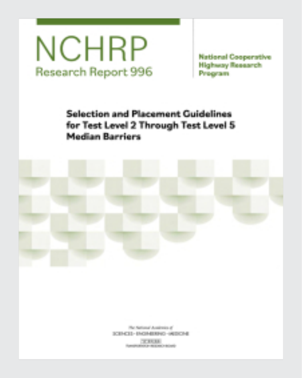

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 996

Selection and Placement Guidelines for Test Level 2 Through Test Level 5 Median Barriers

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Subscriber Categories
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TRB
TRANSPORTATION RESEARCH BOARD

2022

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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NCHRP RESEARCH REPORT 996

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FOREWORD

By Christopher T. McKenney
Staff Officer
Transportation Research Board

NCHRP Research Report 996: Selection and Placement Guidelines for Test Level 2 Through Test Level 5 Median Barriers presents comprehensive guidelines for the selection and placement of Test Level 2 through Test Level 5 median barriers. These guidelines were developed using cost-benefit and risk analysis approaches and based on traffic volume and mix, roadway and median geometry, median barrier placement, in-service performance, and barrier type (e.g., shape, material, and rigidity). In addition to the guidelines, charts were included with associated site-specific adjustment factors for selecting the appropriate median barrier test level and median barrier type and placement within the median. This report will be of immediate interest to roadway design engineers.

Median barriers can be classified into six test levels as defined by the 2009 AASHTO *Manual for Assessing Safety Hardware* (MASH) and *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features*. Each test level is defined by impact conditions (speed and angle of approach) and the type of test vehicle the barrier is designed to redirect (ranging in size from a small car to a fully loaded tractor-trailer truck). The longitudinal barrier is the only classification for which all six test levels are defined at this time. Longitudinal median barriers are also grouped into three general categories: flexible, semi-rigid, and rigid. Although rigid barriers and flexible barriers can be designed to satisfy a given test level, they will have different applications. The rigid barrier will produce higher vehicle decelerations and prevent any lateral deflection, while the flexible barrier will produce lower accelerations. Less rigid barriers result in less energy dissipated by the vehicle; hence, accelerations imparted to the occupants inside the vehicle during an impact are lower as compared with vehicle impacts with rigid barriers. On the other hand, flexible barriers have been shown to have larger lateral deflections, thus limiting their use in narrow medians.

Currently, the AASHTO *Roadside Design Guide* (RDG) is the primary national guideline available to states in preparing their own policies for roadside design. The RDG offers guidance for selecting median barriers and cites a higher percentage of heavy trucks in the traffic flow, adverse geometries, and higher accident rates as conditions that may warrant barriers with a performance level higher than Test Level 3. However, thresholds for these values were not provided.

Under NCHRP Project 22-31, “Recommended Guidelines for the Selection and Placement of Test Levels 2 through 5 Median Barriers,” Roadsafe, LLC, developed proposed guidelines for selecting and placing Test Levels 2 through 5 median barriers suitable for use by all government transportation agencies at state and local levels.

CONTENTS

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.nap.edu) retains the color versions.

CHAPTER 1

Introduction

The roadside safety community has been interested for several decades in developing selection and placement guidance for the multiple test levels of median barriers. The variety of median widths and terrains combined with evolving testing specifications and lack of conclusive data on median crossover crashes have been obstacles to success. The ongoing implementation of the *Manual for Assessing Safety Hardware* (MASH), combined with new data collection efforts and the availability of new analysis tools, has overcome some of the primary obstacles to developing median barrier guidance. (AASHTO 2016)

The objective of this research was to develop, in a format suitable for consideration and possible adoption by AASHTO, proposed guidelines for the selection and placement of MASH Test Levels 2 through 5 (TL2-TL5) median barriers. These guidelines are based on traffic volume and mix, roadway and median geometry, median barrier placement, in-service performance, cost–benefit and risk analyses, and barrier type (i.e., shape, material, rigidity, etc.). These guidelines are suitable for use by government transportation agencies at the state and local levels. It is anticipated that the results will be integrated into an updated edition of the AASHTO *Roadside Design Guide* (RDG).

The approach to the guideline development, as stated in the project statement of work, is risk-based; the frequency and severity of crashes with and without median barriers are estimated and the risk of observing an incapacitating or fatal injury crash is calculated. The third version of the Roadside Safety Analysis Program (RSAPv3) was developed to perform a cost–benefit analysis. NCHRP Project 22-12(03), "Development of Guidelines for Bridge Rails" expanded RSAPv3 to document the risk analyses that are the basis of the cost–benefit analyses. (Ray 2021; Ray 2012b) The statement of work suggested the use of RSAPv3.

As this research progressed, the scope was extended to include MASH roadside barriers in addition to median barriers. Additionally, NCHRP Project 15-65, "Development of Safety Performance Based Guidelines for the Roadside Design Guide," was advertised and awarded. (Ray 2018) NCHRP Project 15-65 has developed an updated approach to roadside design guidance development based on the encroachment probability model programmed with RSAPv3 and conceptualized through a governing equation. The existing guidance in the AASHTO RDG (AASHTO 2011) is being updated to use the systematic approach under development in NCHRP Project 15-65. For these reasons, and so this median and roadside barrier guidance will fit seamlessly into the ongoing update to the AASHTO RDG, the new guidance presented herein for both median barriers and roadside barriers was developed using the NCHRP Project 15-65 governing equation.

This report summarizes the guideline development effort. Substantial technical research was undertaken, much of which is detailed separately in Appendices A through E to allow the reader to focus on the guideline development. The guidelines for assessing median barrier need and selecting the median barrier material are shown in Figure 23. Table 12 can be used to select the appropriate barrier test level. Cost–benefit guidelines are presented in Section 5.3. Guidelines for shielding fixed objects on slopes flatter than 2:1 are presented in Figure 25.

CHAPTER 2

Definitions

The words median and median barrier are defined slightly differently in the AASHTO and State DOT literature. (AASHTO 2006; AASHTO 2011; Caltrans 2012) The National Transportation Safety Board (NTSB) has asked FHWA and AASHTO to provide a consistent definition for cross-median crashes, citing a lack of consistency throughout the states. This section presents the definition of terms used consistently in this report and ultimately in the guidelines that are the result of this research. Reference is made throughout this report to these definitions.

- Median: The portion of a divided highway separating the traveled ways for traffic in opposite directions.
- Median barrier: A longitudinal barrier system intended to reduce the risk of an errant vehicle crossing the highway median. Median barriers are designed to be impacted from either direction of travel.
- Median-related event (MRE): Any event where an errant vehicle enters the median. MREs represent all vehicles that encroach left into the median, regardless of the outcome (i.e., crash or no crash).
- Cross-median event (CME): An event where an errant vehicle fully crosses the median and may or may not collide with another vehicle from the opposite direction. CMEs are a subset of MREs.
- Cross-median crash (CMC): A cross-median crash is one in which an errant vehicle crosses the median of a highway and strikes or is struck by a vehicle from the opposite direction. CMCs are a subset of CMEs, which are, in turn, a subset of MREs.

CHAPTER 3

Literature Review

The following literature review summarizes the impetus for improving median barrier guidance, the history of median barrier guidance through 2015, and the evolution of crash testing specifications for median barriers. Recent additions to the literature on the placement of median barriers are also included.

This review captures the explosion of interest in highway safety modeling. Specifically, the study of crash data to model median-related crashes (Carrigan 2018; Graham 2014; Harwood 2014) and the recent study of vehicle behavior during encroachments on various slopes (Bligh 2020b) have been captured in this review. Available analytical tools are discussed and the ability to build on past research is assessed.

3.1 Interest in Developing Median Barrier Guidance

NTSB is an independent federal agency charged by Congress with investigating significant highway accidents. "The NTSB determines the probable cause of the accidents and issues safety recommendations aimed at preventing future accidents." (NTSB 2016) The following sections contain summaries of MREs that have been investigated by the NTSB in the last 20 years and resulted in a recommendation by the NTSB for the development of median barrier guidance.

3.1.1 1998

On February 12, 1997, a truck-tractor with double trailers lost control while traveling northbound on U.S. Route 41 near Slinger, Wisconsin, and fully crossed the median into the southbound lanes where a flatbed truck traveling southbound struck the tractor. After the collision, the flatbed truck lost control, may have run off the road to the right, then crossed the median, and entered the northbound lanes. A passenger van traveling northbound struck and underrode the flatbed truck and a refrigerator truck also collided with the flatbed truck as shown in the scene diagram in Figure 1. (NTSB 1998)

The double and flatbed truck drivers received minor injuries. The refrigerator truck driver received no injuries. There were nine occupants of the van; the driver and seven passengers were fatally injured and one passenger was seriously injured.

The crash history for this site is summarized in Table 1 and the highway and median characteristics are summarized in Table 2. As a result of this investigation, the NTSB issued several recommendations related to median barrier selection, including:

> **To the Federal Highway Administration:**
>
> Review, with the American Association of State Highway and Transportation Officials, the median barrier warrants and revise them as necessary to reflect changes in the factors affecting the probability of

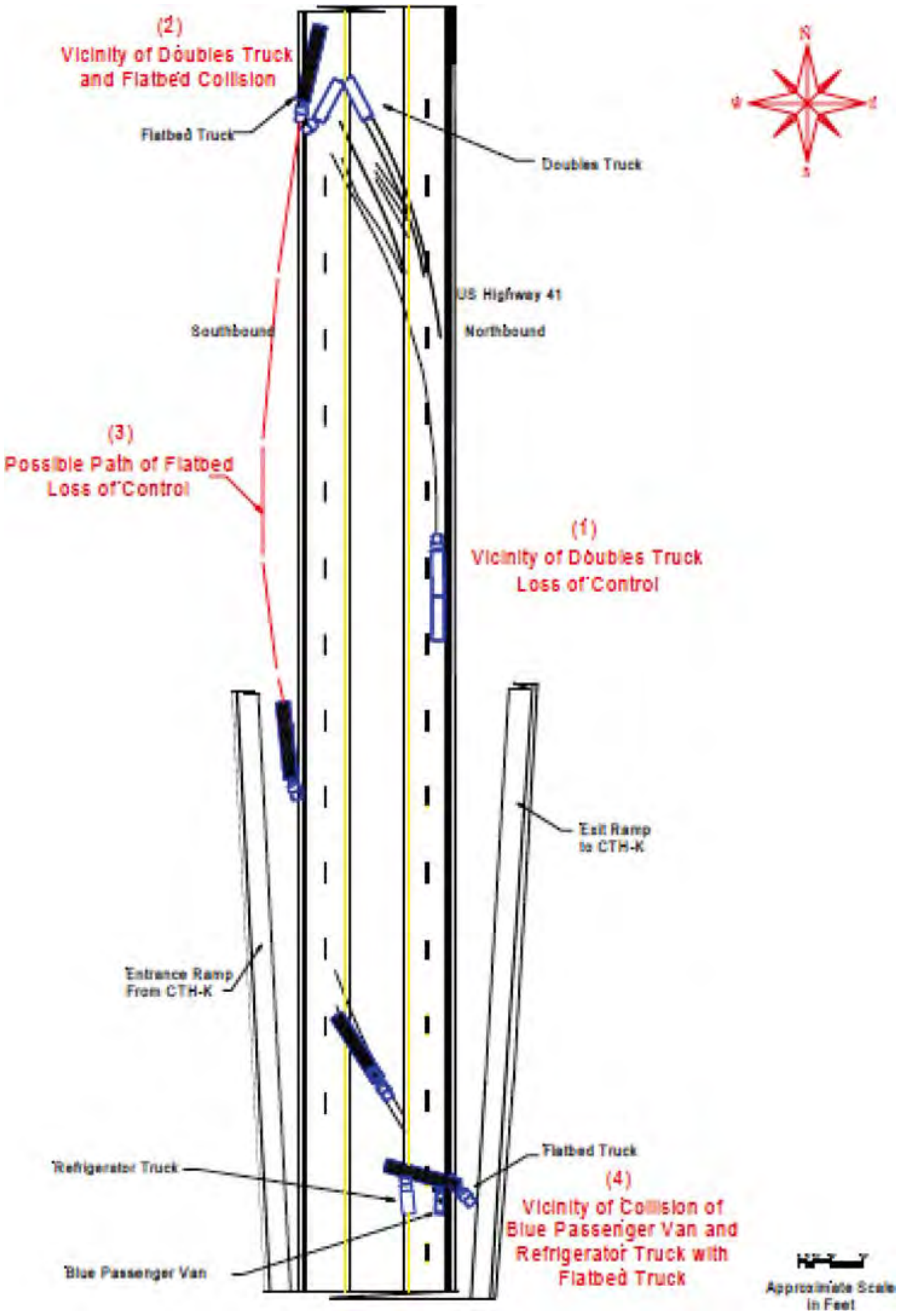


Figure 1. Crash scene diagram: U.S. Route 41 near Slinger, Wisconsin. (NTSB 1998)

Table 1. Summary of crash statistics for NTSB median crossover investigations.

Crash location	U.S. Route 41 near Slinger, Wisconsin	Interstate 65 near Munfordville, Kentucky	Interstate 5 in Orland, California
Statewide fatal accidents	• 0.6% of total head-on collisions with median barriers • 1.9% of total without median barriers	• 1.74 per 100 million vehicle miles traveled (2008)	• Unknown
Site crash statistics	• No cross-median crashes within 6 miles of the site within 3 years	• 0.49 cross-median crashes per mile per year within 10 miles • 0.37 fatal cross-median crashes per mile per year within 10 miles	• No cross-median collision history at the crash site

Table 2. Site summaries for NTSB median crossover investigations.

Crash location	U.S. Route 41 near Slinger, Wisconsin	I-65 near Munfordville, Kentucky	Interstate 5 in Orland, California
Crash date	February 12, 1997	March 26, 2010	April 10, 2014
Highway type	Principal rural arterial	Principal rural arterial	Principal urban arterial
Vehicle crossing	Truck-tractor in combination with 2 empty trailers	Truck-tractor in combination with a 53-foot-long van semitrailer	Truck-tractor in combination with two 28-foot trailers
Lanes	Four 12-foot lanes	Four 12-foot lanes	4 lanes
Shoulders	Left: 6 feet (3-foot paved) Right: 10 feet (6-foot paved)	Left: 4 feet NB and 3.5 feet SB; Right: 11 feet	Left: 4 feet Right: 12 feet
Rumble strips	None present	Located on all 4 shoulders	Located on all 4 shoulders
Median width	50 feet	60 feet	58 feet
Median characteristics	Depressed grassed median with 1:8 slope	Depressed earthen median with 1:4 slope	Gravel earthen median with oleander bushes 3–5 feet tall located near the centerline
Median barrier	None present	4-strand high-tension cable median barrier with cables mounted at 20, 25, 30, and 39 inches	None present
Test level	NA	*NCHRP Report 350* TL3	NA
Barrier placement	NA	8 feet to the left of the NB traveled-way	NA
Grade	0.6% NB	–2.6% SB	Unknown
Horizontal	Tangent	Tangent	Tangent
ADT (veh/day)	24,050 (1996)	36,800 (2008)	23,400 (2012)
%Trucks	21% (1993)	35% (2008)	25% (2012)
Design speed	70 mph	70 mph	Unknown
Posted speed	65 mph	70 mph	70 mph for cars and buses; 55 mph for trucks with 3 or more axles
85th percentile speed for cars	64 mph for all vehicles on the morning of the crash	76 mph	76 mph
85th percentile speed for trucks		70 mph	61 mph

> cross-median accidents, including changes in the vehicle fleet and the percentage of heavy trucks using the roadways. (H-98-12)
>
> Include a data element for cross-median accidents in the Guideline for Minimum Uniform Crash Criteria, which you are developing with the National Highway Traffic Safety Administration and the National Association of Governors' Highway Safety Representatives. (H-98-13)
>
> **To the National Highway Traffic Safety Administration:**
>
> Include a data element for cross-median accidents in the Guideline for Minimum Uniform Crash Criteria, which you are developing with the Federal Highway Administration and the National Association of Governors' Highway Safety Representatives. (H-98-17)
>
> **To the National Association of Governors' Highway Safety Representatives:**
>
> Include a data element for cross-median accidents in the Guideline for Minimum Uniform Crash Criteria, which you are developing with the National Highway Traffic Safety Administration and the Federal Highway Administration. (H-98-18)
>
> **To the American Association of State Highway and Transportation Officials:**
>
> Review, with the Federal Highway Administration, the median barrier warrants and revise them as necessary to reflect changes in the factors affecting the probability of cross-median accidents, including changes in the vehicle fleet and the percentage of heavy trucks using the roadways. (H-98-24)

Safety Recommendation H-98-24 was reclassified "Closed—Superseded" when it was superseded by Safety Recommendation H-11-31, as discussed below.

3.1.2 2011

A tractor-semitrailer truck was traveling south and departed the left lane, crossing a 60-foot-wide depressed median of Interstate 65 on March 26, 2010, near Munfordville, Kentucky. After crossing the median, the truck overrode the high-tension cable median barrier adjacent to the left northbound shoulder. The truck entered the northbound travel lanes where it crossed in front of a 15-passenger van (containing 12 people) traveling northbound on Interstate 65. The passenger van struck the tractor. The truck continued across the northbound lanes to hit a cut rock wall where the truck caught fire. After impact with the truck, the van also hit the cut rock wall. The scene diagram is shown in Figure 2. The truck driver, van driver, and nine van passengers died. Two van passengers sustained minor injuries. (NTSB 2011)

The crash history for this site is summarized in Table 1 and the highway and median characteristics are summarized in Table 2. As a result of this investigation, the NTSB issued several recommendations related to median barrier selection, including:

> **To the Federal Highway Administration:**
>
> Work with the American Association of State Highway and Transportation Officials to establish warrants and implementation criteria for the selection and installation of Test Level Four and Test Level Five median barriers on the National Highway System. (H-11-21)
>
> Work with the American Association of State Highway and Transportation Officials to identify cross-median crash rates that call for special consideration when selecting median barriers. (H-11-22)
>
> Work with the American Association of State Highway and Transportation Officials to define the criteria for median barrier selection, including heavy vehicle traffic volume. (H-11-23)
>
> **To the National Highway Traffic Safety Administration:**
>
> Work with the Governors Highway Safety Association to add a standard definition of "cross-median crash" and a data element for cross-median crash accidents to the Model Minimum Uniform Crash Criteria. (H-11-28)
>
> **To the American Association of State Highway and Transportation Officials:**
>
> Work with the Federal Highway Administration to establish warrants and implementation criteria for the selection and installation of Test Level Four and Test Level Five median barriers on the National Highway System, and publish those warrants and criteria in the Roadside Design Guide. (H-11-31) [This recommendation supersedes Safety Recommendation H-98-24.]

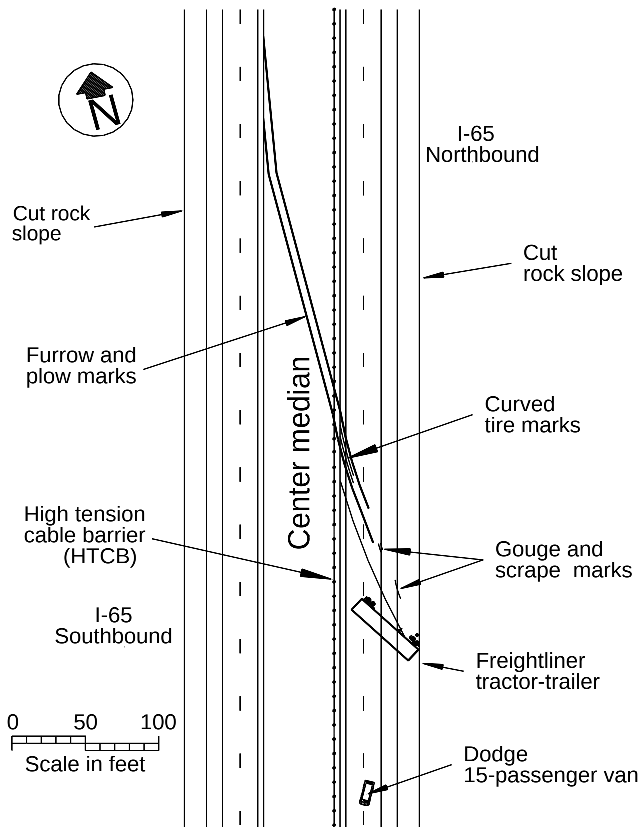


Figure 2. Crash scene diagram: Interstate 65 near Munfordville, Kentucky. (NTSB 2011)

Work with the Federal Highway Administration to identify cross-median crash rates that call for special consideration when selecting median barriers, and publish the rates in the Roadside Design Guide. (H-11-32)

Work with the Federal Highway Administration to define the criteria for median barrier selection, including heavy vehicle traffic volume, and publish the criteria in the Roadside Design Guide. (H-11-33)

To the Governors Highway Safety Association:

Work with the National Highway Traffic Safety Administration to add a standard definition of "cross-median crash" and a data element for cross-median crash accidents to the Model Minimum Uniform Crash Criteria. (H-11-34)

3.1.3 2015

On April 10, 2014, a truck-tractor with double trailers was southbound on Interstate 5 in Orland, California when it crossed a 58-foot-wide median. The truck-tractor first struck a northbound Nissan Altima which subsequently ran off the road. The truck-tractor then struck a northbound motorcoach, the two vehicles ran off the road, and a post-crash fire followed, as shown in Figure 3. The truck and motorcoach drivers as well as eight motorcoach passengers were fatally injured. Thirty-seven motorcoach passengers were injured. The two occupants of the Nissan Altima received minor injuries. (NTSB 2015)

The crash history for this site is summarized in Table 1 and the highway and median characteristics are summarized in Table 2. The NTSB, as part of the investigation, assessed the need for median barriers at this location against current practice. The NTSB found that median

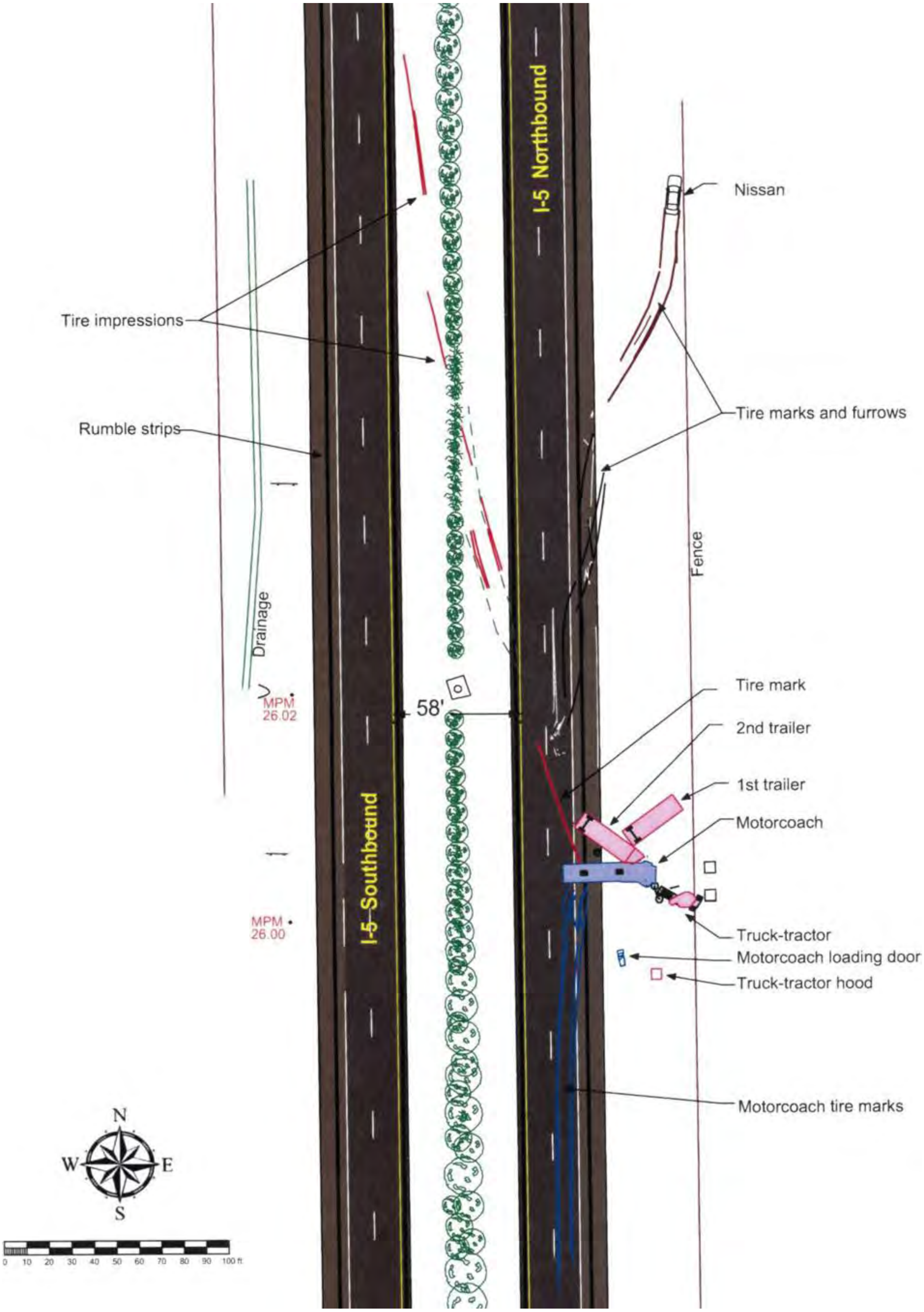


Figure 3. Crash scene diagram: Interstate 5 in Orland, California. (NTSB 2015)

barriers were not warranted at this location, noting "... because of the severity of cross-median crashes, some states, including California, have stronger median barrier application policies than the RDG. . . . Even with the more robust barrier application policies in the State of California, the Orland crash site did not exceed the Caltrans minimum ADT of 45,000 vehicles for the 58-foot-wide median, and the fatal cross-median crash rate had not been exceeded in the preceding 5 years." (NTSB 2015) Although the NTSB made no new recommendations to the FHWA or AASHTO as a result of this investigation, "[t]he NTSB is encouraged by the recent TRB announcement of an NCHRP research project (no. 22-31) to develop guidelines on median barrier placement location criteria and selection of median barriers types. It is anticipated that these guidelines will be integrated into an updated edition of the RDG and, therefore, will augment the criteria used by California and other states." (NTSB 2015)

3.1.4 Summary of Crashes Investigated by NTSB

The crash site characteristics and crash history of these crashes investigated by NTSB are summarized in Table 1 and Table 2. While these crashes only provide anecdotal evidence, these summaries illustrate the types of events the NTSB is called to investigate and try to prevent, through recommendations, in the future.

3.2 Evolution of Median Barrier Guidance

3.2.1 Historic Guidance

Guidelines for installing barriers began with *Highway Research Board Special Report 81* in 1964. In 1967, in *Highway Design and Operation Practices Related to Highway Safety*, (AASHO 1967) the AASHO Traffic Safety Committee published median barrier warrants stating that:

> "Effective median barriers should be installed on all existing and proposed high volume, high speed divided highways with narrow medians where traffic engineering studies establish the need. On multilane undivided highways, where there are similar traffic conditions, median barriers may also be a contribution to safety."

In the 1967 *Highway Design and Operations Practices Related to Highway Safety,* the AASHO Traffic Safety Committee also observed:

> "Throughout the nation there have been many serious cross-median accidents resulting in multiple deaths where the traffic volume has been much less than 40,000 vehicles per day. Some States are proceeding on the basis that on any highway with a median width less than 20 feet a barrier rail should be installed regardless of traffic volume. . . . On a heavily travelled section, say with volumes over 20,000 per day, barriers should be considered on medians up to about 30 feet in width."

NCHRP Report 54: Location, Selection, and Maintenance of Highway Guardrails and Median Barriers was published in 1968. *NCHRP Report 54* presented median barrier warrants based on median width and a 2-year projection of traffic volumes. When the median exceeded 40 feet, median barriers were said to not be warranted, as shown in Figure 4. *NCHRP Report 54* considered median barriers to have the sole purpose of reducing across-the-median, head-on collisions between vehicles in the opposing direction of travel. Consideration of the need for a longitudinal barrier due to the median terrain and/or obstacles was based on roadside warrants. (Michie 1968)

NCHRP Report 118: *Location, Selection, and Maintenance of Highway Traffic Barriers*, published in 1971, superseded *NCHRP Report 54. NCHRP Report 118* reiterated the *NCHRP Report 54* statement about the purpose of median barriers and continued to base the warrant on a 2-year projection of traffic volumes and median width. The minimum width for a median to not have a barrier, however, was extended from 40 feet to 50 feet. A provision was also added that medians that exceeded 50 feet with adverse accident experience may also be considered for

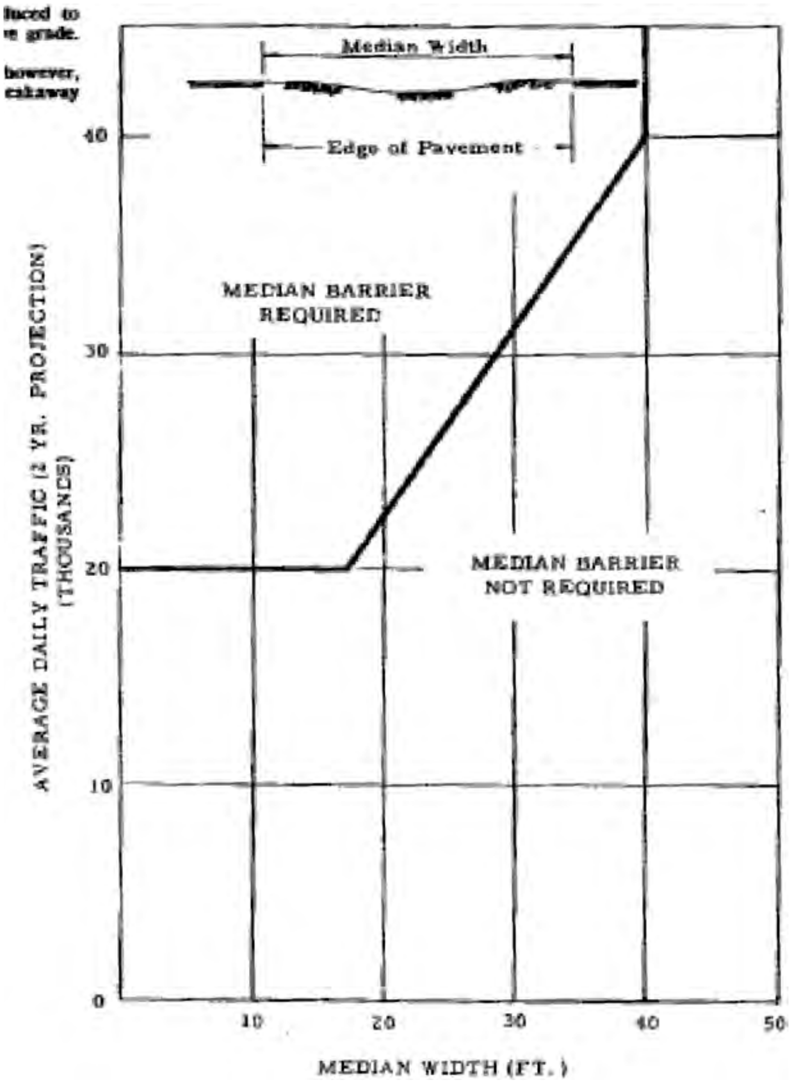


Figure 4. **NCHRP Report 54 *median barrier requirements. (Michie 1968)***

barriers. (Michie 1971) The median barrier requirements from *NCHRP Report 118* are shown in Figure 5.

The second edition of *Highway Design and Operations Practices Related to Highway Safety* was published in 1974, at which time the guidance for the introduction of median barriers was changed, removing any reference to traffic volumes and only referring to median width as follows:

> "For narrow medians, 30 feet or less in width, a flush paved median with internal drainage and a median barrier should be considered. The median should be kept free of abrupt slopes and obstacles. . . ." (AASHTO 1974)

In 1977, AASHTO published the *Guide for Selecting, Locating, and Designing Traffic Barriers* (1977 Barrier Guide), and median barriers were addressed in Chapter 4. (AASHTO 1974) Warrants were suggested for median barriers on high-speed, controlled-access roadways as shown in Figure 6. These warrants were suggested for use ". . . in the absence of cross median accident data for a specific site." It was further suggested that "[a]n evaluation of the number of [median

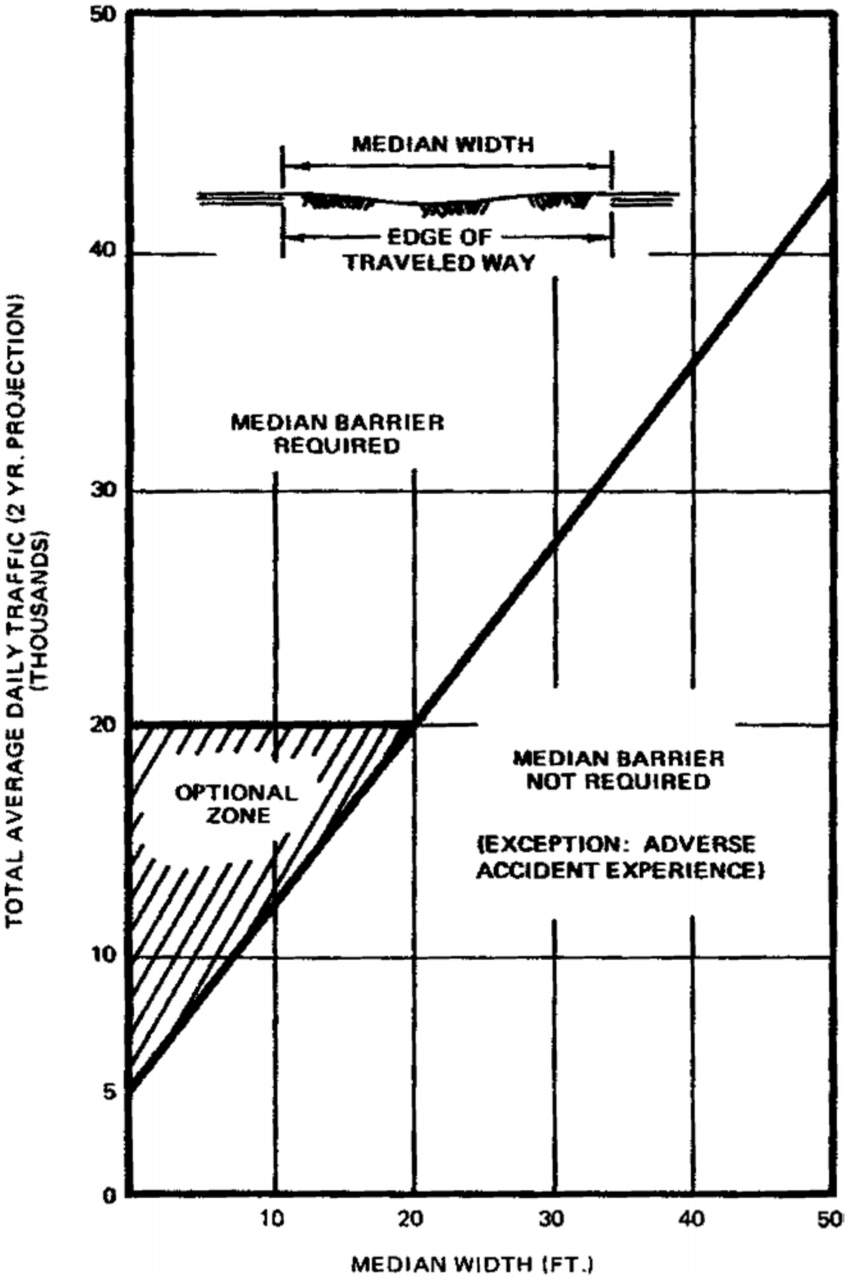


Figure 5. **NCHRP Report 118 *median barrier requirements. (Michie 1971)***

openings], accident history, alignment, sight distance, design speed, traffic volume, and median width should be made prior to non-freeway installations." (AASHTO 1974) These guidelines were based on previous research findings reported by the Traffic Department of the State of California in 1968, by the Texas Transportation Institute (TTI) in 1974 (*Research Report 140-8*), and the judgment of the AASHTO Task Force for Traffic Barrier Systems, the predecessor to today's Technical Committee on Roadside Safety (TCRS).

AASHTO published the first edition of the *Roadside Design Guide* (RDG) in 1989 and Chapter 6 explicitly addressed median barriers. (AASHTO 1989a) The 1989 RDG reiterated the 1977 Barrier Guide warrant. No changes were made to the warrant; however, it was noted

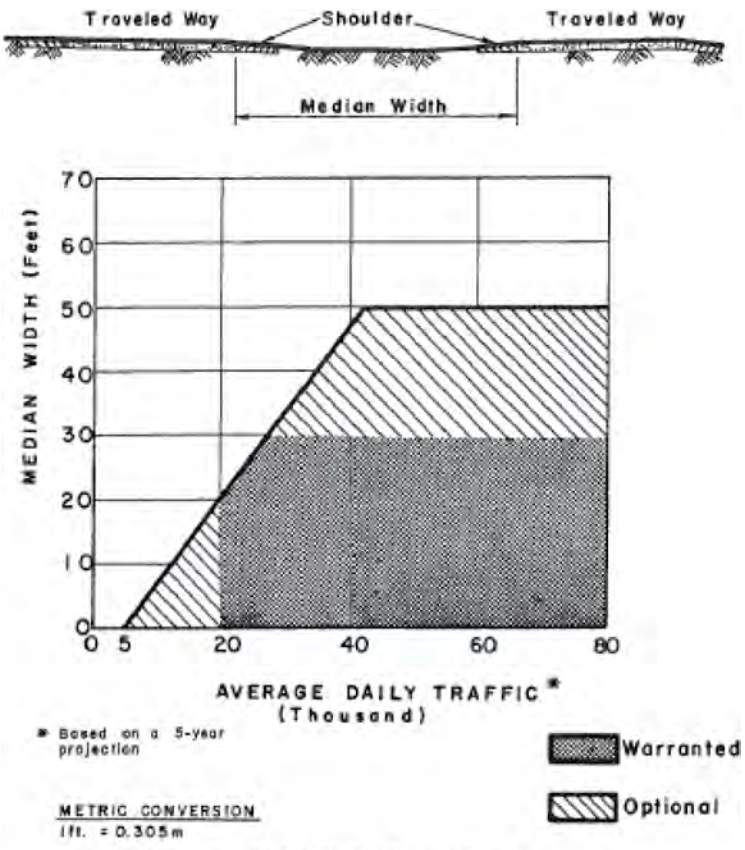


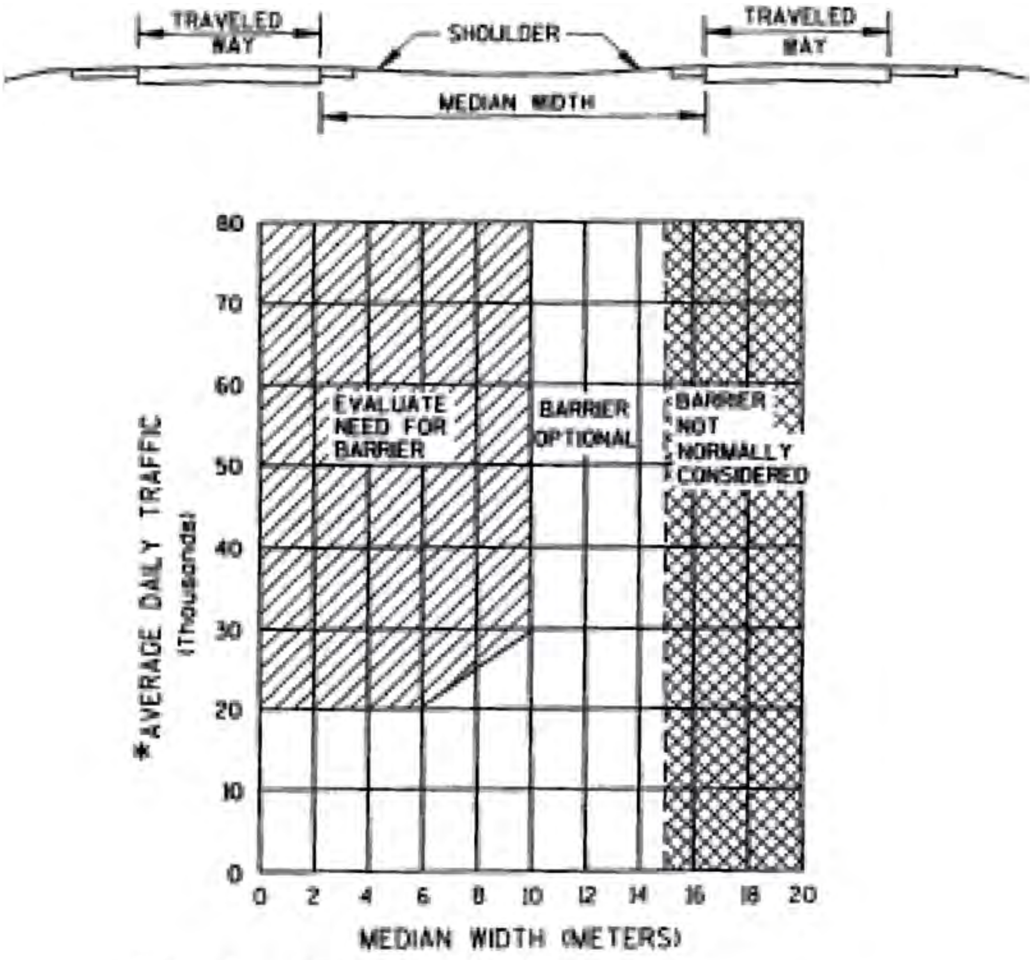
Fig. IV-A-2. Median Barrier Warrants.

Figure 6. 1977 AASHTO Barrier Guide and 1989 Roadside Design Guide median barrier warrants. (AASHTO 1977; AASHTO 1989a)

that the warrant was for freeways and expressways rather than "high-speed, controlled access roadways." (AASHTO 1977; AASHTO 1989a) It was also stated that the guidance was "relatively subjective and does not specifically address the cost-effectiveness issue." It was further noted that guidelines that account for speed, median, slope, vehicle mix, and ADT were under development. (AASHTO 1989a) The 1989 RDG provided factors that would indicate the need to consider higher containment barriers. Specifically, the factors listed include high percentages of heavy vehicles, horizontal curvature, or severe consequences of penetration. (AASHTO 1989a)

Chapter 6 of the AASHTO 1996 RDG addressed median barriers. The 1996 RDG was published using SI units and the two axes of the warrant were flipped. The "optional" portion of the warrant was extended to include all medians with widths between 30 and 50 ft (10 and 15 m) as shown in Figure 7. Additionally, the word "warranted" was changed to "evaluate need for barrier." The warrant continued to apply to "freeways and expressways," as did the 1989 RDG. No changes were made to the language used in the 1989 RDG suggesting factors that would indicate the need to consider higher containment barriers. The ADT portion of the warrant continued to be based on a 5-year projection of traffic. (AASHTO 1989a; AASHTO 1996)

Chapter 6 of the AASHTO 2002 RDG reiterated the 1996 guidance in dual units. No substantive changes were made to the warrant; however, while the 1996 guidelines applied to freeways and expressways, the 2002 guidelines applied to high-speed, fully controlled-access roadways.



* Based on a 5-year projection

Figure 7. 1996 and 2002 AASHTO Roadside Design Guide median barrier warrants. (AASHTO 1996; AASHTO 2002)

The 2002 RDG referenced an ongoing study on median barrier warrants, indicating that changes to the warrant would be forthcoming. (AASHTO 1996; AASHTO 2002) The ongoing study was presumably NCHRP Project 17-14, "Improved Guidelines for Median Safety," which was delayed due to data collection difficulties. When completed, the analysis results were inconclusive. The research effort concluded in 2004, but the results were not incorporated into subsequent editions of the RDG. (Hughes 2004)

3.2.2 Current Guidance

In 2006, AASHTO published an updated Chapter 6 of the RDG. The updated Chapter 6 referenced a 2004 survey of cross-median crashes conducted by the FHWA. The FHWA received responses from 25 states indicating ". . . a significant percentage of fatal cross-median crashes occurring where median widths exceed 10 m [30 ft]. While the survey found that some cross-median crashes occurred in medians in excess of 60 m [200 ft] wide, approximately two-thirds of crashes occurred where the median was less than 15 m [50 ft]." (AASHTO 2006) Unfortunately, the only existing documentation of this survey is a PowerPoint presentation given by Mr. Richard Powers in December 2004 at the Transportation Engineering and Safety Conference held in University Park, Pennsylvania.

The current guidance (i.e., issued in 2006 and reiterated in 2011) for the use of median barriers is shown in Figure 8. These guidelines apply to high-speed, fully controlled-access roadways, as did the 2002 guidelines. Notice that where the guidance was once "evaluate the need for barriers," it is now "barrier recommended." Where barriers were once "optional," barriers are now "considered." "Barrier not normally considered" was changed to "barrier optional." Additionally, the small triangle cutout in the 1996 and 2002 guidelines at 20,000 to 30,000 vehicles per day and 6 to 10 m has been removed. The 2006 guidelines essentially justified barriers for any median less than 50 feet wide at any ADT rate over 20,000 vehicles per day, whereas the 1996 and 2002 guidelines suggested 30 feet wide medians or less at any ADT rate over 20,000 vehicles per day.

There have been two additional subtle changes including highway types and ADT. The 1977, 2002, and 2006 warrants apply to high-speed, controlled-access highways, whereas the 1989 and 1996 warrants applied to freeways and expressways. (AASHTO 1977; AASHTO 1989a; AASHTO 1996; AASHTO 2002; AASHTO 2006) The ADT portion of the warrant has historically been based on a 5-year projection of traffic. This 5-year projection, however, was not carried over to the 2006 RDG. A roadway with a median width of 20 feet that experiences 18,500 vehicles per day with 2% traffic growth per year would fall in the "barrier optional" group according to the 2006 guidance. The same roadway characteristics that "warranted" a barrier according to the 1977 Barrier Guide would have been classified as "evaluate the need" under the 1996 and 2002 guidance.

The barrier test level selection factors first listed in the 1989 RDG and repeated in the 1996 and 2002 versions of the RDG were again repeated in the 2006 RDG. Recall those test level selection

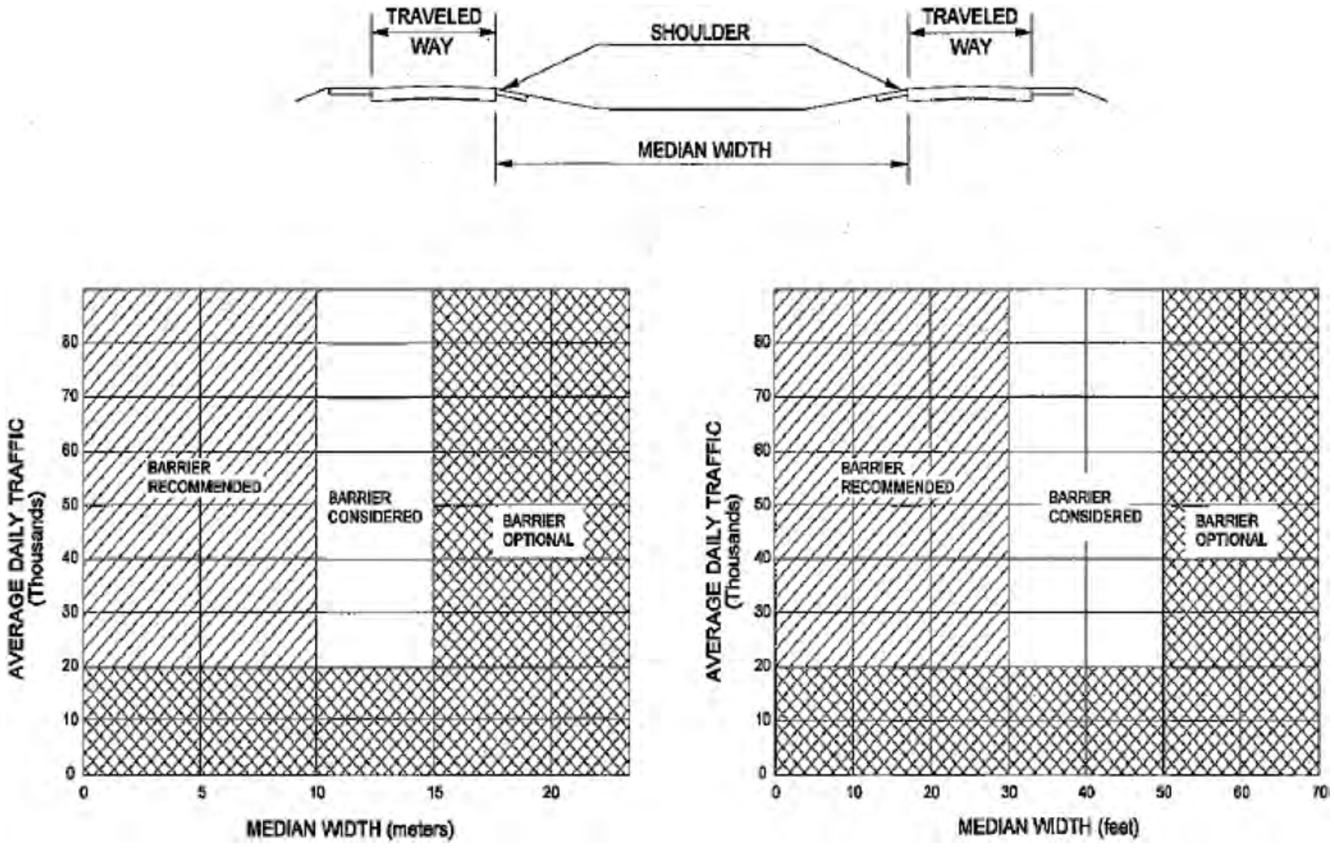


Figure 8. 2006 AASHTO Roadside Design Guide median barrier warrants. (AASHTO 2006)

factors include: high percentages of heavy vehicles, horizontal curvature, or severe consequence of penetration.

Many states adopted the recommendations of the RDG and have incorporated them into their standards. Sometimes, to provide a higher level of safety and address specific local concerns, states adopt policies more stringent than the recommendations in the RDG. The 2006 RDG observed that some states have experienced increases in CMCs and have developed their own guidelines. The following is a summary of some of the state guidelines for the use of median barriers.

3.2.2.1 Arizona. In 1977 the Arizona Department of Transportation (ADOT) published the Manual of Highway Geometric Design that stated that "a barrier is used on any freeway median, or portion thereof, less than 36 feet in width." (ADOT 1977) This general policy was modified in 1996 when median barriers were to be used for rural highways or any controlled-access highway with a median width less than 9 meters (i.e., 30 feet), which conformed to the AASHTO RDG guidance at the time, as shown earlier. Arizona, like several other states, began to re-examine its median barrier warrants in the 1990s in response to the perception of more cross-median crashes. ADOT personnel surveyed numerous states to determine their experience and policy concerning median barriers. After carefully studying the research and experience of other states, ADOT issued a report with new guidance for urban divided highways in 1999. (ADOT 1999) The new median barrier guidelines stated that:

A. "Median barriers will be installed on urban freeway sections having median widths of 50′ and less.
B. Median barriers will be considered for urban freeway sections having median widths of up to 75′ wide when there are three or more through traffic lanes in each direction." (ADOT 1999)

The 1999 guidance was specifically intended for urban roadways. Since 2009 the ADOT guidance has been to use median barriers on urban and rural high-speed, fully controlled-access highways with median widths of 50 ft or less when there are fewer than three lanes in one direction and 75 ft or less when there are three or more lanes in one direction.

The 2012 Arizona Roadway Design Guidelines include guidelines applicable for placement of median barriers with new construction. "Median barrier shall be installed on high-speed fully controlled-access highways having traversable medians under the following conditions:

a) Median widths 50 ft and less.
b) Median widths 75 ft and less when there are three or more through lanes in each direction." (ADOT 2016)

3.2.2.2 California. The 2006 RDG states that "each transportation agency has the flexibility to develop its particular median barrier guidelines." (AASHTO 2006) The RDG further states that for "locations with median widths equal to or greater than 15 m [50 ft], a barrier is not normally considered. The RDG goes on to mention the State of California as an example of a state that developed an accident history-based median barrier warrant, without necessarily endorsing it.

The Caltrans Traffic Manual was published on January 5, 2012, and Chapter 7 addresses the subject of median barriers. Caltrans states "[t]he purpose of median barriers is to reduce the risk of an errant vehicle crossing the median and colliding with opposing traffic." (Caltrans 2012) Caltrans specifically defines a cross-median collision as ". . . one in which an errant vehicle crosses the median of a highway with four or more lanes and strikes, or is struck, by a vehicle from the opposite direction." (Caltrans 2012) Either a collision or volume/width study warrant is suggested to identify locations for study (i.e., this is not a barrier installation warrant but a study warrant).

The collision study warrant applies to freeways, expressways, and conventional highways. The collision study warrant is met if a location with four or more lanes satisfies either of these criteria:

- A location has three or more cross-median collisions of any severity and a total cross-median collision rate of at least 0.5 collisions per mile per year in 5 years, or
- A location has three fatal collisions or more and a fatal cross-median collision rate of at least 0.12 collisions per mile per year in 5 years.

If a highway has two or three lanes, the collision study warrant is met based only on the fatal collision criteria.

Caltrans provides a quantitative definition for each highway type. A brief extract of each definition is shown here to illustrate that these study warrants apply to both divided and undivided highways as well as both controlled- and uncontrolled-access highways.

- "A freeway is defined as a divided arterial highway with full control of access."
- "An expressway is defined as an arterial highway with at least partial control of access, and which may or may not be divided."
- "A multilane conventional highway (two or more lanes in each direction) is defined as a highway without control of access . . . These highways may or may not be divided."
- "Two- and three-lane conventional highways are defined as highways without control of access, and . . . there are at-grade intersections."

Caltrans provides the volume/width study warrant shown in Figure 9, which applies to freeway medians only. "The need for a median barrier should be considered on freeways whenever the volume and median width plot in the gray area." (Caltrans 2012)

When either of these study warrants is met, Caltrans suggests that the location be further studied. "All studies must document the decision to install or not to install a median barrier on the freeway system, and the District Traffic Safety Engineer must approve the decision to install or not install median barrier, and the decision must be documented in the project files." (Caltrans 2012) Notice the Caltrans policy does not mandate the use of a barrier if these crash rates are exceeded; it recommends only that the site be studied for possible installation of a median barrier. As the Caltrans policy explicitly states, these are **study** warrants, not installation warrants. More detailed instructions on how to implement the study warrants are provided in Chapter 7 of the Caltrans Traffic Manual.

Accompanying the study warrants are placement guidelines to be used after the decision to install permanent median barriers has been made. These placement guidelines are shown in Table 3.

3.2.2.3 Connecticut. Chapter 13 of the December 2003 Connecticut Highway Design Manual calls for *NCHRP Report 350* TL3 median barriers on all freeway medians of 66 feet or less regardless of traffic volumes. "On non-freeways, the designer should evaluate the crash history, traffic volumes, travel speeds, median width, alignment, sight distance and construction costs to determine an appropriate median barrier." (CTDOT 2003)

3.2.2.4 Kentucky. Kentucky's "Guidelines for Median Barrier Application on Depressed Medians of Fully Controlled-Access Highways" (Kentucky 2006) dated March 6, 2006, were developed while AASHTO was developing the 2006 RDG with the updated Chapter 6. Kentucky

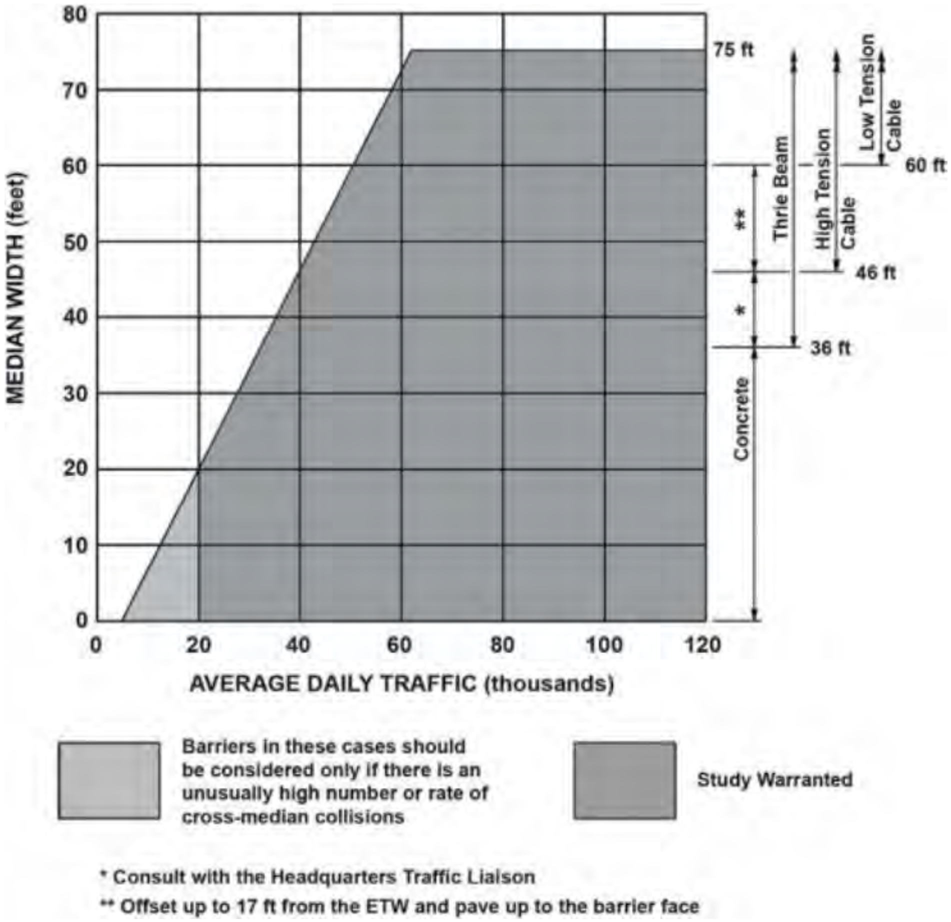


Figure 9. Caltrans freeway median barrier study warrant. (Caltrans 2012)

Table 3. Caltrans median barrier placement guidelines. (Caltrans 2012)

		Median Width			
		Equal to or less than 36 feet (ft)	**Greater than 36 ft to less than 46 ft**	**Equal to 46 ft to less than 60 ft**	**Equal to or Greater than 60 ft**
NO PLANTINGS	**Barrier Type**	Type 60 concrete[1]	Consult HQ Traffic Operations Liaison	Type 60 concrete, Thrie beam or cable[3]	Thrie beam or cable[4]
	Placement	On centerline[2] pave up to face of barrier	Consult HQ Traffic Operations Liaison	Offset up to 17 ft and pave up to it, or on centerline (no paving)	On centerline
PLANTINGS	**Barrier Type**	Type 60 concrete[1]	Type 60 concrete or Thrie beam	Thrie beam	Thrie beam
	Placement	On each side of planting, pave up to the barrier	Consult HQ Traffic Operations Liaison	On each side of plantings, minimum offset 17 ft	On each side of plantings, minimum offset 17 ft

[1] Obtain approval from the Headquarters Traffic Operations Liaison, in consultation with the District Maintenance Engineer for using thrie beam barrier

[2] Except when offset for barrier openings

[3] High tension cable barrier requires approval by the Headquarters Traffic Operations Liaison and Deputy District Directors of Traffic Operations and Maintenance

[4] Low tension cable barrier or high tension cable barrier requires approval by the Headquarters Traffic Operations and Deputy District Directors of Traffic Operations and Maintenance

was aware of the pending 2006 revisions of the RDG. The purpose of the guidelines was to provide ". . . direction to designers, maintenance engineers, and others on the use of crossover protection on depressed medians where the installation of median barrier has not been previously warranted by AASHTO guidance." (Kentucky 2006)

The Kentucky guidelines note that median barrier may be beneficial in cases other than those specified, but specifically, the Kentucky guidance instructs the consideration of median barriers as follows:

- All fully controlled-access highways with traversable, depressed medians up to 30 feet wide;
- Highways with speeds 55 mph or greater, median widths of 30 to 72 feet, and ADT counts exceeding 40,000; or
- For medians of any width or ADT, when at least three CMCs in five years have been observed on the highway section and meeting or exceeding one of these two criteria:
  - CMC rate exceeding 0.50 CMCs per mile per year; or
  - Fatal CMC rate exceeding 0.12 CMCs per mile per year.

The Kentucky guidelines provide designers ". . . wide latitude when selecting the type(s) of barrier and its location within the median." The designers are instructed to ". . . select a median barrier type and location which will reach an optimal balance in minimizing the number and severity of collisions, life-cycle and installation costs, and environmental impacts." (Kentucky 2006)

An update to the Kentucky guidelines was published on April 16, 2008. The change between 2006 and 2008 included an update to the CMC warrant portion of the guidelines such that they would ". . . be more representative of Kentucky crash data. . . ." (Kentucky 2008) The crash warrant portion was updated as follows:

- 0.35 CMCs of any severity per mile per year.
- 0.25 injury or fatal crashes involving CMCs per mile per year.
- 0.20 fatal crashes involving CMCs per mile per year.

3.2.2.5 Maryland. The March 2006 "State Highway Administration Guidelines for Traffic Barrier Placement and End Treatment Design" warrants median barriers along expressways and fully controlled-access highways when the criteria shown in Figure 10 are satisfied. When the criteria are not satisfied, ". . . barrier may be warranted due to accident history or by recommendation of the [State Highway Administration]." (Maryland 2006)

3.2.2.6 New Jersey. The New Jersey Department of Transportation 2015 Roadway Design median barrier warrants are shown in Figure 11. (NJDOT 2015) These warrants apply to high-speed, access-controlled highways with traversable slopes of 10H:1V or flatter. If consultation of the figure indicates a median barrier is warranted, a barrier should only be installed if one of the following conditions are met:

1. 0.50 CMCs per mile per year of any crash severity, or
2. 0.12 fatal CMCs per mile per year.

These study warrants are the same as those used by Caltrans. New Jersey notes that ". . . calculation of conditions 1 and 2 above requires a minimum of three crashes occurring within a five (5) year period." (NJDOT 2015) The gray shaded optional area warrants a median barrier if there has been a history of cross-median crashes. When a median barrier is warranted, the type used is determined using Table 4. Modified thrie beam median barrier is suggested in place of beam guide rail when there are 12% or more trucks, 12,000 vehicles per lane, and other conditions. (NJDOT 2015) New Jersey adds that if the study location is within 1 mile of an interchange, the median barrier may be warranted at lower traffic volumes, as shown in the cross-hatched section of Figure 11.

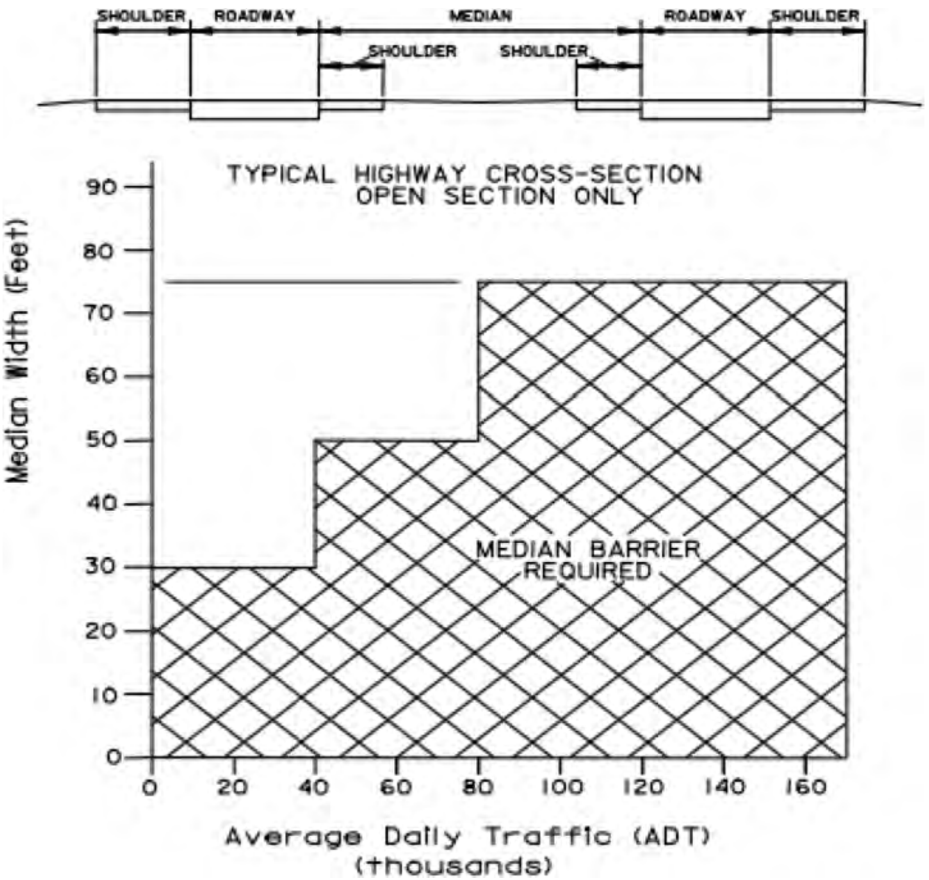


Figure 10. Maryland median barrier warrants. (Maryland 2006)

3.2.2.7 South Dakota. Chapter 10 of the South Dakota Road Design Manual recommends a study to determine whether median barriers are warranted when the criteria shown in Figure 12 are met. The study should include a cost/benefit analysis, a review of crashes, or both. (SDDOT 2016)

3.2.2.8 Texas. Bligh et al. developed median barrier recommendations for the State of Texas in 2006. (Bligh 2006) The guidelines developed by Bligh include both a benefit–cost approach as well as a crash history component. The Texas researchers defined a cross-median crash in the same way it was defined by Caltrans: a vehicle had to completely cross the median and strike another vehicle or be struck by another vehicle in the opposing lanes of travel. The warrants were presented on a volume–width graph, and the graph is divided into four zones as shown in Figure 13.

When implementing the study, TXDOT simplified the results of the research to those shown in Section 8 of Appendix A of the Texas Roadway Design Manual effective October 1, 2014. (TXDOT 2014b) Section 8 addresses the topic of median barriers. Texas considers concrete barriers or high-tension cable barrier systems appropriate median barriers. "The utilization of other median barriers, such as metal beam guard fence, may be appropriate based on the need to protect point obstacles. . . ." (TXDOT 2014b) Texas recommended guidelines are shown in Figure 14. When "Evaluate Need for Barrier" is indicated by the recommended guidelines, the Texas Roadway Design Manual suggests an engineering analysis be performed that considers the following (TXDOT 2014b):

- Type of median (flush, depressed V-ditch or flat-bottom);
- Width of the median;

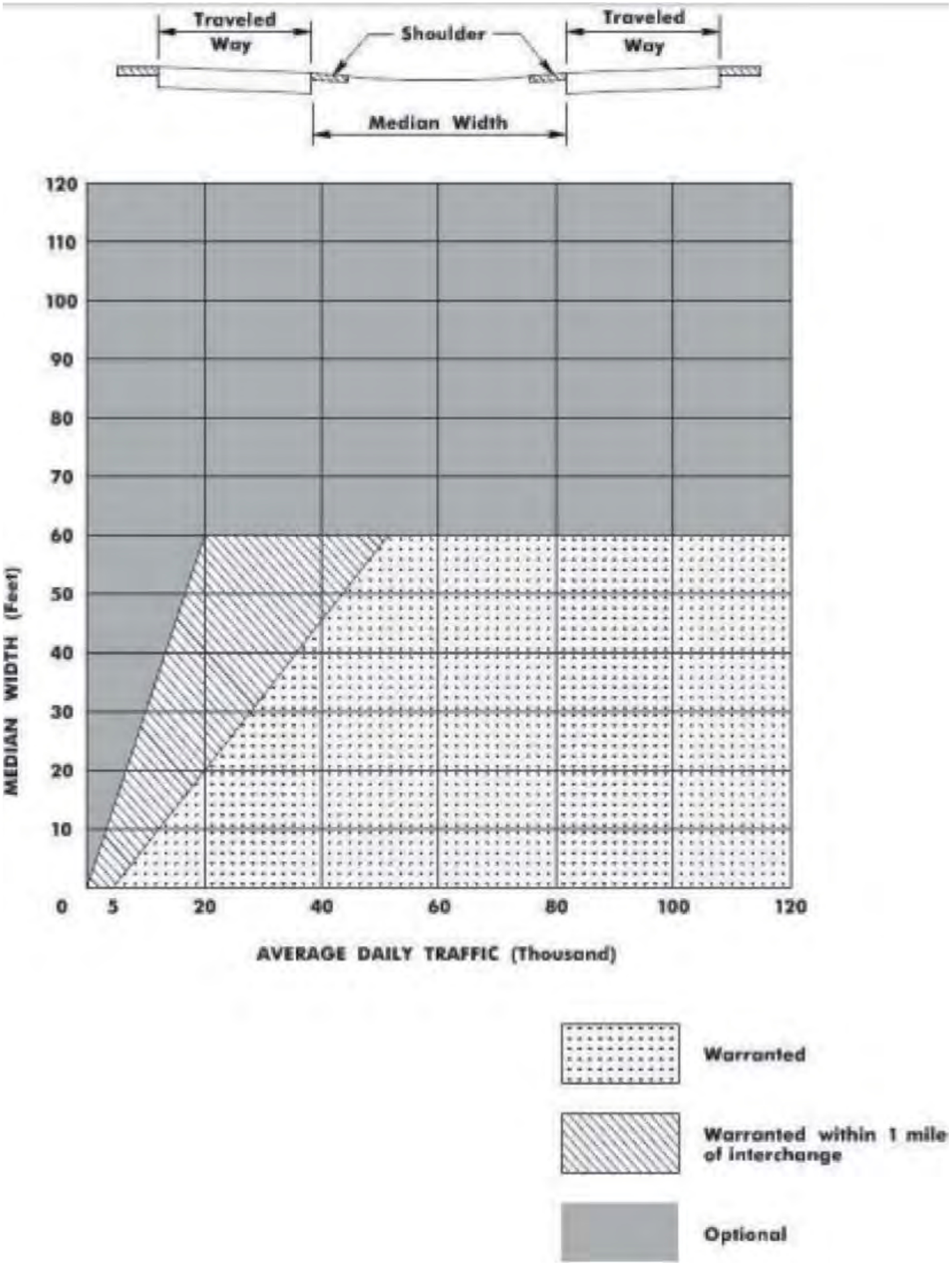
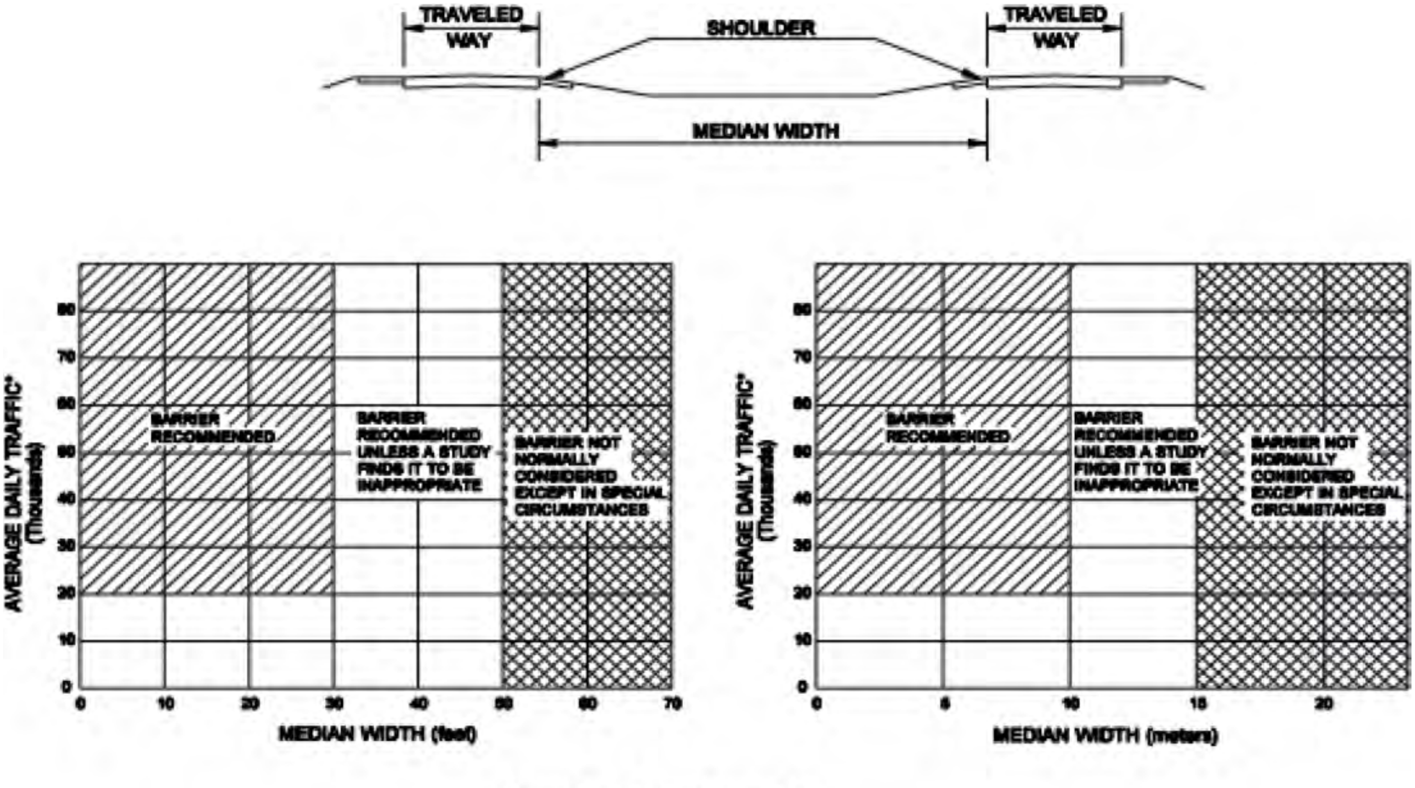


Figure 11. New Jersey warrants for median barrier for freeways and expressways. (NJDOT 2015)

Table 4. New Jersey median barrier type selection guidelines. (NJDOT 2015)

Median Width	Median Barrier Type
Up to 12 feet	Concrete barrier curb (New Jersey-shape)
13 feet to 26 feet	Concrete barrier curb (preferred treatment) or beam guide rail, dual-faced or modified thrie beam, dual-faced
Above 26 feet	Beam guide rail, duel-faced or modified thrie beam, dual-faced



* Based on a 5-year projection

Figure 12. South Dakota median barrier study warrant. (SDDOT 2016)

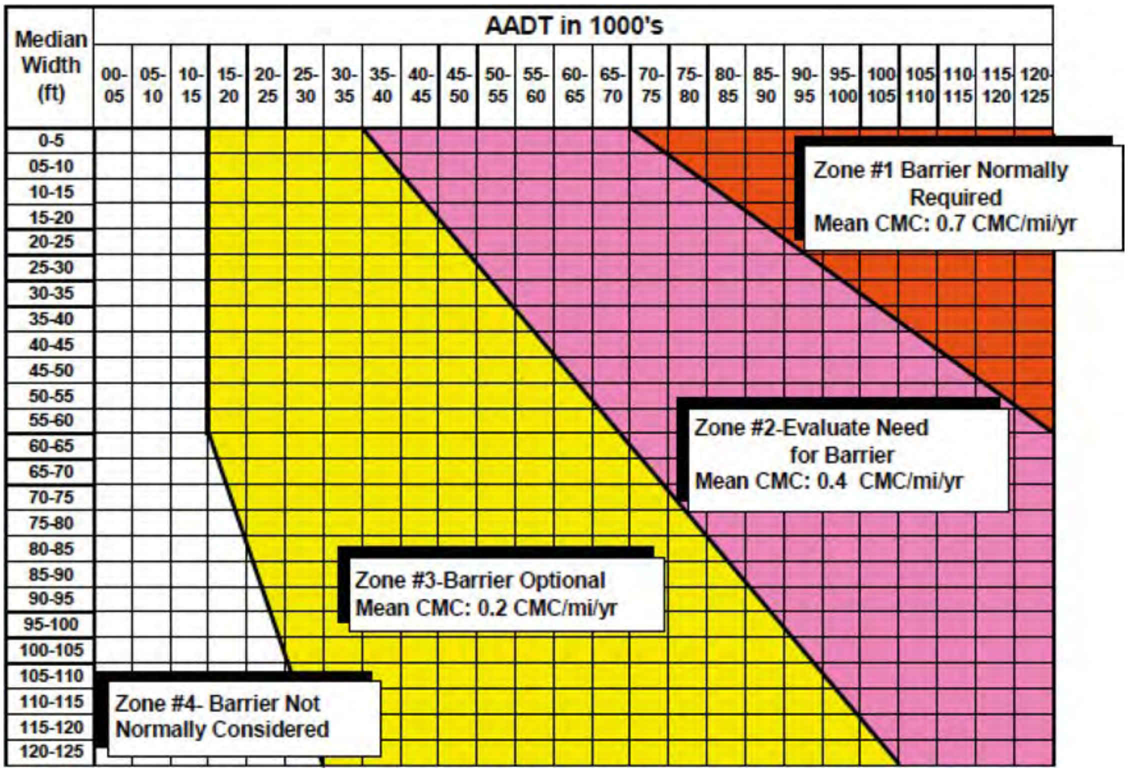


Figure 13. Median barrier warrants developed for TXDOT. (Bligh 2006) AADT, annual average daily traffic.

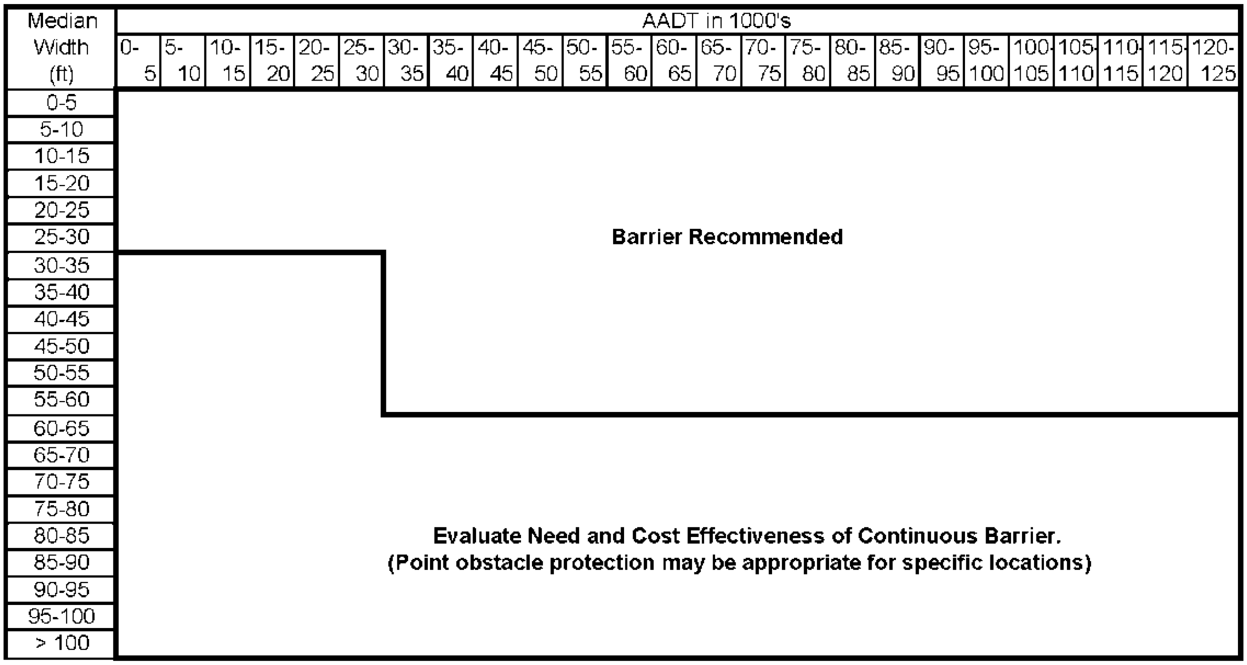


Figure 14. Texas recommended guidelines for installing median barriers on high-speed highways. (TXDOT 2014b)

- Traffic volumes, including estimated traffic growth and percentage of trucks;
- Types and severity of crashes;
- Posted speed limit;
- Type of facility, including controlled-access or non-controlled-access with crossovers;
- Roadway alignment;
- Ramp locations; and
- Elimination of barrier gaps.

3.2.2.9 Washington. Before 2001, the Washington State DOT (WSDOT) median barrier policy essentially followed the AASHTO 1977 Barrier Guide recommendations. (AASHTO 1977) In 2001, the WSDOT *Design Manual* revised its guidance in Chapter 700, Figure 700-7, shown below in Figure 15, such that median barriers were generally warranted at traffic volumes of 20,000 vehicles per day and above when the median was less than 10 m wide. That same year, WSDOT initiated a cost–benefit study to provide guidance on the use of median barriers, particularly cable median barriers, on wider medians. (Olson 2013) That study, in combination with crash test results and pending revisions to the 2006 AASHTO RDG, motivated changes to the 2006 WSDOT Design Manual. (WSDOT 2015)

In response to several dramatic crashes, WSDOT initiated a complete review of their median barrier policy and crash history experience in 2007. The review results are summarized in Figure 16 and are structured quite differently than those of the Caltrans crossover crash history warrant since they are a function of the vehicle miles traveled rather than rate per mile per year. (Olson 2013; WSDOT 2007; WSDOT 2009)

Section 1600.05 of the WSDOT Design Manual now states: "Provide median barrier on full access control multilane highways with median widths of 50 feet or less and posted speeds of 45 mph or higher. Consider median barrier on highways with wider medians or lower posted speeds when there is a history of cross-median crashes." (WSDOT 2015) Median barrier warrants have undergone significant study and updating through the last decade in Washington.

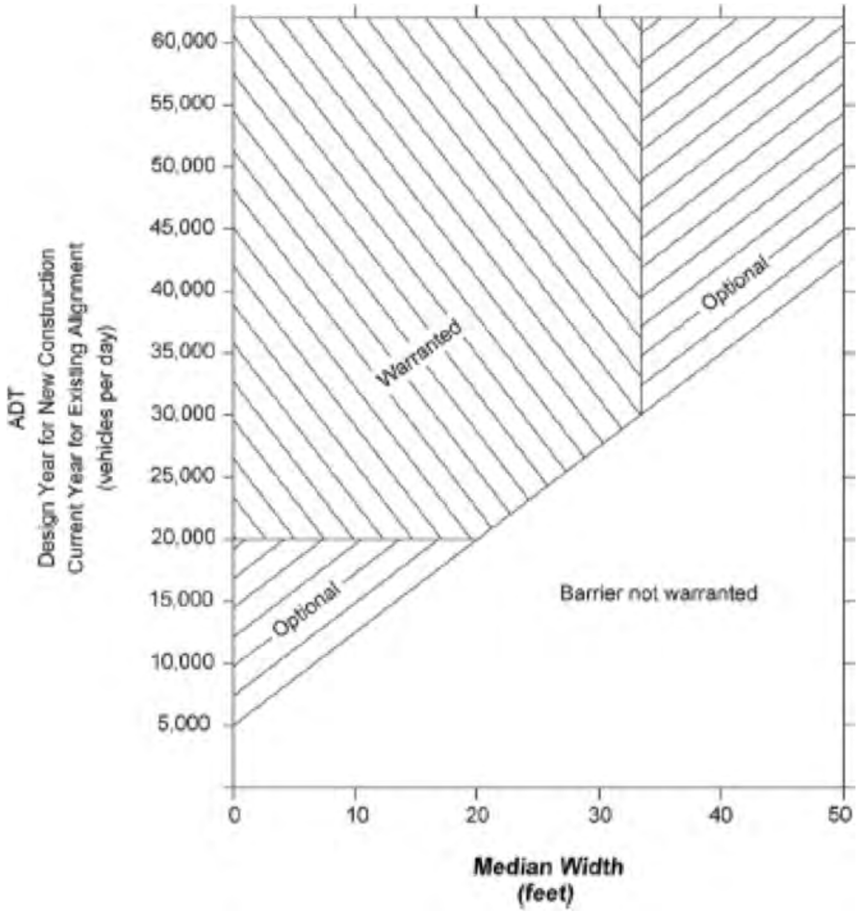
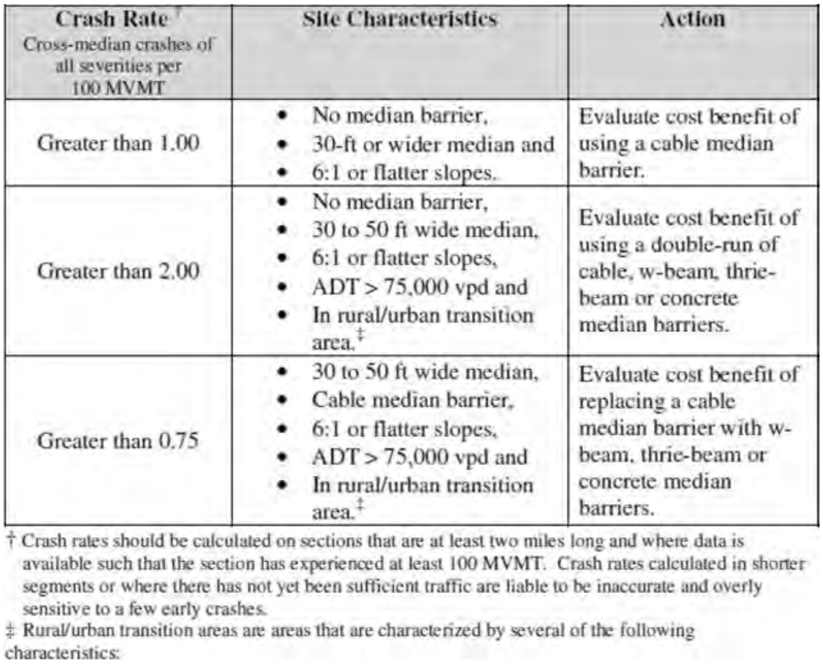


Figure 15. 2001 WSDOT median barrier warrants. (WSDOT 2001)



Crash Rate † Cross-median crashes of all severities per 100 MVMT	Site Characteristics	Action
Greater than 1.00	• No median barrier, • 30-ft or wider median and • 6:1 or flatter slopes.	Evaluate cost benefit of using a cable median barrier.
Greater than 2.00	• No median barrier, • 30 to 50 ft wide median, • 6:1 or flatter slopes, • ADT > 75,000 vpd and • In rural/urban transition area.‡	Evaluate cost benefit of using a double-run of cable, w-beam, thrie-beam or concrete median barriers.
Greater than 0.75	• 30 to 50 ft wide median, • Cable median barrier, • 6:1 or flatter slopes, • ADT > 75,000 vpd and • In rural/urban transition area.‡	Evaluate cost benefit of replacing a cable median barrier with w-beam, thrie-beam or concrete median barriers.

† Crash rates should be calculated on sections that are at least two miles long and where data is available such that the section has experienced at least 100 MVMT. Crash rates calculated in shorter segments or where there has not yet been sufficient traffic are liable to be inaccurate and overly sensitive to a few early crashes.

‡ Rural/urban transition areas are areas that are characterized by several of the following characteristics:

Figure 16. WSDOT median crash history study warrant. (WSDOT 2007)

3.3 Crash Testing Specifications for Median Barriers

NCHRP Report 153: Recommended Procedures for Vehicle Crash Testing of Highway Appurtenances (Bronstad 1974) was published in 1974 to provide uniform barrier testing procedures and criteria. *NCHRP Report 230: Recommended Procedures for the Safety Performance Evaluation of Highway Safety Appurtenances*, (Michie 1981) published in 1981, updated *NCHRP Report 153* and provided more detailed guidelines for performing and evaluating full-scale vehicle crash tests. Neither *NCHRP Report 153* nor *NCHRP Report 230* explicitly included performance or test levels. The so-called minimum crash test matrix included small, medium, and large passenger cars. Supplemental tests for heavier vehicles such as utility buses (i.e., school buses), small and large intercity buses, tractor-trailer trucks, and tanker trailer trucks were included in *NCHRP Report 230*. (Bronstad 1974; Michie 1981)

NCHRP Report 239: Multiple Service-Level Highway Bridge Railing Selection Procedures (Bronstad 1981) included four service levels for bridge railings and attempted to establish the service levels from the capacity of the bridge railings based on the *NCHRP Report 230* supplemental tests. (Bronstad 1981) The AASHTO Guide Specification introduced the concept of multiple performance levels for bridge railings. (AASHTO 1989b) *NCHRP Report 350* was published in 1993 and expanded the concept of performance levels to the other longitudinal barriers, specifying six different test levels (TLs) for roadside hardware. (Ross 1993)

Changes in vehicle fleet characteristics prompted NCHRP Project 22-14(02), "Improved Procedures for Safety-Performance Evaluation of Roadside Features." (Sicking 2008) NCHRP Project 22-14(02) led to the development of the AASHTO *Manual for Assessing Safety Hardware* (MASH), published in 2009. (AASHTO 2009) MASH includes essentially the same TL approach as *NCHRP Report 350* with some changes to vehicle types and impact angles. While *NCHRP Report 350* used a small car, a supplemental small car, and a pickup truck to represent the passenger vehicle fleet (i.e., 820C, 700C, 2000P), MASH eliminated one of the small cars and increased the weight of the remaining small car as well as the weight of the pickup truck (i.e., 1100C and 2270P). The Single Unit Truck (SUT) increased in weight (i.e., 8000S to 10000S). The weight of the tractor van-trailer and tractor tank-trailer did not change between *NCHRP Report 350* and MASH. (FHWA 2009; Ross 1993)

The impact speeds and angles for the length of need (LON) minimum test matrix for longitudinal barriers tested under *NCHRP Report 350* and MASH are shown in Table 5. The changes between *NCHRP Report 350* and MASH are highlighted in a bold-italic font. Notice that the impact speed and angle did not change for the pickup truck, tractor van-trailer, or tractor tank-trailer tests. The impact speed did not change for the small car, but the angle was increased from 20 degrees to 25 degrees to match that of the pickup truck. The impact angle did not change for the SUT, but the speed was increased from 50 mph to 56 mph. (FHWA 2009; Ross 1993) Updates to the MASH longitudinal barrier test matrix for median barriers in a v-ditch were included in the 2016 update to MASH. These updates included crash tests for barriers placed anywhere in the v-ditch and at specific offsets of the v-ditch. An example of the single median barrier placed anywhere in a 4H:1V v-ditch test matrix is shown in Table 6 with placement referenced to the slope breakpoint (SBP)

3.4 Median Barrier Placement

3.4.1 NCHRP Report 711

For *NCHRP Report 711: Guidance for the Selection, Use, and Maintenance of Cable Barrier Systems*, Marzougui et al. performed vehicle dynamics analyses to develop placement guidelines for cable barrier systems where the top cable is 33 inches or higher and the bottom cable is at

Table 5. Recommended longitudinal barrier LON impact speed and angle.

	TL1	TL2	TL3	TL4	TL5	TL6
NCHRP Report 350 **(Ross 1993)**						
Small Car 820C	31 mph/20°	44 mph/20°	62 mph/20°			
Small Car 700C						
Pickup 2000P	31 mph/25°	44 mph/25°	62 mph/25°			
SUT 8000S				50 mph/15°		
Tractor Van-Trailer 36000V					50 mph/15°	
Tractor Tank-Trailer 36000T						50 mph/15°
MASH						
Small Car 1100C	31 mph/***25°***	44 mph/***25°***	62 mph/***25°***			
Pickup Truck 2270P	31 mph/25°	44 mph/25°	62 mph/25°			
SUT 10000S				***56 mph***/15°		
Tractor Van-Trailer 36000V					50 mph/15°	
Tractor Tank-Trailer 36000T						50 mph/15°

NOTE: Content in bold-italic font highlights changes from *NCHRP Report 350* to MASH.

21 inches or lower. Marzougui et al. presented the following general conclusions about cable median barrier placement:

- "Cable barrier systems should not be placed on slopes steeper than 4H:1V (unless the system has been designed for and successfully crash-tested under these conditions).
- Cable barrier systems can be used on 4H:1V or shallower sloped medians or roadsides (6H:1V or shallower sloped medians or roadsides are preferable), provided the placement guidelines listed below are followed." (Marzougui 2012a)

Table 6. Median barrier placed in 4H:1V V-ditch.

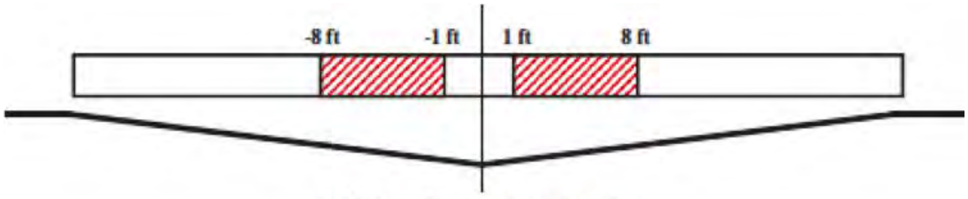
Vehicle Type	Impact Conditions		V-Ditch Width (ft)	Barrier Position	Barrier Location	Critical Impact Point
	Speed (mph)	Angle (deg)				
2270P	62	25	46	Front slope	12 ft from front SBP	1 ft upstream from post
1100C	62	25	46	Front slope	12 ft from front SBP	Midspan location
1100C	62	25	46	Back slope	4 ft from ditch bottom	Midspan location
1100C	62	25	46	Back slope	4 ft from back SBP	Midspan location
1500A	62	25	46	Front slope	Variable	Midspan location
2270P	62	25	46	Back slope	8 ft from back SBP	1 ft upstream from post

A series of placement schematics were included in *NCHRP Report 711* showing shaded areas that should be avoided. The symmetric V-shaped median placement schematics are shown in Figure 17; however, Figure 18 should be used if the slopes of the median exceed 6H:1V. The flat-bottom median schematic is shown in Figure 19; however, Figure 20 should be referenced for median slopes exceeding 6H:1V. For non-symmetrical medians, the authors recommended placing the cable system on the shallower slope and following the placement criteria shown for the appropriate median cross section (e.g., v-ditch, flat-bottom).

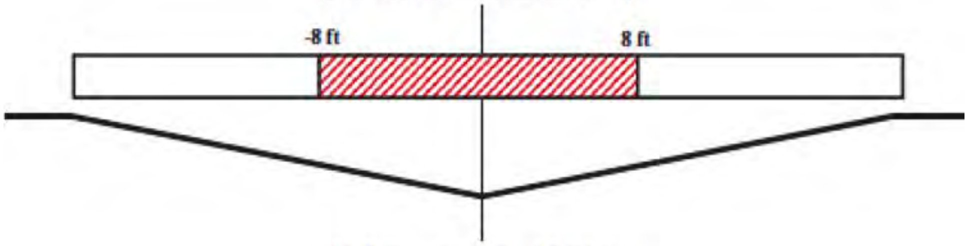
Note that in Figure 17 and Figure 19, the distances are measured from the median centerline out toward the roadway, while in Figure 18 and Figure 20 the distances are measured from the slope breakpoint in toward the median centerline. These placement guidelines were developed to minimize vehicle overrides. It is possible that, for some median widths, the placement guidelines cannot be satisfied, and cable barrier will not be an option when minimizing vehicle overrides is a concern.

3.4.2 NCHRP Project 22-22(02)

The draft final report for NCHRP Project 22-22(02), "Effectiveness of Traffic Barriers on Non-Level Terrain" has been submitted. This draft report provides comprehensive guidelines for the placement of common barriers on median slopes to provide adequate safety performance for impacting vehicles. (Bligh 2020a) The preliminary results of NCHRP Project 22-22(02) were obtained and used in this effort. While the results are not shown explicitly within this report,



(a) Medians shallower than 6H:1V slope



(b) Medians steeper than 6H:1V slope

Figure 17. V-shaped and rounded-bottom medians. (Marzougui 2012a)

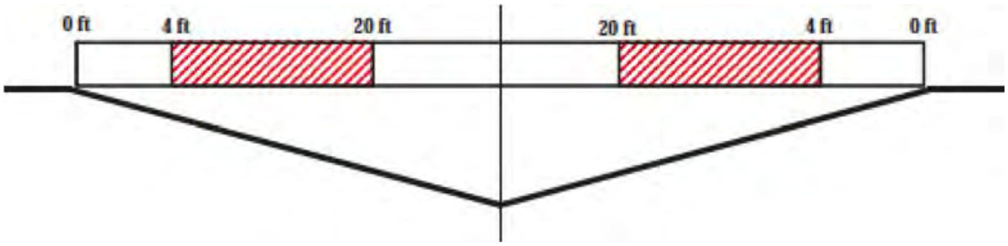
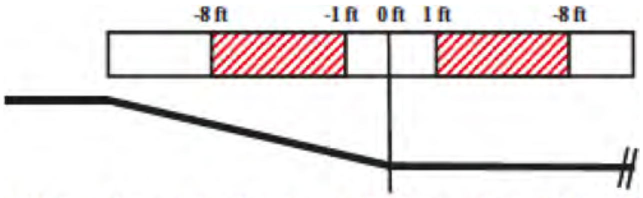
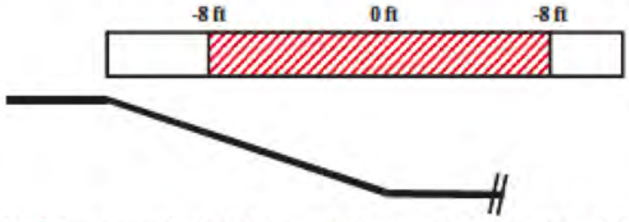


Figure 18. V-shaped medians with slopes steeper than 6H:1V. (Marzougui 2012b)



(a) Medians shallower than 6H:1V slope and flat bottom wider than 2.4 m (8 ft)



(b) Medians steeper than 6H:1V slope or flat bottom width less than 2.4 m (8 ft)

Figure 19. Flat-bottom medians. (Marzougui 2012a; Marzougui 2012b)

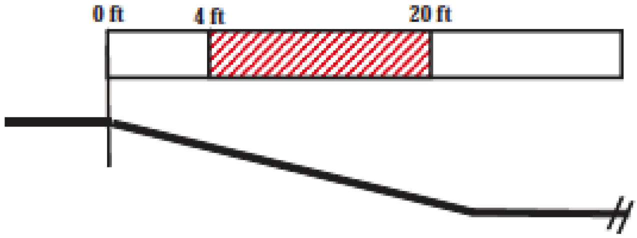


Figure 20. Flat-bottom medians with slopes steeper than 6H:1V. (Marzougui 2012a)

coordination with the NCHRP Project 22-22(02) research team provided the preliminary limits for placement. These results are reflected in the guidance presented herein.

3.5 Run-off-road Crash Modeling

Historically, two methods have been used to model run-off-road (ROR) crashes: crash-based methods and encroachment-based methods. Both methods typically use a regression model with either a crash rate or crash frequency as the dependent variable and highway characteristics such as traffic volume, geometrics, and roadside design as the explanatory variables.

3.5.1 Encroachment-Based Probability Models

The encroachment-based approach models a series of events from when the vehicle "encroaches" onto the roadside through any subsequent events including a crash. This approach allows for accounting for each event and how many vehicles encroach on the roadside as compared with how many events result in a police-reported crash. This approach has been used extensively in roadside safety policy development, in part due to the ability to capture roadside safety successes (i.e., low-severity, non-reported crashes) and the ability to model design alternatives where crash data have not or cannot be collected (e.g., new barrier designs, different roadside alternatives).

The 1977 Barrier Guide presented a hand-calculation encroachment-based method based on work by Glennon. (AASHTO 1977) The 1989 RDG expanded the 1977 Barrier Guide and included a computer program called Roadside based on the encroachment probability model. (AASHTO 1989a) As computer applications became more sophisticated and additional research was performed to refine and improve encroachment models, the Roadside Safety Analysis Program was completed in 2003 and documented in *NCHRP Report 492: Roadside Safety Analysis Program (RSAP)—Engineer's Manual* by Mak and Sicking. (Mak 2003) Additional research on measured vehicle trajectories during encroachments and the replacement of severity indices with the equivalent fatal crash cost ratio (EFCCR), as well as continued advancements in computers, culminated in the third update of RSAP in 2012, RSAPv3. (Ray 2012a) The need to separate and document the risk of a crash from the cost–benefit analysis became apparent during the recent economic downturn when crash costs were still increasing while construction costs were decreasing. This update was incorporated into RSAPv3 under NCHRP Project 22-12(03) such that RSAPv3 can be used to assess both risk and benefit–cost. (Ray 2021)

3.5.1.1 RSAPv3

RSAPv3 is a computer program for modeling encroachment-based ROR crashes and using the results of the modeling effort to evaluate alternative design scenarios through either cost–benefit analysis or risk analysis. The encroachment-based model estimates the frequency and severity of roadside crashes for each particular roadside design alternative.

For example, vehicles will leave the roadway (i.e., encroach) at various speeds, angles, and orientations; vehicles will leave the road at various points along the road segment and the path taken by the vehicle off the road will depend on driver steering and braking input. Not all vehicles that leave the road, however, will strike an object, so there is a probability distribution associated with the likelihood of striking an object once the vehicle leaves the road. Even when a vehicle does strike an object like a median barrier, the severity of the crash can vary from no injuries to multiple fatalities.

Since estimating the frequency and severity of roadside crashes involves several conditional probabilities, the encroachment probability model within RSAPv3 is built on a series of conditional probabilities. The conditional probability model takes this form (Ray 2012a):

$$E(CC)_{\mathrm{N,M}} = \sum \mathrm{ADT} \cdot \mathrm{L_N} \cdot P(Encr) \cdot P(Cr|Encr) \cdot P(Sev_s|Cr) \cdot E(CC_s|Sev_s)$$

where

$E(CC)_{\mathrm{N,M}}$ = Expected annual crash cost on segment N for alternative M.
ADT = Average daily traffic in vehicles/day.
$\mathrm{L_N}$ = Length of segment N in miles.
$P(Encr)$ = The probability a vehicle will encroach on the segment.
$P(Cr|Encr)$ = The probability a crash will occur on the segment given that an encroachment has occurred.
$P(Sev_s|Cr)$ = The probability that a crash of severity *s* occurs given that a crash has occurred.
$E(CC_s|Sev_s)$ = The expected crash cost of a crash of severity *s* in dollars.

First, given an encroachment, the crash prediction module assesses if the encroachment would result in a crash, $P(Cr|Encr)$. If a crash is predicted, the severity prediction module estimates the severity of the crash, $P(Sev|Cr)$. The severity estimate of each crash is calculated using crash cost values, so the output is in units of dollars.

The original version of RSAP estimated the crash costs using a Monte Carlo simulation technique that simulates tens of thousands of encroachments based on a probability distribution of encroachment speed and angle. The probability distribution was calculated using data collected by Cooper in Canada during the late 1970s (i.e., the Cooper data). (Cooper 1980) The frequency and severity of each simulated encroachment are then predicted. Straight-line vehicle trajectories were assumed.

RSAPv3 compares field-collected vehicle paths (i.e., trajectories) that include driver inputs such as braking and steering to the location of roadside features for a possible crash. RSAPv3 proceeds by overlaying field-collected encroachment trajectories on the roadside and examining which trajectories strike objects, the probability of penetration or rolling over the object, and the likely severity of those collisions. The passenger vehicle trajectories used in RSAPv3 were gathered from reconstructed ROR crashes under NCHRP Project 17-22. (Sicking 2009b)

RSAPv3 provides, for the first time, the ability to explicitly examine cross-median crashes using the encroachment probability model. RSAPv3, however, does not model the probability of observing a crash after the errant vehicle has completely traversed the median; rather, a constant probability is assumed. Adding this module to the encroachment probability model was necessary for the development of median barrier guidance under this research effort.

Mathematically, the encroachment probability model used in RSAPv3 is conditional. Therefore, a new condition was added. Given a vehicle has encroached into the opposing traffic lanes, the new model assesses the probability of a head-on collision $P(HCr|OppEncr)$ and the subsequent severity.

3.5.2 Crash-Based Models for Median-Related or Crossover Crashes

Considerable effort has been expended on the development of crash-based models to represent median-related and cross-median crashes. Graham et al. recently summarized the literature on this subject in *NCHRP Report 790: Factors Contributing to Median Encroachments and Cross-Median Crashes*. (Graham 2014) Harwood et al. also summarized the literature in *NCHRP Report 794: Median Cross-Section Design for Rural Divided Highways*. (Harwood 2014) There are research projects nearing completion or recently completed that assembled available crash data on crossover crashes and developed crash-based prediction models from these data. A few of the more germane projects have been highlighted here, including NCHRP Project 17-54, "Consideration of Roadside Features in the Highway Safety Manual." (Carrigan 2018)

3.5.2.1 NCHRP Report 790

The objectives of NCHRP Project 17-44 were to (1) identify design and operational factors and combinations of factors that contribute to the frequency of median encroachments and cross-median crashes and (2) identify potential countermeasures suitable for addressing these contributing factors. The research culminated in the publication of *NCHRP Report 790: Factors Contributing to Median Encroachments and Cross-Median Crashes*. (Harwood 2014)

Hardwood et al. documented extensive literature on both median encroachments and median crashes dating back to Hutchinson and Kennedy's study of median encroachments circa 1962. (Hutchinson 1962) The review also included the data collected by Cooper in 1980 on roadside encroachments in Canada. (Cooper 1980) It is important to note that *NCHRP Report 790* often uses the terms encroachment and crash interchangeably, which could have profound implications since they define two different, though related, events.

Much of the published literature on crash modeling related to medians is, unfortunately, limited to single-vehicle ROR crashes. This assumption has important repercussions. A CMC, by definition, must include multiple vehicles. Recall the cross-median crash definition provided in Section 2. Harwood et al. concluded, after a review of crash data for sites with high frequencies of median-related crashes, "… that 73 percent of median-related crashes began with a single vehicle losing control, while 27 percent resulted from vehicle–vehicle interactions." (Harwood 2014) Neither the review of past efforts summarized in *NCHRP Report 790* nor the past efforts themselves were neglectful, but are simply a reflection of each authors' reliance on older, less detailed crash report coding such as single-vehicle crashes as a surrogate for ROR crashes and a different mindset that only crashes where one vehicle is involved can result in an ROR crash. A review of anecdotal crash reports shows that many median encroachments are initiated by vehicle-to-vehicle interactions like avoidance maneuvers, cutting off vehicles during lane changes, braking due to suddenly backed up traffic, etc. When the data analyses are limited to single-vehicle ROR crashes, crashes that started as multi-vehicle crashes are lost. Many of these multi-vehicle-initiated crashes result in vehicles that leave the road at high angles or while yawing, and these less stable trajectories have important implications on the probability of crossing the median.

Harwood et al. ultimately recommended a slight variation of the forgiving roadside approach long employed by the RDG to improve median safety, specifically:

- "Remove, relocate, or use breakaway design for fixed objects in medians;
- Provide barrier to shield objects in medians;
- Provide wide medians;
- Provide continuous median barrier;
- Flatten median slopes;
- Provide U-shaped (rather than V-shaped) median cross sections; and
- Provide barrier to shield steep slopes in median." (Harwood 2014)

3.5.2.2 NCHRP Report 794

The objective of NCHRP Project 22-21 was to develop improved guidelines for designing typical median cross sections on new and existing rural divided highways, particularly rural freeways. The research included a review of current literature on median design guidelines and a survey of state practices in median design. The survey was a replica of a survey conducted only a few years earlier under *NCHRP Report 790*. The additional research culminated in the publication of *NCHRP Report 794: Median Cross-Section Design for Rural Divided Highways*. (Graham 2014)

Graham et al. documented considerable literature on CMC-based models. Graham et al. developed new crash-based prediction models as part of this study. The crash-based modeling effort showed the performance of traversable medians without longitudinal barriers and non-traversable medians with longitudinal barriers (non-traversable medians without longitudinal barriers were not considered). Crash-based prediction models were developed to represent the following, among other crash types: cross-median crashes (CMCs) and cross-median events (CMEs). The models took this form with the coefficients shown in Table 7:

$$N = e^{b_0 + b_1 lnADT + b_2 MW + b_3 SR}$$

where

N = Predicted crash frequency per mile per year.
ADT = Average daily traffic volume (vehicle per day).
$b_0, \ldots, b_n$ = Regression coefficients determined by model fitting.
MW = Median width (feet).
SR = Slope ratio of the median (i.e., the horizontal component of the median foreslope).

Theoretically, the CMC model divided by the CMC+CME model should approximate the proportion of vehicles that cross the median and are involved in a crash with a vehicle in the

Table 7. Coefficients for CMC and CME models. (Graham 2014)

Model	Highway type	Intercept	ADT	MW	SR
CMC + CME	4-lane freeway	-24.0562	1.9119	0.0000	0.1100
CMC + CME	4-lane non-freeway	-21.7518	2.4317	0.0000	-0.5406
CMC + CME	6-lane freeway	-20.0770	1.5599	-0.0160	0.1810
CMC	4-lane freeway	-29.5036	2.0385	0.0000	0.5523
CMC	4-lane non-freeway	-21.7518	2.4317	0.0000	-0.5406
CMC	6-lane freeway	-23.1034	1.8886	-0.0226	0.1474

opposing lanes as compared with the total number that cross the median. Ideally, the four-lane non-freeway model could be used to develop an encroachment adjustment factor for RSAPv3 because this model most closely resembles the base conditions of the encroachment probability model. Unfortunately, there appears to be a typographical error in the model printed in *NCHRP Report 794*, as both the CMC+CME and CMC models shown are identical. While it is feasible that the difference between the models is small, developing identical models to represent different outcomes from two different data sets is not likely.

3.5.2.3 Texas

Bligh et al. developed crash-based models for medians with and without barriers using Texas crash data from 1998 through 1999. (Bligh 2006) CMCs are not explicitly coded in the Texas crash data; therefore, the analysts searched the data set by vehicle movement and manner of collision to isolate crashes that were apparent CMCs. Using this filtering strategy, models were developed for both CMCs and other median-related crashes. Vehicles that crossed the median but did not have a vehicle-to-vehicle collision were not identified. The authors found the median width, number of lanes, and posted speed limit were significant predictors of a cross-median or median-related crash. The authors also found that ADT was not a significant predictor of crashes for the medians without a barrier; however, ADT was significant for medians with a barrier.

These findings could be explained by unreported encroachments and/or low-severity crashes where vehicles enter the median and recover. As noted by Bligh et al. regarding barrier placement, "[t]he more lateral offset afforded a driver, the better the opportunity for the driver to regain control of the vehicle in the traversable median and avoid a barrier crash." (Bligh 2006)

3.5.2.4 Kansas

Sicking et al. examined 8,233 crashes occurring between 2002 and 2006 that involved a vehicle entering a median on 761 miles of Kansas freeways without median barrier and widths varying from zero to greater than 90 feet. "An accident involving a vehicle traveling completely across the median and entering opposing lanes was identified as a cross-median event (CME). When a CME resulted in a multiple vehicle collision in the opposing travel way, the accident was classified as a cross-median crash (CMC)." The reviewed cases included 525 CMEs and 115 CMCs. The authors concluded that for 60-foot-wide medians, the relationship of median width to CMEs per 100 million vehicle miles (MVM) is more or less constant at 2.2 CME per 100 MVM for a single-direction traffic volume. The authors found that CMCs per 100 MVM is $6.26 \times 10^{-5} \times$ single-direction ADT. (Sicking 2009a)

3.5.2.5 NCHRP Project 17-54

Carrigan and Ray developed, under NCHRP Project 17-54, crash-based models to represent ROR crash frequency for divided and undivided roadways by the edge. This crash-based modeling effort also developed encroachment adjustment factors for both curves and grades to be used in the encroachment probability model to represent the influence of the variety of horizontal curves or vertical grades on encroachment frequency. These models can be used to represent how many vehicles enter the median and subsequently have a crash on divided roadways and how many vehicles cross the centerline of an undivided roadway and crash on the opposite edge of the roadway. Unfortunately, this effort did not include specifically capturing how many vehicles engaged in a cross-median or head-on collision. (Carrigan 2015b) This large modeling effort can be used to develop encroachment adjustment factors for use with the encroachment probability model. It is common to use crash-based modeling to develop encroachment adjustment factors due to the availability of crash data and the lack of new encroachment data.

3.6 Summary

Guidelines for installing barriers in the median first appeared in 1964. Changes to the warranting of the barrier based on width and traffic volumes have been accompanied by an evolution in the language used to describe the different regions of each successive warrant (e.g., optional, considered). Subtle changes have occurred to the traffic volumes used and the applicable highway types. Some states adopted the AASHTO guidance directly, but some states have adopted more stringent guidance including "study warrants" based on crash data. There is a good deal of national variety in median barrier warranting that should be considered as this research progresses.

The NTSB recommendations to AASHTO and FHWA, following investigations of MRE, can be summarized as:

- Define CMCs.
- Identify the factors affecting the probability of CMCs.
- Establish warrants for median barrier selection that include consideration of heavy vehicles.
- Identify CMC rates that call for special consideration when selecting median barriers.

The literature review provided some insights into the factors affecting the probability of CMCs. Median width, median slope, the presence and placement of barriers, and highway geometrics were found to be significant predictors of MREs. (Bligh 2006; Carrigan 2015a; Graham 2014; Harwood 2014) Many studies have found, however, that traffic volume is not a significant predictor of MREs. (Bligh 2006; Sicking 2009a) Despite the long-held tradition of relying upon traffic volume when warranting median barriers, there is a well-recognized complicated relationship between encroachment probability and traffic volume. While much-needed new research is underway to gather new encroachment data, this research will rely upon available research, including the Cooper encroachment data. (Cooper 1980; Gabauer, forthcoming-b)

There is a great variety of past and existing national and regional guidance for median barriers. There is detailed available literature on both barrier crash testing and in-field evaluations of median performance. The past and present median barrier guidance, the performance of medians and median barriers in the field and the crash testing laboratory, and the detailed NTSB investigations of individual crashes will be valuable contributions toward the success of this research.

CHAPTER 4

Methodology

The statement of work for this research called for using both a risk-based and benefit–cost-based approach in the development of the guidelines. In the very short period since this work commenced, two separate but influential research efforts were completed that caused a shift in the approach to both geometric and roadside design. *NCHRP Report 785: Performance-Based Analysis of Geometric Design* established a performance-based framework for highway designers to use in the geometric design of highways. (Ray 2014) At about the same time, NCHRP Project 15-65, "Development of Safety Performance Based Guidelines for the Roadside Design Guide," developed performance-based roadside safety guidance to support quantitative design decisions and promote consistency in interpretation and implementation using a risk-based methodology. (Ray, forthcoming) While NCHRP Project 15-65 has a broader objective to develop quantitative design decisions for the entire RDG, this effort is focused on median barriers (i.e., double-faced) and was extended to include roadside barriers (i.e., single-faced barriers). Ultimately, NCHRP Project 15-65 will result in a framework that all RDG guidance can adopt. The guidelines proposed herein have adopted that risk-based methodological framework to coordinate and be consistent with the NCHRP Project 15-65 methodology. This early adoption will result in the products of this research being more easily integrated into the pending update to the RDG.

Ray et al. proposed a governing equation to represent the sequence of ROR events and sub-events to develop roadside designs that minimize the OUTCOME (e.g., risk, cost) of a crash, as shown below in Equation 1:(Ray, forthcoming)

$$\text{OUTCOME}_S = [\text{Number of Encroachments}] \cdot [\text{Prob. Interacting} | \text{Encr}] \cdot [\text{Prob. of KA} | \text{Interaction}]$$

$$\text{OUTCOME}_j = \left[\frac{\text{BEF}_S \cdot \text{EAF}_S \cdot \text{L}_S}{5280}\right] \cdot \left[\text{P}_{cj} \cdot \text{P}_{\text{SEV}_j} \cdot (1 - \text{THR}_j \cdot \delta_j)\left(\frac{\text{PSL}_s^3}{65^3}\right)\right] \prod_{i=1}^{j-1} \text{THR}_i \qquad 1$$

where

OUTCOME_S = The total number of crashes with the specified outcome on the segment involving all features on the segment.
OUTCOME_j = The number of crashes with the specified outcome involving feature j (e.g., the number of serious injury or fatal crashes involving impacts with a tree) per edge mile per year.
j = Feature number from 1 to n where n is the total number of features evaluated on the segment.
BEF_S = The expected annual number of encroachments on a segment in edge encroachments/mi/yr assuming base conditions as a function of traffic volume (AADT).

EAF_S = Highway and traffic characteristic encroachment adjustment factors for the highway segment of interest.

L_S = Segment length in miles.

P_{cj} = The conditional probability of a vehicle striking an object given an encroachment occurs. The length ratios are the probability of leaving the roadway in the given proportion of the roadway under the assumption that encroachments are equally likely anywhere on the segment. The form of P_{cj} depends on the type of object, as shown below:

Continuous Features (e.g., guardrails, median barriers, terrain)

Discrete Features (e.g., trees, poles, bridge piers, water bodies)

P_{SEV_j} = The conditional probability of observing the severity of interest given that there is an interaction with roadside feature j.

THR_j = The conditional probability of passing through feature j given the vehicle interacts with feature j.

δ_j = $\delta = 1$ if all interactions with the feature do not lead to an increase in harm (e.g., terrain).

$\delta = 0$ if all interactions with the feature lead to an increase in harm (e.g., longitudinal barrier).

PSL_s = The posted speed limit on the segment in mi/hr.

L_j = The effective length of an individual feature j along the segment in feet. (See Figure 21.)

Continuous Features (e.g., longitudinal barriers, terrain, medians)
The length of a continuous feature is measured parallel to the roadway.

Single Discrete Features
For single discrete features such as trees or utility poles, this is equal to the diameter of the feature. For rectangular features, this is the length parallel to the roadway. Add $V_W \sin(\theta_{85})$ to the length or diameter.

Multiple Discrete Features
For features like a line of poles or series of bridge piers, the effective length is the length in feet from the upstream traffic face of the first feature to the

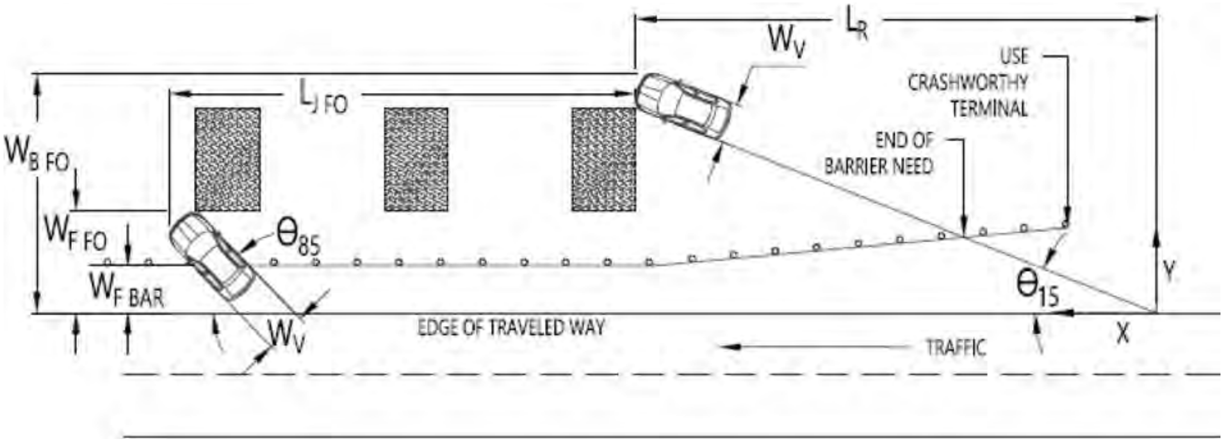


Figure 21. Roadside geometry of discrete features and continuous shielding features. (Ray 2021, forthcoming)

downstream face of the last feature plus $V_W \sin(\theta_{85})$ as long as the spacing between features is less than $W_B/\tan\theta_{15}$. If the spacing between features is greater than $W_B/\tan\theta_{15}$ then treat the individual feature as a single isolated feature.

P_{yj} = The cumulative probability density function of the lateral extent of encroachment when lateral offset y = Y.

$P_x(X_j)$ = Sum of the cumulative probability density function of the maximum longitudinal extent of encroachment.

W_{Bj} = The distance in feet from the edge of the traveled way measured laterally to the farthest point of feature j plus $V_W \cos(\theta_{15})$.

W_{Fj} = The distance in feet from the edge of the traveled way to the closest face (i.e., traffic side) of feature j. For foreslopes, the distance is measured to the bottom of the foreslope.

L_{TMax} = The length in ft of the longest trajectory in the database of trajectories used to calculate $P_x(X_j)$ and P_{yj} (i.e., 1,000 ft).

V_w = Typical passenger vehicle width in feet (e.g., 6.5 ft).

θ_{15} = The 15th percentile encroachment angle in degrees (e.g., 5 degrees (Gabler, forthcoming-a)).

θ_{85} = The 85th percentile encroachment angle in degrees (e.g., 22 degrees (Gabler, forthcoming-a)).

More details on the derivation of Equation 1 can be found in the NCHRP Project 15-65 final report. (Ray, forthcoming) For terrain features such as slopes, the area of concern is generally the entire length of the segment. Similarly, the area of concern when assessing the need for median barriers is also the entire length of the segment. Conversely, fixed objects such as trees, poles, or bridge piers are not equal to the length of the segment because striking the fixed object is only a concern in the portion of the segment where the fixed objects are located.

The guidelines developed in this research use a relative-risk approach: The risk of a fatal or serious injury crash with the roadside feature shielded by a roadside or median barrier is divided by the risk of a fatal or serious injury crash with the unshielded feature. For example, the risk of a median crossover crash with a median barrier installed is divided by the risk when no median barrier is installed.

$$RR_{SHIELDED/UNSHIELDED} = \frac{OUTCOME_{SHIELDED}}{OUTCOME_{UNSHIELDED}} \qquad 2$$

Referring to Equation 1, using the relative risk simplifies the process since the BEF_s, $EAF_{s,}$ and L_s all cancel out when the same road segment is being evaluated in the numerator and the denominator. Guidelines for median barrier need and the need for shielding fixed objects and terrain in the median are all developed using this relative risk approach.

This research included the conduct of and assemblage of the underlying research and subsequent development of many of the variables that comprise the governing equation proposed by Ray et al. under NCHRP Project 15-65. Restated, fundamental components of the governing equation proposed by Ray et al. were developed under this effort and are therefore presented in this final report.

The background and new research conducted to develop and assemble each of these variables for the selection and placement of MASH double-faced barriers within the median and MASH single-faced barriers within the median or on the roadside are discussed in this section. Each heading represents a variable of the governing equation that will be used for MASH median and roadside barrier selection and placement guideline development.

Detailed statistical modeling is provided, when necessary, in the appendices to support these variable summaries, as outlined below.

4.1 Probability of Reaching the Lateral Offset of Feature j—$P_Y(Y_j)$

NCHRP Project 15-65 defines "$P_Y(Y_j)$" as the "cumulative probability density function of the lateral extent of encroachment when lateral offset y = Y." (Ray, forthcoming) Further, W_{Bj} is "the distance in feet from the edge of the traveled way measured laterally to the farthest point of feature . . ." and W_{Fj} is "the distance in feet from the edge of the traveled way to the closest face of feature j." Considerable effort was expended to obtain and model the maximum lateral extent of passenger vehicles on median and roadside terrain for this research project. Details of this modeling effort are documented in Probability of Reaching the Lateral Offset of Feature j—$P_Y(Y_j)$.

The NTSB recommendations to AASHTO and the FHWA regarding median barrier selection and placement guidelines explicitly target heavy vehicles. Little is directly known about heavy vehicle trajectories. Ideally, heavy vehicle trajectory data would have been gathered, however, that endeavor would be extremely costly and was outside the scope of this research. The model developed for passenger vehicles was used for heavy vehicles. It is believed this approach, while not ideal, is conservative.

Trajectory simulations obtained from the recently completed NCHRP Project 17-55 in combination with the encroachment conditions determined in NCHRP Project 17-43 were used to develop the probability distribution for the lateral extent of encroachment, $P_Y(Y_j)$. (Gabler, forthcoming; Sheikh 2019) There is ongoing research to model ditches under NCHRP Project 16-05, "Guidelines for Cost-Effective Safety Treatments of Roadside Ditches" that could be used to further extend this research. (Sheikh 2021)

Probability of Reaching the Lateral Offset of Feature j—$P_Y(Y_j)$ also addresses how to integrate the results of the NCHRP Project 16-05 research into these guidelines.

A summary of the maximum lateral extent (i.e., $P_Y(Y_j)$) used in these guidelines is shown in Figure 22. Details about the development of this figure, the data and the statistical method used, and background are provided in Probability of Reaching the Lateral Offset of Feature j—$P_Y(Y_j)$.

4.2 Probability of Crash Severity (P_{SEV_j})

NCHRP Project 15-65 defines P_{SEV_j} as "the conditional probability of observing the severity of interest given that there is an interaction with roadside feature j." (Ray, forthcoming)The outcome of interest, when considering the median design and the possible need for installing a median barrier or a roadside barrier, includes barrier type, terrain features, fixed objects, and other roadway users (i.e., vehicle occupants in the opposing lanes in a CMC). Many different sources of crash data were used to develop these relationships for various longitudinal barriers, rolling over on the terrain, fixed objects, and CMCs. These data sources and the analysis of the data are documented in PROBABILITY OF CRASH SEVERITY (P_{SEV_J}). The outcome of interest for guidelines development is shown in Table 8.

Y_j (ft)	$P_Y(Y_j)$
0	1.0000
1	0.9761
2	0.9431
3	0.9090
4	0.8844
5	0.8650
10	0.7737
15	0.7191
20	0.6741
25	0.6238
26	0.6120
27	0.6014
28	0.5908
29	0.5815
30	0.5699
35	0.5082
40	0.4603
45	0.4063
50	0.3622
55	0.3254
60	0.2887
65	0.2531
70	0.2307
75	0.2115
80	0.1918
85	0.1752
90	0.1624
95	0.1515
100	0.1416

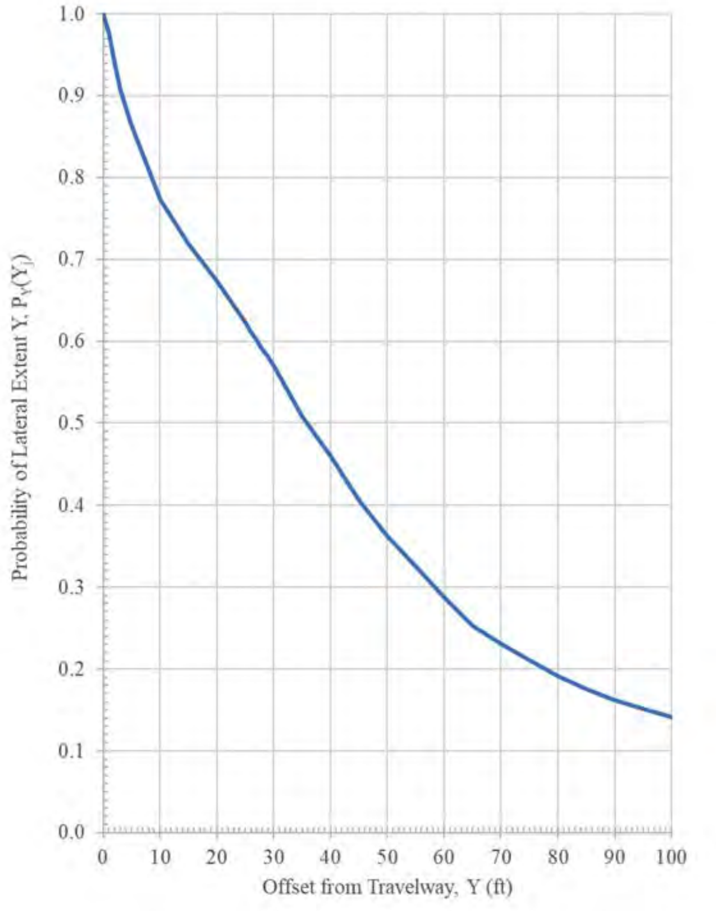


Figure 22. Probability of an encroachment reaching a feature offset Y, $P_Y(Y_j)$.

Table 8. Outcomes for selected roadside and median features (P_{SEV_j}).

Feature	K_{65}	KA_{65}	KAB_{65}	$KABC_{65}$
Longitudinal Barriers				
Cable Barrier	0.0009	0.0050	0.0297	0.0849
Metal-Beam Barrier	0.0013	0.0084	0.0369	0.0895
Concrete Barrier	0.0021	0.0159	0.0810	0.1667
Fixed Objects and Rollover	0.0142	0.0589	0.3138	0.4836
Enter Opposing Lanes	0.0098	0.0451	0.1290	0.1938

4.3 Probability of Passing Through a Feature (THR_j)

THR_j is "the conditional probability of passing through feature j given the vehicle interacts with feature j." (Ray, forthcoming) For example, a vehicle may travel on a median slope, interact with and penetrate a median barrier, and enter the opposing lanes where it may be struck by another vehicle. The proportion that passes through for each category of roadside feature (i.e., the first slope and the median barrier) is dependent on characteristics unique to the specific type of feature. This effort derived values for THR_j across a wide range of features including various barriers, terrain, crossing into opposing lanes, and fixed objects. The background information and derivation of each of these groups are discussed below.

4.3.1 Probability of Passing Through, Under, or Over a Barrier (THR_{BAR})

Vehicle type, barrier material (e.g., cable, metal beam, and concrete) and TL, and barrier placement were evaluated as explanatory variables for THR_{BAR}. Both mechanistic and crash-data-based empirical calculations were employed to model THR_{BAR} due to a lack of empirical data. The objective of the modeling effort was to represent the probability of getting through various barrier types, materials, and TLs (i.e., penetration, rolling over the barrier, vaulting the barrier). It was found that there is not a significant difference between barrier material within a particular TL group. It was further found that while area type (i.e., urban or rural) does influence the mix of the traffic, it does not have a significant influence on the value of THR_{BAR}. It is recommended, therefore, that the values for THR_{BAR} are a function only of barrier TL and PT.

Probability of Passing Through, Over, or Under a Barrier (THR_{BAR}) provides details on the modeling effort. It should be recognized that there are no assurances that all crashes of any type will be contained or not be contained. Table 9 shows values of THR_{BAR} with consideration of traffic mix where PT is expressed as a number, not a decimal.

Table 9. Values for THR_{BAR} for guideline development.

Test Level	THR_{BAR}
2	PT/100
3	PT/100
4	0.75PT/100
5	0

4.3.2 Probability of Passing Through a Terrain Feature ($THR_{TERRAIN}$)

For terrain features like foreslope, backslope, and ditch bottom, the proportion of vehicles that pass through the feature is determined by predicting the proportions of rollover crashes that occur between when the encroachment enters the slope and departs the slope. $THR_{TERRAIN}$, for example, is the proportion of vehicles that travel across the slope feature without rolling over, stopping, or returning to the roadway.

Recall the maximum lateral extent of passenger vehicles on median and roadside terrain was modeled during this research effort, which included the competing risk of rolling over on the terrain. This modeling effort, including the competing risk of rolling over, is documented in Probability of Reaching the Lateral Offset of Feature j—$P_Y(Y_j)$. The proportion of vehicles that rolled over on the slope is not included in THR. The probability of rollover (i.e., do not pass THR) was modeled. Table 10 shows values of $THR_{TERRAIN}$, which are one minus the proportion rolling over on each type of foreslope. Tables like this are needed for backslopes and ditch type and width but have not yet been developed. The study of ditches is underway in NCHRP Project 16-05, "Guidelines for Cost-Effective Safety Treatments of Roadside Ditches." (Sheikh 2021) When implementing these findings, it is recommended that slopes of flatter than −10:1 use the −10:1 finding.

4.3.3 Probability of Passing Across the Opposing Lanes (THR_{EOL})

A model that considered lane volume in vehicles per day was developed to represent the probability of passing across opposing lanes for these guidelines. The model development and

Table 10. Encroachments passing all the way through terrain ($THR_{TERRAIN}$).

Survived the Terrain					
Lateral Extent	**$THR_{TERRAIN}$**				
ft	–10:1 or flatter	–6:1	–4:1	–3:1	–2:1
0	1.0000	1.0000	1.0000	1.0000	1.0000
1	1.0000	1.0000	1.0000	1.0000	1.0000
2	1.0000	1.0000	1.0000	1.0000	1.0000
3	1.0000	1.0000	1.0000	1.0000	1.0000
4	1.0000	1.0000	1.0000	1.0000	1.0000
5	1.0000	1.0000	1.0000	1.0000	1.0000
10	1.0000	1.0000	1.0000	1.0000	0.9995
15	0.9992	0.9993	0.9998	0.9997	0.9985
20	0.9963	0.9962	0.9957	0.9966	0.9948
25	0.9921	0.9911	0.9885	0.9887	0.9835
26	0.9900	0.9896	0.9867	0.9869	0.9802
27	0.9892	0.9887	0.9851	0.9840	0.9762
28	0.9890	0.9876	0.9847	0.9815	0.9736
29	0.9884	0.9867	0.9831	0.9803	0.9696
30	0.9876	0.9851	0.9811	0.9782	0.9659
35	0.9804	0.9784	0.9712	0.9643	0.9356
40	0.9755	0.9731	0.9640	0.9516	0.9092
45	0.9687	0.9639	0.9557	0.9381	0.8813
50	0.9638	0.9567	0.9446	0.9252	0.8577
55	0.9579	0.9507	0.9382	0.9139	0.8320
60	0.9543	0.9451	0.9298	0.9018	0.8073
65	0.9487	0.9384	0.9181	0.8852	0.7832
70	0.9428	0.9330	0.9113	0.8757	0.7670
75	0.9416	0.9296	0.9058	0.8638	0.7514
80	0.9393	0.9264	0.8976	0.8550	0.7392
85	0.9340	0.9227	0.8903	0.8453	0.7267
90	0.9307	0.9168	0.8846	0.8377	0.7186
95	0.9295	0.9139	0.8805	0.8323	0.7068
100	0.9266	0.9104	0.8756	0.8275	0.7001

analysis of the simulated data are documented in Appendix E Probability of Passing Across the Opposing Lanes (THREOL).

The opposing lanes of traffic are another median-related feature with which vehicles may interact. In this case, the probability of passing through the feature (i.e., getting across the opposing lanes without striking another vehicle) is a function of the traffic volume in the opposing lanes. If there is little traffic, a vehicle that enters the opposing lanes is unlikely to interact with another vehicle whereas if there is a high volume, it is more likely a vehicle will be present that the encroaching vehicle may strike.

A CMC model has long been a missing part of the encroachment probability model for modeling CMCs. This effort provided valuable insight into the probability of these events.

The proportions of the vehicles passing through, rather than having a crash (i.e., THR_{EOL}), are shown in Table 11 as a function of lane volume and land use. These values have been tabulated by lane volume in vehicles per day in the opposing lane adjacent to the median. If the lane volume is not known, the bi-directional AADT may be divided by the total number of lanes.

Table 11. Proportion of vehicles passing across the opposing lanes without striking an opposing vehicle when the vehicle enters the opposing lanes (THR_{EOL}).

Lane Volume (veh/day)	THR_{EOL} Rural	THR_{EOL} Urban	Lane Volume (veh/day)	THR_{EOL} Rural	THR_{EOL} Urban
500	0.8861	0.9254	12,000	0.7859	0.7971
1,000	0.8893	0.9214	13,000	0.7693	0.7793
2,000	0.8878	0.9137	14,000	0.7513	0.7600
3,000	0.8830	0.9056	15,000	0.7318	0.7391
4,000	0.8765	0.8970	16,000	0.7106	0.7163
5,000	0.8689	0.8877	17,000	0.6876	0.6916
6,000	0.8602	0.8777	18,000	0.6626	0.6648
7,000	0.8504	0.8669	19,000	0.6356	0.6356
8,000	0.8397	0.8551	19,500	0.6212	0.6201
8,500	0.8340	0.8488	20,000	0.6062	0.6039
9,000	0.8280	0.8423	21,000	0.5744	0.5695
10,000	0.8151	0.8285	22,000	0.5400	0.5321
11,000	0.8011	0.8134	≥23,000	0.5026	0.4914

CHAPTER 5

Guidelines

5.1 Median Barrier Guidelines

The main reason for using a median barrier is to minimize the chance of a vehicle fully crossing the median and striking or being struck by a vehicle in the opposing lanes of traffic. Likewise, median barriers are only considered for medians where roadside barriers are not needed for clear-zone reasons (e.g., shielding is not needed for either fixed objects or terrain features). When there are fixed objects or terrain features within the median, the single-faced barrier shielding guidelines should be considered.

A median barrier should only be installed if it reduces the expected number of fatal and serious injury (KA) crashes on the segment. The 1967 Yellow Book explicitly states that guardrail and median barriers "should only be used where the result of striking the object or leaving the roadway would be more severe than the consequences of striking the rail." (AASHO 1967, 29) In other words, the number of KA median barrier crashes and KA CMCs in a median with a median barrier installed must be less than the number of KA CMCs on the same median segment where no median barrier is installed. Applying the condition that a median barrier should only be installed if it reduces the number of KA crashes on the segment results in the following inequality:

$$\mathrm{OUTCOME}_{\mathrm{CMC}} \geq \mathrm{OUTCOME}_{\mathrm{BAR+CMC}}$$

The right side of this relationship accounts for those vehicles that interact with the barrier and are contained or redirected as well as those that penetrate, rollover or vault over the median barrier and continue across the median, enter the opposing lanes, and strike or are struck by a vehicle in the opposing lanes. The left side of the inequality represents encroachments that fully cross the unshielded median and are involved in a collision with a vehicle in the opposing lanes. This inequality can be further simplified as follows:

$$1 > \frac{\mathrm{OUTCOME}_{\mathrm{BAR+CMC}}}{\mathrm{OUTCOME}_{\mathrm{CMC}}} \therefore \text{Install a median barrier}$$

where

$\mathrm{OUTCOME}_{\mathrm{CMC}}$ = The number of KA CMCs when a barrier is not installed.
$\mathrm{OUTCOME}_{\mathrm{BAR+CMC}}$ = The number of KA crashes with a longitudinal barrier plus those KA crashes that breach the barrier and continue across the median to be involved in a CMC.

Applying the NCHRP Project 15-65 methodology explained earlier, the frequency of KA crashes for an unshielded median ($\text{OUTCOME}_{\text{CMC}}$) and the shielded median ($\text{OUTCOME}_{\text{BAR}}$+CMC) can be estimated as follows:

$$\begin{aligned}\text{OUTCOME}_{\text{CMC}} &= [\text{BEF}_{\text{S}} \cdot \text{EAF}_{\text{S}} \cdot \text{L}_{\text{S}} \cdot 5280] \cdot \left(\frac{\text{PSL}_{\text{S}}^{3}}{65^{3}}\right) \cdot [\text{P}_{\text{c CMC}} \cdot \text{P}_{\text{SEV}_{\text{CMC}}} \cdot (1 - \text{THR}_{\text{EOL}} \cdot \delta_{\text{CMC}})] \\ &= [\text{BEF}_{\text{S}} \cdot \text{EAF}_{\text{S}} \cdot \text{L}_{\text{S}} \cdot 5280]\left(\frac{\text{PSL}_{\text{S}}^{3}}{65^{3}}\right) \cdot \left[\frac{\text{L}_{\text{CMC}} \cdot \text{P}_{\text{Y}}(\text{MW}) \cdot \text{P}_{\text{SEV CMC}} \cdot (1 - \text{THR}_{\text{EOL}})}{\text{L}_{\text{S}}}\right]\end{aligned}$$

$$\begin{aligned}\text{OUTCOME}_{\text{BAR}} &= [\text{BEF}_{\text{S}} \cdot \text{EAF}_{\text{S}} \cdot \text{L}_{\text{S}} \cdot 5280] \cdot \left(\frac{\text{PSL}_{\text{S}}^{3}}{65^{3}}\right) \\ &\quad \cdot [(\text{P}_{\text{c BAR}} \cdot \text{P}_{\text{SEV}_{\text{BAR}}}) + (\text{P}_{\text{c CMC}} \cdot \text{P}_{\text{SEV}_{\text{CMC}}} \cdot (1 - \text{THR}_{\text{EOL}} \cdot \delta_{\text{CMC}}) \cdot \text{THR}_{\text{BAR}})] \\ &= [\text{BEF}_{\text{S}} \cdot \text{EAF}_{\text{S}} \cdot \text{L}_{\text{S}} \cdot 5280] \cdot \left(\frac{\text{PSL}_{\text{S}}^{3}}{65^{3}}\right) \cdot \left[\frac{\text{L}_{\text{BAR}} \cdot \text{P}_{\text{Y}}(\text{MW}/2) \cdot \text{P}_{\text{SEV BAR}}}{\text{L}_{\text{S}}}\right]\end{aligned}$$

$$\text{RR}_{\text{CMC+BAR/CMC}}$$

$$= 1 > \frac{\text{OUTCOME}_{\text{BAR+CMC}}}{\text{OUTCOME}_{\text{CMC}}} = \frac{\text{OUTCOME}_{\text{BAR}} + \text{OUTCOME}_{\text{CMC}} \cdot \text{THR}_{\text{BAR}}}{\text{OUTCOME}_{\text{CMC}}}$$

$$1 > \frac{\left[\left(\dfrac{\text{L}_{\text{BAR}} \cdot \text{P}_{\text{Y}}\left(\dfrac{\text{MW}}{2}\right) \cdot \text{P}_{\text{SEV BAR}}}{\text{L}_{\text{S}}}\right) + \left(\dfrac{\text{L}_{\text{CMC}} \cdot \text{P}_{\text{Y}}(\text{MW}) \cdot \text{P}_{\text{SEV CMC}} \cdot (1 - \text{THR}_{\text{EOL}})}{\text{L}_{\text{S}}}\right) \cdot \text{THR}_{\text{BAR}}\right]}{\left(\dfrac{\text{L}_{\text{CMC}} \cdot \text{P}_{\text{Y}}(\text{MW}) \cdot \text{P}_{\text{SEV CMC}} \cdot (1 - \text{THR}_{\text{EOL}})}{\text{L}_{\text{S}}}\right)}$$

Recognizing that the median barrier is continuous along the whole segment, therefore, $\text{L}_{\text{S}} = \text{L}_{\text{CMC}} = \text{L}_{\text{BAR}}$.

$$1 > \frac{[(\text{P}_{\text{Y}}(\text{MW}/2) \cdot \text{P}_{\text{SEV BAR}}) + (\text{P}_{\text{Y}}(\text{MW}) \cdot \text{P}_{\text{SEV CMC}} \cdot (1 - \text{THR}_{\text{EOL}}))]}{[\text{P}_{\text{Y}}(\text{MW}) \cdot \text{P}_{\text{SEV CMC}} \cdot (1 - \text{THR}_{\text{EOL}})]}$$

where MW = The median width in feet.

The values for $\text{OUTCOME}_{\text{BAR}}$+CMC vary by median barrier material type (e.g., cable, metal beam, or concrete) as discussed above. Conversely, THR_{BAR} is a function of the test level of the median barrier considered and the PT in the traffic mix. The recommendations shown in Figure 23 and Table 12 were derived based on the inequality shown above with consideration of median widths varying between 2 ft to 100 ft, barrier placement, barrier material, and median barrier TL. These guidelines apply to median barriers placed in a traversable median that is free of fixed objects. Single-faced barrier guidelines for obstructed roadsides and medians are described in the next section.

Median barriers may be placed anywhere within the median where analysis, crash testing, or in-service performance evaluation has shown the barrier will likely contain and redirect errant vehicles. Bligh et al. studied MASH concrete and W-beam barriers in NCHRP Project 22-22(02) and found that MASH concrete barriers can be considered effective at any offset from the traveled way across the slope and ditch configurations, whereas MASH W-beam barriers have limited locations where the effectiveness is maintained. (Bligh 2020a) MASH W-beam barriers may be placed before the shoulder/slope breakpoint or generally within 4 ft of the center of a

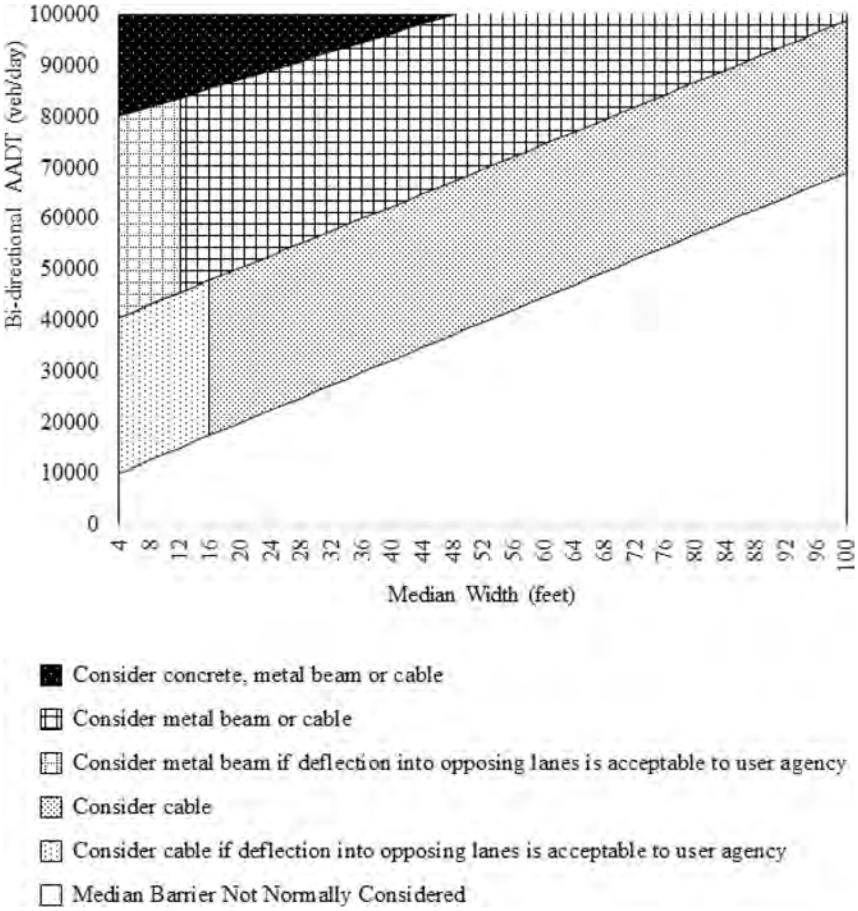


Figure 23. Guidelines for median barrier need determination and material selection.

ditch. Cable barriers may be placed at any location outlined by Marzougui et al. in NCHRP Report 711. (Marzougui 2012a) As additional research is developed, each barrier may be placed at locations determined to satisfy the criteria demonstrated in MASH crash tests.

Generally, the need for a median barrier is determined first, then the TL of the barrier is determined. One could, however, determine which TL is appropriate for situations warranting a barrier and then determine if the barrier is warranted. To determine the need for a median barrier, plot the point corresponding to the design year bi-directional traffic volume and median width in Figure 23. The area where this point plots indicates whether a barrier is needed and the barrier material most appropriate for the site and traffic conditions. For example, a cable median barrier would be most appropriate for a 50-ft-wide traversable median with an AADT of

Table 12. Guidelines for selection of longitudinal barrier test level.

MASH Test Level	Traffic Conditions
2 or higher	0 PT and posted speed ≤ 45 mph
3 or higher	0 < PT ≤ 10
4 or higher	10 < PT ≤ 15
5 or higher	>15 PT or a designated truck or hazardous material route

40,000 vehicles/day, as shown in Figure 23. On the other hand, a 50-ft-wide traversable median on a controlled-access highway with bi-directional traffic volume in the design year of only 10,000 vehicles/day is better left with no median barrier. A rigid concrete, metal beam, or cable median barrier would reduce the median-related crash risk on a controlled-access highway with a 20-ft traversable median and 90,000 vehicles/day as shown in Figure 23. The particular choice between concrete, metal beam, or cable in this situation would be made based on available deflection area, cost, and other factors, but in this area, a median barrier of any material would reduce the risk compared to not having a median barrier. Once the need for a median barrier has been established using Figure 23, the appropriate test level can be determined, as will be discussed shortly.

Two small areas located on the left side of Figure 23 warrant special attention. In these areas, either cable or metal-beam median barriers could reduce the risk of a fatal or serious injury crash compared with not having a median barrier, but median barriers in these areas may allow dynamic deflection of the barrier into the opposing lanes. If the design objective is to accommodate all the barrier deflection within the median, cable median barriers should not be used in medians narrower than 16 ft and metal-beam barriers should not be used in medians narrower than 10 ft because they could deflect into the opposing lanes in a crash. If deflection into the opposing lanes is an acceptable design objective, cable or metal-beam barriers can be used in these areas of Figure 23.

The need for a median barrier in an unobstructed traversable median was determined above using Figure 23. Table 12 is used to select the appropriate median barrier TL as a function of the PT in the traffic mix in the design year. For the example discussed above, a TL3 cable median barrier would be appropriate for a 50-ft-wide median with an AADT of 40,000 vehicles/day and a PT less than 10. For a PT of 12, a TL4 cable barrier would be appropriate. If a TL4 cable median barrier is not available, a TL3 cable barrier should be used, as neither metal-beam nor concrete barriers would provide a lower risk than leaving the median unprotected for these parameters. If a traffic volume and traversable median width for a particular roadway were to plot within the section shown as concrete/metal beam/cable in Figure 23 (e.g., 15-ft-wide median with an AADT of 90,000 veh/day), a cable, metal-beam, or concrete barrier would reduce the risk of a fatal or serious injury crash when compared to an unprotected median. If the PT was 18 at this particular site, a TL5 concrete barrier would be a good choice based on Figure 23 and Table 12.

5.2 Roadside Barrier Guidelines

A longitudinal barrier should only be installed if it reduces the number of KA crashes on the segment compared to the unshielded road segment. In other words, the number of KA longitudinal barrier crashes on a segment must be less than the number of KA fixed object and/or terrain crashes that would have occurred without a shielding barrier. In terms of Equations 1 and 2, the longitudinal barrier should be installed only when the OUTCOME of the barrier and the terrain crashes are less than the OUTCOME of the unshielded terrain (i.e., $\text{OUTCOME}_{GR+TER} < \text{OUTCOME}_{TER}$). If there are fixed objects present, the OUTCOME of the barrier, terrain, and fixed object crashes should be less than the OUTCOME of the unshielded terrain and fixed object crashes (i.e., $\text{OUTCOME}_{GR+TER+FO} < \text{OUTCOME}_{TER+FO}$). Both of these relationships can be rearranged algebraically, such that a longitudinal barrier is installed when either of these inequalities holds:

$$\frac{\text{OUTCOME}_{GR+TER}}{\text{OUTCOME}_{TER}} < 1 \text{ OR } \frac{\text{OUTCOME}_{GR+TER+FO}}{\text{OUTCOME}_{TER+FO}} < 1$$

Recalling Equation 2, the OUTCOME for terrain and the OUTCOME for longitudinal barrier shielding terrain with and without fixed objects are as follows:

$$\mathrm{OUTCOME}_{\mathrm{TER}} = [\mathrm{BEF}_{\mathrm{S}} \cdot \mathrm{EAF}_{\mathrm{S}} \cdot \mathrm{L}_{\mathrm{S}} \cdot 5280] \cdot \left(\frac{\mathrm{PSL}_{\mathrm{S}}^{3}}{65^{3}}\right) \cdot [\mathrm{P}_{\mathrm{c\,TER}} \cdot \mathrm{P}_{\mathrm{SEV\,TER}} \cdot (1 - \mathrm{THR}_{\mathrm{TER}} \cdot \delta_{\mathrm{TER}})]$$

$$\text{Letting } \delta_{\mathrm{TER}} = 1, \text{ and } \mathrm{P}_{\mathrm{c\,FO}} = \frac{\mathrm{L}_{\mathrm{TER}} \cdot \mathrm{P}_{\mathrm{Y}}(\mathrm{W}_{\mathrm{TER}})}{\mathrm{L}_{\mathrm{S}}} \text{ yields:}$$

$$= [\mathrm{BEF}_{\mathrm{S}} \cdot \mathrm{EAF}_{\mathrm{S}} \cdot \mathrm{L}_{\mathrm{S}} \cdot 5280] \left(\frac{\mathrm{PSL}_{\mathrm{S}}^{3}}{65^{3}}\right) \cdot \left[\frac{\mathrm{L}_{\mathrm{TER}} \cdot \mathrm{P}_{\mathrm{Y}}(\mathrm{W}_{\mathrm{TER}}) \cdot \mathrm{P}_{\mathrm{SEV\,TER}} \cdot (1 - \mathrm{THR}_{\mathrm{TER}})}{\mathrm{L}_{\mathrm{S}}}\right]$$

$$\mathrm{OUTCOME}_{\mathrm{TER+BAR}} = [\mathrm{BEF}_{\mathrm{S}} \cdot \mathrm{EAF}_{\mathrm{S}} \cdot \mathrm{L}_{\mathrm{S}} \cdot 5280] \cdot \left(\frac{\mathrm{PSL}_{\mathrm{S}}^{3}}{65^{3}}\right)$$

$$\cdot [(\mathrm{P}_{\mathrm{c\,BAR}} \cdot \mathrm{P}_{\mathrm{SEV_{BAR}}}) + (\mathrm{P}_{\mathrm{c\,TER}} \cdot \mathrm{P}_{\mathrm{SEV\,TER}} \cdot (1 - \mathrm{THR}_{\mathrm{TER}} \cdot \delta_{\mathrm{TER}})) \cdot \mathrm{THR}_{\mathrm{BAR}})]$$

$$\text{Letting } \delta_{\mathrm{TER}} = 1,\ \mathrm{P}_{\mathrm{c\,TER}} = \frac{\mathrm{L}_{\mathrm{TER}} \cdot \mathrm{P}_{\mathrm{Y}}(\mathrm{W}_{\mathrm{TER}})}{\mathrm{L}_{\mathrm{S}}} \text{ and } \mathrm{P}_{\mathrm{c\,BAR}} = \frac{\mathrm{L}_{\mathrm{BAR}} \cdot \mathrm{P}_{\mathrm{Y}}(\mathrm{W}_{\mathrm{BAR}})}{\mathrm{L}_{\mathrm{S}}} \text{ yields:}$$

$$= [\mathrm{BEF}_{\mathrm{S}} \cdot \mathrm{EAF}_{\mathrm{S}} \cdot \mathrm{L}_{\mathrm{S}} \cdot 5280] \left(\frac{\mathrm{PSL}_{\mathrm{S}}^{3}}{65^{3}}\right)$$

$$\cdot \left[\left(\frac{\mathrm{L}_{\mathrm{BAR}} \cdot \mathrm{P}_{\mathrm{Y}}(\mathrm{W}_{\mathrm{BAR}}) \cdot \mathrm{P}_{\mathrm{SEV\,BAR}}}{\mathrm{L}_{\mathrm{S}}}\right) + \left(\frac{\mathrm{L}_{\mathrm{TER}} \cdot \mathrm{P}_{\mathrm{Y}}(\mathrm{W}_{\mathrm{TER}}) \cdot \mathrm{P}_{\mathrm{SEV\,TER}} \cdot (1 - \mathrm{THR}_{\mathrm{TER}} \cdot \delta_{\mathrm{TER}}) \cdot \mathrm{THR}_{\mathrm{BAR}}}{\mathrm{L}_{\mathrm{S}}}\right)\right]$$

$\mathrm{RR}_{\mathrm{TER+BAR/TER}}$

$$= 1 > \frac{\mathrm{OUTCOME}_{\mathrm{TER+BAR}}}{\mathrm{OUTCOME}_{\mathrm{TER}}} = \frac{\mathrm{OUTCOME}_{\mathrm{BAR}} + \mathrm{OUTCOME}_{\mathrm{TER}} \cdot \mathrm{THR}_{\mathrm{BAR}}}{\mathrm{OUTCOME}_{\mathrm{TER}}}$$

$$1 > \frac{\left(\dfrac{\mathrm{L}_{\mathrm{BAR}} \cdot \mathrm{P}_{\mathrm{Y}}(\mathrm{W}_{\mathrm{BAR}}) \cdot \mathrm{P}_{\mathrm{SEV\,BAR}}}{\mathrm{L}_{\mathrm{S}}}\right) + \left(\dfrac{\mathrm{L}_{\mathrm{TER}} \cdot \mathrm{P}_{\mathrm{Y}}(\mathrm{W}_{\mathrm{TER}}) \cdot \mathrm{P}_{\mathrm{SEV\,TER}} \cdot (1 - \mathrm{THR}_{\mathrm{TER}}) \cdot \mathrm{THR}_{\mathrm{BAR}}}{\mathrm{L}_{\mathrm{S}}}\right)}{\left(\dfrac{\mathrm{L}_{\mathrm{TER}} \cdot \mathrm{P}_{\mathrm{Y}}(\mathrm{W}_{\mathrm{TER}}) \cdot \mathrm{P}_{\mathrm{SEV\,CMC}} \cdot (1 - \mathrm{THR}_{\mathrm{TER}})}{\mathrm{L}_{\mathrm{S}}}\right)}$$

Recognizing that the barrier is continuous along the whole segment, therefore, $\mathrm{L}_{\mathrm{S}} = \mathrm{L}_{\mathrm{TER}} = \mathrm{L}_{\mathrm{BAR}}$:

$$\mathrm{RR}_{\mathrm{TER+BAR/TER}} = 1 > \frac{[(\mathrm{P}_{\mathrm{Y}}(\mathrm{W}_{BAR}) \cdot \mathrm{P}_{\mathrm{SEV\,BAR}}) + (\mathrm{P}_{\mathrm{Y}}(\mathrm{W}_{\mathrm{TER}}) \cdot \mathrm{P}_{\mathrm{SEV\,TER}} \cdot (1 - \mathrm{THR}_{\mathrm{TER}})) \cdot \mathrm{THR}_{\mathrm{BAR}})]}{[\mathrm{P}_{\mathrm{Y}}(\mathrm{W}_{\mathrm{TER}}) \cdot \mathrm{P}_{\mathrm{SEV\,TER}} \cdot (1 - \mathrm{THR}_{\mathrm{TER}})]} \qquad 3$$

Similarly, shielding with a longitudinal barrier should be considered for median and roadside slopes where there are both fixed objects and foreslopes present when the inequality holds true, as follows (i.e., Equation 4):

$$\mathrm{OUTCOME}_{\mathrm{FO}} = [\mathrm{BEF}_{\mathrm{S}} \cdot \mathrm{EAF}_{\mathrm{S}} \cdot \mathrm{L}_{\mathrm{S}} \cdot 5280] \cdot \left(\frac{\mathrm{PSL}_{\mathrm{S}}^{3}}{65^{3}}\right) \cdot [\mathrm{P}_{\mathrm{c\,FO}} \cdot \mathrm{P}_{\mathrm{SEV\,FO}} \cdot (1 - \mathrm{THR}_{\mathrm{FO}} \cdot \delta_{\mathrm{FO}})]$$

$$\text{Letting } \delta_{\mathrm{FO}} = 1,\ \mathrm{THR}_{\mathrm{FO}} = 0, \text{ and } \mathrm{P}_{\mathrm{c\,FO}}$$

$$= \frac{\mathrm{L}_{\mathrm{FO}} \cdot \mathrm{P}_{\mathrm{y}}(\mathrm{W}_{\mathrm{F\,FO}})}{\mathrm{L}_{\mathrm{S}}} + \frac{\mathrm{L}_{\mathrm{TMax}} \cdot [\mathrm{P}_{\mathrm{x}}(\mathrm{L}_{\mathrm{TMax}})(\mathrm{P}_{\mathrm{y}}(\mathrm{W}_{\mathrm{F\,FO}}) - \mathrm{P}_{\mathrm{Y}}(\mathrm{W}_{\mathrm{B\,FO}})]}{\mathrm{L}_{\mathrm{S}}} \text{ yields:}$$

$$= [\mathrm{BEF}_{\mathrm{S}} \cdot \mathrm{EAF}_{\mathrm{S}} \cdot \mathrm{L}_{\mathrm{S}} \cdot 5280] \left(\frac{\mathrm{PSL}_{\mathrm{S}}^{3}}{65^{3}}\right)$$

$$\cdot \left[\left(\frac{\mathrm{L}_{\mathrm{FO}} \cdot \mathrm{P}_{\mathrm{y}}(\mathrm{W}_{\mathrm{F\,FO}})}{\mathrm{L}_{\mathrm{S}}} + \frac{[\mathrm{L}_{\mathrm{TMax}} \cdot \mathrm{P}_{\mathrm{x}}(\mathrm{L}_{\mathrm{TMax}})(\mathrm{P}_{\mathrm{y}}(\mathrm{W}_{\mathrm{F\,FO}}) - \mathrm{P}_{\mathrm{Y}}(\mathrm{W}_{\mathrm{F\,FO}})]}{\mathrm{L}_{\mathrm{S}}}\right) \cdot \mathrm{P}_{\mathrm{SEV\,FO}}\right]$$

$$\mathrm{RR}_{\mathrm{FO+TER+BAR/FO+TER}} = 1 > \frac{\mathrm{OUTCOME}_{\mathrm{FO+TER+BAR}}}{\mathrm{OUTCOME}_{\mathrm{FO+TER}}}$$

$$= \frac{\mathrm{OUTCOME}_{\mathrm{BAR}} + \mathrm{OUTCOME}_{\mathrm{TER}} \cdot \mathrm{THR}_{\mathrm{BAR}} + \mathrm{OUTCOME}_{\mathrm{FO}} \cdot \mathrm{THR}_{\mathrm{BAR}} \cdot \mathrm{THRU}_{\mathrm{TER}}}{\mathrm{OUTCOME}_{\mathrm{TER}} + \mathrm{OUTCOME}_{\mathrm{FO}} \cdot \mathrm{THR}_{\mathrm{TER}}}$$

$$> \frac{\left[\begin{array}{l} \left(\dfrac{L_{\mathrm{BAR}} \cdot P_{Y}(W_{\mathrm{BAR}}) \cdot P_{\mathrm{SEV\,BAR}}}{L_{S}}\right) + \left(\dfrac{L_{\mathrm{TER}} \cdot P_{Y}(W_{\mathrm{TER}}) \cdot P_{\mathrm{SEV\,BAR}} \cdot (1 - \mathrm{THR}_{\mathrm{TER}}))}{L_{S}}\right) \cdot \mathrm{THR}_{\mathrm{BAR}} \\ + \left(\dfrac{L_{\mathrm{FO}} \cdot P_{y}(W_{\mathrm{F\,FO}})}{L_{S}} + \dfrac{[L_{\mathrm{TMAX}} \cdot P_{x}(L_{\mathrm{TMAX}})(P_{y}(W_{\mathrm{F\,FO}}) - P_{Y}(W_{\mathrm{B\,FO}})]}{L_{S}}\right) \cdot P_{\mathrm{SEV\,FO}} \cdot \mathrm{THR}_{\mathrm{TER}} \cdot \mathrm{THR}_{\mathrm{BAR}} \end{array}\right]}{\left[\begin{array}{l} \left(\dfrac{L_{\mathrm{TER}} \cdot P_{Y}(W_{\mathrm{TER}}) \cdot P_{\mathrm{SEV\,TER}} \cdot (1 - \mathrm{THR}_{\mathrm{TER}})}{L_{S}}\right) \\ + \left(\dfrac{L_{\mathrm{FO}} \cdot P_{y}(W_{\mathrm{F\,FO}})}{L_{S}} + \dfrac{[L_{\mathrm{TMAX}} \cdot P_{x}(L_{\mathrm{TMAX}})(P_{y}(W_{\mathrm{F\,FO}}) - P_{Y}(W_{\mathrm{B\,FO}})]}{L_{S}}\right) \cdot P_{\mathrm{SEV\,FO}} \cdot \mathrm{THR}_{\mathrm{TER}} \end{array}\right]}$$

$$\mathrm{RR}_{\mathrm{FO+TER+BAR/FO+TER}}$$

$$= 1 > \frac{\left[\begin{array}{l} (L_{\mathrm{BAR}} \cdot P_{Y}(W_{\mathrm{BAR}}) \cdot P_{\mathrm{SEV\,BAR}}) + (L_{\mathrm{TER}} \cdot P_{Y}(W_{\mathrm{TER}}) \cdot P_{\mathrm{SEV\,BAR}} \cdot (1 - \mathrm{THR}_{\mathrm{TER}} \cdot \delta_{\mathrm{TER}})) \cdot \mathrm{THR}_{\mathrm{BAR}}) \\ + (L_{\mathrm{FO}} \cdot P_{y}(W_{\mathrm{F\,FO}}) + L_{\mathrm{TMAX}} \cdot P_{x}(L_{\mathrm{TMAX}})(P_{y}(W_{\mathrm{F\,FO}}) - P_{Y}(W_{\mathrm{B\,FO}})) \cdot \mathrm{THR}_{\mathrm{TER}} \cdot \mathrm{THR}_{\mathrm{BAR}} \end{array}\right]}{\begin{array}{c} [L_{\mathrm{TER}} \cdot P_{Y}(W_{\mathrm{TER}}) \cdot P_{\mathrm{SEV\,TER}} \cdot (1 - \mathrm{THR}_{\mathrm{TER}})] \\ + [L_{\mathrm{FO}} \cdot P_{y}(W_{\mathrm{F\,FO}}) + (L_{\mathrm{TMAX}} \cdot P_{x}(L_{\mathrm{TMAX}})(P_{y}(W_{\mathrm{F\,FO}}) - P_{Y}(W_{\mathrm{B\,FO}}))] \cdot P_{\mathrm{SEV\,FO}} \cdot \mathrm{THR}_{\mathrm{TER}} \end{array}} \qquad 4$$

The solution of these relationships uses variables derived and discussed in the appendices of this report. Additionally, an understanding of the appropriate probable encroachment angle is needed (i.e., θ). Encroachment angles were examined in NCHRP Project 17-43, "Long-term Roadside Crash Data Collection Program." (Gabler, forthcoming) The most current NCHRP Project 17-43 beta data set (i.e., NCHRP1743_Beta_20190624.xlsx) was used to determine the following encroachment angle statistics:

- 85th percentile encroachment angle: 22 degrees
- 50th percentile encroachment angle: 11 degrees
- 15th percentile encroachment angle: 5 degrees

The 15th percentile represents the shallowest angles in the data set, whereas the 85th percentile represents the steepest angles. Using the value of the 15th percentile at the leading end of the guardrail (i.e., θ_{15}) and the 85th percentile at the trailing end (i.e., θ_{85}) maximizes the length of the longitudinal barrier.

5.2.1 Shielding Terrain Free of Fixed Objects

Glennon and Tamburri observed in 1967 and Zegeer et al. observed in 1987 that when slopes are free of all other features, the addition of a W-beam guardrail does not reduce the risk of observing a KA crash. (Glennon 1967; Zegeer 1987) If typical values are substituted into Equation 3, the relative risk of the guardrail to the unprotected slope is always greater than 1, usually much greater. This indicates that for foreslopes between 12:1 and 2:1 and offsets to the bottom of the slope up to 100 ft wide, shielding with a guardrail is likely to do more harm than good if the slope is free of fixed objects and there are no fixed objects at the bottom of the slope. This analytically confirms Glennon and Tamburri's as well as Zegeer's conclusions that shielding slopes that are otherwise free of fixed objects with longitudinal barriers does not reduce the risk of a KA crash, even for foreslopes as steep as 2:1. There is no question that a rollover is a more severe crash than a crash with a W-beam guardrail. A crash with a guardrail, however, is much more probable than a rollover on an unprotected slope due to the proximity of a guardrail to the roadway edge and the independent probability of rollover if a vehicle interacts with the sloped terrain. Longitudinal barriers should not be used to shield foreslopes flatter than 2:1 if the foreslope is smooth and otherwise free of fixed objects and there are no hazardous features at the bottom of the slope.

5.2.2 Shielding Terrain with Fixed Objects

Many roadsides and medians do not have slopes free of features like trees, poles, or bridge piers, so it is often necessary to assess the need to remove fixed objects or shield them with longitudinal barriers on sloping terrain. As a general rule, barriers should be used to shield features when the probability of a KA crash on the segment is reduced with the installation of a longitudinal barrier as compared with the probability of a KA crash without the installation. When considering shielding fixed objects, one should simultaneously consider reducing the density and/or increasing the offset to alleviate the need for a guardrail. Installing hundreds of feet of longitudinal barrier close to the road to shield a small isolated feature like an isolated pole may increase rather than decrease the risk to vehicle occupants. In other words, a longitudinal barrier should only be installed in situations where it will do more good than harm. These are described as risk-beneficial conditions. Roadside features that may need shielding can be categorized as follows:

- Isolated narrow fixed objects like single trees, utility poles, bridge piers, and traffic signal supports (i.e., small dimensions both parallel and perpendicular to the road).
- Multiple narrow fixed objects like a line of utility poles, a series of bridge piers, or a row of roadside trees (i.e., large effective dimension parallel to the road and small dimension perpendicular to the road).
- Continuous parallel features like canals, rivers, and walls parallel to the roadway (i.e., very large dimension parallel to the road and modest dimension perpendicular to the road).
- Continuous perpendicular features like canals, drainage features, and rivers that are more or less perpendicular to the roadway (i.e., modest dimension parallel to the road and large dimension perpendicular to the road).
- General features like buildings and industrial equipment (i.e., moderate dimensions parallel and perpendicular to the road).

A general procedure for determining whether a longitudinal barrier is beneficial can be determined using Equation 4 based on the following assumptions:

- The shielding barrier is a metal-beam barrier (i.e., $P_{SEV\ BAR} = 0.0084$, $\partial_{BAR} = 0$).
- The shielding barrier has a negligible probability of penetration by passenger vehicles (i.e., $THR_{BAR} = 0$).
- The shielding barrier is located 4-ft from the edge of travel (i.e., $W_{F\ BAR} = 4$ ft).
- The shielding barrier is intended to intercept 95% of encroachment trajectories.
- The shielding barrier includes an approach barrier on the upstream end with a terminal that extends 12.5 ft upstream of the end of the length of need.
- The terminal is an *NCHRP Report 350* or MASH tangent (i.e., $P_{SEV\ TRM} = 0.0500$, $\partial_{BTRM} = 0$).
- The foreslope begins at the back of the shielding barrier and ends at the face of the fixed object (i.e., $P_{SEV\ TER} = 0.0589$, $\partial_{TER} = 1$).

All roadside obstacles are assumed to have a crash severity of 0.0589 as discussed in

- PROBABILITY OF CRASH SEVERITY (P_{SEV_J}) (i.e., $P_{SEV\ FO} = 0.0589$, $\partial_{FO} = 0$).

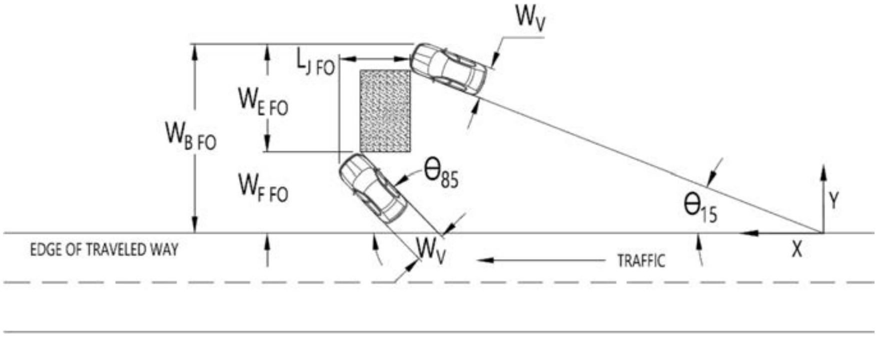


Figure 24. Evaluating shielding for an isolated fixed object.

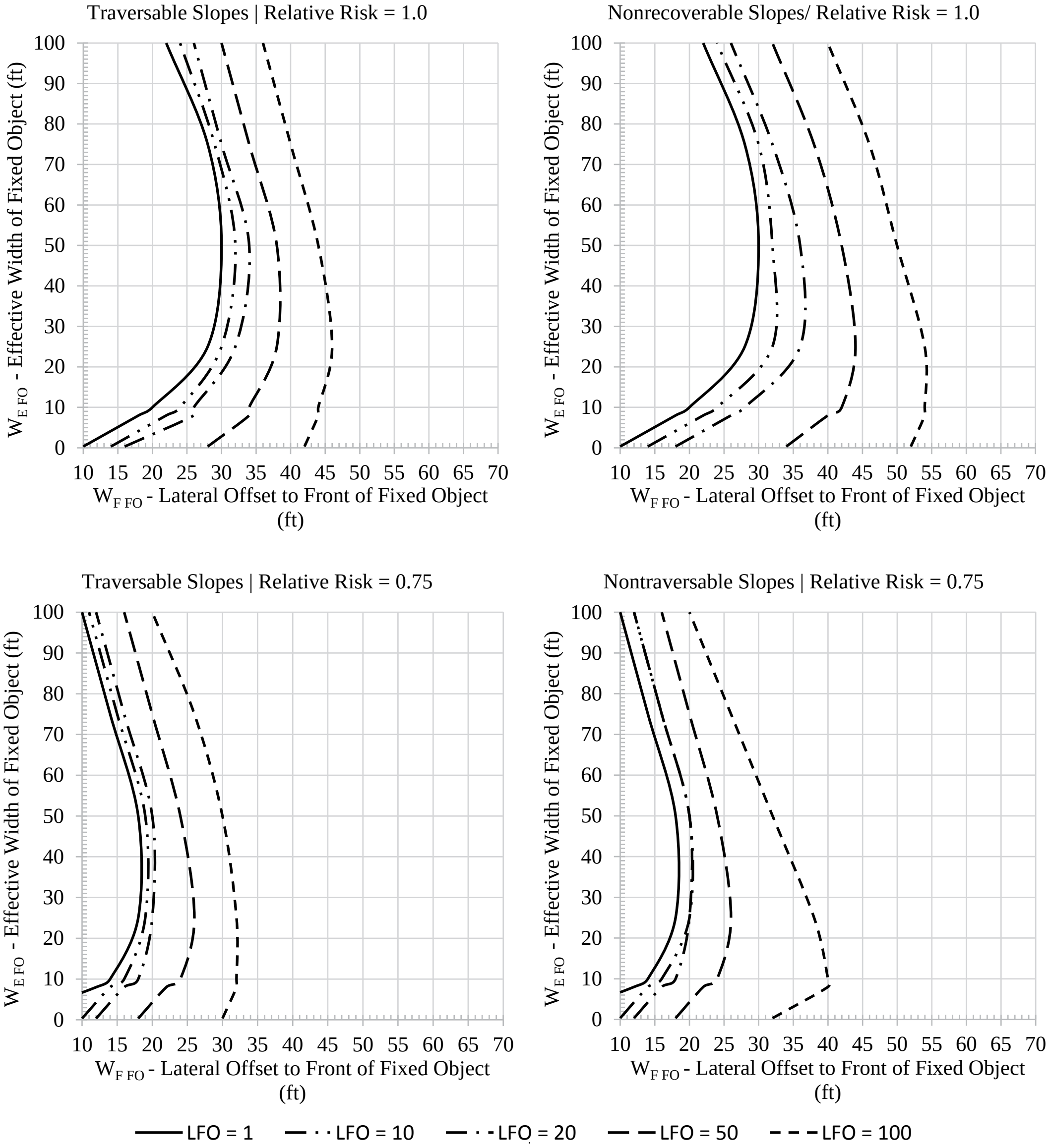
Figure 24 defines the variables used. Notice that the lateral distance to the back of the feature ($W_{B\,FO}$) includes a term $W_v \sin\theta_{15}$, and a term $W_v \cos\theta_{15}$ is added to the length of the feature ($L_{j\,FO}$) to account for the width of the vehicle. Figure 25 provides the results for traversable and non-traversable slopes for two different relative risk ratios, 1 and 0.75. The y-axis of Figure 25 is equal to the width of the fixed object plus the $W_v \sin\theta_{15}$, which is equal to the equivalent width of the fixed object ($W_{E\,FO}$).

A relative risk of 1.0 indicates that the shielding barrier results in essentially the same risk as does the roadside feature. A relative risk of 0.75 indicates that the shielding guardrail results in a 25% risk reduction with respect to the unshielded roadside feature. While the shielding barrier may be risk-beneficial (i.e., 1.0), it may or may not be cost-beneficial, as will be discussed shortly.

Figure 24 illustrates a site with an isolated individual narrow fixed object like a utility pole being considered for shielding with a barrier. The length and width of the utility pole are less than 1 ft so, referring to the solid line in the top left portion of Figure 25, the utility pole need not be shielded if it is more than 10 ft from the edge of the lane, for a relative risk of 1. This means that a guardrail will likely do more harm than good in this situation. While shielding would be risk-beneficial at an offset less than 10 ft, the risk reduction, as shown in the bottom left portion of Figure 25, would be about 25%, which would likely not be cost-effective, as described in Section 5.3.

Figure 26 illustrates a site with multiple narrow fixed objects like a line of utility poles being considered for shielding with a barrier. As for the isolated narrow fixed object, the vehicle width is accounted for in the lateral distance to be back of the feature ($W_{B\,FO}$) and the length of the feature ($L_{j\,FO}$) to account for the width of the vehicle, as shown in Figure 26. If the spacing between the narrow fixed objects is large enough, each feature should be considered a separate individual feature. If the spacing is smaller, the multiple narrow fixed objects are considered one long object. Figure 27 shows the critical spacing that determines when multiple narrow fixed objects should be treated as individual narrow fixed objects or a composite fixed object with a length equal to the sum of all the spacing between the objects and the length of the objects. Figure 27 is based on the work of Johnson and Gabler in which they developed risk corridors that define the length in advance of a feature where shielding would need to be provided to intercept a fixed percentage of the encroachments that would interact with the fixed object. (Johnson 2015) Using Johnson and Gabler's approach, the length of guardrail needed to intercept 95% of the trajectories that would interact with the fixed object on roadways with 55 mi/hr or higher posted speed limits can be found as:

$$L_R = \frac{W_{BFO} + W_V \cos\theta_{15}}{W_V \tan\theta_{15}}$$



Traversable Slopes | Relative Risk = 1.0

Nonrecoverable Slopes/ Relative Risk = 1.0

Traversable Slopes | Relative Risk = 0.75

Nontraversable Slopes | Relative Risk = 0.75

Figure 25. Fixed object risk-beneficial curves for relative risks of 1.0 and 0.75.

If a row of multiple narrow fixed objects is less than this distance, the multiple narrow fixed objects can be considered one object where the length of the fixed object is the sum of all the spacings and the length of the objects. For example, a row of five utility poles spaced 200 ft apart is considered a single 800-ft-long (i.e., 200[5 – 1] = 800 ft) feature if it is more than 12 ft from the edge of travel. In this situation, the width of the feature is less than 1 ft so it lies on the X-axis of Figure 25. The small dashed line in Figure 25 represents a feature length of at least 100 ft and indicates that such fixed objects should be shielded even if they are 64 ft from the edge of travel, for a relative risk of 1. For a relative risk of 0.75 (i.e., 25% risk reduction), the row of utility poles should be considered for shielding if closer than 30 ft from the edge of travel on a traversable slope and 40 ft on a non-traversable slope.

Features that are continuous and parallel to the road like rivers, canals, and walls can be evaluated with Figure 25 as well. In these cases, the width of the vehicle need not be accounted for because the vehicle cannot get behind the feature like it can for a fixed object

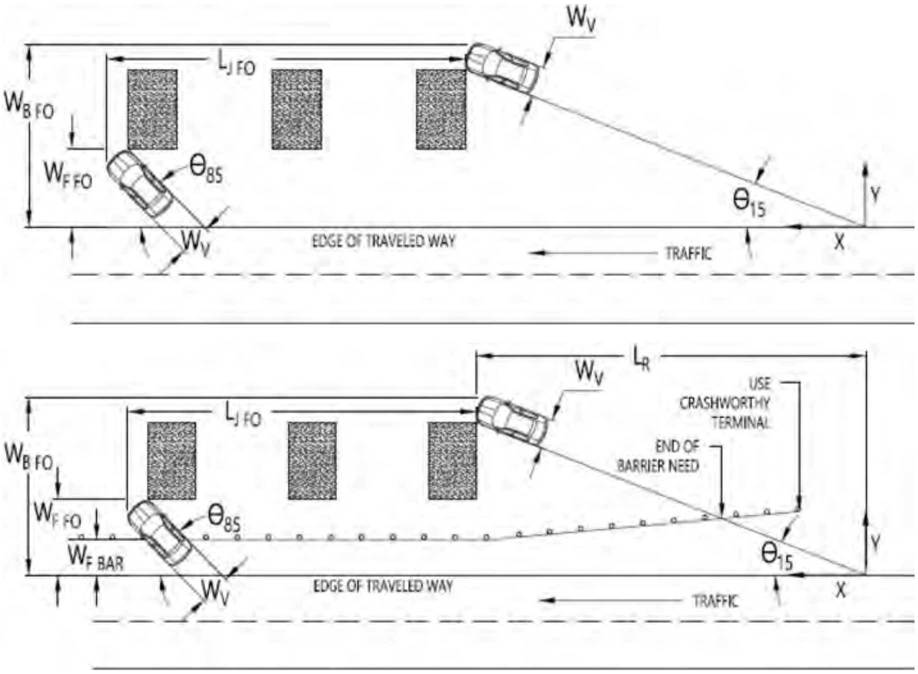


Figure 26. Evaluating shielding for multiple fixed objects.

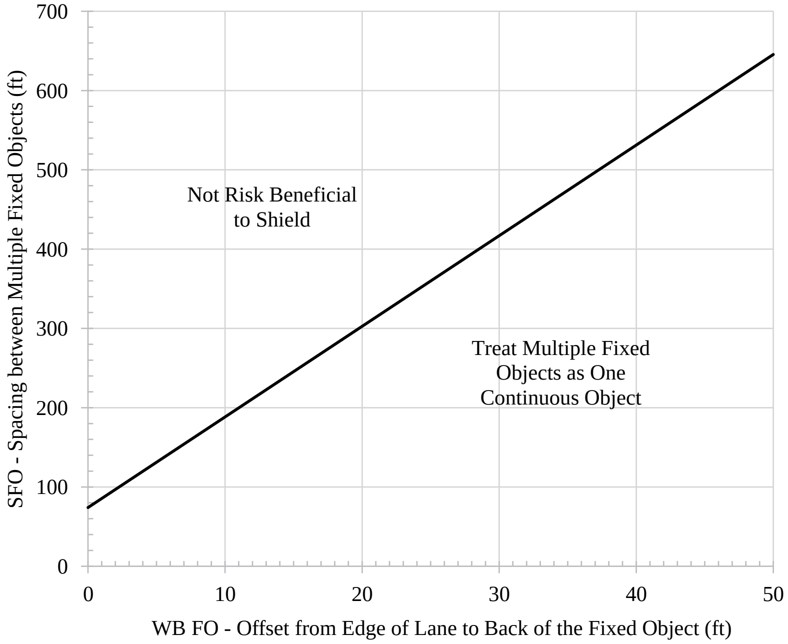


Figure 27. Critical spacing of multiple narrow fixed objects.

like a bridge pier. For example, the lower-left portion of Figure 25 indicates that a 10-ft-wide canal ($W_{B\,FO} - W_{F\,FO} = 10$ ft) parallel to a roadway for 100 ft along its length with a traversable slope should be considered for shielding if it is closer than 32 ft to the edge of the lane, for a relative risk of 0.75. Similarly, a 20-ft-wide (i.e., parallel to the road) open-channel drainage ditch that crosses a 50-ft-wide traversable (i.e., $W_{B\,FO} - W_{F\,FO} = 50$ ft) median should be considered for shielding at the 0.75 relative risk level.

The selection of relative risk levels is a policy decision for highway agencies. A relative risk of unity indicates that the shielding barrier does no more harm than the unshielded feature, but it also does not reduce the risk of a KA crash. A relative risk of 0.75 means that 25% fewer KA crashes are expected for the shielded location. It was found that relative risks of 0.50 were seldom possible except for very long and very wide features. Charts like Figure 25 could be produced for any relative risk between approximately 0.7 and 1.0.

The relative risk can also be used directly in a benefit–cost approach recognizing that the reduction in KA crashes is equal to:

$$\mathrm{OUTCOME_{NULL}} - \mathrm{OUTCOME_{ALT}} = (1-\mathrm{RR}) \cdot \mathrm{OUTCOME_{NULL}}$$

The approach outlined above, therefore, can be used directly where a highway agency chooses an explicit relative risk goal (e.g., 0.75 or less) or determines the need for shielding based on when the barrier does no more harm than the unshielded object (i.e., relative risk = 1) and then determines whether the shielding barrier is cost-beneficial. In either case, the decision to shield or not to shield a roadside feature is based on the quantified risk of observing a KA crash.

5.3 Cost–Benefit Guidelines

Both benefit–cost and cost-effectiveness analyses are discussed here. While benefit–cost has a long history in roadside design, cost-effectiveness analysis is suggested for the implementation of these findings for the reasons discussed below. When these results are implemented, it is suggested that an abridged version of one or both of these two subsections be considered as an appendix to the AASHTO RDG.

5.3.1 Benefit–Cost Analysis

A common technique for maximizing value used in many technical fields is benefit–cost analysis. (Newnan 1977) In the context of roadside safety, the benefit is usually considered to be the reduction in societal costs associated with roadside crashes and the costs are the construction, maintenance, and repair costs expended by the highway agency to achieve that benefit. Since benefits are defined as the reduction in the societal cost of crashes, estimating the number and severity of crashes is at the heart of the benefit–cost method in roadside safety.

To compare design alternatives, an average annual crash cost is calculated by estimating the number and severity of crashes for the considered alternative and the existing condition (i.e., the null alternative) and then converting the estimate to social costs using the willingness-to-pay concept. These crash costs are then annualized over the project life at some predefined rate of return. Any direct highway agency costs (i.e., initial installation, annual maintenance, and periodic repairs) are likewise annualized and the benefit–cost ratio (BCR) is calculated. The BCR is calculated as follows:

$$\mathrm{BCR} = \mathrm{OR_{ALT/NULL}} \cdot \left[\frac{\mathrm{C_{KA}} \cdot \mathrm{VSL}}{\mathrm{DC_{ALT}} \cdot \mathrm{AP_{i,n}} + \mathrm{MC_{ALT}}} \right]$$

where

BCR = The benefit–cost ratio of the barrier alternative with respect to the null alternative.

$OR_{ALT/NULL}$ = The outcome reduction is the estimated difference in the annual frequency of fatal and serious injury crashes for the shielded median (ALT alternative) and the unshielded alternative (NULL alternative). See Table 13 for cable median barrier, Table 14 for metal-beam median barrier, and Table 15 for concrete median barrier. Figure 25 for fixed objects.

$OR_{ALT/NULL} = OUTCOME_{NULL} - OUTCOME_{ALT}$

$OR_{ALT/NULL} = (1-RR_{ALT/NULL})\ OUTCOME_{NULL}$

VSL = The value of statistical life in dollars based on the US DOT recommendation or the agency value for a fatal crash. (Monje 2016)

C_{KA} = A unitless coefficient that transforms the VSL to the average cost of a KA crash.

$AP_{i,n}$ = The capital recovery factor as a function of the interest rate, i, and service life, n, where $AP_{i,n} = P\left[\frac{i(1+i)^n}{(1+i)^n - 1}\right]$. (Newman 1977)

DC_{ALT} = The direct cost of constructing and maintaining the barrier alternative over the service life of the alternative. The direct cost of the null alternative (i.e., the unshielded) is presumed to be zero.

MC_{ALT} = The annual maintenance cost of the longitudinal barrier.

RR = The relative risk of the considered alternative with respect to the null alternative where $RR_{ALT/NULL} = OUTCOME_{NULL} / OUTCOME_{ALT}$

A BCR equal to 1 means that the investment is just equal to the benefit obtained. A value of 1 is the minimum BCR where the alternative should be considered. Most highway agencies expect BCR values between 2 and 4 to maximize the benefit of scarce agency resources.

Calculating the expected frequency of KA outcomes for a shielded and unshielded median was discussed earlier. The differences in the frequency of these outcomes for shielded and unshielded alternatives ($OR_{ALT/NULL}$) are shown in Table 13 through Table 15 for cable, metal-beam, and concrete median barriers, respectively, and in Figure 25 for fixed objects. Linear interpolation between cells is acceptable for non-tabulated values of median width and traffic volume.

For example, a median barrier in a 70-ft traversable median on a four-lane highway with 45,000 veh/day results in a higher frequency of KA crashes than the unshielded median, so a median barrier would not be risk-beneficial, as indicated in Table 13 by a blank cell. On the other

Table 13. KA outcome reduction—cable median barriers (KA CMC/mi/yr).

Bi-Direction AADT (veh/day)	**Traversable Median Width** (ft)										
	25	**30**	**35**	**40**	**45**	**50**	**60**	**70**	**80**	**90**	**100**
25,000	0.0003										
30,000	0.0009	0.0005									
35,000	0.0015	0.0010	0.0003								
40,000	0.0022	0.0017	0.0009	0.0004							
45,000	0.0030	0.0023	0.0015	0.0009	0.0002						
50,000	0.0039	0.0032	0.0022	0.0016	0.0008	0.0003					
55,000	0.0048	0.0040	0.0030	0.0023	0.0014	0.0008					
60,000	0.0060	0.0051	0.0039	0.0031	0.0021	0.0014	0.0003				
65,000	0.0072	0.0062	0.0048	0.0039	0.0028	0.0021	0.0009	0.0001			
70,000	0.0086	0.0074	0.0060	0.0050	0.0037	0.0028	0.0014	0.0006	0.0000		
75,000	0.0099	0.0087	0.0071	0.0059	0.0046	0.0036	0.0021	0.0011	0.0005	0.0002	0.0001
80,000	0.0114	0.0100	0.0082	0.0070	0.0055	0.0045	0.0027	0.0016	0.0009	0.0006	0.0004
85,000	0.0121	0.0107	0.0089	0.0076	0.0060	0.0049	0.0031	0.0019	0.0011	0.0008	0.0006
90,000	0.0121	0.0107	0.0089	0.0076	0.0060	0.0049	0.0031	0.0019	0.0011	0.0008	0.0006
≥95,000	0.0165	0.0147	0.0124	0.0108	0.0089	0.0075	0.0051	0.0035	0.0025	0.0019	0.0016

Table 14. KA outcome reduction—metal-beam median barriers (KA CMC/mi/yr).

Bi-Direction AADT (veh/day)	**Traversable Median Width** (ft)										
	10	**15**	**20**	**25**	**30**	**35**	**40**	**45**	**50**	**55**	**60**
50,000	0.0009										
55,000	0.0033	0.0023	0.0022	0.0008							
60,000	0.0062	0.0049	0.0047	0.0031	0.0015						
65,000	0.0092	0.0077	0.0073	0.0055	0.0038	0.0011					
70,000	0.0128	0.0110	0.0104	0.0083	0.0063	0.0034	0.0016				
75,000	0.0164	0.0144	0.0135	0.0113	0.0090	0.0057	0.0037	0.0011			
80,000	0.0183	0.0162	0.0152	0.0128	0.0104	0.0070	0.0049	0.0021	0.0003		
85,000	0.0183	0.0162	0.0152	0.0128	0.0104	0.0070	0.0049	0.0021	0.0003		
≥90,000	0.0292	0.0263	0.0247	0.0216	0.0184	0.0141	0.0113	0.0078	0.0054	0.0033	0.0015

hand, if a cable median barrier were installed on a four-lane divided highway with 45,000 veh/day and a 45-ft-wide median, Table 13 indicates that 0.0002 fewer KA CMCs can be expected annually. In this case, the cable median barrier is risk-beneficial although it may or may not be cost-beneficial. In other words, the cable median barrier reduces the risk of a CMC, but it remains to be determined whether providing the median barrier will be a good return on the funds invested.

The value of statistical life (VSL) is roughly equivalent to the fatal crash cost. The VSL is periodically defined by the U.S. DOT for use in policy analyses. (Monje 2016) The 2020 VSL is estimated to be $12.3 million based on the published 2016 update procedure. (Monje 2016) Many highway agencies establish their own local values for either VSL or the fatal crash cost, and these should be used as appropriate.

C_{KA} is a coefficient that transforms the VSL into the average cost of a KA crash. C_{KA} is a function of the particular type of crash scenario so there is a specific value for CMCs as opposed to other types of crashes. The Highway Safety Information System data for the State of Washington included 8,638 crossover-centerline crashes that occurred on highways with posted speed limits of 55 mi/hr or greater. Of the 8,638 cross-over-centerline crashes, 431 were fatal and 1,094 were serious injury crashes. Miller determined that, on average, the fatal crash cost (K) is 2,600,000/180,000 =14 times larger than the serious injury crash cost (A). (Blincoe 2002; Miller 1989) The weighted average KA crash cost coefficient of crossover crashes based on the Washington State data is, therefore:

$$C_{KA} = \frac{431+(1,094/14)}{(431+1,094)} = 0.33$$

Although other methods are available, the annualized cost method has been used because the societal benefits are an annually recurring benefit, as are direct maintenance costs. Other techniques like present-worth or future-worth could be used with the same result. Usually,

Table 15. KA outcome reduction—concrete median barriers (KA CMC/mi/yr).

Bi-Direction AADT (veh/day)	**Traversable Median Width** (ft)					
	10	**15**	**20**	**25**	**30**	**35**
80,000	0.0064					
85,000	0.0064					
90,000	0.0064					
≥95,000	0.0270	0.0162	0.0135	0.0127	0.0094	0.0061

highway agencies will determine appropriate values for the rate of return (i) and design life (n) to be used in economic analyses. Generally, the design life should be on the order of 25 to 30 years for typical roadside hardware and rates of return between 2% and 4% are typical for the rate of return.

The next step is to calculate the direct costs. The direct cost of the null alternative is assumed to be zero. The null alternative is the already-existing condition. The direct cost of the longitudinal barrier being considered as an alternative is the direct cost of construction added to the present worth of the annual maintenance cost. For example, assume high-tension cable median barrier has a direct installation cost of \$125,000 per mile of median and an annual maintenance cost of \$2,500 per mile per year. Further, assume that no major earthwork is required before installing the median barrier, the design life is 30 years, and the rate of return is 2%. The present worth of the direct cost of installing the high-tension cable median barrier is, therefore:

$$DC_{ALT} \cdot AP_{i,n} + MC_{ALT} \cdot PA_{i,n} = \$125{,}000 \cdot 0.0446 + \$2{,}500 = \$8{,}075$$

For a highway with a 45-ft-wide traversable median and bi-direction design year traffic of 45,000 veh/day, the expected annual reduction in CMCs ($OR_{ALT/NULL}$) is 0.0002, as shown in Table 13. Given a design year VSL of \$12.3 million and the direct costs above, the BCR can be calculated as follows:

$$BCR = OR_{ALT/NULL} \cdot \left[\frac{C_{KA} \cdot VSL}{DC_{ALT} \cdot AP_{i,n} + MC_{ALT}}\right] = 0.0002 \cdot \left[\frac{0.33 \cdot 12{,}300{,}000}{125{,}000 \cdot 0.0446 + 2{,}500}\right] = 0.1 \ngtr 1$$

A high-tension cable median barrier is not cost-beneficial on a 45-ft-wide median with 45,000 veh/day under these economic assumptions even though the cable median barrier does reduce the risk. A high-tension cable median barrier would have a BCR greater than 1 anywhere in Table 13 with a value greater than 0.0020, as follows:

$$BCR \left[\frac{DC_{ALT} \cdot AP_{i,n} + MC_{ALT}}{C_{KA} \cdot VSL}\right] = OR_{ALT/NULL}$$

$$1.0 \left[\frac{125{,}000 \cdot 0.0446 + 2{,}500}{0.33 \cdot 12{,}300{,}000}\right] = OR_{ALT/NULL} = 0.0020$$

For the 45-ft median highway discussed here, a high-tension cable median barrier will not become cost-beneficial until the traffic volume exceeds 60,000 veh/day. If the traffic volume increases to 75,000 veh/day on this same highway, the BCR will increase to a value of just over 2. The same analysis steps can be used for metal-beam median barriers using Table 14 or concrete median barriers using Table 15.

Due to the wide variety of roadside features and circumstances, risk reduction tables like those shown for median barriers in Table 13 through Table 15 are not available. Benefit-cost analysis can still be performed, however, knowing the relative risk of the considered alternative to the null alternative. For example, a less than 1-ft-diameter utility pole on a traversable slope is risk-beneficial (i.e., relative risk ≤1) if the pole is closer than 10 ft from the edge of the lane. While a shielding barrier may reduce the risk of a KA crash somewhat, it is not clear if shielding would be cost-beneficial. A pole shielded by a W-beam guardrail located 8 ft from the traveled way with a traversable slope has a relative risk of 0.75 (see Figure 25). If the AADT for this two-lane undivided highway is greater than 5,000 vehicles per day 1.1911 encroachments/mi/edge/yr can be expected. The BCR is calculated as:

$$BCR = OR_{ALT/NULL} \cdot \left[\frac{C_{KA} \cdot VSL}{DC_{ALT} \cdot AP_{i,n} + MC_{ALT}} \right]$$

$$BCR = OR_{\frac{ALT}{NULL}} \cdot \left[\frac{C_{KA} \cdot VSL}{DC_{ALT} \cdot AP_{i,n} + MC_{ALT}} \right]$$

$$BCR = (1 - 0.75) \cdot \left[\frac{0.33 \cdot 12{,}300{,}000}{125{,}000 \cdot 0.0446 + 2{,}500} \right] = 0.1 \ngtr 1$$

5.3.2 Cost-Effectiveness Analysis

Cost-effectiveness analysis is very similar to benefit–cost analysis but instead of monetizing benefits, the outcome itself (i.e., the annual reduction in KA crashes) is used. For example, instead of monetizing the societal cost of the crash reduction (i.e., benefit) resulting from shielding a median with a barrier, the number of fatal and serious injury crashes avoided could be used directly. The annualized cost of the median shielding improvement divided by the annual reduction in the number of KA crashes would be the incremental cost-effectiveness ratio.

The incremental cost-effectiveness ratio (ICER) is defined as follows: (Newnan 1976)

$$ICER_{i/j} = \frac{DC_i - DC_j}{PO_j - PO_i}$$

where

$ICER_{i/j}$ = The incremental cost-effectiveness ratio of alternative j with respect to alternative i.
PO_i, PO_j = Performance outcome for alternatives i and j over the project life.
DC_i, DC_j = The annualized cost of the direct (i.e., construction, maintenance, and repair) costs for alternatives i and j.

In the context of comparing median shielding alternatives, the ICER is calculated as follows:

$$ICER = \left[\frac{DC_{ALT} \cdot AP_{i,n} + MC_{ALT}}{OUTCOME_{ALT} - OUTCOME_{NULL}} \right]$$

Like benefit–cost analysis, present-worth, future-worth, and annual cost analyses could all be used with similar results, but annual cost-effectiveness analysis is used here because the reduction in KA crashes is an annual value. As before, the null alternative is the unshielded existing median, so there is no direct cost associated with alternative j. The KA crash reductions are tabulated in Table 13 for cable median barriers, Table 14 for metal-beam barriers, and Table 15 for concrete median barriers. Returning to the example of a four-lane divided highway with an AADT of 45,000 veh/day and a 45-ft-wide traversable median, the ICER can be calculated as follows:

$$ICER_{CABLE} = \left[\frac{125{,}000 \cdot 0.0446 + 2{,}500}{0.0002} \right] = \$40 \text{ million per KA crash avoided}$$

An ICER of $40 million to avoid one KA crash, given that the average KA CMC cost (i.e., C_{KA} VSL = 0.33 • 12.3) is $4.1 million, would appear to be a poor use of funds. Alternatively, if the

AADT increases to 60,000 veh/day, the number of KA crashes avoided is 0.0021 from Table 13, and the ICER is:

$$\mathrm{ICER}_{\mathrm{CABLE}} = \left[\frac{125{,}000 \cdot 0.0446 + 2{,}500}{0.0021}\right] = \$38 \text{ million per KA crash avoided}$$

This is just a little less than the KA crash cost, so it is likely a reasonable expenditure. Notice that these were also the conditions that resulted in a BCR = 1. The values in Table 13 through Table 15 and Figure 25, therefore, can also be used to calculate the incremental cost-effectiveness ratio. One of the advantages of the ICER method of economic analysis is that it does not require the user agency to monetize fatal and serious injury crashes. Better alternatives have lower ICER values and can be chosen on that basis alone. The ICER can be viewed as a priority rank for various projects with the higher values representing a high priority and better use of funding.

CHAPTER 6

Conclusions

As discussed in the Literature Review, the NTSB has recommended since 1998 that median barrier guidelines should consider heavy vehicles in the traffic mix. The NTSB recommendations were one of the catalysts for this research. The recommendations developed in this research provide guidelines that can be easily implemented in the RDG. These recommended MASH median and roadside barrier need, selection, and placement guidelines will be useful to design practitioners and can also be used by the FHWA and AASHTO to satisfy the NTSB recommendations.

The approach to developing the median barrier guidelines in this research used the long-held philosophy of the 1967 Yellow Book, which suggested a barrier "should only be used where the result of striking the object or leaving the roadway would be more severe than the consequences of striking the rail." (AASHO 1967) More particularly, a median barrier should only be installed if it reduces the expected number of KA crashes on the segment from that of a median with no median barrier. One result of this research was a method for assessing the need for a median barrier in situations where roadside barriers are not otherwise needed. In other words, the only hazard to be reduced is minimizing the chance of a vehicle fully crossing the median and striking or being struck by a vehicle in the opposing travel lanes. As shown in Figure 23, these recommendations involve the median width, traffic volume, and barrier material. After the need for a median barrier is assessed according to Figure 23, the proper test level is determined using Table 12 based on the PT in the traffic mix.

Chapter 3 of the AASHTO RDGuide addresses clear-zone widths and provides guidelines for shielding slopes that are free of fixed objects. Embankment height and foreslope are conventionally considered contributory factors to determining the barrier need for shielding slopes. When fixed objects are present, the RDG suggests removing the object or shielding it. (AASHTO 2011)The RDG terrain guidance dates to a 1967 study by Glennon and Tamburri that considered the relative severity of a crash with a barrier to a rollover crash. (Glennon 1967) The RDG acknowledges that this guidance does not account for the different probabilities of a barrier or rollover crash occurring. The Glennon and Tamburri study considered the probability of rolling over on the slope to be unity (i.e., all vehicles that interact with the slope will roll over). This reduced the guidance to a simple comparison of the difference in crash severity of impacting the barrier versus rolling over the slope. This research reconsidered the question whether a barrier is needed to shield slopes by modeling the probability of rollover for various slopes, vehicle types, and encroachment conditions. This re-examination found that barriers should not be used to shield slopes that are unobstructed and otherwise free of fixed objects when the slope is 2:1 or flatter. The injury consequences of striking the barrier outweigh the probability of an injury in a rollover on the slope when the slopes are flatter than 2:1. Guidelines for shielding fixed objects on slopes flatter than 2:1 are presented in Figure 25.

This research developed proposed guidelines for the selection and placement of a broad range of MASH median barriers (i.e., double-faced) and roadside barriers (i.e., single-faced) used within medians or on the roadside for shielding fixed objects. These proposed selection and placement guidelines address variables like the presence or absence of a barrier, the offset to the barrier, the type and test level of the barrier, the highway and median characteristics, and the traffic characteristics including the percentage of heavy vehicles. These guidelines are necessarily complex to address the broad range of these multiple design variables. Agencies that wish to have the greatest flexibility can incorporate the full extent of the guidelines. Agencies with limited geographic or geometric challenges may find that a simplified version with “built-in” assumptions meets their needs.

Before this research effort, roadside safety practitioners have never been able to use the specific site and traffic characteristics to target scarce transportation resources on the particular median sections most at-risk of a CMC. The use of these guidelines is expected to both improve the effectiveness of design guidelines in minimizing CMCs while targeting DOT funds and resources to the highway segments where the most benefit can be achieved.

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Abbreviations

AADT	annual average daily traffic
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ADOT	Arizona Department of Transportation
ADT	average daily traffic
AFT	Accelerated Failure Time (model)
AIC	Akaike Information Criterion
ALT	alternative shielded median
AP	capital recovery factor
BCR	benefit-cost ratio
BIC	Bayesian Information Criterion
Caltrans	California Department of Transportation
CASS	Trinity's cable safety system
CIF	cumulative incidence function
CMC	cross-median crash
CME	cross-median event
CO	cross-over-the-center line/cross-over (crash)
CRR	Competing Risk Regression (model)
DC	direct cost
DOT	Department of Transportation
EFCCR	equivalent fatal crash cost ratio
FHWA	Federal Highway Administration
FO	fixed object
FOHE	first and only harmful crash events
HCM	*Highway Capacity Manual*
HT	high tension
IBC	intermediate bulk container
ICER	incremental cost-effectiveness ratio
ISPEs	in-service performance evaluations
KA	fatal and serious injury (crash scale; term of art)
LB	longitudinal barrier
LL	log likelihood
LON	length of need
LT	low tension
LW	lane width
MaineDOT	Maine Department of Transportation
MASH	*Manual for Assessing Safety Hardware*
MC	annual maintenance cost

mph	miles per hour
MLE	maximum likelihood estimate
MRE	median-related event
MVM	million vehicle miles
MVMT	million vehicle miles traveled
NA	not available
NB	northbound
NCHRP	National Cooperative Highway Research Program
NDRF	non-designed roadside feature
NTSB	National Transportation Safety Board
NULL alternative	unshielded alternative
ODOT	Ohio Department of Transportation
pc	passenger cars
P(CMC)	probability of a CMC
PDO	property damage only
PennDOT	Pennsylvania Department of Transportation
PH	Proportional Hazard (model)
PO	performance outcome
PSEV	probability of crash severity
PSL	posted speed limit
PT	percentage of trucks
RDG	*Roadside Design Guide*
ROR	run-off-road
RR	relative risk
RSAP	Roadside Safety Analysis Program
RSAPv3	Roadside Safety Analysis Program, version 3
RSS	redirection on the same side of the barrier
SB	southbound
SBP	slope breakpoint
SCOD	Subcommittee on Design
SE	standard error
SUT	Single Unit Truck
SV	single vehicle
TCRS	Technical Committee on Roadside Safety
TDOT	Tennessee Department of Transportation
THR	probability of passing through a feature; also used to designate crashes that penetrate, rollover, or vault the feature
THR_{BAR}	probability of passing through, under, or over a barrier
THR_{EOL}	probability of passing across the opposing lanes
TL	test level
TRB	Transportation Research Board
TT	tractor trailer
TTI	Texas Transportation Institute
VSL	value of statistical life
veh/day, vpd	vehicles per day (vpd in Table 16)
WRSF	Brifen’s wire rope safety fence
WSDOT	Washington State DOT

APPENDIX A

Survey of States

This research includes the conduct of two surveys. A survey of the AASHTO Highway Subcommittee on Design (SCOD) Technical Committee on Roadside Safety (TCRS) members and the 50 states was conducted to identify current policies or practices for the selection and placement of median barriers. A second survey was distributed to the TCRS to receive input on the study protocol. The SCOD survey results are summarized here. The TCRS survey results were used to develop the research protocol and guide this research effort.

CONTENTS

CHAPTER 1

INTRODUCTION

This research included the conduct of two surveys. A survey of the AASHTO Highway Subcommittee on Design (SCOD) Technical Committee on Roadside Safety (TCRS) members and the 50 states was conducted to identify current policies or practices for the selection and placement of median barriers. A second survey was distributed to the TCRS for input on study protocol. The SCOD survey results are summarized here. The TCRS survey results were used to develop the research protocol and guide this research effort.

CHAPTER 2

SCOD SURVEY

The purpose of this survey was to gather information on the current practices, policies, and procedures used throughout the United States for median design and median barrier use. This survey served as an update to a previous survey conducted in 2006 as documented by Graham et al. in *NCHRP Report 794*. (Graham 2014) The survey was distributed to the AASHTO SCOD on March 29, 2016. The results, summarized herein, were current as of April 29, 2016.

Question 1: Changes Since 2006

At the onset of this survey, the survey participants were notified that this survey was an update of the survey conducted in 2006, and they were asked if there were any changes to their state's policies since that time. If the respondent indicated that the 2006 responses were still current, the respondent was directed to the end of the survey and thanked for their time. Otherwise, the respondent was taken through the survey questions. Twenty-six individuals viewed this question. Two skipped the question, while 24 responded. The exact wording of the question, answer options, and response counts are shown in Table A-1. Seventeen respondents (more than two-thirds) indicated that they either did not participate in the previous survey or did participate but their policies have changed in the interim.

Table A-1 Question One Summary

This survey was previously conducted in 2006. If your policies concerning median cross section and median barrier use have NOT changed since 2006, simply indicate "No Change" below.		**Response Percent**	**Response Count**
Answer Options	No change. The 2006 responses are still current.	29.2%	7
	Policies or practices have changed since 2006.	29.2%	7
	Did not respond to the 2006 survey.	41.7%	10
Answered question			24
Skipped question			2

Question 2: Typical Median Cross Section

The survey participants were asked to indicate their agency's typical cross section for medians on divided highways. Thirteen respondents provided feedback on this question while 13 respondents skipped it. The responses for median width varied considerably among the respondents who answered Question 2. Rural freeways were reported to have a typical width ranging from 36 to100 feet and urban freeways have a typical width ranging between 10 to 50 feet. Other roadways were reported to have a typical width between 4 to 80 feet depending on the design speed.

Conversely, the reported median slopes were rather consistent with typical values equal to 6H:1V with 4H:1V permitted. One respondent indicated the 10H:1V is typical and two indicated that 8H:1V is typical. Respondents specifically noted that when median barriers are in use, typical median widths are narrower. Some respondents also noted it is difficult to characterize medians by typical values.

The cross-section values from this survey are consistent with values reported in 2014 by Graham et al. in *NCHRP Report 794: Median Cross-Section Design for Rural Divided Highways*.

Question 3: Median Barrier Criteria

The survey participants were asked if their agency references the 2002 AASHTO Roadside Design Guide (RDG) Figure 6-1 criterion to evaluate the need for median barriers or if something else is referenced (e.g., 2006 RDG). Fourteen respondents answered this question while 12 respondents skipped it. Seven responses indicated that the 2002 AASHTO RDG is referenced. One indicated the 2006 RDG is referenced. Three indicated the 2011 RDG is referenced. The three other states reported having state-specific policies in place. The responses are shown graphically in Figure A-1.

The findings reported by Graham et al. in *NCHRP Report 794* in 2014 were from a survey conducted in 2006. Not surprisingly, none of the respondents to the Graham et al. survey used the 2006 AASHTO RDG in 2006. As indicated by the responses to this survey, in 2016, many States continued to use the 2002 AASHTO RDG figures to evaluate the need for median barriers.

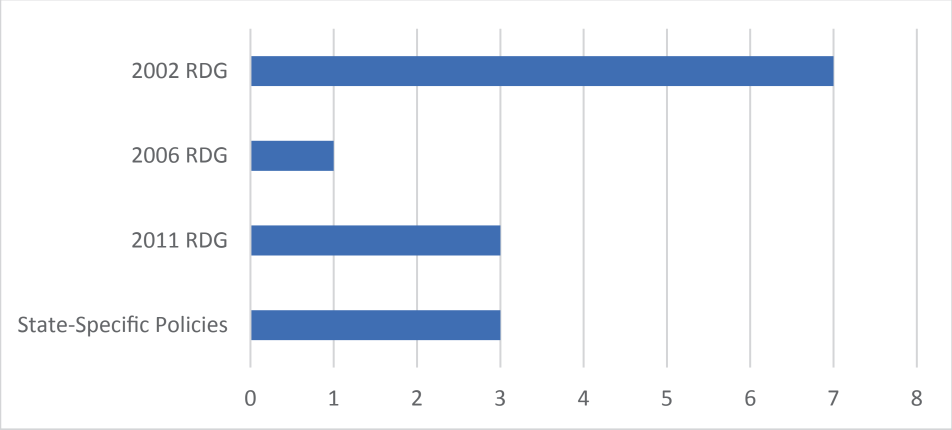


Figure A-1 Responses for median barrier guidance source material.

Question 4a and b: Median Barrier Need

The survey participants were asked which criteria are considered and the corresponding quantitative values to assess the need for median barriers for divided highways. Ten respondents answered this question while sixteen respondents skipped it. The responses listed a variety of median widths ranging from 36 feet to 64 feet, for which a barrier is provided (i.e., median width is a criterion for installation of a median barrier). Additionally, barriers are commonly provided by the respondents on divided highways with traversable narrow medians where the traffic volume was equal to or greater than 20,000 vehicles per day. Other factors considered by the respondents included:

- Crash history;
- Speed;
- Highway curvature;
- Clear zone issues including slopes;
- Highway type (e.g., median barrier required on all freeways);
- Agency experience; and/or
- New construction versus retrofit.

Question 5a, b, and c: Median Barrier Type and Placement

Ten respondents provided feedback on the median barrier types that are currently approved for use on divided highways, the minimum median width (ft) required for the approved barrier, the most common placement location, the maximum median side slope for installation, and the percent usage of each of the approved barrier types.

Comments were not received for weak-post w-beam median barrier or modified thrie-beam median barrier. One respondent offered that box-beam median barrier is used in medians with a width of 36 feet and 10:1 slope. The box-beam barrier is located three feet from the shoulder. This state’s inventory is approximately 40% box-beam.

Three-strand weak-post cable median barrier is typically installed in medians having a width ranging from 30 to 46 feet with a slope of 6:1 or flatter. The three-strand weak-post cable is installed either at the center of the median or four feet from the center.

High-tension cable was found to be installed in medians with widths of 15 to 40 feet. One state ensures the median is wide enough to accommodate the barrier deflection plus 50%. The high-tension cable is in medians with slopes of 10:1, 6:1, or 4:1 at the center of the median or offset eight feet from the centerline of the median ditch. States reported having a high-tension cable median barrier inventory of 5%, 10%, 16%, or 25%.

Blocked-out strong-post w-beam median barrier was found to be installed in medians with widths of 6 to 46 feet. One state reported using it exclusively for median clear zone issues. The strong-post w-beam is installed in medians with slopes of 10:1, 8:1, or 6:1 at a variety of locations, including:

- 6 feet from the edge of the travel lane;
- 2 feet from the outside shoulder;
- 12 feet from the edge of the travel lane;
- Center of median or at shoulder edge on curves;
- 4 feet from edge of pavement; or
- At slope break, beyond the edge of the paved shoulder.

The states responding with use of strong-post w-beam median barrier indicated the inventory was either 20% or 70% to 80%.

A few states reported using blocked-out thrie-beam median barriers in medians 6 to 30 feet wide with a slope of 6:1. The barrier is located at the center of the median and represents 10% of the inventory in states that use it.

F-shaped, single-slope, and New Jersey-shaped concrete median barriers were reported to be used in medians wide enough to accommodate the barrier and shoulder widths. These concrete median barriers are consistently located at the center of the median. The estimated usage for each barrier was reported to have the following range:

- F-shaped concrete barrier: 5% to 43%
- Single-slope concrete barrier: 13% to 50%
- New Jersey-shaped concrete barrier: 5% to 25%

Question 6: Median Barrier Type and Placement

The survey participants were asked if their state maintains a barrier asset inventory and if the inventory could be made available for the research effort. Six survey respondents answered in the affirmative by providing email contact information for their state's inventory point of contact. The States of Arkansas, Tennessee, Ohio, Maine, Wyoming, and Arizona provided contact information to obtain the asset inventory for use in this effort.

Question 7: Ditch Width, Slopes, and Depth

Participants in the survey were asked to provide the typical values used in their state for ditch width, slope, and depth. Twelve respondents answered this question in part or whole while fourteen respondents skipped it. Understandably, the answers to this question received some varied responses; summaries are provided below:

- Ditch widths reported included: 20, 30, 34, 40, 46, 50, 60, and 84 feet.
- The typical ditch slope values reported were 4:1, 6:1, and 8:1.
- Most respondents reported ditch depths of one to five feet. One respondent commented that the ditch depth can become much greater in some cases.

Question 8: ISPEs

The survey participants were asked if their agency had made in-service performance evaluations (ISPEs) to study the safety performance of various median designs or medium barriers. Three ISPEs were made available.

CHAPTER 3

SUMMARY

The purpose of this survey was twofold: (1) to track changes in policy over time and (2) to compile existing practices concerning the selection and placement of median barriers. One-third of the states that responded have not changed their practices since 2006, which reflects the adoption rate of the last update to the RDG. Respondents to this survey were clear that median designs vary considerably within a state and vary more between states. This survey compiled information on the current practices concerning median design and median barrier use. It was found that median widths vary from 30 to 100 feet and median slopes vary between 4:1, 6:1, 8:1, and 10:1. Over time, the existing practice for the assessment of median barrier needs has come to consider the following:

- Crash history,
- Speed,
- Highway curvature,
- Clear zone issues including slopes,
- Highway type,
- Agency experience, and/or
- New construction versus retrofit.

APPENDIX B

Probability of Reaching the Lateral Offset of Feature j—$P_Y(Y_j)$

The work presented in this appendix represents a significant enrichment to the understanding of the lateral extent of errant vehicle trajectories during an encroachment. This effort was possible because of the cooperation of four separate research projects teams. NCHRP Project 16-05, “Guidelines for Cost-Effective Safety Treatments of Roadside Ditches,” NCHRP Project 17-55, “Guidelines for Slope Traversability,” and NCHRP Project 17-43, “Long-Term Roadside Crash Data Collection Program” each contributed data to the undertaking documented herein. This research project and roadside safety have benefited from the willingness of these other research project teams at the Texas Transportation Institute and Virginia Tech to collaborate and share the data collected under those ongoing efforts.

CONTENTS

CHAPTER 1

INTRODUCTION

One objective of this research was to determine the probability of an errant vehicle's trajectory laterally extending to a location of interest (e.g., across the median, to the barrier). The influence of encroachment speed and angle, vehicle type, median/roadside terrain, and the shape of the median on the probable lateral extent, $P_Y(Y_j)$, of the errant vehicle's trajectory were studied. The analysis of $P_Y(Y_j)$ and these causal elements is documented below.

The encroachment probability model, as implemented in RSAPv3 as well as in RSAP and BCAP before it, assesses the probability of a crash based on passenger vehicle trajectories. In the case of BCAP and RSAP, a distribution of encroachment speeds and angles were used and straight-line trajectories were assumed. RSAPv3 included a database of reconstructed vehicle trajectories assembled under NCHRP Project 17-22 and assessed each reconstructed trajectory against individual obstacles. (Mak 2010; Ray 2012) The intent for the guidelines resulting from this research was to develop a selection process that can be included in the AASHTO Roadside Design Guide (RDG) and does not require the use of software such as RSAPv3 for each design decision. A model that represents the probable distribution of vehicle trajectories was therefore the desired outcome, not the continued use of software.

In this study, the statistical field of survival analysis was applied for the ability to model time to event data. Background information on this statistical field and the available data are discussed below. Descriptive methods, as well as statistical methods, were explored to represent these data. Conclusions and recommendations are formed from these analyses and presented at the close of this attachment.

CHAPTER 2

BACKGROUND

The outcome under assessment in epidemiological studies is often the time to an event of interest such as relapse of cancer or relief from disease. This time is generically known as **survival time** regardless of whether time to death or time to cure is being studied. The field of study known as survival analysis has evolved specifically to assess survival time.

Time to event, survival time, life length, and time to death are terms used interchangeably to describe the outcome variable in survival analysis. The "event" may be failure of some mechanical component, length of life after an AIDS diagnosis, time to relapse after alcohol recovery, and others. If the failure of a mechanical component were the event of interest, the study would measure time in service for that component until failure or a pre-determined end of the study data collection. The measurement of time in the example may be hours in service, revolutions, or a different appropriate measure for the said mechanical component. When patients are being studied, as in length of life after an AIDS diagnosis, time would be measured as well as likely interventions (e.g., medicines). The age and/or sex of the patient at the start of the study may also be considered causal.

In this study, the statistical field of survival analysis was applied for the ability to model time to event data. The event under assessment is the maximum lateral extent of an errant vehicle's trajectory. In this context, survival time is considered the maximum lateral distance each trajectory traveled from the encroachment location (i.e., edge of travel). The unit of measure is feet from the encroachment location. The encroachment speed and angle as well as the vehicle type have been assessed for influence on the maximum lateral extent. Intermediate terrain changes are also included in the study to determine, what if any, influence these terrain changes have on survival time.

The genesis of survival analysis can be found in the study of time to death; therefore, it was common to have a data set with events that were not observed (e.g., the study ends before all participants die). In the case of vehicle trajectories, data gathering might stop after, for example, 100 feet from the travel way, but the vehicle may not have been observed stopping. The unobserved events are certain to happen if observation were to continue long enough (e.g., death is inevitable, vehicles eventually run out of momentum). These types of data are known as censored data and are specifically addressed using this analysis technique. On the other hand, death from other causes is not considered censored.

Recall the maximum lateral extent of the vehicle trajectory is the "event of interest." To put a finer point on it, we are interested in those events involving the vehicle stopping or coming to rest with all four wheels on the ground. Using this definition, if a vehicle's maximum lateral extent is observed not from stopping, but from rolling over (i.e., other cause), this is not a censored observation. The observation is complete and known as a competing risk. (Pintilie 2006) We certainly want to capture all the vehicles which traveled each foot of the terrain, and we want to also capture how the trajectory terminated.

The various descriptive and statistical methods examined using survival analysis techniques, including the consideration of the censored data and the competing risks, are summarized below after the discussion of available data.

CHAPTER 3

AVAILABLE DATA

The NCHRP Project 17-22 data contains 787 reconstructed trajectories from run-off-road crashes. (Mak 2010) Also of interest, the ongoing NCHRP Project 17-43 data is augmenting the NCHRP Project 17-22 data. (Gabler 2020) A beta version of the NCHRP Project 17-43 data set was made available for use in this effort. Both data sets include reconstructed trajectories which resulted in a crash, prematurely ending the vehicle trajectory. While neither of these data sets includes the full distribution of the probable lateral extent of a vehicle trajectory when the roadside is free of other obstacles, both data sets do provide a distribution of encroachment angle and speed. Capturing the full lateral extent of vehicle trajectories (i.e., trajectories not involved in a crash) necessitates applying the findings to a more general roadside/median environment. The influence that fixed object or other roadside features such as barriers have on a crash is captured in a separate portion of the encroachment probability model; therefore, it is paramount that this model captures exclusively the influence of terrain, not other roadside features such as fixed objects or barriers.

The ongoing NCHRP Project 16-05, "Guidelines for Cost-Effective Safety Treatments of Roadside Ditches," included the simulation of vehicle trajectories through a variety of median ditches. (Sheikh 2021) The recently completed NCHRP Project 17-55 resulted in *NCHRP Research Report 911: Guidelines for Traversability of Roadside Slopes* that reports on simulated vehicle trajectories on a range of infinite slopes. (Sheikh 2019) Using these simulated data and assuming the simulation results are identical for roadsides and medians, one could determine the probable lateral extent of a vehicle when navigating a host of terrains while not being subjected to other roadside/median features such as fixed objects or barriers.

These simulated data certainly are favored for the richness of information, including both slopes with terrain features such as ditches and simple continuous slopes without complex terrain features. These simulated data, however, do not capture the actual distribution of vehicle encroachment angles and speeds or vehicle types. The NCHRP Projects 17-22 and 17-43 data do include these distributions but are much smaller data sets where the trajectories stop due to a crash (i.e., right-truncated). The favored course of action was to use the strengths of both data sets. The field-collected data were then used to weight the causal elements of the simulated data only after the elements were determined to be influential. The goal of this approach is to maximize the utility of each data set and minimize the complexity of the resulting model.

The simulated data were used as two data sets: (1) a combined data set of simple and complete roadside terrains; and (2) a limited data set of simple terrain without ditches. This dual approach allows for the unambiguous examination of complex terrain features. The simulated data were evaluated for the influence of vehicle type, encroachment angle, and speed.

Data Summary

The TTI research team provided the 57,600 trajectories from NCHRP Project 16-05, which studied trajectories through ditches, and the 43,200 trajectories from NCHRP Project 17-55, which studied trajectories on slopes. Both research projects simulated trajectories for the Ford Taurus, MASH Small Car, Ford Explorer, and MASH Pick up. The TTI data were gathered in SI units and converted to English units for guideline development before analysis. The variable names used throughout this document and the summary statistics for the Projects 16-05 and 17-55 data sets are shown in Table B-1 for the variables treated as factors and Table B-2 for the continuous variables.

Table B-1 Factor Level Summary Statistics and Variable Names

Covariate	Variable Name	Levels	Number of Trajectories	
			16-05	17-55
Foreslope (1V:*x*H)	FS	−10, −6, −4, −3, and −2	11,520 at each level	8,640 at each level
Foreslope width	FSW	8 ft	28,800	10,800
		16 ft	28,800	10,800
		32 ft	0	10,800
		105 ft	0	10,800
Ditch bottom width	BtW	0 ft	19,200	43,200
		4 ft	19,200	0
		10 ft	19,200	0
Backslope (1V:*x*H)	BS	0	14,400	43,200
		2	14,400	0
		3	14,400	0
		4	14,400	0
		6	14,400	0
Backslope width	BSW	8 ft	28,800	43,200
		16 ft	28,800	0
Encroachment speed (mi/h)	Spd	25	0	7,200
		35	0	7,200
		45	14,400	7,200
		55	14,400	7,200
		65	14,400	7,200
		75	14,400	7,200
Encroachment angle (degrees)	EncAng	5	0	7,200
		10	19,200	7,200
		15	0	7,200
		20	19,200	7,200
		25	0	7,200
		30	19,200	7,200
Driver input number (See Appendix A)	DriverInput	1, 2, 3, 4, and 5	11,520 at each level	8,640 at each level
Outcome	Outcome	Gone.Far	6,803	10,766
		Overturn	22,425	6,213
		Returns	16,224	13,008
		Stops	9,061	10,725
		Time.exceeded	3,087	2,488
Vehicle type	Veh	Pickup_Truck	14,400 at each level	10,800 at each level
		FordTaurus		
		Small_car		
		Explorer2002-v1		

Table B-2 shows that in both data sets, the maximum recorded lateral extent in feet (MaxLatF) is above 100 ft by a few decimal places, but the study design included the censoring of data at 100 ft. This minor discrepancy was likely introduced by either converting between units of measure or from translating the vehicle center of gravity to the maximum point of the vehicle on the terrain. The data have been limited to reflect a maximum 100 ft MaxLatF value to ensure the calculations performed for censored data do not overcompensate for this one-half inch value. Thus, the results of this study should be considered to have an accuracy of ± half an inch.

Table B-2 Continuous Variable Summary Statistics and Variable Names

Covariate	Variable	Summary Statistics	16-05	17-55
Maximum lateral extent (feet) as measured from the edge of travel	MaxLatF	Minimum	3.814	0.296
		1st quartile	26.552	16.436
		Median	37.642	46.169
		Mean	46.792	51.396
		3rd quartile	66.277	99.797
		Maximum	100.042	100.029

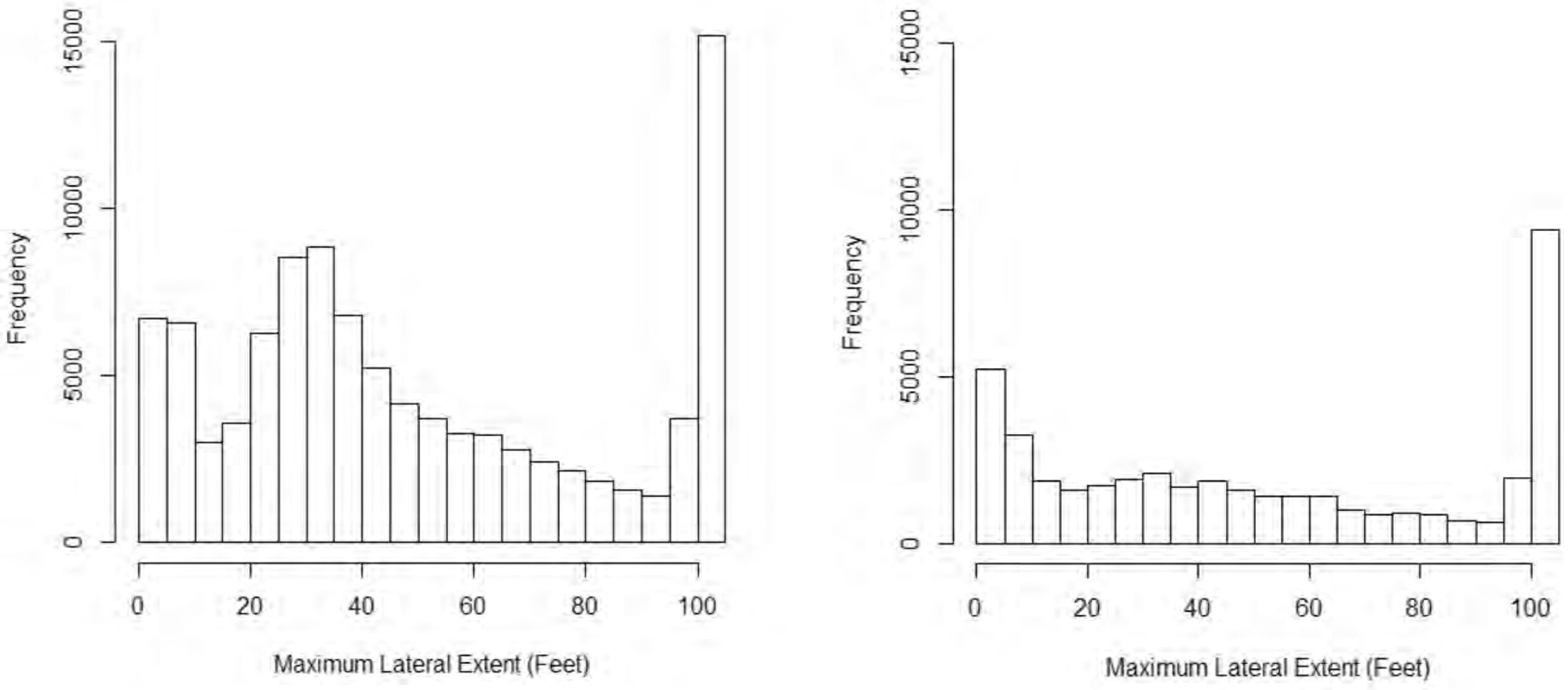
The frequency distribution of the combined Project 16-05 and 17-55 data sets is shown in Figure B-1a. The frequency distribution in Figure B-1b is limited to the Project 17-55 data set (i.e., simple slope data). Notice the large number of trajectories that travel at least 100 feet. The pre-determined stoppage of data collection when the center of gravity of the vehicle traveled 100 ft laterally accounts for this fact. This histogram confirms these data are right-censored, as is often the case in survival analysis. The tools for addressing censoring are discussed more below. These frequency distributions also confirm the complex terrains represented in Figure B-1a have a higher instance of trajectories stopping between 30 and 40 feet, where many of the ditches are introduced.

The data elements were reviewed to determine how closely increases in an element correlate with increases in another data element using the Pearson and Spearman's correlation coefficients as shown in Table B-3 for the combined Projects16-05 and 17-55 data sets and Table B-4 for only the 17-55 data set.

A value of one indicates that an element is a linear function of the other (e.g., when an element is compared to itself). A value of zero indicates the data elements are not correlated. Data elements with higher values are considered more correlated. Negative values indicate inverse correlation.

Pearson's correlation coefficient assumes: (1) the data elements are normally distributed and (2) if a relationship exists between the elements, it is linear. The Spearman test does not make either of these assumptions but is interpreted in the same manner (i.e., values approaching unity are more closely correlated, zero are not correlated and negative values are inversely correlated).

By inspection, EncAng, Spd, DriverInput, and Outcome have the highest correlations to MaxLatF. These elements have higher correlations than the slope of the terrain. Most interestingly, the sign for the correlation of MaxLatF and FS changes between Table B-3 and Table B-4. In other words, the correlation was negative when the complex terrains were considered, but positive when the simple sloped terrain was considered.



a) b)

Figure B-1 Frequency distribution for the maximum lateral extent of the trajectory data sets with *a)* combined Projects 16-05 and 17-55 data sets and *b)* only the Project 17-55 data set.

Table B-3 Correlation Matrix for Data Elements in the Combined Projects 16-05 and 17-55 Data Sets

Pearson’s Correlation

	MaxLatF	Veh	Outcome	DriverInput	EncAng	Spd	BtW	BS	BSW	FS	FSW
MaxLatF	1.0000	-0.0377	-0.5024	-0.5041	0.5051	0.2727	0.0180	0.0063	-0.0497	-0.0513	0.1541
Veh		1.0000	-0.0557	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Outcome			1.0000	0.1693	-0.3482	-0.3103	0.0167	-0.0412	-0.0052	-0.0499	-0.0962
DriverInput				1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
EncAng					1.0000	0.0489	0.0877	0.1259	0.0805	0.0000	-0.0711
Spd						1.0000	0.1986	0.2852	0.1824	0.0000	-0.1610
BtW							1.0000	0.5110	0.3268	0.0000	-0.2885
BS								1.0000	0.4692	0.0000	-0.4143
BSW									1.0000	0.0000	-0.2649
FS										1.0000	0.0000
FSW											1.0000

Spearman’s Correlation

	MaxLatF	Veh	Outcome	DriverInput	EncAng	Spd	BtW	BS	BSW	FS	FSW
MaxLatF	1.0000	-0.0320	-0.5026	-0.5029	0.5557	0.2779	0.0293	0.0202	-0.0320	-0.0343	0.1304
Veh		1.0000	-0.0600	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
Outcome			1.0000	0.2067	-0.3530	-0.3202	0.0116	-0.0479	-0.0107	-0.0779	-0.0438
DriverInput				1.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
EncAng					1.0000	0.0477	0.0970	0.1321	0.0805	0.0000	-0.0673
Spd						1.0000	0.2144	0.2919	0.1779	0.0000	-0.1487
BtW							1.0000	0.5934	0.3617	0.0000	-0.3023
BS								1.0000	0.4922	0.0000	-0.4115
BSW									1.0000	0.0000	-0.2508
FS										1.0000	0.0000
FSW											1.0000

Table B-4 Correlation Matrix for Data Elements Limited to the Project 17-55 Data set

Pearson's Correlation

	MaxLatF	Veh	Outcome	DriverInput	EncAng	Spd	FS	FSW
MaxLatF	1.0000	-0.0333	-0.5713	-0.5018	0.5245	0.4036	0.0371	0.1794
Veh		1.0000	-0.0366	0.0000	0.0000	0.0000	0.0000	0.0000
Outcome			1.0000	0.1994	-0.2898	-0.3636	-0.0447	-0.1830
DriverInput				1.0000	0.0000	0.0000	0.0000	0.0000
EncAng					1.0000	0.0000	0.0000	0.0000
Spd						1.0000	0.0000	0.0000
FS							1.0000	0.0000
FSW								1.0000

Spearman's Correlation

	MaxLatF	Veh	Outcome	DriverInput	EncAng	Spd	FS	FSW
MaxLatF	1.0000	-0.0298	-0.5315	-0.5149	0.5513	0.4111	0.0410	0.1663
Veh		1.0000	-0.0431	0.0000	0.0000	0.0000	0.0000	0.0000
Outcome			1.0000	0.1995	-0.2574	-0.3643	-0.0543	-0.1509
DriverInput				1.0000	0.0000	0.0000	0.0000	0.0000
EncAng					1.0000	0.0000	0.0000	0.0000
Spd						1.0000	0.0000	0.0000
FS							1.0000	0.0000
FSW								1.0000

CHAPTER 4

DATA ANALYSIS

Time, as measured in feet to the trajectory terminus, is the response variable (T). The survival function is the probability that an observation survives longer than t, $S(t) = P(T > t)$. The cumulative distribution can be expressed as $1 - F(t)$. Therefore, at time equal to zero, survival is 100% (i.e., when t=0, S(t)=1), and as time approaches infinity, survival approaches zero (i.e., when t=∞, S(t)=0). In terms of trajectories, at the point where a trajectory exits the travel way (i.e., time equal to zero), the survival of that trajectory is 100% (i.e., when t=0, S(t)=1), and as the maximum lateral extent of the trajectory approaches infinity, the trajectory survival approaches zero (i.e., when t=∞, S(t)=0).

The trajectory may stop for a variety of reasons (e.g., lack of energy, rollover, and exceeded study measurement period). It is generally the goal of data collection to collect complete observations for each trajectory. “Two mechanisms can lead to incomplete observations of time: censoring and truncation. A censored observation is one whose value is incomplete due to factors that are random for each subject. A truncated observation is incomplete due to a selection process inherent in the study design.” (Hosmer 2011) The trajectories that exceed the measurement period are said to be right-censored data. Conversely, left censoring occurs when a trajectory does not originate at the same beginning as the other trajectories. These are simulated data collected as part of a designed study where each of the trajectories originated at the edge of travel (i.e., time zero). Left censoring of these raw data is not considered an issue. The Projects 16-05 and 17-43 data sets of reconstructed crash trajectories discussed above are examples of right-truncated trajectories (i.e., the data collection stopped when a trajectory was involved in a crash).

Software Used

The statistical computing software and language R was used for the model selection, visual inspection, and model development. (R 2017) The survival package (Therneau 2015) available in R was used for the Kaplan-Meier, Cox Proportional Hazard, and Weibull estimates. The SurvRegCensCov package (Hubeaux 2015) available in R was used to interpret the estimated Weibull model. The survminer package (Kassambara 2017) available in R was used to develop faceted plots of data. The cmprsk package (Fine 1999) was used to estimate and evaluate the cumulative incident function (CIF). The riskRegression package (Fine 1999) was used to develop a formula for the CIF. (Gerds 2018)

Assessment of Covariates

The cumulative probability of survival to any point in time can be found through a univariate description of the data. The K-M estimator of the survival function is a univariate, nonparametric estimate of time to event. Assuming each trajectory is independent, S(t) is simply calculated directly from the trajectories:

$$S(t_j) = S(t_{j-1})(1 - \frac{d_j}{n_j})$$

Where:

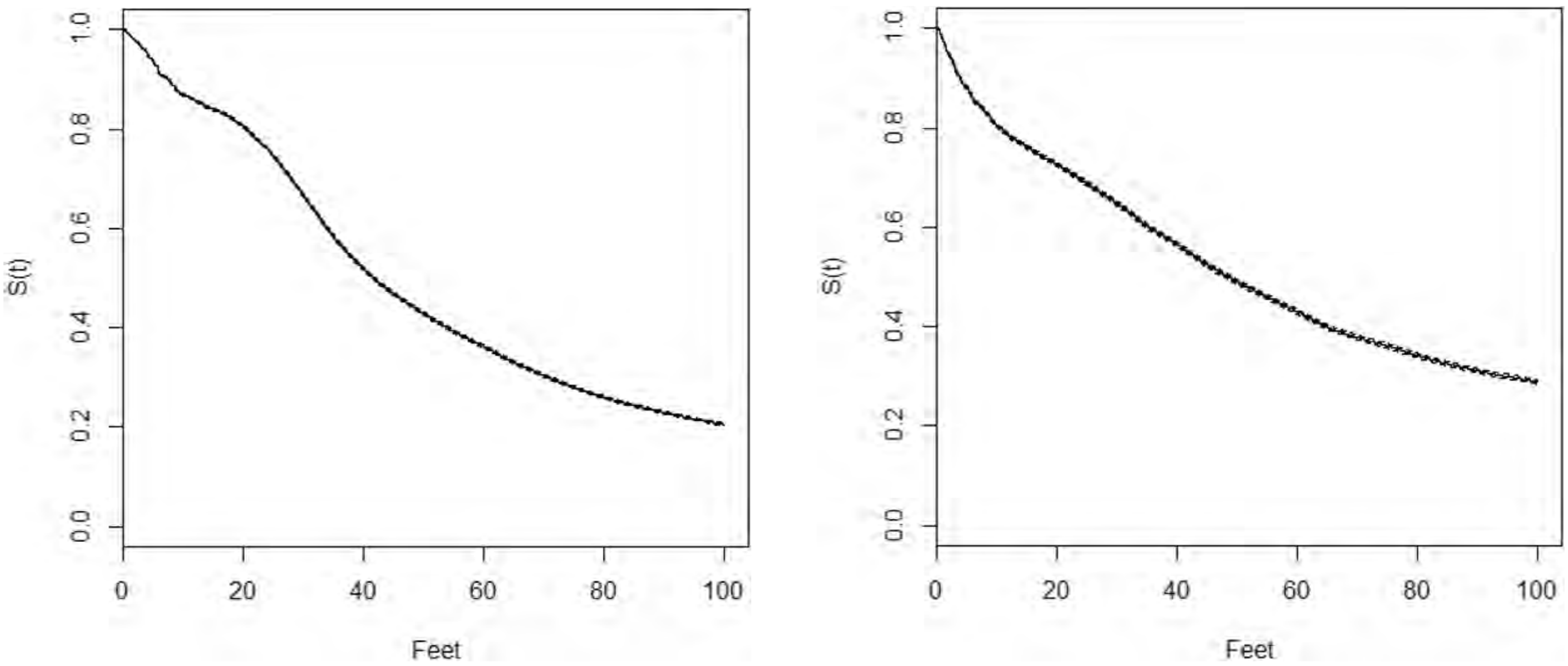
$S(t_j)$	Probability of continued movement at measurement t_j
n_j	Number of trajectories with continued movement just before t_j
d_j	Number of trajectories where movement stopped by measurement t_j

The Kaplan-Meier survival curves essentially provide a visual representation of the collected trajectory data, as shown in Figure B-2a for the combined Projects 16-05 and 17-55 data sets and Figure B-2b for only the Project 17-55 data set. The above function can also be used to generate a lookup table of numeric values.

"The Kaplan-Meier method is the most common as well as the most controversial technique in the competing risks framework." (Pintilie 2006) Parametric inference can be more informative than methods that assume no form for the distribution. Multivariate analysis allows for the consideration of how factors jointly impact survival. A statistical model with multiple covariates, therefore, provides a tool to assess clinical differences, joint influence, and competing risks such as rollover. Several covariates were assessed before undertaking the modeling. The covariates were assessed using the Kaplan-Meier method, a log-rank test, and Gray's test. Covariate correlation with the maximum lateral extent was previously discussed.

Figure B-3 shows one of these visual comparisons between trajectory outcome and vehicle type for the combined Projects 16-05 and 17-55 data sets and Figure B-4 when the data are limited to only the Project 17-55 data set. Notice that the probability of returning to the road decreased for each vehicle type the further the vehicle travels from the road. Also notice that when the censored categories (e.g., gone too far, time exceeded) are considered individually, a probability of survival cannot be calculated.

Differences in survival between groups (e.g., vehicle type, outcome) can be assessed using the log-rank test and/or visually using Kaplan-Meier survival curves. A log-rank test for differences in survival between groups was conducted for the study. This method calculates at each event time, for each group, the number of events one would expect since the previous event if there were no difference between the groups. "While the log-rank test provides a P-value for the differences between groups, it offers no estimate of the actual effect size; in other words, it offers a statistical, but not a clinical, assessment of the factor's impact." (Bradburn 2003) The results are summarized in Table B-5. The p-value for each covariate is less than 0.05; therefore, there is a statistically significant difference between the complete survival curves for each covariate. The statistical models will be used to determine the size effect of these differences. (Clark 2003)



a)

b)

Figure B-2 Kaplan-Meier estimate with 95% confidence bounds for *a)* combined Projects 16-05 and 17-55 data sets and *b)* only the Project 17-55 data set.

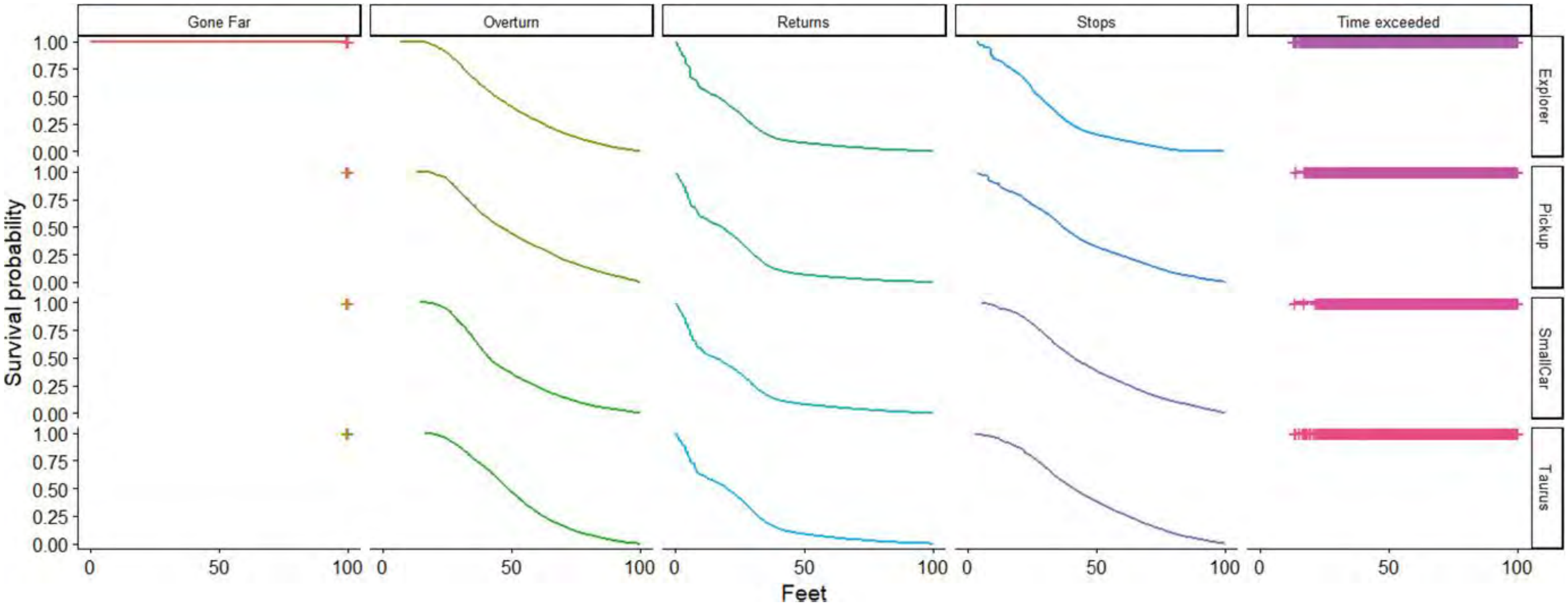


Figure B-3 Survival probability by vehicle type and trajectory outcome for the combined Projects 16-05 and 17-55 data sets.

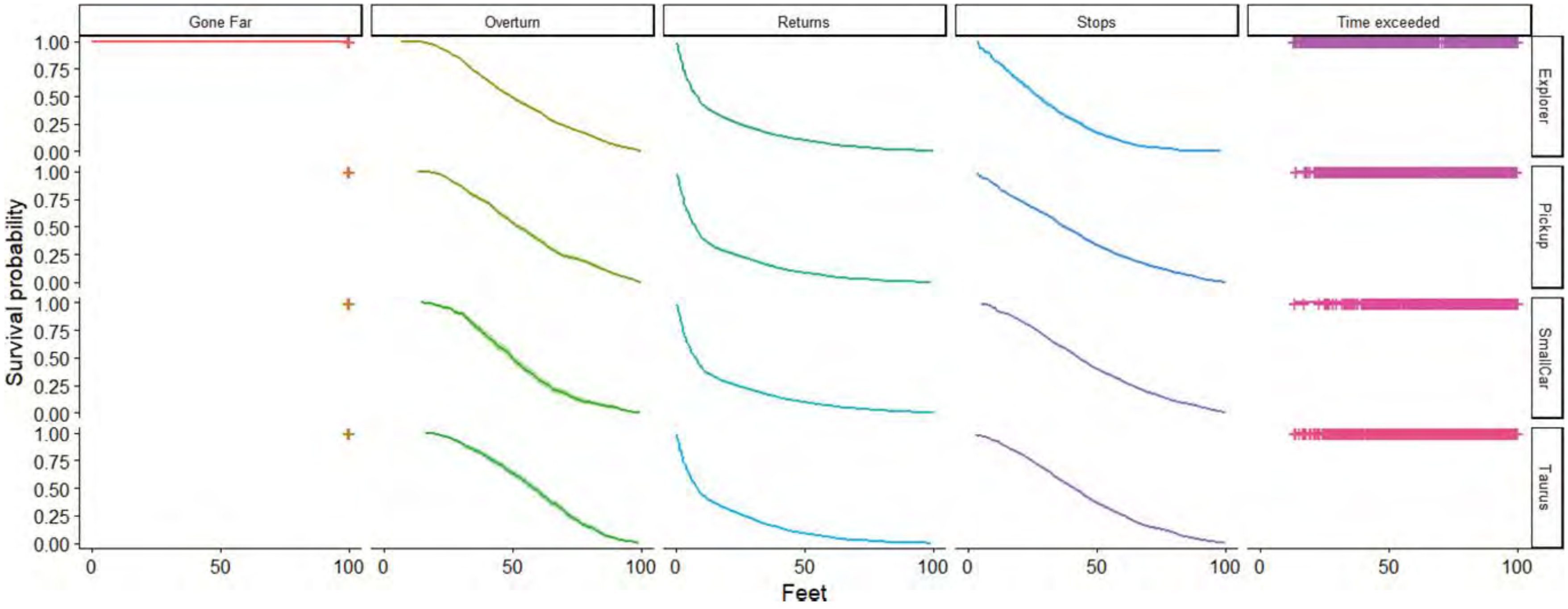


Figure B-4 Survival probability by vehicle type and trajectory outcome limited to only the Project 17-55 data set.

Table B-5 Log-Rank Test of Each Covariate.

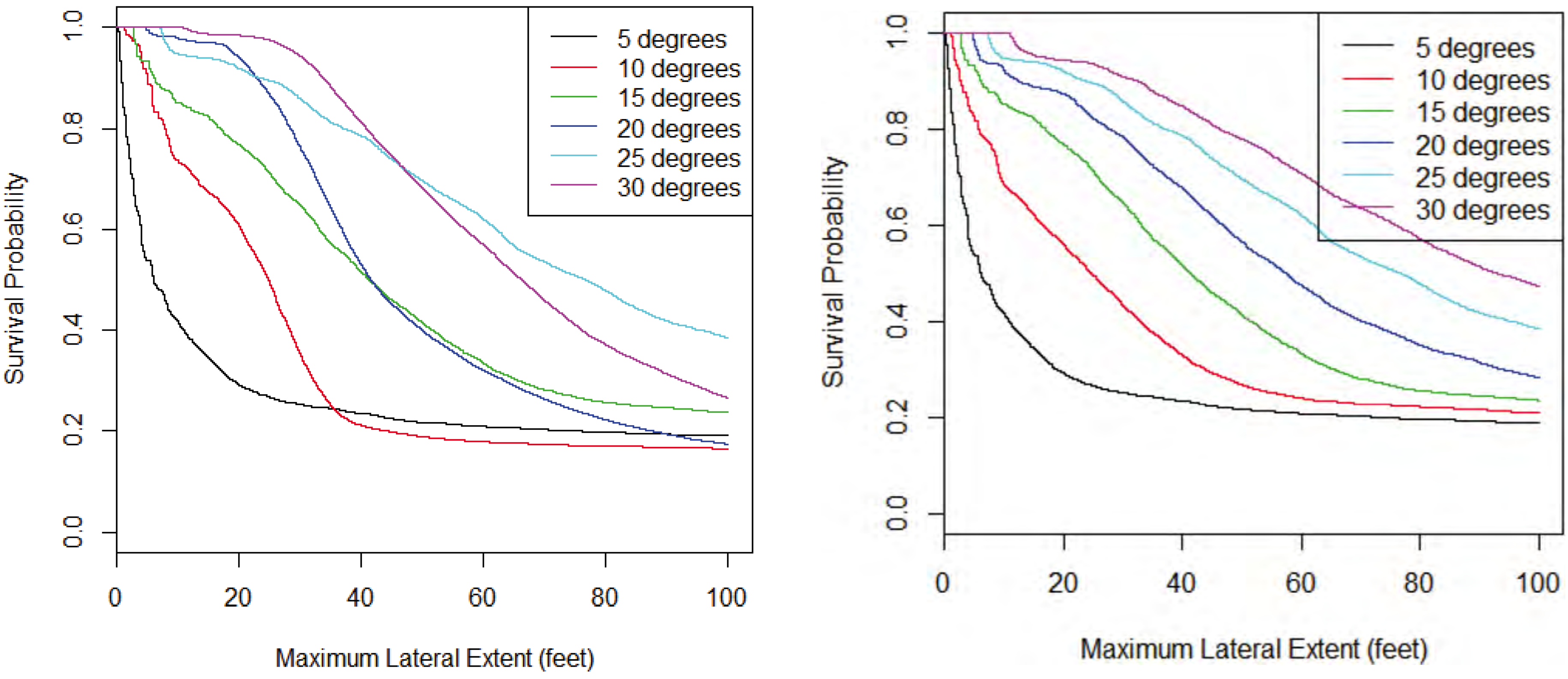
Covariate	16-05 & 17-55 Data sets			17-55 Data set		
	x^2	DF	p-value	x^2	DF	p-value
Veh	155	3	0.0000	59.5	3	7.46e-13
Outcome	78514	4	0.0000	42099	4	0.0000
FS	86.3	4	0.0000	99.2	4	0.0000
BS	1584	4	0.0000	---	---	---
BtW	279	2	0.0000	---	---	---
BSW	82.5	1	0.0000	---	---	---
FSW	1677	3	0.0000	---	---	---
EncAng	34658	5	0.0000	14214	5	0.000
Spd	11364	8	0.0000	7022	5	0.000

It is important to appreciate any possible proportional relationship, which can be accomplished through visual inspection of the data. If the survival curves do not cross, but rather are generally parallel, then the covariates are proportional and could be represented by multipliers. If proportionality exists, there is potential to use a model which is simpler within the guidance documents. If the curves cross, this proportional assumption is violated.

Figure B-5 shows the survival curves by encroachment angle. Recall encroachment angle is the variable most highly correlated with maximum lateral extent (see Tables B-3 and B-4). Table B-5 shows that encroachment angle is a significant predictor of the maximum lateral extent. When the data sets are combined such that complex roadside terrains are included with simple roadside slopes as shown in Figure B-5a, increases to the encroachment angle are not proportionally related to the maximum lateral extent. Figure B-5b, however, shows that when simple slopes are considered alone, the encroachment angle is proportionally related. The encroachment angles appear to influence survivability differently between these two data sets, or it is more likely that the interpretation is marred by the complex terrain.

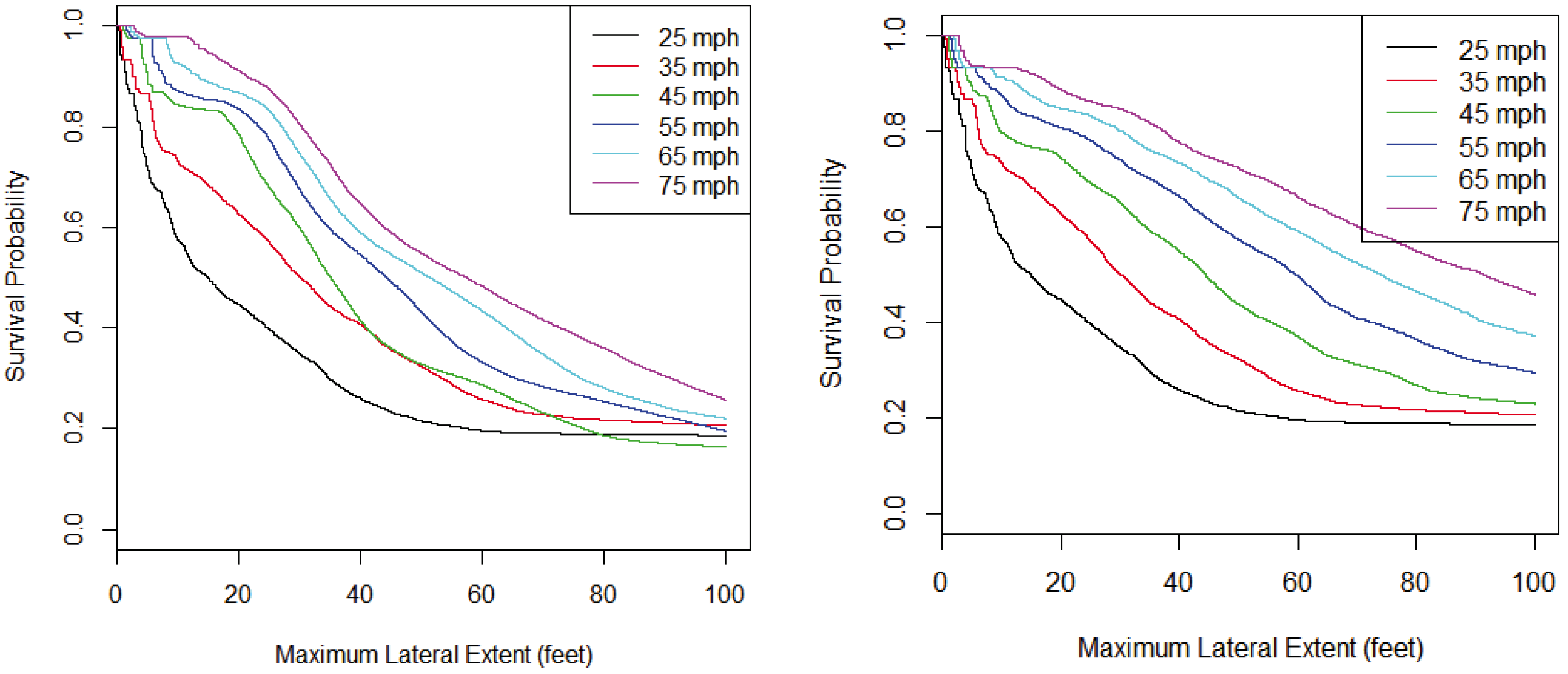
The survival probability by encroachment speed is shown in Figure B-6. Encroachment speed is also one of the more correlated covariates with maximum lateral extent. Note that some of the curves cross in Figure B-6a on the left, while the curves become parallel in Figure B-6b on the right. As with encroachment angle, encroachment speed appears to influence survivability differently between these two data sets, or else complex terrains are impacting the interpretation. When limited to simple roadside slopes, encroachment speed has a multiplicative effect on the maximum lateral extent. When complicated by complex terrains, this multiplicative relationship dissolves.

Vehicle type is the least correlated covariate with maximum lateral extent; therefore, it has the least influence on increases or decreases in value. The p-value for vehicle type is less than 0.05, which indicates a statistically significant difference between curves, but the practical difference is negligible in both data sets, as shown in Figure B-7. Recall Figures B-3 and B-4 where the possible outcomes were assessed by vehicle type and no apparent difference in outcome by vehicle type was observed. These data indicate that the distinctions among passenger vehicles, when modeling maximum lateral extent, are not necessary.



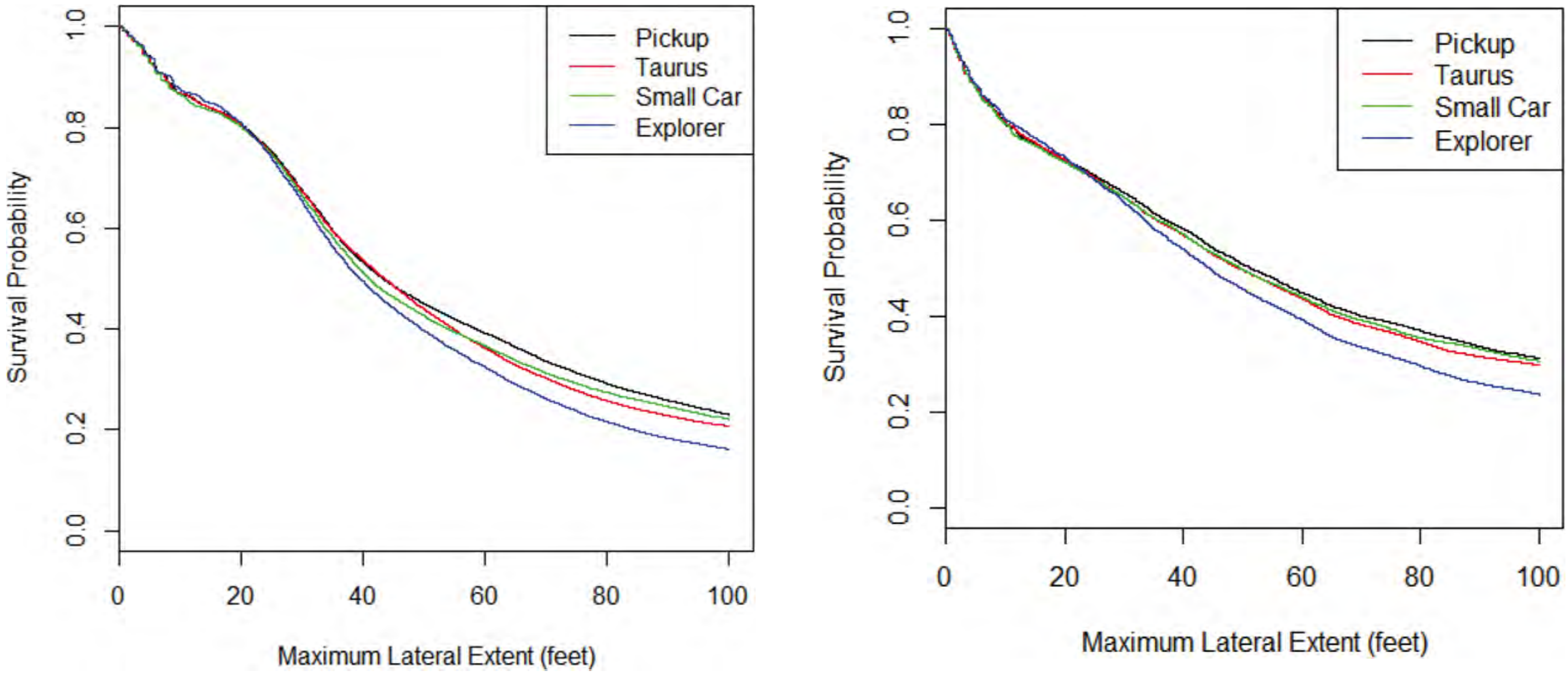
a) b)

Figure B-5 Kaplan-Meier survival curves by encroachment angle with *a)* combined Projects 16-05 and 17-55 data sets and *b)* only the Project 17-55 data set.



a) b)

Figure B-6 Kaplan-Meier survival curves by encroachment speed with *a)* combined Projects 16-05 and 17-55 data sets and *b)* only the Project 17-55 data set.



a) b)

Figure B-7 Kaplan-Meier survival curves by vehicle type with *a)* combined Projects 16-05 and 17-55 data sets and *b)* only the Project 17-55 data set.

Competing Risks

It was found with the Kaplan-Meier (K-M) estimator, tests for correlation, and the log-rank test that the encroachment angle and encroachment speed influence survivability differently between these two data sets. This is believed to be a result of the complex terrains simulated under NCHRP Project 16-05. Until this point, the measurement for maximum lateral extent has not differentiated between the assorted reasons a vehicle trajectory may terminate. These data include five events of interest coded in the data under "Outcome" as shown here:

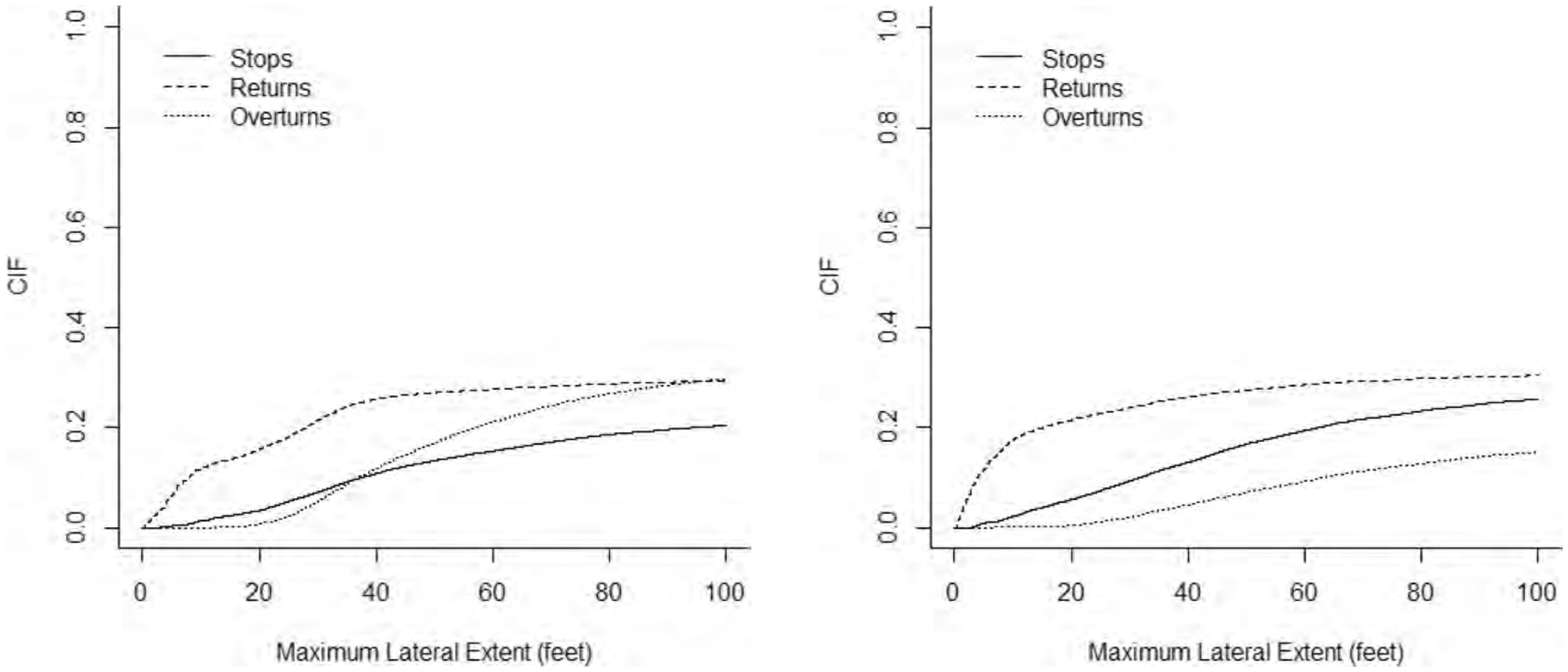
- Gone far
- Overturn
- Returns
- Stops
- Time exceeded

If a vehicle trajectory has exceeded the measurement period (i.e., "Gone Far" or "Time exceeded"), then the data are censored. There is a desire, however, to capture the differences between the vehicle stopping, overturning, or returning to the traveled way. This additional information can better support the application of the encroachment probability model and policy decisions. For example, if there is a 0.70 probability of an errant vehicle traveling 20 ft from the travel way, how does the vehicle come to rest? This vehicle may simply stop or return to the roadway without an increase in crash probability. The vehicle may also overturn which by itself is an increase in crash probability (i.e., overturn crash). While it might be desirable to locate barriers far from the road to minimize the probability of an errant vehicle getting to the barrier and having a crash, this should be balanced with any increased probability of rollover.

The K-M estimator discussed above is a univariate, non-parametric representation of the data appropriate when competing risks (e.g., rollover, stops, returns to road, censored) are not modeled. The CIF is appropriate for modeling competing risks. The CIF is also a non-parametric approach to survival analysis. The CIF is the probability of remaining event-free measured laterally from the encroachment location.

The CIF allows for the consideration of how overturning contributed to the probable maximum lateral extent. The CIF is a joint probability of each of the possible outcomes being observed (or not observed in the case of the censored data). The CIF estimator for each event depends on both the number of trajectories experiencing an event at a time point and the number of trajectories not experiencing any other event at the same timepoint. The sum of the CIFs for each event at each time represents the joint probability at that time of the maximum lateral extent of the trajectory.

The distance to the first observed event was considered. A censoring variable (cens) was created from the outcomes and coded as 0 when no events were observed (i.e., gone too far or time exceeded); 1 if the vehicle stopped on the terrain; 2 if the vehicle returned to the road; and 3 if an overturn was observed. Figure B-8 provides the CIF for the combined data (i.e., the Projects 16-05 and 17-55 data sets) and the data limited to continuous slopes (i.e., only the Project 17-55 data set).



a) b)

Figure B-8 CIF for maximum lateral extent with *a)* combined Projects 16-05 and 17-55 data sets and *b)* only the Project 17-55 data set.

Comparing the CIFs considers each type of event and does not assume independence between the time to the different types of events. (Pintilie 2006) These figures are cumulative risks. Notice that the "risk" of returning to the road quickly ascends to approximately 20%, but no further increase is seen the further the trajectory journeys from the traveled way. Conversely, notice that rollover risk is essentially zero for the first twenty feet, then the risk increases the longer the vehicle stays on the roadside. In Figure B-8a, where the data that include complex terrains are shown, the risk of overturning is not linearly related to time on the terrain but is likely reflective of the introduction of the complex ditch elements. In Figure B-8b, where only simple slopes are shown, the risk of overturning appears to be a linear relationship (after 20 ft) that increases with time on the slope. This would indicate that simple exposure to the slope increases overturning risk while the exposure to the complex terrain elements should also be captured.

The "risk" of the errant vehicle stopping is virtually linearly related to distance. Interestingly, the risk of overturning becomes greater than either the vehicle stopping or returning, but never greater than the combined risks of the vehicle stopping or returning to the traveled way. This certainty merits further consideration.

The CIF is a non-parametric estimate. Neither encroachment angles, nor encroachment speeds are explicitly modeled using this approach. Each technique provides insight. The log-rank test shown in Table B-5 is a test based on the cause-specific risk where the different outcomes are ignored. Each variable captured in this study is considered statically significant using the log-rank test. Variations in outcome by, for example, encroachment speed and angle are not captured in the log-rank test. While the log-rank test is informative, it should be not considered alone.

Gray's test for encroachment angle or speed by outcome is not shown here. Neither encroachment angle nor speed was found to be significant when predicting the differences between possible outcomes (i.e., competing risks) within the combined data, however, when the data is limited to simple slopes, both encroachment angle and speed are highly significant predictors of outcome. Recall encroachment angle and speed are significant when predicting the maximum lateral extent in both data sets. These differences suggest the competing risks are also quite different between groups and databases.

Summary of Covariate Assessment

This covariate assessment considered the covariates in two overlapping data sets. When the data sets are combined such that complex roadside terrains are included with simple roadside slopes, increases to the encroachment angle and speed were not proportionally related to the maximum lateral extent. When simple slopes are considered alone, however, both encroachment angle and speed are proportionally related to maximum lateral extent. Neither encroachment angle nor speed was found to be significant when predicting the differences between outcomes (i.e., competing risks) within the combined data. Both encroachment angle and speed, however, are significant for predicting the various outcomes for the simple slopes. Due to these obvious differences between these data sets for these two highly correlated covariates, the simple slopes data (i.e., the Project 17-55 data set) were used to develop the relationship to represent maximum lateral extent. It is recommended that complex slopes data (i.e., the Project 16-05 data set) be used to explore adjustment factors for the introduction of these complex terrain elements.

Vehicle type was found to be the least correlated covariate with maximum lateral extent and found to have a negligible clinical difference in both data sets. The distinction between vehicles within the passenger vehicle fleet is not justified by these data.

The consideration of various statistical models for (1) competing risks and (2) parametric representation of encroachment speed and angle to allow for weighting these data are discussed below.

Statistical Methods

Models may be justified either on the physics of the failure mode or due to empirical success. In addition to the non-parametric CIF and K-M estimator, models considered include:

- Weibull,
- Extreme Value Distribution,
- Accelerated Failure Time (AFT),
- Cox Proportional Hazard (PH), and
- Competing Risk Regression (CRR).

The Weibull method was considered because it is well suited for engineering manufacturing reliability analysis. It is best suited for extremely small samples (e.g., two or three failures). The database used in this analysis is quite large, therefore it was not examined further.

The Extreme Value Distribution model is used when the variable of interest (i.e., maximum lateral extent) can be positive or negative. Maximum lateral extent is only measured in one direction. After the vehicle returns to the road, the maximum lateral extent had already been achieved at some previous point along the trajectory. Negative values, therefore, are not encroachments and this model is not appropriate.

The AFT model is parametric. The AFT model assumes that the effect of the covariates is to accelerate the life of the trajectories. The AFT model is often favored in engineering studies where mechanical processes are studied for this underlying assumption. The covariates and failure times follow the survival function:

$$S(x|Z) = S_0(x \cdot e^{\theta' Z})$$

The AFT model has a baseline survival rate, S_0, which is expressed as a function. The term $e^{\theta' Z}$ is the acceleration factor. Expressed in a log-linear form, the log of failure time is related to the mean μ, the acceleration factor, and the error term, σW, as shown here:

$$\log X = \mu - \theta' Z + \sigma W$$

The Cox PH model is the most widely used multivariate approach for modeling survival data in medical research. (Bradburn 2003) The Cox PH model has a baseline hazard function, $h_0(t)$, which can be specified as in any other model. The hazard model, h(t), and survival model, S(t), are related as follows:

$$h(t) = h_0(t) \cdot e^{\sum b_j x_j}$$
$$S(t) = e^{-\int_0^t h(x)dx}$$

Where:

$h(t)$ = Hazard function
$h_0(t)$ = Baseline hazard function

x_j = Covariates collected during data collection (e.g., slope, vehicle type)
b_j = Coefficients determined through modeling
$S(t)$ = Probability of continued movement at measurement t_j

The baseline hazard function, $h_0(t)$, is the value of the hazard if all the covariates are equal to zero (i.e., not present) and the baseline hazard function varies with time. The baseline hazard function is estimated nonparametrically and can be thought of as the intercept term that varies with time. Hazard ratios, $e^{\sum b_j x_j}$, do not vary with time but depend on each of the covariates. The hazard ratio of events is equivalent to the relative risk of events.

The Cox PH model has an inherent assumption that the effects of the covariates upon survival are constant over time and that each trajectory only experiences a single event. The standard Cox PH model, however, treats competing risks of the event of interest as censored. (Scrucca 2010) It is desirable to model the time to event of each of the possible outcomes (i.e., overturn, stops, returns to road) while also considering the censored observations (i.e., gone too far and time exceeded).

Fine and Gray, among others, proposed directly regressing the effect of covariates for competing risks, known as CRR. (Fine 1999) CRR models cause (r=1, …, k) for each trajectory considering multiple covariates represented by vector X. The baseline subdistribution hazard of cause r is $\lambda_{ro}(t)$. A partial likelihood approach is applied to estimate the semiparametric PH model for the subdistribution where β_r is the vector of estimated coefficients for the covariates and the model takes the following form:

$$\lambda_r(t|X) = \lambda_{ro}(t)e^{(\beta_r^T X)}$$

When the event of interest is maximum lateral extent, one should also consider how to represent the means of achieving maximum lateral extent. For example, did the trajectory come to a stop, return to the road, or overturn? If the vehicle came to a stop or returned to the road, there is no harm caused by the encroachment alone. If the vehicle overturned, however, there is harm caused by overturning. As was shown above, some trajectories exceeded the study period (e.g., exceeded by measurement or by time). These censoring events prevent the observation of the trajectory stopping, returning to the road, or overturning.

One option is to assume that those who are censored have the same chance of overturning as those who were observed. This is not believed to be the case. Therefore, overturning is a competing risk event that eliminates the chance of stopping or returning to the road. Restated, there are multiple modes of failure.

In summary, a single model is not appropriate. Both the survival function of the trajectory data and the cumulative incidence of the competing risks should be captured. The Cox PH was used to characterize the survival function. A CIF was used to represent the competing risks on the simple slopes. A third model (e.g., CRR) could be used in the ongoing research project NCHRP Project 16-05, “Guidelines for Cost-Effective Safety Treatments of Roadside Ditches” to capture the risk introduced by ditches. A model of competing risks for ditches developed under NCHRP Project 16-05 could be easily integrated into the guidelines developed under this research and the ongoing NCHRP Project 15-65 research to improve the representation of roadside terrain throughout the AASHTO RDG.

Survival

Event of interest is the maximum lateral extent when the vehicle stops or returns to the road. Overturning is treated as a competing risk event that eliminates the chance of either stopping or returning to the road. Recall the hazard model, h(t), and survival model, S(t), are related, as shown here:

$$h(t) = h_0(t) \cdot e^{(b_a \cdot EncAng + b_s \cdot EncSpd)}$$
$$S(t) = e^{-\int_0^t h(x)dx}$$

The baseline hazard function, $h_0(t)$, varies with time. The hazard ratio of events is equivalent to the relative risk of events and is found by exponentiating the estimated coefficients. The hazard ratios do not vary with time. The coefficients have been estimated using the Cox PH model limiting the data set to the trajectories where an event was observed. The resulting estimates for the coefficients of EncAng and Spd as well as the hazard ratios and the corresponding confidence intervals are shown in Table B-6. The model is shown graphically in Figure B-9.

Table B-6 Estimated Survival Function

	Coefficient (b_i)	S.E.	z	Pr(>|z|)	exp(coef)	lower .95	upper .95
EncAng	-0.0677	0.00	-92.28	< 2e-16	0.9346	0.9332	0.9359
Spd	-0.0270	0.00	-75.91	< 2e-16	0.9734	0.9727	0.9740
FS-6	-0.0566	0.02	-3.12	0.0018	0.9450	0.9120	0.9792
FS-4	-0.1218	0.02	-6.68	2.42e-11	0.8853	0.8542	0.9175
FS-3	-0.1298	0.02	-7.12	1.12e-12	0.8783	0.8475	0.9103
FS-2	-0.1469	0.02	-8.08	6.66e-16	0.8634	0.8332	0.8947

The hazard ratios indicate that for every one-unit increase in encroachment angle, the maximum lateral extent where an event is not observed will decrease by approximately 6.5% (i.e., 1 − 0.9347). Similarly, for every one unit increase in encroachment speed, the maximum lateral extent when an event is not observed will decrease by 2.5%. “One of the primary reasons for using a regression model is to include multiple covariates to adjust statistically for possible imbalances in the observed data for making statistical inferences.” (Hosmer 2011) This model will be used below to scale these data using the NCHRP Project 17-43 real-world distributions.

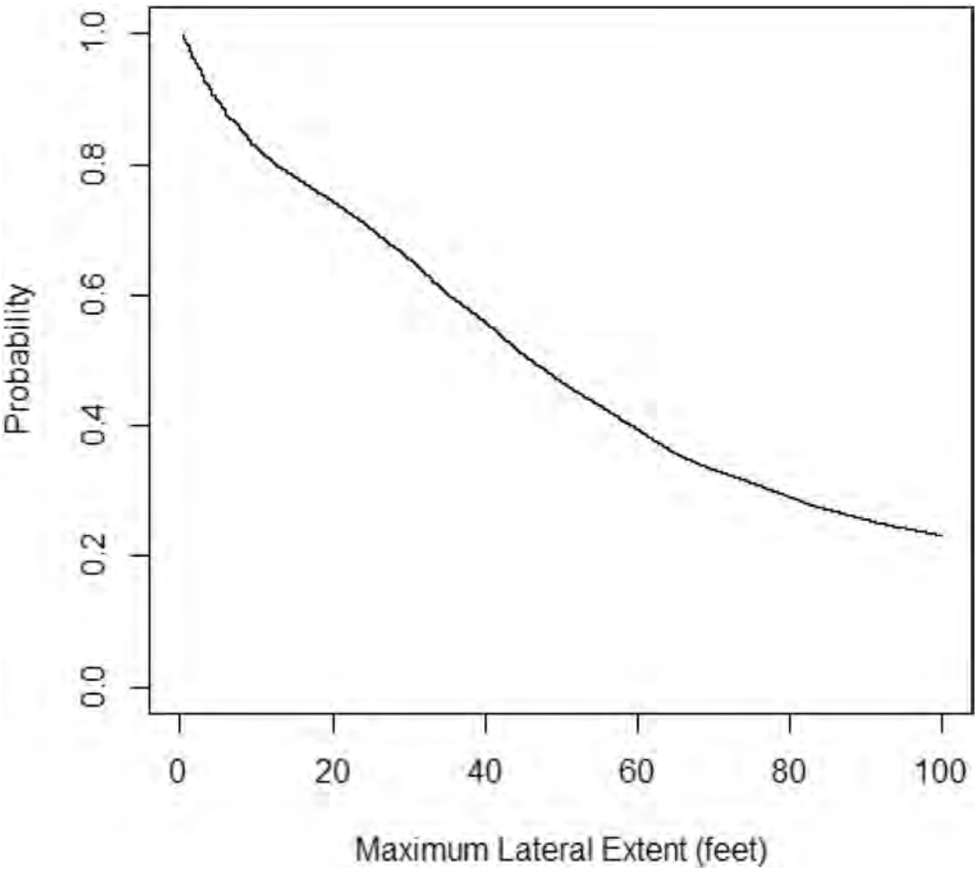


Figure B-9 Estimated survival function.

Competing Risks

The estimated cumulative incidence (risk over time) of overturning in the presence of the other event types (e.g., stopping or returning to the road) was estimated. This estimate of attrition due to the occurrence of the competing risk, overturn by slope, is shown in Figure B-10. Notice the steeper the slope, the higher the rate of attrition.

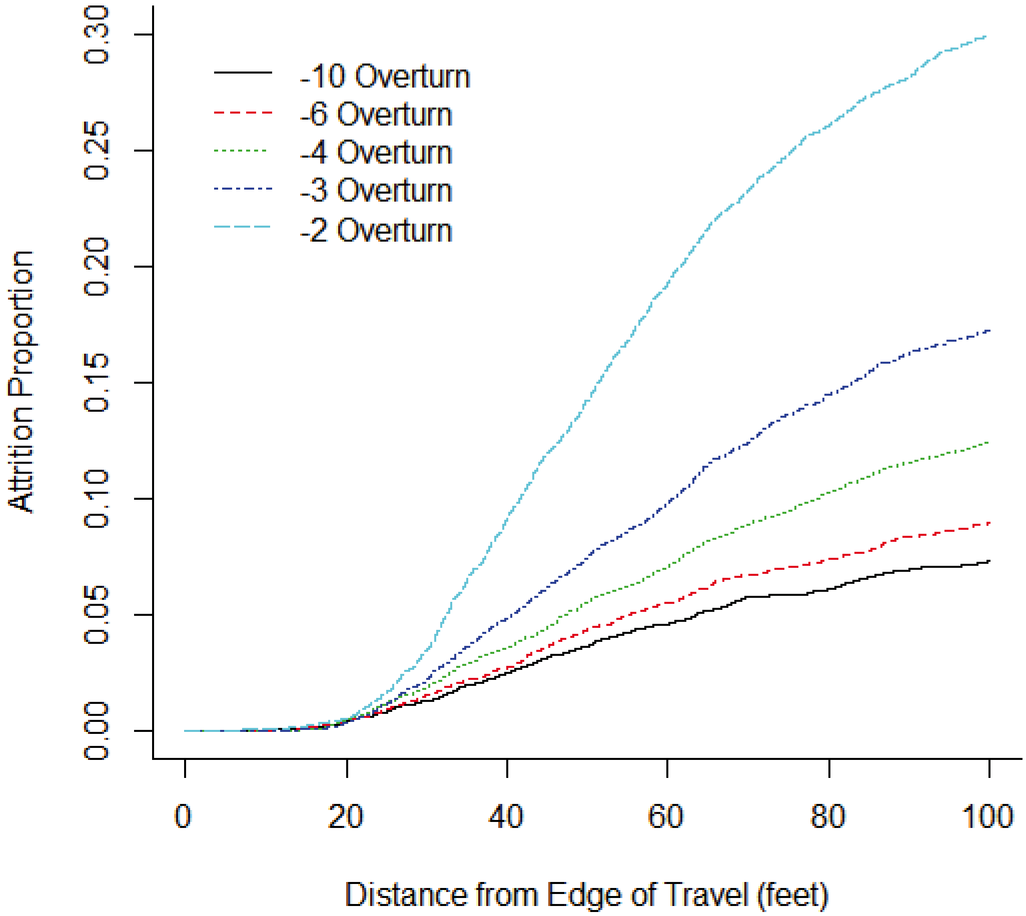


Figure B-10 Estimated competing risk of overturn.

CHAPTER 5

FIELD COLLECTED TRAJECTORIES

NCHRP Project 17-11: Determination of Safe/Cost Effective Roadside Slopes and Associated Clear Distances was completed in 2004 by TTI at Texas A&M. This data set contained 485 National Automotive Sampling System (NASS) Crashworthiness Data System (CDS) cases from 1997 through 1999. (Bligh 2004) NCHRP Project 17-22, “Identification of Vehicular Impact Conditions Associated with Serious Ran-Off-Road Crashes,” was completed in 2009 at the University of Nebraska-Lincoln. This data set contained 392 NASS CDS cases from 2000 and 2001. (Sicking 2009) *NCHRP Report 665: Identification of Vehicular Impact Conditions Associated with Serious Ran-off-Road Crashes* combined the two data sets from NCHRP Projects 17-11 and 17-22. (Mak 2010)

As mentioned earlier in this document, NCHRP Project 17-43, “Long-Term Roadside Crash Data Collection Program,” is in progress at Virginia Polytechnic Institute and State University. (Gabler 2020) The beta version of the data set has been reviewed as part of this effort. A compilation of the average departure speed and angle from each of these studies is provided in Table B-7.

Table B-7 Comparison of Departure Speed and Angle for Specific Field-Collected Crash Databases

Reference	Number of Cases	50th Percentile of Data Set	
		Departure Speed	Departure Angle
NCHRP Project 17-11	485		19.9°
NCHRP Project 17-11*	485	48.9 mph	16.9°
NCHRP Project 17-22	392	49.7 mph	17.2°
NCHRP Report 665	877†	49.3 mph	16.9°
NCHRP Project 17-43	1124	48.6 mph	13.8°

* After reconstruction and manual reviews by the NCHRP Project 17-22 group.

† Combination of the NCHRP Project 17-11 reconstructed data set and the NCHRP Project 17-22 data set.

CHAPTER 6

RESULTS

The mean encroachment speed of the data simulated in the Project 17-55 data set was 50 mph and the mean encroachment angle was 17.5 degrees. Considering the field-collected data, it would appear the mean encroachment speed is 48.6 mph while the encroachment angle is closer to 13.8 degrees. The survival function tabulated in Table B-6 was used to scale the simulated data to better represent field-collected encroachment speeds and angles, as shown in Figure B-11. The solid line represents the unadjusted model developed from the simulated data where the dashed line has been adjusted to represent the field-collected data. It is recommended that the green adjusted line be used in guideline development. No assumptions have been made about median symmetry; this model can be used from either direction of travel and is applicable to the roadside. This representation can be extended in the future to include the competing risk of ditches. This effort is currently underway in NCHRP Project 16-05.

Recall the estimated cumulative incidence (risk over time) of overturning in the presence of the other event types (e.g., stopping or returning to the road) was also estimated. This estimate of attrition due to overturn was shown above in Figure B-10.

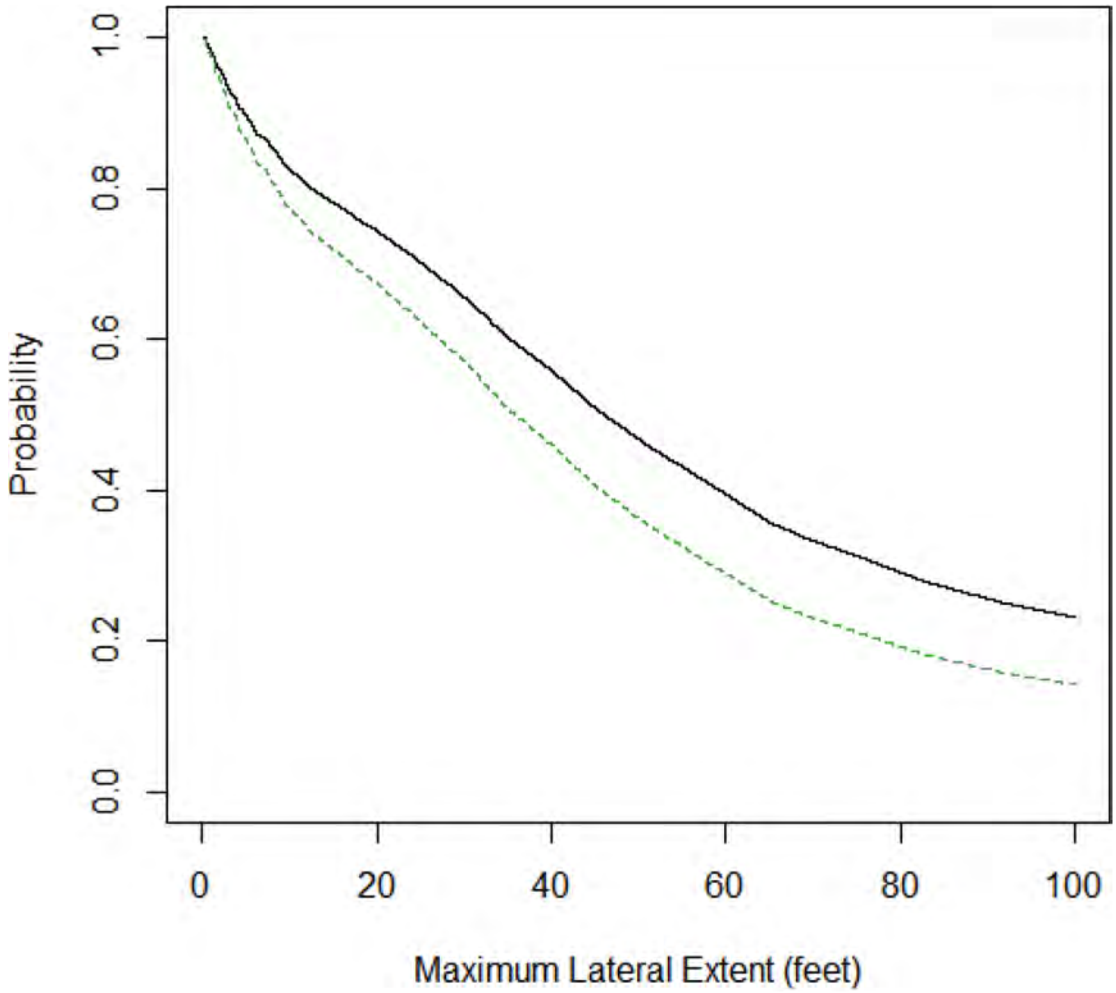


Figure B-11 Estimated survival function (solid) and scale maximum lateral extent model (dashed).

CHAPTER 7

IMPLEMENTING THE RESULTS

NCHRP Project 15-65 defines “$P_{Y\,j}$ [a]s the conditional probability of a vehicle reaching a lateral offset of Y given an encroachment.” (Ray 2018) This research effort is coordinating terminology with NCHRP Project 15-65 to facilitate implementing the resulting guidance in an upcoming update to the AASHTO RDG. The results of this modeling effort to represent the maximum lateral extent have been tabulated, therefore, as $P_Y(Y_j)$, as shown in Figure B-12. Numeric values are provided to the left of the figure for ease of use.

Y_j (ft)	$P_Y(Y_j)$
0	1.0000
1	0.9761
2	0.9431
3	0.9090
4	0.8844
5	0.8650
10	0.7737
15	0.7191
20	0.6741
25	0.6238
26	0.6120
27	0.6014
28	0.5908
29	0.5815
30	0.5699
35	0.5082
40	0.4603
45	0.4063
50	0.3622
55	0.3254
60	0.2887
65	0.2531
70	0.2307
75	0.2115
80	0.1918
85	0.1752
90	0.1624
95	0.1515
100	0.1416

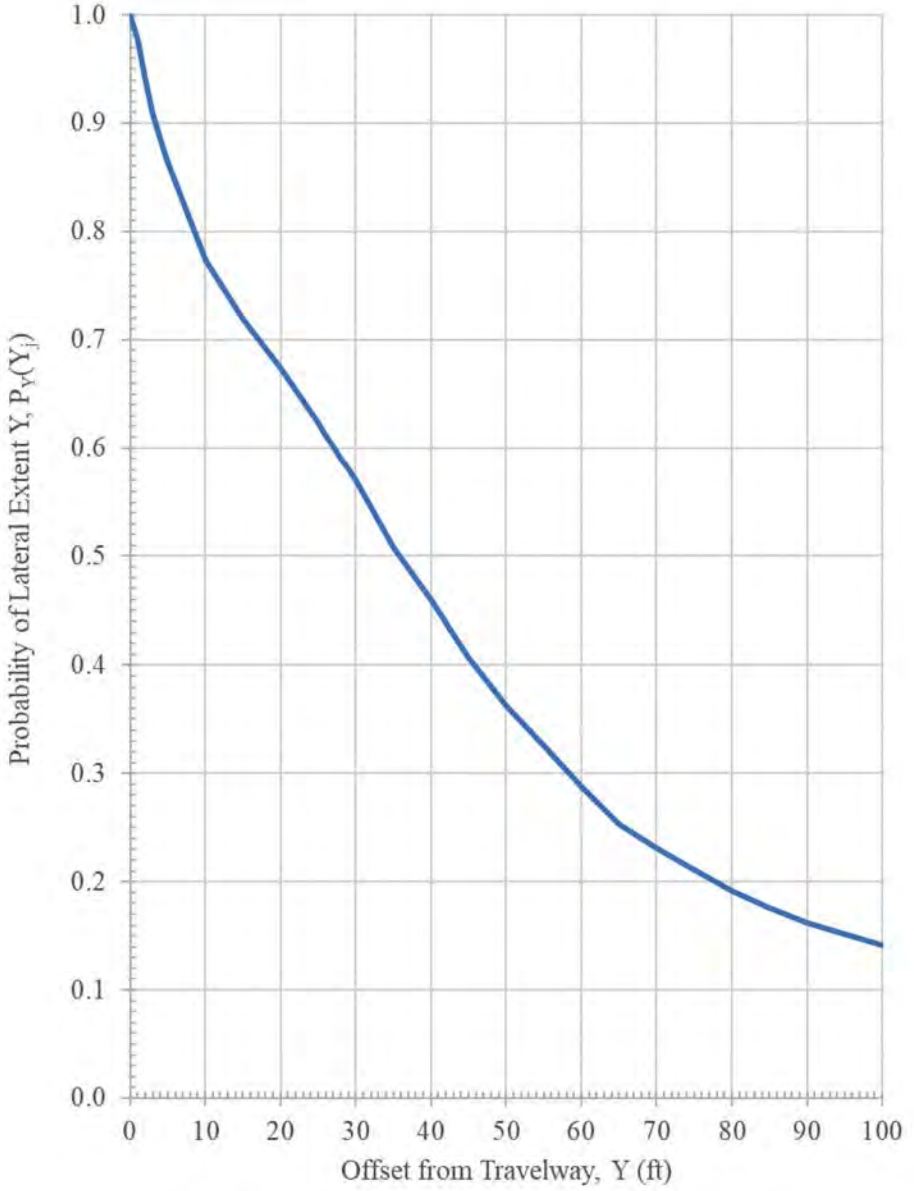


Figure B-12 Recommended scaled maximum lateral extent $P_Y(Y_j)$.

NCHRP Project 15-65 also states that “THR_j is a variable that represents the conditional probability of passing through feature j given the vehicle interacts with feature j.” (Ray 2018) For example, a vehicle may travel on a median slope, interact with and penetrate a median barrier, enter the opposing lanes where it may be struck by another vehicle. The proportion that passes through for each category of roadside feature (i.e., the first slope and the median barrier) is dependent on variables that are unique to the specific type of feature. The vehicles that roll over on the slope do not pass through, THR. The probability of rollover (i.e., do not pass THR) was shown above in Figure B-10. Table B-8 shows a table of values that are one minus the values shown for rolling over. One minus rollover provides the probability of passing THR.

Table B-8 Recommended representation of passing THR terrain ($\text{THR}_{\text{TERRAIN}}$)

Survived the Terrain					
Lateral Extent	**$\text{THR}_{\text{FORESLOPE}}$**				
ft	-10:1	-6:1	-4:1	-3:1	-2:1
0	1.0000	1.0000	1.0000	1.0000	1.0000
1	1.0000	1.0000	1.0000	1.0000	1.0000
2	1.0000	1.0000	1.0000	1.0000	1.0000
3	1.0000	1.0000	1.0000	1.0000	1.0000
4	1.0000	1.0000	1.0000	1.0000	1.0000
5	1.0000	1.0000	1.0000	1.0000	1.0000
10	1.0000	1.0000	1.0000	1.0000	0.9995
15	0.9992	0.9993	0.9998	0.9997	0.9985
20	0.9963	0.9962	0.9957	0.9966	0.9948
25	0.9921	0.9911	0.9885	0.9887	0.9835
26	0.9900	0.9896	0.9867	0.9869	0.9802
27	0.9892	0.9887	0.9851	0.9840	0.9762
28	0.9890	0.9876	0.9847	0.9815	0.9736
29	0.9884	0.9867	0.9831	0.9803	0.9696
30	0.9876	0.9851	0.9811	0.9782	0.9659
35	0.9804	0.9784	0.9712	0.9643	0.9356
40	0.9755	0.9731	0.9640	0.9516	0.9092
45	0.9687	0.9639	0.9557	0.9381	0.8813
50	0.9638	0.9567	0.9446	0.9252	0.8577
55	0.9579	0.9507	0.9382	0.9139	0.8320
60	0.9543	0.9451	0.9298	0.9018	0.8073
65	0.9487	0.9384	0.9181	0.8852	0.7832
70	0.9428	0.9330	0.9113	0.8757	0.7670
75	0.9416	0.9296	0.9058	0.8638	0.7514
80	0.9393	0.9264	0.8976	0.8550	0.7392
85	0.9340	0.9227	0.8903	0.8453	0.7267
90	0.9307	0.9168	0.8846	0.8377	0.7186
95	0.9295	0.9139	0.8805	0.8323	0.7068
100	0.9266	0.9104	0.8756	0.8275	0.7001

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APPENDIX C

Probability of Crash Severity (P_{SEV_j})

CONTENTS

CHAPTER 1

INTRODUCTION

$P(KA|C)$, the conditional probability of a severe or fatal (i.e., KA) crash, given a collision has occurred, is needed for guideline development. NCHRP Project 15-65 has dubbed this conditional probability $P_{SEV\,j}$ and allowed the conditional probability to be for KA crashes or any other severity of interest. The development of the methodology to calculate $P_{SEV\,j}$ is documented below using KA crashes to simplify the example and improve clarity; however, the methodology could be applied to other severity levels of interest. Also documented are the data used when developing the appropriate $P_{SEV\,j}$ for these guidelines.

CHAPTER 2

METHOD

The process used with RSAPv3 to model crash severity includes the ability to account for unreported crashes and to scale crash severity by the posted speed limit (PSL). These features are desirable in roadside crash severity estimation for many reasons. Unreported crashes represent roadside safety "successes." Capturing these unreported crashes ensures that higher severity crashes are not over-predicted. Scaling the crash severity model by PSL allows for lower speed crashes, which can be less severe, to be addressed by the model, as well as higher speed crashes where the severity could be higher. The use of PSL rather than impact speed, for example, allows for broader availability of data. Using impact speed, when it becomes widely available, to scale crash severity could be the subject of future research.

The RSAPv3 crash severity model, which captures both reported and unreported crashes, is scalable by PSL and is called the equivalent fatal crash cost ratio (EFCCR). The process for developing an EFCCR for any roadside feature was documented by Ray et al. in "Method for Modeling Crash Severity with Observable Crash Data." (Ray 2014b) Ray et al. explain that the process includes the following steps:

1. "Isolate a census of police-reported crashes with a particular type of roadside feature, ideally over a range of posted speed limits.
2. Determine the crash severity distribution for crashes that do not have events preceding the crashes with the hazard under evaluation and do not result in penetration or rollover.
3. Determine or estimate the percentage of unreported crashes and add these crashes to the reported crash severity distribution.
4. Calculate the average crash cost of the severity distribution for each posted speed limit and determine the equivalent fatal crash cost ratio (EFCCR), and
5. Adjust for speed effects by determining the equivalent fatal crash cost ratio for a baseline impact speed of 65 mi/hr (i.e., $EFCCR_{65}$) for a particular hazard." (Ray 2014b)

It is desirable to maintain the ability to include unreported crashes and to scale severity by PSL much the same way they are accomplished within RSAPv3. The EFCCR procedure was extended to maintain the calculation of unreported crashes (i.e., Step 3, above) and scaling for speed (i.e., Step 5, above) while allowing for the discrete values for each level of severity to also be maintained and then utilized for a probability calculation.

After completing steps one through three above, the P(KA|C) can be found by summing the total number of KA crashes in the data at each PSL level and dividing by the total number of all crashes of all severities plus the estimated unreported crashes from Step 3, as shown here:

$$\overline{P(KA|C)} = \frac{\sum_{\min PSL}^{\max PSL} K + A}{\sum_{\min PSL}^{\max PSL} (KABCO + Unreported)}$$

where

K+A	Fatal and serious injury crashes across the posted speed limits available

KABCO + Unreported	Crashes of all reported severities plus the estimated unreported crashes from EFCCR step 3 for all posted speed limits.

In this extension of the procedure, rather than calculating an EFCCR (i.e., Step 4, above), the conditional probability P(KA|C) is determined for the entire sample. Step 5 is carried forward but modified to determine the speed-weighted probability of a KA crash given a collision at a base PSL of 65 miles per hour (mph): $P(KA|C)_{65}$. This is calculated using the case-weighted PSL as follows:

$$P(\mathrm{KA}|\mathrm{C})_{65} = \frac{\overline{P(\mathrm{KA\_CUSP}|\mathrm{C})} \cdot 65^3}{(\overline{\mathrm{PSL}})^3}$$

The resulting value can be used in the guidelines and adjusted using the site-specific PSL, as follows:

$$P(\mathrm{KA}|\mathrm{C})_{\mathrm{PSLi}} = \left[\frac{P(\mathrm{KA}|\mathrm{C})_{65}}{65^3}\right] \mathrm{PSL}_{\mathrm{i}}^3$$

These same calculations can be done for each severity level (e.g., KAB, F+I). The available crash data gathered from the literature and state crash databases for the determination of these severity measures are discussed below. The data used will be first and only harmful event crashes (FOHE), where harm-inducing crash events do not precede or follow the event of interest (e.g., barrier, roll over, or cross-median). First, the available crash data are discussed, below, and then the unreported crashes are estimated. The analysis to find $P(KA|C)_{65}$ is documented for use in the guidelines.

CHAPTER 3

AVAILABLE DATA

Data from the Literature

NCHRP Project 22-12(03), "Recommended Guidelines for the Selection of Test Level 2 through 5 Bridge Railings" included the gathering of crash data for the concrete median barrier family. (Ray 2021) One research objective for NCHRP Project 22-12(03) included the field evaluation of the hardware as a project objective. Therefore, under NCHRP Project 22-12(03), the hardware involved in the crashes was extensively verified. The crash severity distribution by PSL with a variety of concrete barriers were gathered under that effort. The data gathered are shown in Table C-1 and Table C-2. NCHRP Project 22-27, "Update of the Roadside Safety Analysis Program" also gathered crash severity data for a variety of barriers across the full severity distribution and by PSL. (Ray 2012) These data are shown in Table C-3.

The severity of a cross-median crash must also be represented. The crash data assembled under this effort and documented in Table C-3 were used to find the severity of cross-median crashes. The severity distribution is shown in Table C-4. In addition to the crash severity distribution of various barriers and cross-median crashes, the crash severity distribution of rollover crashes is necessary for those encroachment events that result in a rollover before impacting the barrier or fully crossing the median. The severity distribution for fixed objects within the median or on the roadside was also captured. The severity distribution of previously documented data collected under NCHRP Project 22-27 (Ray 2012) by PSL is shown for rollover crashes (see Table C-5), tree crashes (see Table C-6), and waterbody crashes (see Table C-7).

Table C-1 New Jersey, Massachusetts, Washington, and Pennsylvania Concrete Safety Shape Barrier Crash Severity Distribution (after Ray 2021)

State	Barrier	PSL	K	A	B	C	PDO/Unk
NJ	TL5 Concrete	55	0	1	12	35	193
NJ	TL5 Concrete	65	0	11	103	307	1395
MA	32" F-Shape	55	0	0	4	4	14
MA	32" F-Shape	65	3	4	36	17	72
MA	42" F-Shape	55	0	0	6	4	24
WA	32" Safety Shape	60	2	4	62	112	369
WA	34" Single Slope	60	0	3	20	28	127
PA	32" F-Shape	55	3	1	6	14	33
PA	32" F-Shape	65	1	0	7	28	71
PA	42" F-Shape	55	1	0	1	3	5
PA	42" F-Shape	65	0	0	4	9	33

Table C-2 Nebraska Crash Severity Distribution (after Ray 2021)

PSL	K	A	B	C	O
29" Vertical Wall					
50 mph or less	0	0	0	0	0
55	0	0	0	0	0
60	0	2	2	3	9
65	0	0	1	1	2
75	0	0	0	0	0
34" Vertical Wall					
50 mph or less	0	1	3	4	33
55	0	4	3	0	20
60	3	6	14	28	131
65	1	5	9	11	61
75	3	4	14	11	102
42" Vertical Wall					
50 mph or less	0	0	0	0	1
55	0	3	3	2	11
60	0	0	0	1	1
65	0	0	2	2	7
75	0	1	0	0	6
32" NJ Shape					
50 mph or less	0	2	4	2	46
55	0	2	1	4	19
60	0	2	4	6	36
65	0	0	4	2	19
75	1	0	1	0	14
42" NJ Shape					
50 mph or less	0	0	1	3	4
55	0	1	2	6	20
60	2	0	3	9	14
65	0	0	1	0	1
75	0	0	0	0	0

Table C-3 Barrier Crash Data Assembled Under NCHRP Project 22-27 (Ray 2012)

State	Barrier Type	PSL	K	A	B	C	O	Unk
WA	TL3 LT Cable MB	70	0	0	6	13	220	7
WA	TL3 LT Cable MB	60	0	1	9	16	312	10
WA	TL3 HT Cable MB	55	0	0	1	2	11	
WA	TL3 HT Cable MB	60	1	0	12	16	238	2
WA	TL3 HT Cable MB	70	1	1	12	16	225	3
AZ	TL3 LT Cable MB	65	0	0	1	4	11	4
IA	TL3 HT Cable MB	65	0	1	0	2	17	
NC	TL3 LT Cable MB	65	0	2	9	28	88	
OR	TL3 LT Cable MB	65	0	0	0	5	15	6
TX	TL4 32" NJ MB	65	8	115	456	209	890	

Table C-4 Washington Crash Data for Cross-Median Crashes

Feature	PSL	K	A	B	C	O	Unk
CMC	70	0	1	3	5	38	0
CMC	65	7	5	7	1	15	0
CMC	60	39	27	77	87	398	3
CMC	55	385	1061	2049	913	3520	0
CMC	50	44	134	256	205	629	3
CMC	45	37	241	615	435	1569	4
CMC	40	22	114	327	315	1119	1
CMC	35	43	438	1317	1417	5656	12
CMC	30	1	14	41	41	415	3
CMC	25	4	74	311	446	1974	1
CMC	20	0	0	0	1	8	0

Table C-5 Washington Crash Data for Rollover Crashes (after Ray 2012)

Feature	PSL	K	A	B	C	O	Unk
Rollover	70	36	96	670	352	731	33
Rollover	65	5	5	110	38	120	15
Rollover	60	27	125	791	542	1088	99
Rollover	55	14	75	389	257	628	62
Rollover	50	9	27	173	131	288	42
Rollover	45	1	5	38	34	58	9
Rollover	40	0	5	31	20	37	5
Rollover	35	1	11	37	35	73	19
Rollover	30	0	2	6	4	9	1
Rollover	25	0	0	8	3	8	1

Table C-6 Washington Crash Data for Tree Crashes (after Ray 2012)

Feature	PSL	K	A	B	C	O	Unk
Tree	70	5	7	30	20	103	8
Tree	65	1	1	2	0	7	0
Tree	60	10	26	86	93	200	34
Tree	55	21	32	112	87	168	35
Tree	50	12	23	75	52	151	29
Tree	45	1	3	19	20	44	10
Tree	40	3	11	21	18	56	9
Tree	35	1	4	26	32	89	26
Tree	30	0	2	4	9	39	9
Tree	25	0	1	4	6	20	5

Table C-7 Washington Crash Data for Waterbody Crashes (after Ray 2012)

Feature	PSL	K	A	B	C	O	Unk
Waterbody	70	0	0	0	1	3	0
Waterbody	65	0	0	1	0	0	0
Waterbody	60	0	0	9	5	15	1
Waterbody	55	1	2	6	4	34	3
Waterbody	50	0	3	2	6	27	1
Waterbody	45	0	0	0	0	5	0
Waterbody	40	0	1	1	0	2	0
Waterbody	35	0	0	1	1	1	1
Waterbody	30	0	0	2	0	5	0
Waterbody	25						

New Data Gathered

New crash data, in addition to data available in the literature, were also collected and evaluated in this study. Barrier inventories and accompanying crash data were made available by the States of Maine, Ohio, Pennsylvania, and Tennessee. The State of Washington also provided their inventory; however, much of the data available in the literature was assembled using the Washington database. A new analysis was not conducted with the Washington database to avoid double-counting of data. A much wider range of crash data was made available by Ohio with their inventory; therefore, a new analysis of the Ohio data was conducted here and the data available in the literature were not included above to avoid double-counting.

Crashes that penetrate, roll over, or vault the feature (THR), or crashes that roll over after redirection on the same side of the barrier (RSS) are excluded from this severity measure such that the result will represent the severity of a single event in the overall crash sequence. This ensures that the severity measure can be confidently associated with the collision with the feature under evaluation. The crashes coded as single vehicle (SV), FOHE, and longitudinal barrier (LB) crashes were isolated from each data set.

While each of these new data sets included barriers located within the median, some did not differentiate between median (i.e., double-faced) barriers and roadside (i.e., single-faced) barriers. The crash severity outcome of median and roadside barriers is assumed to be equal when the barrier is struck on the design-impact side. If a roadside barrier were struck from behind, however, the crash severity outcome could not be assumed to be equal to that of a median barrier because median barriers are designed to be impacted from both sides while roadside barriers are not. When impacts occurred within the median, but it could not be determined whether the vehicle impacted a barrier face, then these cases were eliminated from the data set. SV FOHE LB crashes occurring in the median or on the roadside when the vehicle impacted the barrier face were used because these crashes are the best representations of the crash outcome when events do not precede nor follow the impact with the barrier. The method used to isolate these crashes for each data set is explained here.

The Ohio Highway Safety Information System data for 2003 through 2013 were used in conjunction with state-collected roadside hardware inventory provided by the Ohio Department of Transportation (ODOT). SV FOHE LB crashes were identified using EVENT1, EVENT2, EVENT3, EVENT4, F_HARM, and NUMVEH fields in the crash data. Crashes were considered to be SV FOHE LB if the NUMVEHS field was equal to 1, the F_HARM field was identified as either code ‘30’ (guardrail face) or ‘32’ (median barrier), and the EVENT1-4 fields were either blank or contained codes ‘08’ (ran off road-right), ‘09’ (ran off road-left), or ‘10’ (cross median/centerline). The ODOT hardware inventory was linked to the SV FOHE LB crashes using RTE-NBR and MILEPOST fields along with the roadside location of the hardware in the inventory. The EVENT1-4 codes ‘08’ (ran off road-right), ‘09’ (ran off road-left), and ‘10’ (cross median/centerline) were used in conjunction with the VEH_N_FROM (direction vehicle was traveling from) and VEH_N_TO (direction vehicle was traveling to) fields to determine the location and type of hardware involved in each SV FOHE LB crash.

The Pennsylvania Department of Transportation (PennDOT) crash database for 2010 through 2015 was used in conjunction with the state-collected roadside guide rail inventory. SV FOHE LB crashes were identified using harmful events 1-4, First Harmful Event, and the “TOTAL_UNITS” fields. Crashes were considered SV FOHE LB crashes if “TOTAL_UNITS” = 1, First Harmful Event = 25 (hit guard or guide rail), 28 (hit concrete or longitudinal barrier), and no harmful event (blank entry) in the harmful event immediately succeeding the first harmful event. The County Number, State Route Number, Segment Number, Beginning Offset, Ending Offset, and Guide Rail Side fields were used to attach the barrier database to the SV FOHE LB crashes. The Travel Direction field was used in conjunction with the Harmful Event Side 1-4 fields to determine the location and type of hardware involved in each SV FOHE LB crash. Pennsylvania differentiates between single-sided and double-sided guardrail systems, allowing median barrier crashes on divided highways to be used.

The Tennessee Department of Transportation (TDOT) crash database for 2012 through 2016 was used in conjunction with the state-collected roadside barrier inventory. SV FOHE LB crashes were identified using EVENT SEQ1-6, FIRSTHARMFULEVENTCDE, and TOTAL VEH fields. Crashes were considered SV FOHE LB crashes if: TOTAL VEH was equal to 1, FIRSTHARMFULEVENTCDE equal to "Concrete Traffic Barrier", "Guardrail Face", or "Cable Barrier", and the EVENT SEQ immediately succeeding the first harmful event is either blank or "Cross Center Line", "Cross Median", "Ran Off Road-Left", "Ran Off Road-Right", and immediately followed by a blank entry in the next EVENT SEQ field. Unlike some states, Tennessee has a First Harmful Event field separate from the event sequences. The police report has an entry for this and is listed as “First Harmful Event for the Crash”. (ACTAR 2017) It is implied that this field represents the first **harmful** event in the crash, not simply the first event. Zero crashes had "Cross Center Line," "Cross Median," "Ran Off Road-Left," or "Ran Off Road-

Right" listed as the First Harmful Event, and some instances had one of these entries in the EVENT SEQ1, followed by "Concrete Traffic Barrier," "Guardrail Face," or "Cable Barrier" in EVENT SEQ2, with one of the barrier types listed as the First Harmful Event. The COUNTY, ROUTE_NAME, BEG_LOG, and END_LOG fields were used to attach the barrier inventory database to the SV FOHE LB crashes. The TRAVELDIRCDE field along with "Cross Center Line," "Cross Median," "Ran Off Road-Left," and "Ran Off Road-Right" in the EVENT SEQ1-6 field were used to determine which barrier was involved in each SV FOHE LB crash. Tennessee also differentiates between “Median Right,” “Median Left,” and “Centerline” in the LOC_DESC field of the inventory, thus allowing median barrier crashes to be identified.

The Maine Department of Transportation (MaineDOT) maintains a roadside hardware condition assessment inventory for maintenance purposes and made the inventory available for this research. The inventory can be linked with crash records which MaineDOT also made available for this research. The inventory includes the location and condition of the longitudinal barrier and includes the side of the road and the direction the barrier faces. The inventory includes the specific end treatment for the start and end of each section of longitudinal barrier as well. While the inventory includes the condition of the longitudinal barrier, it unfortunately does not provide information sufficient for this research regarding the type of barrier at each location. The objective of MaineDOT in collecting this inventory is for asset management while the objectives of this research are to positively identify each asset involved in a crash. Regrettably, there is not sufficient information about each longitudinal barrier type within the inventory to support the objectives of this research. The MaineDOT database, therefore, was not used in this analysis. This inventory, however, could prove valuable to those studying features better defined within the database (e.g., condition of the hardware and end treatment type).

After isolating a census of crash data from each state database for particular hazards, the crash severity distribution can be determined for each hardware in the inventory.

Ohio

A total of 31,540 SV FOHE LB crashes were found during the 11-year study period in Ohio. These crashes were then linked to the roadside hardware inventory for each identified longitudinal barrier. Ohio identifies the following longitudinal barriers within the inventory:

- Guardrail
- 32” Jersey Barrier
- 42”+ Jersey Barrier
- Single Slope Barrier (i.e., either 42” or 57”)
- Propriety Cable Barriers (i.e., Brifen’s wire rope safety fence (WRSF), Trinity’s Cable Safety System (CASS), Gibraltar’s Cable Barrier System, and Nucor Steel Marion’s Nu-Cable Barrier)
- Other

A review of the ODOT guardrail standard drawings shows that guardrail is a generic reference for w-beam barriers and that w-beam is the standard guardrail used in Ohio. (ODOT 2013) When guardrail is referenced within the ODOT inventory, W-beam is assumed to be in that location. Single slope barriers may be 42” or 57”. (ODOT 2017)

There were zero reported SV FOHE LB crashes with the inventoried propriety barriers. There were two property-damage-only (“O”) severity SV FOHE crashes with the barrier inventoried as "other." There were 28,141 SV FOHE LB crashes where the type of barrier involved could not be positively identified using the Ohio inventory. The full severity distribution for SV FOHE LB crashes where the barrier type could be identified using the Ohio inventory is summarized in Table C-8 through Table C-11. Those crashes that could not be associated with a particular barrier type are summarized in Table C-12.

Table C-8 Ohio SV FOHE LB Crash Counts by Posted Speed Limit: W-Beam

PSL	K	A	B	C	O
65	2	13	122	104	1081
60	1	5	38	32	299
55	4	25	117	85	817
50	1	0	4	4	64
45	1	1	14	8	88
40	0	0	1	4	34
35	0	2	8	4	60
30	0	0	0	0	0
25	0	0	2	1	6

Table C-9 Ohio SV FOHE LB Crash Counts by Posted Speed Limit: 32" Jersey Barrier

PSL	K	A	B	C	O
65	0	5	15	12	60
60	0	0	5	6	34
55	0	1	5	3	41
50	0	0	1	1	3
45	0	0	1	0	2
40	0	0	0	0	0
35	0	0	0	0	0
30	0	0	0	0	0
25	0	0	0	0	0

Table C-10. Ohio SV FOHE LB Crash Counts by Posted Speed Limit: 42"+ Jersey Barrier

PSL	K	A	B	C	O
65	0	0	3	1	12
60	0	1	4	2	19
55	0	0	0	1	8
50	0	0	0	0	1
45	0	0	0	0	1
40	0	0	0	0	1
35	0	0	0	0	0
30	0	0	0	0	0
25	0	0	0	0	0

Table C-11 Ohio SV FOHE LB Crash Counts by Posted Speed Limit: Single Slope Barriers

PSL	K	A	B	C	O
65	0	1	3	5	54
60	0	0	2	2	5
55	0	1	2	3	8
50	0	0	0	0	3
45	0	0	0	0	0
40	0	0	0	0	0
35	0	0	0	0	0
30	0	0	0	0	0
25	0	0	0	0	0

Table C-12 Ohio SV FOHE LB Crash Counts by Posted Speed Limit: Unable to Associate with a Barrier Type

PSL	K	A	B	C	O
65	9	201	1513	1307	10270
60	11	120	634	813	4119
55	9	144	728	650	4544
50	5	35	173	205	933
45	0	14	49	36	427
40	0	4	26	20	142
35	0	17	94	82	652
30	0	0	3	0	2
25	1	6	14	10	119

Pennsylvania

A total of 5,903 SV FOHE LB crashes were found during the 6-year study period in Pennsylvania. These LB crashes were then linked to the roadside hardware inventory for each identified longitudinal barrier. Pennsylvania identifies the following longitudinal barriers within the inventory:

- Strong Post Cable
- Weak Post Cable
- Strong Post W-Beam with Rub Rail and Offset Bracket
- Strong Post W-Beam with Offset Bracket
- Strong Post W-Beam
- Weak Post W-Beam
- Strong Post W-Beam, Double-Faced
- Weak Post W-Beam, Double-Faced
- Weak Post Box Beam
- Concrete Safety Shape

- Intermediate Bulk Container (IBC) Barrier
- Propriety Cable Barriers (i.e., WRSF, CASS, Blue Systems AB’s Safence, Gibraltar’s Cable Barrier System, and Nucor Steel Marion’s Nu-Cable Barrier)
- Other

Each of these systems is further explained in the PennDOT *Shoulder and Guide Rail Condition Survey Field Manual*, Publication 33. (PennDOT 2017)

The results are shown in Tables C-13 through C-23. The proprietary cable systems have been summarized as one in Table C-24, an individual breakdown by system and crash severity is provided here:

- There were two reported SV FOHE LB crashes with the CASS
    - one property-damage-only (PDO)
    - one Unk
- There were three reported SV FOHE LB crashes with the WRSF
    - three PDO
- There were 13 reported crashes with the Safence
    - one “A”
    - one “B”
    - three “C”
    - six PDO
    - one Unk
- There were 62 reported crashes with the Gibraltar cable barrier
    - 1 “B”
    - 10 “C”
    - 48 PDO
    - 3 Unk
- There were two reported crashes with the Nu-Cable
    - one “C”
    - one PDO

SV FOHE LB crashes that were associated with the inventory code “Other” barrier are shown in Table C-25. All identified crashes were associated with the roadside inventory.

Table C-13 Pennsylvania SV FOHE LB Crash Counts: Strong Post Cable

PSL	K	A	B	C	O	Unk
70	0	0	0	0	0	0
65	0	0	0	0	0	0
60	0	0	0	0	0	0
55	0	0	1	0	9	0
50	0	0	0	0	0	0
45	0	0	0	2	12	0
40	0	0	0	3	11	0
35	0	0	0	1	2	3
30	0	0	0	0	3	1

25	0	0	0	0	2	1
20	0	0	0	0	0	0
15	0	0	0	0	0	0

Table C-14 Pennsylvania SV FOHE LB Crash Counts by Posted Speed Limit: Weak Post Cable

PSL	K	A	B	C	O	Unk
70	0	0	0	0	0	0
65	0	0	0	0	0	0
60	0	0	0	0	0	0
55	0	0	1	1	27	0
50	0	0	0	0	0	0
45	0	0	0	0	0	0
40	0	0	0	0	0	0
35	0	0	0	0	0	0
30	0	0	0	0	0	0
25	0	0	0	0	0	0
20	0	0	0	0	0	0
15	0	0	0	0	0	0

Table C-15 Pennsylvania SV FOHE LB Crash Counts by Posted Speed Limit: Strong Post W-Beam with Rub Rail and Offset Bracket

PSL	K	A	B	C	O	Unk
70	0	0	0	0	0	0
65	0	0	1	4	12	0
60	0	0	0	0	0	0
55	0	1	2	16	69	14
50	0	1	1	2	8	1
45	0	0	1	9	33	10
40	0	1	2	8	27	0
35	0	2	4	7	22	9
30	0	0	0	0	6	0
25	0	0	1	2	5	5
20	0	0	0	1	0	0
15	0	0	0	0	0	0

Table C-16 Pennsylvania SV FOHE LB Crash Counts by Posted Speed Limit: Strong Post W-Beam with Offset Bracket

PSL	K	A	B	C	O	Unk
70	0	0	0	2	5	0
65	1	3	11	79	342	19
60	0	0	0	0	0	0
55	4	25	78	210	753	87
50	0	3	0	11	42	5
45	4	23	34	98	283	42
40	0	3	19	53	168	20
35	3	5	13	38	148	25
30	0	1	3	6	24	2
25	0	0	5	8	23	4
20	0	0	0	1	0	1
15	0	0	0	0	0	0

Table C-17 Pennsylvania SV FOHE LB Crash Counts by Posted Speed Limit: Strong Post W-Beam

PSL	K	A	B	C	O	Unk
70	0	0	0	0	0	0
65	0	0	0	0	0	0
60	0	0	0	0	0	0
55	0	0	0	3	18	0
50	0	0	0	0	0	0
45	0	0	0	0	3	0
40	0	0	0	0	5	0
35	0	0	0	3	6	2
30	0	0	0	0	2	1
25	0	0	1	0	2	1
20	0	0	0	0	0	0
15	0	0	0	0	0	0

Table C-18 Pennsylvania SV FOHE LB Crash Counts by Posted Speed Limit: Weak Post W-Beam

PSL	K	A	B	C	O	Unk
70	0	0	0	0	3	0
65	0	2	9	42	357	8
60	0	0	0	0	0	0
55	0	7	15	65	330	27
50	0	0	1	6	25	5
45	0	2	8	16	91	6
40	0	3	2	4	27	4
35	0	0	3	4	19	4
30	0	0	0	0	2	0
25	1	0	0	0	3	0
20	0	0	0	0	0	0
15	0	0	0	0	0	0

Table C-19 Pennsylvania SV FOHE LB Crash Counts by Posted Speed Limit: Strong Post W-Beam, Double-Faced

PSL	K	A	B	C	O	Unk
70	0	0	0	0	0	0
65	0	0	0	0	0	0
60	0	0	0	0	0	0
55	0	2	2	11	32	7
50	0	0	0	1	1	0
45	0	0	1	1	2	1
40	0	0	0	1	5	0
35	0	0	2	2	2	1
30	0	0	0	0	0	0
25	0	0	0	0	0	0
20	0	0	0	0	0	0
15	0	0	0	0	0	0

Table C-20 Pennsylvania SV FOHE LB Crash Counts by Posted Speed Limit: Weak Post W-Beam, Double-Faced

PSL	K	A	B	C	O	Unk
70	0	0	0	0	0	0
65	0	0	0	0	0	0
60	0	0	0	0	0	0
55	0	0	0	6	52	8
50	0	0	0	0	0	0
45	0	0	0	0	0	0
40	0	0	0	0	0	0
35	0	0	0	0	0	0
30	0	0	0	0	1	0
25	0	0	0	0	0	0
20	0	0	0	0	0	0
15	0	0	0	0	0	0

Table C-21 Pennsylvania SV FOHE LB Crash Counts by Posted Speed Limit: Weak Post Box Beam

PSL	K	A	B	C	O	Unk
70	0	0	0	0	0	0
65	0	0	0	0	0	0
60	0	0	0	0	0	0
55	0	0	0	1	15	5
50	1	0	0	0	0	0
45	0	0	0	1	5	0
40	0	0	0	0	0	0
35	0	0	0	0	5	2
30	0	0	0	0	0	0
25	0	0	0	0	0	0
20	0	0	0	0	0	0
15	0	0	0	0	0	0

Table C-22 Pennsylvania SV FOHE LB Crash Counts by Posted Speed Limit: Concrete Safety Shape

PSL	K	A	B	C	O	Unk
70	0	0	0	0	0	0
65	0	2	9	28	79	6
60	0	0	0	0	0	0
55	1	7	44	158	523	79
50	0	0	12	45	89	22
45	0	1	4	18	66	14
40	0	0	1	20	59	6
35	0	0	3	17	22	7
30	0	0	0	0	2	0
25	0	0	1	2	2	1
20	0	0	0	0	0	0
15	0	0	0	0	0	0

Table C-23 Pennsylvania SV FOHE LB Crash Counts by Posted Speed Limit: IBC Barrier

PSL	K	A	B	C	O	Unk
70	0	0	0	0	0	0
65	0	0	0	4	14	1
60	0	0	0	0	0	0
55	0	0	0	1	4	1
50	0	0	0	0	0	0
45	0	0	0	0	0	0
40	0	0	0	0	0	0
35	0	0	0	0	0	0
30	0	0	0	0	0	0
25	0	0	0	0	0	0
20	0	0	0	0	0	0
15	0	0	0	0	0	0

Table C-24 Pennsylvania SV FOHE LB Crash Counts by Posted Speed Limit: Propriety Cable Systems (All Combined)

PSL	K	A	B	C	O	Unk
70	0	0	0	0	0	0
65	0	1	1	4	9	1
60	0	0	0	0	0	0
55	0	0	1	10	51	4
50	0	0	0	0	0	0
45	0	0	0	0	0	0
40	0	0	0	0	0	0
35	0	0	0	0	0	0
30	0	0	0	0	0	0
25	0	0	0	0	0	0
20	0	0	0	0	0	0
15	0	0	0	0	0	0

Table C-25 Pennsylvania SV FOHE LB Crash Counts by Posted Speed Limit: Other

PSL	K	A	B	C	O	Unk
70	0	0	0	0	0	0
65	0	0	0	0	1	0
60	0	0	0	0	0	0
55	0	1	0	0	5	1
50	0	0	1	0	0	0
45	0	0	1	1	2	1
40	0	0	0	1	1	0
35	0	0	0	1	1	0
30	0	0	0	0	0	0
25	0	0	0	0	0	0
20	0	0	0	0	0	0
15	0	0	0	0	0	0

Tennessee

A total of 2,881 SV FOHE LB crashes were found during the 5-year study period (2012–2016) in Tennessee. These crashes were then linked to the roadside hardware inventory for each identified longitudinal barrier. Tennessee identifies the following longitudinal barriers within the inventory:

- Jersey Barrier
- W-Beam
- Cable Barrier—Gibraltar NCHRP350
- Cable Barrier—Nu-Cable

The severity distributions for each barrier type are shown in Tables C-26 through C-29. There were 124 reported SV FOHE LB crashes with the Jersey Barrier. There were 72 reported SV FOHE LB crashes with the W-Beam.

There were 18 reported SV FOHE LB crashes with the Gibraltar cable barrier including zero fatal and one serious injury crash. There were 37 reported crashes with the Nu-Cable system including zero fatalities and two serious injuries. The combined severity distribution of these proprietary cable systems is shown in Table C-28. Of the reported crashes, 2,630 were not associated with the hardware inventory, the distribution of which is shown in Table C-29. This large number of unassociated crashes is due to the police crash reports often excluding the run-off-road direction, which prevented identification of the barrier involved.

Table C-26 Tennessee SV FOHE LB Crash Counts by Posted Speed Limit: Jersey Barrier

PSL	K	A	B	C	O	Unk
70	0	2	12	11	38	1
65	0	0	1	1	9	1
60	0	0	0	0	0	0
55	0	1	2	9	32	2
50	0	0	0	1	1	0
45	0	0	0	0	0	0
40	0	0	0	0	0	0
35	0	0	0	0	0	0
30	0	0	0	0	0	0
25	0	0	0	0	0	0

Table C-27 Tennessee SV FOHE LB Crash Counts by Posted Speed Limit: W-Beam

PSL	K	A	B	C	O	Unk
70	0	0	1	1	23	0
65	0	0	0	1	9	0
60	0	0	0	0	1	0
55	1	1	2	6	15	0
50	0	0	0	0	0	0
45	1	0	1	3	3	0
40	0	0	0	0	1	1
35	0	0	0	0	0	0
30	0	0	0	0	0	0
25	0	0	0	1	0	0

Table C-28 Tennessee SV FOHE LB Crash Counts by Posted Speed Limit: Proprietary Cable Barrier (All Combined)

PSL	K	A	B	C	O	Unk
70	0	2	1	1	22	0
65	0	1	0	3	21	0
60	0	0	0	0	2	0
55	0	0	0	0	2	0
50	0	0	0	0	0	0
45	0	0	0	0	0	0
40	0	0	0	0	0	0
35	0	0	0	0	0	0
30	0	0	0	0	0	0
25	0	0	0	0	0	0

Table C-29 Tennessee SV FOHE LB Crash Counts by Posted Speed Limit: Unable to Associate with a Barrier Type

PSL	K	A	B	C	O	Unk
70	0	6	29	59	367	9
65	1	9	27	53	370	6
60	0	1	1	4	27	0
55	4	29	97	188	998	29
50	0	2	6	8	76	0
45	0	1	13	12	71	1
40	0	1	4	8	26	1
35	0	0	4	5	39	2
30	0	2	1	2	21	1
25	0	0	0	0	9	0

CHAPTER 4

ESTIMATE UNREPORTED CRASHES

Crash reporting thresholds vary by state, with some states only requiring reports when there is an injury, while others require a monetary threshold to be exceeded. It has long been recognized that police-reported crash data underreport lower severity crashes. "These low-severity crashes represent roadside design successes since the vehicle was able to encroach onto the roadside or median without causing an injury." (Ray 2014b) When the EFCCR approach was developed, it included a step for estimating unreported crashes to account for this bias.

Unreported crashes have been studied in several research studies, including the FHWA Pole Study, *NCHRP Report 490*, and *NCHRP Report 638*. (Mak 1980; Ray 2003; Sicking 2009) In his National Highway Traffic Safety Administration Technical Report on "The Economic Impact of Motor Vehicle Crashes, 2000," Blincoe estimated that for all types of highway crashes, nearly half (i.e., 48%) of all PDO crashes and a little over 20% (i.e., 21.42%) of injury crashes are not reported. (Blincoe 2002)

It has been found that the unreported crash rate is different for different types of roadside objects. For example, 77% of concrete barrier crashes were unreported while 34% of low-tension (LT) cable barrier crashes were unreported. (Fitzpatrick 1999; Hammond 2008)

Building on a model developed by Nilsson (Nilsson 1982), Ray et al. estimate the percentage of non-injury crashes (P_{NIC}) by comparing crashes at two speeds, as follows:

$$P_{NI2} = 1 - (1 - P_{NI1}) \left[\frac{V_2}{V_1}\right]^2 = 1 - P_{I1} \left[\frac{V_2}{V_1}\right]^2$$

This expression allows the unobserved percent of non-injury crashes to be estimated based on the number of observed injury crashes. (Ray 2014b) Next, the percentage of unreported and PDO crashes that is either known or assumed at the base speed of 65 mph is used to extrapolate to all other speeds. When the estimate produces no negative crash estimates, the estimate is balanced and has reached the maximum likelihood estimate of total crashes for the data set.

The data found in the literature and assembled from the asset inventories of Ohio, Pennsylvania, and Tennessee represent validated data where the type of hardware or roadside feature involved in the crash can be confirmed. Summaries of the total number of reported SV FOHE LB crashes for the concrete barrier family, the cable barrier family, the beam barrier family, and other median features are shown in Tables C-30 through C-33. The maximum likelihood estimate (MLE) of unreported crashes for each data set resulted in an assumed ratio of injury crashes to total crashes at 65 mph, expressed as a percentage. This MLE of the percentage of injury crashes is also shown in Tables C-30 through C-33.

Table C-30 Maximum Likelihood Estimate of Injuries for Concrete Barrier Family

State and Barrier	Observed Crashes	MLE % INJ
MA 32”	154	45.45
PA 32” F-Shape	164	33.64
All 32” F-Shape	318	40.16
MA 42” F-Shape	34	41.05
PA 42” F-Shape	56	28.26
All 42” F-Shape	90	28.26
All F-Shape	408	38.24
NE 29” Vertical Wall	20	43.11
NE 34” Vertical Wall	471	17.93
NE 42” Vertical Wall	40	10.73
All Vertical Wall	531	17.57
OH Single Slope	89	14.28
WA 34” Single Slope	178	0.00
All Single Slope	267	14.28
TN Jersey	124	16.66
OH 32” Jersey	195	25.14
NE 32” Jersey	169	9.37
TX 32” TL4 Jersey MB	1,678	0.00
OH 42” Jersey	54	15.51
NE 42” Jersey	67	43.34
All 32” Jersey	2,042	9.38
All 42” Jersey	121	27.77
All Jersey	2,163	9.38
All Concrete	7,325	16.74

Table C-31 Maximum Likelihood Estimate of Injuries for Cable Barrier Family

State and Barrier	Observed Crashes	MLE % INJ
WA TL3 HT Cable	541	10.02
IA TL3 HT Cable	20	15.00
PA HT Cable	82	23.27
TN HT Cable	55	13.26
All HT Cable	698	10.32
WA TL3 LT Cable	594	6.65
AZ TL3 LT Cable	20	25.00
NC TL3 LT Cable	127	30.70
OR TL3 LT Cable	26	19.23
PA LT Cable	29	9.63
All LT Cable	796	6.65
All HT and LT Cable	1,494	8.62

Table C-32 Maximum Likelihood Estimate of Injuries for Beam Barrier Family

State and Barrier	Observed Crashes	MLE % INJ
PA Strong Post W-Beam w/Rub Rail and Offset Bracket	287	26.00
PA Strong Post W-Beam with Offset Bracket	2,737	20.65
PA Strong Post W-Beam	47	19.95
PA MB Strong Post W-Beam	74	38.79
All PA Strong Post W-Beam	3,145	20.97
OH W-Beam	3,052	18.22
TN W-Beam	72	6.89
PA Weak Post W-Beam	1,101	12.67
PA MB Weak Post W-Beam	67	12.69
All PA Weak Post W-Beam	1,168	12.67
All Strong Post W-Beam	6,269	10.77
PA Box Beam	35	6.65
All Weak and Strong Post W-Beam	7,437	9.85

Table C-33 Maximum Likelihood Estimate of Injuries for Non-Barrier Median Features

State and Feature	Observed Crashes	MLE % INJ
WA Cross-Median Crash	23,928	16.51
WA Rollover	7,439	51.87
WA Tree	1,922	30.90
WA Waterbody	144	21.55

CHAPTER 5

DETERMINE P(KA|C)

Carrigan and Ray explained in "Practitioner's Guide to the Analysis of In-Service Performance Evaluation Data" the relationship between absolute risk, portions, percentages, and probability of crashes with roadside hardware. The absolute risk of KA crashes can be found by summing the total number of KA crashes in the data for a hardware category and dividing by the total number of all crashes of all severities for that same category, as shown here (Carrigan 2016):

$$Absolute\ Risk = \frac{KA}{KABCOU}$$

where

KA = Severe and fatal injury crashes

KABCOU = Crashes of all reported severities including U for unknown severities. If unreported crashes have been studied, these unreported crashes should also be included in the denominator.

The keen observer will note that absolute risk is simply a proportion. When multiplied by 100, it is also a percentage. When absolute risk is defined this way, it is also the probability of observing a KA crash given all crashes, P(KA|C).

The absolute risk calculation is a point estimate calculated from a sample of the population of interest. Since the absolute risk of the entire population (p) is unknown, the estimated absolute risk ($\hat{p}$) from the sample is used and expressed with a confidence interval to allow inferences to be made on the larger population. (Kean 1999; Yale 2015) A confidence interval is much more useful than a p-value, as it provides a range of values that the entire population is likely between. For example, if the 95 percentile confidence bounds are provided for an absolute risk estimate, this can be interpreted as: "based on the sample data, we are 95% confident that the 'true' absolute risk of a KA crash with the hardware studied is between x and y." The probability of observing a value outside of the area is less than 0.05 (i.e., 1-0.95=0.05). (Carrigan 2016) Common confidence levels and the corresponding z-values are shown in Table C-34.

Table C-34 Published z-values for Normal Distribution (Carrigan 2016)

Confidence Level	z
0.70	1.04
0.75	1.15
0.80	1.28
0.85	1.44
0.90	1.645
0.92	1.75
0.95	1.96
0.96	2.05
0.98	2.33
0.99	2.58

The confidence interval is calculated for proportional data such as absolute risk using the following equation:

$$\hat{p} \pm z\sqrt{\frac{\hat{p}(1-\hat{p})}{n}}$$

Where:

$\hat{p}$ = Absolute risk calculated from the sample.
z = Number of standard deviations away from the mean (see Table C-34).
n = Sample size.

The analysis and recommendations for P(KA|C) for use in the guidelines are discussed below.

Concrete Barrier Family

P(KA|C) as a proportion and the 95% confidence interval are shown for each barrier within the concrete barrier family in Figure C-1. P(KA|C) for each concrete barrier is shown on the y-axis. The diamond markers represent the point estimate of P(KA|C) with a concrete barrier. The bars extending above and below the diamond markers are the 95% confidence intervals. Based on the sampled data, we are 95% confident that the 'true' P(KA|C) for concrete barriers is within the range shown by the bars for each marker.

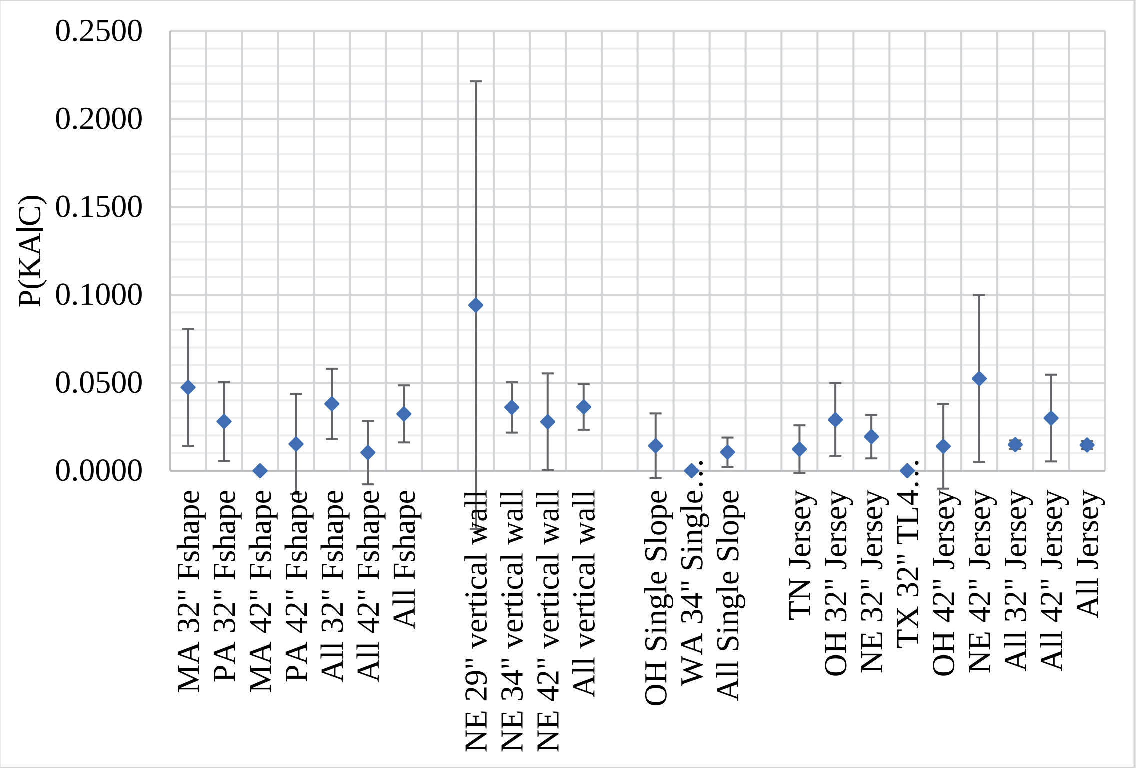

Figure C-1 P(KA|C) for concrete barrier family with 95% confidence intervals.

Notice how the range represented by the bars within the F-Shape family overlap each other. This indicates that there is not a statically observed difference in these data between, for example, the 32” F-Shape barrier in Massachusetts and the 42” F-Shape barrier in Pennsylvania. The same is true for each concrete shape family shown in Figure C-1. A review of the combined estimates for each concrete shape grouping was performed to assess any observable difference and eliminate the individually insignificant findings, as shown in Figure C-2. Note that the y-axis of Figure C-2 has been extremely exaggerated to allow for interpretation of these small differences.

Each concrete barrier shape overlaps with at least one other shape shown. There is, therefore, not an observable difference between all the barriers, but only between pairs of barriers. On the other hand, each barrier type is significant on its own. There are two options, one more restricting than the other: (1) the guidelines could adopt separate measures for each barrier, or (2) the guidelines could adopt a single crash severity measure for the entire concrete family. Adopting a single measure for concrete was preferred here due to the lack of significant difference between systems and because these data are based on *NCHRP Report 350* barriers, while this severity measure will be applied to MASH barriers. As MASH barriers are implemented, this single measure will help to ensure that the crash severity of concrete barriers is estimated with the greatest confidence and smallest range. Of course, individual states can adopt the severity measure appropriate to their state in their state-specific guidance.

The value $P(KA|C)_{concrete} = 0.0159$, 95% CI [0.0139, 0.0178] has been adopted for the concrete family.

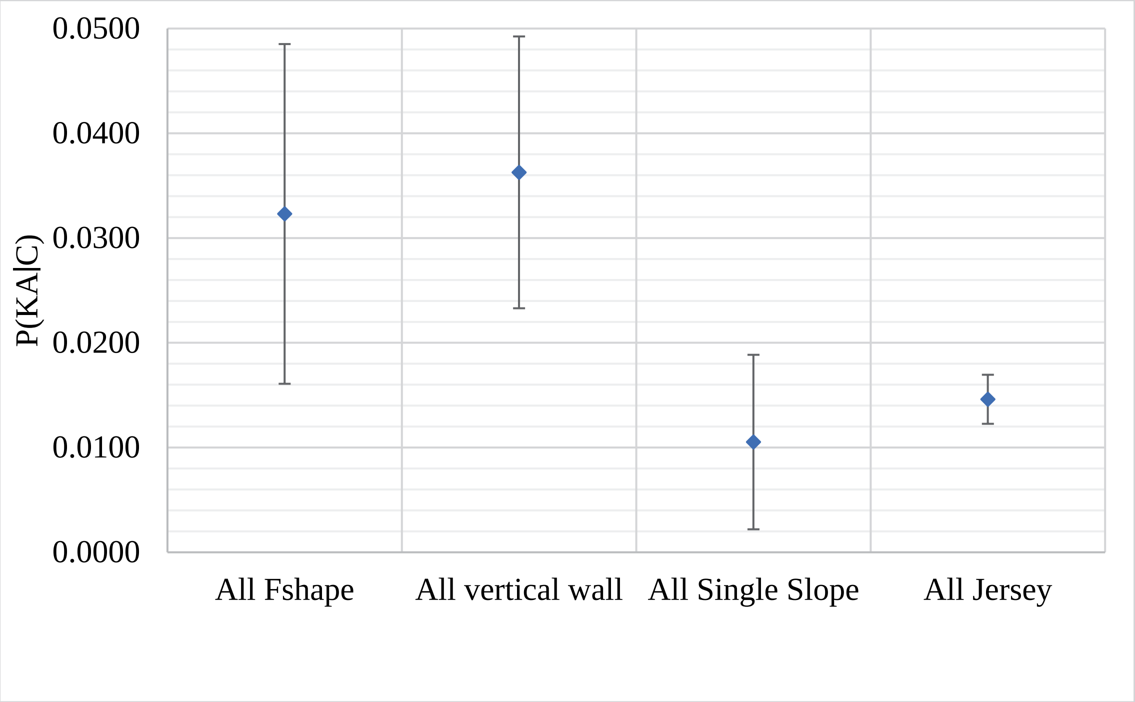

Figure C-2 P(KA|C) limited by concrete shape with 95% confidence intervals.

Cable Barrier Family

P(KA|C) as a proportion and the 95% confidence interval are shown for each barrier within the cable barrier family in Figure C-3. As before, the diamond markers represent the point estimate of P(KA|C) with cable barriers, and the bars represent the 95% confidence interval. Based on the sampled data, we are 95% confident that the “true” P(KA|C) for cable barrier is within the range shown by the bars for each cable system. Recall the proprietary high-tension (HT) systems were combined into a single HT category by state for this analysis.

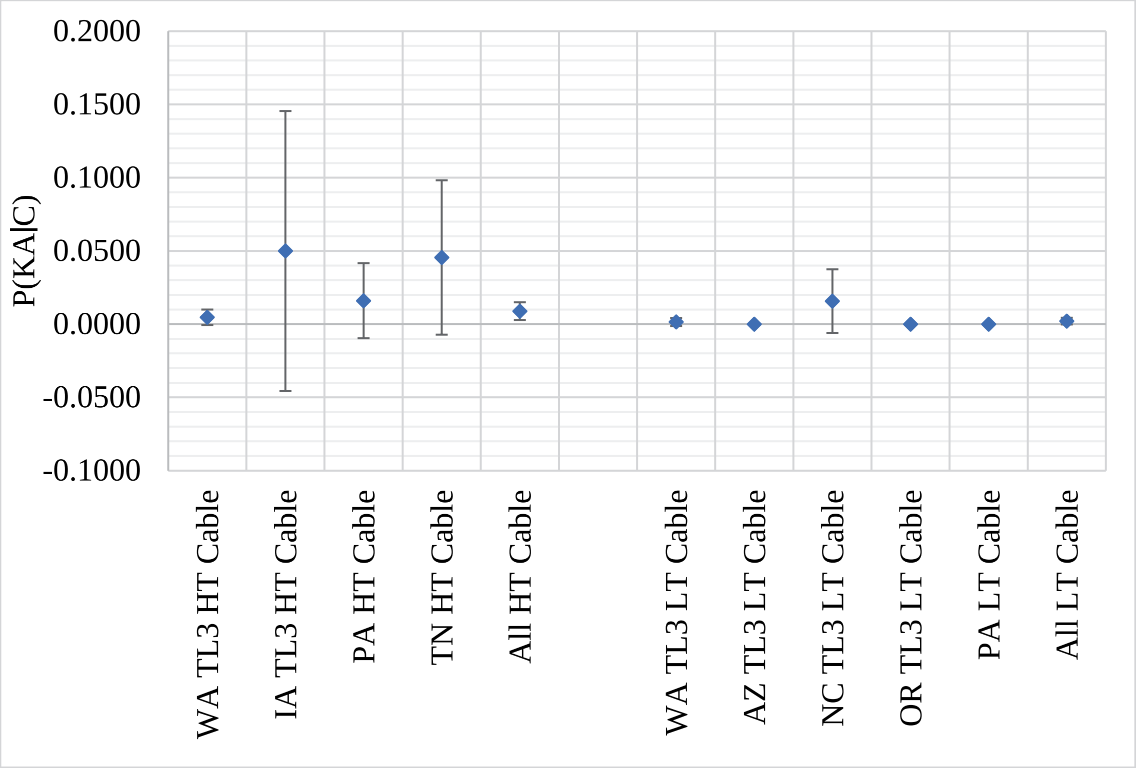

Figure C-3 P(KA|C) for cable barrier family with 95% confidence intervals.

No fatal or severe (K or A) LT cable barrier crashes were observed in the Arizona, Oregon, and Pennsylvania data. The North Carolina data included two A-level injuries and Washington observed one A-level injury. There were no fatal crashes observed in the LT cable data. The HT cable systems were previously combined, which could explain the tight confidence range in this large sample. Figure C-4 exaggerates the y-axis and limits the figure to the combined analysis of HT and LT cable. While the probability of a severe or fatal injury given a crash, P(KA|C), with an LT system does appear to be less than with an HT system, the evidence is inconclusive. It is therefore recommended that crash severity for both HT and LT cable systems be presented simply as crash severity with cable barrier in the guidelines. The value $P(KA|C)_{cable}$ 0.0050, 95% CI [0.0021, 0.0079] has been adopted for the cable family. As MASH barriers penetrate the market and in-service performance evaluations (ISPEs) are completed, this value may be reevaluated.

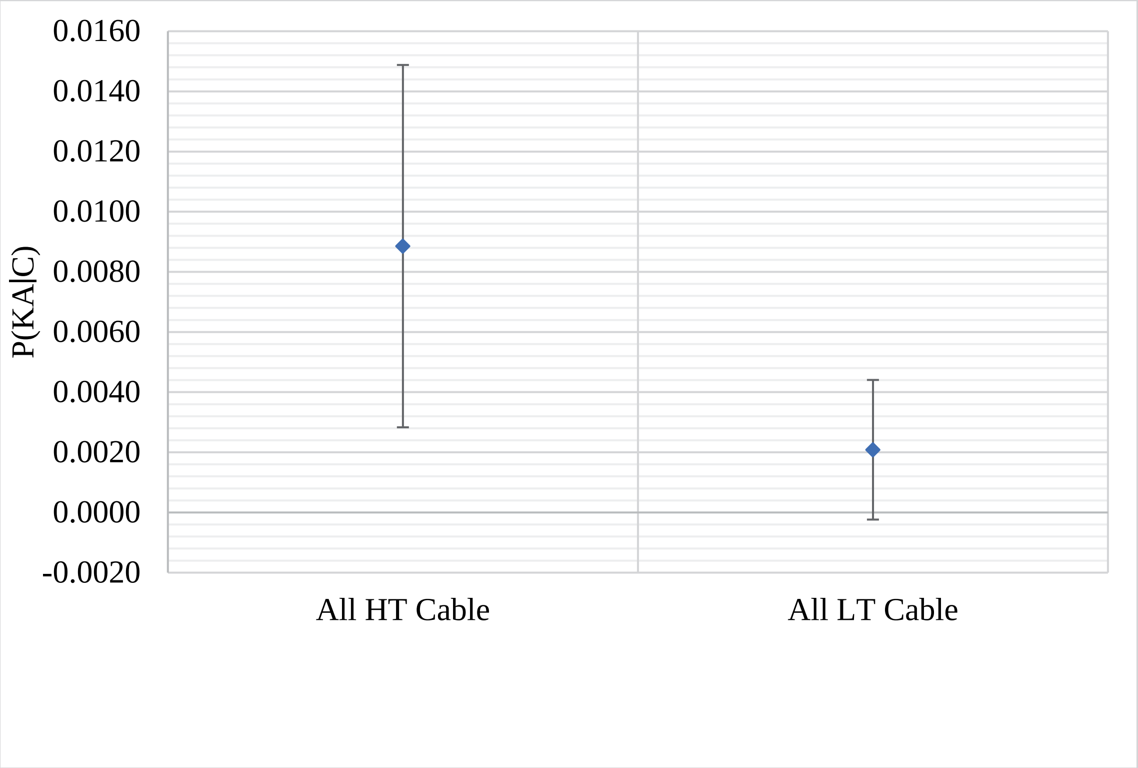

Figure C-4 P(KA|C) for cable system groups with 95% confidence intervals.

Metal Beam Barrier Family

P(KA|C) as a proportion and the 95% confidence interval are shown for each barrier within the metal beam barrier family in Figure C-5. The point estimate of P(KA|C) is shown using diamond markers with corresponding numeric values on the y-axis. Based on the sample data, we are 95% confident that the ‘true’ P(KA|C) for each marker is within the range shown by the bars for each metal beam barrier studied.

The Pennsylvania data provides a wide spectrum of the many types of W-beam installed within Pennsylvania. Notably, the Pennsylvania inventory captures each of these different beam systems. In addition to Pennsylvania data, Ohio and Tennessee results are also shown. The Ohio and Tennessee inventories do not include multiple types of metal beams, either because the state standardizes on a single system or because the inventory does not distinguish between the different metal beam systems. As with the other crash data, there is an underlying assumption that these data represent the crash severity of *NCHRP Report 350* systems and that the crash severity data for *NCHRP Report 350* systems can be extended to MASH systems until additional data become available.

Notice, in Figure C-5, that the Pennsylvania strong post data have been combined into a single category and are shown next to the Ohio and Tennessee data to facilitate review. Like Figure C-4 in the previous analysis, Figure C-6 shows the combined analysis of all the strong post W-beam and the only available weak post data from Pennsylvania. There is no difference in the crash severity between weak post and strong post w-beam, accepting that the results for the weak post, as shown on the extremely exaggerated y-axis, have confidence intervals that overlap those for the strong post.

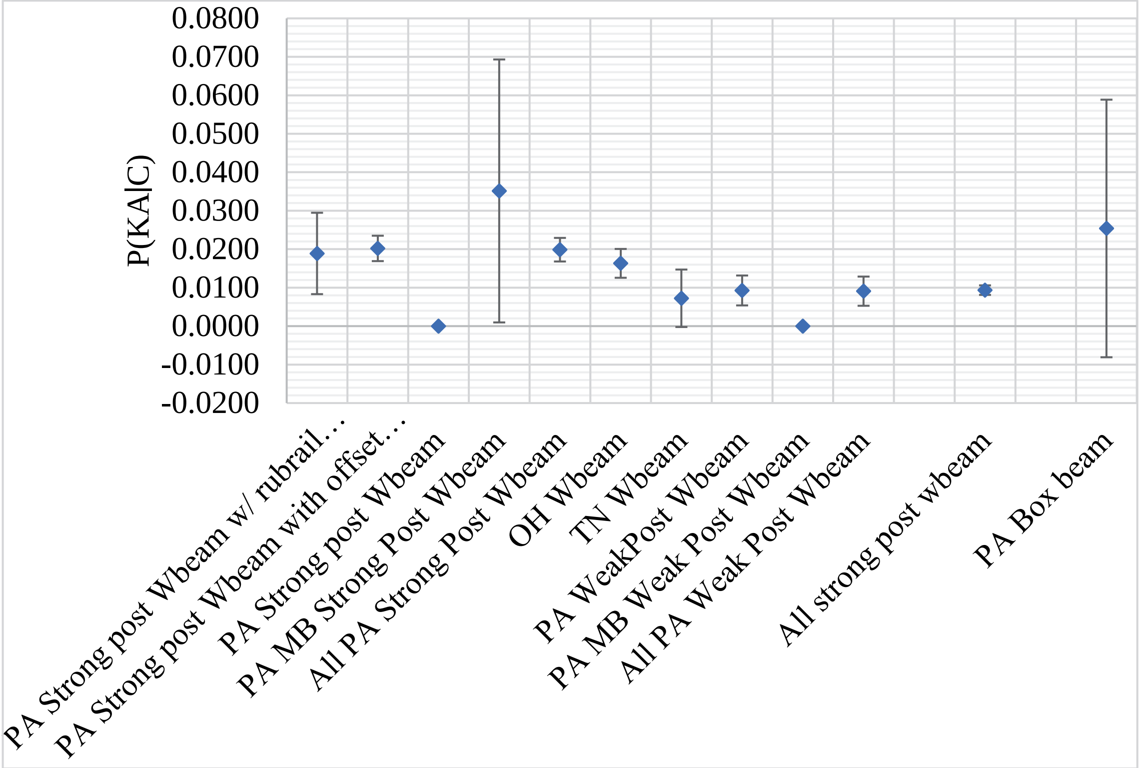

Figure C-5 P(KA|C) for metal beam barrier family with 95% confidence intervals.

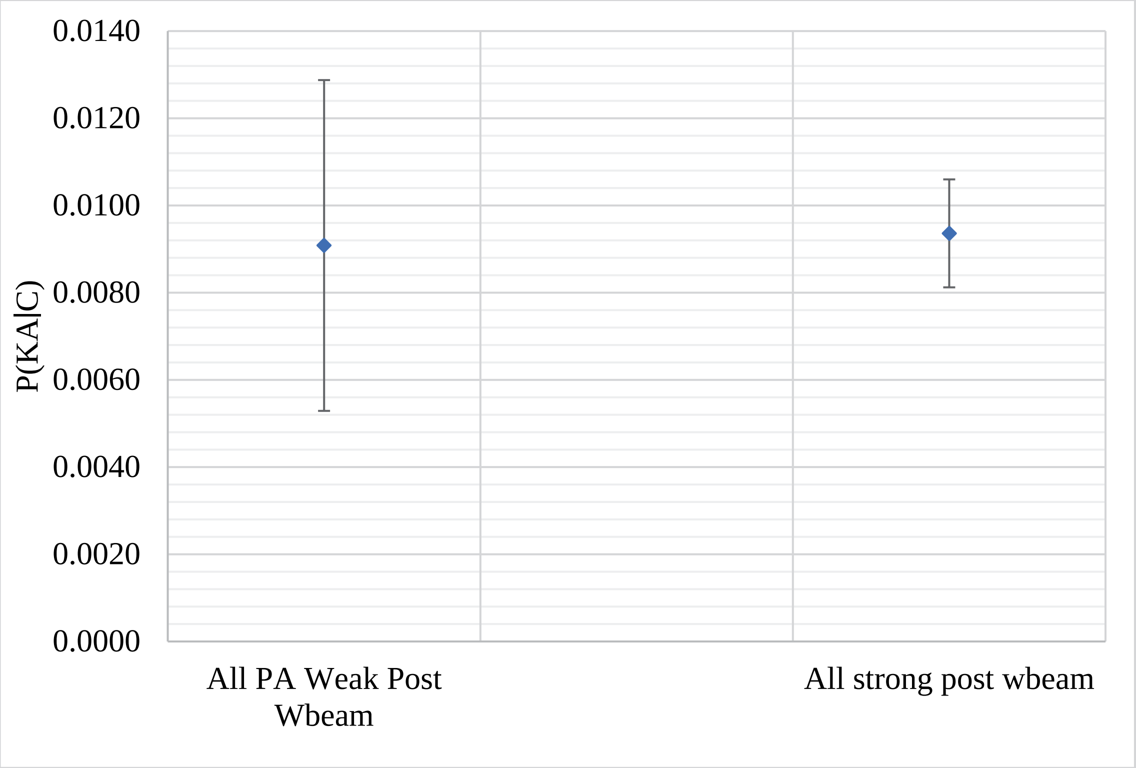

Figure C-6 P(KA|C) for metal beam barrier family with 95% confidence intervals.

One approach for providing P(KA|C) for the metal beam barriers would be to combine the weak post and strong post systems as done for the cable and concrete barrier families. Another approach would be to simply use the strong post value and not provide for weak post in the guidelines. There is little difference in the ultimate result, and there is practicality in offering a value in the guidelines that encompasses both systems. It is therefore recommended to present a single value for the metal beam family which combines weak post and strong post systems. The value $P(KA|C)_{beam}$ = 0.0084, 95% CI [0.0073, 0.0094] was adopted for the metal beam family. As with the other longitudinal barriers, this value should be reexamined as ISPEs of MASH systems become available.

Other Features

P(KA|C) as a proportion and the 95% confidence interval are shown in Figure C-7 for the other features studied. As previously stated, the diamond markers represent the point estimate of P(KA|C), and reference should be made to the y-axis for the corresponding value. Based on the sampled data, we are 95% confident that the ‘true’ P(KA|C) for each feature is within the range shown by the bars for each category.

The cross-median crash value shown was used in the development of these guidelines to represent CMC, $P(KA|C)_{CMC}$ = 0.0451, 95% CI [0.0441, 0.0461]. The values for rollover and fixed objects such as trees cannot be distinguished statistically. A single value for interaction with a non-designed roadside feature (NDRF) has therefore been adopted in these guidelines. $P(KA|C)_{NDRF}$ = 0.0589, 95% CI [0.0549, 0.0629].

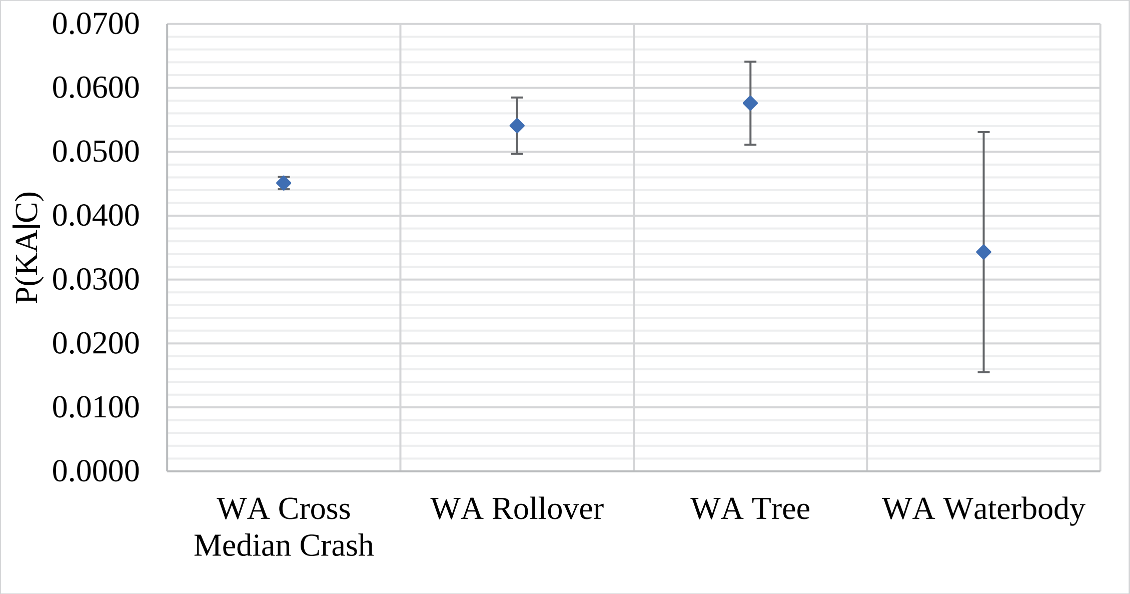

Figure C-7 P(KA|C) for median features with 95% confidence intervals.

CHAPTER 6

RESULTS AND DISCUSSION

The forgoing statistical analysis presented in this document provided the analysis and justification for each recommended grouping of barriers and features. Throughout the analysis, the 95% confidence intervals were presented to ensure high confidence in the recommended groupings. The resulting recommended groupings and $P(K|C)_{65}$ have been summarized in Table C-35. Probability levels for fatal crashes (K); fatal and serious crashes (KA); fatal, serious, and observed injury crashes (KAB); and fatal and any level of injury crashes (F+I) are also included to allow for flexibility as guideline development continues. The resulting values can be used in the guidelines and adjusted using the site-specific PSL, as follows:

$$\mathrm{P(Sev|C)_{PSLi}} = \left[\frac{\mathrm{P(Sev|C)_{65}}}{65^3}\right]\mathrm{PSL_i^3}$$

Table C-35 Recommended Groupings of Barriers and Median Features for Guideline Development

Feature	Observed Crashes	MLE % INJ	Nr+Nu	$P(Sev\|C)_{65}$			
				K	KA	KAB	F+I
Cable	1,494	8.62	2,257	0.0009	0.0050	0.0297	0.0849
Metal Beam	7,437	9.85	28,494	0.0013	0.0084	0.0369	0.0895
Concrete	7325	16.74	15913	0.0021	0.0159	0.0810	0.1667
CMC	26,928	16.51	179,033	0.0098	0.0451	0.1290	0.1938
NDRF	9,361	50.10	13,484	0.0142	0.0589	0.3138	0.4836

Table C-35 includes the Nr+Nu estimate for each grouping. Any confidence interval level can be determined using the z-values shown above in Table C-34. Recall the equation presented above for calculating confidence levels:

$$\hat{p} \pm z\sqrt{\frac{\hat{p}(1-\hat{p})}{n}}$$

where

$\hat{p}$ = P(Sev|C)
z = Number of standard deviations away from the mean (see Table C-34).
n = use value in Nr+Nu column

The values for $P(KA|C)_{65}$ are based on observable police-reported crashes and adjusted to account for unreported crashes based on the model of crash severity discussed above. These severity measures are then standardized at a base PSL of 65 mph and can be adjusted for site-specific speeds. Using $P(KA|C)_{65}$ to estimate crash severity in a conditional probability model such as the guidelines being developed provides a systematic methodology based on observed data and established crash severity relationships.

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APPENDIX D

Probability of Passing Through, Over, or Under a Barrier (THR_{BAR})

CONTENTS

CHAPTER 1

INTRODUCTION

The ability to reasonably predict the number of penetrate-the-barrier, roll-over-the-barrier, and vault-the-barrier crashes (THR_{BAR}) is critical to understanding barrier performance and selecting a barrier. Often, guidelines presented in past editions of the Roadside Design Guide (RDG) have presumed that barriers were 100% effective in preventing a vehicle from crossing to the other side of the barrier. While barriers are highly effective at minimizing penetration, roll over, and vault-over crashes, a small percentage of vehicles still cross the barrier line and interact with hazards shielded by the barrier. Often these penetration-roll over-vault crashes are severe. An accurate prediction of barrier performance must include a reasonable method for estimating the number of penetration, roll over, and vault collisions for a particular barrier. The proportion is assumed to be a function of the vehicle mix where heavier vehicles are more likely to breach the barrier; however, the crash data are dominated by passenger vehicles. Properly incorporating both heavy vehicles and passenger vehicles is important in selecting the appropriate test level barrier.

As discussed here, a penetration implies a complete structural failure of the barrier that allows the vehicle to pass through. A roll-over-the-barrier collision is one where the vehicle rolls over the barrier to the field side, whereas a redirection roll over is one in which the vehicle rolls over after redirection while remaining on the same side of the barrier (i.e., the traffic side). A vault of the barrier is when a vehicle vaults over the barrier to the other side after impact. A study of the probability of a barrier breach (i.e., penetration, roll-over-the-barrier, or vault-the-barrier) given a crash with the barrier was undertaken using RSAPv3. The model development and analysis of the simulated data are documented in this appendix. This appendix documents a model developed from simulated RSAPv3 data to represent THR_{BAR} for these guidelines. Vehicle type, barrier type, and barrier placement were evaluated as explanatory variables for THR_{BAR}.

CHAPTER 2

BACKGROUND

The RSAPv3 Engineer's Manual developed in NCHRP Project 22-27 reviewed the advantages and disadvantages of employing a mechanistic approach or an empirical approach to estimating barrier penetrations. (Ray 2012) Briefly, most mechanistic penetration models assume that penetration occurs once capacity has been reached; however, this is only the beginning of the failure process. The barrier may contain and redirect the vehicle even though there are structural failures, as was determined by Ray et al. in their NCHRP Project 22-12(03) review of 50 full-scale crash tests on concrete bridge rails and median barriers. (Ray 2014) In other words, reaching capacity does not necessarily mean the vehicle will penetrate the barrier.

One way to overcome this overly conservative assumption is by adopting an empirical approach using field-collected crash data. A complete understanding of the physics is not required since the data represents real observed events that incorporate a realistic range of impact conditions and material failures. Sufficient quantities of some vehicle and/or barrier types, however, are not available within the crash data (e.g., new MASH barriers), so the empirical approach is limited by the availability of crash data.

There are, however, reliable data on vehicle mix. *NCHRP Research Report 892: Guidelines for Shielding Bridge Piers* (Ray 2018) recently studied the distribution of vehicle types and vehicle properties for the development of guidelines that are proposed for incorporation in the RDG. The variations and distributions of each vehicle group on different types of roadways were considered. This distribution of vehicle mix varies slightly based on the percentage of trucks (PT) in the traffic stream. The traffic mix findings from *NCHRP Research Report 892* are shown in Table D-1.

Table D-1 *NCHRP Research Report 892* Traffic Mix Summary for Roadside Design (Ray 2018)

		Rural		**Urban**	
FHWA Vehicle Class	**Vehicle Category**	**Interstates and Arterials**	**Collectors and Locals**	**Interstates and Arterials**	**Collectors and Locals**
1	Motorcycles	Unknown	Unknown	Unknown	Unknown
2	Passenger Cars	0.75(1-PT)	0.75(1-PT)	0.80(1-PT)	0.80(1-PT)
3	Pickups, Vans, and SUVs	0.25(1-PT)	0.25(1-PT)	0.20(1-PT)	0.20(1-PT)
4–7	Single-Unit Truck and Bus	0.25(PT)	0.70(PT)	0.35(PT)	0.80(PT)
8–10	Single-Trailer Truck	0.70(PT)	0.30(PT)	0.60(PT)	0.20(PT)
11–13	Multi-Trailer Truck	0.05(PT)	0.00	0.05(PT)	0.00

CHAPTER 3

SIMULATED ENCROACHMENT DATA

RSAPv3 simulations were generated to capture both the mechanistic and empirical calculations from the barrier breach module already coded within the RSAPv3 software. A subset of 114 available field-reconstructed passenger vehicle trajectories included in the analysis is identified in Table D-2 using the identifier from the research project in which the trajectories were gathered. (Mak 2010)

Unfortunately, there are no field-reconstructed trajectories for heavy vehicles. Passenger vehicle trajectories were therefore limited to reasonable encroachment angles and speeds using previously documented methodologies (Ray 2017) to represent Single Unit Trucks (SUTs) and Tractor Trailers (TTs). The limitations resulted in assuming a data set of 38 trajectories to represent the SUTs and 30 trajectories to represent the TTs. These trajectories are also shown in Table D-2 marked with an asterisk or double asterisk for SUT and TT trajectories respectively.

Table D-2 Passenger Vehicle Trajectories Used in Simulations

300421000**	134003385	146000704**	146003943**	209002222	657000589**
102002123**	134003586**	146001442	146003961**	209002882	657000595**
102002626*	134004265	146001661	146004363	209002883	659200356
129000676	134004706**	146001682	157008122	471400344	660500268
129000716	139001022	146001744	166002351	471600569	661100681
129001416**	139001781	146001761**	166002573**	471600589	661300240
129002054	139002264	146001764**	166003213	626300646	661300244
134000865**	139002302	146002182*	170001347**	655800263*	661300266*
134000908	139002405**	146002224**	170002267**	655800450*	661300402
134001646	139002542	146002723	170003586	655800471	778400222
134001707	139002925	146002742	200003532	655800566	819003805
134001745	139003243	146002884	207003902	655800684	881004121
134001987	139003481**	146003082**	207004182*	655800688	881004202
134002205	139003882	146003401*	207004284	655800691	916800203
134002365	139003961	146003481**	207004343	656500481	881004202
134002486	139004242	146003563**	207004742	656500681	916800203
134002507	139004343**	146003703	209000841	656500686*	
134002627	139004501	146003746**	209001561**	657000372	
134003026**	139004541**	146003821**	209001681	657000471	
134003066	139004762**	146003843	209001764**	657000472	

**SUT and TT trajectories
* SUT trajectories

The longitudinal barriers shown in Table D-3 were simulated at offsets from 1 foot to 99 feet from the travel edge in one-foot increments. Offset to the barrier was measured from the travel edge to the center of the barrier.

Table D-3 MASH Barriers Studied

	Name	MASH Test Level	Height (inches)	Width (inches)	Crash Data PRV (%)	Energy Capacity (ft-lbf)	Load Capacity (lbf)
BT_0	Concrete	TL2	24	12	---	47,000	43,200
BT_1	Cable	TL3	30	6	4.00	40,000	110,000
BT_2	W-beam	TL3	31	24	2.00	110,000	40,000
BT_3	Concrete	TL3	29	12	---	47,000	90,000
BT_4	Concrete	TL4	36	12	---	47,000	128,000
BT_5	Concrete	TL5	42	12	---	47,000	264,000

The objective of this study was to model the probability of barrier breach for different barrier types, vehicle types, and barrier offsets. A simple relationship was evaluated for predicting barrier breach explained by the levels of vehicle type and barrier type as well as the continuous measure of offset. It was found that there is not a significant difference between TL3 Cable, TL3 W-beam, and TL3 F-Shape at the 95th percentile. These results show that the development history of test levels influences the ability to distinguish between test levels. It is therefore recommended that each test level of longitudinal barrier consider a single representation of THR_{BAR}.

Further consideration was given to the ability to differentiate between highway types, where the vehicle mix (i.e., mix of sedans, pickups, SUTs, and TTs) does vary, as shown in Table D-1. There is no statistically significant difference of predicted THR_{BAR} values for a particular barrier type on any highway type considered.

The attempted modeling showed it was not possible to distinguish between variations of THR_{BAR} at different values of PT. This is believed to be due to the lack of available empirical data for heavy vehicles.

CHAPTER 4

THR_{BAR} FOR GUIDELINE DEVELOPMENT

It is understood that not all vehicles will be contained under all impact conditions. It is presumed, however, for guideline development, that each test level contains the types of vehicles it was designed for. For example, TL4 barriers are specifically designed to contain SUTs, and TL5 barriers are specifically designed to contain TTs. The distributions of each type of vehicle can be represented by empirical data as shown in Table D-1. Using this equation as a model where PT is a number (i.e., not decimal), the lack of empirical data necessitated the following assumptions to estimate the value of THR_{BAR} for each test level:

$$\mathrm{THR_{BAR}} = \left[\frac{A \cdot PT}{100}\right]$$

TL2 All trucks penetrate, roll over, or vault a TL2 barrier. Passenger vehicles are contained when posted speed limits are less than or equal to 45 mph.

TL3 Barriers contain passenger vehicles but all trucks breach the barrier.

TL4 Barriers contain passenger vehicles and SUTs but all TTs breach the barrier.

TL5 Barriers contain everything.

It should be recognized that there are no assurances that all crashes of any type will be contained or will not be contained; however, these assumptions were necessary to differentiate among different test levels of barriers. Table D-4 shows values for the coefficient A based on the traffic mix documented in Table D-1.

Table D-4 Values for THR_{BAR} Coefficient A for Guideline Development

Test Level	A
2	1.00
3	1.00
4	0.75
5	0.000

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APPENDIX E

Probability of Passing Across the Opposing Lanes (THR_{EOL})

CONTENTS

CHAPTER 1

INTRODUCTION

Traffic volume in the opposing direction is thought to affect the probability of a cross-median crash, P(CMC). Given that an errant vehicle's trajectory extends to the other side of the median, determining the probability it will become a cross-median crash, P(CMC), is the focus of this appendix. P(CMC) is assumed to be a function of both a vehicle fully crossing the median and a second vehicle being present in the opposing travel way. Therefore, the P(CMC) is a function of another vehicle being present. THR_{EOL} is the conditional probability of passing through the opposing traffic given that a vehicle reaches the opposing traffic. THR_{EOL} is therefore $1-P(CMC)$.

CHAPTER 2

MODEL CONSIDERATIONS

The conditional probability of a cross-median crash (CMC) given that a cross-median event (CME) has occurred, P(CMC|CME), is defined by the relationship:

$$P(CMC|CME) = \frac{P(CMC \cap CME)}{P(CME)}$$

In other words, the probability of both a CMC **and** CME, $P(CMC \cap CME)$, compared with the P(CME) determines the conditional probability of a CMC. This modeling technique is founded on the assumption that P(CME) is greater than zero, a reasonable assumption considering the many observed CMCs and the definitions used to establish these variables.

The consideration of how frequently or why vehicles enter the median is not the focus of this appendix. Likewise, the median and vehicle characteristics that influence P(CME) are not the focus of this appendix. The focus of this appendix is to calculate the probability that a vehicle that crosses the median will strike or be struck by a vehicle in the opposing lanes (CMC). For these reasons, it was important to remove and/or account for as many confounding factors as possible.

AVOIDING MEASURING THE SAME VARIABLE TWICE

One focus of other ongoing efforts is to understand the influence of terrain on rollover and barrier performance; therefore, it was desirable to remove the consideration of slopes and terrain from this model to the extent possible to allow for use of the results of the more focused and extensive terrain research efforts to be capitalized upon. In other words, this model of the probability of CMC already assumes the vehicle has crossed the median (CME).

The effect of median width was captured elsewhere; thus, care should be taken to not measure the effect of median width again. It was desirable, therefore, to model what happens when a vehicle reaches the far edge of the median absent the influence of median width and median terrain. This was accomplished here by considering cross-over-the-centerline crashes (CO) on undivided roadways. For modeling, an undivided roadway is assumed to equal a divided roadway with a median width equal to the distance between the double yellow lines (i.e., typically one foot) and no median terrain. Head-on and sideswipe crashes that occurred on undivided roadways were used to develop the data set on which these efforts are based to remove the influence of the median width and median terrain confounders.

For roadways with a median width equal to zero, P(CME) = P(MRE) because, by definition, all left encroachments cross both yellow lines at the center of the roadways at the start of the encroachment event. The conditional probability of CMC given CME established above can be rewritten as follows:

$$P(CMC|CME) = P(CO|MRE) = \frac{P(CO \cap MRE)}{P(MRE)}$$

In other words, the probability of both a crossover crash (CO) **and** MRE compared with the P(MRE) is a surrogate for the conditional probability of a CMC that controls for median width and terrain.

P(MRE) is equal to the frequency of left-encroaching vehicles compared with the AADT of the segment of interest, $P(MRE) = FREQ_{enc}/AADT_{seg\ i}$, while the $P(CO \cap MRE)$ is equal to the frequency of a CO crash and left-encroaching vehicle compared with the AADT of the segment of interest, $P(CO \cap MRE) = FREQ_{co\ \&\ enc}/AADT_{seg\ i}$. The above relationship can then be further simplified as follows:

$$\mathrm{P(CMC|CME) = P(CO|MRE)} = \frac{\mathrm{P(CO \cap MRE)}}{\mathrm{P(MRE)}} = \frac{\mathrm{FREQ_{co\ \&\ enc}/AADT_{seg\ i}}}{\mathrm{FREQ_{enc}/AADT_{seg\ i}}} = \frac{\mathrm{FREQ_{co\ \&\ enc}}}{\mathrm{FREQ_{enc}}}$$

The frequency of left-encroaching vehicles is known. The frequency of crossover crashes when a left encroachment over the centerline has occurred is not known. The focus of model development is to determine the frequency of crossover crashes. The FREQ_{CO} model itself must control for the remaining confounding factors.

METHOD

The state of the practice for modeling count data such as highway crashes is to fit a negative binomial model, usually with a Poisson-gamma mixture distribution. “In statistics, count data refer to observations that have only nonnegative integer values ranging from zero to some greater undetermined value.” (Hilbe 2011) In highway safety, zero counts of crashes are particularly important and represent areas where crashes were not observed (i.e., more safe areas). One approach to tracking zero counts as well as the non-zero counts is to track crashes by highway segment. This approach has the added benefit of allowing the consideration of the influence of segment characteristics on crash frequency.

The crash counts are the response variable, and the segment characteristics such as AADT, percentage of trucks (PT), highway geometrics, and area type become the explanatory variables that explain the occurrence of the crashes. Each segment is associated with each of the predictor variables and the number of crashes that occur on that segment during the study period. The characteristics of the segment are used to explain why each segment experiences more or fewer crashes than other segments.

Ideally, all possible predictor variables would be known. This ideal situation remains unrealized. However, it is common to consider the known predictor variables when developing a model to ensure the effect of the predictor variable of interest is not misrepresented.

Roadway characteristics that may also modify the P(CMC) such as PT, highway geometrics, and area type (i.e., urban and rural) are recognized confounding factors but are accounted for elsewhere in the encroachment probability model. Ensuring that the final representation of P(CMC), when implemented in the encroachment probability model, does not double-count the effect of these confounders is equally important to controlling for their effect. Controlling for these confounders was attempted using two different approaches: (1) explicitly modeling control variables, and (2) limiting the data set to segments where the confounders contained measurements within the base conditions of the previously developed models. The latter is ultimately recommended, as discussed below.

Under both approaches, a negative binomial regression model of crossover crashes was estimated using the COUNT package available in R. (Hilbe 2016; R 2017) The model relates the explanatory variables to the response variable using the method of maximum likelihood to quantify the magnitude of each predictor relationships. Along with each model, the fit statistics are presented. The p-value is a measure of how probable the result observed may have occurred by chance. A low p-value indicates the results are statistically significant and were unlikely to have occurred by chance (e.g., $p < 0.05$). A higher p-value only indicates that the results have not proven the null hypothesis false, not that the null hypothesis is true. The p-value cannot be relied on alone.

The pseudo-R^2 statistic was determined for each model. The pseudo- R^2 is not interpreted the same way as the coefficient of determination is for an ordinary least squares regression. A low value of the pseudo-R^2 can indicate lack of fit while higher values carry no such indication. There is no definition of a low value. The Akaike Information Criterion (AIC) fit statistic provides comparative information, with lower values indicating a better fitting model than the model it is compared with. Bayesian Information Criterion (BIC) is interpreted the same way. Both are calculated from the likelihood function. (Hilbe 2014)

Negative binomial model parameters are estimated using maximum likelihood, where the parameters of the probability distribution that characterize the data are estimated. The log of the likelihood function is used to determine which parameters make the model most likely to be the case when the data is considered. Through an iterative process, the derivative of the log likelihood function is taken and set to zero to estimate the parameters. When the difference between iterative values is less than a specified tolerance (i.e., 10^{-6}), the iterations stop and the values are at the maximum likelihood estimated values. The log likelihood (LL) is also reported with the models; however, is only useful when calculating other fit statistics (e.g., AIC and BIC).

Any measurement has uncertainty, which should be communicated. This uncertainty in statistical analysis can be conveyed by noting the standard error or the confidence interval along with the measurements. The standard error is a measure of how much the estimate could change within the model. The 95% confidence interval is essentially the same type of statistic as standard error; the 95% confidence interval limits indicate that the analyst is 95% confident the true value of the coefficient is within the stated range. It is important to note the 95% confidence interval is equal to twice the standard error for normally distributed error. Negative binomial models are assumed to have normally distributed errors.

CHAPTER 3

DATA USED FOR MODELING

The original intent of this project was to use the models developed under *NCHRP Report 794: Median Cross-Section Design for Rural Divided Highways*. (Graham 2014) Unfortunately, there appears to be a typographical error in the model printed in *NCHRP Report 794,* as both the CMC+CME and CMC models shown are identical.

It was decided to use a previously obtained Highway Safety Information System data set of Ohio and Washington highway crashes that could be linked to highway segment information such as AADT, PT, segment length, area type, speed limit, number of lanes, lane width, and vehicle type. This database was requested for Ohio from 2002 through 2010 and for Washington from 2002 through 2007 under the NCHRP Project 17-54 research effort. (Carrigan 2018)

The NCHRP Project 17-54 data set of homogenous segments were merged with CO and opposite direction sideswipe crashes (i.e., ACCTYPE field codes ‘1’ and ‘4’). The crashes were counted by crash severity and vehicle type and assigned to the appropriate homogenous segment using the recorded route and milepost of each crash. The resulting data set included a list of segments. Each segment had a field for AADT, PT, SegL, area type, SPD_LIMT, NO_LANES, and LANEWID. Each segment also contained a field for the count of crashes occurring on the segment by each crash severity and vehicle type (e.g., passenger car fatal crash = PC_K; heavy vehicle serious crash = HV_A, etc.). The data set includes 1,204,084 segments.

In some instances, the segments included fields where the information was not available (NA) or the field contained a nonsense value (e.g., AADT=0). The data set was filtered to remove these segments from consideration, as shown here, before any modeling. The remaining segments are noted in parentheses.

- Consider only segments where the area type is known (1,202,105).
- Consider only segments where the length in miles is $0.1 \leq L \geq 2$ (404,620).
- Consider only segments where ADT > 0 (403,666).
- Consider only segments where the PT is known (242,862).
- Consider only segments where the value of the number of lanes = 2 (221,171).
- Consider only segments where the posted speed limit > 0mph (220,975).

This filtering of the data set resulted in 220,975 segments being included in the modeling. The descriptive statistics for this data set are shown in Table E-1. This table includes shorthand for the categorical variable names to allow the information to be displayed in table format. PSL=50 is for the posted speed limit equal to 50 mph. LW=10 is for lane width of 10 feet. Each number after the equal sign represents the value of that variable associated with that indicator variable.

Table E-1 Descriptive Statistics for P(CMC) Data Set

Continuous Variables	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
L	0.1	0.13	0.19	0.31	0.35	2
AADT	10	1,110	2,280	3,611	4,760	68,336
PT	0.0	3.8	5.7	7.00	8.6	67
Lane Width	7	10	10	10.97	12	41
Shoulder Width	0	2	3	3.59	4	30
DOC	0	0	0	0.52	0	76
PG	0	0	0	1.52	0	20
PC_KABCOU	0	0	0	0.0345	0	6
HV_KABCOU	0	0	0	0.0075	0	3
MC_KABCOU	0	0	0	0.0008	0	2
KABCOU	0	0	0	0.0445	0	7

Categorical Variables	Proportion of Feature (%)	Categorical Variables	Proportion of Feature (%)	Categorical Variables	Proportion of Feature (%)
PSL=20	68	PSL=40	5,528	PSL=60	1,764
PSL=25	5,783	PSL=45	20,958	PSL=65	229
PSL=30	392	PSL=50	6,868	Rural	185,414
PSL=35	30,921	PSL=55	149,064	Urban	35,561

CHAPTER 4

MODEL DEVELOPMENT

Recall the number of crashes per year was tabulated in the data set. A negative binomial model was fit to the dataset of head-on crashes and the log of the segment length in miles was included as an offset to allow for the frequency of head-on crashes to be evaluated per year per mile. As this research progressed, the encroachment frequency model was changed to include an offset of MVMT, not segment length. These results were not used in this research effort, as explained below.

The resulting parameter estimates are shown in Table E-2 for the crossover model with control variables which takes this form:

$$FREQ_{CO} =\cdot e^{B1} \cdot AADT^{B2} \cdot PT^{B3} \cdot \prod_{i=4}^{N} e^{Bi \cdot Ai}$$

Where:

$FREQ_{CO}$ = Frequency of crossover crashes per year per mile.

AADT = Annual Average Daily Traffic (vpd).

A_i = Control variable values for each segment under consideration.

B_i = Regression coefficients.

N = Total number of control variables considered per segment.

Table E-2 Negative Binomial Model for Cross-Over Crashes

Coefficients:	Parameter Estimate	Standard Error	P-Value	95% Confidence Interval	
(Intercept)	-9.3993	0.49	< 2e-16	-10.4910	-8.5228
log(AADT)	0.9025	0.02	< 2e-16	0.8690	0.9363
log(PT)	0.0235	0.00	1.32e-15	0.0178	0.0293
Urban	0.1343	0.03	6.69e-06	0.0758	0.1928
Rural	1.0000	---	---	---	---
PSL.20	1.0000	---	---	---	---
PSL.25	0.4377	0.47	0.353	-0.3989	1.5042
PSL.30	0.5085	0.50	0.309	-0.3970	1.6172
PSL.35	0.1129	0.47	0.810	-0.7197	1.1770
PSL.40	0.0043	0.47	0.993	-0.8350	1.0725
PSL.45	-0.0708	0.47	0.880	-0.9059	0.9948
PSL.50	-0.3035	0.47	0.521	-1.1438	0.7653
PSL.55	-0.2767	0.47	0.556	-1.1104	0.7880
PSL.60	-0.7111	0.51	0.162	-1.6382	0.4095
PSL.65	-0.6755	0.73	0.357	-2.1498	0.7372
LANEWID	0.0215	0.00	1.13e-06	0.0127	0.0301
DOC	0.0454	0.01	2.73e-14	0.0326	0.0569
PG	0.0454	0.01	1.39e-08	0.0187	0.0386
SHLDR_PRE	-0.0517	0.00	< 2e-16	-0.0606	-0.0429
AIC				68,272	
BIC				68,447	
Dispersion Parameter (α)				1.099	
Standard Error				0.0730	
LL (full)				-34,119	
Pseudo-R^2				0.15	

Recall that the initial data set was filtered to remove segments with missing or nonsense values, which resulted in a data set of 220,975 segments that were used in the model developed with included control variables. A different approach will be taken in this section. The approach taken here is to further limit the data set to include segments that meet the base conditions of the complementary encroachment probability model for which this P(CMC|CME) model is being explored such that this P(CMC|CME) model does not account for variation in highway characteristics which are already accounted for elsewhere in the encroachment probability model. The 220,975-segment data set was further limited for this analysis as shown here, with the remaining segments noted in parentheses:

- Consider only segments where the area type is rural (185,414).
- Consider only segments where the PT ≥ 10 (36,038).
- Consider only segments where the posted speed limit ≥ 45mph (32,069).
- Consider only segments where 10 feet ≤ LANEWID ≥ 12 feet (24,690).

- Consider only segments where the DOC = 0 (21,918).
- Consider only segments where -2% ≤ PG ≥ +2% (17,443).

This limited data set resulted in 17,443 segments being included in this analysis. The descriptive statistics for this limited data set are shown in Table E-3 using the same shorthand for the categorical variables previously discussed for Table E-1.

Table E-3 Descriptive Statistics for Limited P(CMC) Data Set

Continuous Variables	Min.	1st Qu.	Median	Mean	3rd Qu.	Max.
SegL	0.1	0.17	0.32	0.4879	0.65	2
AADT	40	1594	2850	3604	5110	20260
PC_KABCOU	0	0	0	0.0308	0	3
HV_KABCOU	0	0	0	0.0170	0	3
MC_KABCOU	0	0	0	0.0007	0	1
KABCOU	0	0	0	0.0501	0	5

Categorical Variables	Proportion of Feature (%)	Categorical Variables	Proportion of Feature (%)	Categorical Variables	Proportion of Feature (%)
PSL=45	1143	PSL=55	15510	PSL=65	107
PSL=50	562	PSL=60	121		

Again, a negative binomial model was fit to the dataset of head-on crashes and the log of the segment length in miles was included as an offset to allow for the frequency of head-on crashes to be evaluated per year per mile. As noted above, the encroachment frequency model was changed as this research progressed to include an offset of MVMT, not segment length. These results were not used in this research effort, as explained below.

The resulting parameter estimates are shown in Table E-4 for the crossover model with explicitly limits confounders and takes this form:

$$\mathrm{FREQ}_{\mathrm{CO}} =\cdot\, e^{B1} \cdot \mathrm{AADT}^{B2}$$

Where:

$\mathrm{FREQ}_{\mathrm{CO}}$ = Frequency of crossover crashes per year per mile.
AADT = Annual Average Daily Traffic (vpd).
B_i = Regression coefficients.

Table E-4 Negative Binomial Model for Cross-Over Crashes

Coefficients:	Parameter Estimate	Standard Error	P-value	95% Confidence Interval	
(Intercept)	-11.3901	0.49	< 2e-16	-12.3625	-10.4393
log(AADT)	1.1050	0.06	< 2e-16	0.9928	1.2193
AIC				6142	
BIC				6158	
Dispersion parameter (α)				1.296	
Standard Error				0.339	
LL (full)				-3069.25	
Pseudo-R^2				0.12	

The limited data set described above that results in 17,443 segments was used to fit a negative binomial model of head-on crashes with an offset of log(MVMT) to allow for the crash rate of head-on crashes to be directly compared with the reconsidered Cooper encroachment rate model. These results were ultimately implemented in this research effort. The resulting parameter estimates are shown in Table E-5 for the crossover model that explicitly limits confounders and takes this form:

$$\mathrm{FREQ_{CO}}\,/\mathrm{MVMT} =\cdot\, e^{B1}\cdot \mathrm{AADT}^{B2}$$

Where:

$\mathrm{FREQ_{CO}}$ = Frequency of crossover crashes/MVMT.
AADT = Bi-directional Annual Average Daily Traffic (vpd).
B_i = Regression coefficients.
MVMT = Million vehicle miles traveled (AADT·365·L)/1,000,000.

Table E-5 Negative Binomial Model for Cross-Over Crashes Offset MVMT

Coefficients:	Parameter Estimate	Standard Error	P-Value	95% Confidence Interval	
(Intercept)	-3.4744	0.49	1.36e-12	-4.4469	-2.5237
log(AADT)	0.1050	0.06	0.0689	-0.0072	0.2193
AIC				6,142	
BIC				6,158	
Dispersion Parameter (α)				1.296	
Standard Error				0.339	
LL (full)				-3,069.25	
Pseudo-R^2				0.12	

Recall that a FREQ_{CO} model that controls for highway characteristics is desired and that this model is presumed to be a function of AADT. The severity of these crashes is understood through a different model and need not be considered here; rather, this model should consider all observed crashes to allow for the conversion from a frequency model to a probability model.

Further, this model must be offset by MVMT for use with the Cooper data model. The simpler model where the confounders are explicitly controlled through limiting segments considered, as documented in Table E-4, is preferred because (1) the AIC and BIC values are lower, (2) the model makes better engineering sense, and (3) the simpler model best satisfies the principals of parsimony (i.e., Occam's razor). The model shown in Table E-5 has these same qualities but also has an offset of MVMT, and therefore, it is implemented in this research.

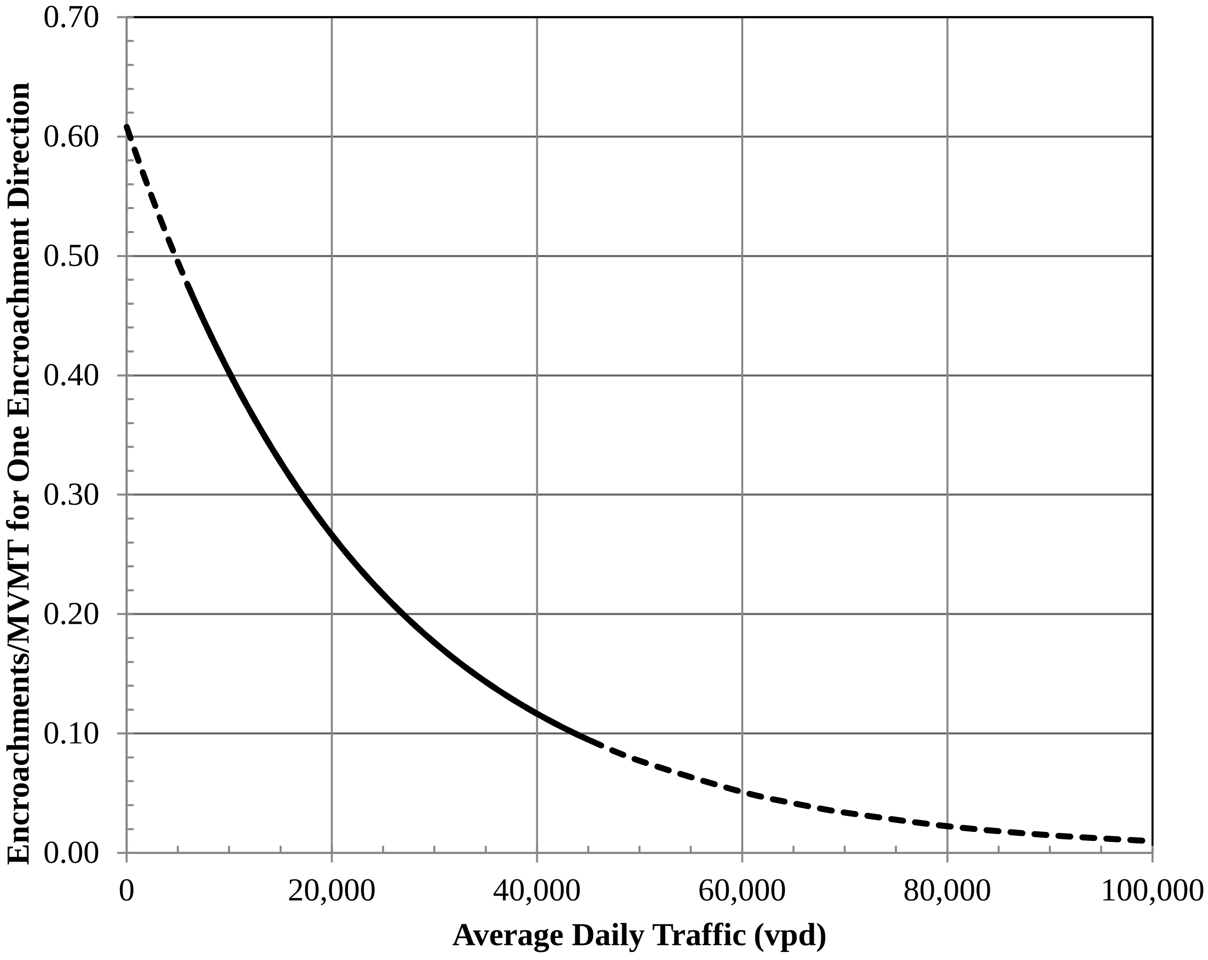
The frequency of CO crashes when a left encroachment over the centerline has occurred is estimated to be:

$$\mathrm{FREQ}_{\mathrm{CO}\,\cap\,\mathrm{enc}}/\mathrm{MVMT} = \cdot\ \mathrm{e}^{-3.4745} \cdot \mathrm{AADT}^{0.1050}$$

It was previously derived that $\mathrm{P(CMC|CME)} = \mathrm{FREQ}_{\mathrm{co}\,\cap\,\mathrm{enc}}/\mathrm{FREQ}_{\mathrm{enc}}$. The frequency of right-encroaching vehicles on four-lane divided highways by MVMT is represented by the model of Cooper data shown in Table E-6. (Ray 2012)

Table E-6 Primary Right Base Encroachments per MVMT for Four-Lane Divided Highways (Ray 2012)

Divided Highways	$\mathrm{ENCR_{BASE}} = 0.7507\, e^{\left[-0.2104-0.04128\cdot\left(\frac{\mathrm{AADT}}{1000}\right)\right]}$



Up to this point, the $\mathrm{FREQ_{CO\,\cap\,enc}}$ model considered the frequency of crossover crashes from both directions. This model must be divided by two to allow for consideration of each direction of travel as the encroachment model shown in Table E-6 estimates a single encroachment direction.

$$\mathrm{FREQ_{CO\,\cap\,enc}/MVMT} = 0.5 \cdot \mathrm{e}^{-3.4745} \cdot \mathrm{AADT}^{0.1050}$$

The encroachment model shown in Table E-6 must be multiplied by the $\mathrm{EAF_{LR}}$ for encroachment side to represent the left encroachments. Since the Miaou-Cooper model in Table E-6 is limited to AADT ≤ 46,000 veh/day, only the adjustment for AADT ≤ 67,000 veh/day was used. The result for an estimate of the encroachment rate from one left-side encroachment on a four-lane divided highway is, therefore, as follows:

$$\mathrm{ENCR_L} = \mathrm{AADT}^{0.2052} \cdot 0.0875\, e^{\left[-0.2104-0.04128\cdot\left(\frac{\mathrm{AADT}}{1000}\right)\right]}$$

Finally, half the frequency of CO/MVMT is then divided by the left-encroachment frequency to determine the probability of a CMC given a CME has occurred P(CMC|CME). The solid line in Figure E-1 shows the curve based on this statistical model.

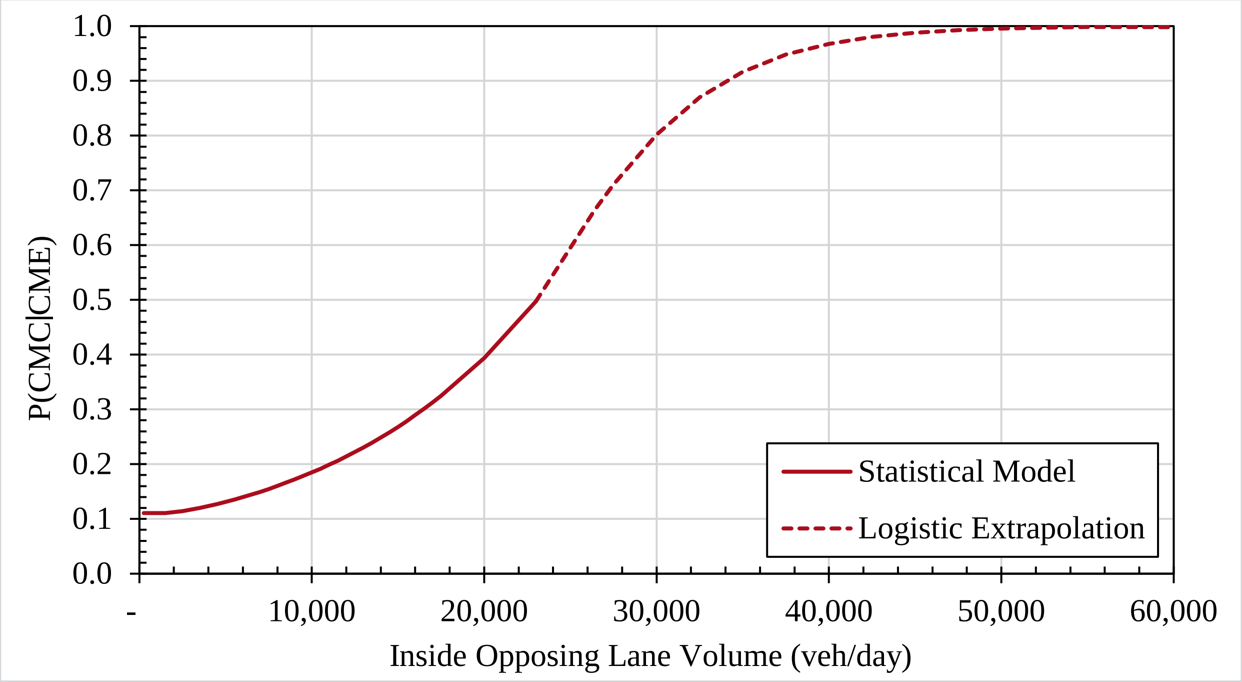


Figure E-1 Probability of a cross-median crash given a cross-median event occurs.

P(CMC|CME) is the probability that a vehicle will collide with a vehicle in the opposing lanes given that the encroaching vehicle has crossed the median and entered the opposing lanes. The Cooper-Miaou data used above to develop the statistical model is limited to traffic volumes below 46,000 veh/day for four-lane divided roadways and 6,000 veh/day for undivided two-lane roadways. The portions of the curves for higher AADT, therefore, are extrapolations that are not based on any observed data.

Predicting P(CMC|CME) for high traffic volumes is also important, so another approach was necessary for the high-volume portion of the figure. A traffic engineering volume-capacity approach was used to supplement the statistical data. The *Highway Capacity Manual* (HCM) assumes lane capacities between 2,250 and 2400 passenger cars (pc)/ln/h for freeways depending on the land use (i.e., downtown, urban, suburban, or rural) and free-flow speed (i.e., between 55 and 70 mi/h associated with the previous land-use categories).(Margiotta 2017; HCM 2016) If a highway operated at a capacity of 2,200 pc/ln/h for 24 h a day, 365 days a year, it would be equivalent to a bi-directional AADT of 2,200·24 = 52,800 veh/day/ln. At capacity, the lanes are full of vehicles operating with minimal headway. The chance of a cross-median crash (CMC) given an encroachment into the opposing lanes (CME) operating at maximum capacity is assumed to be one. In other words, a vehicle entering an opposing lane operating at these extreme conditions is virtually guaranteed to be struck by another vehicle.

A simple model of this would be a straight line between zero AADT corresponding to P(CMC|CME) = 0 and an AADT of 52,800 veh/day corresponding to P(CMC|CME) = 1.0, certainty of a CMC. A linear model, however, is not realistic at the very lowest and highest volumes. A linear model would require an instantaneous change in slope at AADTs of zero and 52,800 veh/day. A more physically compelling model that provides smooth slopes transitions throughout is provided by the following logistic function:

$$\mathrm{P(CMC|CME)} \approx \frac{1}{1+\mathrm{e}^{\left[\frac{52{,}800-\mathrm{AADT}}{20{,}000}\right]}}$$

This logistic function closely replicates the lower half of the curve derived above from the statistical model and provides a reasonable extrapolation for the upper half of the curve. The two curves are coincident at an AADT of 23,00 veh/day, so the statistical model is used for AADT less than 23,000 veh/day, and the logistic model based on traffic capacity is used for AADT greater than 23,000 veh/day as shown in Figure E-1.

CHAPTER 5

APPLICATION OF MODELING RESULTS

If a vehicle enters opposing lanes but does not have a crash with opposing traffic, the vehicle occupants will not experience any harm associated with entering opposing lanes. The proportion of the vehicles passing through, rather than having a crash must therefore be tabulated (i.e., THR_{EOL}). The values of THR_{EOL} are found by subtracting the estimates shown graphically in Figure E-1 from unity and have been tabulated in Table E-7. The values in Table E-7 have been tabulated by lane volume in vehicles per day in the opposing lane adjacent to the median. If the lane volume is not known, the bi-directional AADT may be divided by the number of lanes.

Table E-7 Proportion of Vehicles Passing Across the Opposing Lane Without Striking an Opposing Vehicle Given a Vehicle Enters the Opposing Lanes (THR_{EOL})

Opposing Lane Volume (veh/day)	$THRU_{EOL}$	Opposing Lane Volume (veh/day)	$THRU_{EOL}$	Opposing Lane Volume (veh/day)	$THRU_{EOL}$	Opposing Lane Volume (veh/day)	$THRU_{EOL}$
500	0.8893	12,000	0.7859	24,000	0.4502	36,000	0.0691
1,000	0.8893	13,000	0.7694	25,000	0.4013	37,000	0.0573
2,000	0.8878	14,000	0.7514	26,000	0.3543	38,000	0.0474
3,000	0.8830	15,000	0.7318	27,000	0.3100	39,000	0.0392
4,000	0.8765	16,000	0.7106	28,000	0.2689	40,000	0.0323
5,000	0.8689	17,000	0.6876	29,000	0.2315	41,000	0.0266
6,000	0.8602	18,000	0.6627	30,000	0.1978	42,000	0.0219
7,000	0.8505	19,000	0.6356	31,000	0.1680	43,000	0.0180
8,000	0.8398	20,000	0.6063	32,000	0.1419	44,000	0.0148
9,000	0.8280	21,000	0.5745	33,000	0.1192	45,000	0.0121
10,000	0.8152	22,000	0.5401	34,000	0.0998	50,000	0.0045
11,000	0.8012	23,000	0.5027	35,000	0.0832	60,000	0.0006

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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
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
GHSA	Governors Highway Safety Association
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
TDC	Transit Development Corporation
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

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