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USE OF BARRIERS IN RURAL OPEN ROAD CONDITIONS—A SYNTHESIS STUDY

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16. Abstract

The use of wide medians and clear zones that do not require median and roadside barriers is the current design practice for new and reconstructed rural highway facilities. Constructing or reconstructing roads with full-width medians and clear zones is much more expensive today compared to when the design standards were developed. Considerable costs can be accrued in additional overhead bridge length, earthwork and ROW in new construction projects, and widening of existing right–of-way and bridge structures in reconstruction projects.

This synthesis study focuses on the use of median barriers and roadside barriers and it identifies: (a) the current design practice and the existing body of knowledge, (b) (b) design conditions where adding extra traffic lanes without widening the ROW is acceptable from the point of view of safety and costs if barriers and guardrails are installed, and (c) future research needs.

One of the practical outcomes of the project is a set of Crash Cost Modification Factors (concept found in the German design guidelines) estimated based on the past research for Indiana and simulation experiments executed with the Roadside Safety Analysis Program. These factors can be used to evaluate the safety benefit produced by a modified cross-section of a rural freeway.

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EXECUTIVE SUMMARY

USE OF BARRIERS IN RURAL OPEN ROAD CONDITIONS—A SYNTHESIS STUDY

Introduction

Although sufficiently wide medians and clear zones improve roadside safety, the AASHTO Design Policy allows for the use of barriers under restricted conditions. Recent experience with Indiana's I-69 corridor challenges the current design practice with regard to medians and clear zones in rural areas. Significant savings could be realized by the Indiana Department of Transportation (INDOT) if the medians and clear zones on new and reconstructed facilities were narrower than prompted by the current design standards. Modern protective devices, such as high-tensioned cable barriers, offer protection with a lower risk of vehicle damage and personal injury than do traditional concrete barriers and guardrails. Although the increased cost of right of way (ROW) is the primary reason for this synthesis study, rapidly growing personal injury medical costs must also be considered. The practice of making investments in road infrastructure is based on benefit-cost analysis, which includes both ROW and medical costs.

The objective of this synthesis study is to identify if the existing design guidelines and research reports can support a new practice of narrowing the median and the clear zones of an existing rural four-lane interstate to accommodate two additional traffic lanes without widening the current ROW. The study follows three research steps leading toward the study objective:

1. Identify the existing body of knowledge pertaining to the safety impact of the median and clear zone width and the presence of median and roadside barriers and guardrails.
2. Identify the design conditions and corresponding solutions involving barriers and guardrails that are acceptable from the point of view of safety and costs. This objective will be accomplished only if sufficient knowledge exists to allow making such assertions.
3. Identify research needs to accomplish the second objective, if it is not attainable with the documented current knowledge.

Findings

The efforts presented in this report were conducted by the Purdue research team in order to understand the mechanism of roadway departure crashes and to identify the effects of several potential strategies. This report provides an overview of the statistics at the national level, a literature review from both the United States and other countries where a narrow or no clear zone is used, and a simulation study. Potential strategies for restricted ROW scenarios were identified, as well as the limitations of the study and future research directions.

The results of this study are applicable to depressed medians with a width of about 45 feet and without barriers. The findings are summarized in the table below.

The limitations of this study apply primarily to the simulation study executed with the Roadside Safety Analysis Program (RSAP). Some of our concerns with RSAP might have been addressed in its new version, which became available after we completed our research. Future research should address the limited understanding of the mechanism of vehicle encroachment and rollover, and current knowledge of the safety effect of the barrier offset needs to be confirmed and further extended. The presented results are based on past research and our simulation experiments. A statistical analysis of the safety performance of the existing Indiana barriers should complement our findings.

Implementation

The design recommendations and corresponding tables will be discussed by the INDOT Division of Highway Design and Technical Support and considered for implementation where feasible by means of appropriate revisions to the Indiana Design Manual.

Recommended Design Solutions for Adding Two Traffic Lanes to Four-Lane Rural Freeways

Median Width (ft)	Clear Zone Width (ft)	Hazard Outside Clear Zone	Recommended New Lanes Placement	Recommended Median Barrier	Recommended Clear Zone Barrier	Crashes Cost	Remarks
44	26	No	Both in median	Barrier	None	Increases	Requires benefit-cost analysis
44	26	Yes	One in median; one in clear zone	Barrier	Barrier	Reduces	
44	32–44	No	One in median; one in clear zone	Barrier	None	Reduces	
44	32–44	Yes	One in median; one in clear zone	Barrier	Barrier	Reduces	
58+	32–38	No	Both in median	Barrier	None	—	Not studied
58+	32–38	Yes	Both in median	Barrier	Barrier	—	Not studied

Source: *Fatality Analysis Reporting System (FARS) Encyclopedia*. National Highway Traffic Safety Administration. http://www-fars.nhtsa.dot.gov/Main/index.aspx.

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1. INTRODUCTION

Sufficiently wide medians and clear zones are meant to reduce the risk of collisions with other vehicles and fixed objects. The use of wide medians and clear zones that do not require median and roadside barriers is the current design practice for new and reconstructed rural highway facilities. The current Indiana Design Manual *(1)*, based on the AASHTO Roadside Design Guide (RDG) *(2)*, recommends this practice. The AASHTO Design Policy *(3)* allows for the use of barriers under restricted conditions. Constructing or reconstructing roads with full-width medians and clear zones is much more expensive today compared to when the design standards were developed. Considerable costs can be accrued in additional overhead bridge length, earthwork and right of way (ROW) in new construction projects, and widening of existing ROW and bridge structures in reconstruction projects.

Recent practical design workshops for the new I-69 corridor yielded recommendations which challenge the current design practice in regard to medians and clear zones. Significant savings could be realized by the Indiana Department of Transportation (INDOT) if the medians and clear zones on new and reconstructed facilities were narrower than prompted by the current design standards while the effect on traffic safety might be limited. The use of barrier protection is commonly applied without question in urban areas, which often has higher traffic volumes and collision frequencies than in rural areas. Modern protective devices, such as high-tensioned cable barriers, offer protection at a lower risk of vehicle damage and personal injuries than the traditional concrete barriers and guardrails. The deflection of these new barriers is limited, which warrants their use in relatively narrow medians and clear zones.

Although the increased cost of ROW is the primary reason for this synthesis study, the rapidly growing medical costs must also be considered. The practice of making investments in road infrastructure based on benefit-cost analysis accounts for changes in both the cost components: ROW and medical costs. This study is consistent with the recommended approach.

The objective of this synthesis study is to identify if the existing design guidelines and research reports can support a new practice of narrowing the median and the clear zones of an existing rural four-lane interstate to accommodate additional two traffic lanes without widening the current ROW. If sufficient knowledge is identified, then guidelines will be proposed to help determine promising design strategies justified with the benefit and cost consideration. This synthesis study is limited to interstate segments between interchanges. The study follows three research steps leading toward the study objective:

1. Identify the existing body of knowledge pertaining to the safety impact of the median and clear zone width and the presence of median and roadside barriers and guardrails.
2. Identify the design conditions and corresponding solutions involving barriers and guardrails that are acceptable from the point of view of safety and costs. The second objective will be accomplished if sufficient knowledge exists to allow making such assertions.
3. Identify research needs to accomplish the second objective, if it is not attainable with the documented current knowledge.

Although research studies and a description of successful practice pertaining to Indiana and states with similar conditions are particularly useful, this synthesis will also consider other states and countries. Specifically, European countries that use reduced clear zones in combination with barriers in rural areas will be studied and discussed.

This report consists of six chapters. Chapter 2 will provide an introduction to roadway departure crashes. General statistics on the national level is first provided, followed by an analysis of Fatality Analysis Reporting System (FARS) data *(4)* to provide some commonly accepted theories about the causes and contributing factors of such crashes. Two randomly selected crash reports are then presented for a further understanding of roadway departure crashes.

In Chapter 3, the current design standards and guidelines are studied to obtain the current state of practice understanding of the elements that effect roadside safety. The first section provides a brief review of roadway elements that may have an effect on roadside safety. The second section provides an in-depth discussion of the roadside elements, their design considerations, and the effect of potential safety treatments. The third section focus on the longitudinal barriers. Chapter 3 concludes with an introduction to roadway design guidelines utilized in Germany, where very limited "clear zone" is available along the highways, to show the feasibility of maintaining safety under very restricted ROW scenario.

State of the art research studies focusing on roadside safety and roadway departure crashes are introduced in Chapter 4, which are broadly group in three categories:

1. Studies focused on median/clear zone design
2. Studies focused on roadside features
3. Studies focused on longitudinal barriers

Two special sections also are included in this chapter: Section 4.4 introduces previous studies on this topic conducted in Indiana and Section 4.5 introduces studies outside the U.S., for which the roadway design could be very different from the U.S. design. It is noted in Chapter 4 that, even with the large number of research studies that have been conducted, the mechanism of the roadside safety problem still remains largely unknown.

Chapter 5 provides a full description of a simulation study utilizing the Roadside Safety Analysis Program (RSAP) *(5)*, which is recommended by the AASHTO RDG third edition. The Center for Road Safety (CRS) team first studies the mechanism of the RSAP software, using both NCHRP 492 (the engineer's manual of RSAP) and the user's manual. Then an experiment is designed to represent different scenarios for adding a travel lane for a typical straight rural freeway section. The results from the experiment are then presented and interpreted, and inferences from the results are made. The research team also identifies crash cost modification factors (CCMF) as the most appropriate performance measure for evaluating roadside safety.

Finally in Chapter 6, the study's conclusions are presented based on both the literature review and the simulation study. Also, the limitations of the current study and future research needs are identified and recommendations are made to INDOT based on the available literature and the RSAP case study.

2. ROADWAY DEPARTURE CRASHES

2.1 General Statistics

Roadside and median crashes are often called run-off-road (ROR) crashes or roadway departure crashes, which are a major type of motor vehicle crash. The propensity for severe crashes has brought great attention to roadway departure crashes. According to Traffic Safety Facts (2009) *(6)*, of the 5.5 million motor vehicle crashes that occurred in the U.S. in 2009, 23.8% are crashes off the roadway (i.e. roadside, shoulder, and median). These crashes, as shown in Table 2.1, also account for 45.1% of all fatal crashes and 22.9% of injury crashes.

From Table 2.1, it is easy to see that not only roadway departures tend to be more severe, but they are also over-represented among single vehicle crashes. Differences with on-road crashes need to be considered when studying crash causes and safety countermeasures. The same trend of fatal roadway departures crashes, from the national data in Table 2.1, is verified for the state of Indiana (Table 2.2), which were obtained by querying the Fatality Analysis Reporting System (FARS) database *(4)*. The causes for roadway departure crashes will be studied with the knowledge obtained from the presented statistics: *(1)* roadway departure crashes are mainly single vehicle crashes, and *(2)* roadway departure crashes tend to have higher crash severity than crashes on the roadway.

2.2 Causes for Roadway Departure Crashes

Roadway departure crashes occur due to a variety of causes. In many roadway departure crashes, the driver loses control of the vehicle after running off the roadway; while in other cases, the driver may lose control before running off the roadway. Some crash reports indicate whether the roadside environment or the roadway design is a contributing factor to the cause of a crash. Other reports indicate the "location of first harmful event" to distinguish where the driver originally lost control or where the initial collision occurred.

Mak and Sicking *(5)* describe in NCHRP 492 a four-step process to model a roadway departure crash (most occur from striking fixed objects) and to estimate its cost. The roadway departure crash starts as an

TABLE 2.1
Crashes by Crash Type, Relation to Roadway, and Crash Severity

Crash Type	Relation to Roadway: On Roadway	Off Roadway	Shoulder	Median	Other	Total	Percent On Roadway	Percent Off Roadway
Fatal Crashes								
Single vehicle	5,430	9,891	2,299	823	302	18,745	29.0%	71.0%
Multiple vehicle	11,476	223	198	125	30	12,052	95.2%	4.8%
Total	**16,906**	**10,114**	**2,497**	**948**	**332**	**30,797**	**54.9%**	**45.1%**
Injury Crashes								
Single vehicle	151,000	262,000	12,000	40,000	25,000	489,000	30.9%	69.1%
Multiple vehicle	1,018,000	5,000	1,000	3,000	1,000	1,028,000	99.0%	1.0%
Total	**1,169,000**	**267,000**	**13,000**	**43,000**	**26,000**	**1,517,000**	**77.1%**	**22.9%**
Property-Damage-Only Crashes								
Single vehicle	325,000	584,000	17,000	77,000	245,000	1,247,000	26.1%	73.9%
Multiple vehicle	2,686,000	4,000	2,000	6,000	10,000	2,710,000	99.1%	0.9%
Total	**3,011,000**	**588,000**	**19,000**	**83,000**	**255,000**	**3,957,000**	**76.1%**	**23.9%**
All crashes								
Single vehicle	481,000	856,000	31,000	118,000	270,000	1,756,000	27.4%	72.6%
Multiple vehicle	3,716,000	10,000	3,000	9,000	12,000	3,749,000	99.1%	0.9%
Total	**4,197,000**	**865,000**	**34,000**	**127,000**	**282,000**	**5,505,000**	**76.2%**	**23.8%**

Source: *(4)*.

TABLE 2.2
Indiana Fatal Crashes by Crash Type, Relation to Roadway, and Crash Severity

Crash Type	Relation to Roadway					Total	Percent On Roadway	Percent Off Roadway
	On Roadway	Off Roadway	Shoulder	Median	Other			
Fatal Crashes								
Single vehicle	80	263	9	2	2	356	22.5%	77.5%
Multiple vehicle	270	6	—	—	—	276	97.8%	2.2%
Total	**350**	**269**	**9**	**2**	**2**	**632**	**55.4%**	**44.6%**

Source: *(4)*.

encroachment as the vehicle departs the roadway. Then, if there is any hazard within the vehicle's path, a crash may occur. Once the crash occurs, the occupants of the vehicle may suffer injuries at different levels. Finally, the injury and vehicle damage are converted into dollar value.

It is widely understood that the roadside environment contributes to the severity of roadway departure crashes; thus, inappropriate design of the roadway does have an effect on roadway departure crash severity. Some crash reports indicate that the roadside environment or the roadway design is a contributing factor of the crash severity. Other reports indicate the "most harmful events" contributing most to the crash severity.

Based on the location and nature of the first harmful events, roadway departure crashes can be identified in the following categories:

1. Unforced On Roadway: These crashes were caused by events that are avoidable by normal drivers, and driver lost control or crashed on the roadway.
2. Unforced Off Roadway: These crashes were caused by events that are avoidable by normal drivers, and driver lost control or crashed off the roadway.
3. Forced On Roadway: In these crashes, the first harmful events are usually beyond normal drivers' ability and driver lost control or crashed on the roadway.
4. Forced Off Roadway: In these crashes, the first harmful events are usually beyond normal drivers' ability and driver lost control or crashed off the roadway.

The total number of crashes from the FARS national database for 2009 was utilized for analysis. Rural principal arterials were the selected functional class for this study. The traveled way components selected included the shoulder, median, roadside, outside of the ROW, and unknown locations. The top ten first harmful events with the highest total number of crashes are presented in Table 2.3.

It can be seen in Table 2.3 that the overturn/rollover, trees, and guardrail face events contributed to the highest crash occurrences. The information from this table helps in identifying which elements in the highway system need to be improved. The most harmful events for national data in 2009 were also extracted for analysis. The most harmful events are the events that contribute the most to the injury severity of the vehicle occupants. The top four most harmful events with the greatest number of vehicles/drivers involved are presented in Table 2.4.

As can be seen from Table 2.4, rollovers crashes account for a large portion of all harmful crashes, which may indicate that some other first event crashes could have resulted in a rollover crash after striking an

TABLE 2.3
First Harmful Events for Roadway Departure Crashes in 2009

First Harmful Event	Relation to Roadway					Total
	Shoulder	Median	Roadside	Outside ROW	Off Roadway—Location Unknown	
Overturn/rollover	79	203	283	50	80	**695**
Tree	30	25	197	56	36	**344**
Guardrail face	98	29	108	8	8	**251**
Ditch	32	12	85	10	13	**152**
Embankment—earth	14	7	70	13	8	**112**
Highway/traffic signpost/sign	37	9	52	3	1	**102**
Parked motor vehicle	59	1	7	5	1	**73**
Culvert	12	5	42	4	6	**69**
Embankment—material type unknown	10	6	38	7	6	**67**
Motor vehicle in transport on same roadway	38	3	11	5	2	**59**
Total	**546**	**386**	**1113**	**207**	**190**	**2442**

Source: *(4)*

TABLE 2.4
Most Harmful Events for Roadway Departure Crashes in 2009

	Relation to Roadway					
Most Harmful Event	**Shoulder**	**Median**	**Roadside**	**Outside ROW**	**Off Roadway—Location Unknown**	**Total**
Overturn/rollover	203	285	552	89	104	**1233**
Tree	62	27	253	59	39	**440**
Motor vehicle in transport on same roadway	115	40	71	9	7	**242**
Guardrail face	44	8	45	2	6	**105**
Total	**623**	**433**	**1172**	**212**	**194**	**2634**

Source: *(4)*

object and the rollover resulted in a severe injury. Further insights can be made from the cross-tabulation of first harmful events and most harmful events using national data, as shown in Table 2.5. The top ten first harmful events with the highest total number of crashes and the most harmful events with the highest number of crashes are presented in the table. The crashes selected were those which occurred on rural principal arterials, as well as having off-road components.

For several types of first harmful events, most resulted in overturn/rollover as the most harmful event. This finding could be very helpful in the design of highway elements. To better illustrate the overturn/rollover as the most harmful event phenomena, Figure 2.1 shows the percentage of first harmful events in which the most harmful event was an overturn/rollover event.

From Figure 2.1, the majority of crashes with first events of hitting a ditch, earth embankment, signpost or sign, culvert, unknown embankment, and curb resulted in the most harmful event being an overturn/rollover event, including the overall total first event crashes. Crashes with first harmful events of hitting a guardrail face also had a significant portion of harmful events being overturn/rollover events. Although this data include only fatal crashes, in which the most harmful events tend to be more severe events (such as rollover), these statistics provide useful insight into the causes of roadway departure crashes. These statistics are also useful in determining the highway elements to focus on when improving safety and reducing the occurrence of overturn/rollover crashes.

A departure event may result in a "non-crash" or low-severity event. Such events occur when a driver is able to regain control and avoid a crash completely or reduce the severity of the crash (for example, by reducing speed). Two vital factors are needed for drivers to regain control and perform avoidance maneuvers: (1) an appropriate clear zone width and (2) a forgiving roadside environment. The clear zone width is a major research interest in this study. Determining its role in avoiding off-roadway crashes is essential in reducing the severity of unavoidable crashes. A forgiving roadside environment is a more complicated and broader concept. It not only includes better design of the aforementioned elements, but also many other considerations, which will be covered in later chapters.

TABLE 2.5
Cross-Tabulation of First Harmful and Most Harmful Events in 2009

	Most Harmful Event				
First Harmful Event	**Overturn/Rollover**	**Tree**	**Vehicle in Transport**	**Guardrail Face**	**Total**
Overturn/rollover	656	12	8	1	**677**
Tree	24	295	2	0	**321**
Guardrail face	90	19	20	99	**228**
Ditch	82	26	3	0	**111**
Embankment—earth	60	9	3	0	**72**
Highway/traffic signpost/sign	48	21	2	1	**72**
Parked motor vehicle	1	0	5	0	**6**
Culvert	30	7	0	0	**37**
Embankment—unknown	38	12	1	0	**51**
Curb	22	4	2	2	**30**
Total	**1051**	**405**	**46**	**103**	**1605**

Source: *(4)*

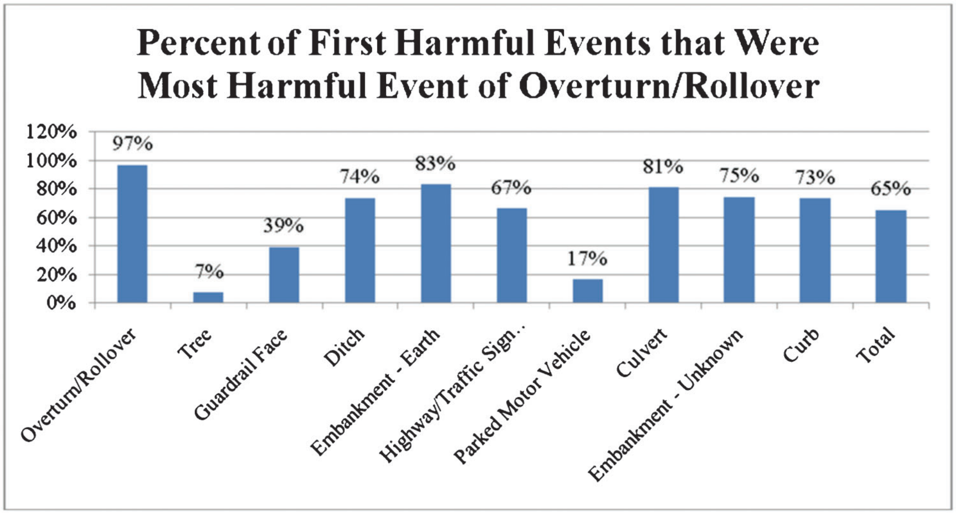


Figure 2.1 Percent of first harmful events that were most harmful event of overturn/rollover.

2.3 Examples of Roadway Departure Crashes

In order to provide a better illustration of the different types of crashes, crash reports were retrieved from National Transportation Safety Board (NTSB) and police reports.

Case 1 *(7)*

A female driver (28 years old, residence in Carnesville, Georgia) of vehicle #1 (passenger utility vehicle) was traveling southbound on State Route 15 near its intersection with County Road 370 (Leechman Road) at approximately 5:45 a.m. on Tuesday, January 7, 1997. Pavement conditions were wet, and it is not known if she was wearing any safety restraints. She was not under the influence of alcohol or drugs. Her vehicle was equipped with an airbag that did deploy upon impact. The road has two southbound lanes and one northbound lane for a total approximate width of 35'-3.'' A 4' paved shoulder is located adjacent to the road. At the location of the crash, the road is curved to the left (for the southbound direction of travel) and is on grade. The posted speed limit is 55-mph.

Vehicle #1 was traveling in the right southbound lane and as the driver attempted to negotiate a curve to the left, she lost control of the vehicle and exited the roadway to the right (onto the west shoulder). The vehicle then traveled through a ditch, rotated clockwise, became airborne and struck a tree with its top driver's side. Vehicle #1 then came to a rest upside down. This final location was 47' from the west edge of the road.

The driver of Vehicle #1was fatally injured and was not taken for medical treatment. Emergency medical services were notified at 5:51 a.m., arrived at the scene at 6:03 a.m., and arrived at the hospital at 6:53 a.m.

Since there was no witness to this crash, the forensic analysis hypothesized a series of potential causes for both the occurrence of the crash and contributing factors for the severity. The crash report exposed the following problems with this section of roadway:

1. Curve on grade was present, which is not a desirable feature for a principal arterial.
2. No lighting or delineators were present, which indicates the visibility in adverse weather conditions could have been poor.
3. There was no mention of rumble strips (the crash happened in 1997, and rumble strips were not often used then).
4. No longitudinal barriers were present.
5. A ditch and a tree very close to the outside of the roadway, near a curve on grade.

The driver possibly was not completely free of fault. According to the report, the driver had "apparently fallen asleep" and was driving too fast for weather conditions.

The crash report stated that the road was not a contributing factor to the crash cause or the crash severity. From an engineering perspective, we know such a crash possibly could be avoided or at least the severity could be reduced by improving the geometric design and properly using appurtenances (rumble strips, delineators, and longitudinal barriers) or proper treatments to the roadside hazards (ditches and trees). These elements will be discussed in detail in the following chapters.

Case 2 *(8)*

On October 9, 2004, about 5:02 a.m., a 1988 Motor Coach Industries, Inc. (MCI), 47-passenger motorcoach was southbound on Interstate 55 (I-55) near Turrell, Arkansas, transporting 29 passengers to a casino in Tunica, Mississippi. Witnesses following the motorcoach prior to the accident estimated that it had been traveling about 70 mph. At the Exit 23A interchange, the motorcoach veered to the right and entered the grassy area between the exit ramp and the entrance ramp. As it rotated in a clockwise direction, the motorcoach struck an exit sign and overturned onto its left side and slid in a southwesterly direction. The left side of the vehicle struck the westernmost side of a 2-foot-deep earthen drainage ditch, and the motorcoach continued to roll over. As it rolled, the roof

> opened up, allowing passengers to be thrown from the open top. The motorcoach landed 65 feet from the drainage ditch and came to rest upside down. Its roof was lying on the ground (top side up), still hinged to the right side of the vehicle.
>
> At the time of the accident, it was dark and there was no highway safety lighting. The roadway was wet from a misting rain, but there was no standing water.

According to the NTSB report, the terrain where this crash occurred is flat and the road section is tangent. There are good lane markings and rumble strips are present along the lane markings. The right shoulder is 10 feet wide and at a 4% cross slope whereas the travel lane is at a 2% cross slope.

As can be interpreted from the crash report, the ditch may have played an important role in causing the vehicle to lose control. This crash could be categorized as a Type 4 crash, whereby the ditch may have caused the driver to lose control and regaining control may have been beyond the ability of a normal driver. This crash ultimately caused the motorcoach to roll over, which undeniably contributed to the majority of the severe injuries. This case, confirmed with the data shown previously, shows that roadside appurtenances may contribute to rollover crashes.

After examining statistics and some cases of roadway departure crashes, we will examine the current design guide and standards for the elements that affect road side safety.

3. CURRENT DESIGN GUIDELINES ADDRESSING ROADWAY DEPARTURE CRASHES

In this chapter, the following current design guides related to the objective of this study are discussed: the AASHTO Roadside Design Guide (RDG) *(1)*, the Indiana Design Manual, the AASHTO Highway Safety Manual *(9)*, and the NCHRP Series, Volume 6, A Guide for Addressing ROR Crashes *(10)*.

The design guide referenced in this chapter is the Third Edition of the AASHTO Roadside Design Guide (RDG). It includes roadside elements, some roadway-related elements, and the traffic and environmental factors that have an effect on roadside safety. By the time this report is submitted, the Fourth Edition of the RDG may be published, which unfortunately could not be included in this study. The RDG also recommends the Roadside Safety Analysis Program (RSAP), which is utilized in this study as well, and it will be introduced in Chapter 5.

The AASHTO RDG states that most of the principles and guidelines presented in the document are generally considered for rural highways and freeways; and a specific section (Chapter 10) is dedicated to urban or restricted environments. Since this current study focuses on rural principal arterials, the more general guidelines from the RDG will be discussed. It is noted that the RDG principles are meant to serve as guidelines only to designers, and proper judgment for specific site conditions should be used by designers when necessary. The *clear roadside* concept in the RDG and how it has evolved over time is discussed here as agencies have begun providing traversable and unobstructed areas (clear zones) beyond the edge of the traveled way. Table 3.1 shows the most current and modified recommendations for clear zone distances in relation to foreslopes, backslopes, traffic volume, and speed.

The RDG specifically states that these clear zone distances are recommendations only, and designers need to consider specific site conditions, such as the environment (rural vs. urban), the traffic volume, and the practicality of application. It can be seen in Table 3.1 that, as speeds and slope steepness simultaneously increase, the clear zone distances also increase. If a high probability of continuing crashes is expected, the distances listed in Table 3.1 should be increased. Further study of foreslope and backslope, along with other elements that have been proven to contribute to roadway departure crashes, will be discussed in Section 3.1.

The Indiana Design Manual is used by highway design engineers in Indiana. An overview of the AASHTO RDG and the Indiana Design Manual shows that, the Indiana Design Manual includes recommendations and examples more specific than the AASHTO RDG; other than that, in terms of design standards and guidelines, the Indiana's Manual is consistent with the AASHTO RDG. A more detailed comparison of the contents of the Indiana Design Manual concerning roadside design did not reveal considerable additions to the AASHTO RDG. The following section of the report discusses elements of the roadside design guidelines in reference to the AASHTO RDG, with the Indiana Design Manual referred to where necessary.

The Strategic Highway Safety Plan (SHSP) *(11)*, approved by AASHTO in 1998, is an effort by AASHTO and all related agencies to improve highway safety. The SHSP describes its methodology as follows:

> A well-planned, coordinated approach to improving roadway safety that involves all elements of the traffic safety community, focuses on low-cost, day-to-day improvements, and effectively implements new strategies that can substantially reduce the nation's highway death toll and improve the future outlook for today's new citizens. This Strategic Highway Safety Plan (SHSP) and the tools developed to facilitate its implementation offer state and local transportation and safety agencies a life-saving blueprint-ready application in developing comprehensive highway safety plans.

The NCHRP 500 Series, Guidance for Implementation of the AASHTO SHSP, was developed to help state and local agencies implement the SHSP and reduce the targeted type of crashes. Volume 6, A Guide for Addressing ROR Crashes, is appropriate for our application in this study.

TABLE 3.1
Clear Zone Distances (Feet) from the Edge of the Traveled Way

Design Speed	Design ADT (ft)	Foreslopes			Backslopes		
		1V:6H or Flatter	1V:5H TO 1V:4H	1V:3H[2]	1V:3H	1V:5H TO 1V:4H	1V:6H or Flatter
40 mph or less	Under 750	7–10	7–10	—	7–10	7–10	7–10
	750–1500	10–12	12–14	—	10–12	10–12	10–12
	1500–6000	12–14	14–16	—	12–14	12–14	12–14
	Over 6000	14–16	16–18	—	14–16	14–16	14–16
45–50 mph	Under 750	10–12	12–14	—	8–10	8–10	10–12
	750–1500	14–16	16–20	—	10–12	12–14	14–16
	1500–6000	16–18	20–26	—	12–14	14–16	16–18
	Over 6000	20–22	24–28	—	14–16	18–20	20–22
55 mph	Under 750	12–14	14–18	—	8–10	10–12	10–12
	750–1500	16–18	20–24	—	10–12	14–16	16–18
	1500–6000	20–22	24–30	—	14–16	16–18	20–22
	Over 6000	22–24	26–32[1]	—	16–18	20–22	22–24
60 mph	Under 750	16–18	20–24	—	10–12	12–14	14–16
	750–1500	20–24	26–32[1]	—	12–14	16–18	20–22
	1500–6000	26–30	32–40[1]	—	14–18	18–22	24–26
	Over 6000	30–32[1]	36–44[1]	—	20–22	24–26	26–28
65–70 mph	Under 750	18–20	20–26	—	10–12	14–16	14–16
	750–1500	24–26	28–36[1]	—	12–16	18–20	20–22
	1500–6000	28–32[1]	34–42[1]	—	16–20	22–24	26–28
	Over 6000	30–34[1]	38–46[1]	—	22–24	26–30	28–30

Source: *(1)*.

[1]Where a site specific investigation indicates a high probability of continuing crashes, or such occurrences are indicated by crash history, the designer may provide clear-zone distances greater than the clear-zone shown in Table 3.1. Clear zones may be limited to 30 ft for practicality and to provide a consistent roadway template if previous experience with similar projects or designs indicates satisfactory performance.

[2]Since recovery is less likely on the unshielded, traversable 1V:3H slopes, fixed objects should not be present in the vicinity of the toe of these slopes. Recovery of high-speed vehicles that encroach beyond the edge of the shoulder may be expected to occur beyond the toe of slope. Determination of the width of the recovery area at the toe of slope should take into consideration right-of-way availability, environmental concerns, economic factors, safety needs, and crash histories. Also, the distance between the edge of the through traveled lane and the beginning of the 1V:3H slope should influence the recovery area provided at the toe of slope. While the application may be limited by several factors, the foreslope parameters which may enter into determining a maximum desirable recovery area are illustrated in Figure 3.2.

In A Guide for Addressing ROR Crashes *(10)*, three objectives in dealing with roadway departure crashes are stated:

1. Keep vehicles from encroaching the roadside.
2. Minimize the likelihood of crashing or overturning if the vehicle travels off the shoulder.
3. Reduce the severity of crashes that occur.

The three objectives each target one step of a typical roadway departure crash: (1) a vehicle first runs off the traveled roadway and either into a median or toward the roadside, (2) a crash occurs once the vehicle fails to regain control or stops before hitting any roadside objects or a rollover occurs, and (3) the occupant(s) may sustain an impact and an injury of a certain level may occur. The strategies for these three objectives are shown in Table 3.2.

As the NCHPR 500 Series, Volume 6, A Guide for Addressing ROR Crashes *(10)* provides a very detailed description and discussion for each strategy; they are not included in this report. Further details are available in the Guide itself.

The Highway Safety Manual (HSM) is a recent publication by AASHTO. The purpose of the HSM, as stated in its preface *(9)* is as follows:

> The Highway Safety Manual (HSM) is a resource that provides safety knowledge and tools in a useful form to facilitate improved decision making based on safety performance. The focus of the HSM is to provide quantitative information for decision making. The HSM assembles currently available information and methodologies on measuring, estimating, and evaluating roadways in terms of crash frequency (number of crashes per year) and crash severity (level of injuries due to crashes). The HSM presents tools and methodologies for consideration of "safety" across the range of highway activities: planning, programming, project development, construction, operations, and maintenance. The purpose is to convey present knowledge regarding highway safety information for use by a broad array of transportation professionals.

Thus, the HSM is also included in this report as an official guide.

In this chapter, the materials will be organized as such: In Section 3.1, the design guidelines regarding

TABLE 3.2
Objectives and Strategies

Objectives	Strategies
15.1 A—Keep vehicles from encroaching on the roadside	**15.1 A1**—Install shoulder rumble strips (T) **15.1 A2**—Install edgeline "profile marking," edgeline rumble strips or modified shoulder rumble strips on section with narrow or no paved shoulders (E) **15.1 A3**—Install midlane rumble strips (E) **15.1 A4**—Provide enhanced shoulder or in-lane delineation and marking for sharp curves (P/T/E) **15.1 A5**—Provide improved highway geometry for horizontal curves (P) **15.1 A6**—Provide enhanced pavement markings (T) **15.1 A7**—Provide skid-resistant pavement surfaces **15.1 A8**—Apply shoulder treatments • Eliminate shoulder drop-offs (E) • Widen and/or pave shoulders (P)
15.1 B—Minimize the likelihood of crashing into an object or overturning if the vehicle travels beyond the edge of the shoulder	**15.1 B1**—Design safer slopes and ditches to prevent rollovers (see "Improving Roadsides," page V-36) (P) **15.1 B2**—Remove/relocate objects in hazardous locations (see "Improving Roadsides," page V-36) (P) **15.1 B3**—Delineate trees or utility poles with retroreflective tape (E)
15.1 C—Reduce the severity of the crash	**15.1 C1**—Improve design of roadside hardware (e.g., bridge rails) (see "Improving Roadsides," page V-36) (T) **15.1 C2**—Improve design and application of barrier and attenuation systems (see "Improving Roadsides," page V-36) (T)

Source: *(10)*
NOTE: (T) denotes tested strategies, (E) denotes experimental strategies, and (P) denotes proven strategies.

roadway design, which are considered to be relative to roadway departure crashes, will be discussed, which includes materials from the NCHRP 500 Volume 6 and the HSM. In Section 3.2, the design guidelines regarding roadside elements will be presented in detail, including the detailed description and design recommendations from the RDG (with the Indiana Design Manual's additional provisions), the causal relations and safety effectiveness from the HSM and potential application and research needs from the NCHRP 500 Volume 6. In Section 3.3, the design guidelines and safety effectiveness of the longitudinal barriers will be presented and will include material from the three guidelines references. Finally, in Section 3.4, design guidelines from Europe will be covered to provide further information.

3.1 Roadway Design

While keeping vehicles from encroaching the roadside is mainly achieved by improvement of the roadway, it is not the main focus of this current study and will only be briefly discussed.

In the Guide for Addressing ROR Crashes *(10)*, the previously shown Table 3.2 identifies potential strategies for keeping vehicles on the traveled way. There are two characteristics for these strategies that should be noted. First, these strategies are mainly "low cost" strategies that can be implemented to hazardous spots with relatively low costs and within a relatively short time period. Second, the letters after each strategy indicate different levels of implementations of such strategies. For instance, P stands for proven strategies, which has seen wide application. T denotes tried strategies, which should have been implemented in at least a number of locations and may have been accepted as standard procedures. E stands for experimental, which are new strategies tried at least once and are considered to be promising for small scale application.

In the HSM, various safety treatments are suggested and their effectiveness is reported in the form of Crash Modification Factors (CMFs). The HSM provides two lists of safety treatments for the roadway and the roadside elements, along with their applicability to each road function level. The HSM also provides CMFs for roadway alignment, signage, and delineation, all of which may have an effect on roadside safety, but which fall outside the scope of this report.

Although the main focus of this synthesis is on the effect of roadside design on traffic safety, converting a four-lane road into a six-lane road without affecting the right-of-way may call for reducing traveled ways, medians, and shoulders. As previously discussed, the HSM provides a list of treatments for roadway elements, which are shown in Table 3.3.

As can be seen from Table 3.3, countermeasures applicable to rural multilane highways and freeways include: widening paved shoulders, providing raised median, and changing the width of existing median, among other methods. However, CMFs are not available for some of the treatments, especially for rural freeways, which will help identify future research needs. Only the CMF figures for the countermeasures

TABLE 3.3
Summary of Treatments Related to Roadway Elements

HSM Section	Treatment	Rural Two-Lane Road	Rural Multilane Highway	Rural Frontage Road	Freeway	Expressway	Urban Arterial	Suburban Arterial
13.4.2.1	Modify lane width	✓	✓	✓	—	—	—	—
13.4.2.2	Add lanes by narrowing existing lanes and shoulders	N/A	—	N/A	✓	—	—	—
13.4.2.3	Remove through lanes or "road diets"	N/A	N/A	N/A	N/A	N/A	✓	N/A
13.4.2.4	Add or widen paved shoulder	✓	✓	✓	—	—	—	—
13.4.2.5	Modify shoulder type	✓	—	-	—	—	—	—
13.4.2.6	Provide a raised median	—	✓	N/A	—	—	✓	—
13.4.2.7	Change width of existing median	N/A	✓	N/A	—	—	✓	—
Appendix 13A.2.2.1	Increase median width	—	T	N/A	T	T	—	—

Source: *(9)*.
NOTE: ✓ indicates that CMF is available for this treatment.
T indicates that CMF is not available but a trend regarding the potential change in crashes or user behavior is known and presented in Appendix 13A.
— indicates that CMF is not available and a trend is not known.
N/A indicates that the treatment is not applicable to the corresponding setting.

relevant to roadway departure crashes are shown in Table 3.4 and are briefly discussed.

Table 3.4 shows the effect of narrowing or eliminating shoulders on rural multilane highways. As expected, the more the shoulder width is reduced, the higher is the CMF observed.

Table 3.5 presents the reduction in crashes (with a CMF lower than 1) when a median is provided for rural multilane highways. In our application, this might suggest an increase in crashes when a median is removed to provide ROW for the added lanes.

Table 3.6 is most relevant to the scope of the current study. CMFs lower than one for increasing the width of the median for full access controlled rural four-lane highways indicates that if the median width is reduced, more crashes could be expected. Table 3.7 shows a very similar trend for partial or no access control rural highways. From the HSM, it is clear that, for rural highways, the provision of median and shoulders could reduce the frequency of crashes. Also, the wider the median is, the lower could be the frequency of cross-median crashes.

3.2 Roadside Design

The design of roadside objects is discussed in detail in the RDG. Our study focuses on the effect of reduced ROW and the use of safety barriers at the corridor level. Although specific point hazards and their treatment, such as barrier ends and crash cushions, are not covered in this chapter, there will be a general discussion of point hazards and their treatment. The organization of this section follows the structure of the RDG.

3.2.1 Roadside Topography and Drainage Features

When sloping roadsides or drainage ditches are present, it is difficult to design a proper clear zone. This

TABLE 3.4
Potential Crash Effects of Paved Right Shoulder Width on Divided Segments

Treatment	Setting (Road Type)	Traffic Volume	Crash Type (Severity)	CMF	Std. Error
8-ft to 6-ft conversion	Rural (multilane highways)	Unspecified	All types (unspecified)	1.04	N/A
8-ft to 4-ft conversion				1.09	N/A
8-ft to 2-ft conversion				1.13	N/A
8-ft to 0-ft conversion				1.18	N/A
Base condition: 8-ft-wide shoulder.					

Source: *(9)*.
NOTE: N/A indicates that standard error of CMF is unknown.

TABLE 3.5
Potential Crash Effects of Providing a Median on Multi-Lane Roads

Treatment	Setting (Road Type)	Traffic Volume	Crash Type (Severity)	CMF	Std. Error
Provide a median	Urban (arterial multilane [a])	Unspecified	All types (injury)	**0.78[b]**	**0.02**
			All types (non-injury)	**1.09[b]**	**0.02**
Provide a median	Rural (multilane [a])	Unspecified	All types (injury)	**0.88**	**0.03**
			All types (non-injury)	**0.82**	**0.03**
Base condition: Absence of raised median.					

Source: *(9)*.
NOTE: Based on U.S. studies: Kihlberg and Tharp 1968; Garner and Deen 1973; Harwood 1986; Squires and Parsonson 1989; Bowman and Vecellio 1994; Bretherton 1994; Bonneson and McCoy 1997 and international studies: Leon 1970; Thorson and Mouritsen 1971; Andersen 1977; Muskaug 1985; Scriven 1986; Blakstad and Giaever 1989; Dijkstra 1990; Kohler and Schwamb 1993; Claessen and Jones 1994.
Bold text is used for the most reliable CMFs. These CMFs have a standard error of 0.1 or less.
[a]Includes minor intersections.
[b]Treatment results in a decrease in injury crashes and an increase in non-injury crashes. See Part D—Introduction and Applications Guide.

TABLE 3.6
Potential Crash Effects of Median Width on Rural Four-Lane Roads with Full Access Control

Median Width (ft)	Setting (Road Type)	Traffic Volume AADT	Crash Type (Severity)	CMF	Std. Error
10-ft to 20-ft conversion	Rural (4 lanes with full access control)	2,400–119,000	Cross-median crashes (unspecified)	**0.86**	**0.02**
10-ft to 30-ft conversion				**0.74**	**0.04**
10-ft to 40-ft conversion				**0.63**	**0.05**
10-ft to 50-ft conversion				**0.54**	**0.06**
10-ft to 60-ft conversion				**0.46**	**0.07**
10-ft to 70-ft conversion				**0.40**	**0.07**
10-ft to 80-ft conversion				**0.34**	**0.07**
10-ft to 90-ft conversion				**0.29**	**0.07**
10-ft to 100-ft conversion				**0.25**	**0.06**
Base condition: 10-ft-wide traversable median.					

Source: *(9)*.
NOTE: **Bold text** is used for the most reliable CMFs. These CMFs have a standard error of 0.1 or less.

TABLE 3.7
Potential Crash Effects of Median Width on Rural Four-Lane Roads with Partial or No Access Control

Median Width (ft)	Setting (Road Type)	Traffic Volume AADT	Crash Type (Severity)	CMF	Std. Error
10- to 20-ft conversion	Rural (4 lanes with partial or no access control	1,000–90,000	Cross-median crashes (unspecified)	**0.84**	**0.03**
10- to 30-ft conversion				**0.71**	**0.06**
10- to 40-ft conversion				**0.60**	**0.07**
10- to 50-ft conversion				**0.51**	**0.08**
10- to 60-ft conversion				**0.43**	**0.09**
10- to 70-ft conversion				**0.36**	**0.09**
10- to 80-ft conversion				**0.31**	**0.09**
10- to 90-ft conversion				**0.26**	**0.08**
10- to 100-ft conversion				**0.22**	**0.08**
Base condition: 10-ft-wide traversable median.					

Source: *(9)*.
NOTE: **Bold text** is used for the most reliable CMFs. These CMFs have a standard error of 0.1 or less.

section will discuss the various elements involved in the proper design for drainage, as well as their impact on roadway departure crashes.

Foreslopes

In the RDG, recoverable foreslopes are defined as "1V:4H or flatter, relatively smooth and traversable," while non-recoverable foreslopes generally fall into a category between 1V:3H and 1V:4H, and critical foreslopes are steeper than 1V:3H. The figures and tables available in the RDG provide specific clear zone distances according to the roadway design speed. In instances of a non-recoverable foreslope, a clear runout area should be provided, and the foreslope break should be rounded to avoid vehicles becoming airborne. Critical foreslopes should be treated if they warrant a barrier, as discussed further in Section 3.1.3.

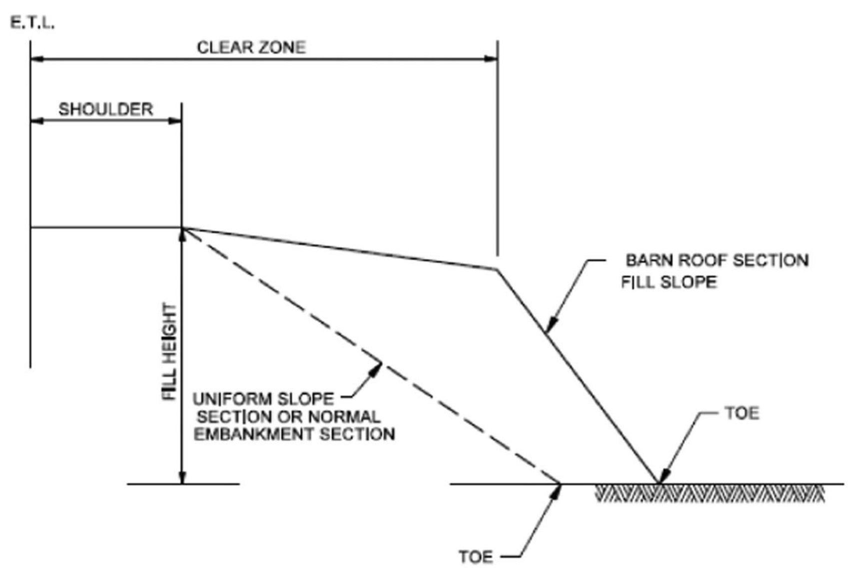
The RDG mentions many states using "barn roof" sections, which consist of a relatively flat recovery area adjacent to the traveled way, followed by a steeper slope, due to ROW restrictions. Such design could provide a greater chance for errant vehicles to recover from an encroachment; however, in severe cases, vehicles that leave the "barn roof" section are more likely to rollover or hit a fixed object. Due to this severe case, longitudinal barriers along the edge of "barn roof" sections should be considered, particularly for sections with a higher expected encroachment rate.

Surface smoothness is also crucial for the recovery of errant vehicles. In locations with a strict restraint on ROW that are expected to have a high encroachment rate, the surface treatment of the clear zone could help reduce the frequency and severity of roadway departure crashes.

In the Indiana Design Manual, Figure 45-3A (Figure 3.1 in this report) summarizes the design recommendations for fill slopes, which is consistent with the AASHTO guidelines (Table 3.1). The Indiana Design Manual clearly states that these values in the table is for recommendation only and fill slopes flatter than the recommended value should be considered wherever possible.

Backslopes

Backslopes generally are traversable in the presence of a cut section with a recoverable foreslope. Smooth, obstacle-free areas are desired, however, in instances were obstacles (such as trees) or a rough-sided face are present, barriers may be warranted.



FACILITY	FILL HEIGHT	FILL SLOPE (1)
Freeways Urban/Rural Arterials Urban/Rural Collectors		6:1 to clear zone edge; 3:1 maximum to toe See Section 49-2.03
Rural Local Roads	0-30 ft > 30 ft	Desireable 4:1 Maximum 3:1 3:1 Maximum
Urban Local Streets	All	3:1 Maximum

(1) Slopes shown in table are for new construction only. See Chapter Forty-nine for reconstruction.

Figure 3.1 Fill slope recommendations in Indiana Design Manual *(2)*.

In the Indiana Design Manual, Figure 45-3C (Figure 3.2 in this report) summarized the design recommendations for the cut slopes, which is also consistent with the AASHTO guidelines.

Transverse Slopes

Transverse slopes are created by median crossovers, driveways, crossing roads, or drainage structures. These transverse slopes are more critical than foreslopes or backslopes, since roadway departure vehicles strike them head-on. Transverse slopes of 1V:10H are desirable, however, the width limitations allow for steeper transverse slopes in low-speed areas.

Drainage Features

In the RDG, options are available for referring to the roadway drainage system to provide both hydraulic efficiency and roadside safety. Those options, in order of preference, are:

1. Keep only the essential drainage structures.
2. Design or modify the drainage structures to be as traversable and as minimally obstructive as possible.
3. Provide a suitable barrier if the drainage feature cannot be effectively redesigned or relocated.

The FARS data presented in Chapter 2 show that ditches are the fourth highest of first harmful events for roadway departure fatal crashes. Both randomly selected example cases involved ditches. These findings support further investigation of the safety of drainage features. Standards and current practices may need to be redesigned to reduce the crash frequency and severity of drainage features as a common first harmful event.

There is an in-depth discussion of a variety of elements of drainage features in the RDG. The following elements have been known to cause the greatest concern for safety in terms of drainage features.

Drainage Channels

The RDG defines a drainage channel as "an open channel usually paralleling the highway embankment and within the limits of the highway right-of-way." Its primary purpose is to collect surface run-off and direct it to the appropriate outlet structure. Drainage channels should take into consideration the safety recommendations for foreslopes and backslopes (preferably flatter than 1V:3H). Drainage channels are less desirable in areas where high-angle encroachments are expected, such as at the outside of sharp curves. There are exceptions for the use of drainage channels (i.e., in instances of a restricted ROW and in low-speed areas, such as urban environments). If modifications cannot be made to ensure a safer environment for possible roadway departure crashes, transforming the drainage channel to a closed shape or providing a barrier where warranted are recommended.

Recommended design details are provided in both the AASHTO RDG and the Indiana Design Manual. In the AASHTO RDG, the recommendations regarding the ditch design include the types of ditch bottom (V shape, rounded bottom, and trapezoidal), two categories of bottom widths, and desirable and undesirable channel cross-sections. The Indiana Design Manual provides three bottom width categories, and the cross-section designs are categorized as desirable, acceptable, and undesirable. Figures 3.3 and 3.4 are design recommendations from AASHTO RDG, while Figures 3.5, 3.6, and 3.7 were taken from the Indiana Design Manual.

FACILITY	FORESLOPE	DITCH WIDTH (2)	BACKSLOPE (3)	
			A	B
Freeway	6:1	1.2	4:1 for 20 ft	$H \leq$ 10 ft; 4:1 $H >$ 10 ft; 3:1
Arterial or Rural Collector	6:1	1.2	4:1 for 20 ft	3:1 max to top
Urban Collector	Des. 6:1 Max. 4:1	1.2	4:1 for 4 ft	3:1 max to top
Rural Local Road $V \geq$ 50 mph $V \leq$ 45 mph	4:1 (max) 3:1 (max)	Des. 4 ft Min. "V"	4:1 (max) 3:1 (max)	
Urban Local Street	3:1 (max)	Des. 4 ft Min. "V"	3:1 (max)	

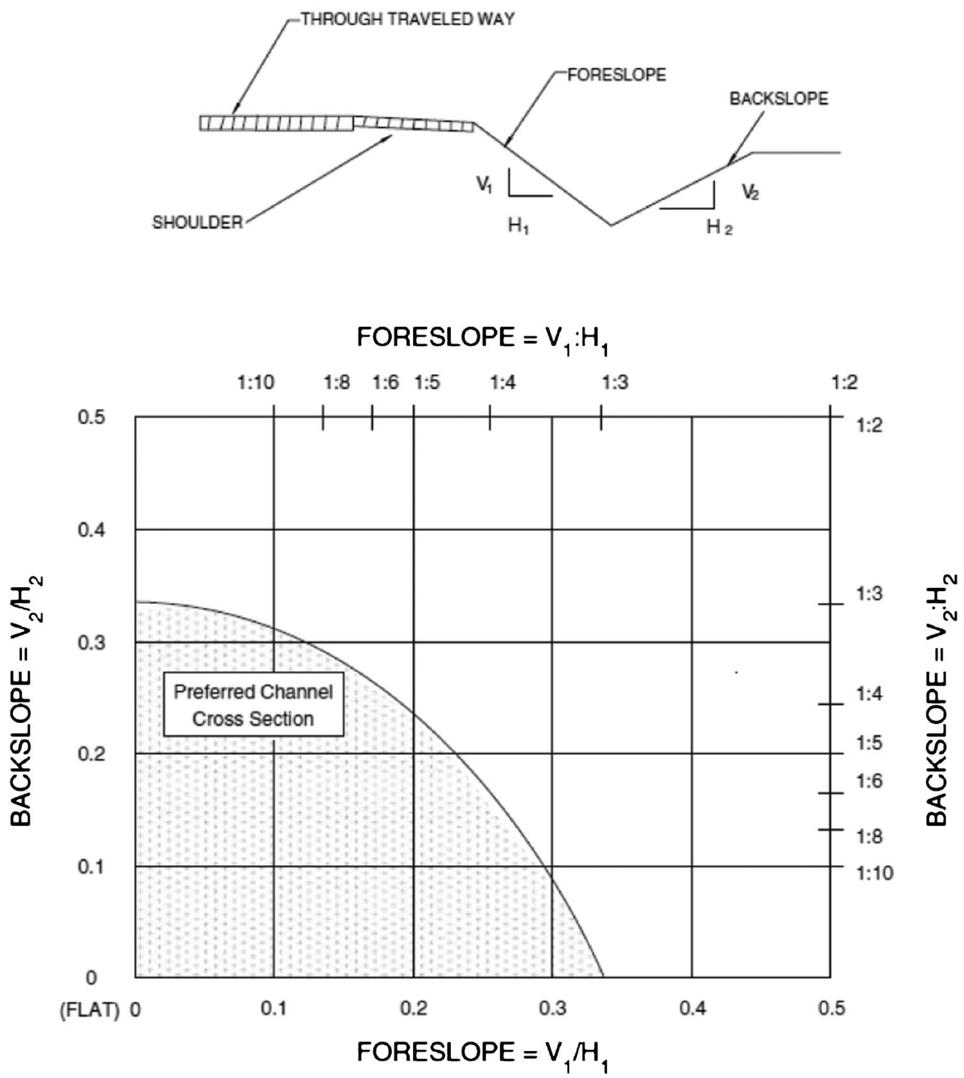
Notes:

(1) *See Sections 49-2.0 and 49-3.0 to determine lateral extent of the foreslope in a ditch section.*

(2) *For a rock cut, see Section 45-8.0. Figure value may be exceeded where drainage capacity or other considerations warrant.*

(3) *Value is for earth cut and represents maximum slope. See Section 45-8.0 for typical rock-cut sections.*

Figure 3.2 Cut slope recommendations in Indiana Design Manual *(2)*.



*This chart is applicable to all Vee ditches, rounded channels with a bottom width less than 2.4 m [8 ft] and trapezoidal channels with bottom widths less than 1.2 m [4 ft].

Figure 3.3 AASHTO ditch recommendation for narrower width *(1)*.

Cross-Drainage Structures

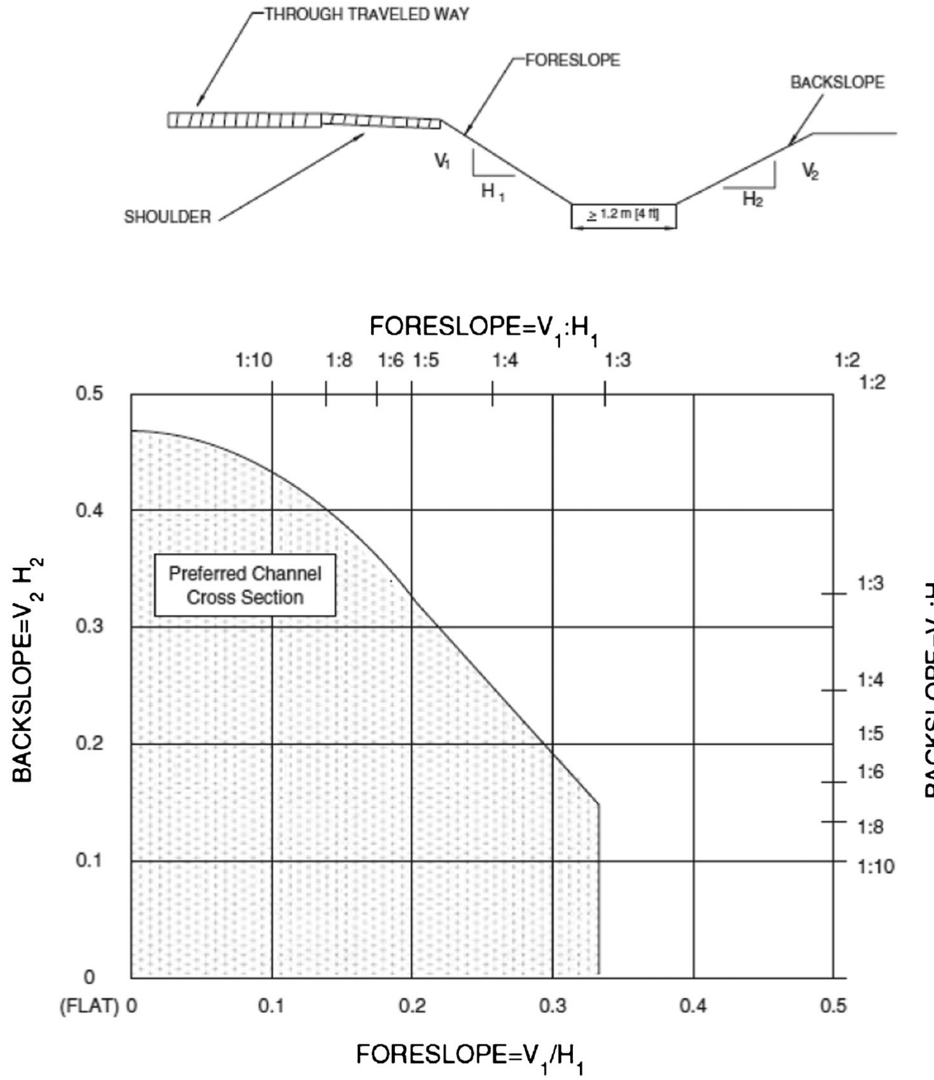
The inlets and outlets of cross-drainage structures can be roadside hazards if the concrete walls or beveled-end sections are not properly designed, which pose the potential for hitting a fixed-object end or falling into an opening for the cross-drainage structures. The RDG suggests design options to minimize cross-drainage structures as obstacles, such as designing them to be traversable, extending the structure to relocate the inlets or outlets at less hazardous locations, providing shielding, or delineating the structure.

3.2.2 Roadside Fixed Objects

Unobstructed roadsides have been previously discussed as the most desirable for roadways. However, there are instances in which obstacles cannot be completely removed, such as roadway signs, roadway lighting, and other objects that are necessary on roadways. The RDG presents the most general types of treatments for all roadside hazards, in order of preference:

1. Total removal of the hazard
2. Redesign of the hazard to make it traversable
3. Relocation of the hazard to reduce the likelihood of collision
4. Using the proper breakaway device to reduce crash severity
5. Shielding the hazard using longitudinal barriers or other crash cushions
6. Delineating the hazard to alert drivers if none of the above treatments apply

There are many roadside features, in this section, referred to as “fixed objects,” which are discussed in the RDG. The scope of the current study is for high speed rural arterials; therefore, features that will not be



*This chart is applicable to rounded channels with bottom widths of 2.4 m [8 ft] or more and to trapezoidal channels with bottom widths equal to or greater than 1.2 m [4 ft].

Figure 3.4 AASHTO ditch recommendations for wider width *(1)*.

commonly found along such roadways are not detailed in this section. The AASHTO RDG provides more detailed recommendations than the Indiana Design Manual.

3.2.2.1 Trees.

The FARS data presented in Chapter 2 show that trees are the highest fixed object first harmful event. Trees are natural objects, the features or existing locations over which highway designers and engineers have no control. Agencies must focus on proper treatments for these special fixed objects.

The RDG recommends, for new construction projects, the removal of existing trees in the clear zone. The RDG follows the recommendations made in the Guide to Management of Roadside Trees by the Zeigler and Michigan Department of Transportation *(12)*. The MDOT guide provides information for identifying and evaluating risks involving trees in various rural environments, along with general guidance for treatments. The treatments include preventing vehicles from encroachment and mitigating the danger of hitting a tree. These treatments are consistent with those identified in A Guide for Addressing Run-Off-Road Collisions *(10)*, and will be discussed in Chapter 4.

3.2.2.2 Manmade fixed objects.

Manmade fixed objects are those that are designed, installed, and maintained by highway agencies. There are more ways for safety considerations in the design of

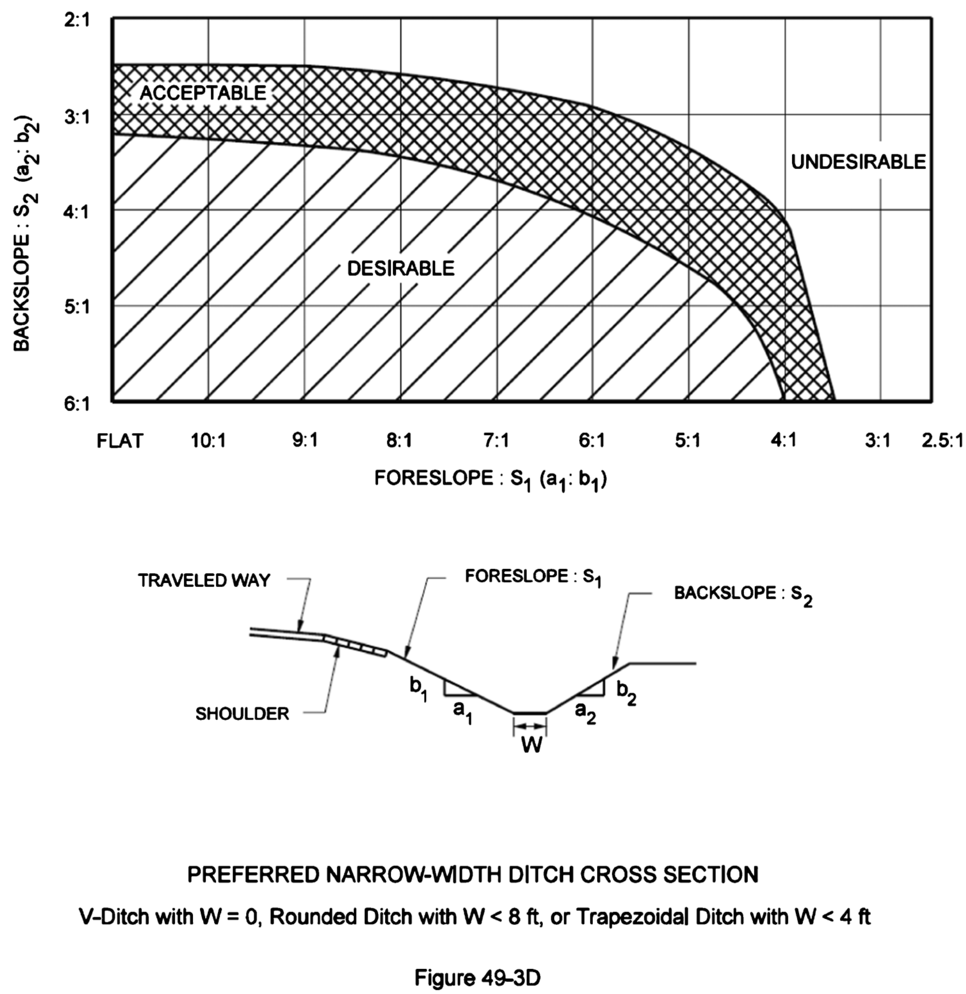


Figure 3.5 Indiana Design Manual recommendations for narrow width design *(2)*.

manmade objects as opposed to natural objects. The FARS data presented in Chapter 2 show that signposts continually rank highly among first harmful events for fatal crashes. The statistics indicate that better design or further treatments are still needed for these appurtenances. The available safety treatments for manmade fixed objects recommended by the RDG are shown below in order of preference:

1. Signs and supports that are not needed should be removed.
2. If a sign or support is needed, locate it in such a way that it is least likely to be hit.
3. Place the sign or support behind existing barriers if possible.
4. Use breakaway devices when none of the above treatments apply.
5. Use barriers or other crash shields only when breakaway devices are not practical.

The first three treatments (removal, traversable designing, and relocation) are usually not applicable for these roadside appurtenances since these objects are placed for a specific function for the roadway. In these cases, breakaway devices become the most desirable option in dealing with treatments for manmade fixed objects and are the focus in the RDG. The following section further detail specific manmade fixed objects.

Signs Posts/Supports

The RDG provides a rather comprehensive discussion on breakaway devices for signpost/supports. The technical details will not be covered in this report, but the general considerations are listed below:

1. The height of the base for such devices should be low enough to ensure vehicles are not being snagged.
2. Breakaway devices should not be placed on soft surfaces or within ditches to avoid steep slopes or any terrain that would affect the impact point or fracture mechanism of such devices.
3. Overhead signs should be preferably mounted on overpasses. If not applicable, the massive supports needed by overhead signs should be shielded by barriers or crash cushions.
4. Large sign supports should be designed strong enough to resist wind and ice loads, but breakable when hit by a vehicle. These supports are either a fracture or slip-base type. The hinge point should be at least 2.1 m in height to ensure no part of the sign penetrates the windshield of a vehicle.

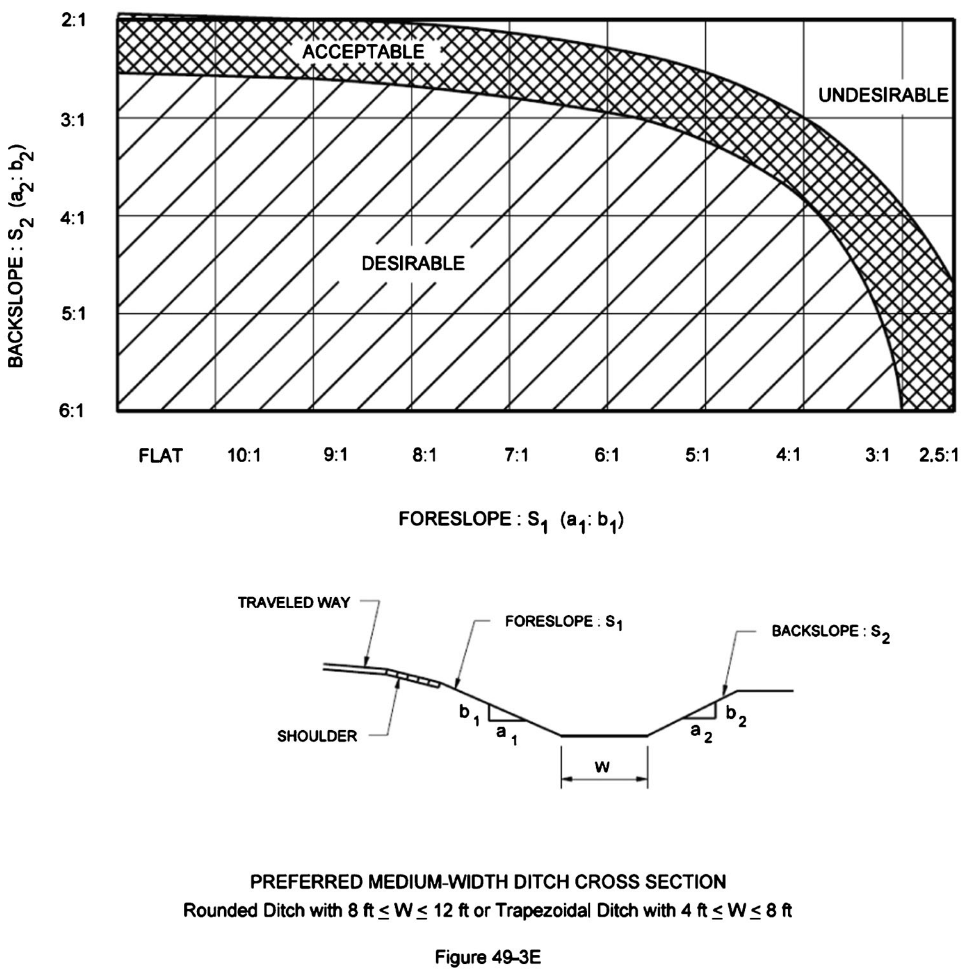


Figure 3.6 Indiana Design Manual recommendations for medium width design *(2)*.

5. Small sign supports are usually of base bending or yielding type. Small signs of these types should be used for lower speed conditions since they are highly likely to penetrate the passenger compartment of certain types of vehicles, regardless of the mounting height. On higher speed roadways, slip base or fracturing supports should be used to avoid passenger compartment penetration.

Luminaire and Other Posts

The diameters and strength of such posts are greater in magnitude when compared to signposts. Generally, the breakaway mechanism will be triggered when the load applied is shear rather than bending and when the impact happens at the designed impact height (typical bumper height). Therefore, two categories of causes will prevent the breakaway mechanism from being triggered:

1. Superelevation, slope rounding, or other facts that will affect the vehicle bumper height.
2. Soft soil or other weak foundation that results in a bending load being applied. It is recommended that the slope be limited to 1V:6H between the roadway and the breakaway luminaire supports, and proper treatment should be given to the foundation where needed.

Utility Poles

Utility poles are a special type of roadside appurtenance since they are owned by utility companies and are located in publicly-owned ROW. This dual responsibility sometimes will make them harder to treat. The preference for utility poles treatments is generally the same as luminaire and other supports, with the exception that utility lines could be buried underground. Breakaway utility poles usually consist of a ground level slip base and upper hinge, but consideration should be given to the consequence of fallen utility poles with respect to their obstruction of traffic.

3.2.3 General Guidance for Improvement

A Guide for Addressing ROR Crashes *(10)* provides general guidance on this topic; however, a detailed discussion is not included. The strategies are grouped into two groups that target reducing frequency and severity of roadway departure crashes.

According to A Guide for Addressing ROR Crashes, there are three broad categories of low cost treatment to minimize the likelihood of crashing into an object or overturning if the vehicle travels off the shoulder:

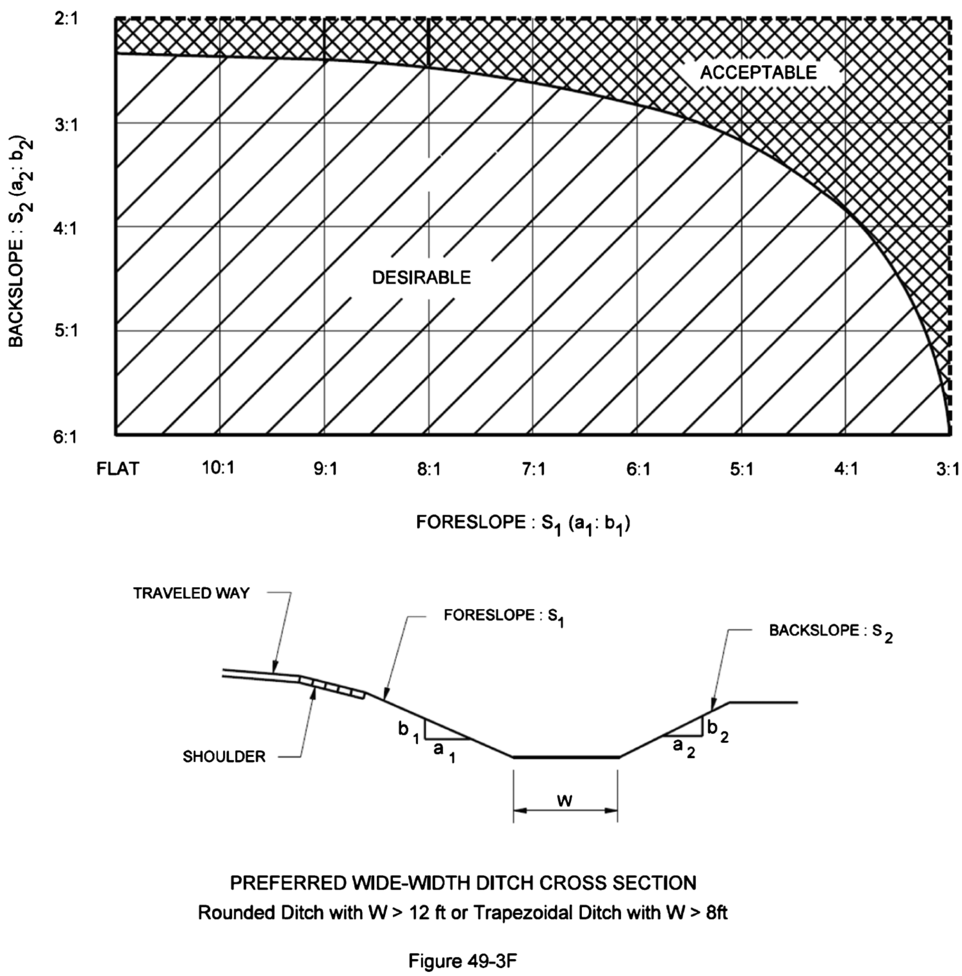


Figure 3.7 Indiana Design Manual recommendations for wide width design *(2)*.

1. Design safer slopes and ditches to prevent rollovers
2. Remove/relocate objects in hazardous locations
3. Delineation of roadside objects

This is generally in agreement with the AASHTO RDG. Two broad categories of strategies are also identified to reduce the severity of the crash:

1. Improve design of roadside hardware
2. Improve design and application of barrier and attenuation systems

3.2.4 Effectiveness of Roadside Treatments

The HSM provides various treatments related to roadside elements for various functional classes. In the HSM, barriers are not listed as a separate section, thus the safety effect of barriers will also be covered in this section. A summary of these treatments is provided in the HSM, as shown in Table 3.8.

As shown in Table 3.8, there are many treatments with an available CMF or trend for "Rural Multi-lane Highways" and "Freeways." Also, for treatments like "reduce roadside hazard rating" and "increase clear roadside recovery distance," the CMF is not available for freeways or multilane highways, which indicates future studies are needed in this area.

This section presents the safety effects on rural multilane highways and freeways for flattening sideslopes, increasing the distance to roadside features, changing barriers to a less rigid type, and installing a median barrier. Table 3.9 shows the crash effects for sideslopes.

The information provided in Table 3.9 displays a higher CMF value for steeper slopes. As previously mentioned in this chapter, roadside barriers are not recommended on sideslopes steeper than 1V:6H. Table 3.10 shows the effects of increasing the distance to roadside features. Roadside features should include both roadside hazards and barriers; however, the HSM does not specify between these two. Table 3.10 provides vital information for evaluating the effect of clear zone width. Table 3.11 shows that less rigid barrier types will reduce the frequency of more severe crashes, however, less rigid barrier types may not always be suitable for specific conditions. Table 3.12 shows the effects of installing a median barrier.

TABLE 3.8
Summary of Treatments Related to Roadside Elements

HSM Section	Treatment	Rural Two-Lane Road	Rural Multi-Lane Highway	Freeway	Expressway	Urban Arterial	Suburban Arterial
13.5.2	Flatten sideslopes	✓	✓	—	—	—	—
13.5.2.2	Increase distance to roadside features	✓	—	✓	—	—	—
13.5.2.3	Change roadside barrier along embankment to less rigid type	✓	✓	✓	✓	✓	✓
13.5.2.4	Install median barrier	N/A	✓	T	—	—	—
13.5.2.5	Install crash cushions at fixed roadside features	✓	✓	✓	✓	✓	✓
13.5.2.6	Reduce roadside hazard rating	✓	—	—	—	—	—
Appendix 13A.3.2.2	Increase clear roadside recovery distance	T	—	—	—	—	—
Appendix 13A.3.2.3	Install curbs	—	—	—	—	T	T
Appendix 13A.3.2.4	Increase the distance to utility poles and decrease utility pole density	T	T	T	T	T	T
Appendix 13A.3.2.5	Install roadside barrier along embankments	T	T	T	T	T	T

Source: *(9)*.
NOTE: ✓indicates that a CMF is available for this treatment.
T indicates that a CMF is not available but a trend regarding the potential change in crashes or user behavior is known and presented in Appendix 13A.
— indicates that a CMF is not available and a trend is not known.
N/A indicates that the treatment is not applicable to the corresponding setting.

TABLE 3.9
Potential Crash Effects of Sideslopes on Undivided Segment

Treatment	Setting (Road Type)	Traffic Volume	Crash Type (Severity)	CMF	Std. Error
1V:7H or flatter	Rural (multilane highway)	Unspecified	All types (unspecified)	1.00	N/A
1V:6H				1.05	
1V:5H				1.09	
1V:4H				1.12	
1V:2H or steeper				1.18	
Base condition: Provision of a 1V:7H or flatter sideslope.					

Source: *(9)*.
NOTE: N/A indicates not applicable.

TABLE 3.10
Potential Crash Effects of Increasing the Distance to Roadside Features

Treatment	Setting (Road type)	Traffic Volume	Crash Type (Severity)	CMF	Std. Error
Increase distance to roadside features from 3.3 ft to 16.7 ft	Rural (two-lane roads and freeways)	Unspecified	All types (all severities)	**0.78**	**0.02**
Increase distance to roadside features from 16.7 ft to 30.0 ft				**0.56**	**0.01**
Base condition: Distance to roadside features of 3.3 ft or 16.7 ft depending on original geometry.					

Source: *(9)*.
NOTE: Based on U.S. studies: Cirillo (1967), Zegeer et al. (1988).
Bold text is used for the most reliable CMFs. These CMFs have a standard error of 0.1 or less. Distance measured from the edgeline or edge of travel lane.

TABLE 3.11
Potential Crash Effects of Changing Barrier to Less Rigid Type

Treatment	Setting (Road Type)	Traffic Volume	Crash Type (Severity)	CMF	Std. Error
Change barrier along embankment to less rigid type	Unspecified (unspecified)	Unspecified	Run-off-the-road (injury)	**0.68**	**0.1**
			Run-off-the-road (fatal)	*0.59*	*0.3*
Base condition: Provision of a rigid roadside barrier.					

Source: *(9)*.
NOTE: Based on U.S. studies: Glennon and Tamburri 1967; Tamburri, Hammer, Glennon, Lew 1968; Williston 1969; Woods, Bohuslav and Keese 1976; Ricker, Banks, Brenner, Brown and Hall 1977; Perchonok, Ranney, Baum, Morris and Eppick 1978; Hall 1982; Bryden and Fortuniewicz 1986; Schultz 1986; Ray, Troxel and Carney 1991; Hunter, Stewart and Council 1993; Gattis, Alguire and Narla 1996; Short and Robertson 1998; and international studies: Good and Joubert 1971; Pettersson 1977; Schandersson 1979; Boyle and Wright 1984; Domhan 1986; Corben, Deery, Newstead, Mullan and Dyte 1997; Ljungblad 2000.
Bold text is used for the most reliable CMFs. These CMFs have a standard error of 0.1 or less. *Italic* text is used for less reliable CMFs. These CMFs have standard errors between 0.2 and 0.3. Distance to roadside barrier is unspecified.

TABLE 3.12
Potential Crash Effects of Installing a Median Barrier

Treatment	Setting (Road Type)	Traffic Volume	Crash Type (Severity)	CMF	Std. Error
Install any type of median barrier	Unspecified (multilane divided highways)	AADT of 20,000–60,000	All types (fatal)	**0.57**[1]	**0.1**
			All types (injury)	**0.70**[1]	**0.06**
			All types (all severities)	**1.24**[1]	**0.03**
Install steel median barrier			All types (injury)	**0.65**	**0.08**
Install cable median barrier				**0.71**	**0.1**
Base condition: Absence of a median barrier.					

Source: *(9)*.
NOTE: Based on U.S. studies: Billion 1956; Moskowitz and Schaefer 1960; Beaton, Field and Moskowitz 1962; Billion and Parsons 1962; Billion, Taragin and Cross 1962; Sacks 1965; Johnson 1966; Williston 1969; Galati 1970; Tye 1975; Ricker, Banks, Brenner, Brown and Hall 1977; Hunter, Steward and Council 1993; Sposito and Johnston 1999; Hancock and Ray 2000; Hunter et al. 2001; and international studies: Moore and Jehu 1968; Good and Joubert 1971; Andersen 1977; Johnson 1980; Statens vagverk 1980; Martin et al. 1998; Nilsson and Ljungblad 2000.
Bold text is used for the most reliable CMFs. These CMFs have a standard error of 0.1 or less.
[1]Treatment results in a decrease in fatal-and-injury crashes and an increase in crashes of all severities. See Part D—Introduction and Applications Guide. Width of the median where the barrier was installed and the use of barrier warrants are unspecified.

As the CMFs show, the overall frequency of crashes will increase with the installation of a median barrier; however, more severe crashes will reduce in number.

The RDG indicates that designing topographic features and drainage components is critical. The close proximity of such elements is unavoidable and treatments are generally not applicable for these elements. For fixed objects, depending on the type and nature of these elements, treatments ranging from removal, relocation, and redesigning to shielding or delineating are applicable to these elements.

The effectiveness of different treatments is indicated in the HSM in terms of CFMs. Steeper slopes and closely located roadside hazards will increase the frequency of roadway departure crashes in all severity categories, while less rigid types of barriers and the installation of median barriers were found to reduce the number of injury and fatal crashes.

3.3 Barrier Design

3.3.1 Roadside Barriers

There are two major considerations for roadside barriers: (1) design criteria to ensure that barriers properly contain and redirect the errant vehicles and (2) systematic methods to identify locations where barriers will alleviate the consequences of roadway departure crashes, which is the primary focus of this study. Roadside barriers serve as more “forgiving” objects than fixed objects. There are three options to consider when determining if a roadside barrier is warranted:

1. Remove or reduce the area of concern so a barrier is no longer required.
2. Install the appropriate roadside barrier.

3. Leave the area unshielded.

This section will detail the concept of a clear roadside in relation to barrier placement, as well as the specific barrier types that may apply to this study.

3.3.1.1 Roadside barrier guidelines.

Barriers should only be installed where needed. There are two reasons for strategic placement of barriers. First, in safety consideration, barriers are considered as a type of roadside object. Even though barriers are designed to absorb energy and feature lower impact severity than the hazard behind the barriers (or no hazard at all), installing barriers could potentially increase the severity of the roadway departure crashes. Second, for economic reasons, the benefit of introducing barriers might not necessarily outweigh the cost (both the safety cost and the economic cost); thus, the total social cost might be increased by installing barriers if the barriers are not justified.

The AASHTO RDG provides warrants for installing barriers. The original warrants developed by AASHTO are based on the costs of severity of crashes with the embankment and barriers. They do not take into account the costs of installing the barriers. Additional warrants developed by an unnamed state take into account these costs. Both warrants are shown below, in Figures 3.8 and 3.9 respectively. The AASHTO RDG encourages states to develop their own warrants that address their conditions. The Indiana Design Manual provides such warrants, but it does not specify whether these warrants consider the costs of installation of barriers. The Indiana warrants for 55 mph and 70 mph are shown in Figures 3.10 and 3.11, respectively.

3.3.1.2 Roadside barrier placement.

For the most desirable position of a barrier, the distance from the traveled way should be maximized, allowing for greater area for an errant vehicle to recover or avoid impact with the barrier and a better sight distance. It is recommended that slopes be 1V:10H or flatter to provide a safe, traversable area. Slopes steeper than 1V:6H are not recommended areas for barriers. A 2-foot minimum distance from the rounded edge of an embankment is recommended, however, this distance is not as critical for rigid objects.

It is also important to prevent the barrier from causing drivers to slow down, change lanes, or shift positions in the travel lane. A barrier distance of 6 feet or more from the traveled way helps to eliminate this problem. It should be noted that this distance is less in the case of median barriers due to the driver having a better depth perception of the distance to the median barrier on the left side.

The offset distance of a barrier is also important to consider when high volumes of large vehicles are present. Some barriers being placed too close to the edge of the traveled way may cause some larger vehicles to overturn. The deflection of a flexible or semi-rigid barrier may also pose problems when a barrier is located close to a fixed object. In this instance, a stronger, more rigid barrier would be suggested.

The general guideline provided in the AASHTO RDG and also used by the Indiana Design Manual is the shy line, which should be treated as the absolute minimum value for installing longitudinal barriers. The shy line values for different speeds provided in the RDG are shown in Figure 3.12.

3.3.1.3 Roadside barrier selection.

In the RDG, the type of barrier selected depends on a variety of factors: barrier performance, deflection, site conditions, cost, maintenance, and others. The performance of roadside barriers is thoroughly confirmed by full-scale crash testing. These crash tests are discussed in detail in the Recommended Procedures for the Safety Performance of Evaluation of Highway Features *(13)*. All barriers discussed in this section are considered acceptable at various test levels (TL) by these guidelines. Figure 3.13 shows the AASHTO roadside barrier types and their corresponding test levels.

TL-2 barriers are developed mainly for passenger cars, whereas TL-4 or greater barriers are recommended for locations with high traffic volumes or speeds, and significant volumes of heavy trucks. A combination of all of the above factors provides designers with the best barrier type for a site. Two specific barrier types will be discussed here, and their advantages and disadvantages will be detailed.

Three-Strand Cable

The three-strand cable system redirects vehicles after tension is developed in the cable. This type of barrier is beneficial due to its low initial cost, its effective vehicle containment for a variety of vehicle sizes, and its open design, which prevents drifting in inclement weather. The cable barrier also has drawbacks of higher maintenance costs after vehicle impact and the need for clear area behind the barrier for deflection. Underride and over-ride problems have also been identified from existing cable barrier systems.

Concrete Barriers

There are several types of concrete barriers listed in the RDG. Each concrete barrier can be found in Figure 3.13, along with the corresponding TLs.

The New Jersey safety-shape barriers have a sloped front face and a vertical back face and are very similar in design to concrete median barriers (CMB). This specific barrier type has been the most commonly tested concrete barrier. Performance tests have placed this short version of the barrier in the TL-4 category, while the tall version is in the TL-5 category. This type of barrier is often used as a median barrier.

F-shape concrete barriers are very similar to the New Jersey shape barriers, and the short and tall versions fall into the same TL categories. The F-shape barrier has performed better than the New Jersey shape barrier in crash testing.

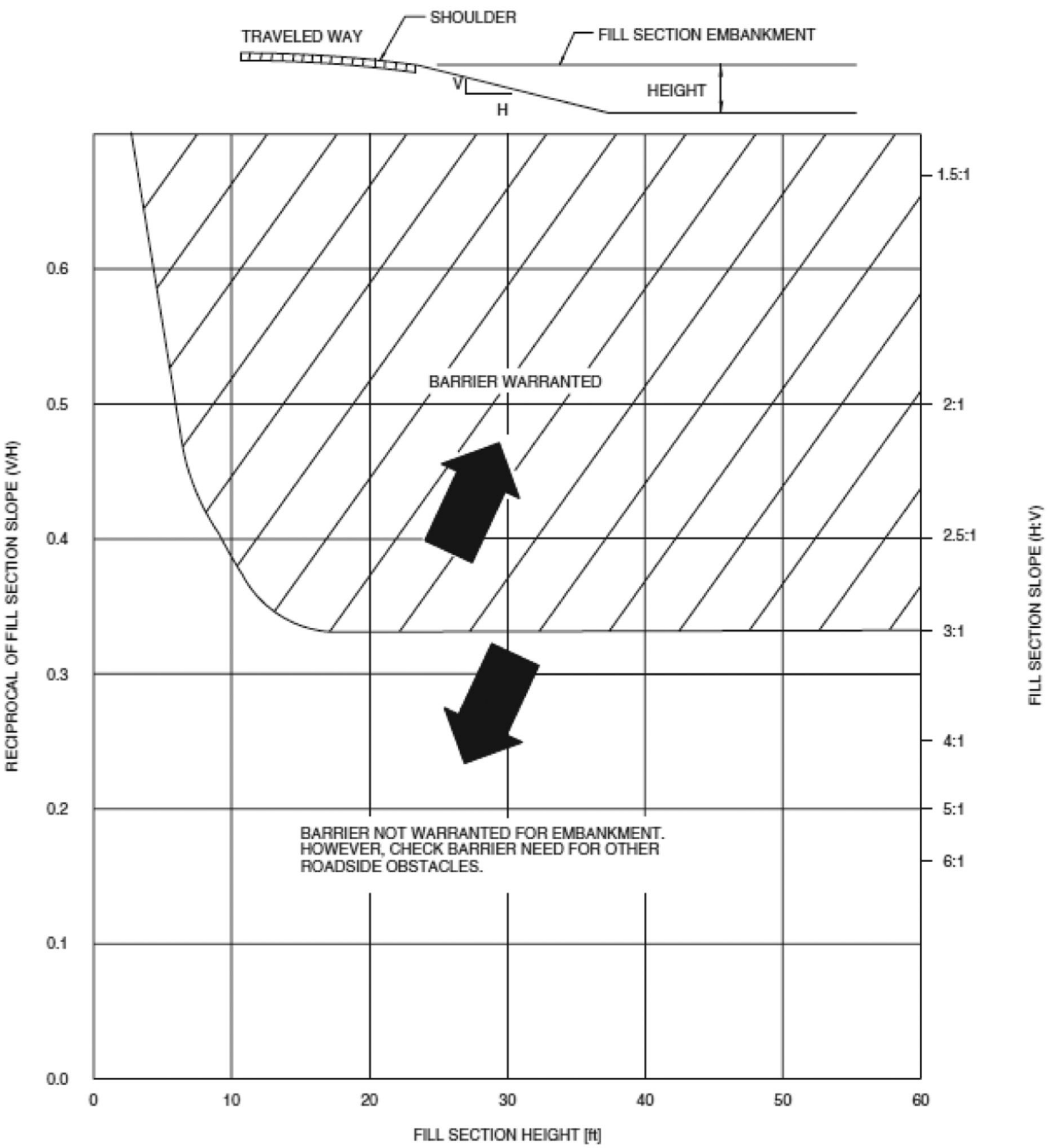


Figure 3.8 Comparative risk warrants for embankments *(1)*.

Slope concrete barriers have been proven to perform well when crash tests were conducted with pick-up trucks and single unit trucks; however, the reduced cross-section of this barrier type makes them more vulnerable to overturning large vehicles. To avoid this problem, extensive footing or further reinforcements are recommended. The short and tall versions of slope concrete barriers are categorized as TL-4 and TL-5, respectively.

The Ontario Tall Wall Median Barrier is a tall version of a New Jersey shape concrete barrier without reinforcements and falls into the TL-5 category.

3.3.2 Median Barriers

Median barriers are most commonly used as a physical division of opposing traffic. The RDG describes median barriers as devices to redirect vehicles that strike either side of the barrier. As suggested by the RDG, median barriers are typically not used in areas where the median width is greater than 30 feet due to previous studies indicating that approximately 80% of errant vehicles are able to recover within this 30-foot buffer. However, statistics and reports indicate that a high number of fatal or severe injury cross-median

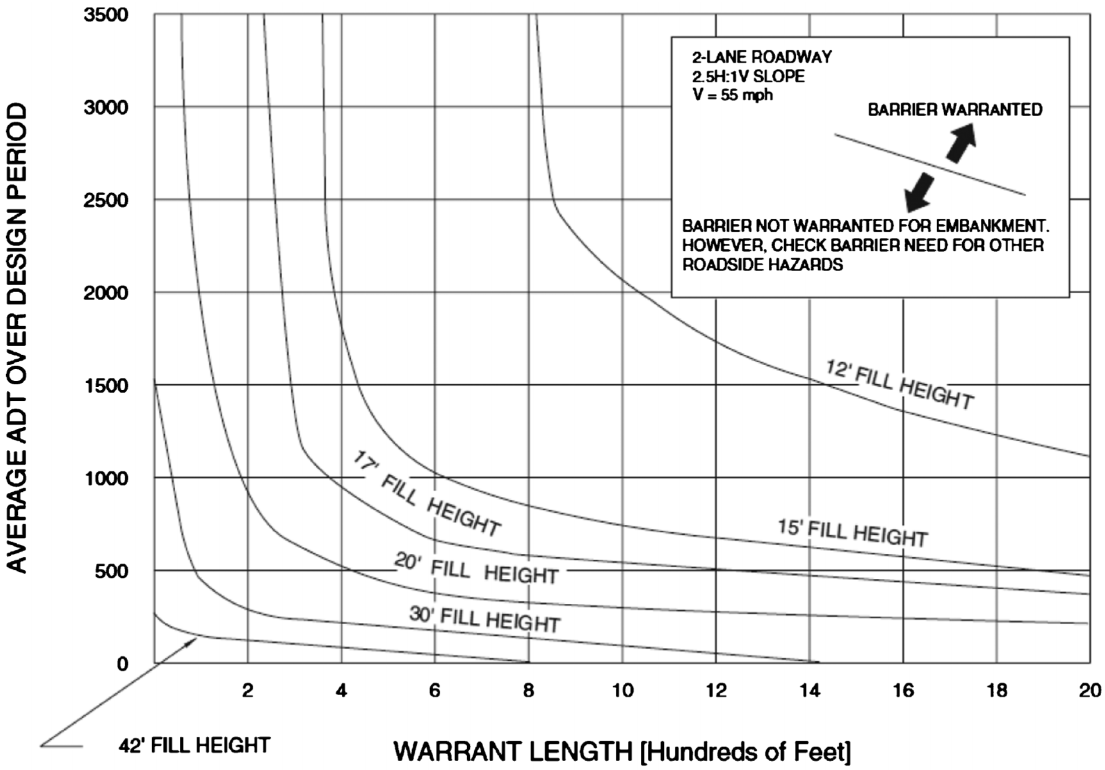


Figure 3.9 Cost effective warrants for embankments *(1)*.

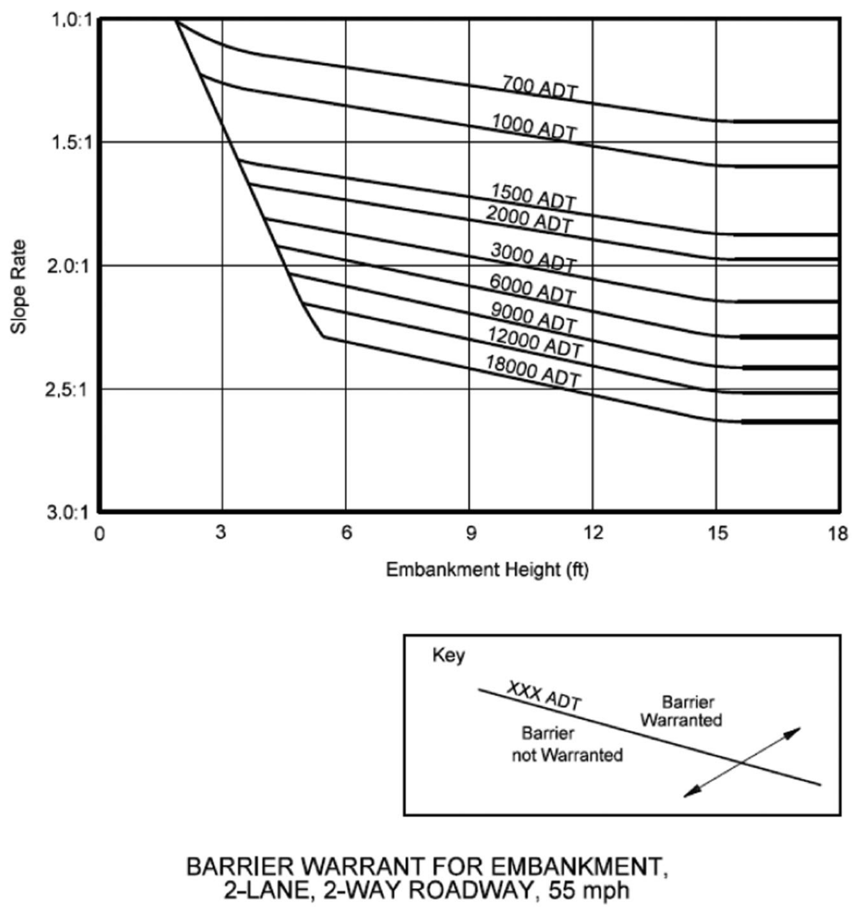


Figure 3.10 Barrier warrant for embankment at 55 mph *(2)*.

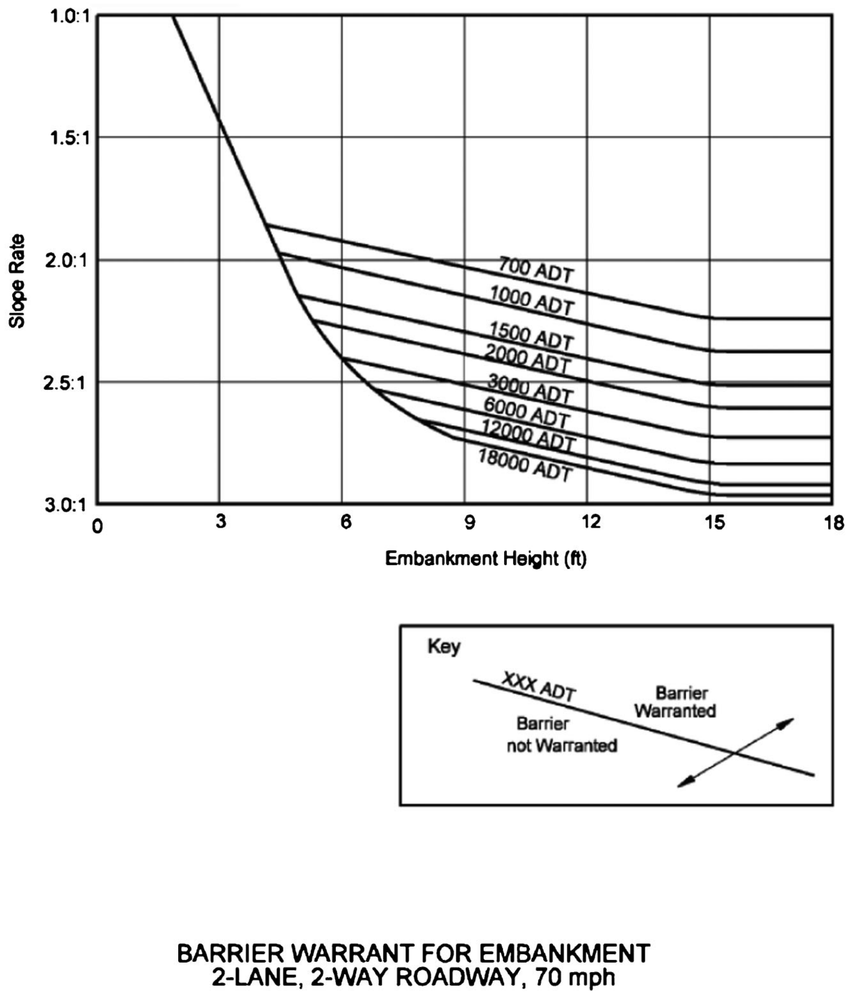


Figure 3.11 Barrier warrant for embankment at 70 mph *(2)*.

crashes occur when median widths are greater than 30 feet.

The installation of median barriers is associated with some disadvantages, such as high initial costs, reduction in the recovery area, and increased costs and exposure of maintenance. Despite these disadvantages, median barriers are shown to significantly reduce the occurrence and severity of cross-median crashes. The RDG recommends the use of median barriers for high-speed, fully controlled access highways with medians less than 30 feet and traffic volumes greater than 20,000 vehicles per day (vpd). Engineering investigations are suggested before deciding upon the use of median barriers when the median is greater than 30 feet but less

Design Speed		Shy Line Offset, L_S	
km/h	[mph]	m	[ft]
130	[80]	3.7	[12.1]
120	[75]	3.2	[10.5]
110	[70]	2.8	[9.2]
100	[60]	2.4	[7.9]
90	[55]	2.2	[7.2]
80	[50]	2.0	[6.6]
70	[45]	1.7	[5.6]
60	[40]	1.4	[4.6]
50	[30]	1.1	[3.6]

Figure 3.12 Shy line values in Roadside Design Guide *(1)*.

BARRIER SYSTEM (with AASHTO-AGC-ARTBA designation)	TEST LEVEL
FLEXIBLE SYSTEMS	
• 3-Strand Cable (Weak Post) (SGR01a & b)	TL-3
• W-Beam (Weak Post) (SGR02)	TL-2
• Modified W-Beam (Weak Post) (SGR02)	TL-3
• Ironwood Aesthetic Barrier	TL-3
SEMI-RIGID SYSTEMS	
• Box Beam (Weak Post) (SGR03)	TL-3
• Blocked-out W-Beam (Strong Post)	
-Steel or Wood Post with Wood or Plastic Block (SGR04a & b)	TL-3
-Steel Post with Steel Block (SGR04a)	TL-2
• Blocked-out Thrie-Beam (Strong Post)	
-Wood or Steel Post with Wood or Plastic Block (SGR09a & c)	TL-3
• Modified Thrie-Beam (Strong Post) (SGR09b)	TL-4
• Merritt Parkway Aesthetic Guardrail	TL-3
• Steel-Backed Timber Guardrail	TL-3
RIGID SYSTEMS (CONCRETE & MASONRY):	
• New Jersey Concrete Safety Shape	
-810 mm [32 in.] tall (SGM11a)	TL-4
-1070 mm [42 in.] tall (SGM11b)	TL-5
• F-Shape Barrier	
-810 mm [32 in.] (SGM10a)	TL-4
-1070 mm [42 in.] (SGM10b)	TL-5
• Vertical Concrete Barrier	
-810 mm [32 in.]	TL-4
-1070 mm [42 in.]	TL-5
• Single Slope Barrier	
-810 mm [32 in.]	TL-4
-1070 mm [42 in.]	TL-5
• Ontario Tall Wall Median Barrier (SGM12)	TL-5
• Stone Masonry Wall/Precast Masonry Wall	TL-3

Figure 3.13 Roadside barrier types and test levels *(1)*.

than 50 feet and has a daily traffic volume greater than 20,000 vpd. It should be noted that each transportation agency has the flexibility to create its own set of guidelines in regard to median barrier usage.

This section will discuss placement and barrier type selection as suggested by the RDG. A previous study by Tarko et al. *(14)* was conducted on median barriers quite extensively. The material in this section will supplement that research.

3.3.2.1 Median barrier placement.

A major factor when considering the use of a median barrier is to also consider the effect of the terrain between the edge of the traveled way and the vehicle trajectory. Ideally, the median area is designed to be relatively flat (1V:10H) and free of objects, in which case the median barrier can be centered in the median area. It is also desirable to use the same median barrier type throughout the entire length needed. Three median types that may warrant a barrier are discussed in the RDG: depressed medians (Section I), stepped medians (Section II), and raised medians (Section III). These median types, along with the barrier placement recommendations can be seen in Figure 3.14 and are described thereafter.

Depressed Medians

In the case of a depressed median, the area should first be checked to determine if a roadside barrier is warranted (see Section 3.1.3). It is recommended that the median barrier be placed on the side with the steeper slope if shielding is not required.

Stepped Medians

Stepped medians, or medians where the terrain makes a significant elevation change, require a median barrier when the embankment is steeper than 1V:10H. If the embankment contains obstacles or rough terrain, a median barrier should be placed on both sides of the embankment. In instances where the cross-slope of the embankment is 1V:10H or flatter, the median barrier can be placed in the middle of the median width.

Raised Medians

In the case of raised medians, a median barrier may not be warranted. The design of the cross section itself, in many cases, is sufficient enough to redirect errant vehicles.

3.3.2.2 Median barrier selection.

Similar to roadside barriers, the same factors apply when determining the best median barrier type for a

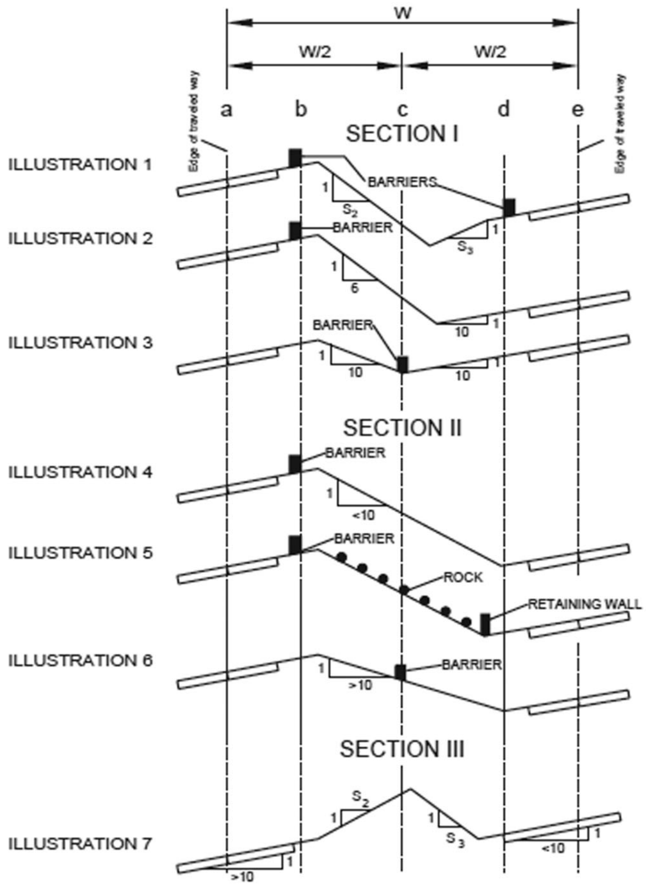


Figure 3.14 Median cross-sections and barrier locations *(1)*.

BOX 1

Type of Median Barrier	Test Level
Weak-post, W-beam guardrail	TL-3
3-strand cable, weak post	TL-3
High-tension cable barrier	TL-3
Box-beam barrier	TL-3
Blocked-out W-beam (strong post)	
•Steel or wood post with wood or plastic block	TL-3
•Steel post with steel block	TL-2
Blocked-out thrie-beam (strong post)	
•Wood or steel post with wood or plastic block	TL-3
Modified thrie beam	TL-4
Concrete barrier	
•Vertical wall	
■32 inches tall	TL-4
■42 inches tall	TL-5
•New Jersey shape	
■32 inches tall	TL-4
■42 inches tall	TL-5
•Single slope	
■32 inches tall	TL-4
■42 inches tall	TL-5
•F shape	
■32 inches tall	TL-4
■42 inches tall	TL-5
Quick-change moveable barrier	TL-3

site: barrier performance, deflection, site conditions, cost, maintenance, and others. The performance of median barriers should be thoroughly confirmed by full-scale crash testing. These crash tests are discussed in detail in the Recommended Procedures for the Safety Performance of Evaluation of Highway Features *(13)*. All of the barriers discussed in this section have been considered acceptable at various TLs by these guidelines. Specific median barriers discussed in the RDG (along with their corresponding TLs) are listed in Box 1.

It is also noted that many versions of the high-tension cable barrier qualified at the TL-4 category. The median barrier types that will be focused on in this section include high-tension cable barriers and concrete median barriers.

High-Tension Cable Barriers

The use of high-tension cable barriers is becoming a popular choice among agencies. When compared to the three-strand cable, the deflection of this cable barrier is reduced and less damage is incurred by the barrier itself when impacted by a vehicle. The high-tension cable barriers have shown to be the best performing barrier when installed on 1V:6H slope and a vehicle travels downhill before impact. In some cases of this installment, some vehicle types may under-ride the barrier. Through testing and software modeling, it was discovered that if the distance from the ditch line was increased, the chances of a vehicle under-riding the cable decreased and the maximum level of redirection was achieved. Many versions of these high-tension cable barriers are presented in the RDG, and modifications to those presented have passed the NCHRP TL-4 crash testing.

Concrete Median Barriers

Concrete median barriers are the most commonly used median barriers today. The variations in the face of the concrete barrier have a significant impact on the effectiveness of the barrier itself. Different footing details and reinforcing options have cause few problems among designs. The TL categories for each concrete barrier were previously listed in this section. Following are further descriptions of concrete barriers.

The New Jersey shape and F-shape barriers are commonly referred to as “safety shapes.” They are designed to minimize the damage to vehicles and reduce the impacts suffered by drivers. Similarly, regarding the roadside barriers, the F-shape has provided better results in terms of performance when compared to the New Jersey shape. Caution should be taken in the design of the height of these barriers to avoid over-turning events for large vehicles and enhance the safety of passenger cars that may become airborne during high-angle and high-speed impacts.

Single slope median barriers provide the advantage of remaining effective even when adjacent pavement is overlaid several times. In this instance, the height of the slope barrier can be reduced while retaining the effective TL.

Vertical concrete barriers help to preserve the available median shoulder width at narrow locations. These median barrier types are the most superior in reducing the rollover potential; however, the vehicle damage when a collision occurs is more extensive.

In A Guide for Addressing ROR Crashes, there is no designated section discussing longitudinal barriers. The safety effectiveness of barriers is included in the roadside elements section in the HSM, and is included in Section 3.2.4 in this report.

In summary of what has been learned regarding the barriers, three questions need to be addressed: are barriers needed, what type of barriers should be used, and where should the barrier be placed. For the first question, the warrant regarding the use of barriers was developed decades ago. This warrant serves as a standard to guide the implementation. As for the second question, NCHRP-350 provides the guidelines for which test level should be used for certain situations. While new types of barriers have emerged, engineers should use their judgment to select the proper type of barrier based on the traffic mix and roadside environment, along with other factors. For the placement of barriers, basic principles regarding the terrain type are available for median barriers. However, no specific guidelines exist for offsetting barriers from the traveled lanes. This topic will be discussed through state of the art research papers in the next chapter.

3.4 Roadway Design Guidelines in Europe

Design guidelines from some European countries were studies as part of this research project. The best available source found was the *Richtlinien für die Anlagen von Autobahnen (RAA) (15,16)*, which is the design guidelines used in Germany. Also found were the Spanish guidelines, *Mejora De La Seguridad Vial A Través Del Diseño De La Carretera (17)*, which include strategies to improve roadside safety. Finally, the guidelines from France, *Traitement des obstacles latéraux sur les routes principales hors agglomération guide technique (18)*, are also presented in this section.

3.4.1 German Guidelines

In this section, the German guidelines (RAA) *(15,16)* will be introduced and compared to the U.S. guidelines.

The German guidelines state that there are several criteria to consider for roadside design, such as:

- Traffic safety
- Quality/efficiency of traffic
- Land development, topography, natural environment, etc.
- Costs

The decision-making process in highway cross-section design needs to consider all of these elements, and, in many cases, compromises must be made. Even though safety is listed first, it is not the sole consideration in designing a highway cross-section.

For the scope of our study, the RAA section which specifically deals with roadside safety will be examined, which covers the following elements: obstacles alongside the road, the distance of obstacles from the edge of the road, and the quality of roadside safety elements (barriers), etc. The clear zone concept does not appear to be used in Germany, and no specific requirements were found for lateral offset of obstacles. One potential explanation for this could be that most of the freeways in Germany are guarded with barriers, and the main concern in the RAA thus is the specifications of the barriers. Typical cross-section designs can be seen in Figure 3.15. The RAA also suggests specific cross section types (RQ43.5, RQ36, and RQ31) for certain Average Daily Traffic (ADT) ranges. These recommendations can be found in Figure 3.16. The cross-section design that is recommended for expressways can be found in Figure 3.17.

Design Class 1 (EKA1) of national highways forms the primary network of freeways in Germany, which is equivalent to the interstate highway system in the U.S. The expressways are similar to freeways, with lower design standards, which could be comparable to major arterials in the U.S. Thus, these two roadways fall into the scope of the current study. Roadside hazards are not discussed in the RAA due to the extensive use of barriers. Specific design guidelines are provided for where and what type of barriers should be used to properly balance the risk of the hazard incurred by the use of barrier.

A new German methodology *(16)* is available for assessing the impact of both existing and planned traffic safety treatment on crashes and their costs. Due to the scope of the current study, only the relevant components are included here. The freeways are divided into the following components: sections between interchanges, collector-distributor roadways, interchange connectors, and sections of access roads directly connected with motorways.

The Crash Cost Rate (CCR) is used as the as the criterion for the safety performance of each road component, which is expressed in Euros per 1,000 vehicles per kilometer (euro/1,000 veh/km). The CCR for a road component is calculated with the following equation:

$$CCR = BCCR + \sum_j \Delta CCR_{L,j} + \sum_j \frac{n \cdot \Delta CCR_{p,j}}{L}$$

(euro/1000veh/km)

where:

$\Delta CCR_{L,j}$ = crash cost rate adjustment for *j* type design exception from the baseline cross-section,

$\Delta CCR_{p,j}$ = crash cost rate adjustment for *j* type point exception from the optimal conditions,

n = number of design exceptions the same along the analyzed road component,

L = length of the road component (in kilometers).

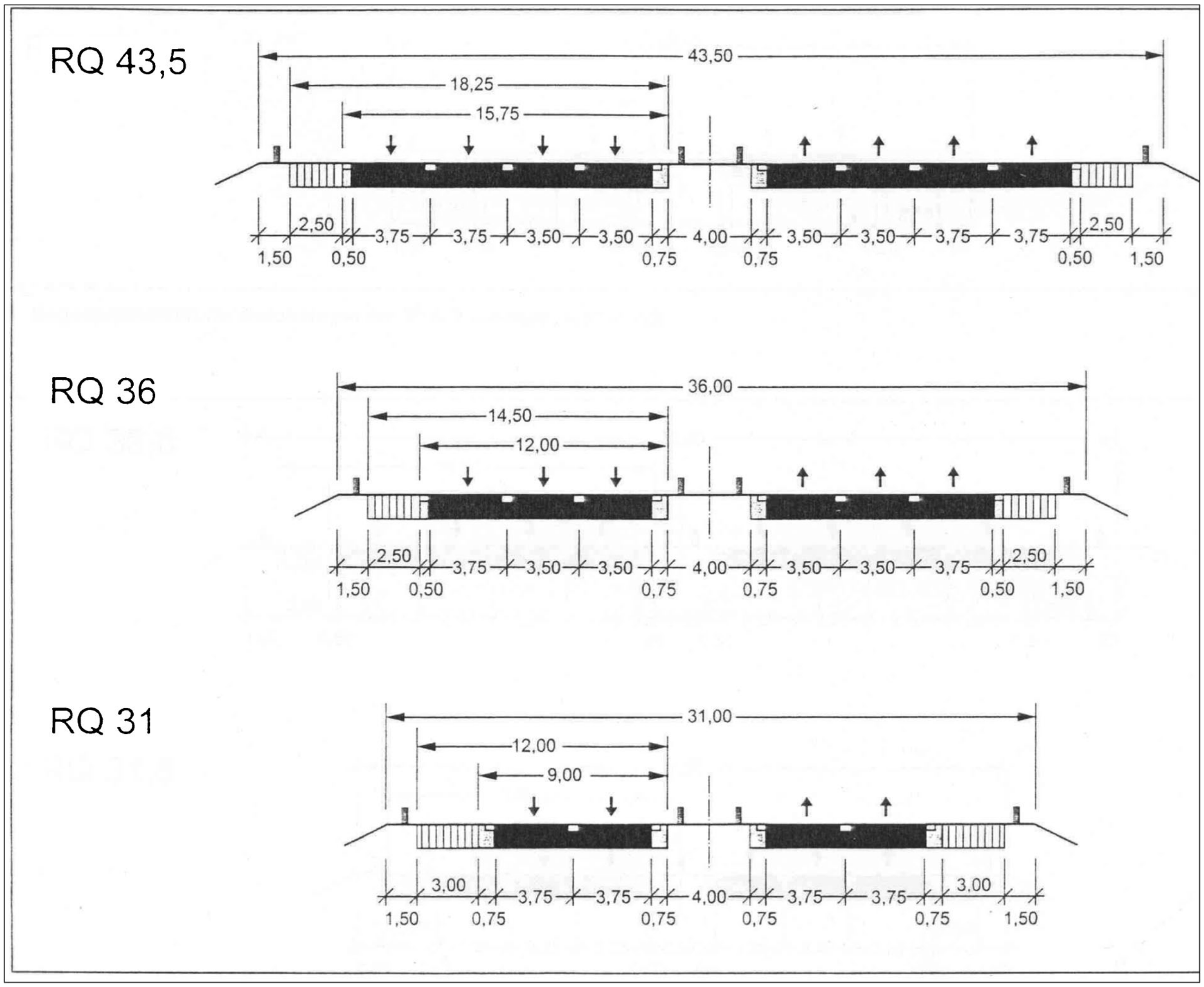


Figure 3.15 Typical cross-sections for national highways (in meters) *(15)*.

Assuming an optimal design with no significant flaws or compromises, a baseline CCR can be calculated for each typical cross section design, as shown in Table 3.13. The ΔCCR that accounts for various design exceptions from the baseline design is calculated for each scenario, shown in Table 3.14 and Table 3.15.

Unlike the CMFs used in the U.S., which are multiplicative, the CCR used in Germany is additive, which means that all of the effects of individual ΔCCRs

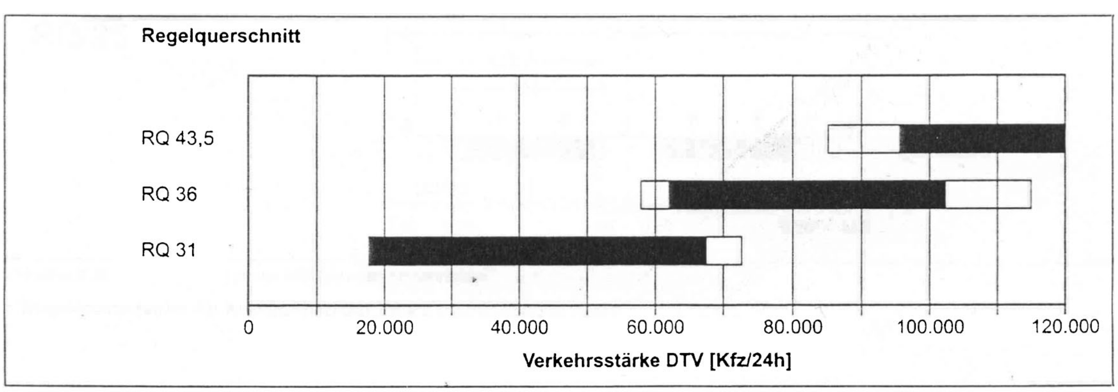


Figure 3.16 Guidelines for selection of cross-sections based on ADT *(15)*.

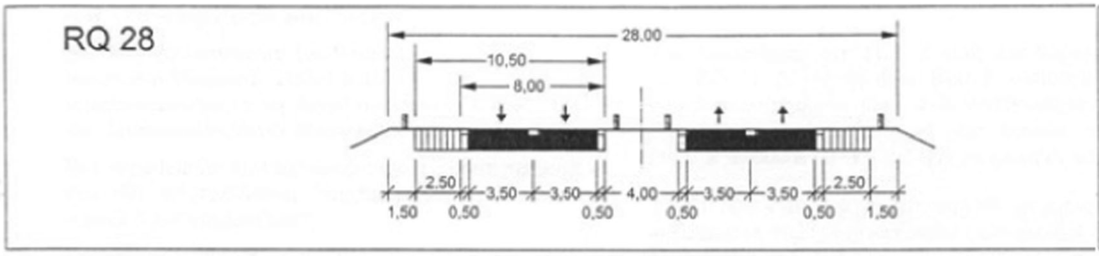


Bild 5: Regelquerschnitt für Autobahnen der EKA 2 (Abmessungen in [m])

Figure 3.17 Cross-section recommended for expressways (EKA2) *(15)*.

TABLE 3.13
Calculated Base Crash Cost Rates

Cross-Section	Number of Traffic Lanes	Design Speed	Base CCR [Euro/1000 veh/km]
RQ36–12-meter 3-lane traveled way per direction, 4-meter shoulder lane (2.5-meter emergency width plus 1.5-meter usable width), 4-meter median with barrier	6	None 120 km/h	17 14
RQ31.5 - 11-meter 3-lane traveled way per direction, 3.5-meter shoulder lane (2-meter emergency width plus 1.5-meter usable width), 2.5-meter median with barrier	6	100 km/h 80 km/h	17 15
RQ31 - 9-meter 2-lane traveled way per direction, 4.5-meter shoulder lane (3-meter emergency width plus 1.5-meter usable width), 4-meter median with barrier	4	None 120 km/h	16 13
RQ28 - 8-meter 2-lane traveled way per direction, 4-meter shoulder lane (2.5-meter emergency width plus 1.5-meter usable width), 4-meter median with barrier	4	120 km/h 100 km/h	15 13
RQ25–7.75-meter 2-lane traveled way per direction, 3.5-meter shoulder lane (2-meter emergency width plus 1.5-meter usable width), 2.5-meter median with barrier	4	100 km/h 80 km/h	16 14

TABLE 3.14
ΔCCR Adjustments for Exceptions from the Baseline Cross-Sections

Design Exception	Cross-section Type				
	RQ36	RQ31.5	RQ31	RQ28	RQ25
Traveled way width 11.50 ≤ B < 12.00	2				
Traveled way width B < 11.50	5				
Traveled way width 10.50 ≤ B < 11.00		2			
Traveled way width B < 10.50		5			
Traveled way width 8.00 ≤ B < 9.00			2		
Traveled way width B < 8.00			5	5	
Traveled way width 7.50 ≤ B < 8.00				2	
Traveled way width 7.25 ≤ B < 7.75					2
Traveled way width B < 7.25					5
Emergency width B < 3.00			2		
Emergency width 2.00 ≤ B < 2.50			2	2	
Emergency width B < 2.00	6	6	6	6	6
No emergency width	8	8	8	8	8
Unpaved shoulder	2	2	2	2	2
Longitudinal roadside hazard—no barrier	10	10	10	10	10
Longitudinal roadside hazard—barrier installed	2	2	2	2	2

TABLE 3.15
ΔCCR Adjustments for Alignment and Point Hazard Design Exceptions

Design Exceptions	Cross-section type				
	RQ36	RQ31,5	RQ31	RQ28	RQ25
Stop sign distance shorter than minimum	6	6	6	6	6
Cross-slope smaller than 2.5%	1	1	1	1	1
Super-elevation on horizontal curve smaller than required	2	2	2	2	2
Total slope on a curve higher than 9%	1	1	1	1	1
Insufficient pavement drainage	6	6	6	6	6
Point roadside hazard—no barrier	3	3	3	3	3
Point roadside hazard—barrier installed	1	1	1	1	1

are totaled and the interactions between different components are not considered. Table 3.14 and Table 3.15 provide insight into the magnitude of the effects experienced by different design exceptions. In Table 3.14, the effects of traveled way width, shoulder width, and longitudinal hazards are uniform values across all levels of highways. In Table 3.15, the effect of point hazards are directly comparable. Short sight distance and insufficient drainage are the most hazardous point elements, followed by unshielded point roadside hazard, improper super elevation, inadequate cross slope, steep slope, and barrier-shielded point roadside hazard. The CMFs provided in the HSM have much more detailed categories than the CCR in the RAA. However, due to the great differences between the driving environment and roadway engineering in Germany and the U.S., the RAA provides a different perspective on the effectiveness of these elements.

In summary, the German design guide does not directly deal with clear zone design or roadside hazards. These issues are dealt with indirectly by providing guidance for cross-section design, which in most cases includes roadside barriers. The safety effect of different inadequate designs and hazards is evaluated by the CCR. As previously mentioned, the CCR should not be directly compared to the CMF, which will be further addressed.

Another issue in making inferences from the German design guidelines is that the U.S. highways are typically designed with a much greater available median and clear zone width. Even in our application, in which a four-lane divided freeway is to be expanded to a six-lane divided freeway with the median and clear zone width to be reduced to provide ROW, the resulting median and clear zone width will still be more liberal than the German designs. An effort was made to match equivalent designs between U.S. highways and German highways, as shown in Table 3.16.

In order to compare the effect of an individual element directly to the CMF in the HSM, the Crash Cost Modification Factor (CCMF) can be calculated with the following equation:

$$CCMF = (BCCR + \Delta DCCR)/BCCR$$

where:

CCMF = crash cost modification factor for narrow clear zones,

BCCR = base crash cost rate (euro/1000 veh/km),

ΔCCR = crash cost rate adjustment for narrow clear zones and other exceptions as applicable.

With the equivalency table and the CCMF, inferences from the German design guide can be made for U.S. situations. CCMF is calculated for each design alternative in cases of constrained ROW, using the

TABLE 3.16
Equivalency of German and U.S. Freeway Cross-Sections

U.S.					Germany			
Design Speed(mph)	Number of Lanes	Traveled Way (ft)	Median (ft)	Clear Zone	Cross section	Design Speed (km/h)	Design Exception 1	Design Exception 2
70	6	36	15	Normative	RQ36	120	Traveled way <11.5 m	None
70	6	36	15	Narrow w/o barrier	RQ36	120	Traveled way <11.5 m	Roadside hazard without barrier
70	6	36	15	Narrow with barrier	RQ36	120	Traveled way <11.5 m	Roadside hazard with barrier
50	6	36	10	Normative	RQ36	80	Traveled way <11.5 m	None
50	6	36	10	Narrow w/o barrier	RQ36	80	Traveled way <11.5 m	Roadside hazard without barrier
50	6	36	10	Narrow with barrier	RQ36	80	Traveled way <11.5 m	Roadside hazard with barrier

TABLE 3.17
Estimation of Crash Cost Modification Factors for the Three Clear Zone Alternatives

Design Speed (mph)	Number of Lanes	Traveled Way (ft)	Median (ft)	Clear Zone Alternative	BCCR (euro/1000 veh/km	ΔCCR_1 (euro/1000 veh/km	ΔCCR_2 (euro/1000 veh/km	CCMF
70	6	36	15	Normative	14	5	—	1.0
70	6	36	15	Narrow w/o barrier	14	5	10	1.5
70	6	36	15	Narrow with barrier	14	5	2	1.1
50	6	36	10	Normative	15	5	—	1.0
50	6	36	10	Narrow w/o barrier	15	5	10	2.0
50	6	36	10	Narrow with barrier	15	5	2	1.1

Source: *(15)*.

CCR from German design guide, and can be used as CMFs for U.S. applications. The CCMF estimation is shown in Table 3.17.

As the CCMFs in Table 3.17 suggest, narrow clear zones with barriers will cause a 10% increase in total crash cost, while narrow clear zones without barriers will cause a 50% increase and 100% increase for 70 mph freeways and 50 mph highways, respectively.

The findings and conclusions from the German RAA are basically in line with those from the AASHTO HSM. However, since the cross section design in Germany is so different (mostly restricted) from that in the U.S., no direct comparison should be made. Nonetheless, the findings from the German RAA confirmed what was learned from the U.S. standards and provided a reference for narrow ROW situations.

3.4.2 Spanish Guidelines

This section is included to present a document developed by Spanish researchers aiming to improve roadside safety, as part of the "Strategic Infrastructure and Transport" effort. This document is called "Mejora de la Seguridad Vial a Través del Diseño de la Carretera" and the development of this document was led by Fundación Agustín de Betancourt, highlighting the activity of its participants Hiasa, Dragados, and the Foundation itself, Grusamar Agustín de Betancourt *(17)*.

The overall objective of this document is to define a methodology for identifying the best strategy for safety improvement based on the geometric and topographical conditions of the road. It established a set of technical standards and state of the art recommendations for roadside safety and roadway departure crashes, both nationally and internationally. The activities of this work include:

- Review existing regulations related to roadside design.
- Review experimental studies on accidents off the road.
- Review treatments actions taken on the infrastructures.
- In 1998, 33.8% of the fatalities in the European Union were the result of single vehicle collisions (Eurostat).

  Accident data collected in the project RISER (Roadside Infrastructure for Safer European Roads) indicate that roadway departure crashes account for approximately 10% of the total traffic crashes in their respective countries. Over 45% of the fatalities occur off the road. In Finland, collisions with roadside objects account for 24% of all fatal crashes, where they were frequently impacting with trees and utility poles. In France, collisions with elements of the roadway account for 31% of all fatal accidents, the most frequently hit objects are trees. In Germany, 18% of all injuries and 42% of all fatalities again involve trees. In the U.K., 18% of all fatal crashes are collisions with trees and lighting poles. In Holland, roadway departure crashes account for 22% of all fatal crashes. In Sweden, 25% of all fatalities are collisions with trees, fences, and utility poles.

In summary, in 2003 more than 20% of motor vehicle fatalities result from vehicles leaving the roadway and hitting a fixed object. These crashes occur in both urban and rural areas, but are most common on rural roads. Also, about 20% of crashes involving fixed objects also are rollovers, which imply the vehicles broke through the containments (safety devices or others). Trees are the most commonly hit objects representing about half of all number of deaths (4,522 fatalities in 2003). Such high percentages of crash involvement cannot be ignored when developing road safety projects. Design considerations must be given to better shielding drivers from trees at hazardous locations.

The RISER statistical database holds almost 265,000 vehicle accidents alone in seven European countries (Austria, Finland, France, Holland, Spain, Sweden, and the UK). In 67% of these cases, the vehicle struck a fixed object. Table 3.18 shows the percentage of cases where it was reported that an object was hit in the accident.

Safety barriers seem to be the object most often hit in crashes. However, this does not necessarily mean that the barriers are more dangerous than other objects at the roadside. This is simply because the impact with safety barrier is expected to be less severe than with other fixed objects, thus the barriers were more likely to be placed in those highly dangerous locations. The level of exposure (i.e., the number of these objects located on

TABLE 3.18
Summary Crash Statistics in Europe

		% of Each Object Hit		
Object Beaten	**% of All Crashes**	**Fatal**	**Serious**	**Slight**
Tree	11.1	17	39	44
Post	8.2	9	31	61
Safety barrier	15.5	6	20	74
Ditch	10.6	8	32	60
Other natural objects	0.9	7	32	61
Other structures	8	11	33	56
Other 12.5	—	—	—	—
Not known	33.2	—	—	—

Source: *(17)*.

the edge of the road and the opportunity of impact) is not considered. Of the objects most frequently impacted, trees and ditches accounted for more than 10% of all accidents, and posts accounted for more than 8%.

When considering the severity of the accident, the results show that natural objects (trees and others) were hit more than other objects in fatal accidents (25% of all fatal accidents). In addition, for crashes with an isolated tree, 17% resulted in fatalities, which is a greater proportion than any other type of object (see Table 3.13). Almost 75% of accidents involving safety barriers reported only minor injuries, which shows that, although safety barriers were impacted more frequently than other objects in single vehicle crashes, the severity was much lower.

Roadside design may affect both the number of accidents and the severity of injuries. On one hand, steep slopes increase the likelihood of rollover (instability of the vehicle). On the other hand, fixed obstacles located near the road can increase the number of accidents while reducing the margin to regain control of the vehicle when run off road. Therefore, the distance between obstacles and the roadway influences the likelihood of a collision with obstacles, especially if they are located on the outside of curves or traffic islands.

A review and discussion of the safety effects of a variety of roadside elements was also included in the Spanish guidelines. The hazards are categorized as such (RISER project):

- Specific hazards (point hazards): trees, various types of poles, piers and abutments of bridges, culverts, underpasses, boulders, terminals of some barriers;
- Hazards distributed (longitudinal hazards): ditches, slopes, earthworks (embankments), clearing rock (rock face cuttings), fences , walls, and forests;
- Containment Systems: outdated barriers, barriers installed incorrectly, short distances between two facilities; and
- Additional risk factors: presence of water bodies (lakes, canals, rivers), railways, and other roads.

A detailed discussion of each type hazard is provided below:

Point Hazards

- Trees—they are dangerous when:
  - Their diameter is greater than 10 cm.
- Bridge piers, bridge abutments, and tunnel mouths—they are dangerous when:
  - Piers are located in the median unprotected.
  - The pier diameter exceeds 1 m.
  - The approach to the road is not progressive (abutments and tunnels).
- Parapets of bridges—they are dangerous when:
  - Height is less than 1.1 m in the case of steel barriers or 0.80 m in the case of concrete barriers.
  - The upper profile is not ready to absorb impact.

Longitudinal Hazards

- Ditches—they are dangerous when:
  - Their depth is greater than 0.5–1 m.
  - Their slopes are greater than 1:4.
- Cut slopes—they are dangerous when:
  - Their slopes are greater than 1:3.
  - Their heights are greater than 0.5 m.
  - There are any obstacles existing in the clear zone.
  - They are less than 4.5 m from the edge of the lane.
- Fill slopes—they are dangerous when:
  - Height is greater than 2–4 m.
  - Their slope is greater than 1:3.
  - There is a deep ditch at the foot of the landfill.
  - They are less than 4.5 m from the edge of the lane.
- Rock cut—they are dangerous when:
  - Their slope is greater than 1:2.
  - Their height is less than 1.5 m above the rail.
  - There is a ditch at the foot of the slope.
  - They are less than 4.5 m from the edge of the lane.

Containment Systems and Medium-Sized Banks

- Containment systems and medium-sized banks—they are dangerous when:
  - They are flexible metal barriers with concrete posts.
  - There are barriers with flexible metal poles.
  - The wooden barriers are not suitable for high speeds (>90 km/h).
  - There are still U-160 poles causing heavy damage when struck.
  - The joints are not rigid because the screws have been loosened over time.
  - Barriers bridges do not have expansion.
  - The screws are tightened too much and the barriers are not deformed as they should.
  - There are no skirts for motorcycles in curves.

The clear zone concept was mentioned in the Spanish guidelines also by way of a summary of the differences of the clear zone for major European counties, which is shown below:

- In Finland, there are three different clear zone standards for cut or fill cross section, with the values ranging from 2 to 9 m according to increasing the speed and average daily traffic.
- In Britain, 4.5 m is required in new and existing roads, but the signs and structures are often placed within the clear zones. Clear zone should be up to 4.8 m in rural roads and up to 3.5 m for urban roads.
- In France, the clear zone expands in proportion to the design speeds under normal conditions. The recommendations are less stringent for existing roads where the available ROW is limited by site specific conditions.
- The German guideline is not included here; please refer to the previous section.
- In the Netherlands, a clear zone of 13 m should be used on new highways with speed of 120 km/h and 10 m wide (or greater) on existing highways or on new highways with speeds of 100 km/h. A clear zone should be 10 m (recommended) or at least 8 m (minimum) on highway with design speed 90 km/h, and 6 m (recommended) or at least 4.5 m (minimum) on roads with design speed 80 km/h.
- In Spain, the width of the clear zone depends on the cross slope on the shoulder and the radius of the horizontal curve. Values up to 16 m are provided for undivided roadways and up to 14 m for divided roadways.
- Sweden has defined a clear zone wider than 10 m as a good standard.

3.4.3 French Strategies

The objective of this section is to show the French strategies to minimize the consequences of roadway departure crashes, through the realization of an area called "recovery area". This "recovery area" is again the French equivalent of the clear zone in the U.S., and this guide provides knowledge and expertise about clear zone from France. This guide is mainly concerned with main roads outside urban areas, but could also be applied to urban motorways. Also, this guide was developed for the improvement of existing roads, but can also provide insights for new infrastructures.

This guide first reviewed the current level of knowledge and practice in roadside safety. Then general guidelines conclusions were presented.

Hit-fixed-object single vehicle crashes are the number three reason for fatalities in the open field, and account for more than 1,800 fatalities each year (geographical region not specified). Moreover, there are another 300 fatalities per year due to multiple vehicle crashes that also involved hitting roadside obstacles. Thus, this issue has caught great attention for all stakeholders.

There are a wide variety of roadside obstacles that constitute potential hazards to errant vehicles. Among all the roadside obstacles, trees are the number one hazard, accounting for 37% of the total fatalities; masonry ranks second, with 12% of the fatality involvement; and utility poles and telephone boxes account for another 10%. Longitudinal roadside features are another major hazard, with ditches, slopes and rock faces together constitute 28% of the fatalities. The offset of the hazard from the traveled way was also found to be significant with 43% of the fatalities involved a hazard within 2 meters from the traveled way, and 78% within 4 meters. This is a clear indication that a greater offset is essential to reduce fatal hit-fixed-object crashes.

Roadway design can also contribute to high fatality rates. Crash statistics show that more than half of the hit-fixed-object crashes occur on a curve. Though the outside of the curve is believed to have a greater danger of crash, the inside of the road is believed to deserve similar treatment when obvious hazard exists.

This guideline also provides a discussion about different types of collisions. For a frontal collision, the vehicle is stopped by the obstacle in a very short distance, with the front part (engine bay) of the vehicle absorbing some of the kinetic energy of the vehicle. This guide describes such collision as two steps: vehicle collides with the obstacle, and the passenger collides with the vehicle. While safety devices like seatbelts and airbags can to some extent absorb the kinetic energy, the passengers could be ejected from the vehicle or hit other passengers or the vehicle interior. However, side impact is even more severe than frontal impact, because there is basically no structure to absorb energy on the side, and the distance between the passenger and the obstacle is much smaller as compared to frontal impacts. With the current (2002) vehicle fleet composition and seatbelt use, it is concluded that a frontal impact of 65 km/h or greater would cause fatal injuries, while for side impacts, fatalities would be expected at a speed as low as 35 km/h.

These guidelines then provide a discussion of using safety barriers to isolate the trees. It is stated that trees do not require a treatment unless the site is diagnosed to have significant risk. It suggests that a safety barrier is the only way to isolate trees from the traveled way; and when barriers are used, a clear zone of at least 2 meters should be provided. Also, "shelters" (full width shoulders for stopped vehicle) should be provided when barriers are in use, and the frequency of shelters should depend on the traffic volume.

Other than the use of safety barriers, a series of "accompanying measures" are suggested in this guideline, when the trees are located very close to the traveled way:

- Reduce speed limit when permitted
- Narrow the roadway and reduce the speed limit (when the lower speed limit is not justified)
- Improve pavement markings
- Make frequent improvement to the state of the road (adhesion, roughness, slope)
- Eliminate the drops between the traveled way and the shoulder
- Develop breakpoints/shelters in the presence of long alignments, or remove trees

Manmade obstacles are also discussed in this guideline. The major manmade obstacles along the roadways are power grids and utility poles. The treatment is generally consistent with that of the trees. However, since more and more utility lines now are buried, the treatment is simpler than that of trees.

In the end, the guideline provides guidance on selection of safety barriers. The categorization is by material types (wooden, metallic, and concrete), which contradicts to the U.S. practice of selection by rigidity type (rigid, semi-rigid, and flexible).

4. RESEARCH ON ROADWAY DEPARTURE CRASHES

In the previous chapter, the official guidelines in the U.S. and other countries were discussed to learn the current state of the practice related to roadway departure crashes. Therefore, in this chapter, state-of-the-art research studies will be identified and presented to help better understand roadway departure crashes and identify potential countermeasures. The research papers were first grouped by country of origin. Those research papers from the U.S. are first presented to understand the current level of knowledge in the U.S., followed by research from countries to gain a broader perspective on this topic.

Also, not all topics relating to roadside safety are included in this report. In the current study, the overall objective is to study the effect of reducing ROW and to introduce barriers at the corridor level. Therefore, manmade roadside fixed objects, other than longitudinal barriers, are not within the scope of this study. An abundant amount of research was found that falls directly under our scope of work, and the U.S. research studies are divided into three types for organization. The first section includes studies related to median/clear zone design and width, the second section includes studies related to roadside features, and the third section includes studies related to the effect of barriers on roadway departure crashes.

4.1 Studies on Median/Clear Zone Design

Knuiman et al. *(19)* conducted an analysis for two-way, four-lane, major highways with speed limits of at least 35 miles per hour (mph) that had a traversable median and used data from Utah and Illinois. The authors made an effort to "re-categorize" crash types to relate the manner of crash to the potential effect of the median. Separate regression models were estimated for the crash rates of both different injury levels and different crash types. The total crash rate was found to decrease with an increasing median width for both states and all crash types. However, in Illinois, head-on crashes decreased at a much greater rate than other types of crashes. A median width beyond 30 to 54 feet was shown to have a very limited marginal benefit in Utah, while in Illinois, the limited marginal benefit median width was found to be 55–64 feet. Even though the models included variables that show up as very insignificant (with very low t-statistics), along with other issues pointed out by Miaou (Section 4.3), this study hopes to shed light on the effect of the median width on crash rate.

Davis and Pei *(20)* reconstructed the median cross crashes using Bayesian Reconstruction to discover the effects of cable barriers in reducing crash severity. Barrier locations (in the median or on the shoulder) were also studied. The following equation was used to explain the injury severity of a median cross crash:

$$IS = 1/2 \cdot M(V \cdot \sin\theta)^2,$$

where V is the impact speed, θ is the impacting angle, and M is the mass of the vehicle. This equation implies that the impact angle is as important as the impact speed. The study also concludes that roadside barriers sustained a higher impact speed with a smaller impact angle, while median barriers sustained lower impact speeds with greater impact angles. The results showed that for non-rollover crashes, barriers closer to the traveled way will result in a lower percentage of injury severity than those located farther away. For rollover crashes, there was no clear advantage shown for either roadside or median barrier placement. However, all of the impact severities did not exceed the standard for NCHRP Report 350's TL 3. The conclusions from this study provide insight on the placement of barriers, as well as the barrier types to consider for specific speeds and impact angles. However, the study did not specify the distance of the barriers from the traveled way, which may warrant future study. To study the effects of the barriers at different distances from the roadway, the PC-Crash trajectory simulation model would be helpful to obtain the speed and angle of the impacting vehicle.

Stine et al. *(21)* used a vehicle dynamic simulation software package to simulate median-related crashes. The authors studied, assuming there was no existing barrier, the effect of different vehicles, encroaching angles, speed, driver responses, and median designs. V-Shaped (VS) trapezoidal medians were studied and were shown to pose a lower risk for both rollover and cross section crashes, while steeper medians and wider medians showed more rollover crashes and less cross median crashes. The simulated data was validated with real world data, and the results make intuitive sense.

In a study conducted by Noland and Oh *(22)*, the importance of controlling for time effect and demographic changes when modeling the effectiveness of safety interventions was researched. In their effort to model the crash frequency and fatality crash frequency using aggregated and controlled county level data from Illinois, it was found that wider outside shoulders will lead to reduced crash frequency, but a positive, statistically insignificant correlation with more fatalities arises.

Hu and Donnell *(23)* studied median barrier crash severity using nested logit models. The results showed that road sections with cable barriers are more likely to have no evident median-related crashes. The interaction of cable barriers and steeper slopes were further studied. The results show a positive coefficient for more severe crashes, but the author mentions that further research is merited. Finally, the study explored the offset distance from the ditch to the barrier. The results indicate that a greater offset generally decreases the likelihood of evident severity crashes and that overturning vehicles have a much greater probability of resulting in a severe crash. This result should draw attention to the need for prevention of vehicle overturning during a roadway departure crash. Shoulder rumble strips were also found to increase the probability of more severe crashes, possibly due to their installation at hazardous locations. Further exploration of this issue is needed.

4.2 Studies Focused on Roadside Features

Lee and Mannering *(24)* used a zero-inflated negative binomial (ZINB) model and a nested logit model to model crash frequency and crash severity, using crash and roadside features data on a 60-mile long state road in Washington State. The results from the ZINB model using both estimated coefficients and elasticity show that median width has a negative effect on crash frequency, and the presence of closely located utility poles and trees could increase crash frequency. Also, a wide shoulder presence increased the chance that the road section falls in the ZERO state, meaning it falls in a binary state in the zero-negative binomial models, and assumes no crash. In the nested logit model results, road sections with asphalt shoulders, guardrails, and a shoulder greater than two meters wide were more likely to have no evident injuries, while the presence of trees led to an increase in evident injuries. It was also discovered that road sections with utility poles, sign supports, and miscellaneous fixed objects have less evident injuries, which deserves further investigation. Finally, this study showed that if a guardrail is present, the chance of having an evident injury could increase by 90 percent. This might be due to the placement of guardrails at very hazardous locations.

Yamamoto and Shankar *(25)* used bivariate ordered probit models to estimate the injury level suffered both by the driver and the most injured passenger in multi-occupant, single vehicle crashes with fixed roadside objects. The correlation parameters in the model output were 0.543 and 0.623, for urban and rural area, respectively, which shows significant correlations between the injury suffered by the drivers and the most injured passengers, and suggest that the use of bivariate ordered probit models in such applications is necessary. The results for rural areas were found to be similar to those in urban areas. Among the roadside features, guardrail ends and trees were found to increase the likelihood of more severe injuries for drivers, while posts, ditches, guardrail faces, concrete barrier faces, bridge faces, and fences were found to decrease the likelihood of more severe injuries for drivers. Trees were also found to increase the likelihood of severe injuries for passengers, while posts, bridge faces, construction machinery, and fences decreased this likelihood.

4.3 Studies Focused on Longitudinal Barriers

A study by Elvik *(26)* conducted a meta-analysis on the existing literature regarding median barriers, roadside barriers, and crash cushions. After screening for publication bias, the author used the log odds method to carry out this meta-analysis. The study concluded that guardrails and crash cushions can reduce both crash frequency and the likelihood of fatal and injury crashes, while median barriers can increase the crash frequency but reduce the likelihood of severe crashes. It was statistically shown that the 95% confidence interval of the estimate of injury accidents covers zero in the case of median barrier results. Some of these estimates were found to be very significant while others were found to be due to random variations in the data. Design specifications were not included in this study, thus no inference could be made on the clear zone width or design. Since each study in the meta-analysis was almost surely designed differently, the results and conclusions should be treated with caution, as noted by the author.

Ray, et al. *(27)* reviewed the applications and experience with cable median barriers in the U.S. Various applications, past and current guidelines, and state agency practices were reviewed and discussed, and a simple before and after study was conducted, using the raw count of cross median crashes. Very significant reductions of median cross crashes were found for most of the states in the study, the majority of the states almost entirely eliminated median cross crashes, while there were also several states that reduced such crashes by as few as only 50%. This paper provided a general review of the effectiveness of median cable barriers on targeting crash types, but it is not comprehensive in terms of other types of crashes or any type of statistical analysis.

Albin et al. *(28)* conducted an in-service evaluation of Washington State cable barriers. The authors stated that a cable median system has both lower capital costs and lower maintenance costs. Its advantages over other barriers include fast repair, relocation ability, and capability for repair each time it sustains a crash. Even though the number of crashes increased significantly with cable barriers, there was a clear decline in the number of severe crashes. Finally, the study concluded that the calculated social cost to drivers was reduced by about $420,000 per mile, annually, after installation of cable barriers.

The Washington State DOT conducted a study *(29)* focused on the placement of cable barriers. This study concluded that if only one run of cable barrier is installed, the barrier should not be placed right after a ditch on either side. This suggestion came from the observation of a large number of cross median crashes in this type of installation where vehicles (mostly sedans) crossed underneath the cable barriers.

Hunter et al. *(30)* also conducted an in-service evaluation of the North Carolina cable barriers. The study area had experienced a high fatality rate before the installation of cable barriers. More run-off-road to the left crashes were reported after the installation of cable barriers, which indicates that the reduction in median width had resulted in more crashes. However, the reduction in the targeted crash type of head-on crashes with opposing traffic was achieved.

Miaou et al. *(31)* developed guidelines for median barrier installation using Texas data. The authors used advanced statistical methods to model median-related crash frequency and severity. The authors modeled different types of median-related crashes, both with and without median barriers. The results show that medians with barriers have higher intercepts, which means a higher crash frequency can be expected for medians with barriers, with everything else being equal. The negative coefficients of median width for all models suggested that wider medians would decrease crash frequency, for medians both with and without barriers. In the severity model, median width was found to increase the likelihood of more severe crashes for median width without barriers, while it was found to decrease the likelihood for medians with barriers. The authors also provided benefit cost (B/C) ratio charts using both mean estimates and low estimates of the B/C ratio, to account for the uncertainty. The study also compared economic preferences of high-tension-cable to the concrete barriers. Their chart of mean B/C ratios showed high-tension-cable barriers were economically superior to concrete barriers. This study did not observe the placement of median types, nor did it analyze the distance from the median type to the edge of the roadway. Therefore, the effect of median width should be treated with caution.

Sicking et al. *(32)* also developed guidelines for implementation of median cable barriers. The authors examined police crash reports related to median encroachment and found that very few of these crash reports provided quality information about the extent to which the vehicle crossed the median. Using the police crash report to generate the lateral encroachment distance was impossible. The authors also found that the weather conditions were a significant factor in installing median cable barriers since winter driving conditions resulted in more crashes, but less severe or fatal crashes. The authors recommended a guideline for installation of median barriers and found many similarities to the AASHTO RDG.

A computer-aided simulation study was also conducted to study the effect of barriers. Marzougui et al. *(33)* conducted a finite element analysis, a vehicle dynamic study, and a full scale crash test to study how cable barriers perform on sloped medians. The computer simulation results were validated by the full scale crash test. It was determined that the current practice of cable barrier placement (four feet from the ditch bottom) would likely allow smaller vehicles to pass under the barriers, and placing the cables closer (one foot) to the ditch bottom would eliminate such problems.

4.4 Previous Study in State of Indiana

A study concerning the type and design of medians for rural freeways was carried out by Tarko et al. *(14)*. Models were estimated to study the safety effect of different medians, using data from nine states, including Indiana. The authors found that converting a four-lane rural interstate to a six-lane facility may require narrowing a wide (more than 50 feet) depressed median and installing median barriers. This section estimates the effect of this treatment on safety through Crash Modifications Factors (CMFs). CMFs are useful in evaluating alternative solutions. The assumption is made that clear zones retain their normative width as recommended by the design guidelines *(1)*.

Another related study by Villwock et al. *(34)* used the same data but focused on the effect of cable barriers. Cable barriers were shown to eliminate 94% of median crossing crashes, and a 70% increase in single vehicle crashes could be observed for wide medians. Also, a slight decrease in the proportion of severe crashes can be expected with the installation of cable median barriers.

The following calculations are based on the research results of the JTRP project SPR-2950 documented in a research report *(35)* and the two journal publications *(34,35)*.

The estimation of CMFs starts with calculating the frequencies of three types of crashes on a one-mile freeway segment with a depressed median wider than 50 feet and no barrier:

1. Single-vehicle crashes (SV)
2. Multiple-vehicle same-direction crashes (MVSD or shortly–SD)
3. Multiple-vehicle opposite-direction crashes (MVOD or shortly–OD)

The annual frequency of crashes of types SV, SD, and OD were calculated for the base case (depressed median wider than 50 feet without barrier) with Equation 1.

$$F_t = \exp\left(b_{K,t} + b_{Q,t}\cdot LQ + b_{S,t}\cdot S + b_{H,t}\cdot H + b_{R,t}\cdot R\right) \quad (1)$$

where F stands for the annual frequency of crashes of type t (SV, SD, or OD) along one mile, LQ is the logarithm of AADT (AADT in vehicles/day), S is the posted speed limit in mph, H is the horizontal curvature 1/radius (radius in miles) averaged along the segment, R is the frequency of ramps per mile, and $b_{.,t}$ are the corresponding coefficients. The values obtained by Villwock et al. *(35)* are shown in Table 4.1.

The annual frequency of crashes type SV, SD, and OD calculated for the base case with Equation 1 were then used to estimate the crash frequencies for two considered cases:

TABLE 4.1
Parameters b of the Annual Crash Frequency Model for the Base Case (Depressed Median Wider than 50 ft and without Barrier)

Variable Description, Symbol (Units)	SV	SD	OD
Log constant, K (-)	−2.202	−12.30	−18.99
Log of AADT, LQ (-)	0.338	1.240	1.384
Posted speed limit, S (mph)	0.0	0.0	0.0304
Average horizontal curvature, H (1/mile)	−0.0266	0.0	0.0
Frequency of ramps, R (1/mile)	0.0	0.0331	0.0

1. Medium width depressed median (between 20 feet and 50 feet) with high-tensioned cable barrier, and
2. Flushed median 30 feet wide with concrete barrier.

The CMFs derived from the before-and-after analysis described by Villwock et al. *(35)*, and then expanded and published in Tarko et al. *(14)* and Villwock et al. *(34)* were used in this calculation (Equation 2).

$$F_{A,t} = CMF_t \cdot F_B,t \tag{2}$$

where $F_{A,t}$ is the crash frequency of type t (SV, SD, or OD) for medium width depressed median with high-tension cable barrier, and flushed median with concrete barrier, $F_{B,t}$ is the crash frequency of type t for the wide depressed median with no barrier base case, and CMF_t is the crash modification factors for crash type t shown in Table 4.2.

The frequencies of crashes calculated for the three types of medians and for the three crash types SV, SD, and OD were then split into two severity levels: fatal-injury crashes (FI) and property-damage-only crashes (PDO) using the proportion of FI crashes U estimated from the following probabilistic model (Equations 3 and 4):

$$U = \frac{\exp \Sigma}{1 + \exp \Sigma} \tag{3}$$

$$\Sigma_t = b_{K,t} + b_{L,t}L + b_{Q,t}Q + b_{PH,t}PH + b_{RB,t}RB + b_{S,t}S + b_{T,t}T + b_{V,t}V + b_{RF,t}RF + b_{RN,t}RN \tag{4}$$

where the inputs are explained in the first column of Table 4.3. The values of the corresponding coefficients are also provided in Table 4.3.

4.5 Research Abroad

Several research studies were found from Europe and other continents, some of which specifically dealt with

TABLE 4.2
Crash Modification Factors for High-Tension and Concrete Median Barriers

	Wide Depressed Median with No Barrier Converted to	
Type of Crash	Medium Width Depressed Median with High-Tension Cable Barrier	Flushed Median with Concrete Barrier
Single vehicle (SV)	1.7	2.2
Multiple vehicles same direction (SD)	0.97	0.8
Multiple vehicles opposite direction (OD)	0.06	0.0

TABLE 4.3
Parameters of the Probabilistic Model of Fatal and Injury for Considered Median Types

	SV		SD		
Variable Description, Symbol (Units)	Wide Depressed No Barrier, Flush with Concrete Barrier	Median Width Depressed with High-Tension Cable Barrier	Wide Depressed No Barrier, Median Width Depressed with High-Tension Cable Barrier	Flush with Concrete Barrier	OD of all Three Types
Frequency of bridges, B (1/mile)			0.0494	0.0494	
Constant, K (-)	−1.546	−2.23	−0.565	−0.5156	−0.669
Total number of lanes (4 or 6), L (-)			0.0542	0.0542	0.184
AADT, Q (veh/day)			-2.43E-06	-2.43E-06	-6E-06
Presence of a horizontal curve, PH (-)	0.161	0.161	−0.115	−0.652	
Presence of a roadside barrier, RB (-)			−0.158	−0.158	−0.843
Posted speed limit, S (mph)			−0.0128	−0.0128	
Percentage of trucks, T (%)			−0.00403	−0.00403	
Presence of a vertical curve , V (-)			0.107	0.107	0.335
Frequency of off-ramps, RF (1/mile)	−0.019	−0.019	−0.0264	−0.0264	
Frequency of on-ramps, RN (1/mile)	−0.033	−0.033			

roadside safety or roadway departure crashes, while others addressed these issues as a subsection.

In an Australian study conducted by Ogden *(36)*, the author first stated that according to the literature, paved shoulders are cost-effective at quite low traffic volumes. For example, an Australian study *(37)* suggested that they were cost-effective at volumes as low as 1,000 vehicles per day, and American data suggested that this practice was cost-effective for volumes above 2,000 vehicles per day *(38)*. A crash data analysis was carried out based on a series of shoulder paving projects. The author found a 41% reduction on fatality crashes (fatal crash/vehicle miles traveled) when shoulders were paved and a cost-effective volume as low as 360 vehicles per day.

In the Safety Strategy for Rural Roads from France *(39)*, one chapter provides a general discussion on roadside obstacles. It points out that roadside objects not only include hazardous obstacles like trees, but also include design elements like ditches and slopes. Another French study, The Reduction of Head-on Collisions and Run-off-road Accidents *(40)*, deals with head-on and roadway departure crashes on two-lane rural roads. This facility type is not in the scope of our study; however, the following countermeasures discussed in this report could be informative in providing guidance to deal with these crashes on higher level roads.

- Speed management
  - Setting speed limits
  - Information about speed limits
  - General description of road engineering measures
  - Enforcement and monitoring
- Measures that aim to keep the vehicle safely in the travel lane or on the roadway
  - Road markings
  - Rumble strips
  - Profiled edge markings
  - Improved delineation
  - Shoulder treatment (hardening/widening)
  - Improved alignment
  - Improved road surface/skid-resistance (including dynamic information systems)
  - Wrong way warning systems
- Measures aimed at minimizing accident risk after unintentional lane or roadway departure
  - Safer slopes
  - Clear roadside areas
  - Shoulder/verge treatments
- Measures aimed at minimizing the impact of collisions
  - Safety (crash) barriers
  - Crash-friendly roadside furniture
  - Directional separation

As can be seen from the list of countermeasures, some of these are only applicable for lower level roadways, such as providing directional separation and road markings. However, most of these countermeasures could also apply to higher level highways. Detailed strategies were not provided in the study's report due to the lower functional classification.

A study conducted in Spain by Pardillo-Mayora et al. *(41)* used cluster analysis and injury (severe and fatal) crash rate to develop a Road Hazardous Index (RHI). Four roadside elements were studied: side slope, the offset of non-traversable obstacles, safety barriers, and barrier alignment. The authors used a single index to evaluate both the likelihood of roadway departure and the probability of sustaining a severe crash. The index is theoretically sound and successfully proved the effectiveness of roadside barriers in preventing injury crashes.

Another study in Spain was conducted by Garcia et al. *(42)*, wherein the authors proposed a solution to address the ever increasing problem of roadside safety. The Spanish government is making great efforts to reduce motor-vehicle crashes and one of their priorities is to design a safer cross-section, which most of the time is the major contributing factor in the severity of crashes. An innovative solution was proposed in this study, which pays special attention to the median and roadside design.

Two primary methods to achieve such safety improvement have been identified:

1. Implementation of safety devices to contain errant vehicles
2. Safer design of the roadway environment to reduce or eliminate the need for such devices

While the first strategy, use of safety devices, seems to be the prevailing practice nowadays, the authors aimed to explore more of the second strategy. Even though achieving an absolutely safe design and totally eliminating the need for safety devices seems unrealistic, the objective of this particular study was to achieve a reasonable balance of these two.

The current criteria for installing safety devices as identified in this study include:

- The initial and maintenance costs of the devices;
- The cost of alternative strategies;
- The likelihood of a collision, as compared to the likelihood of rollover;
- The severity of the crash without the safety devices; and
- The severity of the crash with the safety devices.

While the decision to install safety devices should take into account all these criteria, other potential issues with the use of the safety devices were also pointed out:

- The use of safety devices leaves no safety margin for drivers to avoid a crash;
- Safety devices may rebound vehicles to the traveled lanes and cause secondary crashes; and
- Safety devices may cause serious threat to motorcyclists.

With all these concerns, the authors provided discussion for median treatments and roadside treatments, respectively.

The discussion regarding median mainly involves visibility issues. This is due to the road design practices in Europe since guardrails or other safety devices are usually installed very close to the traveled way, which is not the case in the U.S., thus the discussion is not included here. As a conclusion, the authors stated that it is preferred to design each direction of the road as individual roads to totally eliminate the possibility of cross-median crashes. When this approach is not viable, a greater width of median is preferred over the use of safety barriers.

For the roadside, the authors raised the "safety zone" concept, which is essentially the same as the clear zone concept in the U.S. The authors stated that the width of the clear zone should be according to the following factors:

- The type of road
- The layout plan
- The curvatures
- The transverse slope of the slopes
- The level of roadside hazard

Since this idea is very similar to the clear zone concept in the U.S., no further discussion is provided here.

In a Finnish study conducted by Rasanen *(43)*, the effects of two centerline treatments were researched: solid centerline marking (called centerline barrier line) and centerline rumble strips. Vehicle trajectories were recorded during three periods: before a repainting of a centerline barrier line, after repainting, and after rumble strips were milled. The conclusions stated that a clear repainted barrier line reduces the standard deviation of vehicle lateral position, while rumble strips reduce the standard deviation even further. This study concluded that improved lane marking/signage, along with rumbles strip installation, was effective in helping to keep vehicles in the proper lane position. The findings in this study could potentially be applied to the shoulder lane markings and rumble strips in the U.S.

Montella *(44)* conducted a study in Italy to guide the selection of roadside safety barrier containment levels. This study is perceived to accompany the new European standard, due to the void of a benefit-cost analysis tool for selecting roadside safety features. The proposed model incorporated the effective containment level based on real world crash test results. This model has a very similar approach to Roadside Safety Analysis Program (RSAP), which is recommended in the AASHTO RDG and will be introduced in the next chapter.

5. MODIFICATION FACTORS FOR MEDIAN AND ROADSIDE TREATMENTS

5.1 Performance Measures

Many studies have been carried out in regard to the safety effectiveness of various treatments. While some of the past literature concluded the effectiveness of certain treatments in terms of estimated parameters in models, the ideal output would be "modification factors, similar to the CMFs used in the AASHTO HSM or the CCMFs in the German RAA. In this study, an effort was made to present the most direct output.

When choosing between CMFs and CCMFs, the following sections will present the logic behind the selection of CCMF as the performance measure for the present study.

5.1.1 Trend Suggested by the National Statistics

In Chapter 2, national statistics were presented to show the challenge faced by traffic safety engineers. In this study, we are trying to maintain safety with a significant reduction in ROW width. Roadway departure crashes are currently accounting for almost half of the nation's total fatal crashes (45.1%). From the national statistic, other than reducing the frequency of

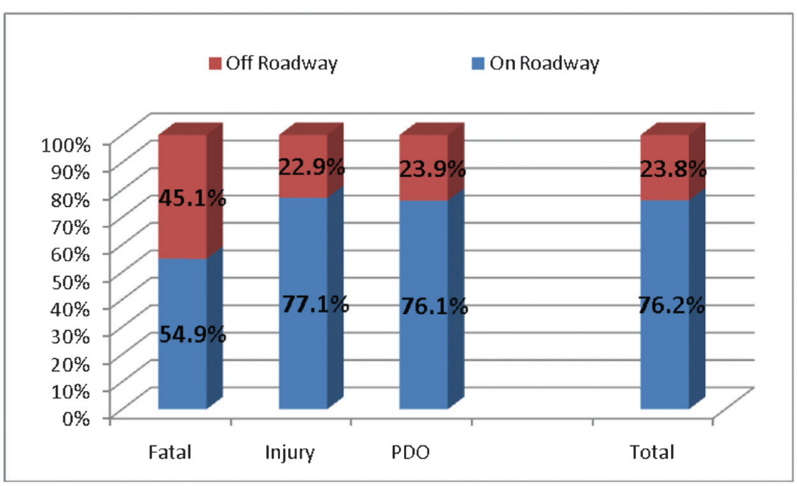


Figure 5.1 Proportion of roadway departure crashes by injury categories.

roadway departure crashes, another potential improvement was identified, namely, to reduce the severity of roadway departure crashes. The proportion of roadway departure crashes by injury categories is shown in Figure 5.1.

From Figure 5.1, it can be seen that roadway departure crashes may be seriously overrepresented in fatal crashes. Thus, even with no reduction in the overall frequency of roadway departure crashes, reducing the proportion of fatal crashes alone is a significant safety improvement.

5.1.2 Findings from the Literature Review

In the literature review, all of the past empirical studies about safety barriers in the U.S. addressed median barriers due to the limited application of roadside barriers at that time. The meta-analysis conducted by Elvik *(26)* reported a reduction both in the frequency and the likelihood of fatalities or injuries after the installation of roadside barriers. It also reported increased roadway departure crash frequency when median barriers were installed, similar to the median barrier studies carried out in the U.S. This finding suggests that while the barriers serve their purpose very well, they also tend to induce more crashes with less severity, which renders the use of crash frequency as the evaluation criterion inappropriate.

5.1.3 German Roadside Design Guideline

Due to the limited application of the narrow clear zone and the use of barriers in the U.S., the roadside design guidelines from Germany, *Richtlinien für die Anlagen von Autobahnen* (RAA) *(15)*, were studied. In the RAA, all evaluation is conducted using the Crash Cost Rate (CCR), and the comparison among alternatives are conducted using ΔCCR or Crash Cost Modification Factor (CCMF). Crash frequency is not used in the German guidelines. The German practice provided further justification for the application of the CCMF when evaluating roadside safety.

5.1.4 Simulation Outcome

A simulation study was conducted during this effort (introduced in the next section), utilizing the RSAP, recommended by the 2006 AASHTO RDG. RSAP simulates each encroachment and its outcome and is capable of estimating crash cost in dollar amount. This estimation of crash cost is based on the outcome of each individual crash and the crash figure specified by the users. Thus, it is both accurate (without any aggregation bias) and adaptive (can use crash figure of the users' choice).

In the simulation study, for the scenarios with hazards outside the ROW, the crash cost estimations showed a significant reduction in total crash cost if guardrails are installed. However, in terms of crash frequency, most of the categories increase in all injury categories other than very serious or fatal because, in RSAP, crashes with barriers are mostly injury crashes. The crash cost-based approach in RSAP uses rather precise categorization of injury severity and corresponding costs. The analysis based on crash statistics may not properly reflect the safety effects due to rather coarse categorization of injury and frequent misclassification of injuries by persons investigating the crash at the scene. The simulation-based approach (RSAP) supplemented with selected results from crash data analysis is used in this study to evaluate the cost-based (CCMF) roadside safety performance.

With the findings from the literature, the German design guidelines, the trends observed from U.S. national crash statistics, and the outcome from the simulation study conducted in this study, crash cost was proven to be a more accurate and comprehensive estimation of roadside safety performance. Thus, CCMF is believed to be a better performance measure than the traditional, widely used CMF in evaluating roadside design alternatives.

5.2 Estimating CMF for the Median Treatments

Even though CCMF is identified in this study as the preferred performance measure for safety treatments, cost was not taken into consideration in the previous median study. Thus, the CMF is first calculated for the median treatments, and the CMF will be converted to CCMF in the following sections.

With the model developed by Villwock et al. *(35)*, the average and relevant characteristics of Indiana rural interstates presented in Table 5.1 were used to calculate the crash frequencies.

The three most popular types of median configurations are considered here:

1. Depressed median with width of 50 feet or wider;
2. Depressed median with width between 30 and 50 feet; and
3. Flush median with intermediate width and concrete barrier.

TABLE 5.1
Values Used to Estimate the CMFs for Alternative Treatments of Median

Variable Description, Symbol (Units)	Value
AADT, AADT (veh/day)	10,000–50,000
Total number of lanes (4 or 6), LNS (-)	6
Percentage of trucks, PT (%)	20
Posted speed limit, PSL (mph)	66
Inside shoulder width, ISW (ft)	4
Presence of an outside barrier, PO (-)	0.044
Frequency of bridges, BRG (1/mile)	0.25
Frequency of off-ramps, ROF (1/mile)	0.59
Frequency of on-ramps, RON (1/mile)	0.67
Presence of a horizontal curve , PHC (-)	0.2
Frequency of horizontal curves, HF (1/mile)	1.8
Average horizontal curvature, HR (1/mile)	0.4
Presence of a vertical curve, PVC (-)	0.244
Average vertical curvature, VK (%/mile)	1.3

The most widely varying input was the AADT, and it was also the strongest safety factor. Therefore, the crash frequencies were calculated for multiple values of AADT between 10,000 and 50,000 vehicles/day at the 5,000 interval and the severity model (see Section 4.4 for details) developed by Villwock et al. *(35)* was used to calculate the frequency of fatal/injury crashes and PDO crashes for the different median types. The details of these models are explained in section 4.4. The frequencies for different injury levels were finally used to calculate the CMFs for converting the base median case to the two considered median alternatives (Table 5.1).

Table 5.2 presents the recalculated CMFs for (1) wide depressed median with no barrier converted to medium width depressed median with high-tension cable barriers and (2) wide depressed median with no barrier converted to flushed median with concrete barrier, calculated for all crashes as well as for the fatal and injury (FI) and property damage only (PDO) categories. Estimating the CMFs for various road treatments, by crash severity, is the most common approach. The HSM *(9)* suggests that different CMFs be calculated for different AADT values if the AADT is a strong factor, which is the step followed in Table 5.2.

This result is based on the models and equations developed in the previous median study *(35)*. While the CCMF has been identified as more accurate and effective in evaluating roadside safety, the CMFs obtained here will be further converted to CCMFs.

5.3 Introduction of NCHRP 492 and RSAP

The Roadside Safety Analysis Program (RSAP), which is recommended by the AASHTO RDG, is used to assist economic analysis for roadside conditions. The software evaluates various alternative scenarios with an incremental benefit/cost (B/C) ratio. By comparing the alternatives to a baseline scenario, the incremental B/C ratio is calculated using the reduction in crash cost over the additional project cost. Both the reduction in crash cost and additional project cost can take a negative value. The alternative with the higher B/C ratio is thought to be more economically desirable. The RSAP software estimates crash costs with four modules: encroachment, crash prediction, crash severity, and B/C analysis. The detailed mechanism of each module will be explained in Sections 5.3.1 through 5.3.5. The total crash cost is shown in the following equation *(5)*:

$$E(C) = V \cdot P(E) \cdot P(C|E) \cdot P(I|C) \cdot C(I),$$

where E(C) is the estimated total crash cost in dollars, V is the AADT for the current year, P(E) is the probability of encroachment, P(C|E) is the conditional probability of a crash occurring given an encroachment, P(I|C) is the probability of the levels of injury given a crash has occurred, and C(I) is the cost for each category of injuries. The users can choose the value of the injury cost from sources such as the Federal Highway Administration (FHWA) or the National Safety Council (NSC), or specify the cost themselves. The modules to estimate crash costs are introduced in the following sections.

5.3.1 Encroachment Module

The encroachment rate is defined by the RSAP manual as the probability of a vehicle running off the roadway. In order to estimate the encroachment rate, the observed wheel tracks in the median or the roadside along the highway must be utilized. Unfortunately, collecting such data is costly. There have been two studies aimed at collecting such data, which are mentioned in the RSAP manual: Hutchinson and Kennedy *(45)* and Cooper *(46)*. The authors of the RSAP prefer the Cooper study because it is more recent, has a larger sample size, and produces better quality results. There are issues with the data used in the Cooper study however. First, due to the presence of paved shoulders, wheel tracks that do not extend beyond the width of the paved shoulders would not be detected and are therefore believed to be underreported. Second, since it will be unlikely to distinguish the controlled and uncontrolled encroachment rate, vehicles intentionally

TABLE 5.2
Crash Modification Factors for Converting the Base Case to Two Alternative Cases

	Base Case/Medium Width Depressed Median with High-Tension Cable Barriers			Base Case/Flushed Median with Concrete Barrier		
AADT (veh/day)	**FI**	**PDO**	**ALL**	**FI**	**PDO**	**ALL**
10000	0.70	1.31	1.19	1.90	2.00	1.98
15000	0.75	1.38	1.26	1.81	1.93	1.90
20000	0.78	1.43	1.31	1.73	1.86	1.84
25000	**0.80**	**1.46**	**1.33**	**1.66**	**1.81**	**1.78**
30000	0.81	1.48	1.35	1.61	1.76	1.73
35000	0.83	1.49	1.36	1.56	1.71	1.68
40000	0.83	1.49	1.36	1.52	1.67	1.64
45000	0.84	1.49	1.36	1.48	1.64	1.61
50000	0.85	1.49	1.36	1.45	1.60	1.57

NOTE: **Boldface row** indicates AADT used in simulation.

pulling off the roadway are also included in this data. These issues led to two adjustment factors being applied while estimating the base encroachment rate, which were incorporated in the RSAP software.

The encroachment rate is expected to change for different road geometries. The authors of the RSAP manual conducted a literature review and applied adjustment factors for horizontal and vertical curves, with distinctions made for the inside and outside of the curve. Traffic growth factors can also be specified to account for increased traffic volume in future years, which will have a direct impact on encroachment.

Finally, RSAP users can define an adjustment factor for the encroachment rate itself. The base adjustment factors for the encroachment rate provided by the RSAP manual are based on very limited historical data *(46)*. Users can choose a proper adjustment factors based on their experience and site-specific crash history. The base encroachment frequency (enc/km/yr) used in the RSAP is shown in Figure 5.2.

The parameters related to each encroachment, such as vehicle type, departure location, departure lane, initial speed, encroachment angle, and vehicle orientation were randomly generated using the Monte Carlo Simulation Technique. This step is introduced in Section 5.3.5.

5.3.2 Crash Prediction Module

Given an encroachment occurs, the Crash Prediction Module is used to determine whether a crash will occur and the manner of how the crash would happen. This module is much more complicated than the previous module and includes three steps:

1. The software sorts the roadside features with their longitudinal and lateral placement to the roadway so that it can decide which feature the vehicle might strike. If there are multiple features along the road, the software determines which feature the vehicle might strike first.
2. The software decides the vehicle path based on the vehicle type, initial speed, and encroachment angle. If there is any roadside feature in its path, the software determines that a collision will happen. If there is no roadside feature in the path of the vehicle, then the crash prediction module will terminate and the software will go to the next encroachment.
3. This step occurs once a collision occurs. Based on the characteristics of the vehicle, the roadside feature, the impact speed, and the impact angle, the software will calculate the impact energy and decide whether the vehicle will penetrate the roadside feature, rollover, or stop after the impact. If the vehicle rolls over or stops, the software will move to the next module. If the vehicle penetrates the roadside feature, the module will recalculate the vehicle path and repeat the second and third steps until the vehicle rolls over or stops, or there are no further roadside features on the studied roadway.

More detailed information about this module can be found in the RSAP manual *(5)*. Some assumptions are made in this module. The most important assumption is that driver input does not affect the vehicle path during the encroachment due to a lack of understanding of the effect of those inputs. The RSAP authors pointed out that this assumption may result in an over-estimation of the crash severity. The vehicle speed and angle follow an empirical distribution, and the lateral extent of the vehicle is also generalized from Cooper, as shown in Figure 5.3.

5.3.3 Crash Severity Prediction Module

In NCHRP 492 (5), the author stated that the Crash Severity Prediction Module is the most important module in estimating the economic impact of motor vehicle crashes. Since the cost for different levels of crashes is very non-linear, the precision of this module will greatly outweigh that of the other modules. Unfortunately, all of the three existing prediction methods (engineering judgment, crash data, and kinetic analysis) have serious limitations, and the precision of these methods cannot be validated.

Also in NCHRP 492, the authors propose a new method which will incorporate crash data and kinetic analysis. Due to time and resource constraints, the methods adopted in the current RSAP are revised

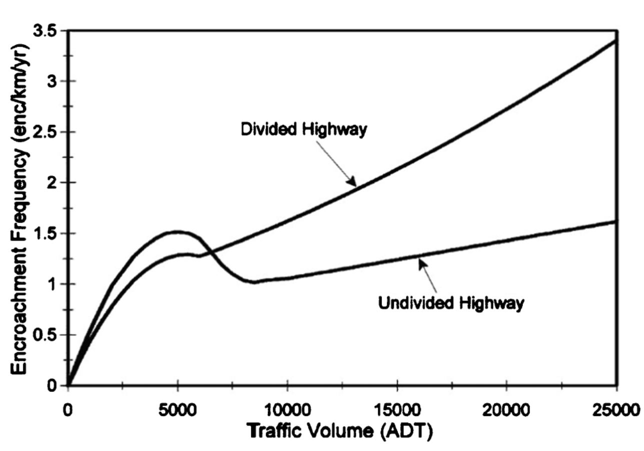


Figure 5.2 Encroachment frequency by average daily traffic (ADT) *(5)*.

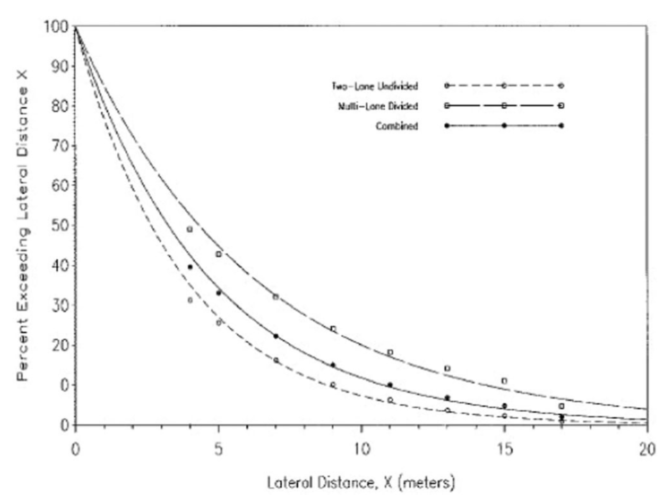


Figure 5.3 Lateral extent of encroachment in RSAP *(5)*.

versions of the Severity Index (SI) method from the 1996 AASHTO RDG. By using the impact speed rather than the roadway design speed, this revised SI method could result in a more accurate estimate of the injury severity level than the method used in the 1996 AASHTO RDG. The SI levels are then related to the appropriate level of the KABCO scale. This relationship is based on a survey of highway engineers, police officers, and safety researchers conducted in a study by Weaver et al. *(47)*. The relationship between the SI and KABCO scale is shown in Figure 5.4.

5.3.4 Benefit/Cost B/C) Analysis Module

In this module, two cost components are considered for each crash: the crash cost and the repair cost for the roadside features. The crash cost is based on KABCO scale. Two established cost figures are included in the software, namely, accident cost figures from the AASHTO RDG and comprehensive accident cost figures from the FHWA. The users can also directly define their own crash cost figures.

A series of adjustment factors are applied to the crash cost based on the vehicle type, departure lane, encroach speed, encroach angle, and vehicle orientation. The repair cost is calculated based on a unit repair cost and the amount of damage sustained (e.g., based on the length of guardrail damaged). Unit repair costs can be retrieved from state DOTs, while the amount of damage is taken from a full-scale crash test and a simulation study. The relationship of the impact speed and the damage amount is established based on Weaver et al. *(47)*. The impact speed calculated in the previous modules is used for calculation. With the crash cost and repair cost calculated, the B/C ratio between each pair of alternatives is calculated by the following equation:

$$\mathrm{B/C\ Ratio}_{2-1} = \frac{(\mathrm{AC}_1 - \mathrm{AC}_2)}{(\mathrm{DC}_2 - \mathrm{DC}_1)}$$

The numerator represents the “reduction” in the total costs, while the denominator represents the increase in the project investment. Since the alternatives are directed to be safety improvements, the crash cost will potentially decrease, but an additional project cost is introduced. This ratio could be negative if the safety improvement failed or if an alternative reduces the crash cost while also reducing the project cost. Generally speaking, a ratio greater than 1 indicates the safety improvement is economically viable, while a greater number is more desirable.

5.3.5 Monte Carlo Simulation Technique

The modules previously mentioned in this chapter are stochastic in nature. The Monte Carlo Simulation Technique was adopted to allow for randomness. One important issue in the Monte Carlo technique is that correlations within some modeling parameters arise and must be accounted for. The parameters with no correlation problems are individually generated, while the correlated parameters must be generated in combinations. Two major examples of the combinations are: (1) encroachment speed and angle and (2) all the parameters related with “location,” such as segment, traveling direction, departure lane, and direction of encroachment. A thorough description of the Monte Carlo Simulation Technique can be found in the RSAP manual *(5)*.

5.4 Simulation Study Experiment Design

5.4.1 Modification and Assumptions

After reviewing the mechanism of the RSAP program, the research team utilized this program to develop an experiment to simulate the potential outcomes of different scenarios. However, as stated in the RSAP manual, a lack of historical data and some other issues can compromise the precision of this program. Some modifications and assumptions were made to address these issues before developing the experiment design, which are as follows:

Severity Index (SI)	Injury Level (%)						
	None	PDO1	PDO2	C	B	A	K
0	100.0	-	-	-	-	-	-
0.5	-	100.0	-	-	-	-	-
1	-	66.7	23.7	7.3	2.3	-	-
2	-	-	71.0	22.0	7.0	-	-
3	-	-	43.0	34.0	21.0	1.0	1.0
4	-	-	30.0	30.0	32.0	5.0	3.0
5	-	-	15.0	22.0	45.0	10.0	8.0
6	-	-	7.0	16.0	39.0	20.0	18.0
7	-	-	2.0	10.0	28.0	30.0	30.0
8	-	-	-	4.0	19.0	27.0	50.0
9	-	-	-	-	7.0	18.0	75.0
10	-	-	-	-	-	-	100.0

Figure 5.4 Relationship of the Severity Index to the KABCO scale *(5)*.

1. The linear relationship between ADT and encroachment frequency. As Figure 5.2 suggests, the number of encroachments follows a linear relationship with the ADT after about 7,000 vehicles per day for divided highways. Since the focus of the current study is on rural principal arterials where the ADT is usually much higher than 7,000 vpd, only one ADT scenario is incorporated in the experiment design for a more parsimonious design.
2. The program cannot handle a large number of features. The manual states that the maximum number of features it can handle is 1,000. In an attempt to obtain a large sample and thus a desirable statistic property, a five-mile section with 200 trees per mile was designed. Using this scenario, the RSAP program crashed. Alternatively, a one-mile section with 200 trees was simulated, but the processing time was infeasible (4–5 hours for each run) for a large-scale experiment. The research team found that a quarter-mile section outputs a reliable result with a reasonable processing time. Thus, the final road section used was a quarter-mile in length with 50 trees on each side.
3. As specified in the manual, all the barriers have the same SI under the same speed. This is an over-simplification since different types of barriers are known to result in different levels of injuries. The user-defined roadside object option allows the users to define the SI under different speeds and the slope of the SI with respect to impact speed; however, users are not able to define penetration rate, deflection, and other features that are standard for distinct barrier types. In the current study, guardrail TL-4 was selected, regardless of the over-simplified specification of the barriers.
4. The estimation of the injury level for each crash is based on the relationship table between the SI index (estimated by the simulation) and the KABCO level (used to calculate crash cost). With a large sample, such injury level estimation should be sufficiently precise. However, due to the previously mentioned capability issues in this program, it was necessary to use a short segment and we thus have very low estimated number of crashes and the sample size became a serious issue. As an alternative to the cost estimation process from the program, the average cost for each SI category was calculated using cost figures from both the federal level (AASHTO and FHWA, which are incorporated in RSAP) and from Indiana *(14)*. The cost figures from Indiana were available for each highway classification, and the costs for rural freeway thus were used. The total crash cost was then estimated using crash frequency, the average SI index, and the crash figures calculated. The cost figures from AASHTO, FHWA, and the State of Indiana are shown in Table 5.3, and the estimated cost for each SI level is shown in Table 5.4.
5. RSAP was designed to study roadside crashes, and the median crash is oversimplified. The software is capable of outputting the frequency and severity of hit fixed object crashes in the median, but not for head-on and other types of multi-vehicle crashes in the median. In a previous median study *(35)*, crashes were categorized as Single Vehicle crashes (SV), multi-vehicle Same Direction crashes (SD) and multi-vehicle Opposite Direction crashes (OD), while the RSAP only simulates SV crashes. Therefore, in this study, the research team only focused on SV crashes and used past research results for SD and OD crashes in the median.

TABLE 5.3
Cost Figures from AASHTO, FHWA, and Indiana

Injury	AASHTO	FHWA	INDIANA
PDO1	$625	$2,000	$4,800
PDO2	$3,125	$2,000	$4,800
C	$3,750	$19,000	$19,800
B	$12,500	$36,000	$35,900
A	$200,000	$180,000	$100,100
K	$1,000,000	$2,600,000	$1,769,100

In summary, the assumption of a linear relationship between encroachment and AADT was made for a relatively high AADT. It was assumed that one quarter-mile is long enough to provide a stable estimation for the crashes on a homogenous road segment. Also, due to a small sample size, the cost figures were calculated and directly applied to each SI level, and the cost estimation provided by RSAP was not used. Finally, the RSAP outcome included only SV crashes.

5.4.2 Simulation Design

The objective of this project is to study the effect of reduced freeway clear zone width on traffic safety as well as to study the effect of placing longitudinal roadside barriers alongside the roadway. Subject to the exploratory nature of this study and the issues found in the RSAP software package, this study is not intended to be a comprehensive B/C analysis, but rather to provide a quick preview of the potential safety effect of various candidate alternatives under different traffic conditions. The results from this study therefore should not be used as guidance for implementation, which would require further study with more recent data and a more solid methodology.

The traffic conditions should include AADT, truck percentage, and speed limit. AADT has been previously found to feature a linear relationship with SV crash frequency. Truck percentage data are not readily available for rural principal arterials and therefore was measured from the INDOT Average Daily Traffic and Commercial Vehicles Interactive Map. Truck percentages were measured from interstates near urban areas to represent road sections that might be candidates for expansion projects. Due to the exploratory nature of this study, one single speed limit and truck percentage were used. The speed limit selected was 70 mph, which is the typical rural freeways speed limit in Indiana, and the truck percentage selected was 20% to represent the typical traffic mix.

The cross-section design used in this simulation follows the AASHTO and INDOT guidelines. A full width outside shoulder of 12 feet was used. The 6:1 foreslope together with 6:1 backslope form a 12-foot wide one-foot deep V channel. A 10:1 foreslope

TABLE 5.4
Estimated Cost for Each SI Level

SI	none	PDO1	PDO2	C	B	A	K	AASHTO	FHWA	INDIANA
0	1	0	0	0	0	0	0	$0	$0	$0
0.5	0	1	0	0	0	0	0	$625	$2,000	$4,800
1	0	0.667	0.237	0.073	0.023	0	0	$1,719	$4,023	$6,610
2	0	0	0.71	0.22	0.07	0	0	$3,919	$8,120	$10,277
3	0	0	0.43	0.34	0.21	0.01	0.01	$17,244	$42,680	$35,027
4	0	0	0.3	0.3	0.32	0.05	0.03	$46,063	$104,820	$76,946
5	0	0	0.15	0.22	0.45	0.1	0.08	$106,919	$246,680	$172,769
6	0	0	0.07	0.16	0.39	0.2	0.18	$225,694	$521,220	$355,963
7	0	0	0.02	0.1	0.28	0.3	0.3	$363,938	$846,020	$572,888
8	0	0	0	0.04	0.19	0.27	0.5	$556,525	$1,356,200	$919,190
9	0	0	0	0	0.07	0.18	0.75	$786,875	$1,984,920	$1,347,356
10	0	0	0	0	0	0	1	$1,000,000	$2,600,000	$1,769,100

separates the shoulder from the V channel. We assumed different obstruction levels along the roadway, with three scenarios: no trees, 200 trees per mile, and 400 trees per mile (equally spaced along the road). The trees assumed here were 12 inches in diameter, which is the largest option provided by the RSAP. The lateral offset to the road varies with the clear zone width. For each clear zone width, there is one scenario without a longitudinal barrier and one scenario with a longitudinal barrier. For the very restricted case with a 20-foot clear zone, there is only one scenario with a barrier placed close to the shoulder. For unrestricted clear zones, barriers are placed close to obstructions with enough space behind the barrier for lateral deflection.

Different scenarios of roadside clear zone width are assumed to reflect different existing conditions. Since the outcome from the software does not provide a comprehensive picture of median-related crashes, only one median condition was used in the experiment. The Indiana Design Manual recommends 30–34 feet of clear zone width for rural freeways, while our measurements from the Google Map™ found some locations to feature an even greater width. Thus, five different existing widths were used in the experiment to represent different levels of availability of existing clear zone, with clear zone widths ranging from 26 to 50 feet in 6-foot intervals (i.e., the width of a half-lane, to represent different placements of the added travel lane). The 12-foot wide paved shoulder and the 12-foot V channel were included in all the cases. The 10:1 foreslope between the shoulder and the V channel was used with the width being 2 feet (26-foot clear zone), 5 feet (32-foot clear zone), 11 feet (38-foot clear zone), 17 feet (44-foot clear zone) and 23 feet (50-foot clear zone) for the five scenarios, respectively.

The type and placement of barriers is also a contributing factor for crash outcomes. As mentioned earlier, since longitudinal cable barriers are not readily available from the RSAP software, a guardrail approved in the TL 4 category is used for all applications. The current design practice is to locate the barriers close to the traveled way or the shoulder. The Indiana Design Manual states that, for reconstructed roads, the desired offset between a barrier and the usable shoulder is 2 feet, and the minimum is zero. The greatest offset of a barrier could be achieved by locating the barrier closest to the obstructions, with enough space for the lateral deflection of the barrier. Also, it is known from the literature that a significant increase in the crash frequency could be alleviated by locating guardrails further away from the travel lane. A guardrail was placed near the outside edge of the clear zone for unrestricted and restricted clear zone cases. Only the 20-foot clear zone width scenario (after adding lanes) was designed differently, with a barrier located close to the shoulder with a one-foot offset and the V channel featuring a 3:1 slope.

The obstructions in the RSAP software are defined with an SI curve with respect to impact speed, along with its location and dimension. The research team selected trees to represent typical obstructions in rural conditions. While the density of trees will affect the probability of an errant vehicle impacting a tree, it was found that this probability is a linear function of the frequency of trees before the spacing gets smaller than a certain threshold (for an impacting angle of 30 degrees, the threshold is 13-foot spacing, at which point the chance of striking it becomes 100%). The moderate hazard scenario (200 trees per mile) was simulated in the experiment and the trees were placed 26 feet apart, equaling a total of 50 trees for a quarter-mile section. The crash outcomes for other tree frequencies were calculated to save time on computer simulation.

The summary of design alternatives is shown in Table 5.5. In the final experiment design, there were five different projects, featuring different existing clear zone widths. In each project, two alternatives were evaluated, one without guardrails and the other with guardrails. The crash frequency and average SI, along with the calculated crash cost figures, were used for the evaluation. The project cost is out of the scope of this

TABLE 5.5
Summary of Design Alternatives

Six Lanes Cross-Section Design (Future)[1]			
Scenario ID	**Total Clear Zone width (ft)**	**10:1 Slope Width**	**Guardrail Placement**
1	20	2	Guardrail close to shoulder
2	26	2	No guardrail
3	26	2	Guardrail close to outer edge of clear zone
4	32	5	No guardrail
5	32	5	Guardrail close to outer edge of clear zone
6	38	11	No guardrail
7	38	11	Guardrail close to outer edge of clear zone
8	44	17	No guardrail
9	44	17	Guardrail close to outer edge of clear zone
10	50	23	No guardrail
11	50	23	Guardrail close to outer edge of clear zone

[1]Median design: 60 feet, 10:1 slope, no barrier.

study; therefore, the safety effect will be the sole criterion in this study.

5.5 Simulation Output

5.5.1 Simulation Study Output

As discussed previously, the simulation output was not directly used. The crash frequency and the average SI for each roadside feature were utilized, and the final cost was calculated using crash cost figures. To be consistent with a previous study on medians in Indiana, the Indiana cost figure shown in Table 5.3 was used.

To better present the safety effect of reducing the clear zone width, CMFs and CCMFs were calculated for different clear zone reduction strategies.

The CMFs and CCMFs in this study apply to rural freeways and SV crashes only in accordance with the scope of the study. The CMFs were calculated using the total crash frequency for all features, both in the clear zone and in the median, where SV crashes could happen. Three scenarios regarding hazards outside the ROW were assumed, and the CMFs were calculated for all of these scenarios. The CMFs are presented in Tables 5.6, 5.7, and 5.8.

From the CMF tables, some trends can be observed:

1. The CMFs for the three different hazard levels are very similar, which is a result of the relatively small magnitude of the frequency of trees striking crashes. The subtle difference in the frequency of trees striking crashes would be augmented in the CCMF since the severity level of tree-striking crashes are much higher than the other categories of crashes.
2. By installing the longitudinal barrier, the crash frequency significantly increases, regardless of the hazard level or the clear zone width. Closer observation found that the narrower the clear zone width, the greater would be the increase.

TABLE 5.6
CMF for SV Crashes with No Hazard outside Clear Zone

Clear Zone Treatment		**No Hazard outside Clear Zone**		
Width (feet)	**Barrier Use**	**PDO**	**Injury**	**All**
26–20	Close to shoulder	1.34	1.83	1.43
32–26	Not used	1.01	1.02	1.01
32–26	Close to outer edge of clear zone	1.74	2.17	1.82
32–20	Close to shoulder	1.36	1.86	1.45
38–32	Not used	1.03	1.05	1.03
38–32	Close to outer edge of clear zone	1.58	1.91	1.63
38–26	Not used	1.05	1.07	1.05
38–26	Close to outer edge of clear zone	1.80	2.28	1.88
44–38	Not used	1.03	1.05	1.04
44–38	Close to outer edge of clear zone	1.50	1.78	1.55
44–32	Not used	1.07	1.10	1.07
44–32	Close to outer edge of clear zone	1.63	2.01	1.69
50–44	Not used	***0.80***	***0.81***	***0.80***
50–44	Close to outer edge of clear zone	***1.28***	***1.50***	***1.32***
50–38	Not used	***0.83***	***0.85***	***0.83***
50–38	Close to outer edge of clear zone	***1.20***	***1.44***	***1.24***

TABLE 5.7
CMF for SV Crashes with Moderate Hazard outside Clear Zone (200 Trees per Mile)

Clear Zone Treatment		Moderate Hazard outside Clear Zone		
Width (feet)	**Barrier Use**	**PDO**	**Injury**	**All**
26–20	Close to shoulder	1.34	1.82	1.43
32–26	Not used	1.01	1.02	1.01
32–26	Close to outer edge of clear zone	1.74	2.16	1.82
32–20	Close to shoulder	1.36	1.86	1.45
38–32	Not used	1.03	1.05	1.03
38–32	Close to outer edge of clear zone	1.58	1.91	1.63
38–26	Not used	1.05	1.07	1.05
38–26	Close to outer edge of clear zone	1.80	2.27	1.88
44–38	Not used	1.03	1.05	1.04
44–38	Close to outer edge of clear zone	1.50	1.77	1.55
44–32	Not used	1.07	1.10	1.07
44–32	Close to outer edge of clear zone	1.63	2.01	1.69
50–44	Not used	***0.80***	***0.81***	***0.80***
50–44	Close to outer edge of clear zone	***1.28***	***1.50***	***1.32***
50–38	Not used	***0.83***	***0.86***	***0.83***
50–38	Close to outer edge of clear zone	***1.20***	***1.44***	***1.24***

3. The CMFs obtained for 50-foot clear zones are problematic. A review of the original output reveals that the crash frequency is higher in the 10:1 foreslope for a 50-foot clear zone as compared to 44-foot and 38-foot clear zones. No theoretical explanation could be found for this phenomenon. The research team speculates that this could due to the uncommonly wide 50-foot clear zone, which might be beyond the capability of the RSAP software. Thus this part of the result should be treated with caution.

The CCMF combined the crash cost of all injury categories for each treatment, and the CCMFs for all three hazard scenarios are presented in Table 5.9.

As shown in Table 5.9, the difference, in the CCMF version, between the hazard levels is very significant, as more trees will result in more severe crashes. Even if the change in frequency is very small, the total cost is greatly affected. Some general conclusion could be observed from this table:

1. Reducing the clear zone and installing barriers reduces the cost of SV crashes (CCMF$<$1) regardless of the initial width of the clear zone if a considerable hazard is present outside the clear zone. This result indicates that the current guidelines seem to overlook the risk of crashes outside of the clear zone. This finding is somehow supported by the national crash statistics indicating a number of crashes outside of the ROW.
2. On the other hand, where there is no hazard outside the clear zone, the cost of SV crashes increases (CCMF$>$1) after reducing the clear zone width and installing barriers. This result is quite expected because barriers are installed without good reason (there is no hazard to justify the barriers).

TABLE 5.8
CMF for SV Crashes with Severe Hazard outside Clear Zone (400 Trees per Mile)

Clear Zone Treatment		Severe Hazard outside Clear Zone		
Width (feet)	**Barrier Use**	**PDO**	**Injury**	**All**
26–20	Close to shoulder	1.34	1.81	1.43
32–26	Not used	1.01	1.02	1.01
32–26	Close to outer edge of clear zone	1.74	2.15	1.82
32–20	Close to shoulder	1.36	1.85	1.45
38–32	Not used	1.03	1.05	1.03
38–32	Close to outer edge of clear zone	1.58	1.90	1.63
38–26	Not used	1.05	1.07	1.05
38–26	Close to outer edge of clear zone	1.80	2.26	1.88
44–38	Not used	1.03	1.05	1.04
44–38	Close to outer edge of clear zone	1.50	1.77	1.55
44–32	Not used	1.07	1.11	1.07
44–32	Close to outer edge of clear zone	1.63	2.00	1.69
50–44	Not used	***0.80***	***0.81***	***0.80***
50–44	Close to outer edge of clear zone	***1.28***	***1.49***	***1.32***
50–38	Not used	***0.83***	***0.86***	***0.83***
50–38	Close to outer edge of clear zone	***1.20***	***1.44***	***1.24***

TABLE 5.9
CCMF for SV Crashes for Different Hazard Scenarios

CCMF for SV Crashes (AADT-25000)				
Clear Zone Treatment		No Hazard outside Clear Zone	Moderate Hazard outside Clear Zone (200 trees/mile)	Severe Hazard outside Clear Zone(400 trees/mile)
Width (feet)	Barrier Use			
26–20	Close to shoulder	2.62	0.80	0.51
32–26	Not used	1.02	1.13	1.15
32–26	Close to outer edge of clear zone	2.71	0.89	0.55
32–20	Close to shoulder	2.66	0.91	0.59
38–32	Not used	1.04	1.11	1.13
38–32	Close to outer edge of clear zone	2.31	0.84	0.55
38–26	Not used	1.06	1.26	1.30
38–26	Close to outer edge of clear zone	2.81	0.99	0.63
44–38	Not used	1.04	1.11	1.13
44–38	Close to outer edge of clear zone	2.12	0.82	0.54
44–32	Not used	1.08	1.24	1.27
44–32	Close to outer edge of clear zone	2.41	0.94	0.62
50–44	Not used	***0.81***	***0.96***	***1.00***
50–44	Close to outer edge of clear zone	***1.77***	***0.80***	***0.54***
50–38	Not used	***0.84***	***1.07***	***1.13***
50–38	Close to outer edge of clear zone	***1.71***	***0.79***	***0.54***

3. As expected, reducing the clear zone width without installing barriers increases the cost of SV crashes as the edge of the travel way is moved closer to the hazard. The cost increase is negligible where there is no hazard outside the clear zone and the cost increases considerably and grows higher if the intensity of the hazard increases (frequency of trees).
4. As shown in the CMF tables, the obtained CCMF values for clear zones 50 feet or wider are highly questionable and shouldn't be used. They are reported to indicate the issue with the RSAP.

5.5.2 Unifying Simulation Output with Median Study

To obtain a comprehensive understanding of the effects of various strategies for adding travel lanes in existing ROW, the results from the simulation study should be combined with the previous median study in order to potentially identify the optimal strategy. However, there are points to be addressed before the results can be combined:

1. In the simulation study, the output includes only SV crashes while, in the median study, the CMF is for all crashes. Multi-vehicle crashes were not as affected when different clear zone treatments were applied, especially for most of the barriers in the simulation study that were placed close to the outside edge of clear zone. Thus, multi-vehicle crashes are assumed to be unaffected for the simulation study when combining the results.
2. In the simulation study, the crash cost was calculated based on the average cost of the ten SI levels with relatively high accuracy. In the median study, the cost is not specifically calculated, and the CMF is available only for two injury categories, FI (includes all fatal and injury levels) and PDO. Such categories are of relatively low accuracy; and if applied to the output of the simulation study, an opposite trend could be observed for scenarios with guardrails (lowered crash cost vs. increased crash frequency for both FI and PDO crashes).

To address the aforementioned points, the research team made an effort to convert the CCMF for SV crashes (from the simulation study) to CCMF for all crashes. The approach included the following steps:

1. Crash data from the State of Indiana were used to calculate the total crash cost for the three different crash types, and the Average Crash Cost (over all injury severity categories) were calculated for a SV crash, a SD crash, and an OD crash.
2. The Annual Total Crash Cost for each crash type was calculated for different AADT levels, using the Average Crash Cost and the crash frequency (as a function of AADT) for each crash type.
3. For the different clear zone treatments, the CCMF for SV crashes were applied to the Annual Total Crash Cost for SV crashes, while the total cost for multi-vehicles crashes were held constant.
4. Finally, by dividing the total cost of all three types of crashes after treatment (with the adjusted SV crash factor) by the total cost before treatment, the overall CCMFs were calculated for different clear zone treatments.

The final CCMFs for all crashes are presented in Table 5.10. The AADT had an effect on the CCMFs, and the results presented in Table 5.10 occurred when the AADT was 25,000 (veh/day).

The final CCMFs were brought back closer to one as compared to the CCMFs for SV crashes due to the assumption that multi-vehicle crashes are not affected. Most of the trends observed for SV crash CCMF still held here but at a smaller magnitude.

The CCMFs for median treatments were also calculated. As previously mentioned, the cost was not specifically calculated in the median study, and only two injury categories were available (FI and PDO). So, the following steps were taken to calculate the CCMF for median treatments:

TABLE 5.10
CCMF for All Crashes for Different Hazard Scenarios

CCMF for All Crashes (AADT=25000)				
Clear Zone Treatment		No Hazard outside Clear Zone	Moderate Hazard outside Clear Zone (200 trees/mile)	Severe Hazard outside Clear Zone (400 trees/mile)
Width (feet)	Barrier Use			
26–20	Close to shoulder	1.75	0.91	0.77
32–26	Not used	1.01	1.06	1.07
32–26	Close to outer edge of clear zone	1.80	0.95	0.79
32–20	Close to shoulder	1.77	0.96	0.81
38–32	Not used	1.02	1.05	1.06
38–32	Close to outer edge of clear zone	1.61	0.93	0.79
38–26	Not used	1.03	1.12	1.14
38–26	Close to outer edge of clear zone	1.85	0.99	0.83
44–38	Not used	1.02	1.05	1.06
44–38	Close to outer edge of clear zone	1.52	0.92	0.79
44–32	Not used	1.04	1.11	1.13
44–32	Close to outer edge of clear zone	1.66	0.97	0.82

1. The baseline case assumed a 60-foot depressed median with no barrier, and the crash frequency models from the median study were used. Crash frequencies for the three types of crashes were calculated as a function of the AADT.
2. The crash frequency for the other two types of medians, 48-foot depressed median with high tension cable barriers and 36-foot flush median with concrete barriers were calculated using the CMF from the median study for each type of crash.
3. The crash severity models from the median study were used to predict the proportion of FI crashes for each crash type and median type. Then the frequency of FI crashes and PDO crashes were calculated (also as a function of the AADT).
4. The average crash cost for FI and PDO crashes were obtained from Indiana crash data in the same manner as for the clear zone treatments. The total crash cost for each crash type and median type were then calculated as a function of the AADT.
5. The total crash costs were summed over the crash types for each median type. Then the CCMFs for different median treatments were calculated using the total crash cost. The CCMF is also a function of the AADT.

The CCMFs for median treatments under different AADTs are shown in Table 5.11.

From Table 5.11, it is noted that converting from wide depressed median with no barrier to medium width depressed median with high-tension cable barrier generally reduces the total crash cost, while the reduction was more significant at a higher AADT. This reduction was achieved by almost eliminating OD crashes and reducing SV severe crashes, even though SV PDO crashes and SD crashes appeared to increase. No reduction was observed when the AADT was 10,000. The wide depressed median with no barrier to flushed median with concrete barrier conversion totally eliminated the OD crashes but also significantly increased SV crashes. The overall effect was an increased total crash cost, as suggested by a CCFM greater than 1. This increase in total crash cost is of lower magnitude for higher AADT values. The CCMFs vary significantly across AADTs. Thus, in this study, CCMFs at different AADT levels were used. The median level AADT was selected to be 25,000 and the high level was selected to be 50,000. A low level AADT was not included since the purpose of this project is to evaluate the safety effect of using existing ROW for adding travel lanes where the low AADT situations would not be applicable.

5.5.3 Combined Median and Clear Zone Treatment

With the effect of various clear zone treatments and median width treatments identified, it was feasible to find a combined treatment that has the best safety performance with travel lanes added within the existing ROW. Since only median types were considered and the width was not specified in the past median study *(35)*, certain assumptions needed to be made. It was assumed that the starting point of all medians is the wide depressed median with no barrier. When the first

TABLE 5.11
CCMF for Median Treatments

	AADT (vpd)								
Median Treatments	10000	15000	20000	25000	30000	35000	40000	45000	50000
Reduce wide depressed median and install high-tension cable barrier	1.00	0.97	0.96	0.94	0.93	0.92	0.91	0.90	0.89
Reduce wide depressed median and install concrete barrier	1.78	1.65	1.55	1.47	1.41	1.35	1.30	1.26	1.22

strategy is used, 24 feet is taken from the median width and a concrete barrier is installed (convert to flushed median with concrete barrier). When the second treatment is used, only 12 feet of median width is taken to accommodate a single traffic lane (another 12 feet is takes form the clear zone) and a median cable barrier is installed (medium width depressed median with high-tension cable barrier). With the assumptions made, the following strategies were applied:

1. All the width needed to accommodate two additional traffic lanes (24 feet) is taken from the median and a concrete median barrier is installed. The clear zone is left unchanged.
2. The width needed for one traffic lanes (12 feet) is accommodated by reducing the median width and a median cable barrier is installed. The width for the second traffic lane (12 feet) is accommodated by reducing clear zone on each side of the road by 6 feet.
3. All the width needed to accommodate two additional traffic lanes (24 feet) is obtained by reducing clear zone on each side of the road by 12 feet. The median remains unchanged.

All possible combinations are shown in Table 5.12. The table includes the clear zone treatments and median treatments, which are grouped by the original clear zone width. The overall CCMFs when AADTs of 25,000 vpd and 50,000 vpd are presented for the three hazard scenarios. The CCMFs marked in a bold font correspond to the most promising solutions for the given original clear zone width and the hazard conditions at the ROW edge. These results are further summarized and recommended solutions discussed in the next chapter.

6. CONCLUSIONS AND RECOMMENDATIONS

The current roadside design guidelines and standards need to be re-evaluated due to the ever increasing cost of acquiring ROW. Even though safety is still the primary concern in terms of roadside design, the new circumstances drive us to investigate the possibility of applying new design standards to balance safety performance and cost.

TABLE 5.12
Overall CCMF for Combined Clear Zone and Median Treatments

	Clear Zone Treatment					AADT = 25,000 vpd			AADT = 50,000 vpd		
	Width (feet)		Barrier Use								
Strategy	Before	After	Before	After	**Median Treatment Type**	**No Hazard**	**Moderate Hazard[1]**	**Severe Hazard[1]**	**No Hazard**	**Moderate Hazard**	**Severe Hazard**
1	26	26	No barrier	No barrier	Type-1[2]	**1.47**	1.47	1.47	**1.22**	1.22	1.22
2	26	20	No barrier	Barrier (shoulder)[3]	Type-2[2]	1.65	**0.85**	**0.73**	1.34	**0.83**	**0.75**
2	32	26	No barrier	No barrier	Type-2	**0.95**	1.00	1.01	**0.90**	0.93	0.93
2	32	26	No barrier	Barrier (clear zone outer edge) [3]	Type-2	1.69	**0.89**	**0.75**	1.37	**0.86**	**0.77**
3	32	20	No barrier	Barrier (shoulder)	No treatment	1.77	0.96	0.81	1.52	0.97	0.87
2	38	32	No barrier	No barrier	Type-2	**0.96**	0.99	1.00	**0.90**	0.92	0.93
2	38	32	No barrier	Barrier (clear zone outer edge)	Type-2	1.52	**0.87**	**0.74**	1.26	**0.85**	**0.76**
3	38	26	No barrier	No barrier	No treatment	1.03	1.12	1.14	1.02	1.08	1.10
3	38	26	No barrier	Barrier (clear zone outer edge)	No treatment	1.85	0.99	0.83	1.57	1.00	0.88
2	44	38	No barrier	No barrier	Type-2	**0.96**	0.99	1.00	**0.90**	0.92	0.93
2	44	38	No barrier	Barrier (clear zone outer edge)	Type-2	1.43	**0.86**	**0.74**	1.21	**0.84**	**0.76**
3	44	32	No barrier	No barrier	No treatment	1.04	1.11	1.13	1.03	1.08	1.09
3	44	32	No barrier	Barrier (clear zone outer edge)	No treatment	1.66	0.97	0.82	1.44	0.98	0.88

[1]Moderate hazard denotes 200 solid point hazards per mile; severe hazard denotes 400 solid point hazards per mile.

[2]Type-1 denotes treatment that converting depressed median with 60 feet width and no barrier to flush median with 36 feet width and concrete barrier; type-2 denotes treatment that converting depressed median with 60 feet width and no barrier to depressed median with 48 feet width and high tension cable barrier;

[3]Barrier (shoulder) denotes installing barrier close to the paved shoulder, while barrier (clear zone outer edge) denotes barrier close to the outside edge of clear zone.

In this study, the primary objective was to study the safety effect of reducing the median and clear zone widths and to identify potential strategies to maintain or even improve safety performance under restricted ROW. Longitudinal barriers, which have been identified as effective safety countermeasures for roadway departure crashes, were evaluated as the potential treatment in this study. Both a literature review and a simulation study were conducted by the Purdue University Center for Road Safety research team, and the major findings are presented below.

6.1 Use of CCMF as Safety Performance Measure

Crash Cost Modification Factors (CCMF) has been used as a convenient performance measure to represent the safety impacts. Crash Modification Factors remain a valid performance measure, but its use is not as effective and straightforward as CCMFs.

6.2 Safety Effects Vary for Roadside Environment

It is a common understanding that for the same safety treatment, the safety effect will vary across different roadside environments. The AASHTO RDG articulates the effect of various roadside and median elements (when barriers are not present), as summarized in Chapter 3. It also presents the effects of safety barriers. Even though the effects vary with different terrain, placement, barrier type, and design standards, the barriers can effectively eliminate their hazardous effects. In the HSM, for the same safety treatment, different CMF values or curves were provided for different scenarios, which further supported this statement.

In the design of the simulation study, different levels of roadside hazard were incorporated into the simulation. The results were presented for three different levels of roadside hazard: no hazard, moderate hazard, and severe hazard. The results from the simulation in this study also support the statement as the three scenarios showed significantly different results.

6.3 The Mechanism of Roadway Departure Crashes Not Well Understood

To predict the frequency and severity of roadway departure crashes and then apply appropriate countermeasures, the mechanism of such crashes should be well understood. Unfortunately, for roadway departure crashes, the mechanism still remains largely unknown.

6.3.1 Contradictive Findings and Inconclusive Statements

In the literature study, some of the research studies have conflicting findings, with the cause unexplained. One example is the effect of the median barrier offset. In a Bayesian Reconstruction study *(20)*, it was found that a greater offset would increase the likelihood of injury; but in another study using a Nested Logit model *(23)*, the authors concluded that greater offset would decrease the injury likelihood. Such contradictory findings, along with some authors stating "it is not clear that" or "the reason remains unknown" in the conclusion of their studies, suggest that the current level of understanding of the mechanism of roadway departure crashes is very limited.

6.3.2 The Current Level of Knowledge

Even though the mechanism of roadway departure crashes still needs much more research work, the current knowledge base of roadway departure crashes can be summarized as follows:

- Roadway departure crashes are usually partitioned into three sequences: encroachment, crash, and injury. Some analysis tools include one more step to convert the damage and injury into cost *(5,44)*.
- The causes for encroachment have not been clearly identified, and very little literature could be found on this topic due to limited data. The features that are believed to reduce the likelihood of encroachment are included in AASHTO RDG and the HSM, but the effects are discussed in terms of how they affect the likelihood of crashes, rather than the likelihood of encroachments.
- The likelihood of hit-fixed-object crashes can be affected by many roadside elements, which include both the terrain and the roadside features. The mechanisms of their effects on roadway departure are introduced in the AASHTO RDG and also in terms of CMFs in the HSM. However, the understanding of rollover crashes is far less comprehensive.
- The current body of literature provides a better understanding of the severity of roadway departure crashes compared to the previous two scenarios. The severity of hit-fixed-object crashes is the most understood, the effects of both roadside hazards and barriers are extensively discussed in AASHTO RDG, and the effect of barriers are also covered in Highway Safety Manual.

As discussed previously, the mechanism for encroachment is largely unknown, while the current literature provides a good level of understanding of the mechanism of hit-fixed-object crashes and the factors that affect crash severity. The causes of rollover crashes also need further exploration.

6.4 Recommended Strategies for Adding Traffic Lanes without Widening ROW

These results are applicable to depressed medians without barriers and width around 45 feet. The following conclusions, summarized in Table 6.1, can be made under the above assumptions:

1. When the original clear zone is restricted (26-foot width) and there is no hazard outside the clear zone, reducing the median width by 24 feet for two additional lanes and installing median concrete barrier might be considered

TABLE 6.1
Recommended Design Solutions for Adding Two Traffic Lanes to Four-Lane Rural Freeways

Median Width (ft)	Clear Zone Width (ft)	Hazard Outside Clear Zone	Recommended New Lanes Placement	Recommended Median Barrier	Recommended Clear Zone Barrier	Crashes Cost	Remarks
44	26	No	Both in median	Barrier	None	Increases	Requires benefit-cost analysis
44	26	Yes	One in median; one in clear zone	Barrier	Barrier	Reduces	
44	32–44	No	One in median; one in clear zone	Barrier	None	Reduces	
44	32–44	Yes	One in median; one in clear zone	Barrier	Barrier	Reduces	
58+	32–38	No	Both in median	Barrier	None	—	Not studied
58+	32–38	Yes	Both in median	Barrier	Barrier	—	Not studied

(strategy 1). This treatment will most likely increase the cost of crashes. The benefit-cost analysis is needed to justify this solution against widening the ROW.

2. Total Reconstruction Projects: When the original clear zone is restricted (26-foot width) and there is considerable hazard outside the clear zone, reducing the median by 12 feet and clear zone on each side by six feet should be considered. Cable barriers in the median and guardrail in the clear zones should be installed. The main safety benefit is produced by the roadside barriers that protect drivers against the hazard.
3. Clear zones wider than 32 ft provide an option of contain at least one traffic lane while the second traffic lane can be placed in the median together with installation of median barrier. The need to add roadside barriers in the clear zone depends on the presence of the hazard outside the clear zone. Regardless of the solution, the overall safety benefit is expected.
4. Crossover collisions on road segments with wide medians would justify the use of cable barriers. Research to confirm the benefit of cable barriers in wide medians is needed.
5. The results indicate that clear zones not much wider than the currently required minimum standards should have installed roadside barriers if a considerable hazard is present outside the clear zone. The results indicate that narrowing such clear zones can be offset by installing roadside barriers. In many cases, the benefit produced by the roadside barriers exceeds the negative effect of clear zone width reduction.

John Wright will be the main implementer and the Division of Highway Design and Technical support will implement the above recommendations where feasible by means of appropriate revisions to the Indiana Design Manual currently under development.

6.5 Limitation and Future Research Needs

The limitations of this study are identified throughout this report. Since the limitations observed from the literature study were summarized in Section 6.3, the focus here will be the limitations of the simulation study. Future research need recommendations will conclude the chapter.

6.5.1 Limitations in Simulation Study

The Purdue Research Team utilized the RSAP to simulate various ROW reduction scenarios and to analyze their cost-effectiveness. While useful conclusions have been made, the limitations of this simulation should be noted as well.

1. The limited features in the software. RSAP has many features and function, but there are improvements that are much needed. For example, the roadside features are different from each other only in the form of a SI curve, whereas the penetration rate and rollover probability are not specified in the manuals. Also, only concrete barriers and guardrails are the available options in the features and they have the same SI, which greatly limited the exploration of applying different types of barriers.
2. The limited capability of the software. As mentioned in the simulation study sections, the research team built a short road segment due to the software lacking the capability to handle a large number of features. Also, when the width of the clear zone was specified at 50 feet, questionable results were generated, which again has the research team questioning the capability of the software.
3. Different sources for clear zone and median CCMF. Since the RSAP software cannot handle median safety treatments, the results from a previous study conducted by the Center for Road Safety were utilized. This previous study used empirical data and a different performance measure to evaluate safety, thus some discrepancy and loss of accuracy would be expected when combining the results from both sources.

Even though the best efforts were made to identify the safety effects in terms of the CCMFs in Table 5.11 and the best strategy under restricted ROW circumstances, the CCMFs provided in Table 5.11 should not be used as a guide for implementation based on the above limitations. An empirical study using real data should be carried out for implementation purposes.

6.5.2 Needs for Future Study

Future research is needed both at the national level to better understand some aspects of roadway departure crashes and at the State of Indiana level to guide the practices in roadside design under restricted ROW circumstances. Some of these needs were previously mentioned. The research needs are summarized below at the national and state levels:

National Level

1. A better understanding of the mechanism of vehicle encroachment is needed. Vehicles might encroach due to various reasons (e.g., human error, vehicle failure, environmental factors, and roadway engineering issues). The current body of literature offers a very limited understanding of this area, mainly due to the limited data available. Tire path data should be collected to study the causes for vehicle encroachments.
2. A full understanding of the mechanism of rollover crashes is needed. Even though many studies were found that deal with rollover crashes, a clear understanding of the mechanism of such crashes has yet to be established. Fortunately, new techniques like finite element studies, kinetics studies, and computer simulation studies are making it possible to study rollover crashes more thoroughly.
3. A better understanding of the effect of barrier offsets is needed. As mentioned earlier, contradictory findings exist in the past literature for the effect of barrier offsets. Thus, further studies are warranted for the development of implementation guidelines.
4. A better analysis tool is needed for roadside safety analysis. The RSAP software package was developed almost a decade ago, and many issues and limitations were found with this program. Also, many studies and important findings were found within this ten-year period. This program is currently being rewritten and updated under NCHRP 22–27 and is slated to be completed in late 2011.

For the State Of Indiana

1. Updating state level guidelines is needed. As the fourth edition of the AASHTO RDG and the AASHTO HSM are published, some revisions should be considered for the Indiana Design Manual.
2. An empirical study with data from Indiana would reliably confirm the recommendations of this study. The simulation study provided some general ideas about the effects of different strategies, but limitations were also identified. An empirical study with data from the State of Indiana would provide more reliable conclusions and would be more site-specific. An empirical study is strongly recommended for implementation purposes.

6.6 Summary

The efforts presented in this report were conducted by the Purdue University Center for Road Safety research team in order to understand the mechanism of roadway departure crashes and to identify the effects of some potential strategies. This study provided an overview of the statistics at the national level, a literature review from both the U.S. and other countries where narrow or no clear zone is used, and a simulation study. Potential strategies for restricted ROW scenarios were identified, as well as the study's limitations and future research directions.

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