonfreeways totaled 355.0 km (220.6 mi). There were 176.7 km (109.8 mi) of traversable medians on urban roadways.

The frequency of crashes for traversable sites on rural freeways is shown in Table 4-2. This table also shows the number and proportion of median-related crashes. On rural freeways with traversable medians, about 26 percent of total crashes were median related. Table 4-2 also gives the frequency and proportion of each crash type that constitutes median-related crashes on traversable medians. Rollover crashes are about 35 percent of median-related crashes on traversable medians. Fixed-object crashes are about 33 percent, and other median-related crashes are about 27 percent of median-related crashes. The CMCs and NCMCs total less than 5 percent of median-related crashes on rural freeways.

The frequency of crashes for traversable sites on rural nonfreeways is shown in Table 4-3. This table is formatted in the same way as Table 4-2. On rural nonfreeways with traversable medians, about 31 percent of total crashes were median related. Fixed-object crashes were 27 percent, and other median-related crashes were about 35 percent. CMCs and NCMCs totaled almost 7 percent of the median-related crashes on rural nonfreeways.

Table 4-2. Crash frequency for traversable medians on rural freeways.

State	Total crashes	Crash type: Median-related crashes (percent of total)	Rollover crashes (percent of median-related)	CMCs (percent of median-related)	NCMCs (percent of median-related)	Fixed-object crashes (percent of median-related)	Other median-related crashes (percent of median-related)
CA	4,651	1,516 (32.59)	698 (46.04)	56 (3.69)	4 (0.26)	273 (18.00)	485 (31.99)
MO	878	297 (33.82)	75 (25.25)	13 (4.37)	15 (5.05)	61 (20.53)	133 (44.78)
NC	595	73 (12.26)	7 (9.58)	0 (0.00)	1 (1.36)	26 (35.61)	39 (53.42)
OH	5,497	1,184 (21.53)	198 (16.72)	33 (2.78)	1 (0.08)	459 (38.76)	493 (41.63)
PA	3,467	844 (24.34)	137 (16.23)	28 (3.31)	24 (2.84)	543 (64.33)	112 (13.27)
WA	3,298	890 (26.98)	589 (66.17)	29 (3.25)	10 (1.12)	211 (23.70)	51 (5.73)
Total	18,386	4,804 (26.12)	1,704 (35.47)	159 (3.30)	55 (1.14)	1,573 (32.74)	1,313 (27.33)

Table 4-3. Crash frequency for traversable medians on rural nonfreeways.

State	Total crashes	Crash type: Median-related crashes (percent of total)	Rollover crashes (percent of median-related)	CMCs (percent of median-related)	NCMCs (percent of median-related)	Fixed-object crashes (percent of median-related)	Other median-related crashes (percent of median-related)
CA	221	68 (30.76)	29 (42.64)	6 (8.82)	1 (1.47)	13 (19.11)	19 (27.94)
MO	1,843	579 (31.41)	143 (24.69)	21 (3.62)	16 (2.76)	171 (29.53)	228 (39.37)
WA	228	55 (24.12)	42 (76.36)	3 (5.45)	0 (0.00)	9 (16.36)	1 (1.81)
Total	2,292	702 (30.62)	214 (30.48)	30 (4.27)	17 (2.42)	193 (27.49)	248 (35.32)

The crash severity distribution for traversable medians on rural freeways is shown in Table 4-4. In traversable medians, CMCs are much more severe than fixed-object or rollover crashes. Although CMCs are only 3.3 percent of total median-related crashes, they represent over 17 percent of the fatal crashes in traversable medians on rural freeways. Rollover crashes also are severe and represent 58 percent of fatal and 52 percent of injury crashes on traversable medians on rural freeways.

The crash severity distribution for traversable medians on rural nonfreeways is shown in Table 4-5. Again, CMCs are much more severe than fixed-object or rollover crashes. Although CMCs are only 4 percent of crashes, they represent almost 17 percent of the fatalities on rural nonfreeway traversable median sites. Rollover crashes are also severe. They are about 30 percent of crashes, but represent almost 42 percent of fatal crashes.

Table 4-4. Crash severity distribution for traversable medians on rural freeways.

State	Severity level	Total crashes	Crash type: Median-related crashes (percent of total crashes)	Rollover crashes (percent of median-related crashes)	CMCs (percent of median-related crashes)	NCMCs (percent of median-related crashes)	Hit-fixed-object crashes (percent of median-related crashes)	Other median-related crashes (percent of median-related crashes)
CA	Fatal	175	102 (58.28)	61 (59.80)	13 (12.74)	1 (0.98)	9 (8.82)	18 (17.64)
	Injury	1,745	762 (43.66)	449 (58.92)	33 (4.33)	2 (0.26)	60 (7.87)	218 (28.60)
	PDO	2,731	652 (23.87)	188 (28.83)	10 (1.53)	1 (0.15)	204 (31.28)	249 (38.19)
MO	Fatal	20	10 (50.00)	3 (30.00)	3 (30.00)	0 (0.00)	1 (10.00)	3 (30.00)
	Injury	240	136 (56.66)	48 (35.29)	7 (5.14)	2 (1.47)	22 (16.17)	57 (41.91)
	PDO	618	151 (24.43)	24 (15.89)	3 (1.98)	13 (8.60)	38 (25.16)	73 (48.34)
NC	Fatal	6	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)	0 (0.00)
	Injury	197	29 (14.72)	5 (17.24)	0 (0.00)	0 (0.00)	10 (34.48)	14 (48.27)
	PDO	392	44 (11.22)	2 (4.54)	0 (0.00)	1 (2.27)	16 (36.36)	25 (56.81)
OH	Fatal	26	17 (65.38)	7 (41.17)	6 (35.29)	0 (0.00)	3 (17.64)	1 (5.88)
	Injury	994	384 (38.63)	124 (32.29)	16 (4.16)	0 (0.00)	109 (28.38)	135 (35.15)
	PDO	4,477	783 (17.48)	67 (8.55)	11 (1.40)	1 (0.12)	347 (44.31)	357 (45.59)
PA	Fatal	73	29 (39.72)	15 (51.72)	6 (20.68)	0 (0.00)	8 (27.58)	0 (0.00)
	Injury	1,453	333 (22.91)	85 (25.52)	14 (4.20)	15 (4.50)	171 (51.35)	48 (14.41)
	PDO	1,941	482 (24.83)	37 (7.67)	8 (1.65)	9 (1.86)	364 (75.51)	64 (13.27)
WA	Fatal	52	22 (42.30)	18 (81.81)	3 (13.63)	0 (0.00)	1 (4.54)	0 (0.00)
	Injury	1,223	416 (34.01)	343 (82.45)	15 (3.60)	1 (0.24)	47 (11.29)	10 (2.40)
	PDO	2,023	452 (22.34)	228 (50.44)	11 (2.43)	9 (1.99)	163 (36.06)	41 (9.07)
Total	Fatal	352	180 (51.13)	104 (57.77)	31 (17.22)	1 (0.55)	22 (12.22)	22 (12.22)
	Injury	5,852	2,060 (35.20)	1,054 (51.16)	85 (4.12)	20 (0.97)	419 (20.33)	482 (23.39)
	PDO	12,182	2,564 (21.04)	546 (21.29)	43 (1.67)	34 (1.32)	1,132 (44.14)	809 (31.55)
	Total	18,386	4,804 (26.12)	1,704 (35.47)	159 (3.30)	55 (1.14)	1,573 (32.74)	1,313 (27.33)

Table 4-5. Crash severity distribution for traversable medians on rural nonfreeways.

State	Severity level	Total crashes	Crash type: Median-related crashes (percent of total crashes)	Rollover crashes (percent of median-related crashes)	CMCs (percent of median-related crashes)	NCMCs (percent of median-related crashes)	Fixed-object crashes (percent of median-related crashes)	Other median-related crashes (percent of median-related crashes)
	Fatal	6	2 (33.33)	0 (0.00)	1 (50.00)	0 (0.00)	0 (0.00)	1 (50.00)
	Injury	92	39 (42.39)	21 (53.84)	4 (10.25)	1 (2.56)	2 (5.12)	11 (28.20)
CA	PDO	123	27 (21.95)	8 (29.62)	1 (3.70)	0 (0.00)	11 (40.74)	7 (25.92)
	Fatal	42	19 (45.23)	8 (42.10)	3 (15.78)	0 (0.00)	4 (21.05)	4 (21.05)
	Injury	548	257 (46.89)	89 (34.63)	13 (5.05)	9 (3.50)	52 (20.23)	94 (36.57)
MO	PDO	1,253	303 (24.18)	46 (15.18)	5 (1.65)	7 (2.31)	115 (37.95)	130 (42.90)
	Fatal	8	3 (37.50)	2 (66.66)	0 (0.00)	0 (0.00)	1 (33.33)	0 (0.00)
	Injury	78	26 (33.33)	24 (92.30)	0 (0.00)	0 (0.00)	2 (7.69)	0 (0.00)
WA	PDO	142	26 (18.30)	16 (61.53)	3 (11.53)	0 (0.00)	6 (23.07)	1 (3.84)
	Fatal	56	24 (42.85)	10 (41.66)	4 (16.66)	0 (0.00)	5 (20.83)	5 (20.83)
	Injury	718	322 (44.84)	134 (41.61)	17 (5.27)	10 (3.10)	56 (17.39)	105 (32.60)
	PDO	1,518	356 (23.45)	70 (19.66)	9 (2.52)	7 (1.96)	132 (37.07)	138 (38.76)
Total	Total	2,292	702 (30.62)	214 (30.48)	30 (4.27)	17 (2.42)	193 (27.49)	248 (35.32)

4.2.5 Statistical Analysis/Modeling of Crash Data for Traversable Medians

Regression models, or safety performance functions (SPFs), were developed to estimate the effect of cross-section design features on traversable median safety performance. Safety performance was estimated as a function of traffic volume, median width, and median slope, as well as four other independent variables found to have a statistically significant relationship with safety. The analysis focused on frequency and severity—total and fatal-and-injury—of the following crash types: all median related; rollover in the median; hit fixed object in median (other than barrier); entered opposing traveled way and collided with an opposing vehicle (CMC); entered opposing traveled way, but did not collide with an opposing vehicle (NCMC); all cross-median collision types; and other median-related collisions. Thus, a total of 14 dependent variables were considered for 7 target crash types and 2 crash severity levels.

SPFs were developed with multiple regression, assuming a negative binomial (NB) error distribution of accident frequencies, using data from all traversable median sites and barrier sites for the period before barrier installation. The decision to include the before period of barrier sites was made to maximize the amount of information used to develop the functions. Separate models were developed for each state as well as combined state models for each of the following three classifications of roadways:

- Four-lane freeway,
- Four-lane nonfreeway, and
- Six-lane freeway.

Two generalized linear modeling techniques were used to fit the data. The first method used a repeated measures correlation structure to model yearly crash counts for a site. In this method, the covariance structure, assuming compound symmetry, is estimated before final regression parameter estimates are determined by general estimating equations. Consequently, model convergence for this method is dependent on the covariance estimates as well as parameter estimates. When the model failed to converge for the covariance estimates, an alternative method was considered. In this method, yearly crash counts for a site were totaled and ADT values were averaged to create one summary record for a site. Regression parameter estimates were then directly estimated by maximum likelihood, without an additional covariance structure being estimated.

Both methods also produced an estimate of the overdispersion parameter, or the estimate for which the variance exceeds the mean. Overdispersion occurs in traffic data when a number of sites being modeled have zero accident counts, which creates variation in the data. In this study, most sites tended to have positive accident counts because they were a mile in length, particularly when accident counts were aggregated across multiple years. When the estimate for dispersion was very small or even slightly negative, the model was re-fit assuming a constant value.

The best estimates of the safety effectiveness of highway design features are likely to be determined from observational before-after studies of projects that changed the design feature in question (and only that design feature). Such evaluations focus solely on the effect of that particular design feature and can be performed using the Empirical Bayes (EB) method to compensate for the potential bias due to regression to the mean. A before-after study of the effects of installing median barrier is presented later in this report in Section 4.3.6. However, before-after evaluations are not often feasible for other roadside design features because such features are seldom changed without accompanying changes to other roadway or roadside features.

Where before-after studies are not feasible, cross-sectioned studies based in regression modeling are usually the best available alternative. The results of cross-sectional studies should be used cautiously because correlations between the study variables may produce regression coefficients whose values do not necessarily represent the incremental effects of those variables on crash frequency. A cross-sectional approach of this type has been applied below to the evaluation of median cross-section design features.

Models produced for both methods, yearly and summary, estimate crashes per mile per year. To include this rate calculation, the first method used site length as an offset in the model while the second method used the number of years of crash data multiplied by site length as the offset. When both methods produce models, parameter estimates are nearly identical. However, confidence intervals for estimates produced with yearly crash counts tend to be wider due to yearly variation. Consequently, statistical significance of the estimates is harder to achieve with yearly models. Both methods were accomplished with the GENMOD procedure of SAS.

The primary difference between methodologies occurred for the combined models from more than one state. The treatment of the state effect differed between methodologies. For the repeated measures or yearly method, the covariance structure used captured most of the variations in the data. Consequently, no additional adjustment was needed to account for the state effect. On the other hand, the summary record method treated state as a random effect in the model. The mixed model for this method was generated with the GLIMMIX procedure of SAS.

Of the independent variables summarized in the previous section, an attempt was made to incorporate as many variables, in addition to ADT, in the SPF to obtain the best possible function to predict crashes at traversable median sites. ADT was included in all models, regardless of its significance, as long as its coefficient was positive. Selection of the remaining variables in the model was performed by evaluating the statistical significance at the 80 percent confidence level. Additionally, the following three independent variables had the additional criterion that the resulting relationship between the characteristic and safety was meaningful in engineering terms:

- Presence of on-ramps increases crashes,
- Presence of horizontal curves increases crashes, and
- Presence of shoulder rumble strips decreases crashes.

All regression models for median-related collision types were developed to predict target crash frequencies per mile per year in the following form:

$$N = \exp(b_0 + b_1 \ln\text{ADT} + b_2 X_2 + \cdots + b_n X_n) \qquad (2)$$

where:

N = predicted accident frequency per mile per year
ADT = average daily traffic volume (veh/day)
$b_0, \ldots, b_n$ = regression coefficients determined by model fitting
$X_1, \ldots, X_n$ = independent design characteristics

A typical model of this type has the form:

$$N = \exp\begin{pmatrix} b_0 + b_1 \ln\text{ADT} + b_2\text{MW} + b_3\text{MS} \\ + b_4\text{SW} + b_5\text{CP} + b_6\text{OR} + b_7\text{RS} \end{pmatrix} \qquad (3)$$

where:

MW = median width (ft)
MS = median slope ratio
SW = shoulder width (ft)
CP = curve presence (= 0 for tangent sites; = 1 for sites on horizontal curves)
OR = on-ramp presence (= 0 for sites with no on-ramp present; = 1 for sites with an on-ramp present)
RS = rumble strip presence (= 0 for sites with no shoulder rumble strip present; = 1 for sites with a shoulder rumble strip present)

The median slope ratio is the ratio of the horizontal component of the median foreslope to the vertical component. For example, if the median foreslope is 1V:4H then MS = 4.

The modeling process often produced more than one suitable model for the purposes of this research. When this occurred, final models were selected from all possible models by the following considerations:

1. Select the model with the most significant variables.
2. When deciding between models with an equal number of independent variables, select the model with more important variables (e.g., median slope took precedence over number of ramps).
3. As part of this process, also consider variable effect size.

The regression models developed with this approach are presented next, where each of the elements of design are fully discussed.

Tables 4-6 and 4-7 present the final SPFs for traversable medians for the total and fatal-and-injury crash severity levels, respectively. Model coefficients including the standard error for each coefficient, as well as the overdispersion parameter for the model, are presented for each crash type

Table 4-6. Safety performance models for all crash severity levels combined for roadways with traversable medians.

Median-related crash type	Road type	Model coefficient (standard error)									Comment
		Intercept	ADT[a]	Median width	Median slope ratio	Shoulder width	Curve presence	On-ramp presence	Rumble strip presence	Overdispersion parameter	
All median-related crashes	Four-lane freeway	–7.9411	0.7946	0.0027	–0.0241	–	–	0.2655	–	0.2851[b]	All years combined
		(0.6817)	(0.0656)	(0.0009)	(0.0116)	–	–	(0.0652)	–	(0.0256)	All states combined
	Four-lane nonfreeway	–12.2034	1.3205	–	–0.0969	–	–	0.3844	–	0.6436	Yearly data
		(3.5107)	(0.3682)	–	(0.0618)	–	–	(0.2090)	–	(0.5840)	Washington data
	Six-lane freeway	–9.4117	0.8980	–	0.0562	–	–	0.2012	–	0.2780	Yearly data
		(1.7015)	(0.1590)	–	(0.0383)	–	–	(0.1463)	–	(0.0543)	All states combined
CMCs + NCMCs	Four-lane freeway	–24.0562	1.9119	–	0.1100	–	–	–	–	0.0598	All years combined
		(5.5618)	(0.5318)	–	(0.0795)	–	–	–	–	(0.3924)	California data
	Four-lane nonfreeway	–21.7518	2.4317	–	–0.5406	–	–	–	–	0.0100	All years combined
		(12.4365)	(1.3494)	–	(0.3270)	–	–	–	–	(0.0000)	Washington data
	Six-lane freeway	–20.0770	1.5599	–0.0160	0.1810	–	–	–	–	0.0100[b]	Yearly data
		(6.0467)	(0.5660)	(0.0073)	(0.1044)	–	–	–	–	(0.0000)	All states combined
CMCs	Four-lane freeway	–29.5036	2.0385	–	0.5523	–	–	–	–	0.0100	All years combined
		(16.1063)	(1.5020)	–	(0.1660)	–	–	–	–	(0.0000)	Ohio data
	Four-lane nonfreeway	–21.7518	2.4317	–	–0.5406	–	–	–	–	0.0100	Yearly data
		(12.4365)	(1.3494)	–	(0.3270)	–	–	–	–	(0.0000)	California data
	Six-lane freeway	–23.1034	1.8886	–0.0226	0.1474	–	–	–	–	0.0100[b]	All years combined
		(6.5012)	(0.6074)	(0.0081)	(0.1087)	–	–	–	–	(0.0000)	All states combined
Rollover crashes	Four-lane freeway	–11.0162	1.1212	–	–0.0596	–0.0661	0.1706	–	–	0.3531	All states combined
		(1.7951)	(0.1696)	–	(0.0243)	(0.0449)	(0.1278)	–	–	(0.0759)	California data
	Four-lane nonfreeway	–4.7235	0.6149[a]	–	–0.2551	–	–	–	–	0.0100	Yearly data
		(9.1502)	(1.0287)	–	(0.0748)	–	–	–	–	(0.0000)	California data
	Six-lane freeway	–6,3372	0.4671[a]	–	–	–	–	–	–	0.2230	Yearly data
		(4.0087)	(0.3614)	–	–	–	–	–	–	(0.3099)	Ohio data
Fixed-object crashes	Four-lane freeway	–13.9439	1.0902	–	0.1420	–	–	0.8715	–	0.9733	Yearly data
		(4.4369)	(0.4011)	–	(0.0789)	–	–	(0.3525)	–	(0.3036)	North Carolina data
	Four-lane nonfreeway	–10.3363	0.9632	–	0.0470	–0.1067	–	–	–	0.0100	Yearly data
		(2.8848)	(0.3008)	–	(0.0255)	(0.0459)	–	–	–	(0.0000)	Missouri data
	Six-lane freeway	–14.4190	1.3915	–0.0107	–	–0.0484	–	0.4502	–	0.1626	All years combined
		(3.5309)	(0.3101)	(0.0040)	–	(0.0316)	–	(0.1452)	–	(0.0658)	Ohio data
Other median-related crashes	Four-lane freeway	–12.9170	1.1565	0.0088	–0.0561	–	0.2330	–	–	0.3001	All years combined
		(1.8619)	(0.1852)	(0.0045)	(0.0267)	–	(0.1353)	–	–	(0.0842)	California data
	Four-lane nonfreeway	–12.9183	1.2754	–0.0050	–	–0.0537	–	–	–	1.4785	Yearly data
		(2.3924)	(0.2407)	(0.0038)	–	(0.0390)	–	–	–	(0.4316)	All states combined
	Six-lane freeway	–15.8412	1.4852	–0.0045	–	–	–	0.4425	–0.2820	0.2692	Yearly data
		(2.6138)	(0.2341)	(0.0032)	–	–	–	(0.1586)	(0.1863)	(0.0911)	All states combined

[a] Coefficient not significant at 80% level.
[b] State variance less than 0.08.

Table 4-7. Safety performance models for fatal-and-injury crashes for roadways with traversable medians.

Median-related crash type	Road type	Model coefficient (standard error)									Comment
		Intercept	ADT[a]	Median width	Median slope ratio	Shoulder width	Curve presence	On-ramp presence	Rumble strip presence	Overdispersion parameter	
All median-related crashes	Four-lane freeway	–11.9079 (1.4800)	1.1423 (0.1498)	0.0070 (0.0035)	–0.0542 (0.0218)	–	–	–	–0.1359 (0.1036)	0.2516 (0.0570)	All years combined California data
	Four-lane nonfreeway	–11.0049 (3.4332)	1.1362 (0.3391)	–	–0.1137 (0.0691)	–	–	–	–	0.0135 (0.6390)	Yearly data Washington data
	Six-lane freeway	–11.5339 (3.0763)	0.9801 (0.2874)	–	0.0875 (0.0444)	–	–	–	–	0.2149 (0.0949)	Yearly data Ohio data
CMCs + NCMCs	Four-lane freeway	–23.9308 (6.7601)	1.9937 (0.6371)	– –	0.1171 (0.0896)	–0.2219 (0.1538)	–	–	–	0.1982 (0.4933)	All years combined California data
	Four-lane nonfreeway	–12.1576 (14.1086)	0.9228[a] (1.4807)	–	–	–	–	–	–	0.0100 (0.0000)	Yearly data California data
	Six-lane freeway	–19.3150 (7.4574)	1.6090 (0.667)	–0.0153 (0.0061)	–	–	–	–	–	0.9550 (1.1955)	Yearly data All states combined
CMCs	Four-lane freeway	–20.2012 (5.3011)	1.8093 (0.5482)	–0.0205 (0.0105)	–	–	–	–	–	0.1453 (0.4660)	All years combined California data
	Four-lane nonfreeway	–10.7480 (18.5931)	0.4192[a] (2.0183)	–	0.2759 (0.1683)	–	–	–	–	0.0100 (0.0000)	Yearly data California data
	Six-lane freeway	–18.6668 (7.6442)	1.5600 (0.6846)	–0.0177 (0.0063)	– –	–	–	–	–	1.1219 (0.2927)	Yearly data All states combined
Rollover crashes	Four-lane freeway	–11.4640 (1.8352)	0.9661 (0.1786)	0.0216 (0.0046)	–0.0328 (0.0243)	–0.1390 (0.0472)	0.2587 (0.125)	–	–	0.1959 (0.0723)	All states combined California data
	Four-lane nonfreeway	–4.4858 (10.2028)	0.5537 (1.1427)	–	0.2469 (0.0866)	–	–	–	–	0.0100 (0.0000)	Yearly data California data
	Six-lane freeway	–6.2621 (5.3068)	0.3234[a] (0.4954)	–	0.1285 (0.0828)	–	–	–	–	0.1616 (0.4834)	Yearly data Ohio data
Fixed-object crashes	Four-lane freeway	–9.7775 (3.9487)	1.1178 (0.41352)	–0.0310 (0.0108)	–0.1835 (0.0549)	–	–	–	–	1.0308 (0.9865)	Yearly data California data
	Four-lane nonfreeway	–9.0654 (13.3950)	1.0969[a] (1.5240)	–	–0.5954 (0.3332)	–	–	–	–	0.0100 (0.0000)	All years combined Washington State
	Six-lane freeway	–14.1827 (5.6230)	1.2062[a] (0.5198)	–0.0092 (0.0064)	–	–	–	0.6540 (0.2738)	–	0.6676 (0.2929)	All years combined Ohio data
Other median-related crashes	Four-lane freeway	–10.960 (2.3981)	0.9733 (0.2327)	–	–0.0569 (0.0336)	–	–	–	–	0.3384 (0.1438)	All years combined California data
	Four-lane nonfreeway	–8.0851 (3.2892)	0.6674 (0.3451)	–	0.0631 (0.0260)	–0.1068 (0.0474)	–	–	–	0.0100 (0.0000)	All years combined Missouri data
	Six-lane freeway	–21.2765 (4.3737)	1.9104 (0.3918)	–0.0065 (0.0045)	–	–	–	0.4578 (0.2104)	–0.5298 (0.2832)	0.1657 (0.1637)	Yearly data All states combined

[a] Coefficient not significant at 80% level.

and roadway type combination. Where no coefficient value is given in the tables, the coefficient was not statistically significant and should be treated as equal to zero in Equations 2 through 4. All model coefficients shown in Tables 4-6 and 4-7 are statistically significant at the 80 percent confidence level unless otherwise noted. A comment indicating the regression method and dataset used is also provided.

For example, the SPF in Table 4-6 for all median-related crashes on four-lane freeways shown in the top line of the table is:

$$N_{4FT} = \exp\begin{pmatrix} -7.9411 + 0.7946 \ln \text{ADT} + 0.0027\text{MW} \\ -0.024\text{MS} + 0.2655\text{OR} \end{pmatrix} \quad (4)$$

where:

N_{4FT} = predicted median-related crash frequency per mile per year on four-lane freeways with traversable medians
ADT = average daily traffic volume (veh/day)
MW = median width (ft)
MS = median slope ratio
OR = on-ramp presence

The signs of the coefficients indicate how the crash rate changes when changes are made in a design variable such as median width, median slope, etc. Equation 3 indicates that median-related crashes increase as median widths increase (positive coefficient), and decrease as median slopes are flattened (negative coefficient).

The safety effect for each design variable is the percent change in crash rate that can be expected for each unit change in a design variable (holding all others constant). For example, the safety effect for median width is shown in Table 4-8. The top line in this table says that for all median-related crashes on four-lane freeways with traversable medians, the rate increases 0.27 percent for each additional foot of median width. The equation used to determine the safety effect is as follows:

$$\text{Safety effect} = 100\left[\exp(\text{coefficient}) - 1\right] \quad (5)$$

This number gives the percent change in crash rate due to an independent variable, provided all other variables remain constant.

The modeling results are described below with cautious wording. Many of the observed effects are logical and represent reasonable findings, but their magnitude and statistical significance may be influenced by correlations between some of the variables studied.

Median Width

The distribution of median widths on the study sites is shown in Table 4-9.

The meaning of the statistically significant safety effects for median width shown in Tables 4-7 and 4-8 is as follows:

1. On four-lane freeways, total median-related crashes increased with wider medians. Fatal-and-injury median-related crashes also increased with wider medians. The safety effects were a 0.3 percent increase for each additional foot of median width for all median-related crashes and a 0.7 percent increase for each additional foot of median width for fatal-and-injury median-related crashes.

Table 4-8. Safety effect of median width for roadways with traversable medians.

		Percent change in crash frequency per unit change in median width					
		Total severity			F & I severity		
Median-related crash type	Road type	Effect	LB	UB	Effect	LB	UB
All median-related crashes	Four-lane freeway	0.27	0.08	0.45	0.71	0.03	1.39
	Four-lane nonfreeway						
	Six-lane freeway						
CMCs + NCMCs	Four-lane freeway						
	Four-lane nonfreeway						
	Six-lane freeway	–1.58	–3.01	–0.14	–1.52	–2.69	–0.33
CMCs	Four-lane freeway				–2.03	–4.02	0.00
	Four-lane nonfreeway						
	Six-lane freeway	–2.23	–3.79	–0.65	–1.76	–2.97	–0.53
Rollover crashes	Four-lane freeway				2.18	1.26	3.11
	Four-lane nonfreeway						
	Six-lane freeway						
Fixed-object crashes	Four-lane freeway				–3.05	–5.08	–0.98
	Four-lane nonfreeway						
	Six-lane freeway	–1.07	–1.84	–0.29	–0.92	–2.16	0.34
Other median-related crashes	Four-lane freeway	0.88	0.00	1.77			
	Four-lane nonfreeway	–0.50	–1.24	0.25			
	Six-lane freeway	–0.45	–1.06	0.17	–0.65	–1.52	0.22

Table 4-9. Median width distribution for study sites.

State	Median type	No. of lanes	Road type	Roadway length (mi) for sites in categories of median width (ft)						
				< = 15	15 to 35	35 to 55	55 to 75	75 to 95	95 to 115	115+
CA	Traversable	4	Freeway		2	17	51	143	50	
			Nonfreeway	1	13	1	12	11		
		6	Freeway				2			
	Barrier	4	Freeway		12	4		24		
			Nonfreeway	4						
		6	Freeway				1	5	4	
MO	Traversable	4	Freeway			56	157			
			Nonfreeway			7	270	17	5	2
	Barrier	4	Freeway		1	81	49			
NC	Traversable	4	Freeway			34		5	6	
	Barrier	4	Freeway	25	79	180	51	16	15	
			Nonfreeway		7	3	7			
		6	Freeway		3	4	7			
OH	Traversable	4	Freeway			1	28	79		
		6	Freeway		7	17		6		
	Barrier	4	Freeway	2				20		
		6	Freeway	1		18	1	1		
PA	Traversable	4	Freeway	14	61	46	194	154	28	13
		6	Freeway				5	1		
	Barrier	4	Freeway	9	40	2	3	6	1	3
		6	Freeway		1					
WA	Traversable	4	Freeway			46	29	110	1	8
			Nonfreeway				26	1	1	5
		6	Freeway		1	1	3	5	1	6
	Barrier	4	Freeway		1	3	1	8		1
		6	Freeway					1		

2. On six-lane freeways, total CMCs plus NCMCs decreased with wider medians, as did fatal-and-injury CMCs plus NCMCs. The safety effects were a 1.6 percent decrease in CMCs plus NCMCs for each additional foot of median width and a 1.5 percent decrease in fatal-and-injury CMCs plus NCMCs for each additional foot of median width.
3. On four-lane freeways, CMC fatal-and-injury crashes decreased with wider medians. The safety effect was a 2.0 percent decrease in CMC fatal-and-injury crashes for each additional foot of median width.
4. On six-lane freeways, CMCs also decreased with wider medians. The safety effects were a 2.2 percent decrease for each additional foot of median width for CMCs and a 1.8 percent decrease for each additional foot of median width for fatal-and-injury CMCs.
5. For four-lane freeways, fatal-and-injury rollover crashes increased with wider medians. The safety effect was a 2.2 percent increase for each additional foot of median width.
6. For four-lane freeways, the fatal-and-injury fixed-object crashes decreased with wider medians. The safety effect was a 3.1 percent decrease for each additional foot of median width.
7. On six-lane freeways, total fixed-object and fatal-and-injury fixed-object crashes decreased with wider medians. The safety effects were a 1.1 percent decrease in total fixed-object crashes for each additional foot of median width and a 0.9 percent decrease in fatal-and-injury fixed-object crashes for each additional foot of median width.
8. On four-lane freeways, other median-related crashes increased with wider medians. The safety effect was a 0.9 percent increase for each additional foot of median width.
9. On four-lane nonfreeways, other median-related crashes decreased with wider medians. The safety effect was a 0.5 percent decrease for each additional foot of median width.
10. On six-lane freeways, other median-related crashes and fatal-and-injury other median-related crashes decreased with wider medians. The safety effects were a 0.5 percent decrease for other median-related crashes and a 0.7 percent decrease for fatal-and-injury other median-related crashes for each additional foot of median width.

In summary, increasing median widths were found to have partially offsetting effects by crash type. Total median-related crashes appear to increase with wider medians. CMCs and NCMCs decreased with wider medians while rollover crashes increased. Fixed-object crashes also decreased with wider medians. Few significant relationships were found for

Table 4-10. Safety effect of median slope ratio for roadways with traversable medians.

Median-related crash type	Road type	Percent change in crash frequency per unit change in median slope ratio: Total severity Effect	LB	UB	F & I severity Effect	LB	UB
All median-related crashes	Four-lane freeway	–2.39	–4.59	–0.13	–5.28	–9.23	–1.15
	Four-lane nonfreeway	–9.24	–19.59	2.45	–10.75	–22.06	2.20
	Six-lane freeway	5.78	–1.87	14.03	9.15	0.06	19.07
CMCs + NCMCs	Four-lane freeway	11.53	–4.48	30.44	12.42	–5.69	34.01
	Four-lane nonfreeway	–41.76	–69.32	10.54			
	Six-lane freeway	19.84	–2.62	47.50			
CMCs	Four-lane freeway	73.72	25.46	140.54			
	Four-lane nonfreeway	–41.76	–69.32	10.54	31.78	–5.25	83.27
	Six-lane freeway	15.88	–6.66	43.86			
Rollover crashes	Four-lane freeway	–5.79	–10.16	–1.20	–3.23	–7.73	1.49
	Four-lane nonfreeway	–22.52	–33.08	–10.28	–21.88	–34.08	–7.43
	Six-lane freeway				13.71	–3.32	33.74
Fixed-object crashes	Four-lane freeway	15.26	–1.25	34.53	–16.76	–25.26	–7.30
	Four-lane nonfreeway	4.81	–0.30	10.19	–44.87	–71.31	5.94
	Six-lane freeway						
Other median-related crashes	Four-lane freeway	–5.45	–10.28	–0.37	–5.53	–11.55	0.90
	Four-lane nonfreeway				6.52	1.22	12.10
	Six-lane freeway						

nonfreeways. Relationships for fatal-and-injury crashes followed the same trends as all crashes.

The vehicle dynamics simulation analysis presented in Chapter 5 includes results that help to explain the crash analysis results for median width presented here.

Median Slope

Safety effects of median slopes are shown in Table 4-10. Each median slope effect found to be statistically significant is discussed below. The distribution of median slopes for the study sites is shown in Table 4-11.

1. Flatter slopes appear to decrease median-related crashes for both four-lane freeways and nonfreeways. The safety effects were a 2.4 percent decrease for each unit change in the median slope ratio for four-lane freeways and a 9.2 percent decrease for each unit change in median slope ratio on nonfreeways. For fatal-and-injury crashes, the corresponding safety effects were a 5.3 percent decrease on four-lane freeways and a 10.8 percent decrease for nonfreeways.
2. Flatter slopes appear to increase total median-related crashes for six-lane freeways. The safety effect was a 5.8 percent increase for each unit change in the median slope ratio. The safety effect for fatal-and-injury median-related crashes was a 9.2 percent increase for each unit change in median slope ratio.
3. Flatter slopes increase both CMCs plus NCMCs and CMCs on both four- and six-lane freeways. The safety effect for CMCs plus NCMCs was an 11.5 percent per unit increase in median slope ratio for four-lane freeways and a 19.8 percent per unit increase in median slope ratio for six-lane freeways. The safety effect for fatal-and-injury CMCs plus NCMCs on four-lane freeways was a 12.4 percent per unit increase in median slope ratio. The observed safety effect for CMCs was a 73.1 percent increase for four-lane freeways and 15.9 percent increase for six-lane freeways.
4. For nonfreeways, flatter slopes appeared to decrease both CMCs plus NCMCs and CMCs. The safety effect was a 41.8 percent decrease per unit change for both CMCs plus NCMCs and CMCs. However, for fatal-and-injury CMCs, flatter slopes appeared to increase crashes. The safety effect was a 31.8 percent increase per unit change in the median slope ratio.
5. As expected, flatter slopes appear to decrease rollover crashes for four-lane freeways and nonfreeways. The same finding was seen for fatal-and-injury rollover crashes on four-lane freeways. The safety effect for rollover crashes was a 5.8 percent decrease per unit change in median slope ratio for four-lane freeways and a 22.5 percent decrease per unit change in median slope ratio for nonfreeways. Fatal-and-injury rollover crashes had a 3.2 percent decrease for four-lane freeways and a 21.9 percent decrease for nonfreeways.
6. On six-lane freeways, fatal-and-injury rollover crashes appeared to increase with flatter slopes. The safety effect was a 13.7 percent increase in crashes per unit change in slope ratio.
7. On four-lane freeways and nonfreeways, fixed-object crashes appeared to increase with flatter slopes. However, fatal-and-injury fixed-object crashes appeared to decrease

Table 4-11. Median slope ratio distribution for study sites.

State	Median type	No. of lanes	Road type	Roadway length (mi) for sites in categories of median slope ratio: Missing	1:4	1:6	1:10	1:14	1:14+
CA	Traversable	4	Freeway	19	2	11	28	204	1
			Nonfreeway	15			3	20	
		6	Freeway					2	
	Barrier	4	Freeway				3	24	13
			Nonfreeway						4
		6	Freeway					1	9
MO	Traversable	4	Freeway		5	97	97	12	2
			Nonfreeway		18	138	126	12	7
	Barrier	4	Freeway		7	61	58	4	1
NC	Traversable	4	Freeway	7			2	35	1
	Barrier	4	Freeway	113		4	91	158	
			Nonfreeway				3	14	
		6	Freeway	5			5	4	
OH	Traversable	4	Freeway	1		3	97	7	
		6	Freeway				28	2	
	Barrier	4	Freeway	2			13	7	
		6	Freeway	3			15	3	
PA	Traversable	4	Freeway	34	6	126	267	77	
		6	Freeway			1	4	1	
	Barrier	4	Freeway	47		4	12	1	
		6	Freeway	1					
WA	Traversable	4	Freeway	1		12	167	14	
			Nonfreeway			4	20	0	
		6	Freeway			1	13	3	
	Barrier	4	Freeway	1		3	10		
		6	Freeway				1		

with flatter slopes. The safety effect for fixed-object crashes was a 15.3 percent increase per unit change in median slope ratio on four-lane freeways and a 4.8 percent increase per unit change in median slope ratio for nonfreeways. Fixed-object fatal-and-injury crashes showed the opposite safety effects of a 16.8 percent decrease per unit change in median slope ratio for four-lane freeways and a 44.9 percent decrease per unit change in median slope ratio for nonfreeways.

8. On four-lane freeways, other median-related crashes appeared to decrease with flatter slopes. Fatal-and-injury other median-related crashes also appeared to decrease with flatter slopes. The safety effects were a 5.5 percent decrease in other median-related crashes per unit change in median slope ratio and a 5.5 percent decrease in fatal-and-injury other median-related crashes per unit change in median slope ratio.
9. On nonfreeways, fatal-and-injury other median-related crashes appeared to increase with flatter slopes. The observed safety effect was a 6.5 percent increase in crashes per unit change in median slope ratio.

In summary, flatter slopes were found to increase both CMCs plus NCMCs and CMCs on four- and six-lane freeways. However, flatter slopes generally decreased rollover crashes and other median-related crashes. Fixed-object crashes generally increased with flatter slopes, but fatal-and-injury fixed-object crashes decreased. All median-related crashes decreased with flatter slopes on four-lane freeways and nonfreeways, but increased for six-lane freeways. Fatal-and-injury median-related crashes followed the same trend.

Median Shoulder Width

Safety effects of median shoulder widths are shown in Table 4-12. Each median shoulder width effect found to be statistically significant is discussed below. The distribution of inside (median) shoulder widths is shown in Table 4-13.

1. Fatal-and-injury CMCs plus NCMCs appear to decrease on four-lane freeways with wider median shoulders. The safety effect was a 19.9 percent decrease for each additional foot of median shoulder width.
2. On four-lane freeways, rollover crashes and fatal-and-injury rollover crashes also decreased with wider median shoulders. The safety effects were a 6.4 percent decrease in all rollover crashes for each additional foot of median shoulder width and a 13.0 percent decrease in fatal-and-injury rollover crashes for each additional foot of median shoulder.
3. Fixed-object crashes decreased on nonfreeways and six-lane freeways with wider median shoulders. The safety

Table 4-12. Safety effect of shoulder width for roadways with traversable medians.

Median-related crash type	Road type	Percent change in crash frequency per unit change in shoulder width inside: Total severity Effect	Total severity LB	Total severity UB	F & I severity Effect	F & I severity LB	F & I severity UB
All median-related crashes	Four-lane freeway						
	Four-lane nonfreeway						
	Six-lane freeway						
CMCs + NCMCs	Four-lane freeway				–19.90	–40.75	8.28
	Four-lane nonfreeway						
	Six-lane freeway						
CMCs	Four-lane freeway						
	Four-lane nonfreeway						
	Six-lane freeway						
Rollover crashes	Four-lane freeway	–6.40	–14.28	2.22	–12.98	–20.66	–4.55
	Four-lane nonfreeway						
	Six-lane freeway						
Fixed-object crashes	Four-lane freeway						
	Four-lane nonfreeway	–10.12	–17.86	–1.66			
	Six-lane freeway	–4.72	–10.45	1.37			
Other median-related crashes	Four-lane freeway						
	Four-lane nonfreeway	–5.23	–12.21	2.30	–10.13	–18.10	–1.39
	Six-lane freeway						

effects were a 10.1 percent decrease on nonfreeways for each additional foot of median shoulder width and a 4.7 percent decrease on six-lane freeways for each additional foot of median shoulder width.

4. On four-lane nonfreeways, wider median shoulders were found to reduce other median-related crashes. The safety effect was a 5.2 percent decrease for each additional foot of median shoulder width. The safety effect for fatal-and-injury other median-related crashes was a 10.1 percent decrease for each additional foot of median shoulder width.

In summary, wider median shoulders decreased all types of crashes where significant effects were discovered. The types of crashes with statistically significant safety effects include

Table 4-13. Distribution of inside shoulder widths for study sites.

State	Median type	No. of lanes	Road type	Roadway length (mi) for sites in categories of inside shoulder width (ft): 0	2	3	4	5	6	7	8	9	10	11	12	12+
CA	Traversable	4	Freeway				190	190	2	3	64		1	3		
			Nonfreeway					32	1	5						
		6	Freeway					2								
	Barrier	4	Freeway					27	1	4	3		1	4		
			Nonfreeway					4								
		6	Freeway					9						1		
MO	Traversable	4	Freeway			30	121	55	7							
			Nonfreeway			15	108	28	19	46	46	14	18	5		2
	Barrier	4	Freeway			29	74	22	6							
NC	Traversable	4	Freeway				26					6	13			
	Barrier	4	Freeway		12		91					117	146			
			Nonfreeway		10								7			
		6	Freeway									4	10			
OH	Traversable	4	Freeway				71	26	7	1		1			2	
		6	Freeway				6						17			7
	Barrier	4	Freeway				12	8						1	1	
		6	Freeway				1						17		1	2
PA	Traversable	4	Freeway				290		4	1	83		111		21	
		6	Freeway								5		1			
	Barrier	4	Freeway	3			9			1	4	29	16		2	
		6	Freeway										1			
WA	Traversable	4	Freeway			1	186	6					1			
			Nonfreeway				33									
		6	Freeway					1	12		2		2			
	Barrier	4	Freeway			1	13									
		6	Freeway						1							

Table 4-14. Safety effect of curve presence for roadways with traversable medians.

Median-related crash type	Road type	No. of ObsUsed	Percent change in crash frequency between sites with and without horizontal curves: Total severity Effect	Total severity LB	Total severity UB	F&I severity Effect	F&I severity LB	F&I severity UB
All median-related crashes	Four-lane freeway	1,194						
	Four-lane nonfreeway	33						
	Six-lane freeway	96						
CMCs + NCMCs	Four-lane freeway	244						
	Four-lane nonfreeway	31						
	Six-lane freeway	90						
CMCs	Four-lane freeway	107						
	Four-lane nonfreeway	31						
	Six-lane freeway	90						
Rollover crashes	Four-lane freeway	244	18.60	–7.69	52.37	29.52	1.37	65.49
	Four-lane nonfreeway	38						
	Six-lane freeway	66						
Fixed-object crashes	Four-lane freeway	61						
	Four-lane nonfreeway	313						
	Six-lane freeway	66						
Other median-related crashes	Four-lane freeway	244	26.24	–3.16	64.57			
	Four-lane nonfreeway	384						
	Six-lane freeway	96						

fatal-and-injury CMC plus NCMC, rollover, fixed-object, and other median-related crashes.

Presence of Horizontal Curves

Safety effects of the presence of horizontal curves are shown in Table 4-14. Each horizontal curve effect found to be statistically significant is discussed below. The distribution of horizontal curve presence is shown in Table 4-15.

1. On four-lane freeways, the presence of a horizontal curve appears to increase rollover and fatal-and-injury rollover crashes. The safety effects were a 18.6 percent increase in rollover crashes where a horizontal curve is present, and a

Table 4-15. Distribution of horizontal curve presence for study sites.

State	Median type	No. of lanes	Road type	Roadway length (mi) for sites with and without horizontal curves: None	Curve present
CA	Traversable	4	Freeway	194	69
			Nonfreeway	25	13
		6	Freeway	2	
	Barrier	4	Freeway	31	9
			Nonfreeway	2	2
		6	Freeway	6	4
MO	Traversable	4	Freeway	272	29
			Nonfreeway	272	29
	Barrier	4	Freeway	123	8
NC	Traversable	4	Freeway	30	15
	Barrier	4	Nonfreeway	17	
			Freeway	297	69
		6	Freeway	14	
OH	Traversable	4	Freeway	86	22
		6	Freeway	25	5
	Barrier	4	Freeway	17	5
		6	Freeway	15	6
PA	Traversable	4	Freeway	287	223
		6	Freeway	2	4
	Barrier	4	Freeway	31	33
WA	Traversable	4	Freeway	164	30
			Nonfreeway	20	13
		6	Freeway	14	3
	Barrier	4	Freeway	6	8

29.5 percent increase in fatal-and-injury rollover crashes where a horizontal curve is present.

2. The presence of a curve increased other median-related crashes on four-lane freeways. The only observed safety effect statistically significant was a 26.2 percent increase in other median-related crashes when a curve was present.

In summary, few statistically significant safety effects were found for the presence of horizontal curves. Curve presence did increase rollover and other median-related crashes.

Presence of On-Ramps

Safety effects of the presence of on-ramps are shown in Table 4-16. Each on-ramp effect found to be statistically significant is discussed below. The distribution of ramp presence is shown in Table 4-17.

1. The presence of an on-ramp appears to increase median-related crashes for all road types considered. The safety effects of the presence of an on-ramp were a 30.4 percent increase for four-lane freeways, a 46.9 percent increase for nonfreeways, and a 22.3 percent increase for six-lane freeways.
2. No statistically significant effects were found for CMC plus NCMC, CMC, or rollover crashes.
3. On freeways, the presence of an on-ramp appears to increase fixed-object crashes. The safety effect for four-lane freeways was a 139.1 percent increase in fixed-object median-related crashes when a ramp was present and the safety effect for six-lane freeways was a 56.9 percent increase in fixed-object median-related crashes when a ramp was present. Fatal-and-injury fixed-object crashes on six-lane freeways increased 92.3 percent when a ramp was present. These observed effects may result from a greater likelihood of fixed objects in the median in the vicinity of on-ramps.
4. On six-lane freeways, other median-related crashes increased when an on-ramp was present. The safety effects were a 55.7 percent increase in all other median-related crashes and a 58.1 percent increase in fatal-and-injury other median-related crashes.

In summary, there were large safety effects for the presence of an on-ramp for all median-related crashes, fixed-object crashes, and other median-related crashes. No statistically significant effects were found for CMC plus NCMC, CMC, or rollover crashes.

Presence of Rumble Strips

Safety effects of the presence of shoulder rumble strips are shown in Table 4-18. Each rumble strip presence effect found to be statistically significant is discussed below.

The distribution of shoulder rumble strip presence is shown in Table 4-19.

1. On four-lane freeways, fatal-and-injury median-related crashes decreased when shoulder rumble strips were present. The safety effect was a 12.7 percent decrease in crashes when rumble strips were present.
2. For six-lane freeways, other median-related crashes and fatal-and-injury other median-related crashes decreased when rumble strips were present. The safety effects were a 24.6 percent decrease for other median-related crashes and a 41.1 percent decrease for fatal-and-injury other median-related crashes.

Table 4-16. Safety effect of on-ramp presence for roadways with traversable medians.

Median-related crash type	Road type	Percent change in crash frequency between sites with and without on-ramps					
		Total severity			F & I severity		
		Effect	LB	UB	Effect	LB	UB
All median-related crashes	Four-lane freeway	30.40	14.75	48.19			
	Four-lane nonfreeway	46.87	–2.50	121.25			
	Six-lane freeway	22.29	–8.21	62.91			
CMCs + NCMCs	Four-lane freeway						
	Four-lane nonfreeway						
	Six-lane freeway						
CMCs	Four-lane freeway						
	Four-lane nonfreeway						
	Six-lane freeway						
Rollover crashes	Four-lane freeway						
	Four-lane nonfreeway						
	Six-lane freeway						
Fixed-object crashes	Four-lane freeway	139.06	19.80	377.04			
	Four-lane nonfreeway						
	Six-lane freeway	56.86	18.00	108.52	92.32	12.45	228.91
Other median-related crashes	Four-lane freeway						
	Four-lane nonfreeway						
	Six-lane freeway	55.67	14.08	112.42	58.06	4.64	138.74

Table 4-17. Distribution of on-ramp presence for study sites.

State	Median type	No. of lanes	Road type	Roadway length (mi) for sites with and without on-ramps: Missing	None	On-ramp present
CA	Traversable	4	Freeway	65	175	23
			Nonfreeway	13	25	
		6	Freeway		2	
	Barrier	4	Freeway	8	29	3
			Nonfreeway	2	2	
		6	Freeway	3	4	3
MO	Traversable	4	Freeway		182	31
			Nonfreeway		270	31
	Barrier	4	Freeway		107	24
NC	Traversable	4	Freeway		31	14
	Barrier	4	Nonfreeway		293	73
			Freeway		12	5
		6	Freeway		11	3
OH	Traversable	4	Freeway		88	20
		6	Freeway		22	8
	Barrier	4	Freeway		18	4
		6	Freeway		17	4
PA	Traversable	4	Freeway		473	37
		6	Freeway		6	
	Barrier	4	Freeway		58	6
		6	Freeway		1	
WA	Traversable	4	Freeway	33	149	12
			Nonfreeway	10	22	1
		6	Freeway	10	7	
	Barrier	4	Freeway	3	11	
		6	Freeway		1	

3. No statistically significant effects were found for CMC plus NCMC, CMC, rollover, or fixed-object crashes.

In summary, shoulder rumble strips were found to decrease total median-related crashes, but no statistically significant effects were found for CMC plus NCMC, CMC, rollover, or fixed-object crashes.

4.3 Analysis of Medians with Barriers

The objective of the safety analysis of medians with barriers is to develop a methodology to predict the safety performance of barrier medians, analogous to the methodology for traversable medians described in Section 4.2. The safety

Table 4-18. Safety effect of rumble strip presence for roadways with traversable medians.

Median-related crash type	Road type	Percent change in crash frequency between sites with and without shoulder rumble strips: Total severity – Effect	Total severity – LB	Total severity – UB	F & I severity – Effect	F & I severity – LB	F & I severity – UB
All median-related crashes	Four-lane freeway				–12.71	–28.75	6.95
	Four-lane nonfreeway						
	Six-lane freeway						
CMCs + NCMCs	Four-lane freeway						
	Four-lane nonfreeway						
	Six-lane freeway						
CMCs	Four-lane freeway						
	Four-lane nonfreeway						
	Six-lane freeway						
Rollover crashes	Four-lane freeway						
	Four-lane nonfreeway						
	Six-lane freeway						
Fixed-object crashes	Four-lane freeway						
	Four-lane nonfreeway						
	Six-lane freeway						
Other median-related crashes	Four-lane freeway						
	Four-lane nonfreeway						
	Six-lane freeway	–24.58	–47.65	8.66	–41.13	–66.21	2.56

Table 4-19. Distribution of rumble strip presence for study sites.

State	Median type	No. of lanes	Road type	Roadway length (mi) for sites with and without shoulder rumble strips: None	Rumble strip present
CA	Traversable	4	Freeway	98	165
			Nonfreeway	13	25
		6	Freeway		2
	Barrier	4	Freeway	9	31
			Nonfreeway	2	2
		6	Freeway	5	5
MO	Traversable	4	Freeway	20	193
			Nonfreeway	50	251
	Barrier	4	Freeway	10	121
NC	Traversable	4	Freeway	21	24
	Barrier	4	Freeway	115	251
			Nonfreeway	7	10
		6	Freeway	7	7
OH	Traversable	4	Freeway	26	82
		6	Freeway	2	28
	Barrier	4	Freeway	3	19
		6	Freeway	1	20
PA	Traversable	4	Freeway	320	190
		6	Freeway	2	4
	Barrier	4	Freeway	55	9
		6	Freeway	1	
WA	Traversable	4	Freeway	23	171
			Nonfreeway	10	23
		6	Freeway	10	7
	Barrier	4	Freeway	3	11
		6	Freeway		1

prediction methodology for barrier medians will combine the results from two analysis approaches: a cross-sectional analysis using regression models similar to the analysis approach used for traversable medians and a before-after evaluation of the installation of barriers in existing traversable medians.

Typical cross sections for barrier medians are defined in terms of the road type, barrier type, and the barrier placement policy.

Barriers are placed in medians primarily to prevent CMCs where a vehicle from one roadway crosses the median and collides with a vehicle on the opposing roadway. However, although the placement of a median barrier prevents most CMCs, it may increase the total number of crashes in the median due to collisions with the barrier. Some vehicles that would have stopped in the median or recovered in the median and returned to the original traveled way will instead collide with the median barrier.

The increase in the number of CMCs and their high severity has resulted in a substantial increase in the use of barriers in medians in the last 10 years. Because of the retrofit of many existing medians with barriers, especially cable barriers, developing a safety prediction methodology for barrier medians should be directed toward comparing the safety performance of alternative barrier types and placements and to use together with the result of the analysis of traversable medians, the analysis results to compare median cross-section designs with and without barriers.

4.3.1 Safety Measures (Dependent Variables)

The safety measures for analysis of barrier medians are similar to those for traversable medians. Specific crash severity levels are the same as in the analysis of traversable medians, but there are additional crash types of interest. Specific median-related crash types of interest primarily in barrier medians include the following:

- Hit barrier;
- Went over or through barrier; hit opposing vehicle (CMC);
- Went over or through barrier; entered opposing roadway but did not collide with opposing vehicle (NCMC);
- Rollover;
- Fixed object; and
- Other median related.

The median-related crash types involving vehicles that do not reach the barrier are the same for barrier medians as for traversable medians.

4.3.2 Median Cross-Section and Roadway Characteristics (Independent Variables)

The median cross-section and roadway characteristics of interest are the same for barrier medians as presented for traversable medians in Section 4.2 except that additional characteristics specific to the median barrier will be added: the barrier type, the offset from the traveled way to the barrier, and the placement policy used to locate the barrier within the median. The barrier types are flexible (cable) barrier, semirigid (guardrail), and rigid barrier (concrete safety shaped).

4.3.3 Data Collection

The data collected for barrier medians was the same as for traversable medians shown in the list provided in Section 4.2.3. The barrier type as well as the placement policy was determined from the responses to the state summary. The automated terrain mapping system (described in Appendix D which is available on the TRB website) measured the sideslope and distance to the barrier in all states except Missouri. The specific type of cable barrier was verified by visual inspection.

Participating States

The participating states for barrier median sections on rural freeways are California, Missouri, North Carolina, Ohio, Pennsylvania, and Washington. The researchers did not include barrier medians on rural divided nonfreeways because there was not sufficient mileage to provide an adequate sample size.

Field Data Collection

Data collection for barrier median sites was conducted jointly with the data collection for traversable medians. The scanning laser system was used in California, North Carolina, Ohio, Pennsylvania, and Washington states. At least 5 years of crash data was obtained as well as yearly ADT data corresponding to the crash data. For the states of California, North Carolina, Ohio, and Washington, crash data were obtained from the FHWA HSIS system. Missouri and Pennsylvania crash data were obtained directly from the Missouri and Pennsylvania DOTs.

4.3.4 Crash Statistics for Barrier Medians

The mileage of traversable and barrier median sites has been presented in Table 4-1. The total roadway length for all study sites was 3,250.8 km (2,020.4 mi). There were 1,277.4 km (792.1 mi) of roadway with barrier medians, including rural freeways. There is a limited mileage of barrier median sites on nonfreeways; the total length of rural nonfreeway sites with barrier medians was 32.8 km (20.4 mi). Because the nonfreeway mileage was minimal, no analysis was made of nonfreeway barrier median sites.

The frequency of crashes for barrier median sites is shown in Table 4-20. This table also shows the number and proportion of crashes that were median-related crashes. On rural freeway barrier median sites, about 37 percent of the crashes were median related. Thus, a larger percentage of crashes are median related in barrier medians as compared to traversable medians (37 versus 26 percent). Table 4-20 also gives the frequency and proportion of each crash type that constitutes median-related crashes on barrier medians.

Hit-barrier crashes represent more than half of median-related crashes on barrier medians. There are few CMCs or NCMCs, and they total less than 1 percent of barrier median crashes. Rollover crashes vary widely from state to state, but average about 7 percent of median-related crashes. Fixed-object crashes average about 17 percent of median-related crashes, but have one reporting variation that should be noted. The Missouri crash database does not have a code

Table 4-20. Crash frequency for barrier medians on rural freeways.

		Crash type													
State	Total crashes	Median-related crashes (percent of total crashes)		Hit-barrier crashes (percent of median-related)		CMCs (percent of median-related)		NCMCs (percent of median-related)		Rollover crashes (percent of median-related)		Fixed-object crashes (percent of median-related)		Other median-related crashes (percent of median-related)	
CA	1,732	586	(33.83)	294	(50.17)	18	(3.07)	0	(0.00)	121	(20.64)	37	(6.31)	116	(19.79)
MO	2,525	687	(27.20)	0	(0.00)	14	(2.03)	14	(2.03)	67	(9.75)	451	(65.64)	141	(20.52)
NC	14,110	5,954	(42.19)	3,702	(62.17)	12	(0.20)	2	(0.03)	275	(4.61)	727	(12.21)	1,236	(20.75)
OH	3,085	721	(23.37)	178	(24.68)	11	(1.52)	0	(0.00)	50	(6.93)	183	(25.38)	299	(41.47)
PA	418	187	(44.73)	179	(95.72)	4	(2.13)	1	(0.53)	1	(0.53)	0	(0.00)	2	(1.06)
WA	699	151	(21.60)	61	(40.39)	0	(0.00)	2	(1.32)	61	(40.39)	24	(15.89)	3	(1.98)
Total	22,569	8,286	(36.71)	4,414	(53.27)	59	(0.71)	19	(0.22)	575	(6.93)	1,422	(17.16)	1,797	(21.68)

for "hit-barrier," so all barrier crashes are coded as fixed-object crashes. In Table 4-20, Missouri has zero hit-barrier crashes, but fixed-object crashes are more than 65 percent of median-related crashes. The fixed-object struck in many of these crashes is probably the median barrier, but the research team was unable to separate those crashes from other fixed-object crashes.

The crash severity distribution for barrier medians is shown in Table 4-21. The small number of CMCs that represent less than 1 percent of the median-related crashes in barrier medians represent over 13 percent of the fatal median-related crashes. Rollover crashes also are severe; they are about 7 percent of the total median-related crashes but account for over 31 percent of fatal median-related crashes. Hit-barrier and fixed-object crashes, on the other hand, represent 52 and 17 percent of total median-related crashes, but just 25 and 9 percent of fatal median-related crashes.

4.3.5 Statistical Analysis/Modeling of Crash Data for Barrier Medians

Regression models, or safety performance functions (SPFs), were developed to estimate the effect of cross-section design features on barrier median safety performance as was done for traversable medians. Safety performance was estimated as a function of traffic volume, median width, and median slope, as well as four other independent variables found to have a statistically significant relationship with safety. The analysis focused on frequency and severity—total and fatal-and-injury—of the following crash types: all median-related; hit-barrier crashes; rollover in the median; hit-fixed-object in median (other than barrier); hit any fixed object; and other median-related collisions. Thus, a total of 12 dependent variables were considered for 6 target crash types and 2 crash severity levels. (CMCs and NCMCs were not modeled due to the small number of these crashes occurring in barrier medians.)

SPFs were developed with multiple regression, assuming a negative binomial (NB) error distribution of accident frequencies, using data from all traversable median sites and barrier sites for the period before barrier installation. The decision to include the before period of barrier sites was made to maximize the amount of information used to develop the functions. Separate models were developed for each state as well as combined state models for each of the following two classifications of roadways:

- Four-lane freeway and
- Six-lane freeway.

Models were developed for three types of median barrier, as follows:

- Flexible barriers (e.g., cable barriers);
- Semi-rigid barriers (e.g., steel guardrail); and
- Rigid barriers (e.g., concrete barriers).

Two generalized linear modeling techniques were used to fit the data. The first method used a repeated measures correlation structure to model yearly crash counts for a site. In this method, the covariance structure, assuming compound symmetry, is estimated before final regression parameter estimates are determined by general estimating equations. Consequently, model convergence for this method is dependent on the covariance estimates as well as parameter estimates. When the model failed to converge for the covariance estimates, an alternative method was considered. In this method, yearly crash counts for a site were totaled and ADT values were averaged to create one summary record for a site. Regression parameter estimates were then directly estimated by maximum likelihood, without an additional covariance structure being estimated.

Both methods also produced an estimate of the overdispersion parameter, or the estimate for which the variance exceeds the mean. Overdispersion occurs in traffic data when a number of sites being modeled have zero accident counts, which creates variation in the data. In this research, most sites tended to have positive accident counts because they were a mile in length, particularly when accident counts were aggregated across multiple years. When the estimate for dispersion was very small or even slightly negative, the model was re-fit assuming a constant value.

Models produced for both methods estimate per mile, per year crashes. To include this rate calculation, the first method used site length as an offset in the model while the second method used the number of years of crash data multiplied by site length as the offset. When both methods produce models, parameter estimates are nearly identical. However, confidence intervals for estimates produced with yearly crash counts tend to be wider due to yearly variation. Consequently, statistical significance of the estimates is harder to achieve. Both methods were accomplished with the GENMOD procedure of SAS.

The primary difference between methodologies occurred for the combined models from more than one state. The treatment of the state effect differed between methodologies. For the repeated measures method, the covariance structure used captured most of the variations in the data. Consequently, no additional adjustment was needed to account for the state effect. On the other hand, the summary record method treated state as a random effect in the model. The mixed model for this method was generated with the GLIMMIX procedure of SAS.

Table 4-21. Crash severity distribution for barrier medians on rural freeways.

State	Severity level	Total accidents	Crash type: Median-related crashes (percent of total crashes)		Hit-barrier crashes (percent of median-related crashes)		CMCs (percent of median-related crashes)		NCMCs (percent of median-related crashes)		Rollover crashes (percent of median-related crashes)		Fixed-object crashes (percent of median-related crashes)		Other median-related crashes (percent of median-related crashes)	
CA	Fatal	56	29	(51.78)	7	(24.13)	7	(24.13)	0	(0.00)	9	(31.03)	2	(6.89)	4	(13.79)
	Injury	692	287	(41.47)	138	(48.08)	6	(2.09)	0	(0.00)	78	(27.17)	15	(5.22)	50	(17.42)
	PDO	984	270	(27.43)	149	(55.18)	5	(1.85)	0	(0.00)	34	(12.59)	20	(7.40)	62	(22.96)
MO	Fatal	41	11	(26.82)	0	(0.00)	4	(36.36)	1	(9.09)	3	(27.27)	0	(0.00)	3	(27.27)
	Injury	602	143	(23.75)	0	(0.00)	8	(5.59)	5	(3.49)	34	(23.77)	46	(32.16)	50	(34.96)
	PDO	1,882	533	(28.32)	0	(0.00)	2	(0.37)	8	(1.50)	30	(5.62)	405	(75.98)	88	(16.51)
NC	Fatal	159	76	(47.79)	23	(30.26)	3	(3.94)	0	(0.00)	25	(32.89)	7	(9.21)	18	(23.68)
	Injury	4,300	1,900	(44.18)	930	(48.94)	4	(0.21)	0	(0.00)	174	(9.15)	218	(11.47)	574	(30.21)
	PDO	9,651	3,978	(41.21)	2,749	(69.10)	5	(0.12)	2	(0.05)	76	(1.91)	502	(12.61)	644	(16.18)
OH	Fatal	10	5	(50.00)	0	(0.00)	2	(40.00)	0	(0.00)	1	(20.00)	1	(20.00)	1	(20.00)
	Injury	669	246	(36.77)	59	(23.98)	5	(2.03)	0	(0.00)	37	(15.04)	51	(20.73)	94	(38.21)
	PDO	2,406	470	(19.53)	119	(25.31)	4	(0.85)	0	(0.00)	12	(2.55)	131	(27.87)	204	(43.40)
PA	Fatal	4	2	(50.00)	1	(50.00)	1	(50.00)	0	(0.00)	0	(0.00)	0	(0.00)	0	(0.00)
	Injury	200	103	(51.50)	19	(18.44)	2	(1.94)	1	(0.97)	0	(0.00)	0	(0.00)	81	(78.64)
	PDO	214	82	(38.31)	79	(96.34)	1	(1.21)	0	(0.00)	1	(1.21)	0	(0.00)	1	(1.21)
WA	Fatal	11	2	(18.18)	0	(0.00)	0	(0.00)	0	(0.00)	1	(50.00)	1	(50.00)	0	(0.00)
	Injury	249	50	(20.08)	10	(20.00)	0	(0.00)	0	(0.00)	33	(66.00)	6	(12.00)	1	(2.00)
	PDO	439	99	(22.55)	51	(51.51)	0	(0.00)	2	(2.02)	27	(27.27)	17	(17.17)	2	(2.02)
Total	Fatal	281	125	(44.48)	31	(24.80)	17	(13.60)	1	(0.80)	39	(31.20)	11	(8.80)	26	(20.80)
	Injury	6,712	2,729	(40.65)	1,156	(42.35)	25	(0.91)	6	(0.21)	356	(13.04)	336	(12.31)	850	(31.14)
	PDO	15,576	5,432	(34.87)	3,147	(57.93)	17	(0.31)	12	(0.22)	180	(3.31)	1,075	(19.79)	1,001	(18.42)
	Total	22,569	8,286	(36.71)	4,334	(52.30)	59	(0.71)	19	(0.22)	575	(6.93)	1,422	(17.16)	1,877	(22.65)

Of the independent variables summarized in the previous section, an attempt was made to incorporate as many variables, in addition to ADT, in the SPF to obtain the best possible function to predict crashes at barrier median sites. ADT was included in all models, regardless of its significance, as long as its coefficient was positive. Selection of the remaining variables in the model was performed by evaluating the statistical significance at the 80 percent confidence level. Additionally, the following three independent variables had the additional criterion that the resulting relationship between the characteristic and safety was meaningful in engineering terms:

- Presence of on-ramps increases crashes,
- Presence of horizontal curves adversely affects crashes, and
- Presence of shoulder rumble strips decreases crashes.

The modeling process often produced more than one suitable model for the purposes of this research. When this occurred, final models were selected from all possible models by the following considerations:

1. Select the model with the most significant variables.
2. When deciding between models with equal number of independent variables, select the model with the more important variables (e.g., median slope took precedence over number of ramps).
3. As part of this process, also consider variable effect size.

All regression models for median-related collision types were developed to predict target crash frequencies per mile per year in the following form:

$$N = \exp\left(b_0 + b_1 \ln \text{ADT} + b_2 X_2 + \cdots + b_n X_n\right) \tag{6}$$

where:

N = predicted accident frequency per mile per year
ADT = average daily traffic volume (veh/day)
$b_0, \ldots, b_n$ = regression coefficients determined by model fitting
$X_1, \ldots, X_n$ = independent design characteristics

The regression models developed with this approach are presented next, where each of the elements of design are discussed.

Tables 4-22 and 4-23 present the final SPFs for barrier medians for the total and fatal-and-injury crash severity levels, respectively. Model coefficients, including the standard error for each coefficient, as well as the overdispersion parameter for the model, are presented for each crash type and roadway type combination. Where no coefficient value is given in the tables, the coefficient was not statistically significant and should be treated as equal to zero in Equations 6 and 7. All model coefficients shown in Tables 4-22 and 4-23 are statistically significant at the 80 percent confidence level unless otherwise noted. A comment indicating the regression method and dataset used also is provided.

As an example the SPF in Table 4-22 for all median-related crashes on four-lane freeways shown in the top line of the table is

$$N_{4FF} = \exp\begin{pmatrix} -5.8329 + 0.7093 \ln \text{ADT} - 0.0047\ \text{MW} \\ -\ 0.0185\ \text{MS} + 0.0341\ \text{SW} + 0.1087\ \text{OR} \end{pmatrix} \tag{7}$$

where:

N_{4FF} = predicted median-related crash frequency per mile, per year on four-lane freeways with flexible median barriers
ADT = average daily traffic volume (veh/day)
MW = median width (ft)
MS = median slope ratio
OR = on-ramp presence
SW = inside shoulder width (ft)

The signs of the coefficients indicate how the crash rate changes when changes are made in a design variable such as median width, median slope, etc. Equation 7 indicates that median-related crashes decrease as median widths increase (negative coefficient) and decrease as median slopes are flattened (negative coefficient).

The safety effect for each design variable is the percent change in crash rate that can be expected for each unit change in a design variable. For example, the safety effect for median width is shown in Table 4-24. The top line in Table 4-24 says that for all median-related crashes on four-lane freeways with flexible median barriers, the rate decreases 0.47 percent for each additional foot of median width. The equation used to determine the safety effect is

$$\text{Safety effect} = 100\left[\exp(\text{coefficient}) - 1\right] \tag{8}$$

This number gives the percent change in crash rate per median width unit increase and all other variables remain constant.

Because the ultimate findings of the research were based on the results of the before-after evaluation presented later in this section, rather than on the regression models presented in Tables 4-22 and 4-23, the regression models are reviewed below in summary form, rather than in detail.

Median Width

In summary, wider medians were found to decrease total median-related crashes, hit-barrier crashes, fixed-object crashes, and hit-fixed-object crashes (including barrier crashes). On four-lane freeways with flexible barrier, wider medians appear to increase rollover crashes; however, for four-lane freeways with rigid barrier, wider medians decreased rollover crashes.

(*text continued on page 76*)

Table 4-22. Safety performance models for all crash severity levels combined for roadways with median barriers.

			Model coefficient (standard error)									
Median-related crash type	**Road type**	**Barrier type**	**Intercept**	**ADT[a]**	**Median width**	**Median slope ratio**	**Shoulder width**	**Curve presence**	**On-ramp presence**	**Rumble strip presence**	**Over-dispersion parameter**	**Comment**
All median-related crashes	Four-lane freeway	Flexible barrier	–5.8329 (0.6651)	0.7093 (0.0665)	–0.0047 (0.0014)	–0.0185 (0.012)	0.0341 (0.0113)	– –	0.1087 (0.0765)	– –	0.4111 (0.0308)	Yearly data All states combined
		Semi-rigid barrier	–8.7702 (1.4092)	0.9924 (0.1295)	–0.0054 (0.0038)	–0.0403 (0.021)	– –	– –	– –	– –	0.2622 (0.0381)	Yearly data All states combined
		Rigid barrier	–10.8816 (9.3988)	1.3769 (0.9373)	– –	–0.1816 (0.0567)	–0.2346 (0.1099)	– –	– –	– –	0.0100 (0.0000)	Yearly data Washington data
	Six-lane freeway	Flexible barrier	–5.7171 (3.8602)	0.6420 (0.3770)		0.0580 (0.0415)				–0.2710 (0.1250)	0.3022 (0.0548)	Yearly data All states combined
		Semi-rigid barrier	–10.2198 (5.7299)	1.0990 (0.5544)		–0.0483 (0.0323)					0.0768 (0.0523)	All years combined California data
		Rigid barrier	–22.6335 (0.6399)	2.1336 (0.0619)	–0.0234 (0.0013)	–0.0317 (0.0051)	0.4198 (0.0224)				0.0100 (0.0000)	Yearly data All states combined
Hit-barrier crashes	Four-lane freeway	Flexible barrier	–7.3188 (1.0030)	0.5179 (0.1038)		0.2557 (0.0208)				–0.2607 (0.1470)	1.0063 (0.0833)	Yearly data All states combined
		Semi-rigid barrier	–12.9287 (2.2728)	1.3718 (0.2229)	–0.0128 (0.0061)	0.0639 (0.0305)	–0.1079 (0.0347)	0.2498 (0.1642)			0.3771 (0.0726)	Yearly data North Carolina data
		Rigid barrier	–9.1685 (2.6535)	0.9703 (0.2532)		0.0551 (0.0180)	–0.2001 (0.0577)				0.2758 (0.1266)	Yearly data All states combined
	Six-lane freeway	Flexible barrier	–19.4212 (6.7768)	1.7994 (0.5761)	–0.0376 (0.0076)	0.3138 (0.0642)	–0.1020 (0.0763)		0.4469 (0.2242)		0.8599 (0.1941)	Yearly data All states combined
		Semi-rigid barrier	–7.2653 (5.5769)	0.8525 (0.5412)		–0.0584 (0.0404)	–0.0668 (0.0358)				0.1797 (0.1274)	Yearly data All states combined
		Rigid barrier	–24.7498 (1.0909)	2.4352 (0.1147)	–0.0203 (0.0019)	–0.0282 (0.0071)					0.0100 (0.0000)	Yearly data All states combined

[a] Coefficient not significant at 80% level.

(continued on next page)

Table 4-22. (Continued)

Median-related crash type	Road type	Barrier type	Model coefficient (standard error)									Comment
			Intercept	ADT[a]	Median width	Median slope ratio	Shoulder width	Curve presence	On-ramp presence	Rumble strip presence	Over-dispersion parameter	
Rollover crashes	Four-lane freeway	Flexible barrier	–10.0023 (2.0666)	0.8419 (0.1971)	0.0196 (0.0043)	–0.1494 (0.0387)					0.3577 (0.1290)	All years combined All states combined
		Semi-rigid barrier	–9.1963 (8.5721)	0.9591 (0.8672)		–0.1059 (0.0566)					0.0100 (0.0000)	All years combined All states combined
		Rigid barrier	–9.3545 (8.0629)	1.1202 (0.8019)		–0.1327 (0.0597)	–0.3715 (0.1774)				0.4131 (0.4668)	Yearly data All states combined
	Six-lane freeway	Flexible barrier	–16.4753 (11.5655)	1.2897 (0.9859)		–0.0811 (0.0619)	0.2591 (0.1490)				0.0100 (0.0000)	Yearly data All states combined
		Semi-rigid barrier	–22.4091 (6.4691)	1.8843 (0.5642)							0.0100 (0.0000)	Yearly data California data
		Rigid barrier	–12.1599 (6.8980)	0.9274 (0.6045)							0.0100 (0.0000)	Yearly data All states combined
Fixed-object crashes	Four-lane freeway	Flexible barrier	–12.5218 (1.2021)	1.2352 (0.1223)	–0.0046 (0.0029)						1.8716 (0.1589)	Yearly data All states combined
		Semi-rigid barrier	–5.2205 (3.8314)	0.4598 (0.3882)		–0.0887 (0.0483)					1.2600 (0.3745)	Yearly data All states combined
		Rigid barrier	–15.6971 (4.8691)	1.4237 (0.4687)		–0.0500 (0.0304)					0.6306 (0.9698)	Yearly data All states combined
	Six-lane freeway	Flexible barrier	–3.6234 (4.2008)	0.5469 (0.4306)	–0.0162 (0.0121)	–0.1956 (0.1043)		0.3674 (0.2338)	1.0642 (0.3754)		0.2238 (0.1569)	All years combined All states combined

[a] Coefficient not significant at 80% level.

Table 4-22. (Continued)

Median-related crash type	Road type	Barrier type	Model coefficient (standard error) Intercept	ADT[a]	Median width	Median slope ratio	Shoulder width	Curve presence	On-ramp presence	Rumble strip presence	Over-dispersion parameter	Comment
Hit-any-fixed-object crashes	Four-lane freeway	Flexible barrier	–7.0339 (0.7116)	0.7027 (0.0678)		0.0413 (0.0182)	0.0495 (0.0126)	0.1863 (0.1073)			0.4570 (0.0450)	Yearly data North Carolina data
		Semi-rigid barrier	–13.1563 (1.7826)	1.3325 (0.1661)		–0.0451 (0.0313)		0.2771 (0.1924)	0.2966 (0.1145)		0.5180 (0.0705)	Yearly data All states combined
		Rigid barrier	–16.0751 (5.7491)	1.4516 (0.5733)		0.0926 (0.0369)	0.3472 (0.0508)				0.3318 (0.2735)	Yearly data All states combined
	Six-lane freeway	Flexible barrier	–11.1972 (3.7262)	1.1812 (0.3403)	–0.0154 (0.0056)	0.0619 (0.0370)			0.2794 (0.1739)	–0.4438 (0.1705)	0.4390 (0.0856)	Yearly data All states combined
		Semi-rigid barrier	–5.0610 (4.7205)	0.6189 (0.4631)		–0.0503 (0.0374)					0.0100 (0.0000)	Yearly data California data
		Rigid barrier	–21.9059 (0.9910)	2.1052 (0.0963)	–0.0236 (0.0021)	–0.0311 (0.0082)	0.2748 (0.0346)				0.0100 (0.0000)	Yearly data
Other median-related crashes	Four-lane freeway	Flexible barrier	–9.8892 (0.9143)	0.9274 (0.0915)	0.0061 (0.0018)	–0.0425 (0.0157)	0.0353 (0.0154)				0.2943 (0.0670)	Yearly data All states combined
		Semi-rigid barrier	–13.6199 (2.0145)	1.2921 (0.1969)	–0.0032 (0.0024)	–0.0324 (0.0180)					0.1623 (0.1005)	Yearly data All states combined
		Rigid barrier	–17.5930 (3.363)	1.7248 (0.3324)		–0.0462 (0.0259)				–0.7422 (0.3123)	0.0100 (0.0000)	Yearly data California data
	Six-lane freeway	Flexible barrier	–11.2964 (6.6773)	0.8519 (0.5387)	0.0148 (0.0106)		0.1871 (0.0755)				0.0636 (0.1287)	Yearly data Ohio data
		Semi-rigid barrier	–16.7856 (4.7485)	1.6695 (0.4625)	–0.0342 (0.0107)						0.0880 (0.2242)	Yearly data All states combined
		Rigid barrier	–16.0186 (9.2481)	1.3739 (0.8151)	–0.0097 (0.0075)		0.1168 (0.0571)				0.3133 (0.3409)	Yearly data All states combined

[a] Coefficient not significant at 80% level.

Table 4-23. Safety performance models for fatal-and-injury crashes for roadways with median barriers.

Median-related crash type	Road type	Barrier type	Model coefficient (standard error)									Comment
			Intercept	ADT[a]	Median width	Median slope ratio	Shoulder width	Curve presence	On-ramp presence	Rumble strip presence	Over-dispersion parameter	
All median-related crashes	Four-lane freeway	Flexible barrier	–14.3896 (7.5048)	1.4652 (0.7175)		–0.1247 (0.0517)					0.4172 (0.2084)	Yearly data Missouri data
		Semi-rigid barrier	–11.1040 (2.2380)	0.9845 (0.2098)		0.0367 (0.0225)	0.0656 (0.0363)				0.2254 (0.0725)	Yearly data All states combined
		Rigid barrier	–13.8073 (2.5907)	1.3157 (0.2362)		0.0358 (0.0148)	–0.0657 (0.0446)				0.0100 (0.0000)	Yearly data All states combined
	Six-lane freeway	Flexible barrier	–10.4765 (3.4162)	1.0742 (0.3481)		–0.1168 (0.0845)			0.2763 (0.2108)		0.0157 (0.1207)	Yearly data Ohio data
		Semi-rigid barrier	–10.7386 (7.3769)	1.1117 (0.7146)		–0.0645 (0.0419)					0.1061 (0.0941)	All years combined California data
		Rigid barrier	–13.3590 (4.8250)	1.2615 (0.4247)							0.2243 (0.1502)	
Hit-barrier crashes	Four-lane freeway	Flexible barrier	–8.3364 (1.0014)	0.6959 (0.0960)	–0.0069 (0.0030)	0.0668 (0.0283)					0.4128 (0.1366)	All years combined North Carolina data
		Semi-rigid barrier	–10.5963 (2.7821)	0.9739 (0.2551)	–0.0139 (0.0085)	0.0593 (0.0431)					0.5638 (0.1800)	Yearly data All states combined
		Rigid barrier	–17.1734 (3.3608)	1.6936 (0.3482)	–0.0241 (0.0174)	0.0494 (0.0159)	–0.1212 (0.0770)				0.0100 (0.0000)	Yearly data All states combined
	Six-lane freeway	Flexible barrier	–20.4821 (5.3176)	1.6574 (0.4924)	–0.0182 (0.0087)	0.2334 (0.0794)					0.6483 (0.3901)	Yearly data All states combined
		Semi-rigid barrier	–9.9114 (7.7448)	1.1557 (0.7506)	–0.0208 (0.0124)	–0.0739 (0.0258)					0.0241 (0.1872)	Yearly data All states combined
		Rigid barrier	–18.8340 (4.6550)	1.7143 (0.4010)							0.0944 (0.1587)	

[a] Not significant at 20% level.

Table 4-23. (Continued)

Median-related crash type	Road type	Barrier type	Model coefficient (standard error): Intercept	ADT[a]	Median width	Median slope ratio	Shoulder width	Curve presence	On-ramp presence	Rumble strip presence	Over-dispersion parameter	Comment
Rollover crashes	Four-lane freeway	Flexible barrier	–6.8911 (2.2656)	0.5274 (0.2182)	0.0170 (0.0046)	–0.1532 (0.0410)					0.2655 (0.1643)	All years combined All states combined
		Semi-rigid barrier	–4.4884 (6.0381)	0.6264 (0.5976)		–0.1332 (0.0462)	–0.2433 (0.0432)				0.4432 (0.3828)	Yearly data Washington data
		Rigid barrier	–8.1647 (35.3887)	0.9959 (3.5398)		–0.4888 (0.3052)					0.0100 (0.0000)	All years combined Washington data
	Six-lane freeway	Flexible barrier	–7.0493 (6.277)	0.6549 (0.5985)		–0.1753 (0.0883)					0.0346 (0.1725)	All years combined All states combined
		Semi-rigid barrier	–27.5126 (8.9451)	2.2787 (0.7853)							0.5836 (1.0540)	Yearly data All states combined
		Rigid barrier	–14.4923 (7.9921)	1.1226 (0.6991)							0.0100 (0.0000)	Yearly data All states combined
Fixed-object crashes	Four-lane freeway	Flexible barrier	–13.2253 (2.4501)	1.2809 (0.2335)		–0.2008 (0.0300)					1.3065 (0.4154)	Yearly data All states combined
		Semi-rigid barrier	–9.2486 (5.9057)	0.7475 (0.5507)		–0.1525 (0.0775)					0.2822 (0.3841)	All years combined North Carolina data
		Rigid barrier	–18.1491 (6.7195)	1.4580 (0.6374)							0.1765 (0.5148)	All years combined California data
	Six-lane freeway	Flexible barrier	–8.9646 (4.7498)	0.7097 (0.4294)							0.0100 (0.0000)	Yearly data Washington, Ohio data
		Semi-rigid barrier	–21.1554 (9.7736)	1.6562 (0.8580)							9.2433 (8.9500)	Yearly data All states combined
		Rigid barrier	–3.3447 (16.3475)	0.2188 (1.5036)	–0.0379 (0.0140)						5.0976 (7.1034)	Yearly data All states combined

[a] Not significant at 20% level.

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Table 4-23. (Continued)

Median-related crash type	Road type	Barrier type	Model coefficient (standard error)									Comment
			Intercept	ADT[a]	Median width	Median slope ratio	Shoulder width	Curve presence	On-ramp presence	Rumble strip presence	Over-dispersion parameter	
Hit-any-fixed-object crashes	Four-lane freeway	Flexible barrier	–8.5609 (0.9977)	0.7349 (0.0993)	–0.0047 (0.0027)	0.0558 (0.0172)					0.4952 (0.1135)	Yearly data All states combined
		Semi-rigid barrier	–14.1843 (2.3132)	1.3338 (0.2112)		–0.0382 (0.0278)					0.6337 (0.1557)	Yearly data All states combined
		Rigid barrier	–16.9305 (2.4229)	1.4933 (0.2366)		0.0604 0.0184					0.0100 0.0000	Yearly data All states combined
	Six-lane freeway	Flexible barrier	–11.3440 (4.5754)	0.9409 (0.4274)		0.0703 (0.0544)		0.4176 (0.2630)		–0.2677 (0.2136)	0.0970 (0.0940)	All years combined All states combined
		Semi-rigid barrier	–7.9611 (10.1298)	0.8718 (0.9815)		–0.0887 (0.0590)					0.3199 (0.1998)	All years combined California data
		Rigid barrier	–13.2134 (11.2166)	1.3236 (1.0773)	–0.0336 (0.0225)						0.2214 (0.2998)	
Other median-related crashes	Four-lane freeway	Flexible barrier	–17.0825 (2.6603)	1.4361 (0.2644)		–0.0462 (0.0302)	0.1402 (0.0493)				0.0428 (0.1608)	All years combined Missouri data
		Semi-rigid barrier	–11.8700 (8.1875)	0.9536 (0.7653)	0.0348 (0.0144)						0.3767 (0.4118)	Yearly data All states combined
		Rigid barrier	–23.5437 (9.8672)	2.1624 (0.9150)	–0.0283 (0.0210)						0.0100 (0.0000)	Yearly data North Carolina data
	Six-lane freeway	Flexible barrier	–35.1204 (10.9298)	3.1728 (0.9841)	–0.0277 (0.0055)						0.5139 (0.7632)	
		Semi-rigid barrier	–14.3896 (7.5048)	1.4652 (0.7175)		–0.1247 (0.0517)					0.4172 (0.2084)	Yearly data California data
		Rigid barrier	–11.1040 (2.2380)	0.9845 (0.2098)		0.0367 (0.0225)	0.0656 (0.0363)				0.2254 (0.0725)	Yearly data All states combined

[a] Not significant at 20% level.

Table 4-24. Safety effect of median width for roadways with median barriers.

Median-related crash type	Road type	Barrier type	Percent change in crash frequency per unit change in median width: Total severity Effect	Total severity LB	Total severity UB	F & I severity Effect	F & I severity LB	F & I severity UB
All median-related crashes	Four-lane freeway	Flexible barrier	–0.47	–0.75	–0.19			
		Semi-rigid barrier	–0.53	–1.27	0.20			
		Rigid barrier						
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier	–2.31	–2.56	–2.07			
Hit-barrier crashes	Four-lane freeway	Flexible barrier				–0.69	–1.28	–0.09
		Semi-rigid barrier	–1.27	–2.44	–0.09	–1.39	–3.02	0.27
		Rigid barrier				–2.38	–5.66	1.01
	Six-lane freeway	Flexible barrier	–3.69	–5.12	–2.23	–1.80	–3.45	–0.12
		Semi-rigid barrier				–2.06	–4.41	0.36
		Rigid barrier	–2.01	–2.37	–1.65			
Rollover crashes	Four-lane freeway	Flexible barrier	1.98	1.12	2.86	1.71	0.80	2.64
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
Fixed-object crashes	Four-lane freeway	Flexible barrier	–0.46	–1.02	0.10			
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier	–1.61	–3.92	0.76			
		Semi-rigid barrier						
		Rigid barrier				–3.72	–6.33	–1.03
Hit-any-fixed-object crashes	Four-lane freeway	Flexible barrier				–0.47	–1.00	0.06
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier	–1.53	–2.60	–0.45			
		Semi-rigid barrier						
		Rigid barrier	–2.33	–2.74	–1.92			
Other median-related crashes	Four-lane freeway	Flexible barrier	0.62	0.27	0.96	–3.31	–7.48	1.06
		Semi-rigid barrier	–0.32	–0.79	0.15			
		Rigid barrier				3.54	0.66	6.50
	Six-lane freeway	Flexible barrier	1.49	–0.61	3.63			
		Semi-rigid barrier	–3.37	–5.37	–1.32	–2.79	–6.71	1.28
		Rigid barrier	–0.96	–2.40	0.50	–2.73	–3.78	–1.68

Table 4-25. Safety effect of median slope ratio for roadways with median barriers.

Median-related crash type	Road type	Barrier type	Percent change in crash frequency per unit change in median slope ratio: Total severity Effect	Total severity LB	Total severity UB	F & I severity Effect	F & I severity LB	F & I severity UB
All median-related crashes	Four-lane freeway	Flexible barrier	–1.64	–3.91	0.69	–11.72	–20.23	–2.30
		Semi-rigid barrier	–3.95	–7.83	0.09	3.74	–0.74	8.42
		Rigid barrier	–16.60	–25.38	–6.79	3.65	0.68	6.70
	Six-lane freeway	Flexible barrier	5.98	–2.30	14.96	–11.02	–24.60	5.00
		Semi-rigid barrier	–4.71	–10.55	1.51	–6.25	–13.65	1.78
		Rigid barrier	–3.12	–4.09	–2.14			
Hit-barrier crashes	Four-lane freeway	Flexible barrier	29.14	23.97	34.52	6.91	1.14	13.01
		Semi-rigid barrier	6.60	0.42	13.16	6.11	–2.49	15.47
		Rigid barrier	5.67	2.01	9.46	5.06	1.84	8.39
	Six-lane freeway	Flexible barrier	36.86	20.67	55.22	26.29	8.08	47.57
		Semi-rigid barrier	–5.67	–12.85	2.09	–7.13	–11.71	–2.31
		Rigid barrier	–2.78	–4.12	–1.42			
Rollover crashes	Four-lane freeway	Flexible barrier	–13.88	–20.19	–7.06	–14.20	–20.84	–7.00
		Semi-rigid barrier	–10.05	–19.49	0.49	–12.47	–20.04	–4.18
		Rigid barrier	–12.42	–22.62	–0.88	–38.66	–66.28	11.55
	Six-lane freeway	Flexible barrier	–7.79	–18.32	4.10	–16.08	–29.67	0.13
		Semi-rigid barrier						
		Rigid barrier						
Fixed-object crashes	Four-lane freeway	Flexible barrier				–18.19	–22.87	–13.23
		Semi-rigid barrier	–8.49	–16.75	0.60	–14.15	–26.24	–0.07
		Rigid barrier	–4.87	–10.38	0.97			
	Six-lane freeway	Flexible barrier	–17.76	–32.97	0.89			
		Semi-rigid barrier						
		Rigid barrier						
Hit-any-fixed-object crashes	Four-lane freeway	Flexible barrier	4.22	0.56	8.01	5.74	2.23	9.37
		Semi-rigid barrier	–4.41	–10.10	1.65	–3.75	–8.85	1.63
		Rigid barrier	9.70	2.05	17.93	6.23	2.47	10.12
	Six-lane freeway	Flexible barrier	6.38	–1.06	14.39	7.28	–3.78	19.62
		Semi-rigid barrier	–4.90	–11.63	2.34	–8.49	–18.47	2.72
		Rigid barrier	–3.06	–4.61	–1.49			
Other median-related crashes	Four-lane freeway	Flexible barrier	–4.16	–7.06	–1.16			
		Semi-rigid barrier	–3.19	–6.55	0.29	–4.52	–10.01	1.31
		Rigid barrier	–4.51	–9.25	0.47			
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						

(*text continued from page 68*)

Results were mixed for other median-related crash types. Fatal-and-injury crashes followed the same trends.

Median Slope

Safety effects of median slopes are summarized in Table 4-25. In summary, flatter slopes appear to reduce the number of rollover and fixed-object crashes, but increase hit-barrier crashes. The safety effects for hit-barrier crashes are larger for flexible barriers, but are generally uniform for all barrier types for rollover crashes. Hit-fixed-object crashes (including hit-barrier crashes) increased with flatter slopes where flexible barriers were present, but decreased where semi-rigid and rigid barriers were in place.

Total median-related crashes generally declined with flatter slopes, and more severe fatal-and-injury median-related crashes generally decreased with flatter slopes.

Median Shoulder Width

Safety effects for median shoulder width statistically significant are shown in Table 4-26. In summary, wider median shoulders generally appear to decrease the number of hit-barrier crashes. Rollover crashes decreased with wider median shoulders on four-lane freeways but increased on six-lane freeways.

Table 4-26. Safety effect of inside shoulder width for roadways with median barriers.

Median-related crash type	Road type	Barrier type	Percent change in crash frequency per unit change in inside shoulder width					
			Total severity			F & I severity		
			Effect	LB	UB	Effect	LB	UB
All median-related crashes	Four-lane freeway	Flexible barrier	3.47	1.19	5.79			
		Semi-rigid barrier				6.78	–0.56	14.66
		Rigid barrier	–20.92	–36.24	–1.91	–6.35	–14.20	2.21
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier	52.17	45.64	59.00			
Hit-barrier crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier	–10.23	–16.13	–3.92			
		Rigid barrier	–18.14	–26.89	–8.34	–11.41	–23.82	3.01
	Six-lane freeway	Flexible barrier	–9.69	–22.24	4.87			
		Semi-rigid barrier	–6.46	–12.80	0.33			
		Rigid barrier						
Rollover crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier				–21.59	–27.95	–14.67
		Rigid barrier	–31.03	–52.27	–0.35			
	Six-lane freeway	Flexible barrier	29.58	–3.24	73.53			
		Semi-rigid barrier						
		Rigid barrier						
Fixed-object crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
Hit-any-fixed-object crashes	Four-lane freeway	Flexible barrier	5.08	2.51	7.71			
		Semi-rigid barrier						
		Rigid barrier	41.51	28.10	56.32			
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier	31.63	23.00	40.87			
Other median-related crashes	Four-lane freeway	Flexible barrier	3.60	0.52	6.77			
		Semi-rigid barrier				15.05	4.45	26.72
		Rigid barrier						
	Six-lane freeway	Flexible barrier	20.57	3.98	39.81			
		Semi-rigid barrier						
		Rigid barrier	12.39	0.49	25.70			

The results for fixed-object crashes (including hit-barrier crashes) were mixed, but the majority of results showed increased crashes with wider shoulders.

Overall, on four-lane freeways, median-related crashes appeared to increase with wider shoulders for flexible and semi-rigid barriers, but decreased for rigid barriers. On six-lane freeways with rigid barrier, median-related crashes increased with wider median shoulders.

Presence of Horizontal Curves

Safety effects for presence of horizontal curves that are statistically significant are shown in Table 4-27. In summary, horizontal curve presence was associated with increased rollover and hit-fixed-object crashes (including hit-barrier crashes). Safety effects were more often significant at sites with flexible barriers.

Presence of On-Ramps

Safety effects of on-ramp presence that are statistically significant are shown in Table 4-28. In summary, the presence of an on-ramp generally increases crashes where statistically significant relationships were found. The amount of increase due to the presence of an on-ramp ranged from 11 to 189 percent.

Table 4-27. Safety effect of curve presence for roadways with median barriers.

Median-related crash type	Road type	Barrier type	Percent change in crash frequency between sites with and without horizontal curves					
			Total severity			F & I severity		
			Effect	LB	UB	Effect	LB	UB
All median-related crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
Hit-barrier crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier	28.38	–6.94	77.11			
		Rigid barrier						
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
Rollover crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
Fixed-object crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier	44.40	–8.69	128.35			
		Semi-rigid barrier						
		Rigid barrier						
Hit-any-fixed-object crashes	Four-lane freeway	Flexible barrier	20.48	–2.37	48.69			
		Semi-rigid barrier	31.93	–9.51	92.35			
		Rigid barrier						
	Six-lane freeway	Flexible barrier				51.83	–10.28	156.94
		Semi-rigid barrier						
		Rigid barrier						
Other median-related crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						

Table 4-28. Safety effect of on-ramp presence for roadways with median barriers.

Median-related crash type	Road type	Barrier type	Percent change in crash frequency between sites with and without on-ramps					
			Total severity			F & I severity		
			Effect	LB	UB	Effect	FB	UB
All median-related crashes	Four-lane freeway	Flexible barrier	11.48	–4.03	29.51			
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier				31.82	–12.79	99.25
		Semi-rigid barrier						
		Rigid barrier						
Hit-barrier crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier	56.35	0.75	142.63			
		Semi-rigid barrier						
		Rigid barrier						
Rollover crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
Fixed-object crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier	189.84	38.86	504.98			
		Semi-rigid barrier						
		Rigid barrier						
Hit-any-fixed-object crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier	34.53	7.48	68.38			
		Rigid barrier						
	Six-lane freeway	Flexible barrier	32.23	–5.96	85.92			
		Semi-rigid barrier						
		Rigid barrier						
Other median-related crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						

Presence of Shoulder Rumble Strips

Safety effects for the presence of shoulder rumble strips found to be statistically significant are shown in Table 4-29. In summary, the presence of rumble strips appeared to reduce hit-barrier and hit-fixed-object crashes (including hit-barrier crashes). No significant safety effects were observed for rollover crashes.

4.3.6 Before-After Evaluation of Median Barrier Installation

An alternative analysis of barrier median crashes was conducted with observational before-after evaluations, comparisons of safety performance before and after placement of barriers in existing medians. Not all sites in the database of barrier medians were usable for this analysis because the construction date when barrier was added to the median was not known in all cases. Sites were used in the states of Missouri, North Carolina, and Ohio. In Missouri, all sites included in the analysis had flexible barrier installed in the median and the years of construction were 2004, 2005, or 2006. In North Carolina, barriers were installed in the years of 1998 through 2001, and in Ohio barrier was installed in 2004.

The before-after evaluations were conducted using the Empirical Bayes (EB) method. This method compensates for the potential bias due to regression to the mean. Regression

Table 4-29. Safety effect of rumble strip presence for roadways with median barriers.

Median-related crash type	Road type	Barrier type	Percent change in crash frequency between sites with and without shoulder rumble strips					
			Total severity			F&I severity		
			Effect	LB	UB	Effect	LB	UB
All median-related crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier	–23.74	–40.30	–2.58			
		Semi-rigid barrier						
		Rigid barrier						
Hit-barrier crashes	Four-lane freeway	Flexible barrier	–22.95	–42.23	2.76			
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
Rollover crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
Fixed-object crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
Hit-any-fixed-object crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						
	Six-lane freeway	Flexible barrier	–35.84	–54.07	–10.38	–23.49	–50.09	17.30
		Semi-rigid barrier						
		Rigid barrier						
Other median-related crashes	Four-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier	–52.39	–74.19	–12.19			
	Six-lane freeway	Flexible barrier						
		Semi-rigid barrier						
		Rigid barrier						

to the mean occurs when a countermeasure is installed at a site with high short-term crash experience such that the crash experience would have decreased in the after study period whether the countermeasure had been implemented or not. Before-after evaluations must be carefully structured to assure that the effect of regression to the mean is not mistaken for an effect of the countermeasure.

The EB method controls regression to the mean by combining the results from predictive models, such as negative binomial (NB) regression, with actual observed crash frequencies for specific sites. The predicted and observed values are combined in a weighting procedure, where the weights are based on the overdispersion parameter from the NB regression model. The NB models used in these steps were developed from a group of reference sites similar to the before-period condition at the sites where barrier medians are installed. The safety prediction models for traversable medians whose development is described in Section 4.2 served this purpose.

The primary output from this type of evaluation is an estimate of the overall safety effectiveness of the barrier installation, usually expressed as a percent change in crash frequency. The resulting percent increase or decrease in total median-related crashes after the installation of median barrier, along with their standard errors, are shown in Table 4-30. All median-related crashes increased after the installation of barrier. The increase was greatest for sites where flexible barrier was installed, having a 277 percent increase in the number of crashes.

The analysis of specific crash types indicates that CMC and NCMC were virtually eliminated, however hit-fixed-object crashes increased six to nine times. Fixed-object crashes have a reporting oddity that should be noted. The Missouri crash database does not have a code for "hit-barrier," so all barrier crashes are coded as fixed-object crashes. Therefore, in Table 4-30 the category for hit-fixed-object crashes includes hit-barrier crashes. Rollover crashes decreased after installation of median barrier. The decrease in rollover crashes was nearly 80 percent on four-lane freeways and 23 percent on six-lane freeways. It is evident that a median barrier eliminates cross-median crashes and decreases rollover at the cost of greatly increased fixed-object crashes.

The percent increase or decrease in fatal-and-injury crashes after the installation of median barrier is shown in Table 4-31.

Table 4-30. Crash reduction factors: percent decrease (increase) in median-related crashes after the installation of median barrier.

Road type	Median-related crash type	Barrier type installed	Sites	Percent decrease (increase) in crashes after barrier installation	Standard Error	Significance at 5% level
Four-lane freeway	All median-related crashes	All	302	(225)	10.55	Yes
		Flexible	238	(277)	14.94	Yes
		Semi-rigid	63	(152)	14.09	Yes
		Rigid	1	(140)	68.21	*
Six-lane freeway	All median-related crashes	Flexible	25	66	14.37	Yes
Four-lane freeway	CMCs	All	302	97	1.18	Yes
		Flexible	238	96	1.44	Yes
		Semi-rigid	63	98	1.83	Yes
		Rigid	1	100	-	*
Six-lane freeway	CMCs	Flexible	25	73	27.27	Yes
Four-lane freeway	CMCs + NCMCs	All	302	69	6.71	Yes
		Flexible	238	55	10.66	Yes
		Semi-rigid	63	89	6.13	Yes
		Rigid	1	100	-	*
Six-lane freeway	CMCs + NCMCs	Flexible	25	74	25.9	Yes
Four-lane freeway	Rollover crashes	All	302	79	2.23	Yes
		Flexible	238	74	3.24	Yes
		Semi-rigid	63	88	2.71	Yes
		Rigid	1	100	-	*
Six-lane freeway	Rollover crashes	Flexible	25	23	31.53	No
Four-lane freeway	Hit-fixed-object crashes (including hit-barrier crashes)	All	302	(604)	42.66	Yes
		Flexible	238	(720)	62.61	Yes
		Semi-rigid	63	(426)	52.64	Yes
		Rigid	1	(892)	465.36	*
Six-lane freeway	Hit-fixed-object crashes	Flexible	25	(209)	31.17	Yes
Four-lane freeway	Other median-related crashes	All	302	(103)	9.66	Yes
		Flexible	238	(128)	14.11	Yes
		Semi-rigid	63	(72)	13.01	Yes
		Rigid	1	(40)	74.80	*
Six-lane freeway	Other median-related crashes	Flexible	25	16	15.45	No

* Not stated due to small sample size.

Table 4-31. Crash reduction factors: percent decrease (increase) in fatal-and-injury median-related crashes after installation of median barrier.

Road type	Median-related crash type	Barrier type installed	Sites	Percent decrease (increase) in crashes after barrier installation	Standard Error	Significance at 5% level
Four-lane freeway	All median-related crashes	All	302	(55)	6.24	Yes
		Flexible	238	(60)	8.60	Yes
		Semi-rigid	63	(50)	9.15	Yes
		Rigid	1	(8)	51.29	*
Six-lane freeway	All median-related crashes	Flexible	25	(17)	20.07	No
Four-lane freeway	CMCs	All	302	96	1.81	Yes
		Flexible	238	92	3.43	Yes
		Semi-rigid	63	100	-	*
		Rigid	1	100	-	*
Six-lane freeway	CMCs	Flexible	25	69	31.20	Yes
Four-lane freeway	CMCs + NCMCs	All	302	67	8.20	Yes
		Flexible	238	62	10.11	Yes
		Semi-rigid	63	83	12.02	Yes
		Rigid	1	100	-	*
Six-lane freeway	CMCs + NCMCs	Flexible	25	69	31.20	Yes
Four-lane freeway	Rollover crashes	All	302	61	4.98	Yes
		Flexible	238	57	6.35	Yes
		Semi-rigid	63	69	7.77	Yes
		Rigid	1	100	-	*
Six-lane freeway	Rollover crashes	Flexible	25	31	34.71	No
Four-lane freeway	Hit-fixed-object crashes (including hit-barrier crashes)	All	302	(123)	14.84	Yes
		Flexible	238	(132)	19.82	Yes
		Semi-rigid	63	(113)	22.17	Yes
		Rigid	1	(23)	85.97	*
Six-lane freeway	Hit-fixed-object crashes	Flexible	25	(128)	53.78	Yes
Four-lane freeway	Other median-related crashes	All	302	(57)	9.21	Yes
		Flexible	238	(67)	12.80	Yes
		Semi-rigid	63	(47)	13.38	Yes
		Rigid	1	14	62.78	*
Six-lane freeway	Other median-related crashes	Flexible	25	14	26.11	No

* Not stated due to small sample size.

All median-related fatal-and-injury crashes increased by 55 percent after the installation of median barrier. Cross-median crashes were virtually eliminated and rollover crashes were decreased by nearly 70 percent on four-lane freeways and 30 percent on six-lane freeways. Fatal-and-injury hit-fixed-object crashes more than doubled.

The interpretation of these results is strongly influenced by the findings (based on Tables 4-4 and 4-21) that CMCs, in particular, are much more severe than other crash types, including rollover and fixed-object crashes. The application of the before-after evaluation results is addressed in Chapter 6 of this report.

CHAPTER 5

Median Encroachment Simulation

Crash modeling is a relatively crude tool for determining the effects of individual roadway or roadside design factors. Vehicle dynamics simulation provides a much more direct and experimentally controlled method to examine these effects. Therefore, a vehicle dynamics simulation study was conducted as part of the research.

5.1 Introduction

For at least four decades, vehicle dynamics software packages such as Vehicle Dynamics Analysis Non Linear (VDANL) and CarSim (*34*, *35*) have been used to aid in vehicle performance analysis, stability analysis, and accident reconstruction. Although some of the earliest vehicle simulation software were programs to aid in highway design (*36–39*), the use of multi-body vehicle simulation to study roadway design changes remains relatively rare. Many simulations have been compared with experimental data during the past few decades (*40–50*), and are being continually validated and updated.

This study investigated the safety of highway medians by simulating median encroachments for several different vehicle classes, initial speeds, and encroachment angles. Both bumper height and vehicle positions during the simulation were considered as a means of analyzing roadway safety design factors such as location and height of cable barriers to be installed for that particular median. Furthermore, this study analyzes the impact of a driver's input on the resulting crash scenario. Unlike previous studies where these varying steering and braking inputs were usually disregarded or grossly simplified, this study incorporates several steer–brake combinations, and reveals the influence of these effects to be significant.

For the present study, a relatively new software package called CarSim (developed by Mechanical Simulation) is used for the simulations. It was selected because it is the most widely used vehicle dynamics software in the industry, and it is easy to interface with external MATLAB and Simulink scripts. CarSim also has an advanced graphic user interface (GUI) allowing the user to build customized roadway profiles easily, select specific vehicles, and control the driver's steering, accelerator, and braking inputs (*35*).

The remainder of this chapter discusses details of a specific study using vehicle dynamics simulations to examine the safety of rural divided highway medians.

5.2 Brief History of Vehicle Dynamics Simulations

In recent years, vehicle dynamics simulations have been used for highway design and safety analysis purposes. In 1997, the software packages VDANL and Vehicle Dynamics Models for Roadway Analysis and Design (VDM RoAD) were used to predict the dynamics of a 1994 Ford Taurus (*46*). Results from this study showed a very realistic trend, both in the linear and non-linear range of the vehicle response, when compared to experimental data. Similarly, a program called PC-CRASH was used to reconstruct rollover crashes (*49*). When compared to real-life crash test data, the model was again validated.

Benekohal and Treiterer's 1998 study was one of the first to apply CarSim as the vehicle dynamics software package for highway design analysis (*51*). In their study, traffic patterns on the highway in both normal and stop-and-go driving scenarios were simulated. Speed, steering, position, and suspension outputs from the simulation were all compared to real-life experimental data and, after a regression analysis, an R-squared value of 0.98 proved the validity of the simulations.

Another recent study published by FHWA created an in-depth driver vehicle module (DVM) to predict the driver's response in certain crash situations on the highway (*52*). This study combined the VDANL model with a computational driver model that attempted to simulate the driver's cognitive processes during driving. Although VDANL was originally designed for passenger cars, light trucks, and multi-purpose vehicles, DVM has only been created for passenger cars and Class 8 tractor trailers. The need for further use and testing of such software is apparent. For example, additional vehicle types should be included in the model, as should driver steering inputs.

Further testing involving vehicle dynamics simulations was carried out by the Federal Highway Administration (FHWA)/National Highway Traffic Safety Administration (NHTSA) National Crash Analysis Center (NCAC) in 2008 (*53*). In this study, vehicle dynamics simulations with the Human-Vehicle-Environment (HVE) software package were compared with physical testing of a large passenger, pickup truck, and small passenger vehicle. Using cable barriers designed in accordance with the guidelines established in the *NCHRP Report 350* study (*54*), this investigation examined the occurrence of barrier underrides seen in real-life crash report data. Simulation results were strikingly similar to the data (from high-speed video footage and vehicle sensors) obtained in the physical testing. Although significant challenges remain related to the simulation of fine details of vehicle behavior during deep soil traversal, this study goes to further prove that the simulation of gross vehicle motion is accurate enough that off-road simulations are representative of physical crash tests.

5.3 Methodology for Highway Median Safety Analysis

The methodology used to analyze the safety of highway medians in the simulation portion of this study can be decomposed into the following six steps:

1. Define the roadway cross section,
2. Choose the vehicle,
3. Establish the simulation's initial parameters,
4. Determine the driver's inputs,
5. Run the simulation, and
6. Summarize the outputs, revert to Step 3, change the simulation parameters, and repeat.

Each of these steps is outlined below in a specific example analyzing the influence of median cross-section design on vehicle trajectory during a median encroachment.

5.3.1 Step 1: Define the Roadway Cross Section

To define the median cross section, both on- and off-road profiles and friction maps were created in CarSim. This study predominantly used an 18-m (60-ft) wide V-shaped median with a slope of 1V:6H, and a 2.4-m (8-ft) wide shoulder with a cross-slope of 4 percent as laid out in the Pennsylvania Department of Transportation's design standards shown in Figure 5-1 (*55*). Additional medians of varying slope and width also were examined including: 12-m (40-ft) wide V-shape with 1V:6H slopes, 18-m (60-ft) wide V-shape with 1V:5H slopes, 18-m (60-ft) wide trapezoidal shape with 1V:5H slopes, and 18-m (60-ft) wide V-shape median with 1V:10H slopes. Further investigation of the importance of the median width was conducted. A 1V:6H V-shape profile was used with varying widths for this part of the study.

5.3.2 Step 2: Choose the Vehicle

The next step in preparing the simulation was to specify the vehicle to be used. Using an external MATLAB script, nearly every parameter of the vehicle—from geometric configurations to inertial properties—can be defined. This study uses vehicle parameters obtained by averaging data collected in the 1998 New Car Assessment Program (NCAP) (*56*). Although this survey is now a bit dated, in 2003, the NCHRP Roadside Safety Analysis Program (RSAP) Engineer's Manual used vehicle distributions that matched closely to those in NCAP (*57*). Sprung mass, wheel base, track width, Center of Gravity (CG) location, and inertial properties were averaged for each vehicle class from NCAP, and Table 5-1 shows a summary of these parameters (*58*).

5.3.3 Step 3: Establish the Simulation's Initial Parameters

To begin the simulation, the initial conditions must be specified. This study varied only the vehicle's initial speed and departure angle upon encroachment, and all other vehicle states, including roll, pitch, and sideslip, were set to zero. Representative encroachment angles and vehicle speeds were obtained from the RSAP Engineer's Manual (*57*). The angles varied from 2.5 to 32.5 degrees in 5-degree increments and speeds ranged from 8 to 88 km/h (5 to 55 mph) in 16 km/h (10 mph) increments, also including 115 km/h (70 mph). These speeds were chosen to represent the range of conditions under which an encroachment would occur.

5.3.4 Step 4: Determine the Driver's Inputs

A driver's steering and braking inputs during a median encroachment are usually unknown, and therefore this study considered several generic but likely scenarios for driver intervention. Two scenarios represented active driver input: (1) steer the vehicle to the center of the median, and (2) attempt a return to roadway by steering to the edge of the pavement on the original travel lane shoulder. To imple-

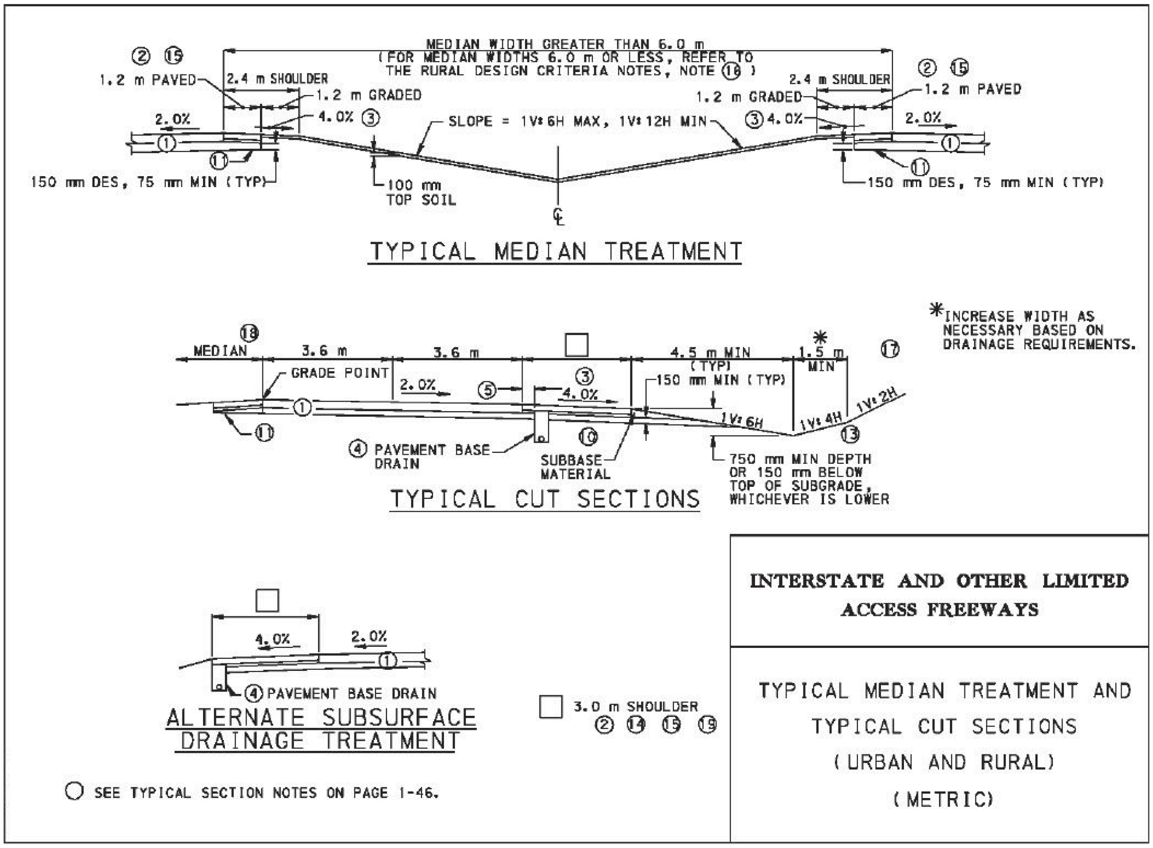

Figure 5-1. 1V:6H V-shape median cross section.

ment these situations, the CarSim driver model was used with representative target point trajectories. A third steering scenario, the "no steer" condition in which the driver takes his/her hands completely off of the steering wheel, was also modeled. Figure 5-2 shows a top view of these targeted steering paths.

Due to the specific encroachment angle and speed combination, the driver's attempt to recover to the shoulder edge, or even to the middle of the median, may not be physically possible. However, the steering inputs were defined in a way that simulates the driver's attempt to direct the vehicle to a particular target point, whether or not the vehicle actually reaches that target point. In fact, in most of the simulations with high speeds and large encroachment angles, the targeted paths defined by the chosen steering input are different from the actual trajectory of the vehicle during the encroachment due to the severe vehicle dynamics of these maneuvers.

The braking was defined to be either a light braking (5 MPa of pressure at the cylinder) or hard braking (15 MPa) condition,

Table 5-1. Vehicle parameters.

Vehicle class	Sprung mass (kg)	Wheel base (m)	Track width (m)	Front axle to CG	CG height (m)	I_{xx} (kg-m^2)	I_{yy} (kg-m^2)	I_{zz} (kg-m^2)
Passenger, Small	969.0	2.524	1.446	1.021	0.519	392.60	1632.20	1798.80
Passenger, Large	1403.0	2.679	1.468	1.277	0.585	632.30	2749.70	2893.30
Pickup, Small	1409.4	2.948	1.424	1.396	0.620	571.25	3142.75	3326.25
Pickup, Large	1885.8	3.425	1.619	1.581	0.684	940.50	5344.00	5642.25
SUV, Small	1718.5	2.683	1.496	1.350	0.688	803.33	3367.00	3522.17
SUV, Large	2251.1	3.032	1.579	1.628	0.767	1157.25	5960.75	6111.00
Van	1847.5	2.947	1.589	1.480	0.698	992.33	4410.67	4617.83

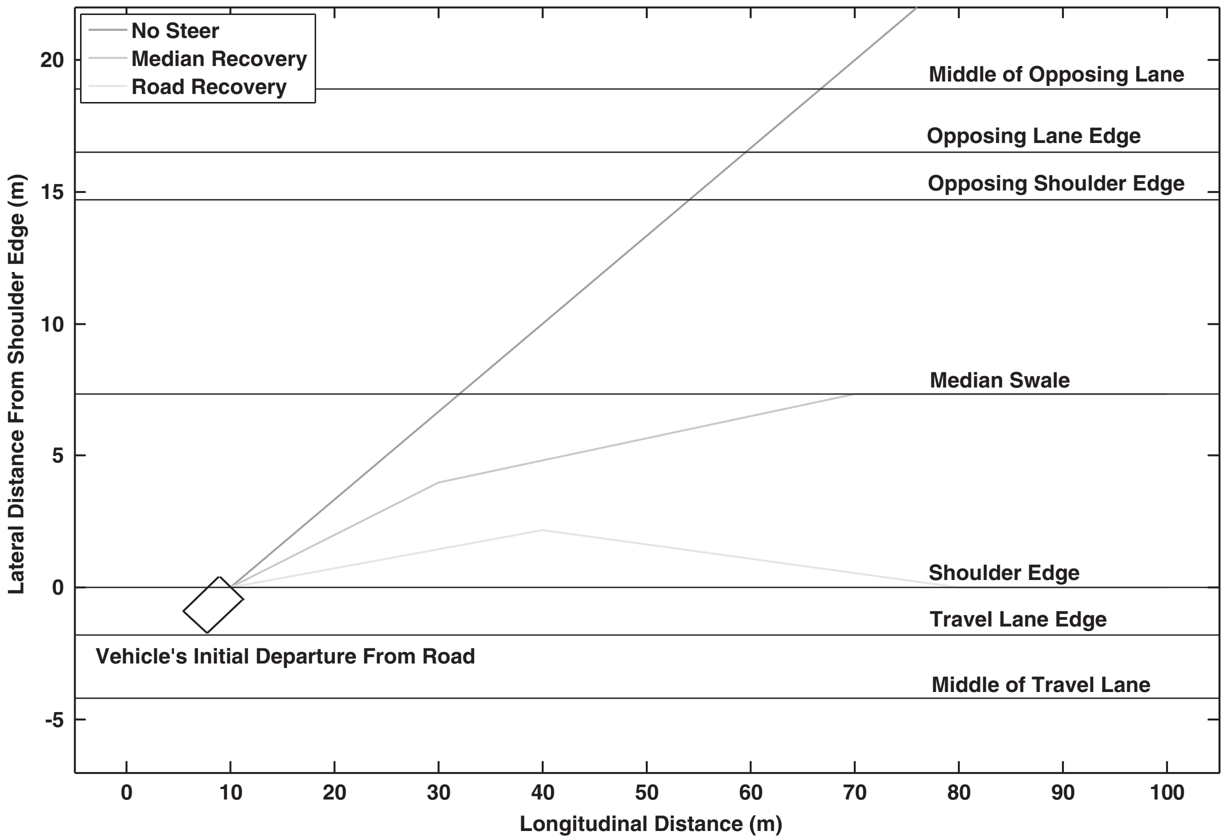

Figure 5-2. Steering inputs used in simulations.

both with an anti-lock braking system (ABS) onboard. Each steering-braking combination was simulated for all possible vehicle-speed-angle runs tested, for a total of six driver actions simulated for each vehicle-speed-angle run.

5.3.5 Step 5: Run the Simulation

To run the simulation, a MATLAB script was used to automate the loading of vehicle parameters, initial conditions, median cross section, and the driver input scenarios. The vehicle was then simulated using a time step of 0.002 seconds, and the output variables were stored in a MATLAB structure file for analysis and post processing. Each scenario was simulated for a total of 16 seconds, or up until the moment rollover was confirmed, whichever happened first.

5.3.6 Step 6: Summarize the Outputs and Repeat

The simulation process was repeated over every possible vehicle, speed, encroachment angle, steering input, and braking combination. This resulted in a total of 2,058 different simulations for each median profile, and the analysis of these results is provided in the next section of this report.

5.4 Data Post-Processing and Analysis

Each simulated scenario generates one specific vehicle trajectory; however, some of these trajectories are far more likely to occur than others. To better represent the likelihood of each specific encroachment in real-life crash scenarios, a weighting method was used. Probabilities for the occurrence of each encroachment angle and speed were obtained from the RSAP Engineer's Manual (*57*), thereby producing weighting factors for all possible speed and encroachment combinations. These are summarized in Table 5-2.

Likewise, the probability of each vehicle class appearing on the highway was extracted from the 2001 National Household Travel Survey (*59*). It was assumed that the probability of accidents for each class is equal to the representation of each vehicle class on the road, which in turn is assumed equal to the class representation within the passenger vehicle fleet. The results of this study are summarized in Table 5-3.

Although these statistics may seem a bit outdated, a more recent distribution produced in a 2006 study showed comparable data. Passenger cars consisted of 54 percent of the roadway population while SUVs, vans, and pickup trucks collectively held 39.5 percent. Motorcycles, buses, and truck

Table 5-2. Speed and encroachment weighting factors.

		Encroachment angle (deg)						
		2.5	7.5	12.5	17.5	22.5	27.5	32.5
Initial speed (km/h)	8	0.0002	0.0005	0.0005	0.0003	0.0002	0.0001	0.0002
	24	0.0049	0.0119	0.0118	0.0088	0.0057	0.0034	0.0042
	40	0.0151	0.0364	0.0359	0.0268	0.0174	0.0104	0.0127
	56	0.0215	0.0519	0.0513	0.0382	0.0248	0.0149	0.0181
	72	0.0205	0.0494	0.0488	0.0364	0.0236	0.0142	0.0173
	88	0.0152	0.0367	0.0362	0.0270	0.0176	0.0105	0.0128
	115	0.0200	0.0484	0.0478	0.0356	0.0231	0.0139	0.0169

Table 5-3. Vehicle class weighting factors.

Vehicle	Weighting factor
Small passenger	0.089
Large passenger	0.501
Small pickup	0.090
Large pickup	0.101
Small SUV	0.063
Large SUV	0.063
Van	0.093

combinations accounted for the remaining vehicles on the road (*60*).

Because there is no prior study that incorporates the probability of the driver's actions, the steering and braking inputs were weighted evenly across all runs.

The total weighting factor used for each individual simulation is then a product of the individual weighting factors for each parameter used in the simulation. For example, for a crash scenario involving a large passenger vehicle (50.1 percent of vehicles on the road) departing the roadway at an angle of 12.5 degrees and a speed of 56 km/h (35 mph) (representing 5.13 percent of departures), the total weighting factor would be: $0.501 \times 0.0513 = 0.0257$. This quantity shows that of all the crash scenarios on the highway, this specific one occurs 2.57 percent of the time.

After incorporating the weighting factors into the simulation data to better represent the probability of each specific crash scenario (vehicle, speed, departure angle, and driver actions combined), several contributing factors were analyzed to determine their influence on accident causation. The following sections present the analysis of these factors, including median geometry, bumper height during the off-road trajectory, and driver intervention during the incident.

5.5 Influence of Median Geometry

In an attempt to determine the influence of median cross-section design on the vehicle response during a median encroachment, simulations were run with varying median shape, slope, and width. All 2,058 possible combinations of inputs (vehicle, speed, angle, steering, and braking) were tested for each median. For the initial test of the median cross section, the five medians in question were as follows:

1. 1V:6H, 18-m (60-ft) wide, V-shape,
2. 1V:6H, 12-m (40-ft) wide, V-shape,
3. 1V:5H, 18-m (60-ft) wide, V-shape,
4. 1V:5H, 18-m (60-ft) wide, trapezoidal shape, and
5. 1V:10H, 18-m (60 ft) wide, V-shape.

A key concern with median design is the increasing number of SUV rollovers seen in median encroachment events. One downfall to using vehicle dynamics simulation programs to model these rollover situations is that currently there are no commercial software packages that correctly predict deep soil tire forces and hence soil-tripped rollover. However, this condition can be inferred by experimental criteria and post-processing of the vehicle trajectory. Criteria for soil-tripped rollover were found in a 2004 SAE experimental study wherein rollover is consistently seen when the vehicle exhibits a side-slip greater than 45 degrees at speeds greater than 32 km/h (20 mph) (*60*). After applying this designation for rollover to the simulation results for each vehicle class, the scenarios that did exhibit rollover during the off-road trajectory were recorded. Figure 5-3 displays the resulting distribution of rollover scenarios for all five medians listed above, filtered by vehicle class. As to be expected, and in agreement with existing crash statistics, the small SUV category experiences more than twice the number of rollovers as a small passenger vehicle.

Figure 5-4 shows the same rollover scenarios as a function of the median cross-section. These results indicate that the width and shape of the median do influence rollover occurrence. The narrow median (12 m or 40 ft wide) exhibited less rollover than the other medians, but this is most likely due to the smaller length of traversal and hence larger number of vehicles that enter the opposing lane, many of which rollover thereafter (which is not captured in these results).

Because the median cross-section was shown to have a large effect on the vehicle response, specific aspects of the median were investigated. First, an 18-m (60-ft) wide, V-shape median with varying slope was considered. The evaluated slopes ranged from 1V:4H to 1V:10H, in increments of unit of median slope

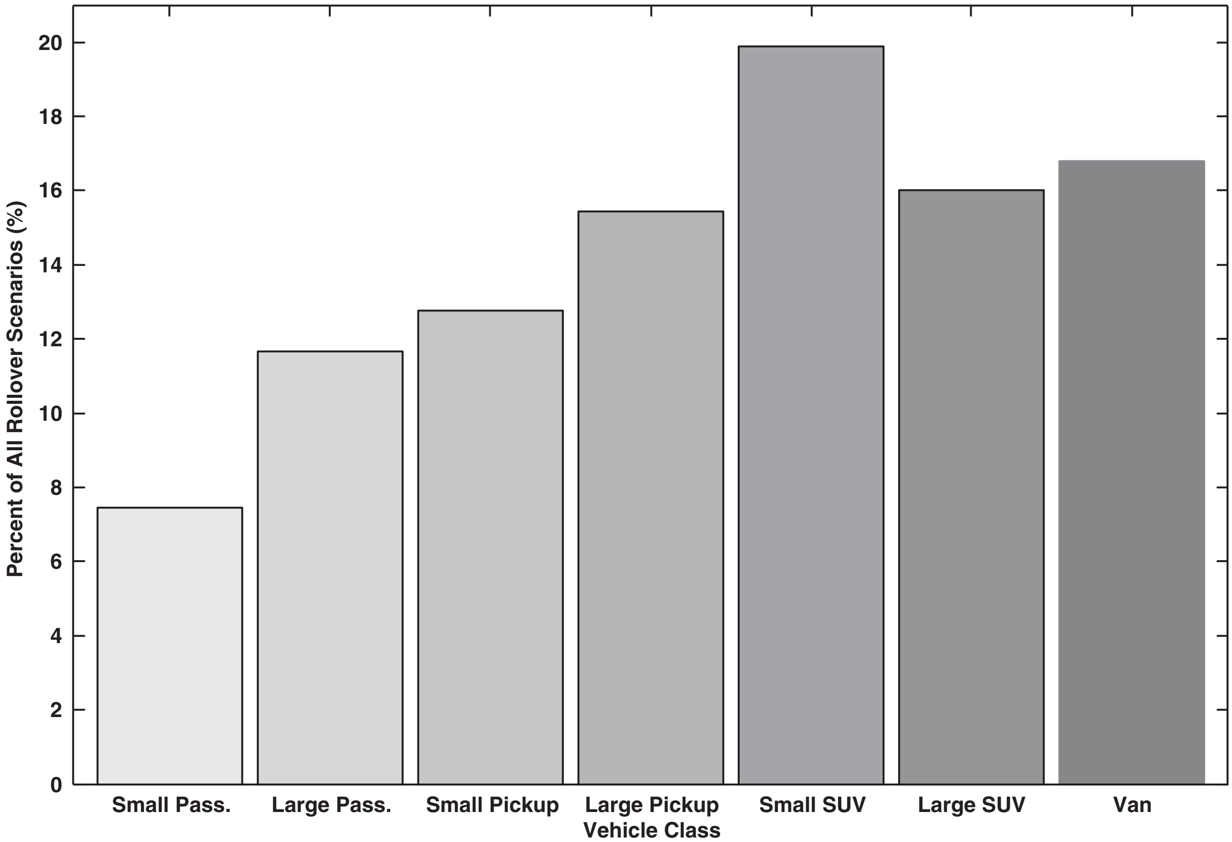

Figure 5-3. Rollover scenarios for all vehicle classes.

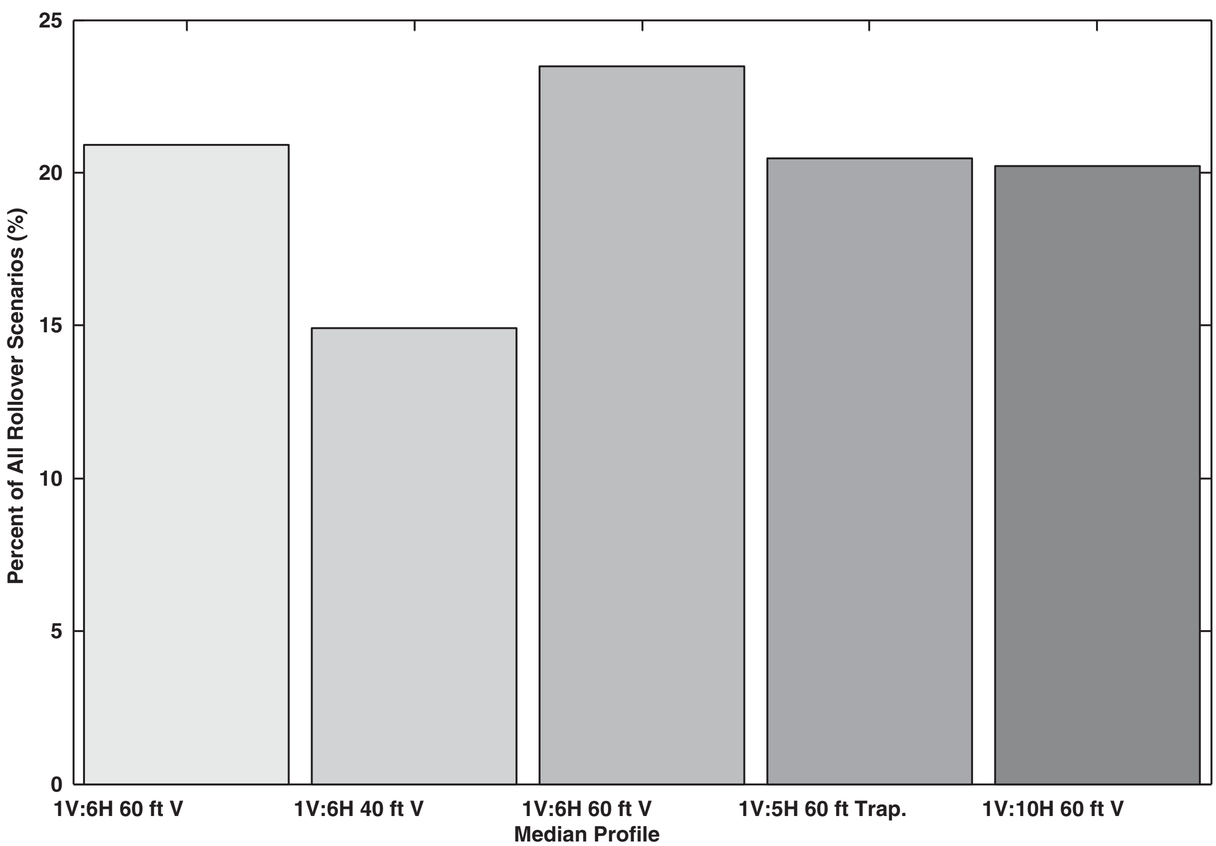

Figure 5-4. Effect of median profile on vehicle rollover.

ratio (1V:4H, 1V:5H, etc.). Figure 5-5 shows the resulting rollover scenarios in these simulations, sorted by the median upon which they were simulated. Figure 5-6 also shows the same rollover cases, sorted by the class of the simulated vehicle. In agreement with what was shown in Figure 5-3, the SUV and van population accounted for more rollovers than passenger vehicles and, generally speaking, the steeper sloped medians resulted in more rollover scenarios than did shallower slopes. These results give an initial impression that a less aggressive slope would lead to a safer median for all vehicles on the highway, but upon further investigation, a more complex tradeoff between vehicle rollover and entry into the opposing lane is present.

To help increase the understanding of this tradeoff, the location at which the vehicles came to a rest during the simulation was observed. Furthermore, the situations in which the vehicle rolled over were separated from those where the vehicle remained upright. The resulting data are displayed in Figures 5-7 and 5-8, respectively.

Even though these data are useful, they still do not provide a clear understanding of the tradeoff under investigation. To provide more insight into this tradeoff, a ratio of those cases in which the vehicle entered the opposing lane to those which exhibited rollover, was created. Figure 5-9 shows this ratio for each simulated median slope, clearly displaying what was imbedded in the previous figures. It is now evident that a flatter median side slope will lead to a smaller number of rollovers, but at the cost of increasing the likelihood of an encroaching vehicle entering the opposing lane of traffic, and henceforth risking a head-on collision.

To further investigate the impact of the median cross-section on vehicle response, all scenarios were run again for a 1V:6H, V-shaped median with varying width. The widths tested ranged from 12 to 23 m (40 to 76 ft), in increments of 1.8 m (6 ft). Figure 5-10 indicates that the widest median results in the highest number of rollovers and the narrowest median the least. Although this may seem indicative that a narrower median is safer, in reality, the same tradeoff between vehicle rollover and entrance into the opposing lane is present here as well.

Again, for the cases in which a vehicle did not exhibit rollover, the location at the end of the simulation was recorded. Figure 5-11 shows the results from this portion of the experiment. From the figure, it can be seen that as the median width decreases, the number of vehicles entering the opposing lanes of traffic increases drastically.

It is now evident that a narrower median does reduce the number of rollovers, but at the cost of the vehicle entering the

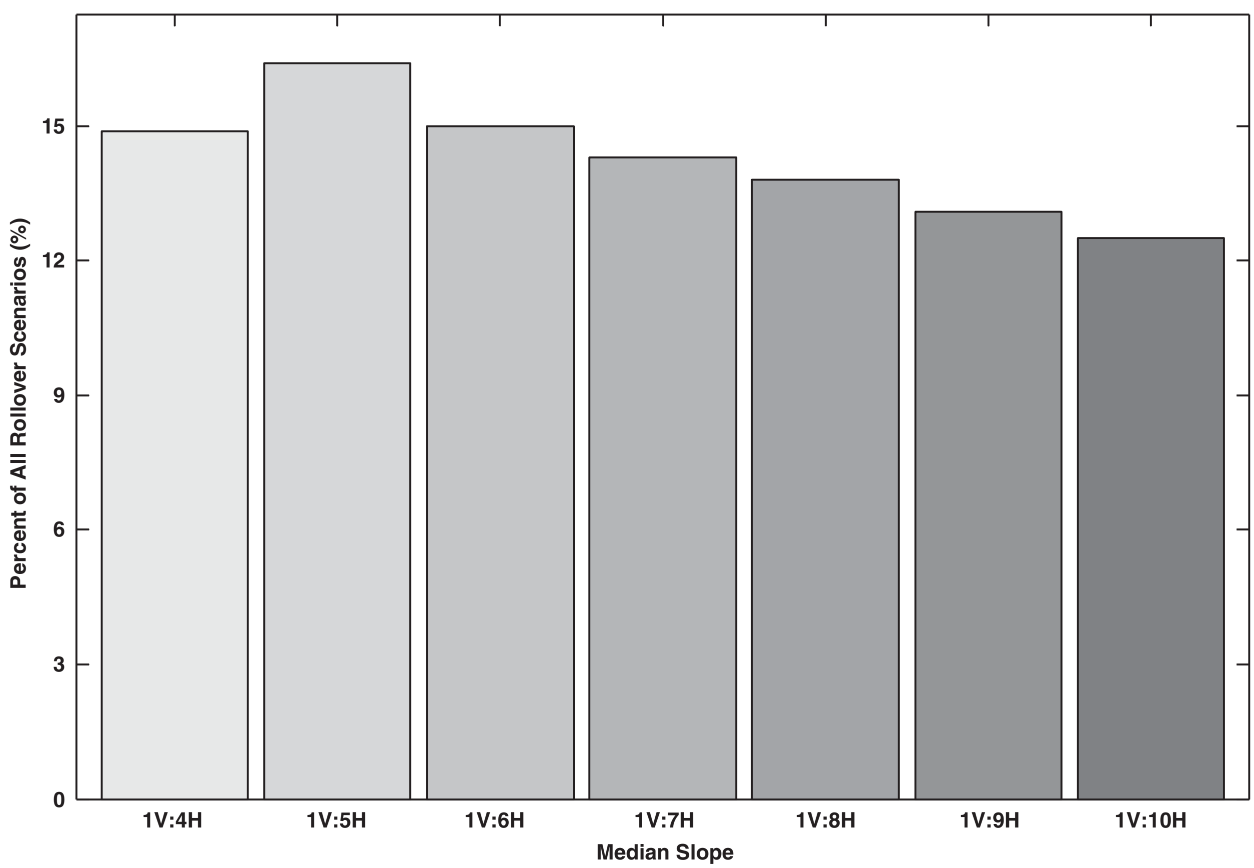

Figure 5-5. Effect of median slope on vehicle rollover.

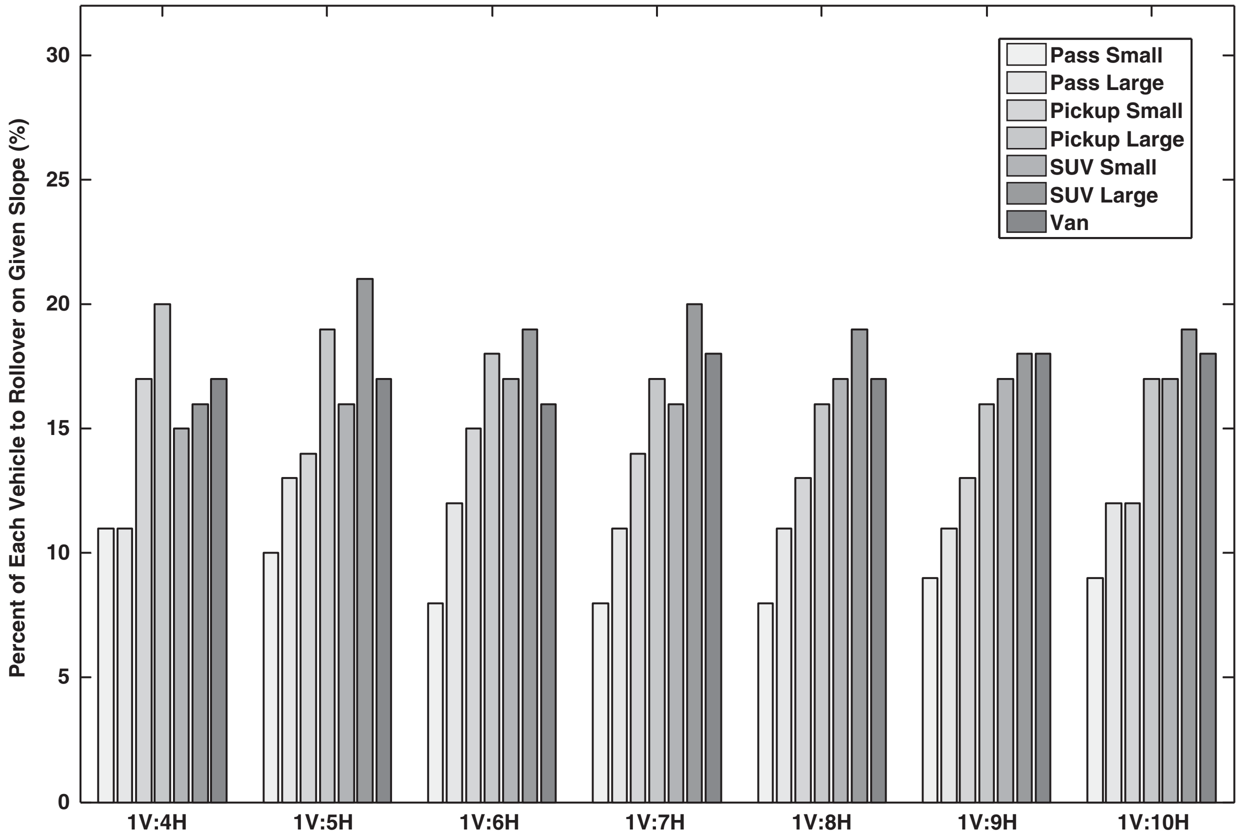

Figure 5-6. Rollover in medians of varied slope by vehicle class.

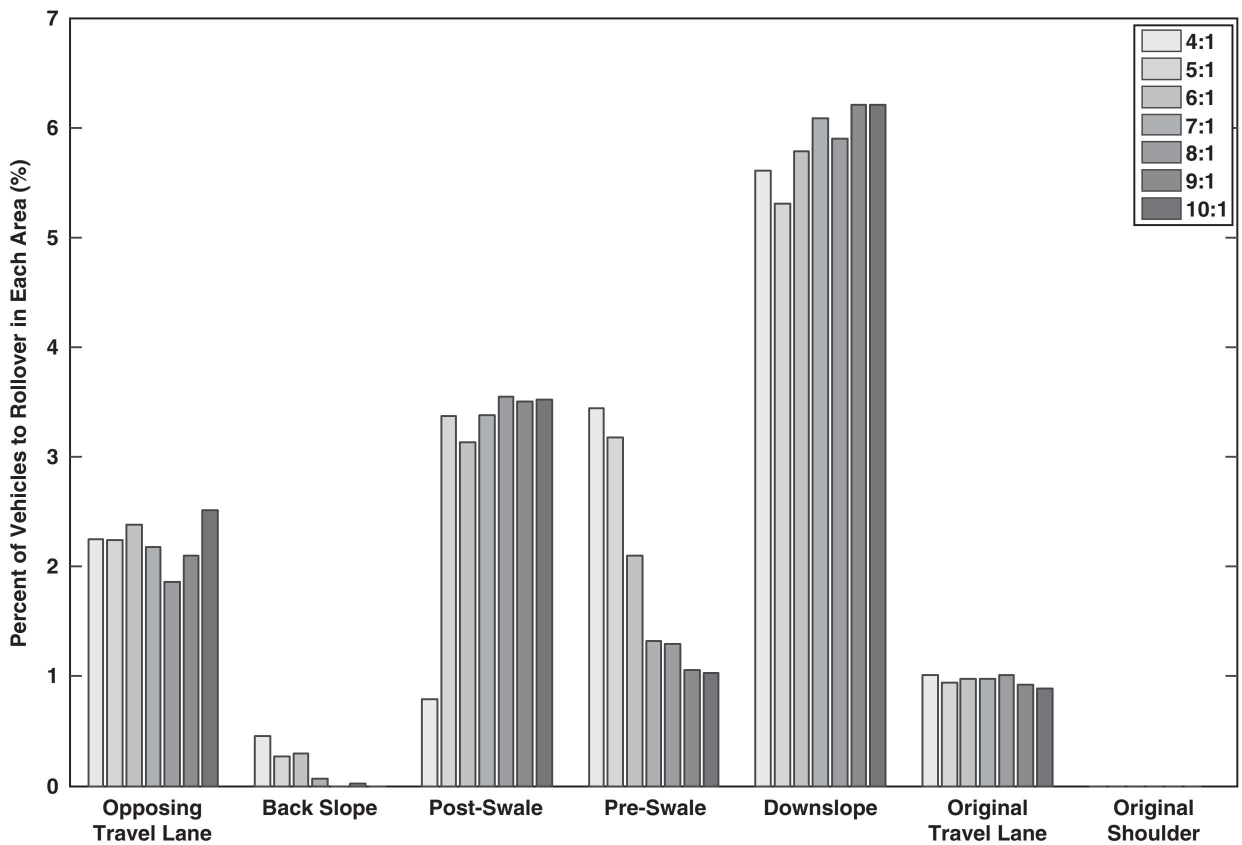

Figure 5-7. Vehicle locations at the onset of rollover for medians of varied slope.

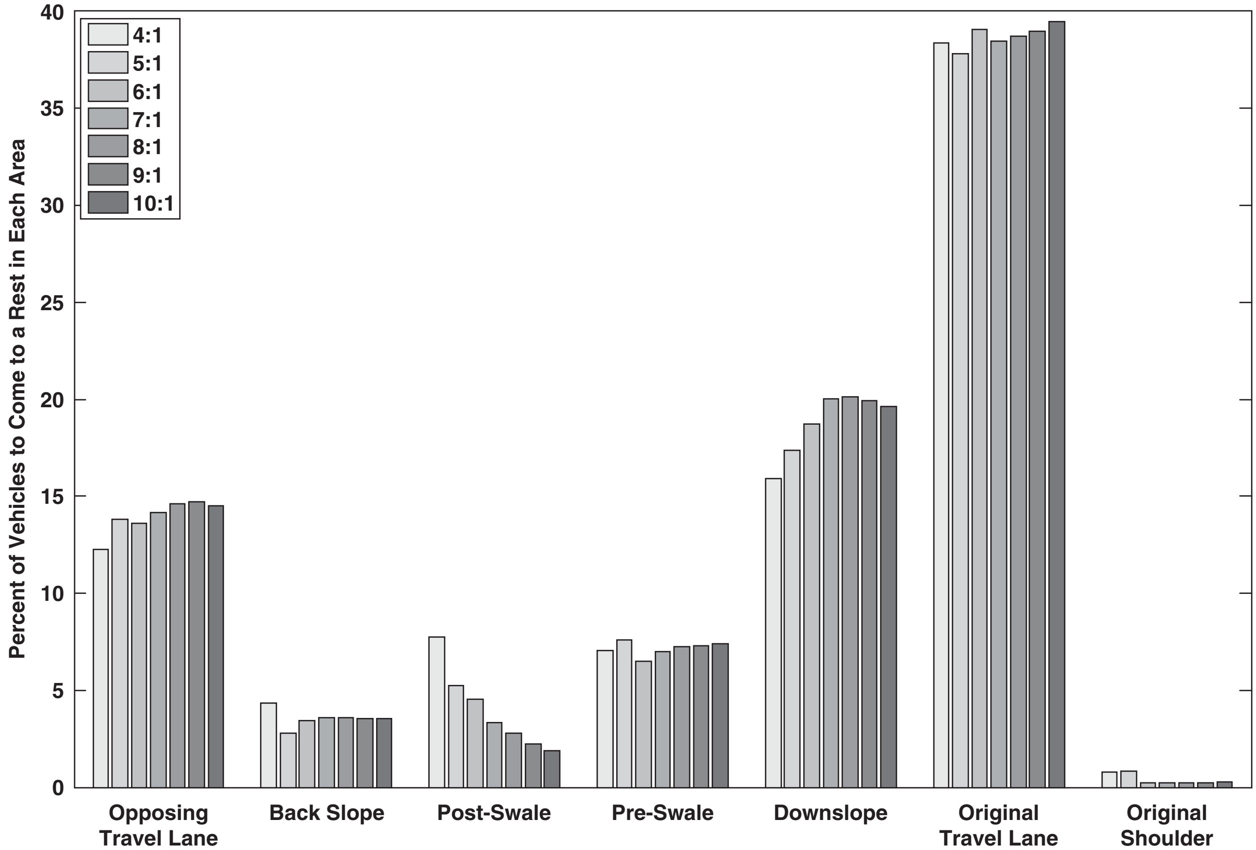

Figure 5-8. End locations for non-rollover simulation runs for medians of varied slope.

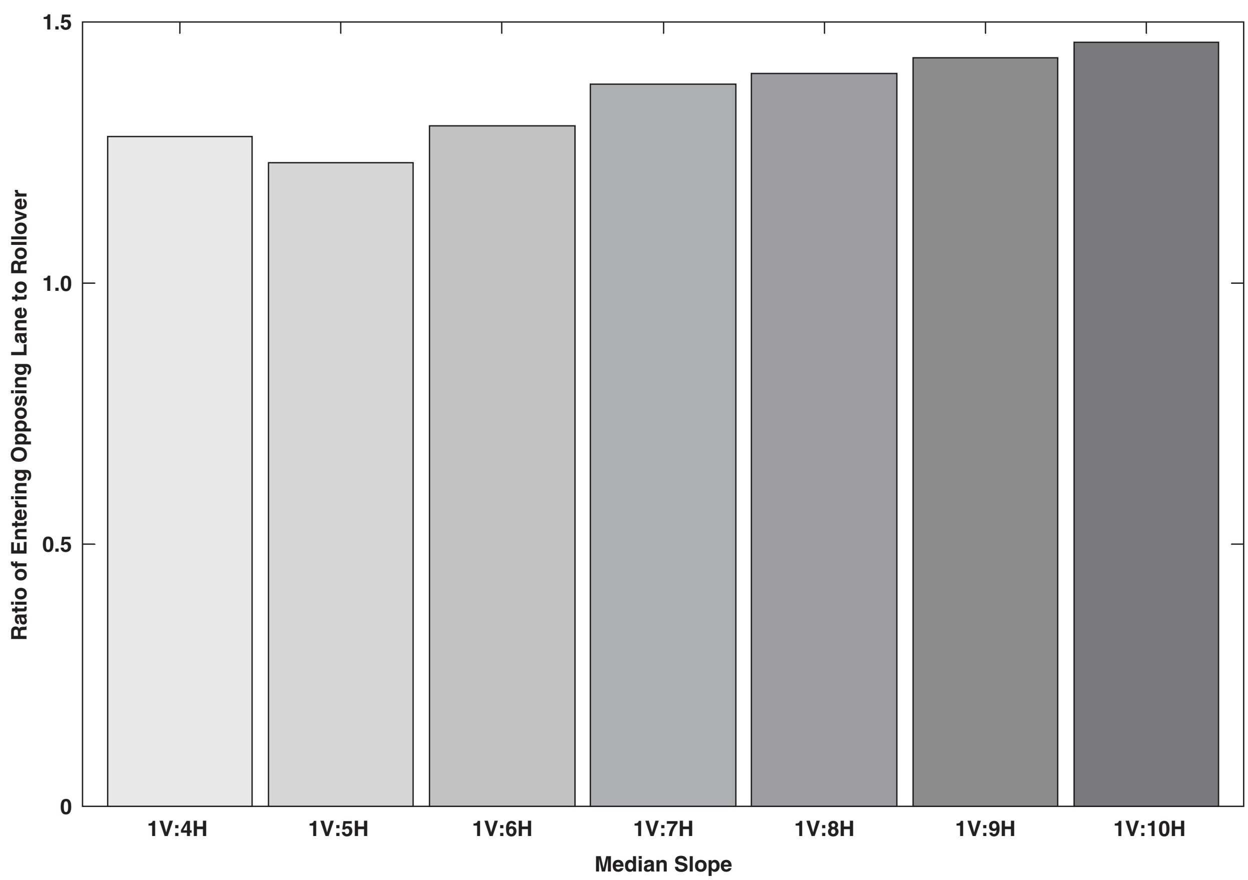

Figure 5-9. Ratio of vehicles entering opposing lane to rollover for medians of varied slope.

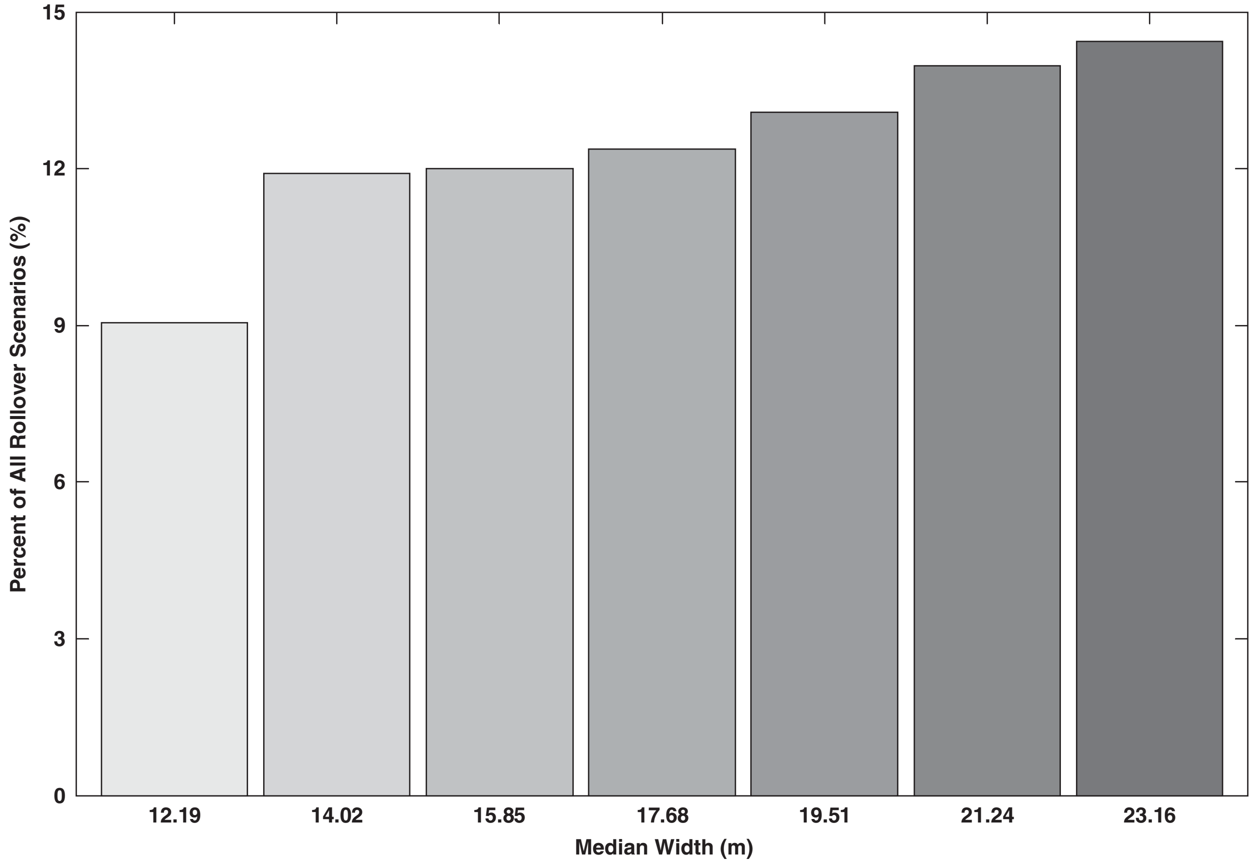

Figure 5-10. Effect of median width on vehicle rollover.

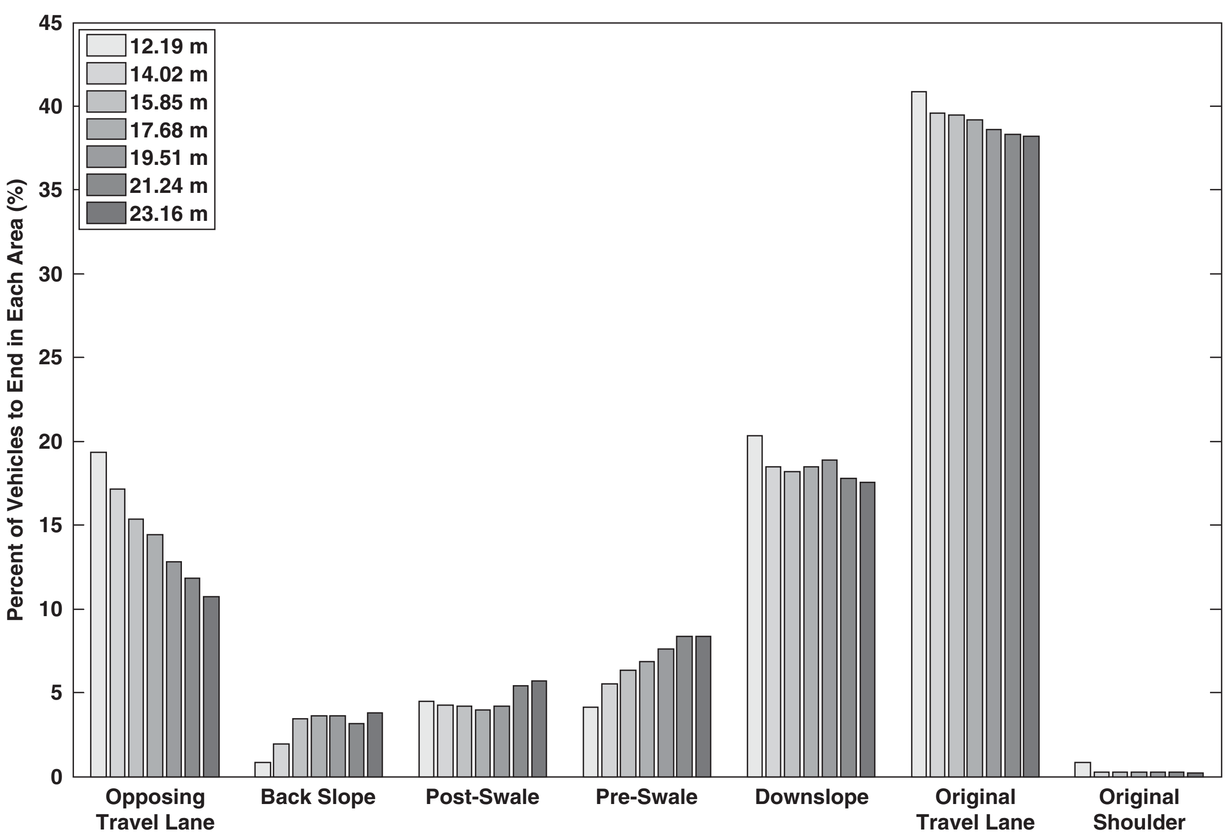

Figure 5-11. End locations for non-rollover simulation runs for medians of varied width.

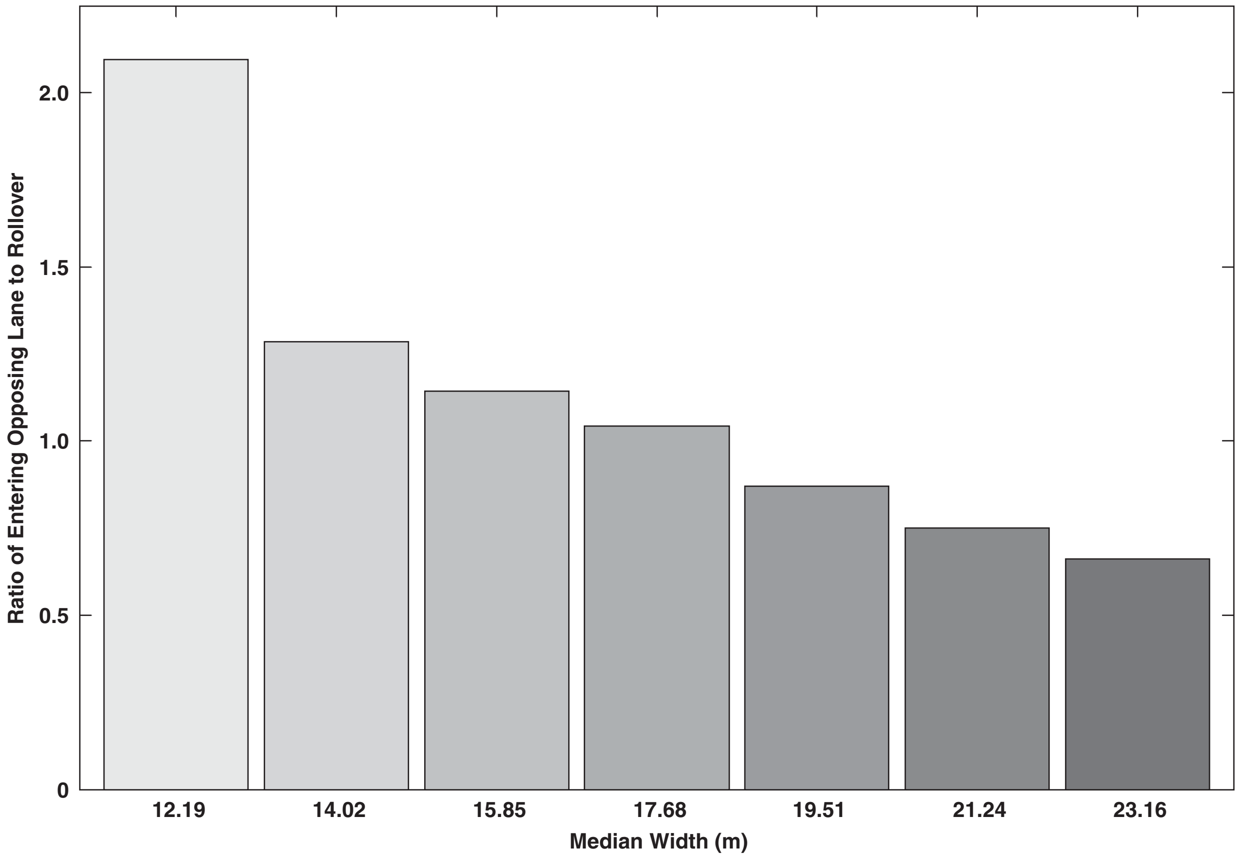

Figure 5-12. Effect of median width on vehicle response.

opposing lane, thus resulting in an increased probability of a head-on collision. Using the same ratio of incursion into the opposing lane to rollover at any time during the simulation as used in the median slope investigation, Figure 5-12 shows that a vehicle entering a 12-m (40-ft) wide median is almost twice as likely to enter the opposing lane as a vehicle on any other median width tested. These results again portray an obvious tradeoff between vehicle rollover and entrance into the opposing lane.

5.6 Bumper Height During the Off-Road Trajectory

The position data from each simulation were recorded at the vehicle's CG, and so the bumper position must be inferred. As a result, a market survey was conducted to estimate the average bumper heights for each vehicle class. Ground clearance data were obtained from vehicle manufacturers' websites. Bumper clearance, measured to the bottom of the bumper of these surveyed vehicles, was determined by repeated measurements in a parking lot.

After plotting the measured bumper clearance versus provided ground clearance, a linear trend between the two emerged. From this trend, the average bumper clearances for each vehicle class were inferred from the average ground clearances calculated from the manufacturer's data. From these bumper clearances, the average distance between the bumper and the vehicle's CG was easily calculated. This distance was then subtracted from the position data (output at the CG), resulting in the position of the bottom of the bumper throughout the entire simulation. Figure 5-13 shows the resulting correlation between the two sets of data, and these results agree with similar surveys (*61*). Hereafter, manufacturer-reported bumper clearance was used to infer bumper height for all simulation trajectories.

As the term "bumper height" is commonly accepted in practice to be the distance between the ground and top of the bumper, the height of the bumpers themselves also was measured and then averaged. This quantity added to the calculated position of the bottom of the bumper to produce a value for the bumper height (e.g., top of the bumper) during the simulation.

In Figure 5-14, the weighted distribution of bumper heights is shown after the previously defined weighting factors were applied. The first mode of data corresponds to the population of passenger cars and vans, whereas the second mode

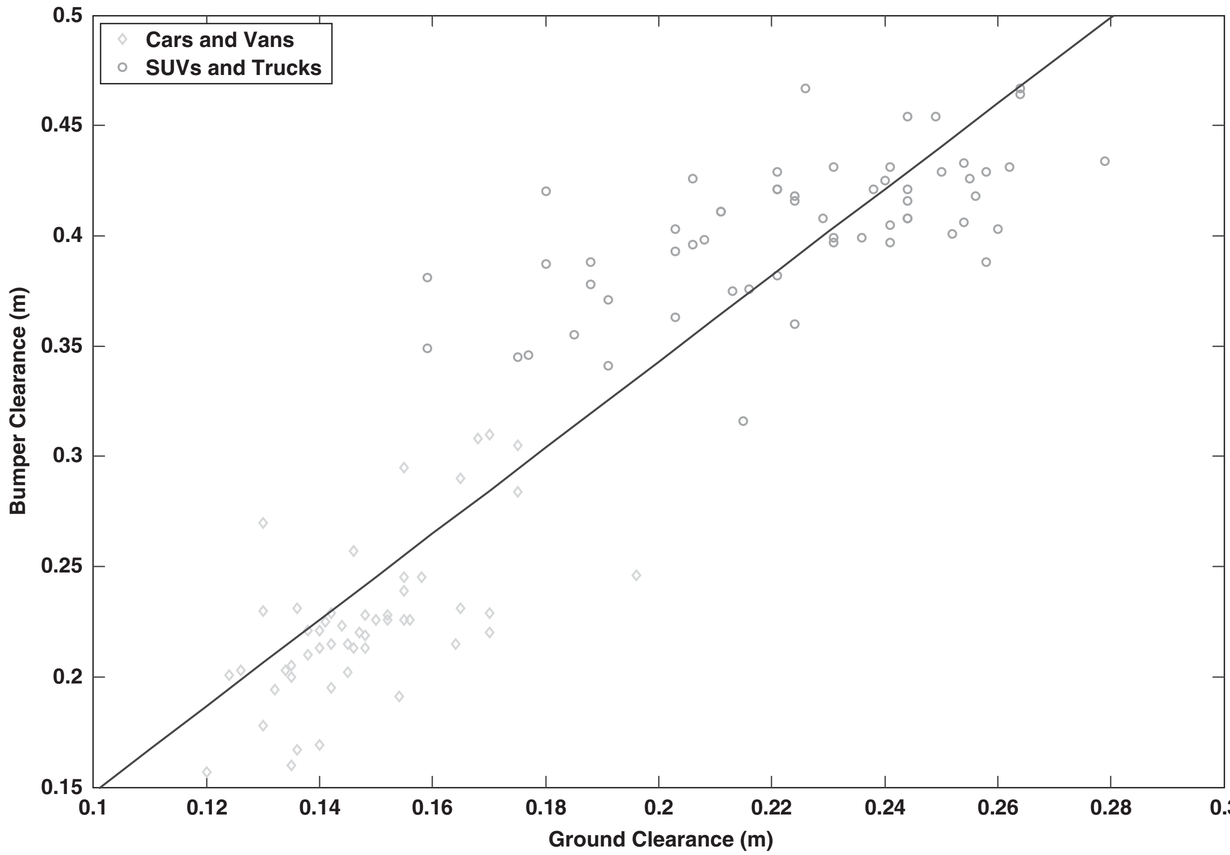

Figure 5-13. Inferring initial bumper height.

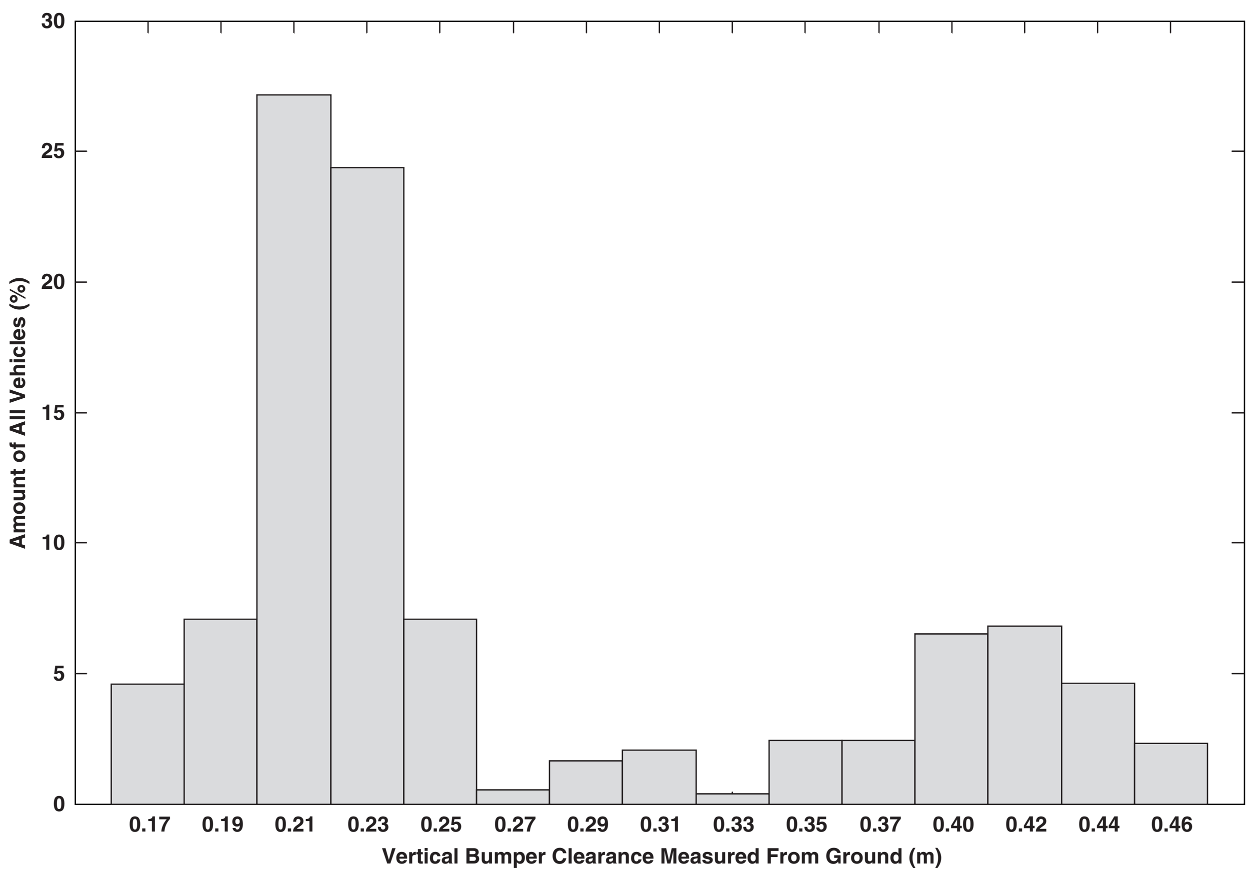

Figure 5-14. Initial bumper clearance distribution.

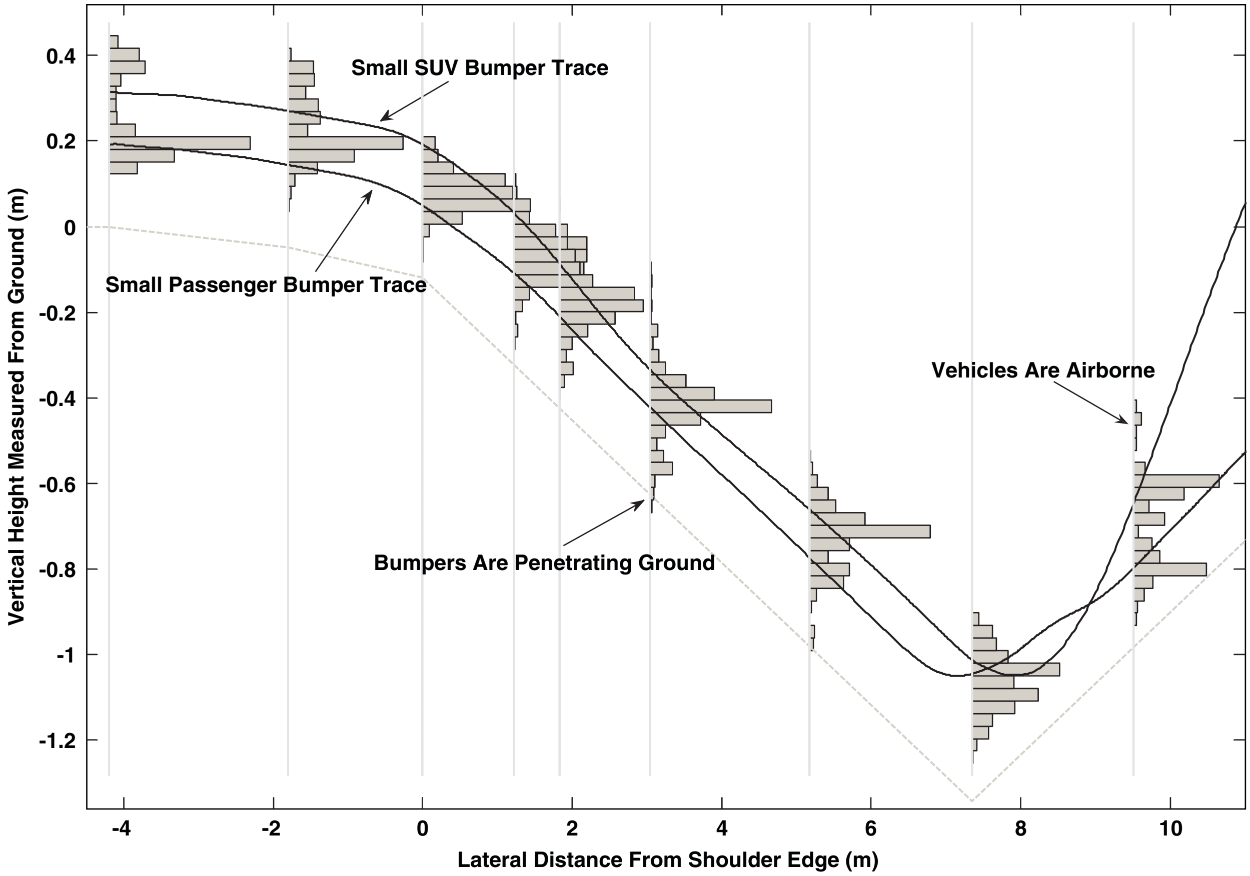

Figure 5-15. Bumper height distributions at various lateral offsets from shoulder edge.

is representative of the SUV and truck population. There is clearly a disparity of about 20.5 cm (8 in.) between the two modes reflecting a great deal of incompatibility among bumpers on the highway today.

Using results from all simulations, weighted distributions of bumper heights were generated for the following conditions: when the vehicle was at the shoulder edge, when at the median swale, and at several intermediate points. Figure 5-15 shows these resulting distributions overlaying a cross-section of the median type used in the analysis. For this particular median, the original travel lane is laterally defined at –4.2 m (–13.8 ft), the shoulder edge is at 0 m, and the median swale is at 7.344 m (24.079 ft).

As can be seen in the figure, the initial bimodal distribution disappears to have a single mode shortly after the vehicle departs the shoulder surface, and then it reappears before the vehicle reaches the swale point. Bumper traces representative of a small SUV and small passenger vehicle are shown on top of the distributions as a means of investigating how these distributions are changing as the vehicle traverses the median. To isolate the effect of vehicle class, these two runs have the same initial conditions and driver inputs. After the SUV enters the median, it impacts the front slope, compressing the suspension and lowering its bumper to a height much closer to that of the passenger vehicle. As seen in the distributions, some vehicles impacted the ground surface, resulting in a slight ground penetration with the front edge of the bumper. Figure 5-16 shows an image of the animation of this phenomenon.

Figure 5-16. Bumper ground penetration.

As the vehicles continued down the slope, the two modes appeared to separate again. At the swale point, most vehicles impacted the back slope at roughly the same height but major differences between vehicles emerged thereafter. For example, the passenger vehicle in Figure 5-15 is seen to bounce off of the ground before coming to rest on the upslope of the median, whereas the SUV becomes airborne and will most likely rollover after departure from the median area. Rollovers and crashes during and beyond entry into the opposing lane were not examined due to the obvious increase in contributory factors. Even so, these bumper location profiles are clearly useful in the design of median barriers as a function of offset distance from shoulder.

5.7 Influence of Driver Intervention

To illustrate the importance of steering input, the same vehicle, speed, encroachment angle, and braking was simulated three times on an 18-m (60-ft) wide, 1V:6H, V-shaped median. Each time, a different steering input was implemented. Figure 5-17 shows the vast differences in the vehicle response between these three scenarios. The white vehicle simulates the road recovery input, red is the median recovery, and the yellow vehicle has the no-steer condition as previously discussed (see web PDF for color image).

As can be seen here, only one of the three steering inputs led to rollover even though the simulations were otherwise identical. Looking at Figures 5-18 through 5-21, four different vehicle states (position, yaw, roll, and sideslip) are plotted for each of these three simulations. Again, the results are drastically different with only a variable factor being the steering input.

To further illustrate the effects of steering input, the end locations of the vehicles were examined. Figure 5-22 shows the resulting data, and once again, vast disparities between simulations of different steering input are seen. As expected, clusters of data along each departure angle and speed are visible, especially in the "no steering" case. As the steering input is altered, these clusters become more erratic and dispersed.

If rollover events are organized by steering input, the resulting distribution is seen in Figure 5-23. As expected, aggressive road recovery steering leads to the highest amount of rollovers, while the passive "no steer" condition results in the fewest. These findings indicate that the driver's input is a primary contributing factor to rollover initiation and cannot be ignored in consideration of median geometric design.

5.8 Implications of Simulation Results for Median Design

As presented in this section, there is one main safety tradeoff in the design of earth-divided, traversable medians without longitudinal barrier. That is, the highway engineer must choose between designing a median to prevent vehicular rollover or to design it with the intention of preventing against vehicles from encroaching upon the opposing lane of traffic. In medians with a longitudinal barrier, a major concern is where to place barriers in order to maximize the safety of vehicles departing the roadway. This section presents the results from this portion of the investigation and offers

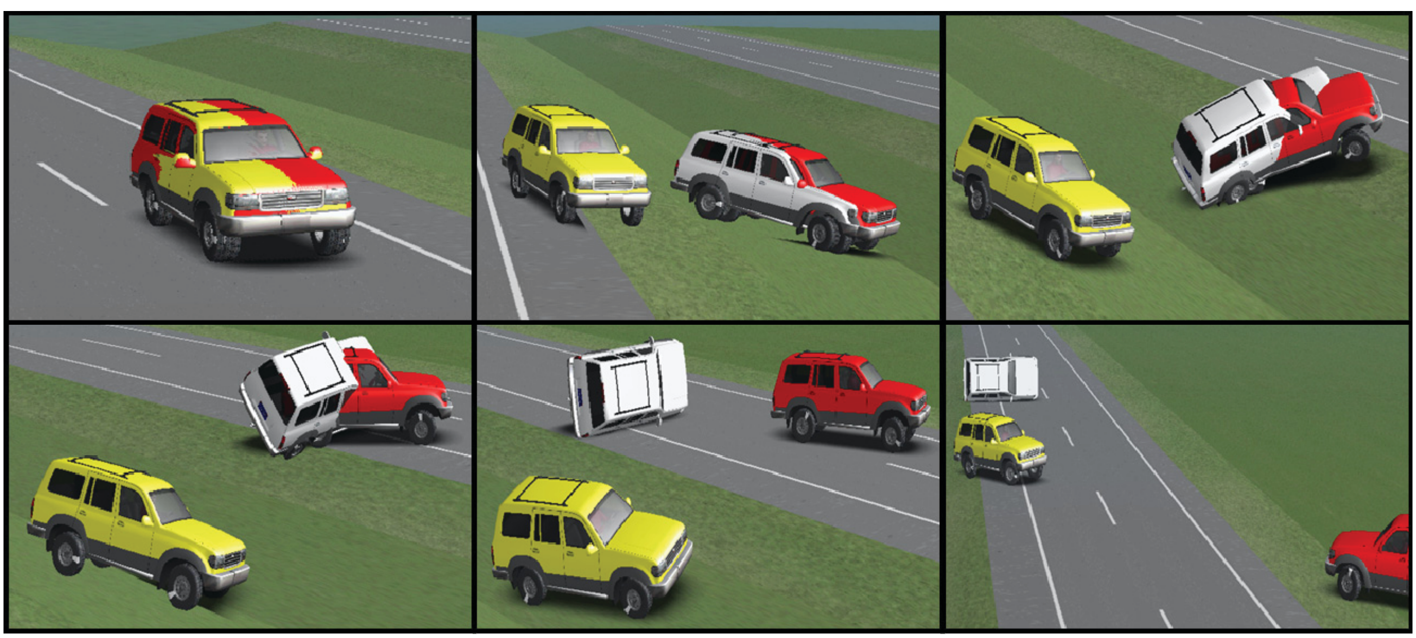

Figure 5-17. Influence of varied steering input.

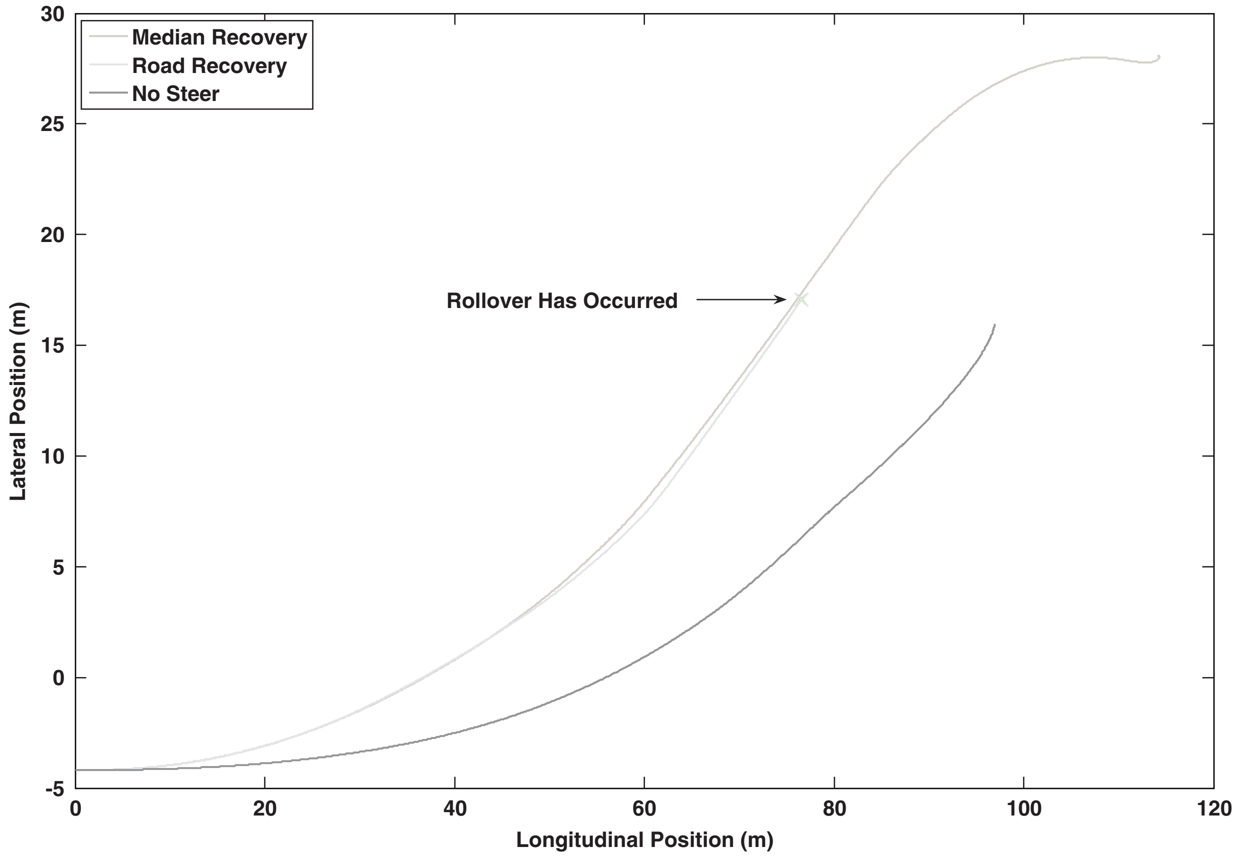

Figure 5-18. XY position for varied steering input.

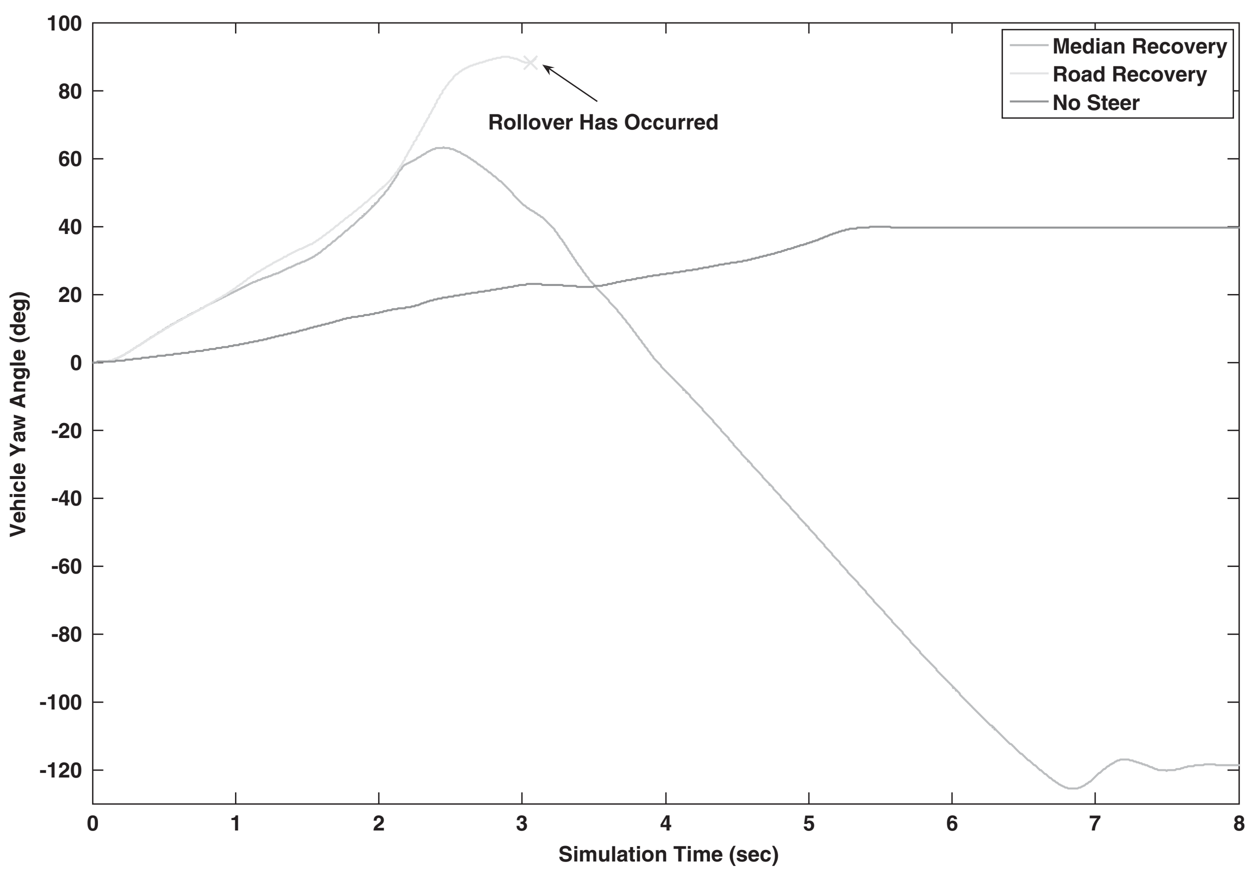

Figure 5-19. Yaw angle for varied steering input.

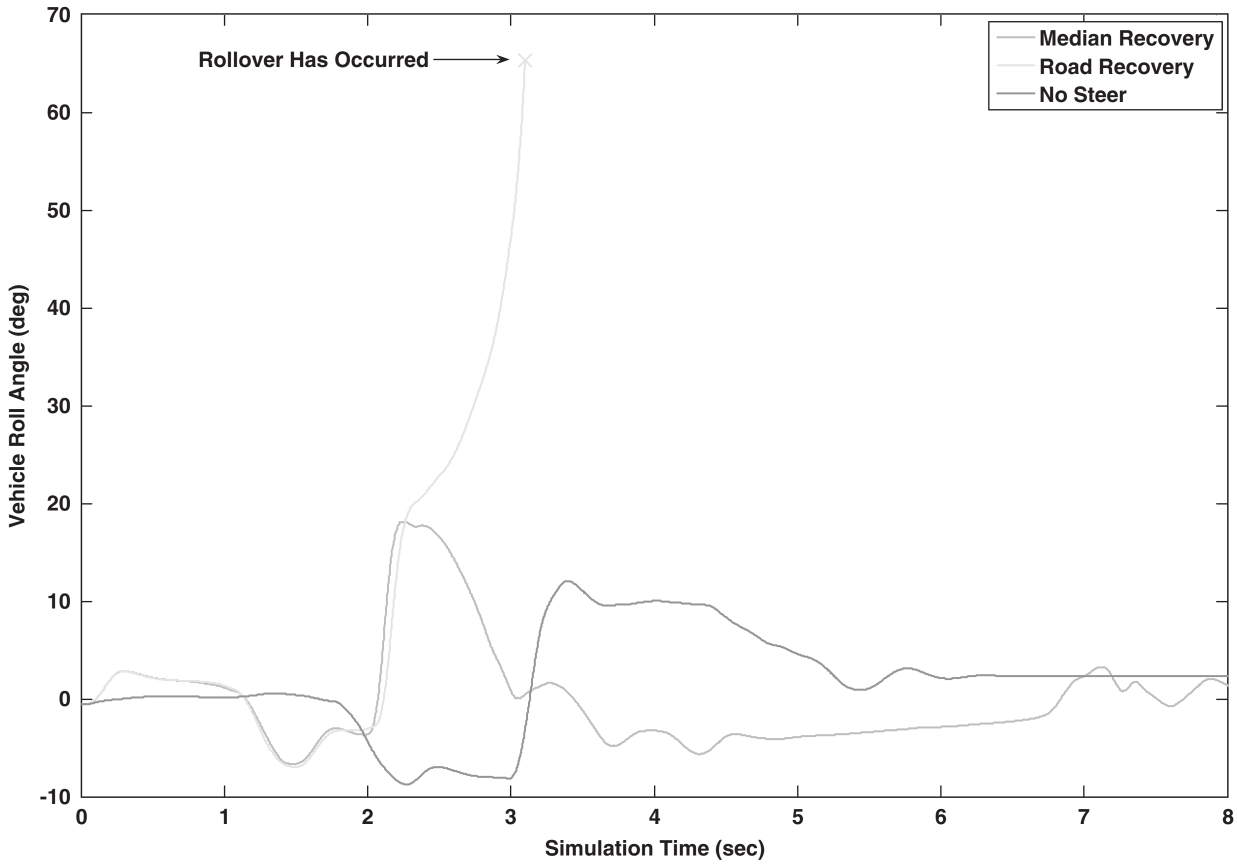

Figure 5-20. Roll angle for varied steering input.

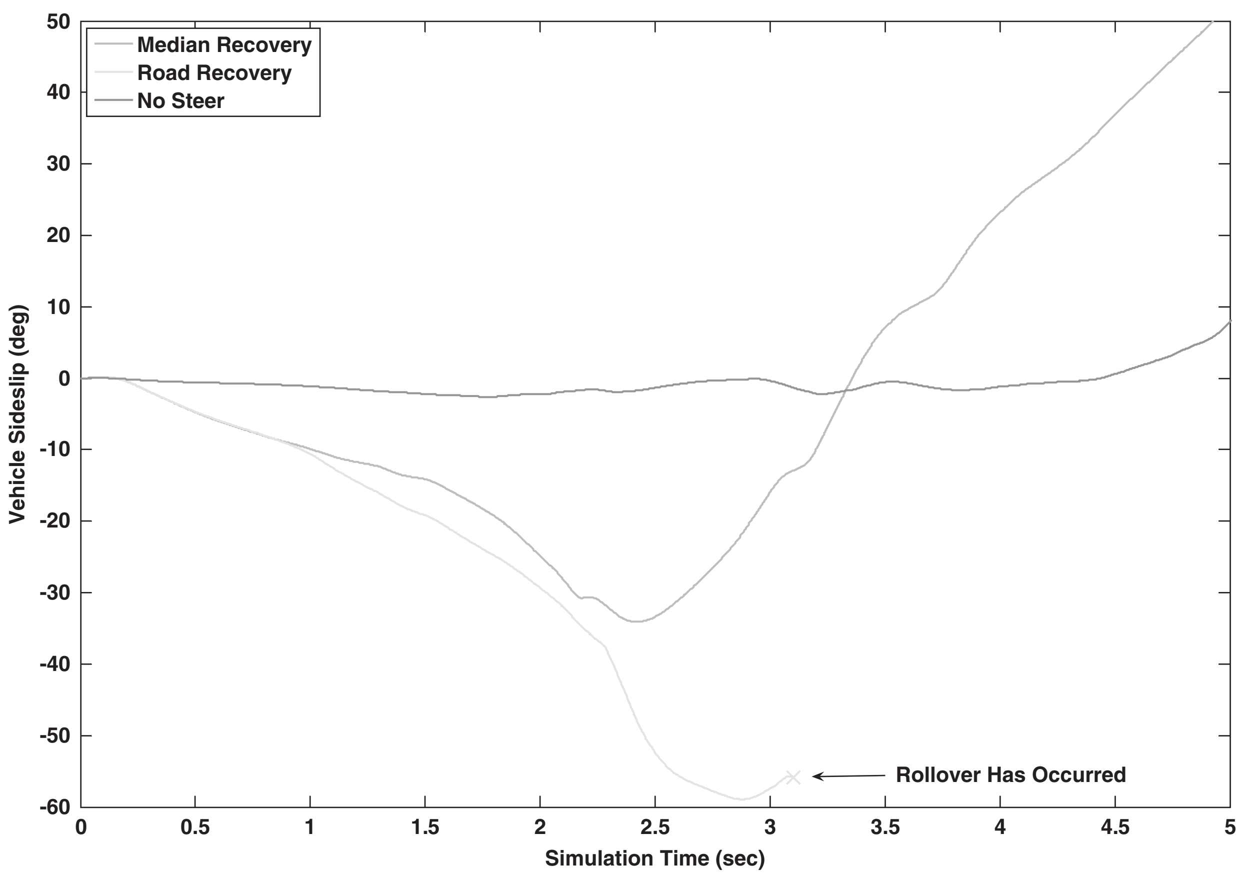

Figure 5-21. Sideslip for varied steering input.

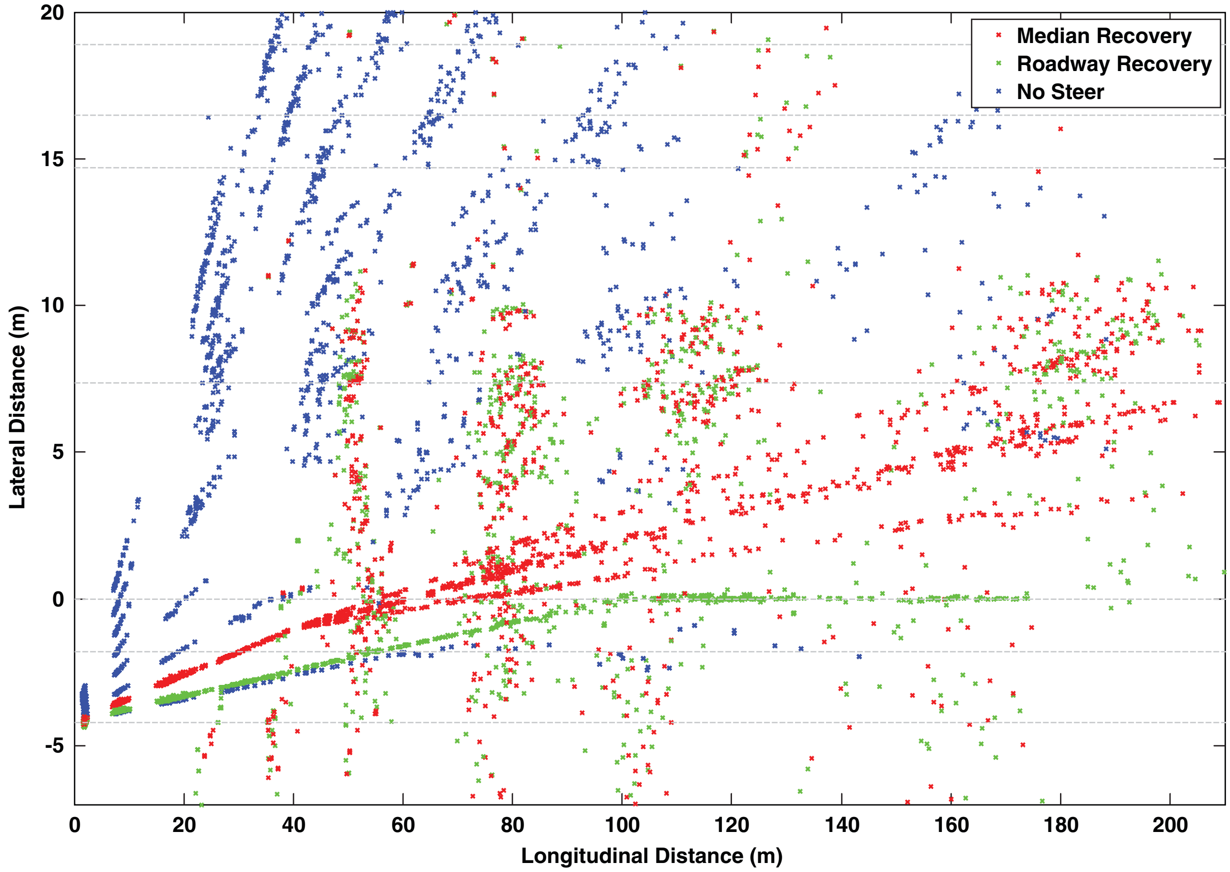

Figure 5-22. Final vehicle position.

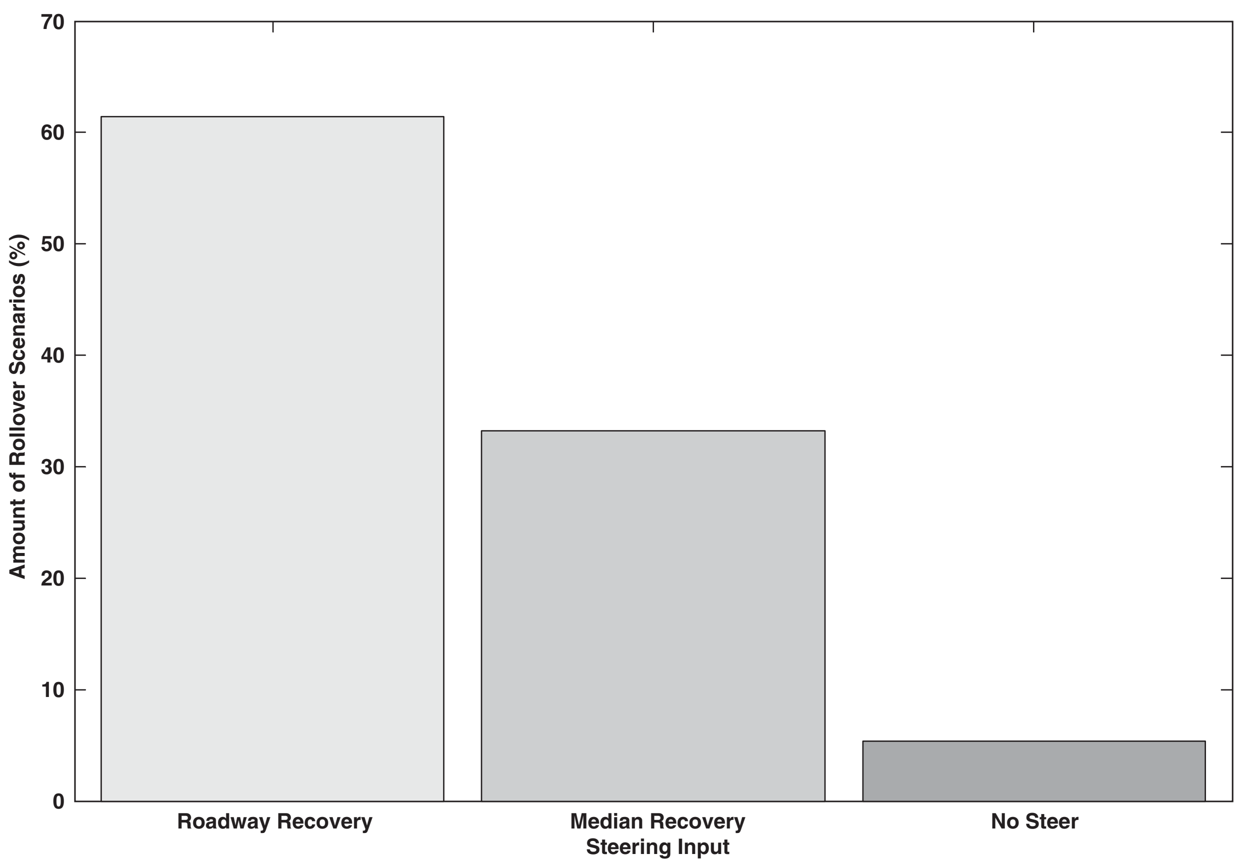

Figure 5-23. Effect of steering input on vehicle rollover.

guidance for the design of median cross sections on divided highways.

From the simulation data, general trends depicted the relationship between a design parameter (median shape, width, etc.) and the frequency of both rollovers and cross-median crashes. For instance, when all other design variables are held constant, as the median width is increased, the frequency of rollover increased (see Figure 5-10). Table 5-4 shows the resulting effect of an increase in each parameter. In Table 5-4, an increase in slope means a steeper slope.

From the simulation data, a trapezoidal median profile generally led to different outcomes than a typical V-ditch median profile. As seen in Table 5-4, the trapezoidal median decreased both the frequency of rollover incidents as well as the frequency of cross-median crashes. The vehicles in these simulations either steered back into the original travel lane safely or they were safely contained within the median. From these results, it can be concluded that a trapezoidal median cross-section will ultimately be safer than a V-ditch profile in the event of an off-road incursion.

Additionally, when examining the vehicle's roll angle and yaw rate for the two median shapes, the values for a trapezoidal median are much lower. This difference in the vehicle states ultimately shows that not only does a trapezoidal ditch lead to a safer end result of the incursion (rollover, crossover, etc.), it also results in a much less aggressive and violent incursion for the vehicle as well.

Even though the driver's intervention is not technically a design parameter, as shown in the previous section, the driver's actions must be taken into consideration. When the driver attempts to steer the vehicle after encroaching into the median, the propensity for vehicle roll increases. On the converse, if the driver does not give the vehicle any steering input, the vehicle is more likely to cross over the median and enter the opposing lane of traffic if there is insufficient median width. As these driver inputs are typically unknown factors, it is extremely difficult to anticipate them. However, when considering the installation location of median barrier, the driver will most likely react in an effort to avoid impacting the barrier. In this manner, the anticipated driver intervention must be considered as an additional design parameter. The data presented in this study implemented three generic steering conditions, and did not account for the effect of a median barrier on the driver's perception.

Even with these generalities in design parameters, there still are no clear "optimal" median slope-width combinations. To help highlight these median combinations, the simulations that led to either a rollover or cross-median crash scenario were marked. The median slope and width were recorded for each of these simulations. Probabilities of rollover and cross-median scenarios occurring were then calculated for each slope-width combination. From here, it was determined if each of the median cross-section combinations was more likely to lead to rollover or cross-median crash. The results from this analysis were plotted on an XY scatter to show the resulting trends between the parameters in question. Figure 5-24 shows the outcome of this analysis.

As can be seen, there is a dividing line or boundary where any combinations of median width and slope below the line are most likely to lead to a cross-median crash and any combination of median width and slope above the line are most likely to lead to a rollover. Thus, Figure 5-24 provides guidance that can be used by highway engineers to determine the tradeoff between median design parameters as a function of likelihood of cross-median and rollover crashes.

Another design characteristic of the median is where to install a median barrier to help maximize safety for all travelers on the highway. Figure 5-15 shows the clearance height of the vehicle's bumper during a median encroachment, but the top of the bumper (typically referred to as the "bumper height") must be considered as well as the bottom. Using averages (per vehicle class) for the thickness of the bumper itself, the bumper height was calculated from the already calculated bumper clearance data. The two modes, representing the passenger and SUV vehicle populations respectively, were recorded at various offsets from the shoulder edge. The bumper position trace during a median encroachment was then created from this position by position mode data. The resulting traces of bumper top and bottom are shown in Figure 5-25.

The most likely vertical position for the top and bottom of the bumper of all vehicles is represented with the four position traces shown in Figure 5-25.

Figure 5-25 shows vehicle bumper clearance height distributions for small passenger cars and small SUVs during

Table 5-4. Effect of increase in each parameter on rollover and crossover crashes.

Increase in	Frequency of rollover	Frequency of cross-median crashes
Median width	↑	↓
Median slope	↑	↓
Median shape (trapezoid vs. V-ditch)	↓	↓
Driver's intervention	↑	↓

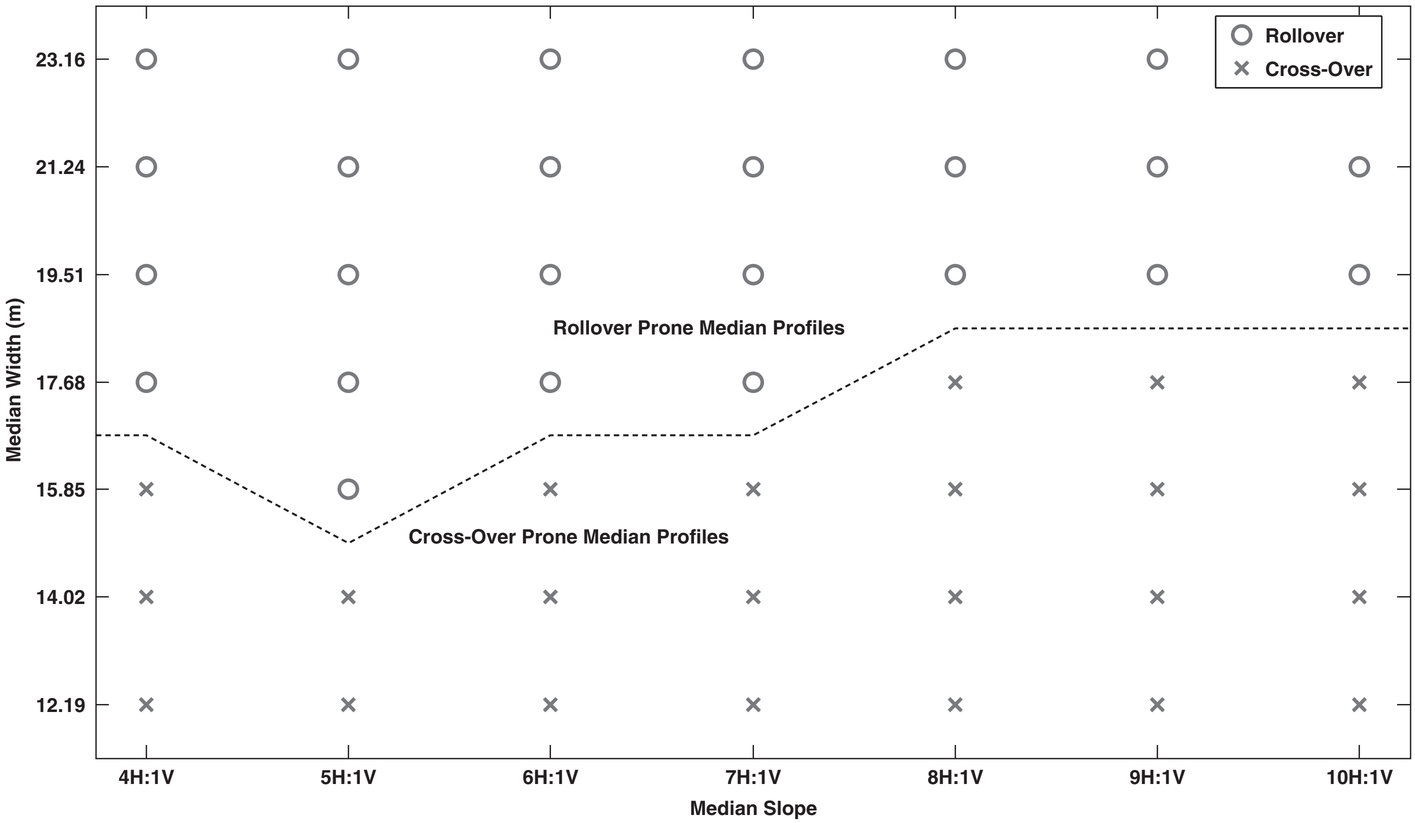

Figure 5-24. Optimal median geometry analysis.

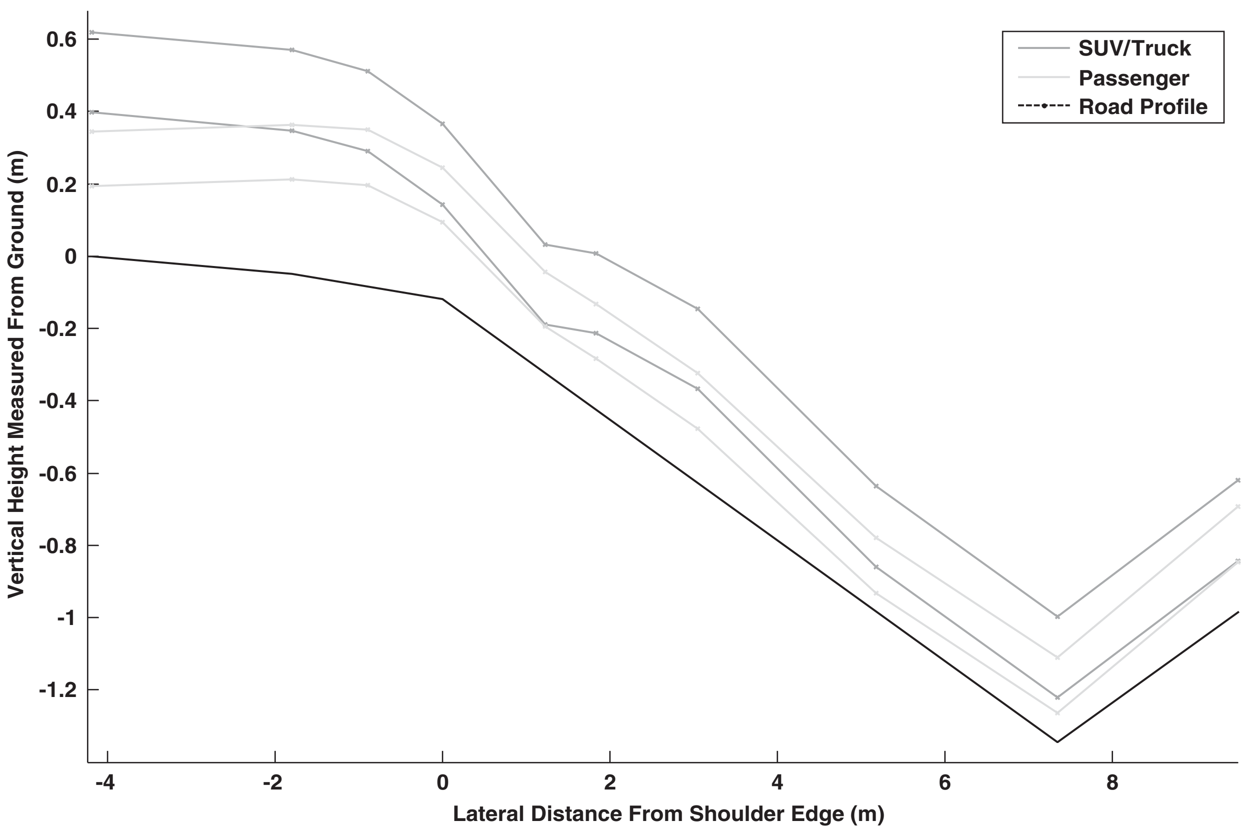

Figure 5-25. Bumper height and clearance modes throughout the median incursion.

a median encroachment. The median cross-section simulated was 18 m (60 ft) wide with 1V:6H cross-slopes. The AASHTO *Roadside Design Guide* (*2*) and results from the survey in the present study indicate that barriers placed in medians with a similar cross-section to that which was simulated are typically placed near the edge of the shoulder or near the swale point in the center of the median where the foreslope and backslope intersect. The vehicle dynamics simulation results for the height of the vehicle bumper during a median encroachment, shown in Figure 5-25, indicate that at the outside edge of a 1.2-m (4-ft) paved shoulder (represented by a zero offset in Figure 5-25), the mode (or most common value) for the clearance height of a small passenger car bumper is approximately 0.2 m (8 in.) above the ground. A small SUV has a mode value for bumper clearance height of approximately 0.32 m (12.5 in.). A typical small passenger car has a bumper height of 0.15 m (6.0 in.), while a small SUV has a typical bumper height of 0.22 m (8.7 in.). This suggests that bumper profiles of small passenger cars and small SUVs range from 0.20 to 0.36 m (8 to 14 in.), and 0.32 to 0.54 m (12.5 to 21.2 in.), respectively. The suggested mounting heights (*2*) of cable median barrier are 0.69 to 0.76 m (27 to 30 in.) to the top cable in a three-strand system. The bottom cable height is typically 0.51 to 0.61 m (20 to 24 in.) above the ground. For the strong post W-beam guardrail, the mounting height recommended is 0.69 m (27 in.) to the top of the rail element. The bottom of the rail element is typically 0.43 m (17 in.) above the ground. The bumper height envelope from the vehicle dynamics simulations suggests that strong post W-beam will likely be impacted by the bumpers of some small SUVs within the mounting height range of the barrier when installed at the edge of the paved shoulder in accordance with AASHTO policy. This is not necessarily the case for small passenger cars, because the bumper height envelope is lower than strong post W-beam barrier profile. The same findings apply for three-strand cable median barriers, where the bumper height envelope for some small SUVs will impact the barrier within the range of mounting heights for the barrier, but the bumpers of small passenger cars will not necessarily impact a three-strand cable barrier within the typical range of mounting heights.

The results in Figure 5-25 show that the mode value of the bumper clearance height trajectories remains relatively consistent as small passenger cars and SUVs traverse a 6H:1V foreslope during a median encroachment; however, a small proportion of vehicles were found to penetrate the ground before reaching the swale point. The AASHTO *Roadside Design Guide* (*2*) suggests that cable median barriers can effectively redirect vehicles on 1V:6H foreslopes if placement of the barrier in the area between 0.3 and 2.4 m (1 to 8 ft) offset from the swale is avoided. The vehicle dynamics simulation results in the present study indicate that ground penetrations occurred at approximately 2.0 m (7 ft) and approximately 3.5 m (12 ft) from the swale point, respectively. The latter value is larger than that suggested by AASHTO. The bumper clearance height trajectories approximately 0.3 m (1 ft) from the swale point on the foreslope are similar to those at the edge of the shoulder, and no ground penetrations were identified in the simulations at this location. This suggests that median barrier mounting heights, when offset approximately 0.3 m (1 ft) from the swale point on 1V:6H foreslopes, may be effective in redirecting small passenger vehicles as the bumper clearance height remains relatively constant with respect to the ground for approximately 1.0 m (3 ft) after crossing the swale point, particularly if the barrier deflection is less than 1.2 m (4 ft). The same is not necessarily true for small SUVs because the bumper clearance heights (and the range of simulated bumper height values) immediately before and after the vehicle traverses the swale point change considerably over a short lateral distance.

In summary, the vehicle dynamics simulation results in Figure 5-25 show a broad range of simulated bumper heights for vehicles traversing a median, particularly after those vehicles have passed the swale and are traversing the upslope toward the opposing roadway. This has potential implications for barrier placement and barrier mounting height. The results in Figure 5-25 suggest small passenger car bumper traces remain relatively constant near the median swale, so that placement of a median barrier near the swale may be effective for this vehicle class. However, the range of bumper heights is larger for small SUVs after crossing the swale point, so the effectiveness for SUVs of barriers placed on the upslope is a potential concern. No simulations of barrier impacts have been performed in this research; such simulations, especially for barriers located on the upslope beyond the median swale, should be considered in NCHRP Project 22-22.

CHAPTER 6

Interpretation of Results and Design Guidelines

This chapter discuss the interpretation of the analysis results presented in Chapters 4 and 5 of the report and presents design guidelines based on those results.

6.1 Median Width

In assessing median width effects from the crash analysis for rural divided highways, the results for rural four-lane freeways are of primary interest, because the smaller sample sizes for four-lane divided nonfreeways and six-lane freeways were too small to provide useful or consistent results. The fatal-and-injury crash analysis results for rural four-lane freeways generally indicate that CMCs decrease with wider medians, while rollover crashes generally increase with wider medians. These two effects are of almost equal magnitude, but in opposite directions. The logical interpretation of this result is that, as median width increases, out-of-control vehicles have more opportunity to roll over before reaching the opposing roadway. Thus, the choice of an appropriate median width depends on a tradeoff between the likelihood of CMC and rollover crashes. The net result of the combined effects of median width on CMC and rollover crashes discussed above (along with the smaller effects on other crash types) is a slight increase in fatal-and-injury crashes as median width increases.

The tradeoff between CMC and rollover crashes discussed above is strongly influenced by the difference in severity between these crash types, as shown in Table 6-1. The table shows that for CMCs, fatal crashes constitute 26.7 percent of fatal-and-injury crashes, while for rollover crashes, fatal crashes constitute only 9.0 percent of fatal-and-injury crashes. Thus, because wider medians lead to more of the less severe rollover crashes and fewer of the more severe CMCs, the research results suggest that generally wider medians should be preferred.

The crash analysis results indicate that wider medians generally will have more crashes. But, as indicated in Table E-1 in Appendix E (available on the TRB website), there would be fewer severe crashes as the median gets wider, resulting in a net crash cost savings. The effect shown in Table E-1 might be even more pronounced if crash data that distinguished serious injuries from other injuries were available; however, such data were not available for sites under the jurisdiction of some, but not all, of the participating agencies.

The crash analysis shows a monotonic relationship between crashes and median width, suggesting that CMCs would keep decreasing, and rollover crashes would keep increasing continuously as the median width increases. The results of the vehicle dynamics simulation illustrated in Figure 5-24 show a more subtle interpretation of this relationship. Specifically, the vehicle dynamics simulation analysis found that, at a median width in the range from 15 to 18 m (50 to 60 ft), there is a boundary at which the probability of a CMC becomes less than the probability of a rollover crash. This suggests that, when the lower severity of rollover crashes is taken into account, there are diminishing returns in continuing to make the median wider.

Figure 5-24 shows that this boundary is itself a function of median slope; therefore, this effect is examined further in the next section, which addresses median slope effects.

6.2 Median Slope

The crash analysis indicates that the median slope ratio also has opposing effects for CMC and rollover crashes, but that these opposing effects for median slopes are opposite to the effects for median width. The models for rural four-lane freeways in Table 4-7 show that higher median slope ratios (i.e., flatter slopes) are associated with more CMCs and fewer rollover crashes. Table 4-7 also indicates that flatter slopes on rural four-lane freeways are associated with fewer fixed-object crashes. As in the case of median width, the crash analysis indicates a monotonic effect in which the observed trends continue across the full range of median slope ratios.

The results of a benefit-cost analysis for flattened median slopes presented in Table E-2 in Appendix E (available on the TRB website) confirms that providing flatter slopes has a net

Table 6-1. Summary of crash severity distributions by median type and crash type.

Crash severity level	Traversable medians					Barrier medians				
	CMCs	NCMCs	Rollover crashes	Hit-fixed-object crashes	Other median-related crashes	CMCs	NCMCs	Rollover crashes	Hit-fixed-object crashes[a]	Other median-related crashes
Crashes by crash severity level as a percentage of fatal-and-injury median-related crashes										
Fatal	26.7	4.8	9.0	5.0	4.4	40.5	14.3	9.9	2.7	3.0
Injury	73.3	95.2	91.0	95.0	95.6	59.5	85.7	90.1	97.3	97.0
Crashes by crash severity level as a percentage of total median-related crashes										
Fatal	19.5	1.8	6.1	1.4	1.7	28.8	5.3	6.8	0.7	1.4
Injury	53.5	37.5	61.9	26.6	36.7	42.4	31.6	61.9	25.9	45.3
PDO	27.0	60.7	32.0	72.0	61.6	28.8	63.2	31.3	73.3	53.3

[a] for barrier medians, includes hit-barrier crashes.
Note: Based on data for all agencies combined from Tables 4-4 and 4-21.

positive effect on safety. This effect is cost-effective, even though earthwork/grading costs increase. However, a supplementary analysis considering differences in the severity distributions between crash types found that flatter slopes still had a positive effect on safety, but the benefit-cost ratios were less than 1.0. The crash analysis and benefit-cost results should be taken only as a general indication of the desirability of flattening slopes, both because the crash analysis results may oversimplify a complex relationship (see the discussion of the vehicle dynamics simulation results below) and because of variability in the earthwork/grading costs needed to achieve flatter slopes.

The vehicle dynamics simulation analysis again provides a more complete understanding of the subtleties of median slope effects, as it did for median width effects. In this case, the vehicle dynamics simulation results indicate an interaction between median slope and median width not evident in the crash analysis results. For median slopes in the range from 1V:4H to 1V:7H, the boundary between medians for which CMCs are most prevalent and those for which rollover crashes are most prevalent falls in the median width range from 15 to 17 m (50 to 55 ft). For median slopes of 1V:8H or flatter, that boundary falls at 18 m (60 ft). Thus, the vehicle dynamics simulation results indicate that the concerns about high-severity CMCs are of greatest concern for median widths less than 18 m (60 ft) and for median slopes steeper than 1V:8H. Furthermore, the vehicle dynamics simulation results suggest that the likelihood of CMCs does not continue increasing as the median slope becomes flatter than 1V:8H.

Chapter 1 of this report noted that there has been speculation that flatter median slopes may contribute to an increase in CMCs. The crash analysis indicates that this is true to an extent, but may be counterbalanced by a decrease in rollover crashes. The vehicle dynamics simulation results indicate the conditions under which CMCs become less probable than rollover crashes; as the median width increases, less severe rollover crashes become more likely than more severe CMCs, whatever the median slope.

The vehicle dynamics simulation results also indicate that the most favorable median shape from the standpoint of roadside safety is a trapezoidal shape, sloping down from the inside shoulders, with the center of the median being flat. Practical drainage considerations make it undesirable to grade the center of the median as completely flat, but slopes near the center of the median flatter than those closer to the traveled way appear desirable. It appears that the most desirable median slope should be 1V:8H or flatter immediately outside the traveled way and, where practical, still flatter near the center of the median.

6.3 Median Barriers

The cross-sectional (regression) models developed in the crash analysis for traversable and barrier medians can be used to estimate the safety differences between traversable and barrier medians with various geometric characteristics and barrier types. However, this approach is likely to be less accurate than using the crash reduction factors (CRFs) for median barriers developed in the EB before-after evaluation and documented in Tables 4-30 and 4-31. Table 6-2 presents a summary of these CRFs.

The CRFs for median barriers can also be expressed as CMFs, the form of countermeasure/treatment effectiveness measure used in the AASHTO *Highway Safety Manual* (*63*). CMFs have a nominal value of 1.0. CMF values less than 1.0 indicate crash types whose frequency is reduced by a countermeasure or treatment. CMF values greater than 1.0 indicate crash types whose frequency is increased by a countermeasure or treatment. Table 6-3 presents a summary of the effectiveness of median barriers that is equivalent to Table 6-2, but expressed as CMFs, rather than CRFs.

Tables E-3 through E-5 in Appendix E present benefit-cost analyses based on the crash prediction models for fatal-and-injury crashes on rural four-lane freeways presented in Table 4-7 and the median barrier effectiveness estimates shown in Table 4-31. This analysis focused on fatal-and-injury crashes because there are no explicit CMFs for property-damage-only (PDO) crashes. A supplementary analysis showed that PDO crashes were unlikely to substantially affect the benefit-

Table 6-2. Summary of CRFs for median barrier installation.

Crash type	Crash reduction factor (%)					
	Flexible median barriers		Semi-rigid median barriers		Rigid median barriers	
	Total median-related crashes	F & I median-related crashes	Total median-related crashes	F & I median-related crashes	Total median-related crashes	F & I median-related crashes
Rural four-lane freeways						
All median-related crash types combined	–227	–60	–152	–50	–140	–8
CMCs	96	92	98	100	100	100
CMCs + NCMCs	55	62	89	83	100	100
Rollover crashes	74	57	88	69	100	100
Hit-fixed-object crashes[a]	–720	–132	–426	–113	–892	–23
Other median-related crashes	–128	–67	–72	–47	–40	14
Rural six-lane freeways						
All median-related crash types combined	–66	–17	—	—	—	—
CMCs	73	69	—	—	—	—
CMCs + NCMCs	74	69	—	—	—	—
Rollover crashes	23	31	—	—	—	—
Hit-fixed-object crashes[a]	–209	–128	—	—	—	—
Other median-related crashes	16	14	—	—	—	—

[a] Increases in crash frequency include hit-barrier crashes.
Note: Statistical significance and standard errors are shown in Tables 4-30 and 4-31.

cost analysis results. The analysis results show that flexible barriers (i.e., cables), semi-rigid barriers (i.e., steel guardrail), and rigid barriers (i.e., concrete) can all be cost-effective in reducing crashes under appropriate conditions. As shown in Tables 6-2 and 6-3, each of these barrier types reduces the more severe CMCs while increasing less severe hit-fixed-object crashes (including hit-barrier crashes).

Rigid barriers generally are used only in narrow medians. The benefit-cost analysis results in Appendix E show that flexible and semi-rigid barriers are generally more cost-effective than rigid barriers and generally should be preferred where the median is wide enough to accommodate the deflection that occurs when a vehicle strikes a flexible or semi-rigid barrier.

Figure 5-25, based on vehicle dynamics simulation results, provides guidance on appropriate barrier heights so that the barrier and vehicle bumpers interact appropriately when a collision occurs.

6.4 Design Guidelines

The following design guidelines have been derived from the research results:

- The AASHTO Green Book (*1*) recommends 1V:6H slopes within medians, with 1V:4H slopes considered adequate in some cases. Based on the research results, it is recommended that the Green Book be changed to recommend 1V:8H slopes within medians, with 1V:6H slopes considered adequate in some cases. It also is recommended that slopes flatter than 1V:8H be considered near the center of the median, where practical.
- It is recommended that the median barrier warrants in the AASHTO *Roadside Design Guide* (*2*) be changed to indicate that barrier be considered for median widths up to 18 m (60 ft) where the median slope is less than 1V:8H.
- It is recommended that the CMFs for median barrier installation shown in Table 6-3 be considered for inclusion in the AASHTO *Highway Safety Manual* (*63*), potentially in conjunction with the SPFs for median-related crashes presented in Tables 4-6 and 4-7. These CMFs are suitable for planning of roadside design policies that would be applied over many sites or to analyses conducted with a combination of an SPF for median-related crashes and the application of the EB method. However, these CMFs are probably not a suitable tool for application to individual sites without use of an SPF and the EB method, because individual sites are unlikely to have experienced a sufficient number of CMCs to make application of the CMFs accurate.
- Benefit-cost analysis suggests that flexible median barriers may be cost-effective even at lower traffic volumes than suggested in AASHTO median barrier warrants.

Table 6-3. Summary of CMFs for median barrier installation.

Crash type	Crash modification factor					
	Flexible median barriers		Semi-rigid median barriers		Rigid median barriers	
	Total median-related crashes	F & I median-related crashes	Total median-related crashes	F & I median-related crashes	Total median-related crashes	F & I median-related crashes
Rural four-lane freeways						
All median-related crash types combined	3.27	1.60	2.52	1.50	2.40	1.08
CMCs	0.04	0.08	0.02	0.00	0.00	0.00
CMCs + NCMCs	0.45	0.38	0.11	0.17	0.00	0.00
Rollover crashes	0.26	0.43	0.12	0.31	0.00	0.00
Hit-fixed-object crashes[a]	8.20	2.32	5.26	2.13	9.92	1.23
Other median-related crashes	2.28	1.67	1.72	1.47	1.40	0.86
Rural six-lane freeways						
All median-related crash types combined	1.66	1.17	—	—	—	—
CMCs	0.27	69.00	—	—	—	—
CMCs + NCMCs	0.26	69.00	—	—	—	—
Rollover crashes	0.77	31.00	—	—	—	—
Hit-fixed-object crashes[a]	3.09	1.28	—	—	—	—
Other median-related crashes	0.84	14.00	—	—	—	—

[a] Increases in crash frequency include hit-barrier crashes.

Note: Statistical significance and standard errors are shown in Tables 4-30 and 4-31.

CHAPTER 7

Conclusions and Recommendations

The conclusions of the research are as follows:

1. For traversable medians, median widths were found to have partially offsetting effects on median-related crashes. CMCs and NCMCs decrease with increasing median width, while rollover crashes increase. The net result of these effects is typically a slight increase in total median-related crashes with increasing median width. Even so, wider medians generally have a positive safety effect, because the severity of CMCs is much greater than for rollover crashes. Predictive models or SPFs for all median-related crashes and specific crash types are presented in Tables 4-6 and 4-7. The severity distributions for specific crash types are shown in Table 6-1.
2. For traversable medians, the crash analysis results indicated flatter slopes generally lead to more CMCs and fewer rollover crashes. This is a concern for use of flatter slopes, because CMCs are substantially more severe than rollover crashes. However, the results of vehicle dynamics simulation analysis do not indicate any trend toward CMCs becoming more likely for slopes flatter than 1V:8H.
3. Vehicle dynamics simulation indicates that there is an identifiable dividing line between combinations of median width and median slope for which the most likely result of a vehicle encroachment is a CMC and those combinations for which the most likely result is a vehicle rollover. The dividing line or boundary is generally a median width in the range of 15 to 17 m (50 to 55 ft) for median slopes steeper than 1V:8H and 18 m (60 ft) for median slopes of 1V:8H or flatter. This result is shown in Figure 5-24.
4. Vehicle dynamics simulation results suggest that a median with flatter slopes in the center is less conducive to CMCs than a median with uniform slopes that meet at the center of the median.
5. CMFs for flexible, semi-rigid, and rigid barriers have been developed in a before-after evaluation using the EB method. These CMFs are presented in Table 6-3, with supporting documentation in Tables 4-30 and 4-31.
6. A benefit-cost analysis based on the CMFs in Table 6-3 indicates that each of the three barrier types—flexible, semi-rigid, and rigid—is cost-effective when applied in appropriate situations. Flexible median barriers are typically used continuously for extended sections of median. Flexible median barriers may be cost-effective even at lower traffic volumes than suggested in the AASHTO median barrier warrants. Semi-rigid barriers are typically used in shorter lengths than flexible barriers and are placed at specific obstacles. Rigid barriers are less cost-effective in rural divided highway medians and are primarily applicable to continuous sections of median than are too narrow to accommodate the deflection of a flexible barrier.

The following recommendations were developed in the research:

1. The AASHTO Green Book (*1*) recommends 1V:6H slopes within medians, with 1V:4H slopes considered adequate in some cases. Based on the research results, it is recommended that the Green Book be changed to recommend 1V:8H slopes within medians, with 1V:6H slopes considered adequate in some cases. It also is recommended that slopes flatter than 1V:8H be considered near the center of the median, where practical.
2. It is recommended that the median barrier warrants in the AASHTO *Roadside Design Guide* (*2*) be changed to indicate that barrier be considered for median widths up to 18 m (60 ft) where the median slope is less than 1V:8H.
3. It is recommended that the CMFs for median barrier installation shown in Table 6-3 be considered for inclusion in the AASHTO *Highway Safety Manual* (*63*), potentially in conjunction with the SPFs for median-related crashes

presented in Tables 4-6 and 4-7. These CMFs are suitable for planning of roadside design policies that would be applied over many sites, or to analyses conducted with a combination of an SPF for median-related crashes and the application of the EB method. However, these CMFs are probably not a suitable tool for application to individual sites without use of an SPF and the EB method, because individual sites are unlikely to have experienced a sufficient number of CMCs to make application of the CMFs accurate. Median barrier installation is more appropriately determined from policies based on median widths and traffic volumes, like those included in AASHTO policy, than on the analysis of crash data for individual sites.

4. The vehicle dynamics simulation results in Figure 5-25 show a broad range of simulated bumper heights for vehicles traversing a median, particularly after those vehicles have passed the swale and are traversing the upslope toward the opposing roadway. This has potential implications for barrier placement and barrier mounting height. The results in Figure 5-25 suggest that small passenger car bumper traces remain relatively constant near the median swale, so that placement of a median barrier near the swale may be effective for this vehicle class. However, the range of bumper heights is larger for small SUVs after crossing the swale point so, for SUVs, the effectiveness of barriers placed on the upslope is a potential concern. No simulations of barrier impacts have been performed in this research; such simulations, especially for barriers located on the upslope beyond the median swale, should be considered in NCHRP Project 22-22.

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Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S.DOT	United States Department of Transportation