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INDIANA DEPARTMENT OF TRANSPORTATION  
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## Performance Assessment of Road Barriers in Indiana



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## **JOINT TRANSPORTATION RESEARCH PROGRAM**

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<b>16. Abstract</b> <p>Road barriers have been used as an effective countermeasure to prevent exposure of errant vehicles to both vehicles travelling in the opposite direction and to roadside hazards. The objective of this study was to evaluate the in-service safety performance of three types of road barriers (concrete barriers, steel W-beam guardrails, and high-tension cable barriers) in Indiana using cross-sectional analysis based on crash data. The quantitative evaluation was comprised of three components: 1) the effect of the road, barrier scenarios, and traffic on the barrier-relevant (BR) crash frequency, 2) the effect of the road and the barrier scenarios on the BR harmful events, and 3) the effect of the BR events and other conditions on the injury outcomes.</p> <p>The introduction of the BR harmful events linked the crash onset with its outcome. The three developed statistical models were connected through their inputs-outputs and followed the sequence of various BR events during the BR crash. This improvement allowed a more comprehensive and insightful analysis of the barriers' safety effects and a more efficient use of data. The injury outcomes were estimated for all the individuals in a crash rather than for the most severe outcome of a crash. Further improvement of the cost estimates was accomplished by utilizing hospital data.</p> <p>For median barriers, this study found that the total number of BR crashes was higher with the use of median barriers, mostly due to the introduction of collisions with barriers and an increase in the collisions after redirecting vehicles back to traffic. These undesirable effects of barriers were surpassed by the positive results of reducing hazardous events such as cross-median crashes, rollover events, and collisions with roadside hazards, which substantially reduced the number of severe injuries and fatalities.</p> <p>The average (unit) crash costs were estimated for roads without barriers and for roads with various barrier scenarios. The crash costs were reduced by 50% where cable barriers were in medians wider than 50 feet and where concrete barriers or guardrails were in medians less than or equal to 50 feet wide. Roadside barriers (guardrails) reduced the unit crash costs by 20% to 30%.</p> <p>Median cable barriers were found to be the most effective among all the studied barriers due to the smallest increase in the crash frequency and least severe injuries in barrier-relevant crashes. A cable barrier's offset to the travelled way was also investigated in this study. When considering vehicles moving in one direction, the nearside cable barriers installed at an offset less than or equal to 30 feet performed better than far-side cable barriers with a larger offsets thanks to the better protection they provide for vehicles against rollovers in the median and impact with the median drain. Consequently, the biggest safety benefit can be expected where cables barriers are installed in the median at both edges.</p> <p>The results were implemented through a set of crash modification factors and unit crash costs estimated for 51 road-barrier scenarios. An implementation procedure is provided to quantify the crash costs and the safety benefits for these scenarios.</p>			
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## EXECUTIVE SUMMARY

### PERFORMANCE ASSESSMENT OF ROAD BARRIERS IN INDIANA

#### Introduction

An in-service performance study of widely used types of barriers was conducted for various road conditions in Indiana to help designers and highway engineers select the most promising solutions among viable alternatives. The current guidelines for median barriers recommend conducting such studies. The recent introduction of high-tension cable barriers in medians has provided highway agencies with an additional barrier alternative that must be evaluated together with the other alternatives.

The in-service performance study investigated three types of road barriers: concrete walls, W-beam guardrails, and high-tension cable barriers installed on divided roads in Indiana. The performance for barriers on undivided roads was not analyzed in this study due to the limited crash data and the lack of embankment information. Nevertheless, the results obtained for the studied roads and the past research on the impact of medians on safety allowed extrapolation to include undivided multilane roads among the results for implementation. Furthermore, the obtained results for cable barriers allowed including double-run median cable barriers, which are not yet implemented in Indiana.

#### Findings

The evaluation of the in-service performance of barriers considered all types of crashes whose frequency and severity might be affected barriers: run-off-road crashes, rollovers, collisions after vehicle's redirection, and head-on collisions. Three effects of barriers were investigated: the effect of barriers on the crash frequency (road level), the effect of barriers on the probability of harmful events (crash level), and the effect of harmful events on the probability of injury outcomes (person level).

For median barriers, this study found that the number of barrier-relevant crashes was higher with the use of median barriers, mostly due to the additional collisions with barriers and the increased redirecting of vehicles back to traffic. These undesirable effects of barriers were surpassed by reducing the frequency of highly hazardous events such as cross-median crashes, rollover events, and collisions with firm roadside hazards. This shift from more harmful to less harmful events substantially reduced both the fatalities and the severe injuries.

The average (unit) crash costs were estimated for roads without barriers and for roads with various barrier scenarios. The crash costs were reduced by 50% where cable barriers were in medians wider than 50 feet and where concrete barriers or guardrails were in medians less than or equal to 50 feet wide. Roadside barriers (guardrails) reduced the unit crash costs by 20% to 30%.

Median cable barriers were found to be the most effective among all the studied barriers due to both the smallest increase in crash frequency and least severe injury outcomes. A cable barrier's offset to the travelled way was also investigated in this study. When considering vehicles moving in one direction, the nearside cable barriers installed at an offset of less than or equal to 30 feet performed better than far-side cable barriers with a larger offset, thanks to the better protection they provide against rollovers in the event of impact with the median drain. Consequently, the biggest safety benefit can be expected where cable barriers are installed in the median along both its edges.

#### Implementation

Implementation of the results of this study is facilitated with a set of crash modification factors (CMFs) and unit crash costs (UCCs) estimated for the studied 51 road-barrier scenarios. These scenarios involve concrete walls, guardrails, and single- and double-run cable barriers installed in medians, as well as roadside guardrails installed on one or both sides of divided and undivided multilane roads. The estimated CMFs and UCCs are key components of a procedure developed for evaluating the safety benefits of barriers using either comprehensive or economic costs. The procedure is applicable to multilane new and modernized existing roads.

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## LIST OF ABBREVIATIONS

### Median Scenarios

M_NB_Nar	median 50 feet or narrower and no median barrier
M_NB_Wide	median wider than 50 feet and no median barrier
M_BW	median concrete barrier placed in the center of a narrow median
M_GR	median guardrail (steel W-beam) placed in the median center or near its edge
M_CB_Near	median cable barrier (nearside) with a lateral clearance 30 feet or less to the travelled way
M_CB_Far	median cable barrier (far-side) with a lateral clearance more than 30 feet to the travelled way

### Roadside Scenarios

S_GR	roadside guardrail
S_NB_Low	no guardrail, roadside hazard rating 1 or 2
S_NB_High	no guardrail, roadside hazard rating from 3 to 7

### Event Categories

XH	cross-median head-on event
XNH	cross-median non-head-on event
RHV	redirected and hit another vehicle event
MB/BW	median concrete barrier wall collision
MB/GR	median guardrail (face) collision
MB/CB1	nearside median cable barrier collision (offset 30 feet or less)
MB/CB2	far-side median cable barrier collision (offset more than 30 feet)

SB	roadside barrier collision event
HR	non-cross-median high-risk event (e.g., rollover or hitting a sturdy fixed object)
MR	non-cross-median moderate-risk event (e.g., hitting a weak object, running over a ditch, etc.)

### KABCO Injury Scale

K	fatality
A	incapacitating injury
B	non-incapacitating injury
C	possible injury
O	property-damage-only

### Others

AADT	annual average daily traffic
ADT	average daily traffic
AASHTO	American Association of State Highway and Transportation Officials
ARIES	Automated Reporting Information Exchange System
BR	barrier-relevant
CMF	crash modification factor
INDOT	Indiana Department of Transportation
RDG	Roadside Design Guide
ROR	run-off-road
SPF	safety performance factor or function
MAIS	Maximum Abbreviated Injury Scale
MASH	Manual for Assessing Safety Hardware
NCHRP	National Cooperative Highway Research Program
UCC	unit crash cost
WMS	Work Management System

## 1. INTRODUCTION

A philosophy that should drive road design is appropriate allocation of limited resources to maximize the system-wide performance. This approach targets investment decisions to the roadway system as a whole and systemic improvements that provide for the greatest expected crash reduction statewide. A well-defined and documented design scope provides a reliable statement of project costs. Any tools developed to evaluate safety performance should provide an accurate early assessment of the safety. This report describes research aimed to develop a method of predicting the safety performance of road barriers – an important means of improving safety.

Run-off-road (ROR) crashes, or roadway departure crashes, tend to be severe if the off-roadway environment exposes the occupants of errant vehicles to unforgiving roadside features. ROR crashes, combined with other travel lane departure crashes, such as head-on and same-direction-sideswipe, often lead to severe (fatal and incapacitating injury) crashes. These crash types together typically account for over 50% of all fatal crashes in any given year. The worst case scenario is that a vehicle crosses the median or centerline and collides with vehicles travelling in the opposite direction.

Forgiving design, such as dividing roads with sufficiently wide medians and providing sufficiently wide roadside clear zones, are used to mitigate the occurrence and outcome of roadway departure crashes. While these countermeasures are efficient in enhancing safety, such liberal cross-section dimensions are not a viable option where the land is developed with costly structures or where the terrain topography requires expensive engineering solutions. Another viable countermeasure, the use of road barriers, is becoming increasingly attractive at a time when land development along existing roads is growing, thereby reducing the availability of inexpensive land for new roads.

Road barriers can be divided into the following categories based on the deflection range into rigid barriers (e.g., concrete barriers), semi-rigid barriers (e.g., W-beam guardrails), and flexible barriers (e.g., cable barriers). Depending on their placement, barriers can be installed either in the median or along the roadside. Concrete barriers (or barrier walls) and W-beam guardrails (here on called guardrails) have been in use for a long time. Concrete barrier walls are mostly used in narrow medians on high-traffic routes. Guardrails are used either in the median or along the roadside with the latter being the majority. High-tension cable barriers were introduced recently to the U.S. and are garnering attention due to their considerable safety benefits. Compared to its predecessor, the low-tension cable barrier, the high-tension cable barrier has a much smaller deflection. High-tension cable barriers are generally used in wider medians as an alternative to guardrails when the clearance to the obstruction behind the barriers is sufficiently large. The Indiana Department of Transportation (INDOT)

began installing high-tension cable barriers in 2006 on interstates with wide medians.

Official federal and state guidelines support the decision-making process for the use of barriers. The American Association of State Highway and Transportation Officials (AASHTO) Roadside Design Guide (RDG) (AASHTO, 2011) suggests that roadside barriers are to be used based on the premise that striking a barrier is less dangerous than a rollover or striking a roadside object. This premise of a less hazardous barrier may involve a large dose of uncertainty in cases where knowledge is limited. To reduce this uncertainty, there is a need for research on the differences in the risk and severity of the injuries associated with barriers and various roadside hazard conditions.

According to the RDG, a median barrier is optional when the median width is 30 to 50 feet and normally is not considered when the median width is larger than 50 feet. However, the use of road barriers has expanded during the last several years and some states have installed have begun to install median barriers on medians wider than 50 feet (Ray, Silvestri, Conron, & Mongiardini, 2009). For cable barriers in particular, most states now recommend their use in 40 to 75 feet wide (Sheikh, Alberson, & Chatham, 2008).

The expanded scope of the application of median barriers and the recent introduction of high-tension cable barriers have provided designers with more viable barrier alternatives. Understanding the safety performance of various types of barriers with different barrier placement setups under various conditions is important. More than one type of barrier may be used for the given traffic, roadway cross-section, and roadside hazard conditions. For instance, both high-tension cable barriers and W-beam guardrails could be viable median barrier alternatives for a wide median (e.g., 60 feet), whereas both concrete barrier walls and W-beam guardrails could be considered in a narrow median (e.g., 30 feet). Careful consideration of the alternatives is required before a barrier type is selected, but once a barrier type is selected, its proper placement is also worthy of consideration.

Uniform guidelines were established to assess the structural performance of road barriers through full-scale crash tests. Although the evaluation based on the testing results are necessary at the beginning stage of a new or modified barrier design, the real-world barrier application conditions are so complex that the actual barrier performance should be obtained by in-service evaluation. Unlike the standard tests which measure barrier performance under specified impact angles and vehicle types, in-service performance evaluation focuses on the observed average safety performance. Moreover, in-service performance evaluation can lead to reliable cost-benefit analyses with information on installation, maintenance, and repair costs. In-service evaluation is particularly useful in an agency's decision-making on whether or not to use barriers, as well as what barriers should be used under given roadway and roadside characteristics.

Thus, the objectives of this study are as follows:

1. Assess the in-service safety performance of barriers based on the comparison of crashes with and without barriers under similar roadway conditions.
2. Compare the in-service safety performance among different types of barriers and different placement setups.
3. Develop procedures to predict the safety benefits due to barrier treatments.
4. Provide guidance for deciding whether, where, and which types of barriers should be installed.

The studied barriers include median and roadside barriers and are composed of three types: concrete barriers, guardrails, and high-tension cable barriers, all of which are longitudinal barriers. The presented study does not consider barrier end treatments, noise barriers, and temporary work zone barriers. The roadway segments with/without barriers include the INDOT-administered divided freeways and rural/suburban non-freeway roads. The studied crashes are barrier-relevant (BR) crashes and include barrier collision crashes, cross-median crashes, and fixed roadside object collision crashes. Off-roadway rollover crashes and crashes in which vehicles run off the roadway, are redirected back to the roadway, and collide with other vehicles are also included. Thus, the BR crashes include both single and multiple vehicle crashes.

This report is divided into ten chapters and two appendices:

- Chapter 1 introduces the research problem, objectives, and scope of the reported study.
- Chapter 2 reviews the existing literature on the use and in-service performance of road barriers.
- Chapter 3 introduces the research approach applied in this study.
- Chapter 4 details the data collection, cleaning, and summary.
- Chapter 5 analyzes the crash frequency affected by barriers and discusses the corresponding crash frequency model.
- Chapter 6 analyzes the probability of events involved in a ROR crash and discusses the corresponding event model.
- Chapter 7 analyzes the personal injuries and discusses the corresponding injury model.
- Chapter 8 describes the method and results for estimating the unit crash cost by applying the events and injury models.
- Chapter 9 explains the procedures for calculating the safety benefit of various road-barrier scenarios.
- Chapter 10 summarizes the primary findings and contributions of this study.
- Appendix A provides the instruction manual, which will be helpful for defining and selecting homogeneous road segments.
- Appendix B lists the ROR-related variables extracted from the crash reports.

## 2. LITERATURE REVIEW

This chapter comprehensively reviews the literature addressing the use and in-service performance of road

barriers. The relevant federal and Indiana guidelines and manuals are reviewed first, followed by the findings of the in-service performance evaluation of road barriers. The chapter concludes with a discussion of both the limitations of the past research and the gaps this study intends to fill.

### 2.1 Official Guides and Manuals

#### 2.1.1 Crashworthy Performance Evaluation

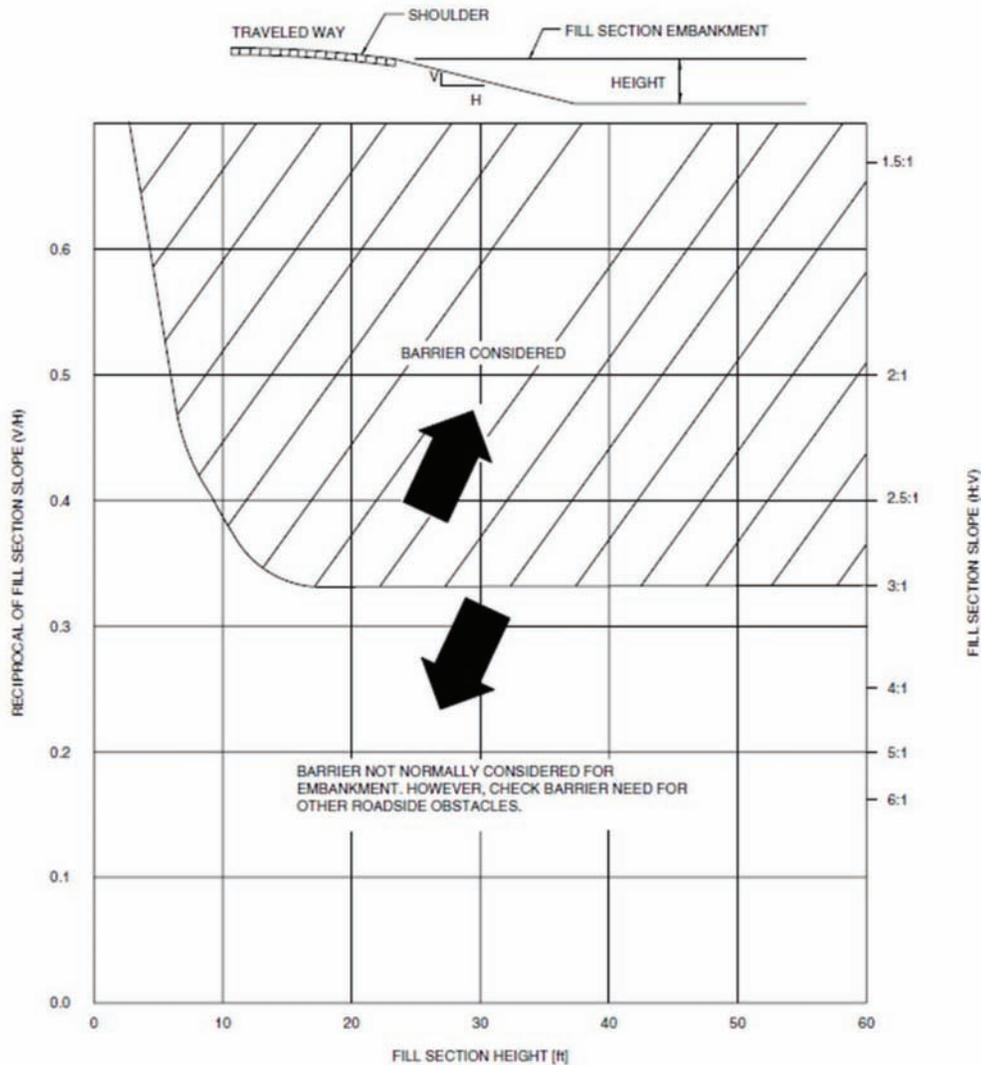
The AASHTO Manual for Assessing Safety Hardware (MASH) and NCHRP Report 350, "Recommended Procedures for the Safety Performance Evaluation of Highway Features" (Ross, Sicking, & Zimmer, 1993), provide full-scale crash testing and evaluating procedures for new or modified road barriers before barriers are implemented. MASH replaced and updated NCHRP Report 350. As of January 1, 2011, new roadside safety hardware must meet the MASH criteria, while products accepted under NCHRP Report 350 before that date are not required to be retested under MASH. Six test levels were established to represent the crashworthy performance of barriers under different combinations of speed and impact angle. Crashworthy performance is represented by the occupant risk, the structural integrity of the barrier, and the post-impact behavior of the vehicle.

#### 2.1.2 Barrier Use Guidelines

The AASHTO Road Design Guide (RDG) provides guidelines and recommendations on the use of both roadside barriers and median barriers. The RDG defines a roadside barrier as "a longitudinal barrier used to shield motorists from natural or man-made obstacles located along either side of a traveled way." Roadside barriers are generally considered when the consequences of running off the roadway without the protection of barriers are believed to be more serious than barrier collisions. Embankments and roadside obstacles are the two most common conditions that need to be shielded by roadside barriers. Figure 2.1 shows the RDG's suggested criteria for assessing the need for a barrier based on the embankment's characteristics.

Median barriers are used to separate opposing traffic on divided highways and to redirect vehicles striking the barriers from either side. The RDG provides recommendations on the use of median barriers based on the average daily traffic (ADT) and median width as shown in Figure 2.2. The RDG also indicates that some states have expanded the use of median barriers due to the increased number of observed cross-median crashes. A cost/benefit analysis is recommended to justify the decision to expand the use of median barriers.

The 2013 Indiana Design Manual of the Indiana Department of Transportation (INDOT) adopted barrier warrant criteria similar to the RDG but classified the criteria into more roadway scenarios. For roadways of four or more lanes (divided and undivided), INDOT's warrant for roadside barriers based on the



**Figure 2.1** Roadside barrier consideration for embankments (AASHTO, Roadside Design Guide, 2011).

characteristics of embankments is the same as that for the RDG as shown in Figure 2.1. For two-lane two-way roadways, it also considers the ADT and design speed as criteria. Figure 2.3 is an example of the roadside barrier warrant for embankments on two-lane two-way roadways with a design speed of 35 mph or 40 mph.

The median barrier warrant in the Indiana Design Manual, shown in Figure 2.4, is similar to the RDG, but the traffic criteria in the Indiana Design Manual is the 20-year projected ADT while the RDG criteria is the five-year projected ADT. The Indiana Design Manual also requires the use of a median barrier on free-ways or expressways with a design speed of 50 mph or higher and median crossings at least one mile apart.

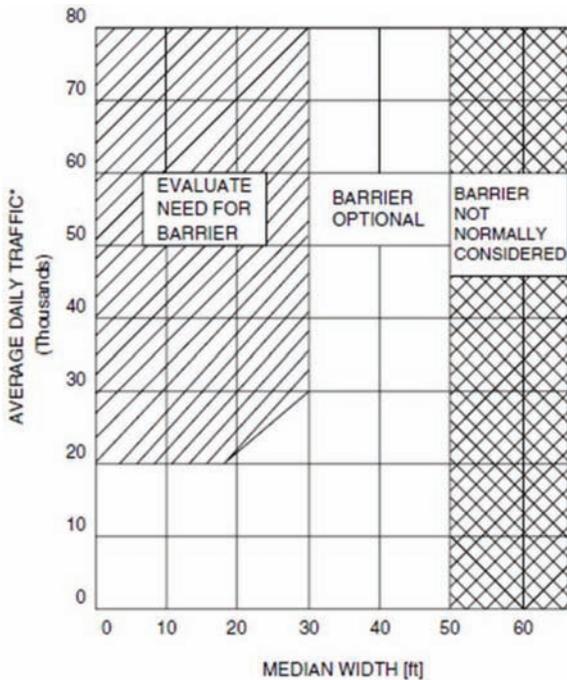
### 2.1.3 Summary of the Official Guides and Manuals

NCHRP Report 350 and MASH established a standard procedure to test the performance of road barriers before they are fully implemented in the field. They classified barriers into different test levels depending on

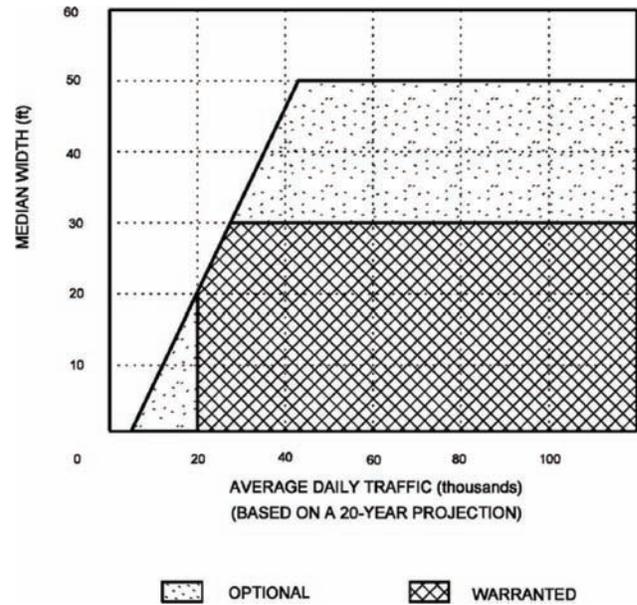
the local traffic composition and geometrics. The crash tests are limited to certain types and weights of test vehicles, and the testing is conducted for pre-determined impact angles, which might not represent in-field impacts from errant vehicles. Thus, both guidelines indicate that in-service evaluation is necessary and important in assessing the efficiency of a roadside product and providing in-depth knowledge.

The guidelines and warrants for the use of median and roadside barriers are available in the RDG and the Indiana Design Manual. The ADT and median width are used as the criteria for considering median barriers; and the embankment height, embankment slope, and roadside obstacles are for considering roadside barriers. These guidelines not only help agencies properly select and install barrier systems but also provide the structural and safety characteristics of different types of barriers.

It is important to note that for median barriers, many states have expanded their use and thus have developed their own specific median barrier guidelines,



**Figure 2.2** Median barrier guidelines on high-speed, fully controlled-access roadways (AASHTO, Roadside Design Guide, 2011).



**Figure 2.4** Median barrier warrants (INDOT, 2013).

Almost all of the aforementioned guides and manuals state that there is no one-size-fits-all recommendation on the use of barriers and conducting in-service evaluations are therefore suggested of the safety performance of barriers to validate their cost-effectiveness for local applications. The RDG recommends that the in-service evaluation include factors such as traffic volumes, vehicle classifications, median crossover history, crash incidents, vertical and horizontal alignment relationships, and median-terrain configurations.

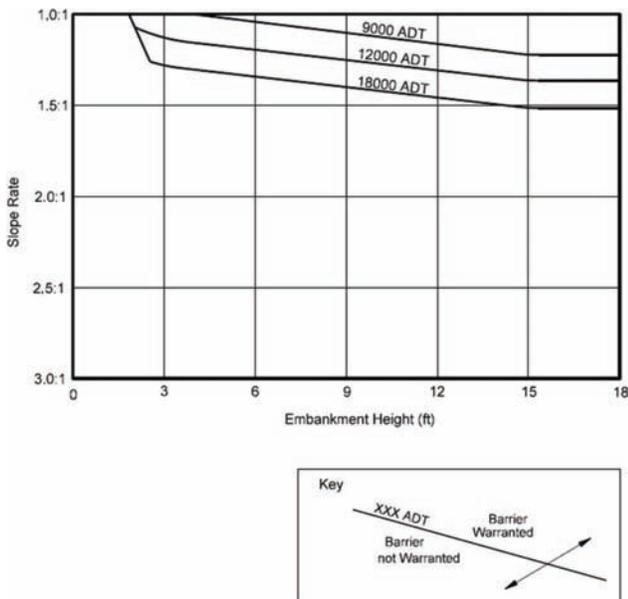
## 2.2 In-Service Evaluation

According to NCHRP Report 490: “In-Service Performance of Traffic Barriers” (Ray, Weir, & Hopp, 2003), the purpose of in-service evaluations of roadside features such as road barriers is twofold:

1. Determine how barriers perform under field conditions, and
2. Assess how full-scale crash tests are representative of the way collisions occurred under field service conditions.

As NCHRP Report 490 pointed out, although the importance of in-service evaluation is well recognized, there is no universal formal process at the current time for in-service evaluation; the procedures and methods that have been used are ad-hoc and provide varied results.

In-service evaluation of the safety performance of road barriers generally includes an assessment of the barrier’s crash frequency, crash injury-severity and cost-effectiveness. Since the use of barriers reduces the recovery zone for errant vehicles, many states have found that the crash frequency has increased since barriers were installed. However, not all types of crashes have increased proportionally. Rather, certain crashes that are normally associated with more severe injuries



**Figure 2.3** Roadside barrier warrant for embankment (two-lane, two-way, 35 or 40 mph) (INDOT, 2013).

with consideration of their state’s median crossover history and number of fatalities. For example, many states have installed median cable barriers on wide medians ranging from 40 feet to 75 feet (Sheikh et al., 2008). Due to the considerable attention given to cable barriers and their rather short history, it is important to investigate their in-service performance.

(e.g., cross-median crashes, fixed roadside object collisions, etc.) have greatly decreased, while some less severe crashes began to occur (e.g., barrier collisions) or increased (e.g. same direction side swipe crashes). Since barriers themselves are hazards, their forgiveness compared to the hazards they prevent also needs to be investigated. Installing and repairing barriers can be costly, thus the cost-effectiveness of barriers must be checked as well.

### 2.2.1 Crash Frequency

Past research has found that the number of severe crashes has been reduced through the use of barriers. Given the growing attention to forgiving roadside design, more recent research studies focused on the performance of cable barriers. Sheikh et al. (2008) summarized the advantages of using high-tension cable barriers by pointing out their low installation cost, low impact on errant vehicles, minimal visual intrusiveness, and large sight distance. The disadvantages include their high repair cost (must be repaired after each impact), increased deflection distance, and required periodic re-tensioning.

Past investigation of the effect of barriers on crash frequency focused on selected types of crashes rather than on all the types of crashes possibly affected by the presence of road barriers. The investigated types of crashes were defined based on the manner of collision, the hazardous events, and/or the number and type of vehicles involved. A few of these studies are discussed in the following subsections.

**Manner of collision or hazardous event.** Crash types by the manner of collisions or hazardous events include ROR crashes, head-on crashes, cross-median crashes, fixed object collisions, etc. In North Carolina, one of the states that pioneered the use of cable barriers, Hunter et al. (2001) found that the number of total crashes, rear-end crashes, ran-off-road-left and hit-fixed-object crashes increased at locations with installed cable barriers. However, serious crashes, such as head-on crashes, decreased. Consequently, the overall safety measured with an equivalent property-damage-only index improved.

Donnell and Manson (2006a) investigated the relationship between median-related crashes and geometry and traffic variables. The obtained modeling results revealed that the frequency of cross-median crashes and median barrier crashes tended to be lower on segments with wider medians and larger barrier offsets. Another study (Donnell & Manson, 2006b) investigated the frequency of median barrier crashes on Pennsylvania interstate highways. Crash frequency models based on negative binomial regression were developed for the non-toll portion of the interstate highway and the turnpike toll road. The modeling results indicated that the presence of interchange entrance ramps were associated with a higher frequency of crashes with median barriers on the non-toll portion while there was a lower crash frequency on the turnpike toll road. In addition,

the frequency of crashes with median barriers tended to be higher where the speed limit was higher.

Chimba, Emaasit, Allen, Hurst, and Nelson (2014) investigated the factors of the frequency of median-related crashes. They found that frequencies of median crashes higher than elsewhere were on road segments with high traffic volumes, horizontal curves, cable barriers placed close to the median edge, and a considerable difference in elevation of the opposite travelled ways.

**Frequency change of crashes by number of vehicles involved.** Tarko, Villwock, and Blond (2008) investigated the impact of median designs on crash frequency and severity. The investigated crashes were classified as three types: single-vehicle, multiple-vehicle same direction, and multiple-vehicle opposite direction. The authors found that reducing the median width without adding barriers increased the crash severity and reducing the median width and installing concrete barriers eliminated opposite direction crashes. However, in so doing, the frequency of single vehicle crashes doubled and the crash severity tended to increase. Before-and-after studies conducted by Villwock, Blond, and Tarko (2011) indicated that installing high-tension median cable barriers can eliminate 94% of multiple vehicle opposite-direction crashes but can increase single vehicle crashes on wide depressed medians by 70%.

**Frequency change of crashes by vehicle type.** Although most of the past barrier studies investigated barrier performance based on the fact that the majority of the involved vehicles were passenger cars and trucks, a few studies specifically focused on the safety performance of barriers on motorcycle crashes.

Daniello and Gabler (2011a) investigated the effect of the barrier type on motorcycle-barrier crashes in North Carolina, Texas, and New Jersey and concluded that motorcycles comprise only 3% of the vehicles on the road but account for nearly 50% of all fatalities in guardrail collisions and 22% of the fatalities in concrete barrier collisions.

Jama, Grzebieta, Friswell, and McIntosh (2011) conducted a retrospective study on fatal motorcyclist-road barrier collisions in New Zealand and Australia and found that the fatalities involving W-beams, concrete, wire rope barriers, and other barriers (e.g., bride rails) accounted for 72.7% (with a total length of 5,565.4 km), 10.4% (with a total length of 672.9 km), 7.8% (with a total length of 1234.6 km), and 9.1% respectively. Their results also suggested that inappropriate speed and the consumption of alcohol and drugs were the frequent circumstances associated with motorcyclist-road barrier fatalities.

### 2.2.2 Crash Injury

The objective of most injury analysis studies is to identify the changes in the probability of certain injury outcomes due to the use of barriers. Most studies classified crash severity with the KABCO scale. The

original five levels are often combined due to the limited number of severe injuries (e.g., K+A, B+C, O).

Hu and Donnell (2010) developed a nested logit model to investigate median barrier crash severity on rural divided highways in North Carolina. The results indicated that collisions with cable median barriers tended to result in less severe injuries (i.e., fatality, incapacitating injury, and non-incapacitating injury) than collisions with concrete or guardrail median barriers. They also found that the probability of severe outcome crashes was lower when the offset of a median cable barrier is higher or the fore-slope is flatter. Based on an ordinal logistic regression model, injury analysis on cross-median crashes and median-related crashes by Donnell and Manson (2006a) found that drivers under the influence of drugs and dry pavement surfaces were more likely to result in fatalities and injuries. An analysis of fatal motorcycle collisions conducted by Daniello and Gabler (2011b) concluded that collisions with trees, guardrails, and concrete barriers were 15 times, 7 times, and 4.1 times more likely, respectively, to be fatal than an impact with the ground after a fall.

Based on the results of a nested logit model, Holdridge, Shankar, and Ulfarsson (2005) concluded that striking concrete barriers and guardrails resulted in a lower probability of incapacitating and non-incapacitating injuries when compared to collisions with fixed roadside objects. Martin, Mintsá-Eya, and Goubel (2013) found that concrete barriers are less effective than W-beam guardrails in reducing cross-median crashes.

Zou, Tarko, Chen, and Romero (2014) investigated the risk of injury associated with colliding with a barrier. The results indicated that from the viewpoint of injury risk, nearside cable barriers (offset between 10 and 29 feet) performed best, followed by far-side cable barriers (offset at least 30 feet), guardrails, and concrete barriers.

### 2.2.3 Cost-Effectiveness

Cost-effectiveness studies must consider the barrier's effect on the crash frequency and severity. Crashes of certain types and with certain injury outcomes are represented with corresponding costs. The reduction in the cost of all crashes after installing a barrier is the benefit of the barrier. The benefit-cost ratio is estimated by including the costs of barrier installation, maintenance, and crash repair during the barrier's service life.

Miaou, Bligh, and Lord (2005) conducted a benefit-cost analysis and a sensitivity analysis to develop the guidelines for concrete and high-tension cable barriers. They obtained the mean benefit-cost ratios for high-tension cable barriers and concrete barriers.

Donnell and Manson (2006a) conducted a benefit-cost analysis of median concrete barriers and W-beam guardrails and developed median barrier placement guidelines based on the benefit-cost ratio. The developed guidelines considered the directional ADT and the

median width. The authors also provided a crash-based warrant for the use of median barriers in medians wider than 70 feet.

Sicking, Albuquerque, Lechtenberg, and Stolle (2009) examined crashes that occurred in Kansas and developed guidelines for the use of median cable barriers based on the Roadway Safety Analysis Program software developed to evaluate the impacts of roadside safety improvements. The benefit-cost ratios estimated under various combinations of ADT and median width indicated that a median cable barrier generally should not be considered in medians wider than 70 feet.

Chitturi, Ooms, Bill, and Noyce (2011) estimated the comprehensive injury costs of cross-median crashes and median barrier crashes. Their results showed that the injury costs for concrete median barriers were roughly 20% of that of multiple vehicle cross-median crashes and 50% of single vehicle cross-median crashes. They recommended the use of crash type-specific costs.

### 2.2.4 Summary of In-service Evaluation Studies

Previous research also studied the in-service safety performance of road barriers from various perspectives, with the safety performance of high-tension cable barriers being the recent research focus. The in-service study can be generally divided into three areas: (1) crash frequency, (2) crash injury, and (3) cost-effectiveness.

For crash frequency analysis, numerous studies focused on the use of median barriers, especially median cable barriers. Many studies reported that cross-median crashes were substantially lower if a median barrier was present. These studies also developed statistical models to identify the factors that affect the median barrier crash frequency. Before-after or cross-sectional approaches have been used. However, a limited number of studies examined crashes that were affected by barriers other than cross-median crashes and median barrier crashes. Even for cross-median crashes, however, many of the studies were not able to properly handle those crashes using statistical models due to their infrequency. Analysis based on only a portion of the crashes that are affected by barriers might either underestimate or overestimate a barrier's performance.

Injury analysis studies have found that the use of barriers results in lower probability of fatalities or severe injuries. However, all the past barrier-related injury research reviewed in this study was based on the crash level. That is, they did not analyze the personal injury directly but instead used the most severe injury level of all the occupants involved in a crash to represent the injury level of the crash and then analyzed the barrier's effect on the crash injury.

Crash level injury analysis is associated with limitations, particularly in the context of analyzing the effects of barriers. There is an irrefutable possibility that the studied conditions, in this case barrier-oriented, affect not only the highest personal injury of people involved in a crash but also the number of people injured. The

average crash costs are typically estimated for less refined scenarios, thus the effect of the condition cannot be fully reflected. The more appealing approach is to investigate the injury outcomes of the individual persons involved in a crash.

Most of the past studies that considered the individual occupants of the involved vehicles and did not necessarily focus on the barriers, were limited to specific types of occupants such as drivers (Kockelman & Kweon, 2002; Ulfarsson & Mannering, 2004) or front-seat passengers (Hutchinson, 1986; Shimamura, Yamazaki, & Fujita, 2005). The common reason for limiting studies to certain types of occupants was the limited crash data available and the concern about possible error dependence for occupants sharing the same vehicle. Only a few studies attempted to investigate the injury severity of all the vehicle occupants (Eluru, Paleti, Pendyala, & Bhat, 2010; Zhu & Srinivasan, 2011).

Most of the previous studies addressing the cost-effectiveness of barriers estimated the benefit-cost ratios under various scenarios of AADT and median width. Some of these studies also included the history of cross-median crashes to supplement the guidelines. The key component of these studies was estimation of the crash cost reduction attributed to the use of barriers.

Overall, most of the past studies focused on particular types of barriers or particular types of crashes (e.g., cross-median crashes, cable barriers, motorcycles, etc.), and did not fully capture the barriers' effects on all the involved vehicle occupants. Furthermore, the effects of barrier placement factors, such as the barrier's offset, were not addressed by most of the past studies due to the lack of data (Hu & Donnell, 2010). Ray et al. (2009) pointed out that the placement of median cable barriers varied considerably across the states. For example, in some states cable barriers are placed almost in the center of the median while in other states they are offset at least 6 feet from the centerline of the ditch. The authors suggested more research on this subject.

## 2.3 Modeling Approaches

### 2.3.1 Crash-Frequency Modeling

Crash-frequency modeling in traffic safety has focused on the association between the studied road and its traffic variables and the total number of crashes on a road segment or at an intersection over a time period (Lord & Mannering, 2010; Mannering & Bhat, 2014). Since the crash count is a non-negative integer, simple linear regression is not appropriate. Count models as generalized linear models have been applied instead. The Poisson model is the simplest generalized linear model. Its assumption of the conditional mean equal to the conditional variance is often violated due to the over- and under-dispersion exhibited by the crash data. Negative binomial models (Miaou, 1994; Poch & Mannering, 1996) – an extension of Poisson models – can handle over-dispersed crashes and eventually replaced the Poisson model.

Other extensions based on Poisson models include the Conway-Maxwell-Poisson model (Lord, Geedipally, & Guikema, 2010; Lord, Guikema, & Geedipally, 2008), the double Poisson model (Zou, Geedipally, & Lord, 2013), the hyper-Poisson model (Khazraee, Sáez-Castillo, Geedipally, & Lord, 2014), the Poisson-lognormal model (Park & Lord, 2007), the Poisson-Weibull model (Cheng, Geedipally, & Lord, 2013), among others. The Conway-Maxwell-Poisson model, double Poisson model, and hyper-Poisson model can handle both over- and under-dispersion, although under-dispersion is rarely seen in crash data. Extensions of the negative binomial models include the negative binomial-Lindley model (Geedipally, Lord, & Dhavala, 2012). To take care of a large number of zero counts found in some crash data (particularly for a short segment in a short period), zero-inflated Poisson and negative binomial models (Carson & Mannering, 2001; Lee & Mannering, 2002; Miaou, 1994; Shankar, Milton, & Mannering, 1997) have been applied for their improved statistical fit. Their use in highway safety should be accompanied with caution since the dual-state data generating process in the zero-inflated models might not reflect the actual safety situation (Lord et al., 2005; Lord et al., 2007).

Recent advancements in crash-frequency modeling include random parameter models (Anastasopoulos & Mannering, 2009; Chen & Tarko, 2014; Mitra & Washington, 2012) and finite mixture/Markov switching frequency models (Malyskina & Mannering, 2010; Park & Lord, 2009). The major difference between the two approaches is that the former assumes a continuous distribution (e.g., normal distribution) on the parameters for different observations while the latter uses a discrete distribution (e.g., distinct subgroups). Recent advancements also include non-parametric approaches such as the artificial neural network (Chang, 2005) and the support vector machine (Li, Lord, Zhang, & Xie, 2008). Although these methods have weaker assumptions and tend to provide a better fit, their interpretability is relatively poorer and the estimation is more complex.

### 2.3.2 Crash-Severity Modeling

Crash-severity studies typically focus on the association between the probability of an observation (normally a crash) resulting in a certain injury outcome and investigated variables (e.g., vehicular and occupants' characteristics) conditioned on the crash occurrence (Savolainen, Mannering, Lord, & Quddus 2011). A severity analysis is often conducted at the crash level, and the injury outcome of a crash is represented by the injury outcome of the most severely injured occupant. Since the injury outcome is often measured based on the injury scales (e.g., KABCO scale) which have more than two levels, it is tempting to use the discrete outcome models such as the ordered logit/probit models (Abdel-Aty & Keller, 2005; Khattak, 1998) that can take care of the natural ordering. However, ordered discrete

outcome models should be used with caution due to their problems related to the underreporting of crash data and its restriction on the direction of how variables affect ordered outcomes (Washington, Karlaftis, & Mannering, 2011).

Extensions based on the ordered logit/probit have focused on addressing the endogeneity (de Lapparent, 2008), the unobserved heterogeneity across observations (Srinivasan, 2002), the heteroskedasticity in error terms (Quddus, Wang, & Ison, 2010), and the correlation among occupants involved in the same crash (Eluru et al., 2010).

Unordered discrete outcome models also have been widely used to model injury outcomes since they have fewer restrictions and tend to be more robust, although their use does not take advantage of the information in ordering. The basic unordered discrete outcome models are binary logit/probit models (Lee & Abdel-Aty, 2008; Shibata & Fukuda, 1994) and multinomial logit/probit models (Malyshkina & Mannering, 2008; Shankar & Mannering, 1996). The binary logit model often has been used when the number of observations for certain injury levels is limited and collapsing the categories will lead to binary outcomes such as injury vs. non-injury. The use of the multinomial logit model has been based on satisfaction with the independence of irrelevant alternatives (IIA) assumption (Washington et al., 2011). The IIA assumption can be tested using the nested logit model (which can be seen as a generalization of the multinomial logit model), and the violation of the IIA assumption would lead to the use of the nested logit model or other models that relax the IIA assumption (e.g., mixed logit model).

Models that can handle the unobserved heterogeneity across observations such as the mixed logit model (i.e., random parameters logit models) (Anastasopoulos & Mannering, 2011; Milton, Shankar, & Mannering, 2008) and the finite mixture/Markov switching multinomial model (Eluru et al., 2012; Malyshkina & Mannering, 2009) have been the more recent focus of modeling crash-severity. The mixed logit model is particularly noteworthy since it allows the unobserved effects of alternatives to be correlated and thus does not require a test on IIA assumption. More generalized and flexible models (Xiong & Mannering, 2013, 2014) in modeling injury also have been investigated by combining random parameters models with finite-mixture/Markov switching models. Moreover, some researchers proposed the use of non-parametric methods (Abdelwahab & Abdel-Aty, 2001; Chimba & Sando, 2009). As previously mentioned, non-parametric methods are superior in prediction but not in making inferences.

### 2.3.3 Summary of Modeling Approaches

Generally speaking, recently developed crash frequency and injury models have shown advantages in handling datasets with particular characteristics (e.g., low mean or small sample size) and gaining more insights (e.g., multiple-stage data generating process or

unobserved heterogeneity). However, the estimation of those models is more complex and often there is no closed form solution to maximum likelihood estimation. They may need to be estimated using Bayesian methods (e.g., Markov Chain Monte Carlo) or based on other numerical methods, which are likely to encounter convergence problems. Furthermore, the results of some models may not be easily transferable to other datasets (Lord & Mannering, 2010).

## 3. RESEARCH APPROACH

The literature review in Chapter 2 revealed the drawbacks of the past studies and the gaps in the current knowledge. The presented study aimed to overcome some of the weaknesses of the past research and to fill some gaps in the knowledge. The safety performance of barriers was analyzed in a broad context to achieve a comprehensive and consistent assessment of various barrier and non-barrier alternatives and was accomplished by utilizing available knowledge and data to the maximum extent and by specifying and estimating a model that represents the complete effect of barriers on safety without limiting the context to certain types of crashes or certain types of vehicle occupants involved.

The previous studies modeled crash frequency and injury without considering the intermediate events that occur, which are the important link between the onset of the crash and the eventual crash because the outcomes of these events are affected by the presence of barriers. We therefore included consideration of these events in this study, which makes the proposed approach distinctive from the past studies. Two important benefits can be achieved with the proposed expansion:

1. Increased transparency of the crash process model allows capturing additional effects inside the process, thus better representing the injury causality, and
2. There is efficient use of data by utilizing two samples, which is further discussed in the remainder of this report.

The frequency of crashes and the probability of hazardous events and their severity outcomes were estimated using existing models. All the crashes relevant to the various barriers were considered in the analysis, including single-vehicle and multiple-vehicle crashes such as (e.g., severe cross-median head-on collisions and non-severe collisions with sign posts). Both median and roadside barriers were analyzed jointly and included three types of barriers: concrete barriers, guardrails, and cable barriers. The effect of the lateral position of the barriers was also investigated together with the width of the median and the level of hazard on the roadside. This inclusive approach led to a comprehensive estimation of the crash costs for various barrier and non-barrier scenarios.

This chapter introduces the tree of events utilized in this study to conceptualize the safety effects of road barriers in a more comprehensive manner than in the

past studies. The initial complexity of the tree of events is simplified into three components corresponding to three models. Then, the techniques applied to estimate the frequencies and probabilities of events in the tree are discussed. Each individual component is captured by a statistical model, with the modeling form and relevant important setups (e.g., response variable, explanatory variable, and observation) are introduced. Finally, the usefulness of the individual results to estimate the safety benefits of barriers is briefly explained.

The types of roadways, barriers, and crashes considered in this study are specified, with emphasis on how the road type–barrier scenarios were created and how crashes relevant to the use of barriers were identified.

### 3.1 Safety Effect of Road Barriers

To comprehensively analyze the effects of barriers on safety, let us first discuss the sequence of possible hazardous events and outcomes which a vehicle (or occupant) might experience after leaving the roadway where no barrier is present (see Figure 3.1). A vehicle leaves the roadway (due to driver fatigue, bad weather, etc.) and becomes a run-off-road (ROR) vehicle. This ROR event is typically not reported if the occupants do not sustain injury and the driver is able to return to the roadway. Thus, no information is recorded about this event even if it might be considered a crash (vehicle's damage exceeds the minimum threshold). This study analyzed only reported crashes due to the lack of information about unreported crashes. Attempts were made in the past to evaluate the rate of underreporting, but these attempts did not yield confident results.

A vehicle may depart the roadway to the right (towards the roadside) or to the left (towards the roadway center). In the first case, the vehicle may be involved in a roadside crash when colliding with a roadside object or rolling over down an embankment. The vehicle also may be redirected back to the roadway (by a driver correction or by rebounding from a roadside object) and subsequently collide with another vehicle on the roadway. If the vehicle departs the roadway to the left and there is no median on the roadway, it may collide head-on with a vehicle moving in the opposite direction. Another possibility is that the vehicle may continue moving until it collides with a roadside object on the other side or rolls over the embankment. If there is a median present, the vehicle may cross the median and collide head-on with a vehicle in the opposite direction or may continue moving until it collides with a roadside object or rolls over the embankment. If the vehicle does not cross the median, it may roll over in the median or collide with an object in the median. In summary, the occupants in a ROR vehicle may be involved in various hazardous events with consequent injury outcomes. It should be noted that secondary crashes that could be caused by the original ROR crashes are not included in the analysis due to insufficient data.

The presence of barriers changes the probability of certain events and the probability of their outcomes. According to the tree of events shown in Figure 3.1, barriers affect the number of ROR vehicles reported because the use of barriers reduces the recovery zone. Barriers also are assumed to change the probability of certain crash events. For example, cross-median and median rollover events are reduced or eliminated. On the other hand, barriers may redirect vehicles back to the roadway and thereby may increase the probability of a roadway crash. Due to such a redistribution of the probabilities of crash events, the overall injury outcomes may consequently change.

### 3.2 Road Type–Barrier Scenarios

This study focused the use of barriers on all INDOT-administered roads. The roads of interest are generally divided into three types:

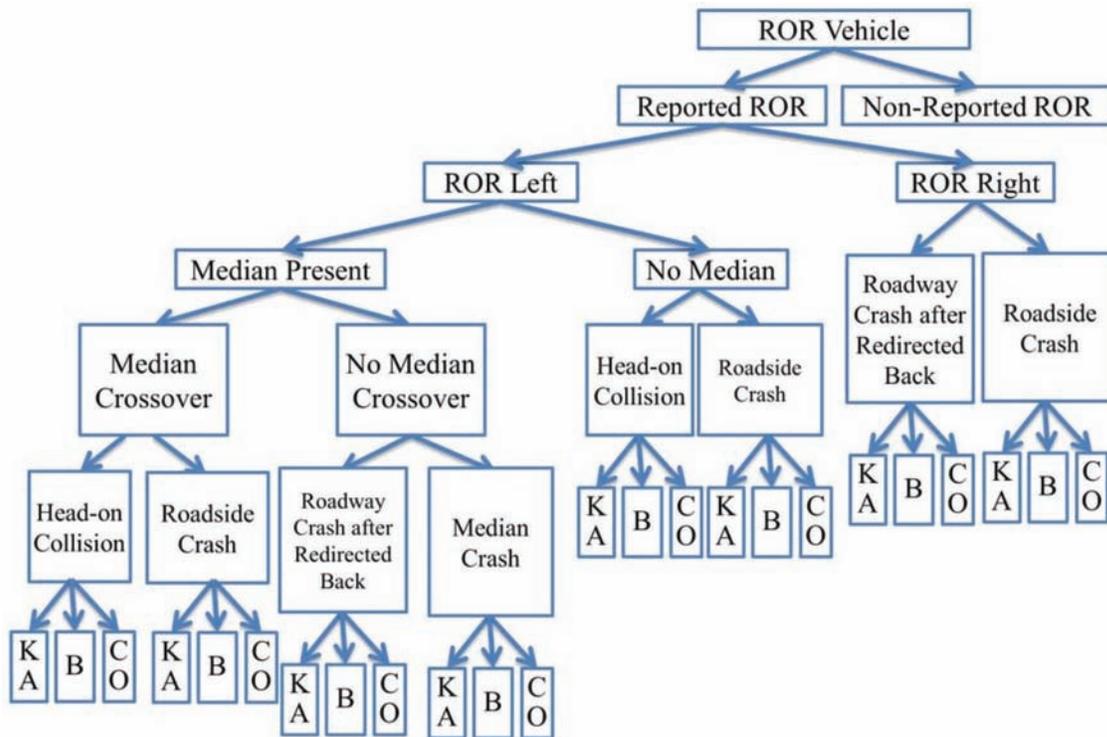
- HF: high speed freeways with speed limit equal to or larger than 65 mph. It typically represents rural freeways.
- LF: low speed freeways with a speed limit equal to or lower than 60 mph. It typically represents the urban freeways.
- NF: non-freeway that has no curb and speed limit equal to or larger than 45 mph.

The safety performance of three types of barriers was investigated: concrete barriers, W-beam guardrails, and high-tension cable barriers. The placement of barriers varies even within the same barrier type. Different barrier scenarios (including non-barrier scenarios) can be divided based on their in-field use in Indiana. They can be used to represent the median and roadside environment of a directional roadway segment.

It is assumed in this study that the median environment (may include a median barrier) and the roadside environment (may include a roadside barrier) for a given directional roadway segment are independent, with each of them represented by a set of explanatory variables in the modeling process. Each set of variables is composed of several dummy variables representing different barrier and non-barrier scenarios, with one scenario selected as the reference condition or reference category.

In this study, the median design was divided into six scenarios (or categories):

1. M\_NB\_Nar: median 50 feet or narrower and no median barrier.
2. M\_NB\_Wide: median wider than 50 feet and no median barrier.
3. M\_BW: median concrete barrier wall placed in the center of a narrow median.
4. M\_GR: median guardrail placed in center of a median or at the nearside edge.
5. M\_CB\_Near: median cable barrier (nearside) with a lateral clearance 30 feet or less to the travelled way.
6. M\_CB\_Far: median cable barrier (far-side) with a lateral clearance more than 30 feet to the travelled way.



**Figure 3.1** The tree of events affected by barriers.

It should be noted that within a median scenario, the actual median width or barrier offset to the edge of the travelled way may vary considerably. Thus, it was justified to specify a typical range for each median scenario such that the values falling in this range fit this scenario while the values outside of this range were not represented well by this scenario. The typical range was defined using 5% quantile and 95% quantile as the endpoints. Below is the typical range of each of the six median scenarios:

1. M\_NB\_Nar: typical median width from 28 to 50 feet, and no median barrier.
2. M\_NB\_Wide: typical median width from 51 to 82 feet, and no median barrier.
3. M\_BW: concrete barrier, typical offset 7 to 18 feet from the edge of travelled way.
4. M\_GR: median guardrail, typical offset 6 to 19 feet from the edge of travelled way.
5. M\_CB\_Near: nearside cable barrier, typical offset 11 to 16 feet from the edge of travelled way.
6. M\_CB\_Far: far-side cable barrier, typical offset 42 to 46 feet from the edge of travelled way.

The roadside design was divided into three scenarios (or categories):

1. S\_GR: roadside guardrail.
2. S\_NB\_Low: no guardrail, roadside hazard rating 1 or 2.
3. S\_NB\_High: no guardrail, roadside hazard rating from 3 to 7.

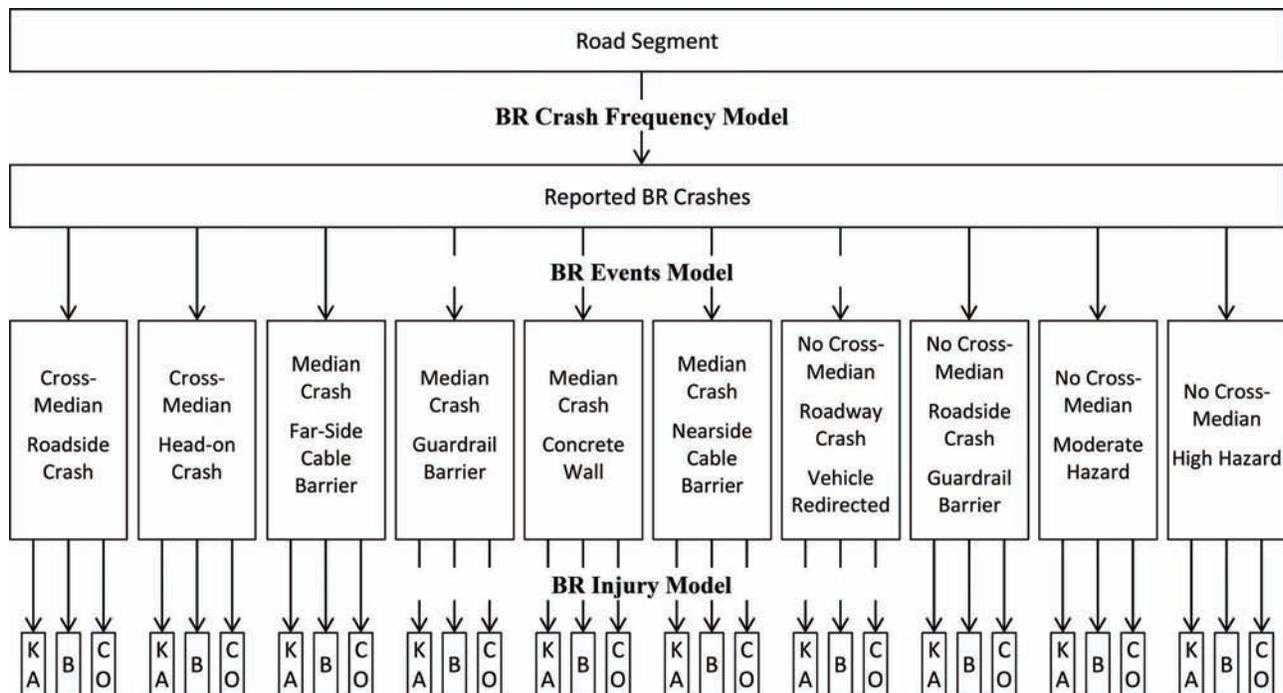
The roadside hazard rating index applied in this study follows the Highway Safety Manual (AASHTO, 2010).

The analysis in this study applies to a directional roadway segment. For a directional segment, each combination of a road type, a median scenario, and a roadside scenario represents a unique road-barrier scenario. Thus, a total of  $3 \times 6 \times 3 = 54$  road-barrier scenarios were defined.

The identified road-barrier scenarios were decided based on the data collected in this study and are believed to represent the majority of barrier cases in Indiana. It is important to note that some real-world road-barrier scenarios might not be covered due either to the rarity of their appearance in Indiana or to the lack of crash data. However, the results of this study might still be somewhat applicable to those other cases on the basis of the similarity between covered and uncovered scenarios or by extrapolating the results outside of the covered scenarios.

### 3.3 Barrier-Relevant Crashes

It is important to emphasize that this study did not analyze all the crashes that occurred on the segments where the data were collected but rather focused on the barrier crashes that were relevant to the objectives of the study. We defined barrier-relevant (BR) crashes as those whose occurrence or outcome (injury severity) may have been affected by a barrier had the barrier been installed or removed. A crash is considered apparently barrier-relevant if at least one involved vehicle enters the median or the roadside regardless of whether it collides with a barrier or not. This definition applies to roads with barriers and to roads where



**Figure 3.2** The simplified tree of events affected by barriers.

barriers are not installed but are allowed by the design standards.

Following this definition, single-vehicle crashes that involved collisions with barriers, rigid roadside objects (e.g., trees, utility poles), and semi-rigid roadside objects (e.g., highway traffic signs and fences) were relevant as well as crash events that were non-collisions such as rolling over on an embankment or crossing a ditch.

BR crashes may also include multiple vehicles. An example is a crash in which a vehicle runs off the roadway, crosses the median, and collides head-on with another vehicle moving in the opposite direction. Damages to both the involved vehicles and injuries of their occupants should be considered as barrier-relevant because a median barrier could have prevented this crash. Another case is when a vehicle leaves the roadway and collides with a barrier, bounces off the barrier and returns to the roadway, and then collides with an on-road vehicle in the same direction. In some cases, a vehicle leaves the road as the result of an interaction with other vehicles. If the most harmful event for the ROR vehicle occurs off the road, then the damage to this vehicle and the injuries of its occupants should be account for while other vehicles involved that did not leave the road should be ignored.

The detailed process of how BR crashes were identified from the available databases is presented in Section 4.4.

### 3.4 Statistical Models

The complexity of the tree of events discussed in Section 3.1 was simplified into four components as shown in Figure 3.2:

1. A segment road with its geometry, barriers, and traffic (each way considered separately).
2. BR crashes reported during the period of analysis.
3. BR events occurring during the BR crashes.
4. Injuries of persons involved in the BR crashes.

The connections between these four components can be characterized as follows:

1. The effects of the road, barrier scenarios, and traffic on the BR crash frequency.
2. The effects of the road and the barrier scenarios on the BR hazardous events.
3. The effects of the BR events and other conditions on the injury outcomes.

The corresponding models are as follows: BR crash frequency model, BR events model, and BR injury model, which are briefly discussed in the following sections.

#### 3.4.1 BR Frequency Model

The purpose of barriers is to alter crash hazardous events into less hazardous ones. However, the observed impacts of barriers go further. For example, many researchers observed that installing barriers increased the total number of reported crashes, which is brought by the following barrier characteristics: (1) barriers are placed closer to the roadway than the hazardous objects they shield, and (2) continuous barriers may shield a group of point hazards, such as trees, thus increasing the exposure. In other words, barriers reduce the width of the recovery area and eliminate the chance of missing a roadside hazard. Thus, the risk of striking barriers can increase and the frequency of reported BR crashes

can increase as well. A crash frequency model was developed in this study to estimate the BR crash frequency on a segment where a change in the BR crashes could be expected due to the installation or removal of barriers. A negative binomial regression model was applied to one-way travelled ways to predict the number of BR crashes on a given segment over a certain time period from the traffic, speed limit, and roadway and roadside characteristics. The details of the frequency model are provided in Chapter 5.

### 3.4.2 BR Events Model

Barriers are expected to eliminate or reduce the occurrence of roadside hazardous events such as cross-median events or collisions with roadside fixed objects. Although eliminating roadside dangerous events is difficult to accomplish, the risk can be effectively reduced by the use of barriers. Unfortunately, barriers may have unintended effects, such as collisions with barriers and increased redirected multi-vehicle collisions. Therefore, it is useful to know the probabilities of these events with and without barriers given that a BR crash occurs. Therefore, in this study, BR events were identified and a model developed to estimate their conditional probabilities.

A BR event connects the BR crash onset with the crash injury outcome. Inclusion of BR events is the major improvement in modeling the impacts of barriers proposed in this study. It allows better understanding of the barrier impact mechanism through redistribution of the BR events, thus shedding more light on the BR crash process. It also allows a more efficient use of available data. Specifically, the need for a sample with detailed road information sufficiently large to properly estimate the probability of fatality is eliminated by applying two samples:

1. A sample of BR events supplemented with detailed road information.
2. A sample of personal injury records supplemented with general road information.

BR events are much more frequent than fatalities, thus the first sample need not be large to estimate the probabilities of BR events. Reducing the size of this sample is important because collecting and assembling detailed road data is labor-demanding. On the other hand, the injury outcome strongly depends on the BR event, vehicle, and their occupants and less on the road geometry. Thus, the injury model estimated with the second sample relies on the crash data and general road characteristics that are available for all roads in the existing road inventory datasets. Assembling a second sample sufficiently large to estimate the probability of fatality was manageable.

A BR events model estimates the probabilities of BR events given that a BR crash occurs on a segment with certain roadway and roadside characteristics. A BR event may be viewed as the most harmful event of a BR crash and may involve a single vehicle or multiple

vehicles. A multinomial logit model with a variable outcome set was selected to estimate the BR event probabilities. The explanatory variables are the speed limit, segment roadway and roadside detailed characteristics, and other. Chapter 6 provides details about the BR events model.

### 3.4.3 BR Injury Model

A barrier itself is a hazard which may cause injury to vehicle occupants. Thus, installing a barrier is not viable if collisions with the barrier produce outcomes more severe than the hazardous events. Therefore, an important question is whether or not a certain barrier under certain conditions is sufficiently “forgiving.” To answer this question, a personal injury model is needed to predict the severity outcome of a BR crash under given road-barrier scenario.

A BR personal injury model was estimated to predict the probabilities of five injury outcomes on the KABCO scale of vehicle occupants involved in a BR event (the most harmful event of a BR crash). A multinomial logit model was selected to be estimated with the data included in the crash and road inventory databases. The explanatory variables are the BR event, the vehicle type, the occupants’ demographic characteristics, the general roadway characteristics, the speed limit, and other. Chapter 7 provides the details of the BR injury model.

## 3.5 Implementation Procedure

The statistical models represent the three relationships between the considered four BR components, which are defined at different levels of data aggregation. The BR crash frequency model applies to segments, the BR events model applies to crashes, and the BR injury model applies to vehicle occupants. These models complement each other and must be used jointly to estimate the expected number of BR injuries for a given road segment, which eventually are converted to the total cost of BR crashes.

A user-friendly implementation of the results of this study requires a practical procedure to evaluate the crash costs and the safety benefits for a given roadway and alternative barrier scenarios. Such a procedure should deploy engineering concepts that are well established and well known to transportation engineers. The concepts of safety performance functions (SPF), crash modification factors/functions (CMF), and unit crash costs meet the requirement and are sufficient to facilitate the needed calculations.

The SPFs and CMFs can be derived from the BR crash frequency model, whereas the Indiana-representative unit crash costs for various road-barrier scenarios can be obtained from statistical simulation performed on the BR events sample by jointly applying the BR events and injury models. The estimation of the unit crash cost is described in Chapter 8. The obtained step-by-step procedure is presented in Chapter 9.

## 4. SOURCE DATA AND SAMPLES

This study required information about the roadway segments, crashes, vehicles, occupants, costs, and other items such as traffic volumes, speed limits, etc. This chapter details the collection and cleaning of the data, provides a basic summary of the data used in the study, and describes the major data processing steps to assemble three samples: a road segments sample, a BR events sample, and a BR injury sample.

The data used for this research were obtained from state agencies as well as data collected by the research team specifically for this study. The INDOT database provided road inventory data, barrier inventory data, and traffic data. Crash records that included personal injury data were obtained from the Indiana State Police (ISP). The hospital discharge data for the injured individuals were obtained from the Indiana State Department of Health (ISDH). Additional effort was made by the research team to collect detailed information on randomly selected roadway homogeneous segments and to identify the BR crashes in the ISP crash database. Overall, the existing INDOT, ISP, and ISDH databases provided most of the information needed for this research, and the additional data collection by the research team filled the gaps where additional detailed and specific data were necessary.

### 4.1 Source Databases

#### 4.1.1 Crash Data

The detailed crash information provided by ISP includes the following data: location, vehicles involved, drivers, injured occupants, weather, road conditions, and contributing circumstances. The Indiana data contain records for all drivers and injured vehicle occupants, pedestrians, or bicyclists involved in 190 to 200 thousand crashes per year.

#### 4.1.2 Hospital Discharge Data

The hospital discharge data provided by ISDH were used to assess the injury severity of crash victims according to the Maximum Abbreviated Injury Scale (MAIS). These hospital data, which were available from 2003 through 2013 for this study, are comprised of close to 800,000 inpatients and 4,000,000 outpatients per year. Of these, the records for about 600,000 patients exhibiting some form of traumatic injury are extracted yearly and their MAIS scores are calculated using the ICDMAP-90 program (Mackenzie & Sacco, 1997).

The hospital records exhibiting traumatic injuries are subsequently linked probabilistically to the approximately 300,000 records of yearly crash victims, using protocols developed under the CODES project implemented under the guidance of NHTSA.

#### 4.1.3 Road Inventory Data

INDOT administers a total of 11,169 centerline miles, 8,798 rural and 2,372 urban. The state-administered road network representation contains 30,675 segments and 23,570 intersections. Each element is associated with the Indiana road inventory, which provides geometric data and includes the number and width of lanes, the type and width of shoulders, the type and width of medians, AADT, and other information. For this study, these data were also linked to the bridge data extracted from the National Bridge Inventory (NBI) online database and to the county, township, and city/town boundaries shape files available at the Indiana Map website. Additional information from other sources was included as well, such as land-use, demographics, and employment data.

#### 4.1.4 Traffic and Speed Limit Data

The AADT and speed limit data were provided by the Purdue University Center for Road Safety (CRS) and were linked to each selected segment using ArcGIS software. The AADTs for different years were calculated based on the adjustment factors suggested by INDOT.

#### 4.1.5 Barrier Inventory Data

The barrier inventory dataset contained three separate sets of data, one for each type of road barriers: concrete barrier walls, guardrails, and cable barriers. The barrier location information in the dataset is coded in a linear reference (route and mile post). The barrier installation dates were only available for cable barriers while for the other two types of barriers, although they have been used for a long time, their installation dates were difficult to find. The barrier inventory data did not include information about the specific locations of barrier; therefore, it was necessary to retrieve their locations from Google Earth images. This effort is described in Section 4.2.

The inventory data for guardrails and concrete barrier walls were obtained from INDOT's Work Management System (WMS). The guardrail database contained 34,214 records and covered a total of 2,483 miles of roadway, including interstates, U.S. highways, and state roads. For each guardrail section, the dataset provided information about the route, the side of the road, and the start and end mileposts. The concrete barrier wall inventory data were arranged in a similar fashion.

The cable barrier inventory data contained 49 records with a total length of around 370 miles which were installed gradually beginning in 2006 on I-64, I-65, I-69, I-70, I-74, I-80, and I-265. Year 2012 was the latest installation date provided in the dataset.



**Figure 4.1** Segment selection using street view and satellite view in Google Earth.

## 4.2 Segment Data Collection and Preliminary Analysis

### 4.2.1 Segment Selection

Detailed roadway segments data were needed for developing the BR crash frequency model and the BR events model. For the unbiased estimation of the crash frequency and unit crash costs, the segments were selected randomly within each road-barrier scenario. This existing barrier inventory dataset was used to select homogenous road segments with barriers. The mileposts were randomly selected from the Indiana barrier inventory dataset within each barrier type to ensure sufficient presence of all types of barriers in the sample.

Trained assistants extracted detailed geometry and barrier information from the randomly selected homogeneous roadway segments using Google Earth images. Figure 4.1 illustrates the segment selection process in Google Earth. The beginning and end of a segment were determined in such a way that no obvious change in the cross-section and the roadside features were present along the obtained segment. Time-stamped older Google Earth images were inspected to make sure the barrier installation did not happen during the period of analysis or that the road did not undergo any major geometry changes (e.g., adding a lane, narrowing the shoulder, etc.).

The assistants also extracted a wealth of information about the roadway and roadside hazards, including the shoulder types and widths, the median type and width,

the number of lanes, the presence of horizontal curves, the presence of rumble strips, the total number of access points, and the roadside hazard rating index according to the Highway Safety Manual (AASHTO, 2010) guidelines. The procedure and details for selecting homogenous segments and extracting that information are included in the training manual for segment selection in Appendix A.

After the sample of segments with barriers was selected, each barrier segment was matched with a homogeneous segment with no barrier located on the same route and as nearby as possible. The purpose of the pair matching was to reduce the heterogeneity between the roads with and without barriers by maintaining the same roadway geometry, roadside hazard, traffic volume, driver population, and weather conditions in each pair.

The originally selected barrier segments and the paired non-barrier segments were bi-directional (two-way traffic) with information recorded for each direction. The final sample consisted of 629 two-way divided segments and 311 two-way undivided segments.

For the divided segments, each bi-directional segment was then divided into two separate directional segments. All the recorded specific information on those directional segments formed a divided segment dataset, which contained 1,258 directional segments covering nearly 330 miles of state-administered roads. Table 4.1 presents the number of directional segments classified by different median and roadside scenarios.

TABLE 4.1  
Number of Collected Directional Divided Segments by the Median and Roadside Scenario.

Median Scenario	Roadside Scenario			Total
	High-Hazard Roadside (hazard rating 3 to 7)	Low-Hazard Roadside (hazard rating 1 or 2)	Guardrail	
Nearside Cable Barrier (offset $\leq$ 30 feet)	42	35	16	93
Far-Side Cable Barrier (offset $>$ 30 feet)	39	37	17	93
Concrete Barrier	98	12	44	154
Guardrail	14	7	41	62
Narrow Median (width $\leq$ 50 feet)	41	66	69	176
Wide Median (width $>$ 50 feet)	202	362	116	680
Total	436	519	303	1258

The undivided bi-directional segments contained 305 two-lane rural road segments (eight of them were separated by a two-way left-turn lane) and six four-lane road segments covering 49 miles of state-administered roads.

#### 4.2.2 Barrier Summary Statistics

The barrier's use and placement was analyzed in the collected divided segment dataset. Placement of a barrier in a median was characterized with the median width and the barrier offset from the travelled way. Placement of a barrier on a roadside was described by its offset from the travelled way. All the concrete barrier walls were placed in the center of paved medians; all the cable barriers were near one side of the roadway in unpaved medians; and guardrails were either in unpaved medians or on the roadside or in both locations. There is a new practice in Indiana of placing median guardrails in narrow paved medians, but this case was not included in this study due to the scarcity of data.

Figure 4.2 shows the histograms of the median width for the three types of median barrier segments. It is clearly seen that concrete barrier walls are used on narrow medians with median widths less than 40 feet, while cable barriers appear to be consistently used on wide medians with median widths around 60 feet. The use of median guardrails was much more flexible. As the data in Figure 4.2 show, a median 16 to 40 feet wide may have a concrete barrier wall or a guardrail installed while a median 50 to 70 feet wide may have either a cable barrier or a guardrail installed. Thus, concrete walls and guardrails are viable alternatives for medians narrower than 40 feet while cable barriers and guardrails are viable alternatives for medians wider than 50 feet.

Figure 4.3 shows the histograms of the median barrier offsets for directional segments. The offsets of median concrete barrier walls are lower than 20 feet, and the distribution of offsets of median cable barriers are two-modal. The two modes around 16 feet and 44 feet represent typical nearside or far-side locations

in relation to a path travelled by a vehicle involved in a BR crash. Median guardrail offsets are distributed similarly to median cable barriers, although the dispersion is larger.

Only guardrails were observed on the roadside, which tended to follow a distribution similar to the normal distribution (Figure 4.4). The offsets in the dataset ranged from 2 to 18 feet with the majority between 10 and 12 feet.

#### 4.3 Road Segments Sample

The number of BR crashes which occurred on the selected segments during the period of analysis was important for estimating the BR crash frequency model. It is important to note that not all crashes were correctly assigned to the road segments based on their geo-coordinates. The subsections below discuss how BR crashes and vehicles were assigned to the selected road segments and verified. A consistency check was one of the methods used to verify the crash data.

##### 4.3.1 Initially Assigned Crashes

Based on the homogeneous segments mentioned above, a total of 20,370 crashes from 2003 to 2012 were assigned to specific segments based on their geo-referencing information. Other useful information available in the existing INDOT crash database was also joined. The crash-related dataset included the following four datasets:

1. The crash dataset (20,370 records): Crash level information such as crash date, crash location, crash type, number of vehicles, roadway surface conditions, etc. was recorded.
2. The vehicle dataset (29,402 records): Involved vehicle level information, including other units such as trailers, bicycles, etc.; vehicle level information such as the occupancy, vehicle type, travelling direction, road type, sequence of events, etc. was recorded.
3. The individual dataset (63,150 records): Person level information, such as the person type (e.g., driver, injured, pedestrian, etc.) and address was recorded.

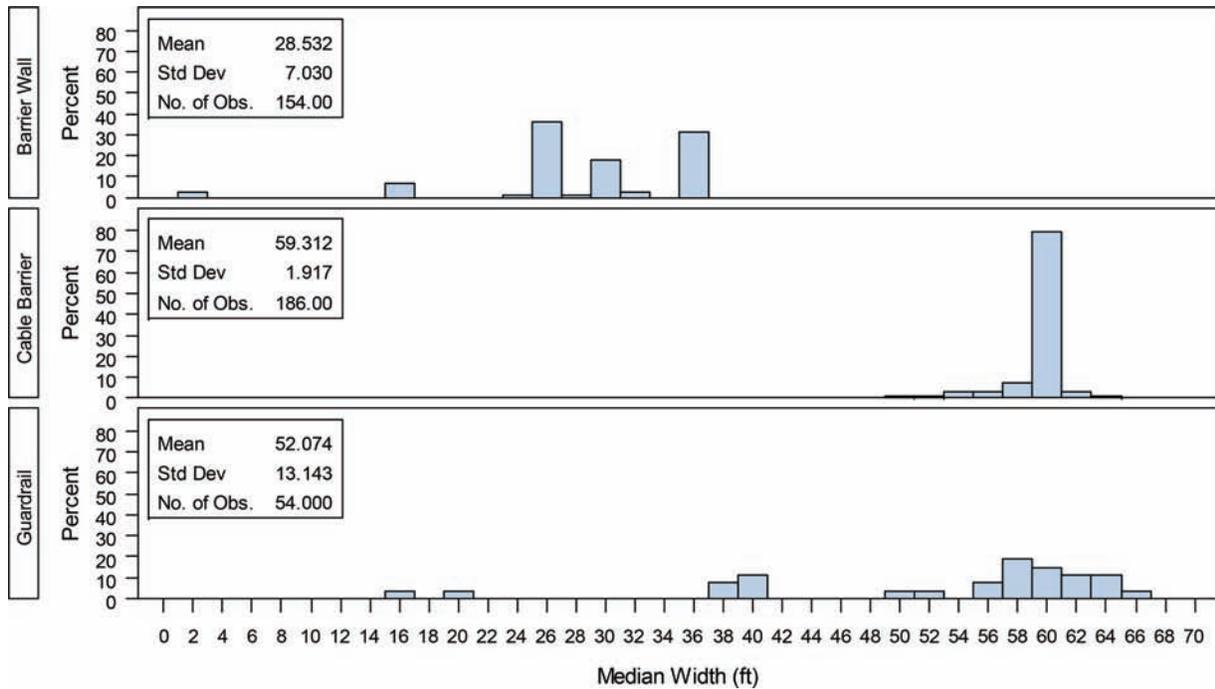


Figure 4.2 Histograms of the median width.

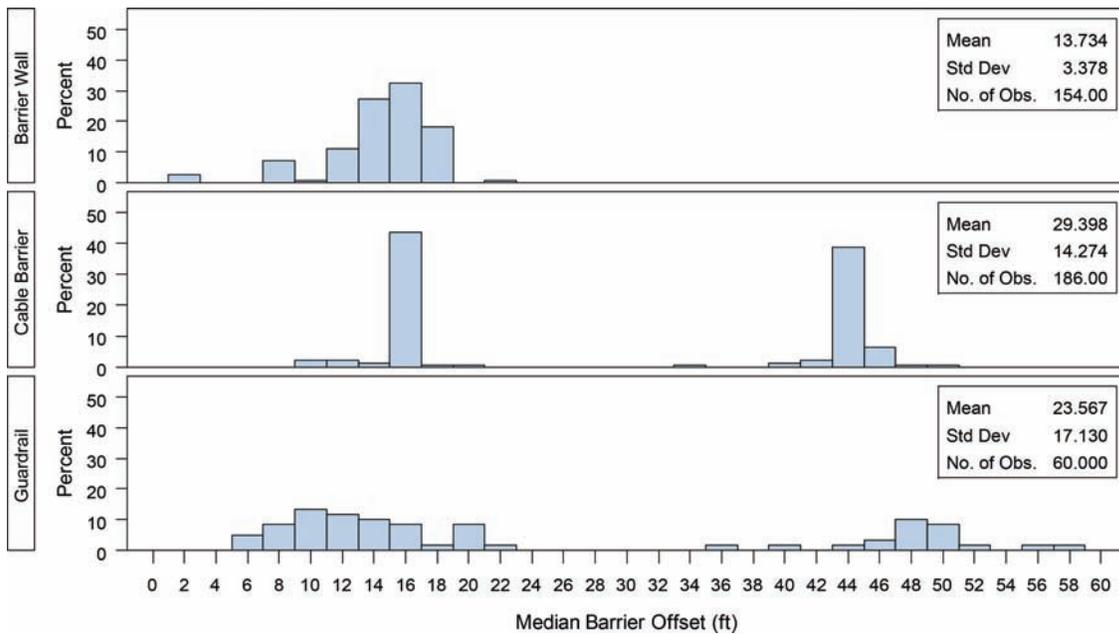


Figure 4.3 Histograms of the median barrier offset.

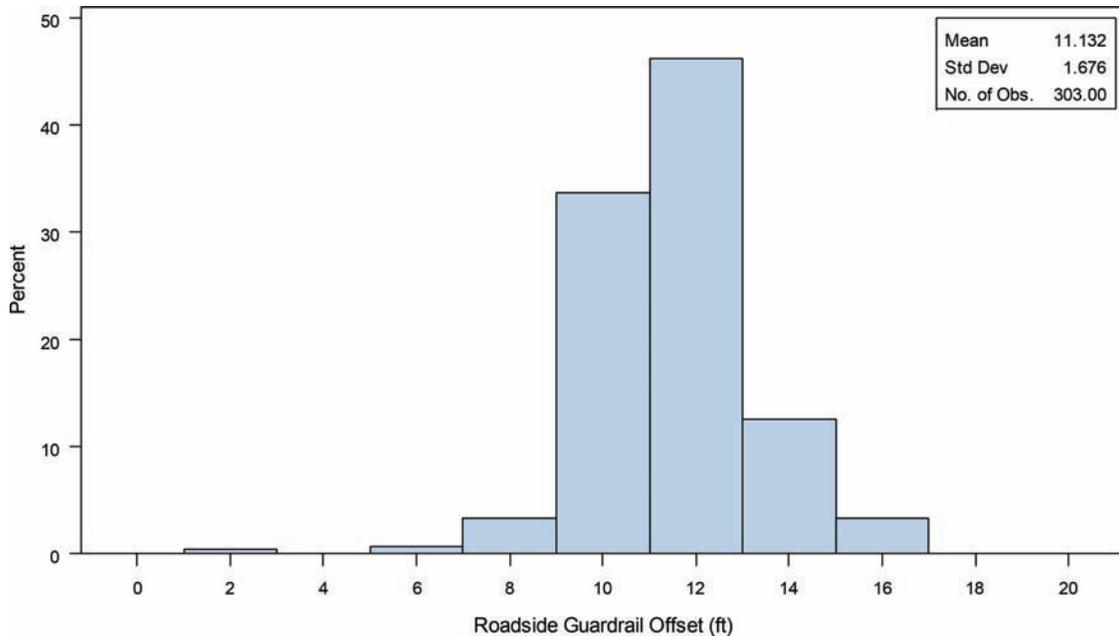
4. The injury dataset (29,726 records): Age, gender, injury level (KABCO scale) information for the driver and injured occupants (person-level) was recorded.

#### 4.3.2 BR Crash Identification

BR crashes are defined in Section 3.3. The following three steps were conducted to select the BR crashes.

1. Selected candidate crashes using information in available databases.
2. Removed crashes that occurred on or before the installation year of cable barriers.
3. Cleaned crashes and extract information using police narratives and collision diagrams.

In the first step, the candidate crashes were selected by taking advantage of the information available in the



**Figure 4.4** Histogram of roadside guardrail offset.

INDOT existing crash-related databases. Two sources of information were used: the type of crash (“manner-collcde” in the crash dataset) and the sequence of events (“eventcollwithcde,” “eventcollwithcde2,” “eventcollwithcde3” and “eventcollwithcde4” in the vehicle dataset). The candidate crashes were those with type of crash entry codes 02, 04, 05, 06, 12, and 13 (see below for the entry coding) and with any of the four event entry codes 01, 15, 20, 30, 32, 35, 37, 38, 39, 40, 41, 42, 43, 45, 47, 48, 49, 50, 51, 52, 53, 55, 59, 60, 61, or 62 (entries 53 to 62 are only available for crashes that occurred in 2011 or later). Below are the available entries for those two variables. The entries in bold typeface were those used to select the candidate crashes.

**For the type of crash:**

- 01 – Rear end
- 02 – Head on**
- 03 – Rear to rear
- 04 – Same direction sideswipe**
- 05 – Opposite direction sideswipe**
- 06 – Ran off road**
- 07 – Right angle
- 08 – Left turn
- 09 – Right turn
- 10 – Left/right turn
- 11 – Backing crash
- 12 – Other – explain in narrative**
- 13 – Non-collision**

**For the sequence of events:**

- 01 – Another Motor Vehicle**
- 02 – Pedestrian
- 03 – Bicycle
- 04 – Railway Vehicle/Train/Engine
- 05 – Deer

- 06 – Animal other than Deer
- 07 – Animal Drawn Vehicle
- 15 – Overturn/Rollover**
- 16 – Fire/Explosion
- 17 – Immersion
- 18 – Jackknife
- 19 – Cargo/Equipment Shift or Loss
- 20 – Off Roadway**
- 21 – Fell from Vehicle (Non Collision)
- 30 – Impact Attenuator/Crash Cushion**
- 31 – Bridge Overhead Structure
- 32 – Bridge Pier or Abutment**
- 33 – Bridge Parapet End
- 34 – Bridge Rail
- 35 – Guardrail Face**
- 36 – Guardrail End
- 37 – Median Barrier**
- 38 – Highway Traffic Sign Post**
- 39 – Overhead Sign Post**
- 40 – Light/Luminaire Support**
- 41 – Utility Pole
- 42 – Other Post/Pole or Support**
- 43 – Wall/Building/Tunnel**
- 44 – Work Zone Maintenance Equipment
- 45 – Embankment**
- 46 – Curb
- 47 – Ditch**
- 48 – Culvert**
- 49 – Fence
- 50 – Mailbox**
- 51 – Tree**
- 52 – Other – Explain in Narrative**
- 53 – Crossing Center Line/Median**
- 54 – Equipment/Mechanical Failure
- 55 – Downhill Runaway**
- 56 – Separation of Units

- 57 – Thrown or Falling Object
- 58 – Parked Motor Vehicle
- 59 – Ran off Roadway**
- 60 – Cable Barrier**
- 61 – Concrete Traffic Barrier**
- 62 – Other Traffic Barrier**

The second crash selection step removed the crashes that occurred on or before the installation year of cable barriers, given that Indiana recently began installing cable barriers.

Although the first and second steps removed the crashes which were irrelevant to this study, it was still uncertain if the remaining candidate crashes were BR crashes due to the outdated entries for the sequence of events in earlier years and the inconsistency of coding those events among different police officers. For example, the entry for cable barrier had not been an available entry until November 2011. The police officer might have coded a collision with cable barriers as a fence, impact attenuator, or other items before November 2011. Even for crashes which occurred in the same manner, different police officers might have coded them differently.

In addition to the necessity of improving the selection accuracy of BR crashes, more work was needed to extract the detailed characteristics of the errant vehicles and to verify the crash locations, which the current existing INDOT databases did not fully cover. The questions that remained to be addressed included:

- Did the vehicle leave the roadway at any point?
- Did the vehicle leave the roadway to the left or right?
- Did the vehicle cross the median?
- What type of event did the vehicle encounter after it left the roadway?
- What was the vehicle’s status after its hazardous event?
- Where did the vehicle finally come to a rest after its hazardous event?

Additional questions on the barrier collision crashes of interest which also needed to be addressed were as follows:

- What type of barrier did the vehicle strike?
- Was the collided barrier a median barrier or roadside barrier?

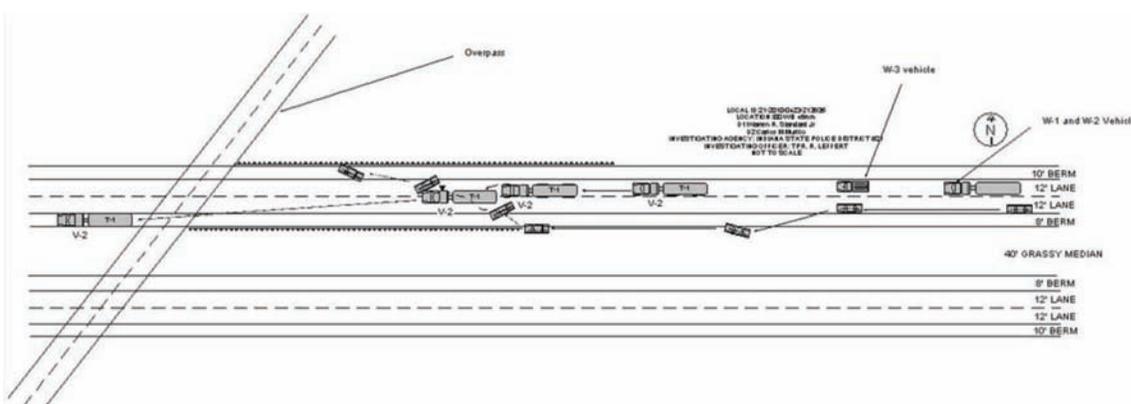


Figure 4.5 An example of crash diagram.

Thus, a third crash selection step was conducted with the aim to improve BR crash selection and information extraction of vehicles’ ROR characteristics. This step was supported by independent data collection on the crash-by-crash interpretation of police narratives and collision diagrams documented in electronic police crash reports. Crash reports were accessed from the Automated Reporting Information Exchange System (ARIES), and each report was interpreted by trained data collectors. The ROR-related variables of interest were recorded for each involved vehicle in a carefully designed spreadsheet. Figure 4.5 and Figure 4.6 are examples of the crash diagram and narration, respectively.

Moreover, the geometric characteristics (i.e., the presence of a junction and a horizontal curve and the number of lanes) at the crash site were also extracted from crash diagrams. These crash site geometry features were useful in verifying correct assignment of the crashes. See Appendix B for a list of the variables that the trained data collectors used to characterize the vehicles’ ROR details and crash site geometry.

After the third step, BR crashes and vehicles were finally identified. The corresponding recorded information was stored in a dataset called the ROR dataset; and an occupant-level dataset called the BR occupant dataset contained information about the BR occupants. All the information from the INDOT existing databases (individual dataset, injury dataset, vehicle dataset, and crash dataset) and our independent data collection (ROR characteristics, crash site characteristics, and segments’ roadway and roadside characteristics) were joined to each occupant.

#### 4.3.3 Data Consistency Check

The aforementioned barrier-relevant occupant dataset contained a wealth of information from different data sources, some of which was available from multiple data sources. The data consistency check took advantage of the information redundancy and identified records with their shared information inconsistently recorded among different data sources. Inconsistencies in the shared information were indications of potential data reporting problems or crash location assignment

## Narrative

Vehicle 1 was traveling south on Interstate 65 at the 28 mile marker in the right lane. Witness 1 was traveling north on Interstate 65 at the 28 mile marker in the left lane. Vehicle 1 was traveling south on Interstate 65 at the 28 mile marker in the right lane when he ran off the road onto the right shoulder. Vehicle 1 struck the guard rail face with it's right side. Vehicle 1 then struck the bride support for the County Road 150 overpass with it's right side. Vehicle 1 then veered across Interstate 65 south, entered the median, crossed onto Interstate 65 north, and came to rest in the right lane and shoulder of Interstate 65 north. The damage to Vehicle 1 was caused by the impact to the guard rail and bridge support. Vehicle 1 lost most of the right side of the tractor and ripped opened the trailer causing the load to eject throughout the median and onto Interstate 65 north. Witness 1 was traveling north on Interstate 65 at the 28 mile marker in the left lane when he advised he saw Vehicle 1 coming across the median toward him. Witness 1 was able to pull his tractor/trailer into the median to avoid being struck. Witness 1 had to have his vehicles wrenched out of the median due to the muddy conditions. Driver 1 advised he was traveling south on Interstate 65 at the 28 mile marker in the right lane when he took a drink of coffee. Driver 1 advised he aspirated the coffee and began to choke. Driver 1 advised he was coughing frantically trying to catch his breath. Driver 1 advised he tried to ease Vehicle 1 onto the shoulder until he regained himself. Driver 1 advised he came to on the opposite side of Interstate 65 and did not remember striking anything or crossing the median. Driver 1 further advised he had falsified his log book. Driver 1 relinquished his log book for a level III inspection. The log page for March 30, 2010 showed him in Whiteland, Indiana at 2015 hours. This crash occurred at 2002 hours in Scottsburg, Indiana. Driver 1 advised he went ahead and pre-planned his trip on his log page. Driver 1 advised he drew a ten hour break but only took eight hours. Driver 1 had a total of fifteen hours of drive time at the time of the crash. Driver 1 did advised me of the log violation before I began the inspection.

Figure 4.6 An example of crash narration.

precision problems. Crashes with inconsistencies in the important characteristics were removed from the analysis. Below is the selected information used to conduct the consistency check.

**Number of lanes.** Information on the number of lanes for a given crash was recorded by three datasets: the vehicle dataset, the segment dataset, and the ROR dataset. Inconsistent descriptions of the number of lanes among the three datasets could be due to the operator's incorrect counting, road construction work, and crash location reporting errors. Crashes with inconsistent descriptions of the number of lanes were removed given that they were very likely inaccurately assigned to the segment.

**Presence of intersection.** Since all of the crashes were originally selected based on homogeneous road segments, all the crashes in this study were not to have any indication of the presence of any type of intersection. Information on the presence of intersections was available in the crash dataset and the ROR dataset. Inconsistencies in this data most likely were due to crash location reporting errors. Thus, such crashes were removed if the presence of an intersection was indicated in either the crash dataset or the ROR dataset.

**Presence and type of barriers.** Three datasets (vehicle dataset, segment dataset, and ROR dataset) contained information on the barrier presence and barrier type. Barrier information in the vehicle dataset was overridden by the information in the ROR dataset since those two datasets followed the same entry coding format, but the latter used the most up-to-date coding entries for barriers with higher resolution and consistency. Inconsistencies in the barrier presence and the barrier type between the ROR dataset and the segment dataset most likely indicated the presence of crash location reporting errors. Thus, the inconsistent records were removed from the analysis.

**Presence of horizontal curve.** Three datasets (crash dataset, segment dataset, and ROR dataset) described the presence of horizontal curves. Note that the horizontal curve was allowed in our homogeneous segment selection. Inconsistent descriptions of the presence of horizontal curves among three different datasets may have been due to different curve judgment criteria provided by operators or crash location reporting errors. Investigation of a sample group of horizontal curve inconsistent crashes indicated the former reason dominated (i.e., whether or not a given segment was deemed as horizontally curved varied person by person). Therefore, horizontal curve inconsistent crashes were not removed, but their use in the analysis was done with caution.

### 4.3.4 Divided Road Segments Sample Summary

The divided road segments sample was composed of 1,604 BR crashes, which occurred from 2008 to 2012 on 655 out of the 1,258 directional homogeneous roadway segments selected from divided INDOT-administered roads. Although we extracted 10 years of data (2003 to 2012) for most of the segments, the divided road segments sample only counted crashes that occurred from 2008 to 2012 due to poorer accuracy in the crash assignment process in the earlier records. The number of BR crashes classified by segments with different barrier scenarios is summarized in Table 4.2.

### 4.3.5 Undivided Road Segments Sample Summary

After the data reduction and cleaning, only 129 BR crashes were found to have occurred on all the selected 315 bi-directional undivided segments from 2003 to 2012. The infrequency of crashes on undivided road segments was due to (1) lower traffic volume and (2) smaller segment length (roadside guardrails generally have shorter spans such that the selected barrier

TABLE 4.2  
Number of Barrier-Relevant Crashes by Barrier Scenarios in the Road Segments Sample.

Median Scenario	Roadside Scenario			Total
	High-Hazard Roadside (hazard rating 3 to 7)	Low-Hazard Roadside (hazard rating 1 or 2)	Guardrail	
Nearside Cable Barrier (offset ≤30 feet)	43	49	17	109
Far-Side Cable Barrier (offset >30 feet)	43	41	10	94
Concrete Barrier	363	14	129	506
Guardrail	40	36	60	136
Narrow Median (width ≤50 feet)	9	14	16	39
Wide Median (width >50 feet)	229	379	112	720
Total	727	533	344	1604

segments were shorter). For the majority of the undivided roads, two lane rural roads, only roadside barriers might be used and the corresponding guidelines have not changed much over time and across states. Both the embankment height and slope were used in existing AASHTO and Indiana RDG roadside barrier guidelines. However, information about them was hard to obtain from Google Earth images or other databases.

The insufficient crash data and embankment information and the lack of resources to considerably increase the sample size forced the research team to exclude the undivided roads from further analysis. The reduction of the research scope was also justified from the point of view of the limited need for investigating two-lane roads. Unlike for median barriers, the existing guidelines are sufficiently specific about where roadside guardrails should be installed.

#### 4.4 BR Events Sample

The BR events sample was prepared for the event analysis presented in Chapter 6, which focuses on how roadway and roadside characteristics affect a BR crash, resulting in different crash event outcomes. The sample included all the identified BR crashes assigned on the divided road segments sample from 2003 to 2012. The segment collection process and detailed BR crash identification process were documented in Section 4.2 and Section 4.3, respectively. Unlike the segment sample in which each observation was a directional segment, the BR events sample took each BR crash as an individual observation, with information on the crash event category carefully assigned and information on the roadway and roadside characteristics properly linked. How the event categories were formed and how a crash event category was assigned are discussed below.

##### 4.4.1 Event Categories

As mentioned in Section 4.3, the actual hazardous event for each BR vehicle was identified by interpreting

the crash narratives and diagrams documented in the police report. The originally recorded BR events, however, covered a large variety of collisions with roadside objects and non-collision events. To simplify the interpretation and modeling, those original events with their hazardous levels were grouped in a similar fashion into ten BR event categories. The ten BR event categories include all the possible events for a barrier-relevant vehicle to encounter on a divided road segment are as follows:

- Event XH: cross-median head-on event
- Event XNH: cross-median non-head-on event
- Event RHV: vehicle redirected and hit another vehicle event
- Event MB/BW: median concrete barrier wall collision
- Event MB/GR: median guardrail (face) collision
- Event MB/CB1: nearside median cable barrier collision (offset 30 feet or less)
- Event MB/CB2: far-side median cable barrier collision (offset more than 30 feet)
- Event SB: roadside guardrail collision
- Event HR: non-cross-median high-risk event (e.g., roll-over or hitting a sturdy fixed object)
- Event MR: non-cross-median moderate-risk event (e.g., hitting a weak object, running over a ditch, etc.).

Below is a detailed description of each BR event category:

- Event XH designates an event in which an errant vehicle crosses the median, enters the opposite roadway, and strikes at least one vehicle in the opposite direction. The occurrence of event XH is rare; but once it occurs, the occupants involved are severely injured.
- Event XNH designates an event in which an errant vehicle crosses the median, enters the opposite roadway, and stops at the opposite roadway or the opposite roadside without striking opposite direction vehicles. Event XNH is similar to event XH, but the former is usually less dangerous. Median barriers are primarily used to prevent the occurrence of events XH and XNH.
- Event RHV designates an event in which a vehicle departs from the roadway first, but then is redirected back to its roadway (due to driver's correction or rebound from a collided object), and eventually collides with at least one normal driving on-road vehicle.

- Event MB/BW designates an event in which an errant vehicle collides with a median concrete barrier.
- Event MB/GR designates an event in which an errant vehicle collides with a median guardrail (face).
- Event MB/CB1 designates an event in which an errant vehicle collides with a nearside median cable barrier (offset 30 feet or less).
- Event MB/CB2 designates an event in which an errant vehicle collides with a far-side median cable barrier (offset more than 30 feet).
- Event SB designates an event in which an errant vehicle collides with a roadside barrier (i.e., guardrail).
- Event HR designates an event in which an errant vehicle rolls over or collides with a rigid fixed object, such as a tree, utility pole, bridge pier or abutment, overhead sign post, light/luminaire support, other post/pole or support, wall/building/tunnel, embankment, culvert, etc. The vehicle does not cross the median. Barriers may be used to prevent a HR event.
- Event MR designates an event in which an errant vehicle collides with a non-rigid fixed object, such as a highway traffic sign post, ditch, crash cushion, fence, mailbox, etc. The vehicle does not cross the median. Barriers are not used to prevent an MR event. However, if a barrier happens to be there, those events are also prevented.

Events XH and RHV involve multiple vehicles while other event categories usually involve a single vehicle.

#### 4.4.2 Vehicle and Crash Event Category Assignment

A BR vehicle might be involved in multiple events at the same time. This study used the most hazardous event to decide its event category. Other than vehicles, each BR crash was also assigned to an event category. The assignment was based on the event category for its involved BR vehicles. If a BR crash involved multiple vehicles, the most hazardous event category across vehicles was used to represent the crash event category.

#### 4.4.3 BR Events Sample Summary

The BR events sample was comprised of 2,049 BR crashes that occurred from 2003 to 2012. Each BR crash's event category was assigned and its roadway and roadside information linked. Table 4.3 summarizes the number of BR crashes classified by the crash event category.

TABLE 4.3  
Number of Barrier-Relevant Crashes by Event Category in the Crash Events Sample.

Event Category	Crash Count	Percentage (%)
Non-cross-median high-risk event	627	30.6
Median barrier wall collision	382	18.64
Nearside median cable barrier collision	62	3.03
Far-side median cable barrier collision	42	2.05
Median guardrail (face) collision	69	3.37
Non-cross-median moderate-risk event	551	26.89
Vehicle redirected and hit another vehicle	47	2.29
Roadside guardrail collision	158	7.71
Cross-median head-on	23	1.12
Cross-median non-head-on	88	4.29

## 4.5 BR Injury Sample

The BR injury sample was prepared for the injury analysis presented in Chapter 7, which investigates how different crash event categories affected the probability of a vehicle occupant facing different injury outcomes. Each observation was a vehicle occupant involved in a BR crash. The injury outcomes used for modeling were classified based on the KABCO scale, and the developed model was intended to predict the outcome of each injury level. However, the BR crashes identified in Section 4.3, which were used in both the road segments sample and the BR events sample were found to be insufficient for the injury modeling due to the limited number of fatal or severe injuries. Thus, the BR injury sample included more BR crashes which occurred on the roads not limited to those Google Earth-selected road segments. How the crashes included in the BR injury sample differ from those for other models and how the BR injury sample were formed based on the existing crash and roadway databases are discussed below.

### 4.5.1 Crash Requirement for Different Models

The BR crashes identified in Section 4.3 occurred on the selected homogeneous segments and therefore were linked with the more accurate and detailed information on the roadway and roadside characteristics measured from Google Earth images. Those crashes were specifically prepared for developing the frequency model (using the road segments sample) and the event model (using the BR events sample). Furthermore, the events surrounding each of those crashes were determined with high accuracy after verification from the police narratives. This detailed verification process was particularly important and necessary as it ensured that all the BR crashes that occurred on our selected homogeneous segments were correctly selected, assigned, and included in the modeling such that the frequency model and event model built upon them would not under- or over-predict the crash frequency and its event proportions.

However, the BR crashes identified in Section 4.3 were not enough for developing a reliable injury model due to the limited number of fatal or severe injuries.

An injury model built on those crashes would lead to unreliable results for the probability of those severe injuries. Thus, the BR injury sample used for the injury analysis was composed of more crashes which occurred on roads not limited to the Google Earth-selected road segments. The BR injury sample did not have detailed information about the roadway and roadside characteristics, which were costly to obtain, but that information was not required for the injury model since the model was particularly interested in how the injury outcome would change across different event categories conditioned on the fact that the event had occurred and had been identified. The injury outcome and crash event were directly obtained from the existing Indiana crash database.

The injury model, unlike the frequency model and event model, also did not need to include all the BR crashes. In other words, the count and proportion of each event in the BR injury sample did not affect the validity of the injury modeling results as long as each event had enough observations. The practical merits of this fact were that we could simply select crashes whose crash event information was directly available and unambiguous in the existing database to form the BR injury sample, thereby avoiding the expense that otherwise would be spent on crashes whose event information was ambiguous, for which police narratives were needed to remedy the information loss.

#### 4.5.2 Crash Identification

The selection of the crashes in the BR injury sample was primarily based on the information already available in the existing crash database. When that information was not specific enough, information from the barrier inventory database was used as a complement. The key was to make sure the crashes included were barrier-relevant and that their crash events could be assigned correctly.

It was important to select a sufficient number of crashes under each of the ten categories (see Section 4.4 for the description of the ten categories). Crashes in some event categories (e.g., non-cross-median high-risk event) were directly identified based on the existing crash database; crashes of some events (e.g., median guardrail collision) were identified by using both the crash database and barrier inventory database (i.e., the crash database did not always distinguish barrier types and thus the barrier inventory database was used if needed); and crashes of some events (nearside and far-side cable barrier collisions) had to be verified using Google Earth images. The following section introduces how crashes and their events were selected and determined.

First, crash reduction was conducted. From all the crashes that occurred on INDOT-administered roads from 2003 to 2013, those most likely irrelevant to the performance of barriers were excluded. Generally speaking, those irrelevant crashes were of two types: (1) crashes that occurred on segments where barriers were

not allowed, and (2) crashes that would have occurred the same way even if a barrier had been there. Furthermore, crashes that occurred on roads with speed limits of 45 mph or less or had a curb present were removed given that those crashes very likely occurred on urban arterial roads, where the use of road barriers was not considered in most cases.

Crash selection then was conducted, and the following section discusses how the crashes of each category were selected based on the existing information available in the current crash database and barrier inventory database.

#### **Median cable barrier collision (nearside or far-side)**

- The number of vehicles involved was equal to 1.
- The most hazardous event was “cable barrier” or “median barrier.”
- The sequence of events did not include “cross the median.”
- The crash location was where a cable barrier was installed.
- The year of the collision was after the year of the cable barrier installation.

#### **Median concrete barrier wall collision**

- The number of vehicles involved was equal to 1.
- The most hazardous event was “concrete barrier wall” or “median barrier.”
- The sequence of events did not include “cross the median.”
- The crash location was where a barrier wall was installed.
- The type of median was “barrier wall.”

#### **Median guardrail collision**

- The number of vehicles involved was equal to 1.
- The most hazardous event was “guardrail face” or “median barrier.”
- The sequence of events did not include “cross the median.”
- The crash location was where the median guardrail was installed and no roadside guardrail was installed.

#### **Roadside guardrail collision**

- The number of vehicles involved was equal to 1.
- The most hazardous event was “guardrail face.”
- The sequence of events did not include “cross the median.”
- The type of median was “drivable.”

#### **Cross-median head-on collision**

- The manner of collision was “head on.”
- The number of vehicle involved was equal to or larger than 2.
- The vehicle travelling directions were different.
- The most hazardous event was “another vehicle.”
- The median type was “drivable.”

TABLE 4.4  
Summary of Crashes by Event Category in the Big Crash Sample.

Event Category	Crashes	Vehicles	Occupants
Non-cross-median high-risk	34418	34418	48151
Far-side median cable barrier collision	362	362	557
Nearside median cable barrier collision	754	754	1184
Median barrier wall collision	4499	4499	6496
Median guardrail (face) collision	268	268	379
Non-cross-median moderate-risk event	32077	32077	44774
Vehicle redirected and hit another vehicle	1899	3946	6422
Roadside guardrail collision	3630	3630	5439
Cross-median head-on	4303	8701	12793
Cross-median non-head-on	400	400	579
Total	82610	89055	126774

#### Cross-median non-head-on collision

- The number of vehicle involved was equal to 1.
- The sequence of events included “cross the median.”

#### Non-cross-median high-risk event

- The number of vehicles involved was equal to 1.
- The most hazardous event was any one of the following: “roll over,” “bridge or abutment,” “overhead sign post,” “light/luminaire support,” “utility pole,” “other post/pole or support,” “wall/building/tunnel,” “embankment,” “culvert,” or “tree.”
- The sequence of events did not include “cross the median.”

#### Non-cross-median moderate-risk event

- The number of vehicles involved was equal to 1.
- The most hazardous event was any one of the following: “off roadway,” “impact attenuator/crash cushion,” “highway traffic sign post,” “ditch,” “fence,” “mailbox,” or “downhill runaway.”
- The sequence of events did not include “cross the median.”

#### Redirected and hit another vehicle event

- The manner of collision was one of the following: “same direction sideswipe,” “head on,” “opposite direction sideswipe,” or “ran off roadway.”
- The number of vehicles involved was equal to or larger than 2.
- The vehicle travelling directions were the same.
- The most hazardous event was “another vehicle.”
- The sequence of events did not include “cross the median.”

The number of selected crashes for different event categories largely depended on how specific the existing information available in the current database was. For example, “cross the median” entry was a key piece of information in selecting crashes for the cross-median non-head-on event category. However, this entry was not available in the crash database until November

2011. So the number of crashes of this event category was smaller than anticipated.

The selected crashes with a redirected and hit another vehicle event in the BR injury sample were extracted following this ratio: head on (21.05%), same direction sideswipe (44.74%), opposite direction sideswipe (2.63%), and ran off roadway (31.58%). The ratio was determined from the same events found in the BR events sample. For median cable barrier collisions, whether they were nearside or far-side was determined by examining the Google Earth images for the crash location.

#### 4.5.3 BR Injury Sample Summary

A total of 126,774 occupants that were involved in 82,610 BR crashes and 89,055 vehicles were finally selected to form the BR injury sample. The sample included a number of 1,748 fatal occupants. Table 4.4 shows the number of crashes and occupants classified by the event category.

### 5. BR CRASH FREQUENCY MODEL

The BR crash frequency model is a component of this study’s in-service safety evaluation of barriers. This chapter discusses the BR crash frequency model estimated with the divided road segment sample. The statistical modeling approach and the sample are discussed, as well as a summary of the model and its results.

The purpose of the BR crash frequency model was to estimate the effect of the investigated types of barriers on the BR crash frequency. The obtained model could be used to improve the estimation of the BR crash frequency in before-and-after studies aimed to select the best barrier treatment on existing roads and to predict the BR crash frequency in design alternatives involving the use of barriers for new roads.

A change in the crash frequency due to the presence of barriers is an important and necessary component of this study. The positive effect of barriers (i.e., reducing the crash injury level) is typically weakened by increasing the crash frequency. Barriers increase

both the risk of a roadside collision and the risk of uncontrolled returning to the roadway. Thus, the frequency of reported BR crashes tends to increase after a barrier is installed. Thus, the evaluation of the in-service performance of barriers without accounting for the changes in crash frequency could yield incorrect results.

The crash frequency analysis is the first step toward a full assessment of the overall performance of barriers. The barriers effects on BR events, BR injury outcomes, and subsequently the costs of BR crashes are discussed in Chapters 6, 7, and 8 respectively.

## 5.1 Sample

The response variable is the number of BR crashes on a directional homogeneous segment over its analysis period. Consequently, the exploratory variables are direction-specific. For example, the traffic volume ADT is one-half of the bi-directional segment's ADT.

The number of years with crash data varied in the sample with the barrier type. For segments with barriers installed before 2008 and their matched non-barrier segments, the analysis period was 2008 to 2012, which was the case for segments with concrete barriers, guardrails, and a small portion of cable barriers. For segments with barriers installed in or after 2008, which was the case for the majority of cable barriers, the analysis period was from the year after installation through 2012. Although we extracted ten years of data (2003 through 2012), the frequency analysis focused on the last five years when the accuracy of the crash data was higher than in the previous years. To account for the different periods with crash data, the number of years was set as an offset variable.

The explanatory variables important in this study included the one-way ADT averaged over the analysis period, the adjusted segment length (see details in Section 5.3), the roadway functional class, the speed limit, the median and roadside barriers.

Due to the strong correlation between the roadway functional class and the speed limit, these two variables were converted into three mutually exclusive categories: (1) freeway with speed limit 65 mph or higher, (2) freeway with speed limit 60 mph or lower, and (3) non-freeway. The non-freeway category was set as the reference category. The coefficients for the other two categories reflected the change in the annual BR crash frequency in relation to the reference category.

The focus of the analysis was obviously on the barrier's presence, its type, and its offset. These effects were modeled via barrier median and roadside scenarios. Section 3.2 introduced these scenarios. The median or roadside alternatives were divided into barrier and non-barrier cases. The barrier case was further divided into scenarios different by barrier type and offset to the edge of the travelled way; and the non-barrier case was further divided into scenarios that differed by their median width (where a median was present) and roadside hazard rating. The

scenarios with estimated similar effects on the BR crash frequency were eventually combined.

Table 5.1 and Table 5.2 provide the sample summary for the continuous and categorical variables, respectively.

## 5.2 Model

A negative binomial regression model was developed to estimate the BR crash frequency based on the collected segment data and crash data for 2008 through 2012. The negative binomial models frequently have been used to model crash frequency due to their simpler variance function and closed form likelihood function. Although many alternatives are available in frequency modeling, as mentioned in Section 2.3, the results of some models may not be easily transferable to other datasets (Lord & Mannering, 2010). Given that this study is not only focused on the statistical inference but also on implementing the developed models to engineering practice, a traditional negative binomial regression model was deemed adequate to meet the research objective.

## 5.3 Adjusting for Crash Migration

There is a tendency in crash reporting to leave an entry blank or enter "0" distance between the crash location and the road milepost. This omission is manifested via clusters of crashes attached to mileposts where there is no logical explanation of such crash grouping. This problem is called "crash migration" from their correct location to the nearby milepost. Since the studied segments were selected via the mileposts in a segment, the mileposts were included in all the studied segments. If not accounted for, the crash migration problem could have caused overestimation of the BR crashes on such segments and might also lead to biased estimates of the effects.

The crash frequency on a homogeneous road segment is expected to grow in proportion to the segment's length. Contrary to this expectation, the model parameter associated with the log of the segment length was much lower than 1. This result suggested that the rate at which the number of BR crashes increased became smaller when the segment length increased. This is a clear indication of the presence of crash migration.

To address the problem, we applied an adjustment to the segment length. It is plausible to assume uniform density  $d$  of crashes along a homogenous segment with length  $L$ . Thus, the expected number of crashes to occur on that segment is  $Ld$ . Let us assume that crashes migrate to the nearest milepost. Thus, if only  $k$  portion of crashes migrates, any milepost receives  $kd$  migrating crashes from the one-mile segment around it. The number of crashes that migrate from outside to the studied segment of length  $L$  is  $k(1-L)d$ . Crashes that migrate inside the segment do not contribute to the estimation problem and are not considered. The

TABLE 5.1  
Summary of Statistics of the Continuous Variables in Crash Frequency Model (Segment Level).

Variable	Number of observations	Mean	Standard deviation	Minimum	Maximum
Number of BR crashes that occurred from 2008 to 2012	1258	1.275	1.933	0.000	14.000
Average daily traffic (vehicle/day)	1258	15,439	9,731	1,215	77,801
Segment length (mile)	1258	0.261	0.179	0.057	0.965
Median width (feet)	1258	57.59	32.35	1.00	420.00
Inside shoulder width (feet)	1258	6.667	3.583	0.000	21.000
Outside shoulder width (feet)	1258	10.804	1.504	0.000	22.000

TABLE 5.2  
Summary of Statistics of the Categorical Variables in Crash Frequency Model (Segment Level).

Variable	Categories	Count	Percentage (%)
Functional class and speed limit	Freeway with a speed limit 65 mph or higher	940	74.72
	Freeway with a speed limit 60 mph or lower	80	6.36
	Non-freeway	238	18.92
Urban area indicator	Urban	342	27.19
	Rural	916	72.81
Median scenario	Nearside Cable Barrier (offset ≤30 feet)	93	7.39
	Far-side Cable Barrier (offset >30ft)	93	7.39
	Concrete Barrier	154	12.24
	Guardrail	62	4.93
	Narrow Median (width ≤50 feet)	176	13.99
Roadside scenario	Wide Median (width >50 feet)	680	54.05
	High-hazard roadside (hazard rating 3 to 7)	436	34.66
	Low-hazard roadside (hazard rating 1 or 2)	519	41.26
Number of lanes	Guardrail	303	24.09
	Two lanes	1,147	91.18
	Three lanes	96	7.63
	Four lanes	8	0.64
	Five Lanes	7	0.56

expected crash count obtained from the data is  $(Ld)+k(1-L)d=L'd$ , where  $L'$  is the adjusted segment length, which can be interpreted as the actual length of the segment  $L$  plus an equivalent extra length  $k(1-L)$  to account for the crash migration.

The segment length is adjusted in a way that restores the linear relationship between the crash frequency and the segment length. Thus, the value of  $k$  corresponds to the coefficient of the adjusted segment length close to 1. Table 5.3 presents the model estimated for various values of  $k$ . It can be seen that the  $k$  value considerably affected only the coefficient of the adjusted segment length, while other coefficients were quite stable. The value of  $k=0.28$  was selected to adjust the segment length, which means that 28% of crashes on average “migrated” to the nearby mileposts.

## 5.4 Results

The modeling results for the crash frequency analysis are shown in Table 5.4. The coefficient for the variable log of the one-half of the two-way ADT was smaller

than 1 but was reasonably close. When the coefficient was close to 1, the rate of increase in the BR crash frequency was somewhat equal to the rate of the increase in the one-half of the two-way ADT, which reflected its attribute as an exposure variable. Nonetheless, when the coefficient was smaller than 1, it was suggested that the increase rate of the former was less than the latter, which could be explained by the fact that, for an individual driver, an increase in the traffic volume on a segment could make the driver more focused and thus less likely to leave the roadway.

As the modeling results indicate, a freeway with a higher speed limit experienced the highest expected BR crash frequency, which was  $\exp(1.6661)=5.29$  times that of a non-freeway. The crash frequency for a freeway with a lower speed limit was 2.60 times that of a non-freeway. These comparison results can be explained by two known facts: (1) drivers are more likely to lose control of a vehicle under higher speeds, and (2) drivers are more likely to drive when fatigued on a freeway compared to a non-freeway.

TABLE 5.3  
Parameter Estimates and Goodness-of-Fit Statistics under Different k Values.

Variable	Parameter Estimates							
	k=0	k=0.10	k=0.20	k=0.26	k=0.28	k=0.30	k=0.40	k=0.90
Intercept	-8.0841	-8.0317	-7.9864	-7.9629	-7.9556	-7.9485	-7.9162	-7.8002
Log of the one-half of two-way ADT in vehicles per day	0.5966	0.6011	0.6026	0.6031	0.6033	0.6034	0.6040	0.6053
Log of adjusted segment length in miles	0.3797	0.5726	0.7841	0.9310	0.9845	1.0407	1.3719	12.4531
Freeway with speed limit 65 mph or higher	1.6667	1.6638	1.6648	1.6657	1.6661	1.6664	1.6682	1.6759
Freeway with speed limit 60 mph or lower	0.9682	0.9584	0.9561	0.9558	0.9557	0.9557	0.9561	0.9604
Non-freeway	Reference							
Median concrete barrier	0.9666	0.9768	0.9806	0.9817	0.9820	0.9823	0.9831	0.9832
Median guardrail (face)	0.6492	0.6102	0.5932	0.5864	0.5845	0.5827	0.5753	0.5549
Median cable barrier	0.3255	0.3141	0.3081	0.3056	0.3048	0.3041	0.3012	0.2928
No Median Barrier	Reference							
Dispersion	0.3827	0.3819	0.3814	0.3813	0.3812	0.3812	0.3811	0.3817
Log likelihood	-1662.7	-1663.1	-1663.3	-1663.5	-1663.5	-1663.5	-1663.7	-1664.6
AIC	3343.5	3344.2	3344.6	3344.9	3345.0	3345.1	3345.5	3347.2
No. of observations	1258	1258	1258	1258	1258	1258	1258	1258

In the modeling results for barriers, six original median scenarios were combined into four categories: (1) median concrete barrier wall, (2) median guardrail, (3) median cable barrier, and (4) median with no barrier installed. The median with no barriers installed was set as the reference category. No statistical difference was found across the three original roadside scenarios so the roadside scenarios, such as guardrail, were not included in the final modeling results.

The results show that all three types of median barriers were associated with increased BR crash frequency compared to a median with no barriers. Median barrier walls were associated with the largest increase, followed by median guardrails, and median cable barrier exhibited the smallest increase. The number of BR crashes on a segment with a median concrete barrier wall was 2.67 times that of a segment with no median barrier. For a segment with median cable barriers installed, the crash frequency was 1.36 times that of a segment with no median barrier. The difference across the three types of median barriers could be explained by the relative likelihood of a crash being reported when a vehicle strikes one of them. In barrier wall collisions, drivers were more likely to be injured due to the high structural rigidity of barrier walls, and thus more crashes were likely to be reported. Cable barrier collisions were more likely to go unreported due to the more forgiving design of cable barriers.

## 5.5 Discussion

Some road characteristic variables were also available in this study but were not included in the final model due to their high correlation with the included variables. For example, the number of lanes is not only highly correlated with the ADT, but also depends a lot on the median barrier type. That is, segments with median barrier walls are mainly associated with at least three lanes while those with cable barriers normally only have two lanes. Another example is the left shoulder width, which is generally larger than 12 feet when the median is treated with a barrier wall but is a different width when the median is treated with other types of barriers or there are no barriers. Imposing those highly correlated variables on a model can cause the near-multi-collinearity problem, which leads to the increased standard errors of those related variables.

In this study, the roadside characteristics did not significantly affect the BR crash frequency, for which there are two possible explanations. First, homogenous segments with a roadside guardrail installed tend to be short in length compared to median barriers, which tend to be continuously present for a longer roadway section; the placement of roadside guardrails therefore depends more on the site characteristics and often exist in a shorter and more intermittent way. As previously mentioned, shorter segments tended to be more affected by the crash location migration problem. Thus, the low

TABLE 5.4  
**Estimation Results of the Frequency Model (Negative Binomial Regression).**

Variables	Parameter Estimate	Standard Error	Wald Chi-Square	P-Value
<b>Intercept</b>	-7.9556	0.7917	100.99	<.0001
<b>Log of the one-half of two-way ADT in vehicles per day</b>	0.6033	0.0847	50.70	<.0001
<b>Log of adjusted segment length in miles</b>	0.9845	0.1360	52.38	<.0001
<b>Freeway with speed limit 65 mph or higher</b>	1.6661	0.1555	114.79	<.0001
<b>Freeway with speed limit 60 mph or lower</b>	0.9557	0.2043	21.89	<.0001
<b>Non-freeway</b>	Reference			
<b>Median concrete barrier</b>	0.9820	0.1044	88.50	<.0001
<b>Median guardrail (face)</b>	0.5845	0.1403	17.35	<.0001
<b>Median cable barrier</b>	0.3048	0.1077	8.02	0.0046
<b>No median barrier</b>	Reference			
<b>Dispersion</b>	0.3812	0.0523		
<b>Log likelihood</b>	-1663.5			
<b>AIC</b>	3345.0			
<b>Number of observations</b>	1258			

accuracy of the crash counts on short segments might reduce the ability to isolate the effect of roadside guardrails. Second, a median without a barrier may offer a better chance for errant vehicles to recover than a roadside without a guardrail. A guardrail installed in a roadside area may increase the frequency of reported crashes to a smaller extent than a barrier installed in a median.

### 5.6 Chapter Summary

This chapter investigated the factors influencing the BR crash frequency. A negative binomial regression model was developed based on the number of barrier relevant crashes that occurred on a number of 1,258 directionally divided roadway segments from 2008 through 2012. For segments with cable barriers installed on or after 2008, only the crashes that occurred after the installation year were counted. With the estimated coefficients, the developed model could be used to predict BR crash frequency under different median and roadside scenarios.

All three types of median barriers were found to increase the BR crash frequency compared to a median with no barriers. Median concrete barrier walls increased the frequency most, followed by median guardrails and median cable barriers. Roadside guardrails were not found to significantly increase the frequency. As expected, increases in the ADT increased the crash frequency; however, the rate of the increase in frequency was smaller than for the ADT. The non-freeway segments tended to have a lower crash frequency

than freeway segments, of which those with lower speed limits tended to have smaller crash frequencies than those with higher speed limits.

## 6. BR EVENTS MODEL

A BR event is the most harmful event of a BR crash. It may involve single or multiple vehicles. A BR event links the onset of a crash and its final outcome, namely, the injury severity of the individuals involved in the crash. The frequency and type of the BR events are important for the injury severity outcome of a BR crash.

A multinomial logit model with variable outcomes was developed to analyze the effect of barriers, as well as other influencing factors, on the type and probability of various BR events. The statistical modeling framework, variable processing, summary statistics of the data, and modeling results are discussed in this chapter.

### 6.1 Introduction

The purpose of a barrier is to eliminate the most hazardous events, such as head-on collisions, collisions with strong objects, and rollovers. When a barrier is installed only on one side of a travelled way, then hazardous events can occur on the other side. Even when vehicles on a travelled way are protected on both sides, a hazardous event may still occur. For example, a median cable barrier is typically placed in Indiana near one of the median edges. A vehicle entering a wide median through the other edge is exposed to the

potentially damaging impact of a ditch located in the median center. In another case, a tall vehicle hitting a guardrail at a high speed may roll over after the impact.

Using barriers may also increase some undesirable events. Our site inspections based on the police narratives and collision diagrams in crash reports revealed that after running off the roadway and colliding with a barrier, some vehicles bounced off the barrier and, redirected back to the on-road traffic, collided with other vehicles.

Thus, most of the time, a barrier reduces the risk of hazardous events while introducing new events (collision with a barrier), or increasing additional events, such as the aforementioned redirecting of a vehicle that may lead to a multi-vehicle collision. The following questions will be addressed in this chapter:

- By what percentage can cross-median crashes be reduced after a median barrier is installed?
- How much less likely would a crash result in a hazardous event after a barrier is installed?
- How likely will a crash end up being a barrier collision given that the barrier is installed?
- How likely will an errant vehicle bounce off the barrier and be redirected to collide with other on-road vehicles?
- What factors influence these probabilities?

Therefore, how to quantify the change in the probabilities of barrier-relevant hazardous events due to the installation of barriers was not only important in gaining insight into the safety impact, but also was critical in the evaluation of the overall in-service performance of the barriers. It is important to note that the aforementioned probabilities were conditioned on a BR crash having occurred.

To address the above questions, a multinomial logit model with variable outcomes was developed to predict the probability of a BR crash resulting in each considered event category on a given segment with given roadway and roadside characteristics. The model also provided insight about variables that affected the BR events probabilities.

## 6.2 BR Events

Various road conditions determine the possible most harmful events when a crash occurs, which could be adequately represented with a multinomial logit model with variable outcomes, which is an extension of a standard multinomial logit model. Before introducing the model, we first will introduce the universal and conditional event sets for a BR crash that were needed to properly define the response variable.

### 6.2.1 Universal BR Events Set

A universal set of BR events is a collection of all possible types of events that may result from BR crashes. The universal BR events set applies to all the different BR crashes. In the considered here case, the

universal BR events set includes the following event types:

- Event XH: cross-median head-on event
- Event XNH: cross-median non-head-on event
- Event RHV: redirected and hit of another vehicle event
- Event MB: median barrier collision event
- Event SB: roadside barrier collision event
- Event HR: non-cross-median high-risk event
- Event MR: non-cross-median moderate-risk event

These are the same event categories discussed in Section 4.4 with one modification. The four types of median barrier collisions were combined into one event category, which is the median barrier collision event (Event MB). Combining event categories with similar occurrence mechanisms helped reduce the complexity of the BR events model. It must be emphasized that combining these four events still allowed estimating the probabilities and the severity outcomes for each of these events separately.

### 6.2.2 Conditional BR Event Set

A conditional set of BR events is a subset of the universal set that includes eligible outcomes under a certain roadway and barrier scenario. For example, a crash on a non-barrier segment cannot generate events MB and SB, thus these events were excluded from the universal set of BR events. Likewise, events XH and XNH did not occur on the studied roadway segment with median barriers and had to be excluded from the universal set. This exclusion was due to the small size of the sample. Previous studies identified cross-median events that were not eliminated with median barriers, which will be discussed in Section 8.2. This shortcoming of the sample was rectified during the implementation of the results of this study and is described in Section 8.2.

The conditional BR events set in this study depended on the presence of barriers in the median and on the roadside. The following four conditional BR events sets were included in the BR events sample:

1. Both median and roadside barriers installed: {RHV, MB, SB, HR, MR}
2. Only median barriers installed: {RHV, MB, HR, MR}
3. Only roadside barriers installed: {XH, XNH, RHV, SB, HR, MR}
4. No barriers installed: {XH, XNH, RHV, HR, MR}

Within each conditional events set, the sum of the probabilities of the included events was 1. Events XH and XNH, although possible, were not included in conditional sets 1 and 2 due to the lack of such observations in the sample. This omission was remedied later by adding them to these two sets. The probabilities of these two events were assumed based on the literature and the probabilities of other events in the sets being re-distributed to ensure that the sum of all the probabilities equaled 1 in each set.

### 6.2.3 Distribution of BR Events

Figure 6.1 presents the sample distribution of the BR events conditional on a barrier scenario. The highly hazardous cross-median events XH and XNH occurred in 9% to 11% of the BR crashes on segments without median barriers. The head-on events occurred in 2% to 3% of the BR crashes.

Non-cross-median high-risk events HR and non-cross-median moderate-risk events MR were the two most common BR events on the travelled ways without barriers. The frequency of HR and MR events was surpassed by the frequency of barrier collision events MB and SB on the travelled ways with median or roadside barriers installed. However, non-cross-median high-risk HR and non-cross-median moderate-risk events MH were not eliminated even when both sides of a travelled way were protected with barriers. Non-cross-median high-risk events still occurred in 5.5% of the BR crashes. Most of these events were rollovers that occurred in front of a barrier placed at a large offset or after a collision with a barrier.

Redirected vehicle events RHV occurred in 1% of the BR crashes on the segments without barriers, in 2% to 3% of the BR crashes on segments when only one side of the travelled way was shielded with a barrier, and in 5.5% of the BR crashes where both sides of the travelled way were protected by barriers. These results indicate the tendency for barriers to increase the probability of redirecting ROR vehicles back to the travelled way.

Figure 6.1 demonstrates the general effects of the presence of barriers on the distribution of BR events. This distribution also may depend on other variables, such as the median width, the barrier type and offset, the roadside hazard rating, etc. A statistical model was estimated to analyze the effect of other variables.

### 6.3 Model Specification

Some of the advanced unordered discrete outcome models reviewed in Section 2.3 were considered for this study as promising alternatives to a standard multiple logit model. The nested logit models and mixed logit

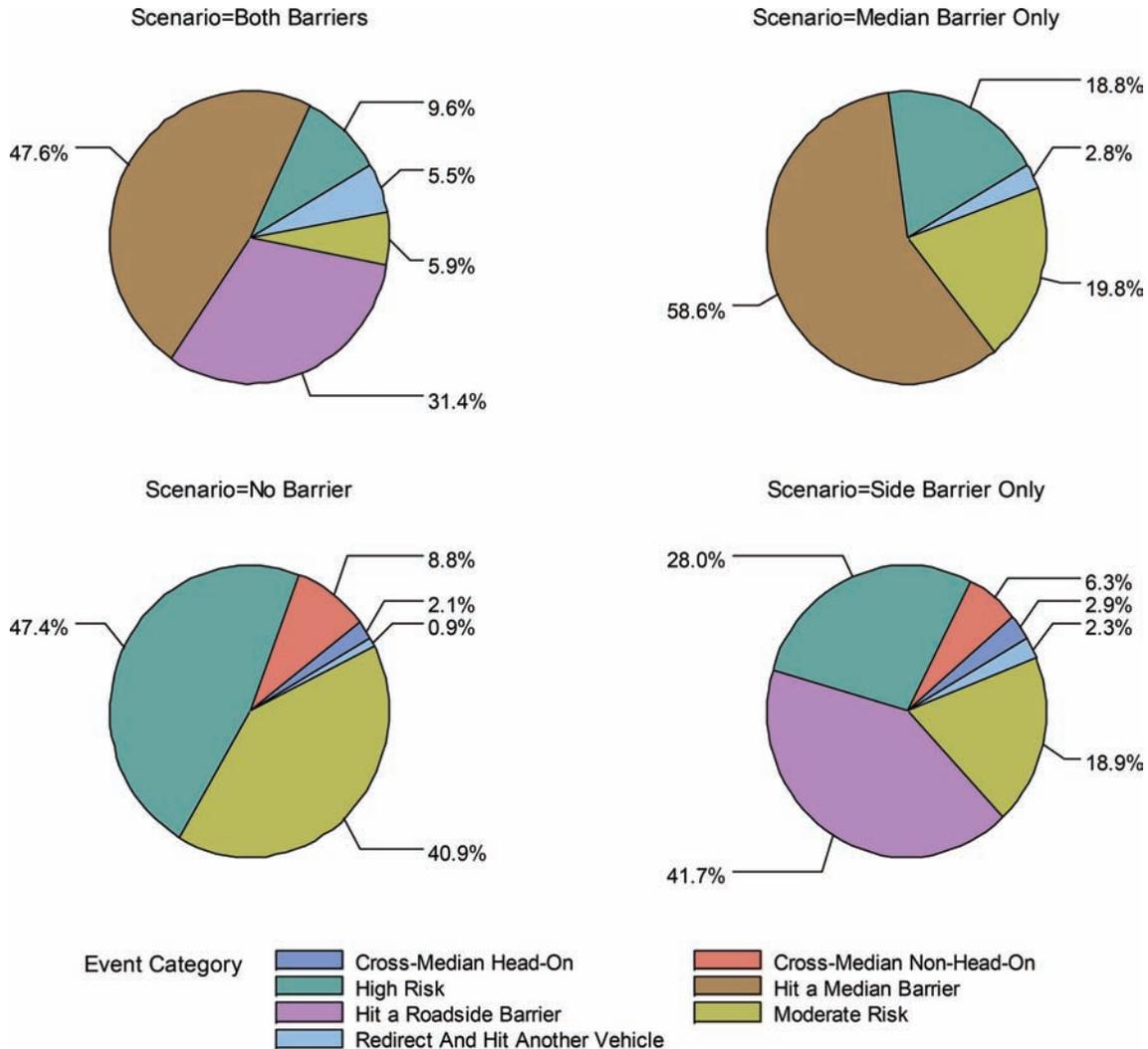


Figure 6.1 Distribution of different event categories.

models seemed to be appropriate. Several nesting structures were specified under the nested logit model framework. The corresponding coefficients for the logsum parameters were not shown to be greater than 0 and less than 1, which indicated that the IIA assumptions would not be violated by a standard multinomial logit model. Then, the mixed logit models were attempted with a normal distribution assumed for each random parameter variable. No variable was found to have an observation-specific effect. Thus, the standard multinomial logit model was ultimately selected as the most convenient and sufficient among the considered models.

The BR events sample was used to estimate the multinomial logit model with variable outcomes. The sample was composed of 2,049 BR crashes and corresponding BR events that occurred from 2003 through 2012 on the selected homogenous segments (unidirectional travelled ways). Since a BR event is the most harmful event of a BR crash, there is a one-to-one correspondence between the two events. Each observation is a BR crash with its conditional events set and a single BR event that actually occurred during the crash. The observation is supplemented with the corresponding travelled way, median, and roadside variables. Section 4.4 provides more information about the sample.

Multinomial logit models were applied by many researchers to model crash-injury severity (Lee & Mannering, 2002; Ulfarsson & Mannering, 2004). The multinomial logit model with variable outcomes selected for this study differed from the standard multinomial logit models by its ability to deal with the number of eligible outcomes varied from one observation to another. This feature made the selected model suitable for this study where the possible BR events depend on the presence of median and roadside barriers as discussed in Section 6.2. The econometric software, NLOGIT, was used to estimate the model (Greene, 2007).

In the modeling framework of a multinomial logit model, the propensity function of BR event  $j$  given BR crash  $i$  occurred is expressed in a linear form:

$$U_{ij} = \hat{\alpha}_j X_{ij} + \hat{\epsilon}_{ij} \quad (6.1)$$

where  $X_{ij}$  is a vector of the measurable roadway and the roadside characteristics of the directional travelled way on which BR crash  $i$  occurred,  $\hat{\alpha}_j$  is a vector of estimated coefficients for BR event  $j$  and  $\hat{\epsilon}_{ij}$  is the error term assumed to follow the generalized extreme value distribution (McFadden, 1981). The expected value of the propensity is:

$$\bar{U}_{ij} = \hat{\alpha}_j X_{ij} \quad (6.2)$$

The probability of BR event  $j$  given BR crash  $i$  out of a number of  $J_i$  eligible events is calculated as:

$$Pr(E_{ij}) = \frac{\exp(\hat{\alpha}_j X_{ij})}{\sum_{\forall j \in J_i} \exp(\hat{\alpha}_j X_{ij})} = \frac{\exp(\bar{U}_{ij})}{\sum_{\forall j \in J_i} \exp(\bar{U}_{ij})} \quad (6.3)$$

It should be noted that the denominator term in Equation (6.3) is the summation of all the events in the conditional set but not in the universal set. For example, the probability of event RHV for a BR crash on a segment with only median barrier installed is

$$Pr(E_{RHV}) = \exp(\bar{U}_{RHV}) / [\exp(\bar{U}_{RHV}) + \exp(\bar{U}_{MB}) + \exp(\bar{U}_{HR}) + \exp(\bar{U}_{MR})],$$

whereas the same event probability for a crash on a segment with no barrier installed is

$$Pr(E_{RHV}) = \exp(\bar{U}_{RHV}) / [\exp(\bar{U}_{XH}) + \exp(\bar{U}_{XNH}) + \exp(\bar{U}_{RHV}) + \exp(\bar{U}_{HR}) + \exp(\bar{U}_{MR})]$$

The coefficient for each propensity function was estimated using the maximum likelihood method. It should be noted that all the propensities estimated were relative propensities. That is, an individual event's probability was not dependent on how large its propensity was but rather how different it was from the propensities of the reference event.

The focus of this analysis was on the explanatory variables representing the median and roadside characteristics captured through different median and roadside scenarios (including barriers and non-barriers), which were presented in Section 3.2. Six median scenarios were defined based on the median width, barrier type, and offset. Three roadside scenarios were defined based on the presence of a roadside guardrail and the roadside hazard rating. The six median scenarios were introduced to the model as a categorical variable "median scenario" coded with five binary variables (dummy variables); and one binary variable for a narrow median without barrier M\_NB\_N was omitted to serve as a reference case. The roadside scenarios were represented the same way with a roadside without guardrail and high hazard rating S\_NB\_H as a reference case.

Other variables considered in the modeling were traffic volume, presence of a horizontal curve, roadway functional class, and speed limit. Table 6.1 shows the summary statistics of the variables considered in the development of the BR events model.

#### 6.4 Estimated Model

The modeling results are shown in Table 6.2. The non-cross-median high-risk event (event HR) was the reference event (or baseline) and therefore its propensity was set at zero and no coefficients were estimated

for this event. The coefficient values of the explanatory variables for a non-reference event reflect how much the propensity for that event (relative to the reference HR event) changed due to these variables. Furthermore, each categorical explanatory variable represented with a set of binary variables also had its own reference category with the corresponding coefficient set at zero. For example, the median scenario had six categories among which the narrow median without barrier (M\_NB\_N) was used as the reference. The coefficient of the wide median without barrier (M\_NB\_W) in the propensity head-on collision event (XH) was negative and equal to -1.618. This result indicates that a wide median had a lower probability of a head-on collision event (XH) than the reference narrow median (M\_NB\_N). Other scenarios were not relevant to the XH event because the conditional BR events sets for medians with barriers did not include event XH as earlier explained.

On the other hand, just comparing the M\_NB\_W coefficient across the BR events was insufficient to claim that among all the probability reductions caused by M\_NB\_W, the reduction of the XH probability was the largest. These reductions also depended on the effects of other explanatory variables and on the events included in the conditional sets.

Discussion of the estimated effects is straightforward in certain types of models while much more involved in other types. In negative binomial count models with fixed parameters, individual effects are represented by exponential functions of the corresponding variables and their coefficients. The marginal effects are fixed and independent of any variables. Another example is binary logit models, where the effects are again isolated from other effects and take the form of fixed odds ratios. The effects of individual variables included in the obtained multinomial logit model with variable outcomes are not easy to calculate for three reasons:

1. The effect of a variable depends on other variables and on the conditional sets of outcomes,
2. All the variables are discrete which requires evaluating the model at two discrete values of the subject variable. Setting other binary variables at their average values is a convenient approach to estimating the average response, but its validity is questionable for non-linear models.
3. Evaluating a joint effect of several variables may be more meaningful than evaluating individual variables. For example, a complete barrier scenario includes median and roadside barriers' presence, types, and offsets.

Keeping the three motivations in mind, the probabilities of BR events were estimated for the individual road-barrier scenarios using sample observations by setting the median and roadside variables at values that represented a meaningful road-barrier scenario in all the observations of the sample. The BR event probabilities for this scenario were calculated in all the observations and then the average probabilities across the observations were calculated. This procedure was repeated for all the studied road-barrier scenarios. The obtained average probabilities were based on the

realistic mix of Indiana conditions, and thus the bias caused by the average inputs of a non-linear model was avoided. The results are compared across the scenarios and discussed in the following section.

#### 6.4.1 Probabilities of BR Events

The BR events model returned the conditional probability of BR event  $h$  for each observation  $j$ :  $\Pr(e_{jh}|b_{jk},x_j)$ . The average probability of BR event  $h$  for road-barrier scenarios  $k$  was calculated as follows:

$$\Pr(e_h|b_k) = \frac{1}{N_e} \sum_{j \in J} \Pr(e_{jh}|b_k, x_j) \quad (6.4)$$

where:

$e_h$  = indicator of BR harmful event  $h$ ,

$b_k$  = indicator of road-barrier scenario  $k$ ,

$N_e$  = number of observations in the BR events sample,

$J$  = set of observations in the BR injury sample,

$x_j$  = values of additional variables included the model.

In accordance with Equation (6.4), the original values  $b_{jk}$  in the sample were replaced with  $b_k$  when calculating the average probability of BR event  $h$ . The results are presented in Table 6.3.

The average probabilities of the road-barrier scenarios on the BR events are summarized in Table 6.3. The original six median scenarios and three roadside scenarios were combined, producing 18 road-barrier scenarios. The original MB event was broken down into four events that depended on the type and the lateral position of the median barrier in relation to the unidirectional travelled way. Thus, the current matrix of road-barrier scenarios and BR events was  $18 \times 10$  in size. The hyphen symbols indicate the events excluded from the conditional outcome set for a given road-barrier scenario as impossible or not represented in the sample.

For example, the BR events allowed for vehicles moving on a travelled way with a narrow median (30–50 feet wide); high roadside hazard (rating 3–7); and neither median nor roadside barrier (M\_NB\_N and R\_NB\_H) are: a cross-median head-on collision (XH), a cross-median non-head-on collision (XNH), a multiple-vehicle collision after a ROR vehicle was redirected to a travelled way (RHV), a moderate-risk median or roadside crash (MR), and a high-risk median or roadside crash (HR). The corresponding probabilities of these BR events are: 7.1% for XH, 19.5% for XNH, 0.8% for RHV, 36.3% for MR, and 36.3% for HR.

Returning to the travelled way can occur after a vehicle hits an unshielded off-road object or poorly controlled steering maneuvers of a driver. Table 6.3 presents a few interesting road safety effects through the redistribution of the probabilities of BR events. Some of these events are known to produce more severe injuries than other.

TABLE 6.1  
Summary of the Response and Explanatory Variables in the BR Event Sample.

Variables	Categories	Count	Percentage (%)
BR event	Non-cross-median high-risk event	627	30.6
	Median barrier wall collision	382	18.64
	Nearside median cable barrier collision	62	3.03
	Far-side median cable barrier collision	42	2.05
	Median guardrail (face) collision	69	3.37
	Non-cross-median moderate-risk event	551	26.89
	Vehicle redirected and hit another vehicle	47	2.29
	Roadside guardrail collision	158	7.71
	Cross-median head-on	23	1.12
Functional class and speed limit	Cross-median non-head-on	88	4.29
	Freeway with a speed limit 65 mph or higher	1,720	83.94
	Freeway with a speed limit 60 mph or lower	249	12.15
Horizontal curve	Non-freeway	80	3.91
	Left curve	77	3.76
	Right curve	93	4.54
Urban area indicator	Tangent	1,879	91.7
	Urban	686	33.48
	Rural	1,386	66.52
Median scenario	Nearside Cable Barrier (offset $\leq$ 30 feet)	111	5.42
	Far-side Cable Barrier (offset $>$ 30 feet)	95	4.64
	Concrete Barrier	624	30.45
	Guardrail	168	8.2
	Narrow Median (width $\leq$ 50 feet)	61	2.98
Roadside scenario	Wide Median (width $>$ 50 feet)	990	48.32
	High-hazard roadside (hazard rating 3 to 7)	914	44.61
	Low-hazard roadside (hazard rating 1 or 2)	689	33.63
Number of lanes	Guardrail	446	21.77
	Two lanes	1,457	71.11
	Three lanes	512	24.99
	Four lanes	34	1.66
	Five lanes	46	2.24

**Cross-median collisions.** The occupants of vehicles that cross a median are exposed to head-on collisions XH with vehicles moving in the opposite direction. Two facts are known about these collisions: (1) they are the most dangerous among all crashes, and (2) wide medians reduce the risk of these collisions. The average probability of a head-on collision XH on roads with medians 30–50 feet wide and without barriers M\_NB\_N was 6.4% given that a barrier-relevant crash occurred. This likelihood on similar roads M\_NB\_W but with wider medians of 50–80 feet was reduced to 2.0%. Similarly, cross-median crashes other than head-on collisions XNH were reduced from 14.7% to 7.5%. These results were consistent with expectations.

**Collisions of vehicles redirected back to the roadway.** Barriers may increase the risk of RHV collisions of vehicles redirected from a median or a roadside back to the moving vehicles on the travelled way. The conditional risk of RHV collisions on the studied road segments without barriers (M\_NB and R\_NB) was estimated at 1%. The frequency of RHV collisions

were three to three and one-half times higher on travelled ways with a median concrete wall and without roadside barrier (M\_BW and R\_NB). This tendency was even stronger for median guardrails (M\_GR and R\_NB): around four and one-half times. The comparison of the RHV probabilities indicated that median concrete walls do a better job of containing vehicles than median guardrails.

One surprise result was that there were four and one-half to five times more RHV collisions after an impact with a cable barrier installed near the edge of the travelled way (M\_CB\_N and R\_NB). This result contradicts the general belief that the cable barriers (high-tensioned) contain vehicles better than other types of barriers. The explanation may come from the high forgiveness of these barriers that allows drivers of many involved vehicles to drive away. It seems plausible that a hasty return to the travelled way may expose these drivers to a collision with another vehicle. As expected, cable barriers installed on the side of the median far from the travelled way (M\_CB\_F) do not increase RHV collisions.

TABLE 6.2  
Parameter Estimates (t value) of the Event Model (Multinomial Logit Model).

Explanatory Variables	Response Variables					
	XH	XNH	RHV	MR	MB	SB
Intercept	-1.636 (-2.96)	-0.621 (-1.68)	-4.066 (-12.64)		1.325 (15.03)	1.122 (5.54)
M_NB_N				Reference		
M_NB_W	-1.618 (-2.8)	-1.099 (-2.83)		-0.347 (-3.72)	–	-1.035 (-3.73 )
M_BW	–	–	1.893 (4.47)			
M_CB_N	–	–	2.288 (3.86)			
M_CB_F	–	–			-0.727 (-3.25)	
M_GR	–	–	1.890 (3.81)		-0.649 (-3.52)	
S_NB_H				Reference		
S_NB_L				0.324 (3.01)		–
S_GR	0.776 (1.48 )		1.452 (4.48)		0.613 (3.31)	
Rural area				Reference		
Urban area			0.563 (1.6)			
NHF				Reference		
HF						0.337 (1.30)
No. of Obs	2049					
LogL	-2252.9					
AIC	4545.8					

The non-cross-median high-risk event (i.e., event HR) is set as the reference category for all the event categories.

A blank cell indicates the coefficient for this variable is not significantly different from the coefficient for its reference condition.

“–” indicates the response event is not an eligible event (i.e., the probability is always equal to 0) when the corresponding explanatory variable is equal to 1.

XH: cross-median head-on event.

XNH: cross-median non-head-on event.

RHV: redirected and hit another vehicle event.

MB: median barrier collision event.

SB: roadside barrier collision event.

HR: non-cross-median high-risk event.

MR: non-cross-median moderate-risk event.

M\_NB\_N: median 50 feet or narrower and no median barrier.

M\_NB\_W: median wider than 50 feet and no median barrier.

M\_BW: median concrete barrier wall placed in the center of a narrow median.

M\_GR: median guardrail placed in the center of a median or at the nearside edge.

M\_CB\_N: median cable barrier with a lateral clearance 30 feet or less to the travelled way.

M\_CB\_F: median cable barrier with a lateral clearance more than 30 feet to the travelled ay.

S\_GR: roadside guardrail.

S\_NB\_L: no guardrail, roadside hazard rating: 1 or 2.

S\_NB\_H: no guardrail, roadside hazard rating from 3 to 7.

NHF: non-freeway or freeway with speed limit lower than or equal to 60 mph.

HF: freeway with speed limit greater than or equal to 65 mph.

**Crashes with off-road objects other than barrier.** Barriers are supposed to prevent both collisions with median and roadside objects (MR and HR) and roll-overs on steep embankments. Ideally, such crashes should be eliminated by barriers. In reality, such collisions are possible when a barrier is penetrated, a vehicle rolls over the top of a barrier, or there are dangerous objects between the travelled way and the

barrier. On average, hitting an off-road object and rolling over (MR plus HR) constitutes 75% to 88% of BR crash events on roads without barriers (M\_NB and R\_NB). Other events not included in the above percentages were cross-median crashes (XH and XNH) and crashes of redirected vehicles (RHV). In the RHV case, the redirections were obviously not caused by barriers but by other off-road objects or by drivers themselves.

TABLE 6.3  
BR Events Probabilities.

Median Scenario	Roadside Scenario	Crash Event Probability									
		XH	XNH	RHV	MR	HR	MB/BW	MB/GR	MB/CB1	MB/CB2	SB
M_CB_N	R_NB_H	–	–	0.03534	0.16740	0.16740	–	–	0.62986	–	–
M_CB_N	R_NB_L	–	–	0.03322	0.21749	0.15733	–	–	0.59196	–	–
M_CB_N	R_GR	–	–	0.06475	0.07171	0.07171	–	–	0.49818	–	0.29365
M_CB_F	R_NB_H	–	–	0.00559	0.26045	0.26045	–	–	–	0.47351	–
M_CB_F	R_NB_L	–	–	0.00509	0.32743	0.23686	–	–	–	0.43062	–
M_CB_F	R_GR	–	–	0.00967	0.10489	0.10489	–	–	–	0.35213	0.42841
M_BW	R_NB_H	–	–	0.02410	0.16935	0.16935	0.63719	–	–	–	–
M_BW	R_NB_L	–	–	0.02264	0.21987	0.15905	0.59844	–	–	–	–
M_BW	R_GR	–	–	0.04463	0.07326	0.07326	0.50896	–	–	–	0.29989
M_GR	R_NB_H	–	–	0.03453	0.24344	0.24344	–	0.47859	–	–	–
M_GR	R_NB_L	–	–	0.03159	0.30786	0.22271	–	0.43783	–	–	–
M_GR	R_GR	–	–	0.05886	0.09683	0.09683	–	0.35152	–	–	0.39596
M_NB_N	R_NB_H	0.07075	0.19514	0.00780	0.36316	0.36316	–	–	–	–	–
M_NB_N	R_NB_L	0.06212	0.17134	0.00685	0.44081	0.31888	–	–	–	–	–
M_NB_N	R_GR	0.05936	0.07538	0.01296	0.14028	0.14028	–	–	–	–	0.57173
M_NB_W	R_NB_H	0.01984	0.09201	0.01103	0.36331	0.51381	–	–	–	–	–
M_NB_W	R_NB_L	0.01742	0.08079	0.00968	0.44096	0.45114	–	–	–	–	–
M_NB_W	R_GR	0.02387	0.05095	0.02620	0.20120	0.28455	–	–	–	–	0.41322

“–” indicates the event category is not eligible for the given median and roadside scenario.

XH: cross-median head-on event

XNH: cross-median non-head-on event

RHV: redirected and hit another vehicle event

MB/BW: median concrete barrier wall collision

MB/GR: median guardrail (face) collision

MB/CB1: nearside median cable barrier collision (offset 30 feet or less)

MB/CB2: far-side median cable barrier collision (offset more than 30 feet)

SB: roadside barrier collision event

HR: non-cross-median high-risk event (e.g., rollover or hitting a sturdy fixed object)

MR: non-cross-median moderate-risk event (e.g., hitting a weak object, running over a ditch, etc.)

M\_NB\_N: median 50 feet or narrower and no median barrier

M\_NB\_W: median wider than 50 feet and no median barrier

M\_BW: median concrete barrier wall placed in the center of a narrow median

M\_GR: median guardrail placed in the center of a median or at the nearside edge

M\_CB\_N: median cable barrier with a lateral clearance 30 feet or less to the travelled way

M\_CB\_F: median cable barrier with a lateral clearance more than 30 feet to the travelled way

R\_GR: roadside guardrail

R\_NB\_L: no guardrail, roadside hazard rating: 1 or 2

R\_NB\_H: no guardrail, roadside hazard rating from 3 to 7

Comparing the probabilities of MR and HR events between roads with narrow medians without barriers M\_NB\_N and roads with wide medians without barriers M\_NB\_W yielded an interesting result: the MR and HR events tended to be more frequent on roads with wide medians. If the roadside areas in both the road categories contribute to a similar extent, then the main source of the discrepancy had to come from

the difference between the narrow and wide medians. Two differences may be pointed out: (1) the sheer effect of the median width reduced the number of median cross-over events and thus increased the number of median-related events classified as MR or HR, and (2) wide medians may have more obstructions and less controlled surface than narrow medians thus vehicles retained by these medians may be exposed to a stronger impact.

The off-road crashes were reduced by concrete walls (M\_BW) and cable barriers installed near the travelled way (M\_CB\_N) to around 35%, by guardrails (M\_GR) to 49%–53%, and by cable barriers installed on the far side of the median (M\_CB\_F) to 52%–56%. The effectiveness of the far-side cable barriers M\_CB\_F was lower than the nearside cable barriers M\_CB\_N, which was caused by median ditches that vehicles crossing a median must pass. These reductions were associated with the increased percentage of collisions with barriers (MB).

Roadside guardrails (R\_GR) further reduce the hazardous off-road crashes MR and HR to the level of 7%–10% of all BR events.

**Collisions with barriers.** The original BR event – collision with a median barrier MB – was divided into four collision subcategories dependent on the barrier type and location: median wall barrier MB/BW, median guardrail MB/GR, median nearside cable barrier MB/CB1, and median far-side cable barrier MB/CB2. As expected, collisions with a far-side cable barrier MB/CB2 were considerably less probable than with a nearside cable barrier CB1, 35% versus 50% for a the roadside protected by a guardrail. These percentages for travelled ways with unprotected roadsides were 43%–47% versus 59%–63%. This difference in performance was partly offset by the increase in the non-barriers events when vehicles traversed a median towards the far-side cable barrier.

Another interesting result was a similar probability of reporting collisions with nearside cable barriers M\_CB\_N and concrete walls M\_BW (50%–63% versus 51%–64%). Cable barriers are much more forgiving than concrete barriers, thus a lower percentage of reported collisions might be expected. A simple explanation is that cable barriers are capable of retaining a vehicle by holding it in place with the cables. Drivers of trapped vehicles cannot leave the scene and they report the event to get help or are reported by passing drivers.

The percentage of reported BR events that were collisions with median guardrails (M\_GR) was 35%–48% and was lower than for collisions with concrete wall barriers. Guardrails are more forgiving than concrete walls and more drivers can leave the scene without reporting to the police.

## 6.5 Chapter Summary

A barrier reduces the risk of high-risk events, but it introduces the risk of barrier collisions and increases the risk of redirecting vehicles back to traffic. This chapter quantified the change in the probabilities of the barrier-relevant hazardous events caused by the presence, type, and location of barriers. First, a multinomial logit model with variable outcomes was specified and estimated based on 2,049 barrier-relevant crashes that occurred between 2003 and 2012 on 1,258 directional travelled ways.

The results indicate that a BR crash was less likely to lead to a median crossover event on roads with medians 50–80 feet wide than on roads with medians 30–50 feet wide and where no median barriers were present. This benefit was associated with an increase in other events, such as median rollover events. When a median barrier was present, the collected data did not show any cross-median events. Although this suggests that the use of median barriers is very effective in reducing or even eliminating cross-median events, total elimination is hard to achieve and some cross-median events are still expected.

The presence of barriers near a travel way was associated with a higher risk of redirecting errant vehicles back to the roadway where they may collide with other on-road vehicles. The nearside cable barriers were also associated with the increased risk of multiple-vehicle crashes involving vehicles that had come in contact with a cable barrier.

The type and offset of the barriers were found to affect the probabilities of BR events. The far-side cable barriers were associated with a lower probability of redirecting vehicles or being hit by errant vehicles than the nearside cable barriers. On the other hand, the probability of off-road non-barrier crashes was higher. The ability of cable barriers to trap vehicles contributed to the surprisingly high percentage of reported cable barrier collisions, which was comparable to the percentage for concrete walls and median guardrails.

The roadside guardrails were confirmed to reduce the percentage of hazardous off-road crashes.

The developed model provided additional insights into the safety effects of several types of barriers by revealing the redistribution of the probabilities of different hazardous events associated with barriers. The important value of the model, however, is in predicting the probabilities of BR events using the studied median and roadside barrier scenarios that lead to different crash severity outcomes. The use of the model is discussed in Chapter 8.

## 7. INJURY MODEL

This chapter estimates the effects of the BR hazardous events and other variables on the personal injuries of people involved in BR crashes. Personal injuries are important components of the in-service evaluation of the safety performance of barriers. A multinomial logit model was developed for this purpose. The statistical model and its variables, a summary of the sample, and the results are discussed in this chapter.

### 7.1 Introduction

Collisions with barriers theoretically are expected to be less risky than the events they prevent. It is imperative to install a barrier where the collisions are likely to be more severe otherwise. An important related question is: which event is more dangerous,

a collision with a barrier or a hazardous event when the barrier is not installed?

The injury risk involved in colliding with a barrier varies considerably with the barrier type, its location, vehicle type, position of an occupant inside a vehicle, and other variables. Cable barriers are flexible and concrete barrier walls are rigid, while guardrails are more rigid than cable barriers but less rigid than concrete walls. Barrier collisions, even with the same barrier, may lead to different injury outcomes due to many uncontrollable factors.

Median cable barriers are used in Indiana on freeways with medians around 60 feet wide. They are placed near one side of the median edge at the typical offset of 16 feet from the travelled way. Therefore, the injury risk involved in leaving a travelled way and colliding with a median cable barrier may depend on the side from which the median is entered. Guardrails are installed either in a median or on a roadside. Thus, the injury risk in a crash involving a median guardrail may be different from a crash involving a roadside guardrail.

This chapter evaluates the injury outcomes associated with different BR hazardous events, including collisions with barriers under different road-barrier scenarios as well as BR events preventable by barriers. The hazardousness of an event is represented by the probabilities of different levels of injuries which could be inflicted during the hazardous event. One of the tasks of this study was to develop a model for estimating the injury probabilities.

As with the BR crash frequency and BR events analyses in Chapters 5 and 6, the BR injury analysis presented here is an important component of evaluating the in-service safety performance of road barriers.

## 7.2 Data and Variables

The BR injury sample prepared for the injury analysis consisted of 126,774 occupants in 82,610 BR crashes. See more details in Section 4.5. An observation is comprised of an occupant of a vehicle involved in a BR crash with the injury level experienced by that occupant, the BR event, vehicle type, road type, speed limit, presence of aggressive driving, driver's gender and age, lighting conditions, weather conditions, road surface conditions, ADT, etc. Table 7.1 shows the selected statistics of variables considered in the injury model. Table 7.2 shows the frequency of occupants with different injury outcomes classified by BR event.

### 7.2.1 Injury Outcome Levels

The injury outcome levels for modeling were based on the police-reported KABCO scale (K: fatality, A: incapacitating injury, B: non-incapacitating injury, C: possible injury, and O: property-damage-only). Vehicle occupant-specific information, such as age, gender, and injury level, was recorded only for the driver and the injured passengers. Vehicle occupants for

whom injury levels were not reported by the police were assumed to be uninjured.

### 7.2.2 BR Events

As mentioned in Section 4.4, the actual hazardous events were classified as ten BR events:

- Event XH: cross-median head-on event
- Event XNH: cross-median non-head-on event
- Event RHV: vehicle redirected and hit another vehicle event
- Event MB/BW: median concrete barrier wall collision
- Event MB/GR: median guardrail (face) collision
- Event MB/CB1: nearside median cable barrier collision (offset 30 feet or less)
- Event MB/CB2: far-side median cable barrier collision (offset more than 30 feet)
- Event SB: roadside guardrail collision
- Event HR: non-cross-median high-risk event (e.g., roll-over or hitting a sturdy fixed object)
- Event MR: non-cross-median moderate-risk event (e.g., hitting a weak object, running over a ditch, etc.).

The BR events above are consistent with those discussed in Chapter 6 (see Section 6.2) and in Chapter 7 where the median barrier collision event MB was divided into four events based on the type of median barrier and its location: MB/BW, MB/GR, MB/CB1, and MB/CB2.

The sequence of events and their outcomes in a BR crash is presented in Figure 3.2. Following this concept, the BR events model presented in Chapter 6 estimated the probabilities of the BR events as outcomes of a BR crash and dependent on the barrier types and their offsets. In this chapter, the BR events are explanatory variables in a BR injury model that estimates the probability of the personal injury levels of people involved in a BR crash.

## 7.3 Model

A standard multinomial logit model was applied to model the personal injury probability based on the KABCO scale. As mentioned in Chapter 6, the standard multinomial logit model was used by many researchers to model crash-injury severity. Due to the large sample size, extension to more advanced models such as the random parameters logit model (mixed logit model), random effects logit model, and nested logit model was not directly supported by current software packages.

Common unexplained heterogeneity may be expected in the error term for occupants of the same vehicle (due to shared unobserved characteristics). This random effect could not be handled in the standard multinomial logit model and therefore the modeling results could be biased. Thus, it was important to test for the presence of the random effects, or at least for their impact on the estimated model coefficients, if they were not accounted for by the model. To do so, the sample was divided into three subsamples: (1) drivers in

TABLE 7.1  
Selected Statistics of Variables Considered in the Injury Model (Occupant Level).

Variables	Categories	Count	Variables	Categories	Count
Crash severity level	Fatality (K)	1748	Vehicle type	Motorcycle	2173
	Incapacitating (A)	4128		SUV	18499
	Non-incapacitating (B)	26937		Truck	8170
	Possible injury (C)	3757		Car and other	97932
	Property damage only (O)	90204		Event category	Non-cross-median high-risk event
Driver indicator	Yes	87807	Median barrier wall collision		6496
	No	38967	Nearside median cable barrier collision		1184
Driver age	55 and older	11812	Far-side median cable barrier collision		557
	younger than 55	75995	Median guardrail (face) collision		379
Driver gender	Male	55650	Non-cross-median moderate-risk event	44774	
	Female	32157	Vehicle redirected and hit another vehicle	6422	
Safety* device use	Yes	83039	Roadside guardrail collision	5439	
	No	4768	Cross-median head-on	12793	
Alcohol or drug use	Yes	2154	Cross-median non-head-on	579	
	No	85653	Horizontal curve	Curve	29888
Fatigue	Yes	5066		Tangent	96886
	No	82741	Functional class and speed limit	Freeway (speed limit $\geq 65$ mph)	31275
Aggressive driving	Yes	3236		Freeway (speed limit $\leq 60$ mph)	12079
	No	84571		Non-freeway	83420
Road surface condition	Good (dry and clean)	64221	Weather condition	Clear	53761
	Poor (ice, snow, etc.)	42171		Cloudy	21890
	Wet	20382		Rain	15346
Light condition	Daylight	69292	Snow	20830	
	Dawn or dusk	7302	Sleet or hail or freezing rain	6719	
	Dark (lighted)	7477	Fog or smoke or smog	1057	
	Dark (not lighted)	42530	Severe cross wind	841	
	Unknown	173	Blowing soil or snow	6330	

\*The variable "Safety device use," "Alcohol or drug use," "Fatigue," "Aggressive" were only for drivers.

vehicles without passengers, (2) drivers and passengers in vehicles with only two occupants, and (3) remaining drivers and passengers in vehicles with more than two occupants. The random effects were not present in the first subsample while it could be in the second and third.

Let us focus on the second subsample including pairs: a driver and a passenger. To investigate the potential bias in the model estimated for this subsample without accounting for the random effects, the likelihood ratio test for models transferability was applied, which measured the difference between a single model estimated for both occupants and two models estimated for drivers and passengers separately. Passing the test

would indicate that the model combining two occupants does not produce significantly different results than the two models estimated independently, which could be interpreted as neglecting the random effects shared by drivers and passenger of the same vehicles.

The test statistic for the likelihood ratio test was  $-2(LL_{DP} - LL_D - LL_P)$ , where  $LL_{DP}$  is the log-likelihood estimated using both the driver and passenger data,  $LL_D$  is the log-likelihood estimated using the driver data only, and  $LL_P$  is the log-likelihood estimated using the passenger data only. The test statistic followed the chi-square distribution with a degree of freedom equal to the difference between the total number of

TABLE 7.2  
Frequency of occupants with different injury levels (KABCO) by event category.

Event Categories	Injury Levels					Total
	K	A	B	C	O	
Non-cross-median high-risk event	700	1790	12770	1785	31106	48151
Non-cross-median moderate-risk event	230	885	7756	1136	34767	44774
Vehicle redirected and hit another vehicle	17	54	418	68	5865	6422
Roadside guardrail collision	11	43	647	70	4668	5439
Median barrier wall collision	7	77	974	70	5368	6496
Median guardrail (face) collision	1	6	44	9	319	379
Nearside median cable barrier collision	0	3	56	13	1112	1184
Far-side median cable barrier collision	0	1	36	3	517	557
Cross-median head-on	775	1239	4096	589	6094	12793
Cross-median non-head-on	7	30	140	14	388	579
Total	1748	4128	26937	3757	90204	126774

parameters estimated in the driver and passenger models and the number of parameters estimated in the joint model.

The performed likelihood ratio test yielded a chi-square statistic equal to 34.34 with 64 degrees of freedom and the corresponding P value equal to 99.91%. This result indicated that there was no evidence that the single joint model was different from the two separate models considered jointly. It also indicated that the random effects within vehicles may be neglected in the joint model.

A similar test for the third subsample with more than one passenger could not be applied because the data did not allow making distinctions among passengers. Nevertheless, the difference between additional passengers and the already tested two occupants should not share commonalities stronger than the ones already refuted for the two tested occupants. In a majority of cases of more than two occupants, the additional occupants sat in the back seats and were thus exposed to the impact very differently than the front seat occupants. We concluded that the random effects within vehicles can be neglected when estimating a joint model for the entire sample of occupants.

The propensity function that determines vehicle occupant  $n$ 's injury level outcome  $i$  in the multinomial logit model is:

$$U_{ni} = \hat{a}_i X_{ni} + \hat{\epsilon}_{ni} \quad (7.1)$$

where  $X_{ni}$  is a vector of the measurable characteristics (crash event category, vehicle characteristics, occupant characteristics, roadway and roadside characteristics, etc.),  $\hat{a}_i$  is a vector of the estimated coefficients for injury outcome  $i$  ( $i$  = fatality, incapacitating injury, non-incapacitating injury, possible injury or property damage only) and  $\hat{\epsilon}_{ni}$  is the error term and assumed

to be the generalized extreme value distributed (McFadden, 1981).

The probability of vehicle occupant  $n$  sustaining injury level  $i$  out of a number of  $I$  possible event categories is calculated as:

$$P(S_{ni}) = \frac{\exp(\hat{a}_i X_{ni})}{\sum_{\forall i \in I} \exp(\hat{a}_i X_{ni})} \quad (7.2)$$

Table 7.3 shows the estimated coefficients of the injury model (standard multinomial logit model). All the included variables in Table 7.3 were significant at least in one injury at the 10% significance level, and most of the variables were significant under all injury levels at the 10% significance level. The most important variable to this study was the crash event category. The coefficients for the nearside and far-side cable barrier collisions under the fatal category were extremely small because there were no cable barrier collisions that led to fatalities as observed from the data (see Table 7.2). The coefficient for a variable under a certain injury level indicated whether it was more likely (if the sign was plus) or less likely (if the sign was minus) for this variable (relative to its corresponding reference condition) to result at that specific injury level (relative to property-damage-only).

#### 7.4 Effect of BR Events

To help interpret the connection between the BR events and safety, the average probabilities of the KABCO outcomes were calculated for each BR event with the estimated BR injury model. The calculations are similar to the procedure described in Chapter 6. The BR injury model returns the conditional probability of injury at level  $i$  for each observation  $j$ :  $\Pr(y_{ji} | e_{jh}, x_j, r_{jt})$ .

The average probability of BR injury at severity level  $i$  for BR harmful event  $h$  is calculated as follows:

$$\Pr(y_i|e_h) = \frac{1}{N_y} \sum_{j \in J} \Pr(y_{ji}|e_h, x_j, r_{jt}) \quad (7.3)$$

where:

$y_i$  = indicator of injury level  $i$ ,

$e_h$  = indicator of BR harmful event  $h$ ,

$r_t$  = indicator of road type  $t$ ,

$N_y$  = number of observations in the BR injury sample,

$J$  = set of observations in the BR injury sample,

$y_{ji}$  = indicator of injury level  $i$  in observation  $j$ ,

$x_j$  = values of additional variables included the model,

$r_{jt}$  = indicator of road type  $t$  in observation  $j$ .

Equation (7.3) requires that original value  $e_{jh}$  in each observation  $j$  was replaced with the indicator of harmful event  $h$ . Table 7.4 presents the probabilities estimated with Equation (7.3).

#### 7.4.1 Barrier Collision Events vs. Non-barrier Collision Events

The results in Table 7.4 indicate that the five barrier collision events were less severe than the five non-barrier collision events. The former five events are generally associated with smaller likelihoods of fatality, incapacitating injury and non-incapacitating injury. Even the most hazardous events among the barrier collisions, the roadside guardrail collision (due to the higher fatality likelihood) or the median barrier wall collision (due to higher likelihood of incapacitating and non-incapacitating injury), had probabilities close to the probabilities of the least hazardous event among the non-barrier collision events, the redirected vehicle collision.

This comparison generally suggested that all barriers had the potential to reduce the occurrence of severe injury crashes when compared to collisions with untreated hazards. A flexible barrier deflects to absorb as much energy of the impact as possible while containing a vehicle. A rigid barrier, on the other hand, is placed in a way that promotes impact with a barrier at a small angle. A vehicle in contact with a barrier slows down along the barrier. The increased impact time reduces the intensity of energy transfer on the occupants.

#### 7.4.2 Barrier Collisions

Cable barriers (nearside and far-side) demonstrated unequal performance among the studied types of barriers. Table 7.4 indicates that a collision with a cable barrier was associated with the lowest probability of fatality, incapacitating injury, and non-incapacitating injury. The difference between the nearside and far-side cable barriers, although small, may demonstrate the

advantage of the nearside location having a possibly smaller impact angle. This advantage could be reduced with a small offset leading to a larger impact speed and smaller recovery zone.

The similar performance of nearside and far-side cable barriers did not necessarily mean that the overall safety benefit generated by these two alternatives was also similar. The overall safety comparison must consider the impact on the frequency of BR crashes and on the probabilities of other BR events as discussed in Chapter 5 and Chapter 6.

Median barrier walls exhibited slightly worse performance than guardrails (median or roadside) which was manifested through the higher probability of injury. The difference between median and roadside guardrails was not that pronounced; median guardrail collisions were less likely to produce fatality and non-incapacitating injury but were more likely to produce incapacitating injury.

In summary, it may be confirmed that flexible barriers are more forgiving and produce less severe outcomes when struck by a vehicle than semi-rigid and rigid barriers. The larger deflection distance of flexible barriers functions as intended. This consistency with expectations and the past research of other authors builds more confidence about the results of this study. The main objective of this analysis was to provide results that would be useful in a comprehensive estimate of the in-service safety performance of the studied types of barriers in various road-barrier scenarios.

#### 7.4.3 Non-barrier Collisions

As expected, cross-median head-on events, as shown in Table 7.4, produced more severe injuries than other events. The outcome severity of a cross-median non-head-on event and a non-cross-median high-risk event was similar; the former was less associated with fatalities and non-incapacitating injuries but was more strongly associated with incapacitating injuries. These differences are not significant as evidenced by the coefficients and standard errors provided in Table 7.3.

Compared to the aforementioned three events, non-cross-median moderate-risk events tended to be more forgiving with a much smaller probability of fatality, incapacitating injury, and non-incapacitating injury. Collisions of redirected vehicles (vehicle may or may not collide with a barrier before returning to traffic) were found to be the least hazardous events among the non-barrier collision events.

The findings for non-barrier collision events indicated that the three highly hazardous events were cross-median head-on, cross-median non-head-on and non-cross-median high-risk events. Interestingly, the collisions of redirected vehicles increased with the use of barriers but were not as hazardous as other events. This side effect of using barriers should not be a major concern as these events are not frequent. Nevertheless, they were included in the evaluation.

TABLE 7.3  
**Parameter Estimates (Standard Errors) of the Personal Injury Model (Multinomial Logit Model).**

Variable	Parameter Estimates (Standard Errors)			
	Fatal	Incapacitating	Non-incapacitating	Possible
Intercept	-3.9603 (0.0708)	-2.7678 (0.0432)	-0.8811 (0.0189)	-2.6859 (0.0424)
<b>Vehicle type</b>				
SUV	0.1932 (0.0760)	0.2230 (0.0478)	0.2735 (0.0202)	0.3112 (0.0458)
Motorcycle	2.1171 (0.1174)	2.4476 (0.0865)	2.0450 (0.0634)	1.8943 (0.1074)
Truck	-0.9671 (0.1425)	-0.7953 (0.0970)	-0.3476 (0.0353)	-0.1624 (0.0846)
Car and other	Reference			
<b>Crash event categories</b>				
Nearside median cable barrier collision	-10.7027 (46.9546)	-2.6852 (0.5803)	-1.8713 (0.1388)	-1.0877 (0.2833)
Far-side median cable barrier collision	-10.5304 (59.1900)	-3.1020 (1.0026)	-1.5929 (0.1745)	-1.8345 (0.5813)
Median barrier wall collision	-2.1527 (0.3923)	-0.8129 (0.1322)	-0.4861 (0.0432)	-0.7710 (0.1378)
Median guardrail (face) collision	-1.8472 (1.0087)	-0.8533 (0.4189)	-0.9324 (0.1641)	-0.2705 (0.3424)
Roadside guardrail collision	-1.9590 (0.3085)	-1.4461 (0.1581)	-0.8493 (0.0451)	-0.9352 (0.1257)
Cross-median head-on	1.7781 (0.0584)	1.2685 (0.0417)	0.4909 (0.0237)	0.4572 (0.0506)
Cross-median non-head-on	-0.2063 (0.3889)	0.2892 (0.1963)	-0.1300 (0.1016)	-0.4783 (0.2743)
Redirected and hit another vehicle	-1.8716 (0.2506)	-1.6117 (0.1424)	-1.6100 (0.0535)	-1.3696 (0.1277)
Non-cross-median moderate-risk event	-1.4249 (0.0798)	-0.9771 (0.0439)	-0.6735 (0.0171)	-0.6055 (0.0394)
Non-cross-median high-risk event	Reference			
<b>Driver/passenger</b>				
Driver	0.1934 (0.0792)	0.3428 (0.0468)	0.4544 (0.0199)	0.3983 (0.0443)
Passenger	Reference			
<b>Driver characteristics</b>				
Mature driver (>55 years)	0.9133 (0.0675)	0.3661 (0.0523)	0.2206 (0.0249)	0.2304 (0.0571)
Younger driver (≤55 years)	Reference			
Male driver	0.0183 (0.0659)	-0.3134 (0.0415)	-0.3784 (0.0181)	-0.6039 (0.0418)
Female driver	Reference			
No use of any safety device	2.8728 (0.0735)	2.1801 (0.0578)	1.3600 (0.0393)	1.3601 (0.0737)
Otherwise	Reference			
Alcohol or drug use for driver	0.0725 (0.1360)	0.5257 (0.0832)	0.3889 (0.0461)	0.5907 (0.0890)
Otherwise	Reference			
Fatigue for driver	-0.9948 (0.1723)	0.0107 (0.0730)	0.1756 (0.0304)	0.1818 (0.0697)
Otherwise	Reference			
Aggressive driving behavior	1.0144 (0.0810)	0.6981 (0.0627)	0.2930 (0.0365)	0.5477 (0.0725)
Otherwise	Reference			
<b>Roadway characteristics</b>				
Wet road surface	-0.6331 (0.0738)	-0.6373 (0.0497)	-0.2989 (0.0205)	-0.2217 (0.0465)
Poor road surface (ice, snow, etc.)	-1.9050 (0.0950)	-1.3497 (0.0497)	-0.7948 (0.0180)	-0.7954 (0.0437)

(Continued)

TABLE 7.3  
(Continued)

Variable	Parameter Estimates (Standard Errors)			
	Fatal	Incapacitating	Non-incapacitating	Possible
Good road surface (dry and clean)	Reference			
High speed freeway ( $\geq 65$ mph)	0.3321 (0.0726)	-0.0943 (0.0486)	-0.1056 (0.0194)	-0.4469 (0.0496)
Low speed freeway ( $\leq 60$ mph)	-0.5202 (0.1523)	-0.4387 (0.0873)	-0.2607 (0.0329)	-0.7976 (0.0948)
Non-freeway	Reference			
AIC	192610.3			
-2 Log L	192418.3			
No of observations	126774			

TABLE 7.4  
Average Personal Probabilities of KABCO Outcomes by Event Category.

Event Categories	Personal Injury Probability				
	Fatal	Incapacitating	Non-incapacitating	Possible	Not Injured
Nearside median cable barrier collision	0.00000	0.00488	0.06506	0.01931	0.91076
Far-side median cable barrier collision	0.00000	0.00314	0.08469	0.00903	0.90314
Median barrier wall collision	0.00221	0.02061	0.19475	0.01995	0.76247
Median guardrail (face) collision	0.00332	0.02171	0.13416	0.03540	0.80540
Roadside guardrail collision	0.00313	0.01249	0.14940	0.01867	0.81630
Cross-median head-on	0.05234	0.08657	0.30864	0.04053	0.51192
Cross-median non-head-on	0.01178	0.04974	0.23631	0.02272	0.67945
Redirected and hit another vehicle	0.00421	0.01271	0.07965	0.01378	0.88964
Non-cross-median moderate-risk event	0.00480	0.01832	0.16772	0.02445	0.78470
Non-cross-median high-risk	0.01390	0.03575	0.25870	0.03520	0.65645

## 7.5 Other Effects

The variables that significantly affected the personal injury probability included: vehicle type, driver versus passenger, driver characteristics (gender, age, use of any safety device, alcohol or drug use, fatigue, and aggressive driving behavior), and roadway characteristics (functional class, speed limit, and road surface condition). Non-driver characteristics were not included because the data for this category of occupants were incomplete. The effects of the variables included in the model were represented by the coefficients and standard errors reported in Table 7.3.

The types of vehicles considered in the analysis included: passenger car, pickup, van, recreational vehicle, and other types. Severe injury outcomes were found to be strongly associated with motorcycle occupants and to a lesser extent with SUV occupants. As expected, occupants of trucks were the least exposed to the risk of

injury. These differences were attributed to the size and weight of the vehicles and the level of protection afforded the occupants. Motorcyclists had the lowest protection while the structural rigidity and long bumper-to-passenger distance of heavy vehicles were safer for their occupants.

Drivers are more likely to be injured in BR events than passengers. Previous studies revealed that the seat position affects the passengers' injuries. Front-seat passengers were more likely to be injured than drivers (Eluru et al., 2010; Hutchinson, 1986) whereas rear-seat passengers were less likely (Mayrose & Priya, 2008; Smith & Cummings, 2004). This factor was not included in the analysis of this study due to the lack of specific seating information in the available data.

Drivers older than 55 and female drivers were exposed to a higher risk of severe injury, which could be attributed to different physical conditions of drivers, but it also may have been a possible biased perception

by police officers who reported the events. Drivers under the influence of alcohol and drugs, which has been linked to a higher likelihood of aggressive behavior and a lower likelihood of using seat belts, resulted in an increased probability of severe injury. The reduced propensity for fatalities (negative coefficient) for drivers under the influence of alcohol or drugs was surprising. This result was barely significant and may have been caused by a relatively small number of observations in this category. Alcohol consumption increased the probability of fatalities as well as injuries.

The results indicated that driver fatigue was associated with a lower probability of fatal and non-incapacitating injuries. This surprising result may be explained by possible underreporting of being fatigued when drivers cannot be interviewed by the investigating police officer.

Wet and poor pavement surfaces (i.e., mud, snow, slush, ice, water, or loose material on the road) were associated with a lower probability of severe injury outcomes when compared to dry pavements, which may be explained by motorists being more alert and driving at lower speeds in adverse weather and road surface conditions.

The three road types, defined by their functional class and speed limit, also were shown to be significantly associated with the injury outcome. The low-speed freeways (speed limit  $\leq 60$  mph) had a lower probability of injury than non-freeways (uncurbed and speed limit  $\geq 45$  mph). The two roadway types had similar a speed limit range but their roadside and median designs were considerably different. Lower severity BR crashes on low-speed freeways could be explained by their more forgiving median and roadside design than that of non-freeways.

Interestingly, the high-speed freeways (speed limit  $\geq 65$  mph) were associated with a higher probability of fatality but a lower probability of injury than non-freeways. This mixed result reflects the complexity of the effects (i.e., the high-speed freeways have higher speeds than non-freeways but safer median and roadside design).

## 7.6 Variables Not Included in the Model

Certain variables considered important in this study were not included in the model due to lack of data, insignificant coefficients, or high correlation with other variables. The insignificant variables included the presence of a rumble strip and the interactions of the vehicle type and event categories. Although multiple studies reported the reduction of crash frequency attributed to rumble strips, it seems that crashes that occurred under the presence and absence of rumble strips had the same severity. The insignificant interactions of vehicle types and event categories indicated that the main effects of BR events and vehicle types included in the model were sufficient.

## 7.7 Chapter Summary

This chapter investigated the factors of personal injury severity measured on the KABCO scale. The important factors considered in this analysis were the BR events, which included collisions with barriers and other non-barrier events. Those events were classified into ten categories:

- Cross-median head-on collision
- Cross-median non-head-on crash
- Redirected vehicle collision with another vehicle
- Median concrete barrier wall collision
- Median guardrail collision
- Nearside median cable barrier collision
- Far-side median cable barrier collision
- Roadside guardrail collision
- Non-cross-median high-risk event
- Non-cross-median moderate-risk event

A total of 126,774 occupants in 82,610 BR crashes that occurred between 2003 and 2013 on all INDOT-administered uncurbed roads with a speed limit of at least 45 mph were analyzed. A multinomial logit model was developed to estimate the effects of BR events and other variables on the probability of KABCO-based crash injury outcomes for all the vehicle occupants. The developed model estimated an occupant's risk of injury produced by a BR event under certain conditions.

The analysis revealed that barriers reduced the probability of severe injury outcomes compared to the non-barrier event categories. The injury probability varied across the barrier types considerably. The median cable barriers exhibited the lowest risk of injury among the studied barriers. The injury risk after colliding with a median guardrail was similar to the risk associated with a roadside guardrail and slightly lower than colliding with a median concrete barrier.

Cross-median head-on or non-head-on crashes and non-cross-median high-risk crashes were much more likely to result in severe injuries than other BR events. Collisions of vehicles redirected to traffic increased when barriers were present, but the collisions were the least hazardous, making this adverse increased effect of barriers an insufficient risk to forego barriers.

Overall, all the studied barriers exhibited desirable performance in reducing the probability of fatalities and severe injuries, and cable barriers in particular exhibited particularly encouraging performance. It is important to remember that the safety performance of barriers in this chapter was investigated from the perspective of a single BR crash. A comprehensive evaluation must also consider the effects of barriers on the total number of reported BR crashes. It is also important to aggregate all these effects into a practical measure of performance that can be conveniently used in engineering analysis of various alternative road solutions.

## 8. COST OF CRASHES

The models developed in the previous chapters were used to derive two key components of safety benefit

estimation: the crash modification factors (CMFs) and the unit crash costs (UCCs) for road-barrier scenarios under consideration for implementation. The CMFs were obtained directly from the frequency model in Chapter 5; and the UCCs were estimated from the BR events and personal injuries probabilities by applying the BR events and the injury models presented in Chapters 6 and 7.

This chapter explains the estimation process to obtain CMFs and UCCs and provides the intermediate and final results applied to the scenarios in this study. The full procedure that utilizes the obtained CMFs and UCCs to predict the safety benefit of various road-barrier alternatives is presented in Chapter 9.

With the estimated BR injury model (based on person-level data) in Chapter 7 and the BR events model (based on crash-level data) in Chapter 6, as well as some information directly obtained from the data sample, statistical simulation, and prediction were conducted to calculate the unit crash cost under all the studied scenarios: 18 barrier scenarios, which also includes no-barrier scenarios, on three types of roadways (high speed freeway with a speed limit higher than or equal to 65 mph, low speed freeway with a speed limit lower than or equal to 60 mph, and uncurbed non-freeway with a speed limit higher than or equal to 45 mph). This can be done by calculating several major components as shown below.

## 8.1 Average Injury Costs

Calculating the average cost  $C_{ht}$  of an injury of a person involved in BR harmful event  $h$  on road type  $t$  was the first step to estimate the average costs  $UCC_{kt}$  of the BR crash for various road-barrier scenarios. Calculation of these average values required estimating the probabilities of BR events and injuries.

### 8.1.1 Probability of Personal Injury

The probability of injury of level  $i$  of person involved in BR event  $h$  on road type  $t$  must be calculated first as follows:

$$\Pr(y_i|e_h, r_t) = \frac{1}{N_t} \sum_{j \in J_t} \Pr(y_{ji}|e_h, x_j, r_{jt}) \quad (8.1)$$

where:

- $y_i$  = indicator of injury level  $i$ ,
- $e_h$  = indicator of BR most harmful event  $h$ ,
- $r_t$  = indicator of road type  $t$ ,
- $i$  = number of observations for road type  $t$ ,
- $J_t$  = set of observations for road type  $t$ ,
- $y_{ji}$  = indicator of injury level  $i$  in observation  $j$ ,
- $x_j$  = values of additional variables included the model,
- $r_t$  = indicator of road type  $t$  in observation  $j$ .

The results for the average probabilities of KABCO injury outcomes in event category  $j$  under road type  $k$  are summarized in Table 8.1. For example, a person involved in a non-cross-median high-risk event on a high-speed freeway was likely to be killed at probability 0.0136.

### 8.1.2 KABCO Economic and Comprehensive Costs

The severity of personal injuries can be measured on two scales: MAIS and KABCO. The MAIS values are available for individuals who seek medical attention in hospitals. The MAIS values are derived from the results of injury evaluation performed by medical professionals at hospitals. These data are considered more reliable than KABCO values, which are determined at the crash scene by police officers, sometimes with input from paramedics. Recent methodological developments in adjusting for selectivity bias were found in Tarko and Azam (2011). NHTSA provides personal injury costs (comprehensive and economic values) on the MAIS injury scale (Blincoe, Miller, Zaloshnja, & Lawrence, 2014). Although the MAIS scale is considered to better reflect the internal damage of the injured, only about one-fifth of individuals involved in crashes are locatable in hospital data. This is the primary reason why the KABCO scale is commonly used and therefore is used in this study as well. The available average costs of KABCO crashes are typically the effect of "translation" using the MAIS-KABCO conversion tables (Blincoe et al., 2014; Tarko et al., 2010).

The KABCO personal injury costs in this study focused on the barrier-relevant category of crashes. To better address the barrier-relevant conditions, the MAIS costs were converted to KABCO costs based on the BR injury sample linked with the hospital data. The linkage was performed with a probabilistic method by Fellegi and Sunter (1969) and Jaro (1989, 1995). The method uses a full Bayesian and imputation models developed by McGlinchey (2004) and implemented in CODES 2000, which is software provided by NHTSA. The MAIS values were estimated using ICDMAP-90 software from Johns Hopkins University (MacKenzie & Sacco, 1997).

The BR injury sample included 126,774 occupants; 23,448 of which were linkable with the hospital data. The initial conversion table  $\Pr(MAIS|KABCO)$  obtained from the linked data was adjusted to account for the unlinked data.  $MAIS=0$  was assumed for the police-reported KABCO values that did not have counterparts in the hospital data. The MAIS costs used in the conversion are shown in Table 8.2 (Blincoe et al., 2014). The estimated KABCO costs of BR crashes and the conversion probabilities are shown in Table 8.3.

### 8.1.3 Conditional Average Costs $C_{ht}$

The average cost of injury can be calculated as:

$$C_{ht} = \sum_{i \in I} C_i \cdot \Pr(y_i|e_h, r_t) \quad (8.2)$$

where:

- $C_{ht}$  = expected cost of personal injury of a person involved in BR event  $h$  on road type  $t$ ,
- $C_i$  = average cost of injury of severity  $i$  in any BR crash taken from Table 8.3,

TABLE 8.1  
Average Probabilities of KABCO Injury Outcomes by Event Category by Road Type.

Road Type $t$	Event Categories $h$	Event Symbols	Personal Injury Probability $\Pr(y_i e_h, r_t)$				
			K	A	B	C	O
High speed freeway	Non-cross-median high-risk	HR	0.01370	0.02852	0.22909	0.02481	0.70388
	Far-side median cable barrier collision	MB/CB2	0.00000	0.00205	0.06707	0.00567	0.92520
	Nearside median cable barrier collision	MB/CB1	0.00000	0.00317	0.05144	0.01212	0.93327
	Median barrier wall collision	MB/BW	0.00203	0.01547	0.16636	0.01353	0.80261
	Median guardrail (face) collision	MB/GR	0.00299	0.01600	0.11340	0.02376	0.84386
	Non-cross-median moderate-risk event	MR	0.00435	0.01360	0.14232	0.01647	0.82326
	Vehicle redirected and hit another vehicle	RHV	0.00346	0.00865	0.06432	0.00882	0.91474
	Roadside guardrail collision	SB	0.00274	0.00902	0.12486	0.01238	0.85099
	Cross-median head-on	XH	0.05556	0.07323	0.28257	0.02962	0.55902
	Cross-median non-head-on	XM	0.01157	0.03947	0.20807	0.01591	0.72498
Low speed freeway	Non-cross-median high-risk	HR	0.00789	0.02457	0.22163	0.01987	0.72604
	Far-side median cable barrier collision	MB/CB2	0.00000	0.00172	0.06289	0.00441	0.93097
	Nearside median cable barrier collision	MB/CB1	0.00000	0.00267	0.04829	0.00944	0.93960
	Median barrier wall collision	MB/BW	0.00115	0.01311	0.15821	0.01067	0.81687
	Median guardrail (face) collision	MB/GR	0.00170	0.01358	0.10778	0.01872	0.85822
	Non-cross-median moderate-risk event	MR	0.00248	0.01154	0.13536	0.01298	0.83763
	Vehicle redirected and hit another vehicle	RHV	0.00198	0.00732	0.06061	0.00689	0.92320
	Roadside guardrail collision	SB	0.00156	0.00763	0.11823	0.00972	0.86286
	Cross-median head-on	XH	0.03321	0.06539	0.28322	0.02454	0.59363
	Cross-median non-head-on	XM	0.00664	0.03390	0.20073	0.01271	0.74603
Non-freeway	Non-cross-median high-risk	HR	0.01484	0.04008	0.27516	0.04132	0.62860
	Far-side median cable barrier collision	MB/CB2	0.00000	0.00376	0.09444	0.01095	0.89084
	Nearside median cable barrier collision	MB/CB1	0.00000	0.00584	0.07259	0.02343	0.89814
	Median barrier wall collision	MB/BW	0.00243	0.02363	0.21068	0.02371	0.73955
	Median guardrail (face) collision	MB/GR	0.00368	0.02503	0.14577	0.04218	0.78333
	Non-cross-median moderate-risk event	MR	0.00531	0.02107	0.18194	0.02911	0.76257
	Vehicle redirected and hit another vehicle	RHV	0.00482	0.01502	0.08815	0.01664	0.87538
	Roadside guardrail collision	SB	0.00350	0.01450	0.16312	0.02233	0.79655
	Cross-median head-on	XH	0.05391	0.09464	0.32210	0.04693	0.48242
	Cross-median non-head-on	XM	0.01261	0.05588	0.25205	0.02672	0.65273

$I$  = five levels of KABCO scale,  
 $\Pr(y_i|e_h, r_t)$  = probability of injury severity  $i$  in BR event  $h$  on road type  $t$  (Equation (8.1)).

The results of the calculations with Equation (8.2) and the input values from Table 8.2 and Table 8.3 are presented in Table 8.4. Both the comprehensive costs and economic costs are provided.

## 8.2 Average Crash Costs

### 8.2.1 Accounting for Cross-Median Events

As mentioned in Chapter 6, the BR events sample collected in this study on selected segments did not represent cross-median crashes on segments with any

type of median barrier installed due to a rather small sample and low probability of such events, which could lead to overestimation of the effectiveness of median barriers in the modeling results. Based on a review of the use of median cable barriers by different states conducted in a previous study (Ray et al., 2009), the 100% reduction in cross-median crashes experienced by some states after the installation of median cable barriers was due to the short history of their use. The authors stated that the reduction rate due to cable barriers was generally closer to 95%. A recent study that investigated the in-service performance of both median cable barriers and median guardrails in Florida reported that cross-median crashes were reduced by 97.4% for median cable barriers and by 98.3% for median guardrails (Alluri, Haleem, & Gan, 2012a, 2012b). On the other hand, median concrete barriers seemed to eliminate the cross-median crashes (Tarko et al., 2008).

Based on the findings of previous studies, it can be concluded that no adjustments were needed for scenarios with median concrete barriers, but adjustments were necessary for the median cable barriers and median guardrails. The following assumptions were made in regard to these adjustments:

- Five percent of vehicles hitting a single run-cable median barrier or a median guardrail were not stopped and entered the travelled way in the opposite direction where they were involved in a BR event. This is rather a conservative (pessimistic) assumption about the variable barriers performance assumption given no cross-median events in the BR events sample with 104 and 59 hits of median cable barriers and median guardrails, respectively.
- One percent of these events were cross-median head-on crashes, and 4% of them were cross-median non-head-on crashes. The ratio between head-on and non-head-on crashes corresponds to the ratio observed in the data from non-median barrier segments (23 for head-on crashes and 88 for non-head-on crashes).

Introducing non-zero probability  $\Pr(e_h^*|b_k^*)$  of event  $e_h^*$  (here cross-median event) for a certain barrier scenario  $b_k^*$  (here median cable barriers) required adjusting the probabilities of the remaining BR events with adjustment factor  $k$  to ensure that the sum of all the new probabilities for the  $b_k^*$  barrier scenario was one. The  $k$  adjustment factor is:

$$k = 1 - \Pr(e_h^*|b_k^*) \quad (8.3)$$

TABLE 8.2  
Original Unit Personal Injury Cost based on the MAIS and KABCO from NHTSA (Blincoe et al., 2014).

Injury Scale	Injury Level	Unit Cost per Person (\$ in thousands, 2010)	
		Economic	Comprehensive
MAIS	6	1398.916	9145.998
	5	1100.597	5679.122
	4	513.949	2551.432
	3	282.197	1087.894
	2	104.974	445.846
	1	22.779	46.02
	0	4.38	4.38

### 8.2.2 Average Probabilities of BR Events

Estimation of the average probability of a BR crash under certain road-barrier scenario  $k$  on type of road  $t$  required calculation of the corresponding average probabilities of BR events:

$$\Pr(e_h|b_k, r_t) = \frac{1}{N_t} \sum_{j \in J_t} \Pr(e_{jh}|b_k, x_j, r_{jt}) \quad (8.4)$$

where:

- $e_h$  = indicator of BR harmful event  $h$ ,
- $b_k$  = indicator of road-barrier scenario  $k$ ,
- $r_t$  = indicator of road type  $t$ ,
- $N_t$  = number of observations for road type  $t$ ,
- $J_t$  = set of observations for road type  $t$ ,
- $e_{jh}$  = indicator of BR harmful event  $h$  in observation  $j$ ,

TABLE 8.3  
Unit Personal Injury Cost Calculated based on the Probability Conversion between KABCO and MAIS.

KABCO Level $i$	Probability of MAIS level $\Pr(MAIS KABCO)$								Unit Cost per Person $C_i$ (\$ in thousands, 2010)	
	0*	1	2	3	4	5	6	Total	Economic	Comprehensive
K	0	0	0	0	0	0	0	1	1398.92	9146.00
A	0.542636	0.146318	0.159157	0.103682	0.039729	0.0084787	0.542636	1	81.43	342.38
B	0.561978	0.317407	0.093403	0.02142	0.005383	0.0004084	0.561978	1	28.76	98.07
C	0.631089	0.263242	0.080916	0.01943	0.005057	0.0002662	0.631089	1	25.63	86.51
O	0.948217	0.040808	0.009589	0.001142	0.000222	0.0000222	0.948217	1	6.55	12.24

\*Crashes with no MAIS level available were assigned as MAIS level 0.

TABLE 8.4  
Average Personal Injury Cost by Event Category by Road Type.

Road Type $t$	Event Category $h$	Event Symbol	Personal Injury Cost $C_{ht}$ (\$ in thousands, 2010)	
			Economic	Comprehensive
High speed freeway	Non-cross-median high-risk	HR	33.323	168.303
	Far-side median cable barrier collision	MB/CB2	8.302	19.101
	Nearside median cable barrier collision	MB/CB1	8.161	18.606
	Median barrier wall collision	MB/BW	14.481	51.127
	Median guardrail (face) collision	MB/GR	14.878	56.299
	Non-cross-median moderate-risk event	MR	17.103	69.924
	Vehicle redirected and hit another vehicle	RHV	13.618	52.916
	Roadside guardrail collision	SB	14.057	51.927
	Cross-median head-on	XH	96.229	570.314
	Cross-median non-head-on	XM	30.538	149.982
Low speed freeway	Non-cross-median high-risk	HR	24.680	112.941
	Far-side median cable barrier collision	MB/CB2	8.161	18.539
	Nearside median cable barrier collision	MB/CB1	8.003	17.971
	Median barrier wall collision	MB/BW	12.846	41.422
	Median guardrail (face) collision	MB/GR	12.686	42.901
	Non-cross-median moderate-risk event	MR	14.118	51.267
	Vehicle redirected and hit another vehicle	RHV	11.333	38.459
	Roadside guardrail collision	SB	12.103	39.869
	Cross-median head-on	XH	64.451	363.337
	Cross-median non-head-on	XM	23.033	102.252
Non-freeway	Non-cross-median high-risk	HR	37.112	187.698
	Far-side median cable barrier collision	MB/CB2	9.139	22.410
	Nearside median cable barrier collision	MB/CB1	9.047	22.146
	Median barrier wall collision	MB/BW	16.835	62.087
	Median guardrail (face) collision	MB/GR	17.596	69.798
	Non-cross-median moderate-risk event	MR	20.117	85.472
	Vehicle redirected and hit another vehicle	RHV	16.656	69.996
	Roadside guardrail collision	SB	16.556	64.646
	Cross-median head-on	XH	96.747	567.017
	Cross-median non-head-on	XM	34.397	169.469

$x_j$  = values of additional variables included the model,  
 $r_{jt}$  = indicator of road type  $t$  in observation  $j$ .

The probabilities of BR events (with adjustments for non-zero cross-median events on segments with median cable barriers or with median guardrails) calculated

with Equation (8.4) are listed in Table 8.5 for high-speed freeways, Table 8.6 for low-speed freeways, and Table 8.7 for non-freeways.

The BR event probabilities were similar across different road types but varied considerably across the

TABLE 8.5  
Crash Event Probability (High-speed Freeway).

Median Scenario	Roadside Scenario	Crash Event Probability									
		XH	XM	RHV	MR	HR	MB/BW	MB/GR	MB/CB1	MB/CB2	SB
M_CB_N	R_NB_H	0.00552	0.02209	0.03270	0.16307	0.16307	0.00000	0.00000	0.61355	0.00000	0.00000
M_CB_N	R_NB_L	0.00512	0.02047	0.03080	0.21228	0.15356	0.00000	0.00000	0.57778	0.00000	0.00000
M_CB_N	R_GR	0.00418	0.01674	0.05932	0.06940	0.06940	0.00000	0.00000	0.48218	0.00000	0.29878
M_CB_F	R_NB_H	0.00552	0.02209	0.00517	0.25333	0.25333	0.00000	0.00000	0.00000	0.46056	0.00000
M_CB_F	R_NB_L	0.00512	0.02047	0.00471	0.31913	0.23086	0.00000	0.00000	0.00000	0.41971	0.00000
M_CB_F	R_GR	0.00418	0.01674	0.00874	0.10043	0.10043	0.00000	0.00000	0.00000	0.33714	0.43235
M_BW	R_NB_H	0.00000	0.00000	0.02292	0.16956	0.16956	0.63797	0.00000	0.00000	0.00000	0.00000
M_BW	R_NB_L	0.00000	0.00000	0.02152	0.22012	0.15923	0.59912	0.00000	0.00000	0.00000	0.00000
M_BW	R_GR	0.00000	0.00000	0.04169	0.07231	0.07231	0.50239	0.00000	0.00000	0.00000	0.31130
M_GR	R_NB_H	0.00479	0.01918	0.03207	0.23802	0.23802	0.00000	0.46793	0.00000	0.00000	0.00000
M_GR	R_NB_L	0.00439	0.01754	0.02940	0.30159	0.21817	0.00000	0.42891	0.00000	0.00000	0.00000
M_GR	R_GR	0.00345	0.01382	0.05372	0.09351	0.09351	0.00000	0.33944	0.00000	0.00000	0.40268
M_NB_N	R_NB_H	0.07078	0.19521	0.00741	0.36330	0.36330	0.00000	0.00000	0.00000	0.00000	0.00000
M_NB_N	R_NB_L	0.06214	0.17140	0.00650	0.44096	0.31899	0.00000	0.00000	0.00000	0.00000	0.00000
M_NB_N	R_GR	0.05755	0.07308	0.01184	0.13601	0.13601	0.00000	0.00000	0.00000	0.00000	0.58552
M_NB_W	R_NB_H	0.01986	0.09206	0.01048	0.36351	0.51410	0.00000	0.00000	0.00000	0.00000	0.00000
M_NB_W	R_NB_L	0.01743	0.08083	0.00920	0.44118	0.45136	0.00000	0.00000	0.00000	0.00000	0.00000
M_NB_W	R_GR	0.02339	0.04992	0.02424	0.19712	0.27878	0.00000	0.00000	0.00000	0.00000	0.42654

- XH: cross-median head-on event
- XNH: cross-median non-head-on event
- RHV: redirected and hit another vehicle event
- MB/BW: median concrete barrier wall collision
- MB/GR: median guardrail (face) collision
- MB/CB1: nearside median cable barrier collision (offset 30 feet or less)
- MB/CB2: far-side median cable barrier collision (offset more than 30 feet)
- SB: roadside barrier collision event
- HR: non-cross-median high-risk event (e.g., rollover or hitting a sturdy fixed object)
- MR: non-cross-median moderate-risk event (e.g., hitting a weak object, running over a ditch, etc)
- M\_NB\_N: median 50 feet or narrower and no median barrier
- M\_NB\_W: median wider than 50 feet and no median barrier
- M\_BW: median concrete barrier wall placed in the center of a narrow median
- M\_GR: median guardrail placed in the center of a median or at the nearside edge
- M\_CB\_N: median cable barrier with a lateral clearance 30 feet or less to the travelled way
- M\_CB\_F: median cable barrier with a lateral clearance more than 30 feet to the travelled way
- R\_GR: roadside guardrail
- R\_NB\_L: no guardrail, roadside hazard rating: 1 or 2
- R\_NB\_H: no guardrail, roadside hazard rating from 3 to 7

barrier scenarios. The probabilities of cross-median events (columns XH and XNH) were substantially reduced with the use of median barriers. Median barriers (particularly for nearside cable barriers and barrier walls) and roadside guardrails were shown to effectively reduce the probabilities of non-cross-median high and moderate-risk events (columns MR and HR). The probabilities of median barrier collisions were found to

vary with the barrier type and offset. The probabilities of colliding with a nearside barrier (column MB/CB1) were close to those with a barrier wall (column MB/BW), both of which were larger than the probabilities of colliding with a far-side cable barrier (column MB/CB2) or a median guardrail (column MB/GR). Another interesting finding was that the probabilities of redirected vehicle events (column RHV) increased with the use

TABLE 8.6  
Crash Event Probability (Low-speed Freeway).

Median Scenario	Roadside Scenario	Crash Event Probability									
		XH	XM	RHV	MR	HR	MB/BW	MB/GR	MB/CB1	MB/CB2	SB
M_CB_N	R_NB_H	0.00548	0.02192	0.04395	0.16115	0.16115	0.00000	0.00000	0.60634	0.00000	0.00000
M_CB_N	R_NB_L	0.00508	0.02033	0.04142	0.20993	0.15186	0.00000	0.00000	0.57139	0.00000	0.00000
M_CB_N	R_GR	0.00460	0.01840	0.08620	0.07411	0.07411	0.00000	0.00000	0.51490	0.00000	0.22767
M_CB_F	R_NB_H	0.00548	0.02192	0.00701	0.25290	0.25290	0.00000	0.00000	0.00000	0.45978	0.00000
M_CB_F	R_NB_L	0.00508	0.02033	0.00639	0.31864	0.23050	0.00000	0.00000	0.00000	0.41906	0.00000
M_CB_F	R_GR	0.00460	0.01840	0.01353	0.11430	0.11430	0.00000	0.00000	0.00000	0.38372	0.35115
M_BW	R_NB_H	0.00000	0.00000	0.03090	0.16817	0.16817	0.63275	0.00000	0.00000	0.00000	0.00000
M_BW	R_NB_L	0.00000	0.00000	0.02904	0.21843	0.15801	0.59452	0.00000	0.00000	0.00000	0.00000
M_BW	R_GR	0.00000	0.00000	0.06124	0.07810	0.07810	0.54262	0.00000	0.00000	0.00000	0.23993
M_GR	R_NB_H	0.00474	0.01895	0.04311	0.23530	0.23530	0.00000	0.46259	0.00000	0.00000	0.00000
M_GR	R_NB_L	0.00434	0.01735	0.03956	0.29844	0.21589	0.00000	0.42442	0.00000	0.00000	0.00000
M_GR	R_GR	0.00383	0.01531	0.08084	0.10342	0.10342	0.00000	0.37545	0.00000	0.00000	0.31784
M_NB_N	R_NB_H	0.07059	0.19470	0.01004	0.36234	0.36234	0.00000	0.00000	0.00000	0.00000	0.00000
M_NB_N	R_NB_L	0.06200	0.17100	0.00882	0.43993	0.31825	0.00000	0.00000	0.00000	0.00000	0.00000
M_NB_N	R_GR	0.06880	0.08736	0.01923	0.16258	0.16258	0.00000	0.00000	0.00000	0.00000	0.49945
M_NB_W	R_NB_H	0.01978	0.09172	0.01419	0.36215	0.51217	0.00000	0.00000	0.00000	0.00000	0.00000
M_NB_W	R_NB_L	0.01738	0.08056	0.01246	0.43973	0.44988	0.00000	0.00000	0.00000	0.00000	0.00000
M_NB_W	R_GR	0.02638	0.05631	0.03718	0.22235	0.31446	0.00000	0.00000	0.00000	0.00000	0.34333

XH: cross-median head-on event  
 XNH: cross-median non-head-on event  
 RHV: redirected and hit another vehicle event  
 MB/BW: median concrete barrier wall collision  
 MB/GR: median guardrail (face) collision  
 MB/CB1: nearside median cable barrier collision (offset 30 feet or less)  
 MB/CB2: far-side median cable barrier collision (offset more than 30 feet)  
 SB: roadside barrier collision event  
 HR: non-cross-median high-risk event (e.g., rollover or hitting a sturdy fixed object)  
 MR: non-cross-median moderate-risk event (e.g., hitting a weak object, running over a ditch, etc.)  
 M\_NB\_N: median 50 feet or narrower and no median barrier  
 M\_NB\_W: median wider than 50 feet and no median barrier  
 M\_BW: median concrete barrier wall placed in the center of a narrow median  
 M\_GR: median guardrail placed in the center of a median or at the nearside edge  
 M\_CB\_N: median cable barrier with a lateral clearance 30 feet or less to the travelled way  
 M\_CB\_F: median cable barrier with a lateral clearance more than 30 feet to the travelled way  
 R\_GR: roadside guardrail  
 R\_NB\_L: no guardrail, roadside hazard rating: 1 or 2  
 R\_NB\_H: no guardrail, roadside hazard rating from 3 to 7

of either a median barrier or a roadside guardrail, with its probability being largest when both sides were protected with barriers.

### 8.2.3 People and Vehicles Involved in BR Events

The BR events sample (data was verified with police reports and corrected if needed) was used to calculate the average number of vehicles ( $V_h$ ) and the average

number of vehicle occupants ( $O_h$ ) involved in each BR event  $h$ . The obtained numbers  $V_h$  and  $O_h$  did not vary much across certain event types and were aggregated for groups of events as follows:

- Multiple-vehicle BR events (XH and RHV):  $V_h=2.071$ ,  $O_h=3.100$
- Single-vehicle BR events (events other than XH and RHV):  $V_h=1$ ,  $O_h=1.557$

TABLE 8.7  
Crash Event Probability (Non-freeway).

Median Scenario	Roadside Scenario	Crash Event Probability									
		XH	XM	RHV	MR	HR	MB/BW	MB/GR	MB/CB1	MB/CB2	SB
M_CB_N	R_NB_H	0.00549	0.02198	0.04040	0.16176	0.16176	0.00000	0.00000	0.60861	0.00000	0.00000
M_CB_N	R_NB_L	0.00509	0.02037	0.03807	0.21067	0.15240	0.00000	0.00000	0.57340	0.00000	0.00000
M_CB_N	R_GR	0.00462	0.01848	0.07946	0.07466	0.07466	0.00000	0.00000	0.51873	0.00000	0.22937
M_CB_F	R_NB_H	0.00549	0.02198	0.00643	0.25304	0.25304	0.00000	0.00000	0.00000	0.46003	0.00000
M_CB_F	R_NB_L	0.00509	0.02037	0.00586	0.31879	0.23062	0.00000	0.00000	0.00000	0.41927	0.00000
M_CB_F	R_GR	0.00462	0.01848	0.01241	0.11442	0.11442	0.00000	0.00000	0.00000	0.38412	0.35151
M_BW	R_NB_H	0.00000	0.00000	0.02839	0.16861	0.16861	0.63440	0.00000	0.00000	0.00000	0.00000
M_BW	R_NB_L	0.00000	0.00000	0.02667	0.21896	0.15840	0.59597	0.00000	0.00000	0.00000	0.00000
M_BW	R_GR	0.00000	0.00000	0.05636	0.07851	0.07851	0.54544	0.00000	0.00000	0.00000	0.24118
M_GR	R_NB_H	0.00476	0.01902	0.03963	0.23616	0.23616	0.00000	0.46427	0.00000	0.00000	0.00000
M_GR	R_NB_L	0.00435	0.01741	0.03636	0.29943	0.21661	0.00000	0.42584	0.00000	0.00000	0.00000
M_GR	R_GR	0.00386	0.01542	0.07449	0.10414	0.10414	0.00000	0.37804	0.00000	0.00000	0.32004
M_NB_N	R_NB_H	0.07065	0.19486	0.00921	0.36264	0.36264	0.00000	0.00000	0.00000	0.00000	0.00000
M_NB_N	R_NB_L	0.06204	0.17113	0.00809	0.44026	0.31848	0.00000	0.00000	0.00000	0.00000	0.00000
M_NB_N	R_GR	0.06891	0.08750	0.01765	0.16284	0.16284	0.00000	0.00000	0.00000	0.00000	0.50025
M_NB_W	R_NB_H	0.01981	0.09182	0.01302	0.36258	0.51278	0.00000	0.00000	0.00000	0.00000	0.00000
M_NB_W	R_NB_L	0.01739	0.08064	0.01144	0.44018	0.45034	0.00000	0.00000	0.00000	0.00000	0.00000
M_NB_W	R_GR	0.02646	0.05649	0.03416	0.22304	0.31544	0.00000	0.00000	0.00000	0.00000	0.34440

- XH: cross-median head-on event
- XNH: cross-median non-head-on event
- RHV: redirected and hit another vehicle event
- MB/BW: median concrete barrier wall collision
- MB/GR: median guardrail (face) collision
- MB/CB1: nearside median cable barrier collision (offset 30 feet or less)
- MB/CB2: far-side median cable barrier collision (offset more than 30 feet)
- SB: roadside barrier collision event
- HR: non-cross-median high-risk event (e.g., rollover or hitting a sturdy fixed object)
- MR: non-cross-median moderate-risk event (e.g., hitting a weak object, running over a ditch, etc)
- M\_NB\_N: median 50 feet or narrower and no median barrier
- M\_NB\_W: median wider than 50 feet and no median barrier
- M\_BW: median concrete barrier wall placed in the center of a narrow median
- M\_GR: median guardrail placed in the center of a median or at the nearside edge
- M\_CB\_N: median cable barrier with a lateral clearance 30 feet or less to the travelled way
- M\_CB\_F: median cable barrier with a lateral clearance more than 30 feet to the travelled way
- R\_GR: roadside guardrail
- R\_NB\_L: no guardrail, roadside hazard rating: 1 or 2
- R\_NB\_H: no guardrail, roadside hazard rating from 3 to 7

#### 8.2.4 Average Cost of Vehicle Damage

The average cost of vehicle damage  $C_v$  was taken from a NHTSA publication (Blincoe et al., 2014) and its value is:  $C_v = \$6,076$ .

#### 8.2.5 Average Crash Cost $UCC_{kt}$

The average cost of a BR crash depends not only on the costs of possible harmful events but also on the number of involved vehicles and persons:

TABLE 8.8  
Unit Crash Cost by Barrier Scenario.

Median Scenario	Roadside Scenario	Cost per Crash $C_{kt}$ (\$ in thousands, 2010)					
		Comprehensive			Economic		
		High Speed Freeway	Low Speed Freeway	Non-freeway	High Speed Freeway	Low Speed Freeway	Non-freeway
M_CB_N	R_NB_H	104.89	79.48	120.40	31.01	27.12	34.28
M_CB_N	R_NB_L	105.30	79.74	121.31	31.08	27.15	34.43
M_CB_N	R_GR	91.41	72.55	109.61	29.16	26.46	32.98
M_CB_F	R_NB_H	129.60	94.61	146.71	34.91	29.41	38.41
M_CB_F	R_NB_L	128.49	93.95	146.23	34.75	29.31	38.35
M_CB_F	R_GR	101.15	78.03	119.35	30.28	26.65	33.93
M_BW	R_NB_H	123.69	93.79	145.49	34.90	30.18	39.39
M_BW	R_NB_L	123.16	93.31	145.11	34.76	30.06	39.27
M_BW	R_GR	105.19	83.65	129.09	31.93	28.72	36.87
M_GR	R_NB_H	153.86	110.96	179.28	39.55	32.89	44.63
M_GR	R_NB_L	150.60	108.88	175.94	38.97	32.49	44.03
M_GR	R_GR	121.61	94.28	151.21	34.43	30.44	40.31
M_NB_N	R_NB_H	313.31	210.97	338.48	65.83	49.93	71.02
M_NB_N	R_NB_L	289.12	195.75	314.21	61.79	47.27	66.92
M_NB_N	R_GR	225.10	172.93	274.33	51.17	43.44	60.32
M_NB_W	R_NB_H	238.93	163.87	266.31	53.38	41.69	58.82
M_NB_W	R_NB_L	223.81	154.39	250.84	50.86	40.03	56.21
M_NB_W	R_GR	192.40	143.98	231.88	45.82	38.53	53.30

M\_NB\_N: median 50 feet or narrower and no median barrier

M\_NB\_W: median wider than 50 feet and no median barrier

M\_BW: median concrete barrier wall placed in the center of a narrow median

M\_GR: median guardrail placed in the center of a median or at the nearside edge

M\_CB\_N: median cable barrier with a lateral clearance 30 feet or less to the travelled way

M\_CB\_F: median cable barrier with a lateral clearance more than 30 feet to the travelled way

R\_GR: roadside guardrail

R\_NB\_L: no guardrail, roadside hazard rating: 1 or 2

R\_NB\_H: no guardrail, roadside hazard rating from 3 to 7

$$UCC_{kt} = \sum_{h \in H_k} (C_{ht} \cdot O_h + C_v \cdot V_h) \cdot \Pr(e_h | b_k, r_t) \quad (8.5)$$

where:

$UCC_{kt}$  = the average cost of a BR crash under road-barrier scenario  $k$  and on road type  $t$ ,

$H_k$  = set of possible events in road-barrier scenario  $k$ ,

$O_h$  = average number of occupants involved in BR even  $h$ ,

$C_v$  = average cost of vehicle damage, and

$V_h$  = number of vehicles involved in BR event  $h$ .

Equation (8.5) was applied with inputs from Table 8.4, Table 8.5, Table 8.6, and Table 8.7, and other values already presented to calculate the average costs of crashes in the studied road-barrier scenarios on the studied types of roads. The obtained unit crash costs  $UCC_{kt}$  for each

barrier scenario  $k$  on each road type  $t$  are summarized in Table 8.8. Both the comprehensive cost and economic cost are shown.

### 8.2.6 Discussion of the Results

Comparing the comprehensive costs across various scenarios yielded similar conclusions for comparing the economic costs. Nevertheless, the comprehensive costs were considerably higher than the economic costs, particularly for severe injuries such as fatality and incapacitating injury. Since the barriers were effective in preventing severe injuries, by using the comprehensive costs, the effectiveness of the barriers was higher.

**Road types.** As could be expected, low-speed freeways experienced the lowest average costs of BR crashes, followed by high-speed freeways, and non-freeways. The lowest cost of BR crashes on low-speed freeways could be explained by the lower vehicle running speed and forgiving roadside design on freeways, which are both factors that reduce injury severity. The higher crash costs on high-speed freeways were due to the higher vehicle running speed encouraged by the more liberal speed limits. The most costly crashes on non-freeways could be explained by the lower roadside design standards than on freeways while the speeds were comparable to those on low-speed freeways.

**Median barriers.** All the barrier crashes had lower associated costs than non-barrier crashes. Among the median barrier scenarios, crashes with a nearside cable barrier yielded the lowest costs, followed by crashes with concrete barrier walls, far-side cable barriers, and median guardrails. The inferior performance of far-side cable barriers and median guardrails in terms of the unit crash costs can be attributed to the higher probability of high-risk events under these barrier scenarios. Under the far-side cable barrier scenarios, vehicles were still about 40 to 50 feet away from the barrier and had a reasonable chance of rolling over in the median. For the median guardrails, vehicles were more likely to roll over the guardrails after the impact than for other median barriers. For non-barrier median scenarios, the wide median scenarios experienced lower cost than narrow median scenarios due to the lower expected probability of cross-median events.

In terms of comprehensive cost, the nearside and far-side median cable barrier scenarios resulted in around 60% and 50% reductions in unit crash costs, respectively, when compared to wide median (no barrier) scenarios. When compared to the narrow median (no barrier) scenarios, unit crash costs for median concrete barrier scenarios and median guardrail scenarios were lower by around 60% and 40%, respectively.

**Roadside.** The comparisons across roadside scenarios indicated that the roadside guardrail scenarios performed better than the non-barrier scenarios, which was due to the guardrail's effectiveness in reducing high-risk events. The use of roadside guardrails produced a 20% to 30% reduction in crash unit cost (comprehensive).

## 9. IMPLEMENTATION

This chapter introduces a procedure that uses the findings reported in the previous chapters to help agencies select barriers that are beneficial and most cost-effective among alternatives. The step-by-step procedure covers two cases: (1) selecting barrier design on new roads and (2) selecting barrier improvement alternatives on existing roads.

The average unit costs estimated for the median and roadside barrier scenarios on three types of roads were estimated and are reported in Table 8.7. The effect of the roadside hazard ratings on the unit costs in scenarios with median cable barriers was small, thus these scenarios were combined. The original 54 scenarios were appropriately reduced.

As mentioned in Section 3.2, the studied scenarios represented the majority of barrier use in Indiana. Yet, they did not cover double-run median cable barriers due to the lack of implementation in Indiana and undivided roads due to the insufficient crash data. With the aim to widen the scope of implementation, the double-run cable barriers and undivided multilane roads were included through extrapolation of the results of this study and other authors' results or by using analogy. These efforts together yielded a total of 57 road-type barrier scenarios, which are presented in this chapter.

Double-run median cable barriers are installed on both sides of a median. Double-run cable barriers were expected to experience BR events similar to those experienced by nearside cable barriers when a unidirectional travelled way was considered. The only exception was a higher effectiveness of the latter in preventing cross-median crashes. Consequently, the calculations for the double-run cable barrier scenarios were applied by following the nearside cable barrier case assuming 1% of cross-median events were crashes (a reduction from 5%).

Undivided multi-lane roads were expected to have more crashes with more severe outcome than divided roads. Le and Porter (2013) developed a CMF (function) for the median width from a sample that included 1/3 of divided and 2/3 of undivided roads. This function was used in this study to estimate the CMF for Indiana undivided roads where the reference case was a divided roadway with the average median width in the sample. The unit crash costs for undivided roads were obtained by linearly extrapolating the average costs for wide median and narrow median scenarios into the no median case. The three median widths used in the calculations were: the average wide median, the average narrow median, and the zero median cases.

The obtained CMFs and unit crash costs for implementation are presented in the next sections. Thereafter, a procedure is described that yields the safety benefits expressed as the annualized cost of crashes prevented. The chapter ends with an example calculation.

### 9.1 Crash Modification Factors and Unit Crash Costs for Implementation

The CMFs derived from the SPFs presented in Chapter 5 and in Le and Porter (2013) are included in Table 9.1. The SPFs were in the form of  $a = \exp(\sum_i \hat{\alpha}_i x_i)$ ,  $CMF_i$  corresponding to a change  $\Delta x_i$  in variable  $x_i$  is  $CMF_i = \exp(\beta_i \Delta x_i)$ . In the case of a binary variable, the equation was simply  $CMF_i =$

$\exp(\beta_i x_i)$  if the reference case in the SPF was the same as the road situation before the change.

Most of the unit crash costs in Table 9.1 are the values estimated in Chapter 8, the other costs were estimated for combined similar cases, for double-run median cable barriers, and for undivided roads. The costs for double-run cable barriers were very reliable. The results for undivided roads were based on extrapolation and previous studies and therefore should be used with caution.

## 9.2 Procedure for Road Design Alternatives

The proposed procedure in this section estimates the annual cost of BR crashes on a newly designed segment with an uncurbed divided roadway with speed limits higher than or equal to 45 mph. This method is helpful for selecting a design alternative with the best barrier scenario.

### Step 1. Identify road segments with consistent design

First, the designed road section should be broken into segments with consistent design and traffic including:

- unchanged traffic volume.
- no change in the road type (non-freeway with speed higher than 40 mph, freeway with speed limit consistently below 65 mph or above 60 mph).
- if no median barrier then median width consistently below 51 feet or above 50 feet.
- if median barrier present, then unchanged median barrier type (barrier wall, single-run cable at the same edge, double-run cable, guardrail).
- if no roadside guardrail, then similar roadside hazard rating (1–2 or 3–7); otherwise continuous presence of roadside guardrail.

(Steps 2 and 3 are conducted for each traffic direction separately.)

### Step 2. Calculate the expected annual number of BR crashes

For each direction, determine the barrier scenario. Then, for each consistent road segment and each direction, calculate the annual number of BR crashes using the following SPR:

$$a = (AADT/2)^{0.6033} \cdot LEN^{0.9845} \cdot \exp\{-7.9556 + 1.6661 \cdot HSF + 0.9557 \cdot LSF\} \cdot CMF \quad (9.1)$$

where:

$a$  = number of BR crashes in the implementation year (crashes/year)

$AADT$  = annual average daily traffic in the implementation year (veh/day)

$LEN$  = segment length (miles)

$HSF$  = 1 if freeway with speed limit  $\geq 65$  mph, = 0 otherwise

$LSF$  = 1 if freeway with speed limit  $\leq 60$  mph, = 0 otherwise

$CMF$  = crash modification factor from Table 9.1 reflecting the barrier design scenario

### Step 3. Calculate the annual cost of BR crashes

Find in Table 9.1 the average UCC for the traffic direction on the design-consistent segment. Calculate the annual cost of BR crashes  $CC$ :

$$CC = a \cdot UCC \quad (9.2)$$

where:

$CC$  = cost of the BR crashes in the implementation year in one traffic direction and on a road segment in 2010 dollars

$a$  = annual number of BR crashes in the implementation year

$UCC$  = unit crash cost of a BR crash from Table 9.1 for the traffic direction on the road segment

### Step 4. Calculate the total cost of barrier-relevant crashes on the study road section

Steps 2–3 should be repeated for each direction on each design-consistent road segment and all the obtained costs are then combined.

### Remaining calculations

Calculate the total cost of BR crashes for other barrier scenarios. These costs are for the implementation year. Repeating the calculations for other barrier scenarios, including the current or reference scenario, allows estimating the differential costs of crashes or safety benefit. Calculating the barrier costs and annualizing the benefits and costs will determine the benefit-cost ratios and the annual net benefits that will be the basis of selecting the barrier scenario.

## 9.3 Procedure for Existing Roads with Barriers Consideration

The proposed procedure estimates the annual cost of BR crashes on the existing road section and after installing new or modifying existing barriers. The method applies to uncurbed divided roadways with speed limits higher than or equal to 45 mph. The method is helpful for estimating the benefit of the barrier-related countermeasure.

### Step 1. Identify road segments with consistent design

First, the existing road section is broken into segments with consistent design and traffic including:

TABLE 9.1  
Crash Modification Factors and Unit Crash Costs.

Median	Roadside	Crash Modification Factor* CMF	Unit Crash Cost UCC (\$ in thousands, 2010)					
			Comprehensive			Economic		
			High <sup>1</sup> Speed Freeway	Low <sup>2</sup> Speed Freeway	Non-freeway <sup>3</sup>	High Speed Freeway	Low Speed Freeway	Non-freeway
Double-run cable <sup>4</sup>	No Guardrail	1.36	95.42	73.53	<i>111.09<sup>5</sup></i>	29.42	26.08	<i>32.70</i>
Double-run cable	Guardrail	1.36	83.61	67.14	<i>100.90</i>	27.86	25.53	<i>31.52</i>
Near-edge cable	No Guardrail	1.36	105.10	79.61	<i>120.86</i>	31.05	27.14	<i>34.36</i>
Near-edge cable	Guardrail	1.36	91.41	72.55	<i>109.61</i>	29.16	26.46	<i>32.98</i>
Far-edge cable	No Guardrail	1.36	129.05	94.28	<i>146.47</i>	34.83	29.36	<i>38.38</i>
Far-edge cable	Guardrail	1.36	101.15	78.03	<i>119.35</i>	30.28	26.65	<i>33.93</i>
Barrier wall	No Guardrail	2.68	123.43	93.55	145.30	34.83	30.12	39.33
Barrier wall	Guardrail	2.68	105.19	83.65	129.09	31.93	28.72	36.87
Guardrail	No Guardrail	1.80	152.23	109.92	177.61	39.26	32.69	44.33
Guardrail	Guardrail	1.80	121.61	94.28	151.21	34.43	30.44	40.31
No median <sup>6</sup>	Hazard 3–7	1.66	<i>387.69</i>	<i>258.07</i>	<i>410.65</i>	<i>78.28</i>	<i>58.17</i>	<i>83.22</i>
No median	Hazard 1–2	1.66	<i>354.43</i>	<i>237.11</i>	<i>377.58</i>	<i>72.72</i>	<i>54.51</i>	<i>77.63</i>
No median	Guardrail	1.66	<i>257.80</i>	<i>201.88</i>	<i>316.78</i>	<i>56.52</i>	<i>48.35</i>	<i>67.34</i>
Narrow <sup>7</sup> , no barrier	Hazard 3–7	1	313.31	210.97	338.48	65.83	49.93	71.02
Narrow, no barrier	Hazard 1–2	1	289.12	195.75	314.21	61.79	47.27	66.92
Narrow, no barrier	Guardrail	1	225.10	172.93	274.33	51.17	43.44	60.32
Wide <sup>8</sup> , no barrier	Hazard 3–7	1	238.93	163.87	266.31	53.38	41.69	58.82
Wide, no barrier	Hazard 1–2	1	223.81	154.39	250.84	50.86	40.03	56.21
Wide, no barrier	Guardrail	1	192.40	143.98	231.88	45.82	38.53	53.30

\*Crash Modification Factor = (1 – Crash Reduction Factor/100).

<sup>1</sup>Speed limit higher than or equal to 65 mph.

<sup>2</sup>Speed limit lower than or equal to 60 mph.

<sup>3</sup>Uncurbed non-freeway road with speed limit higher than or equal to 45 mph.

<sup>4</sup>One cable barrier on each side of median.

<sup>5</sup>The result in italics is based on extrapolation; caution is advised.

<sup>6</sup>Four-lane undivided roads with no median barrier.

<sup>7</sup>Median narrower than or equal to 50 feet.

<sup>8</sup>Median wider than 50 feet.

- unchanged traffic volume.
- no change in the road types (non-freeway with speed higher than 40 mph and freeway with speed limit consistently below 65 mph or above 60 mph).
- if no median barrier, then median width consistently below 51 feet or above 50 feet.
- if median barrier present, then unchanged median barrier type (barrier wall, single-run cable at the same edge, double-run cable, guardrail).
- if no roadside guardrail, then similar roadside hazard rating (1–2 or 3–7); otherwise continuous presence of roadside guardrail.

*Step 2. Identify the BR crashes during the data period before improvement*

BR crashes are the occurrence or outcomes (injury severity) that may be affected by a barrier had the barrier been installed or removed. A crash is apparently barrier-relevant if at least one involved vehicle collides with a barrier. Another sufficient condition is that at least one involved vehicle leaves the roadway. This definition applies to roads where barriers are allowed.

To identify the BR crashes, first identify all the crashes that occurred on the segment using the crash address. Then, inspect the information available in the

crash record and the police report. Be aware that crash record may include incorrectly coded information. For example, a collision with a fixed object or deer may be coded as a head-on collision, which is reserved for two vehicles moving in opposite directions. Inspecting narratives and police drawings is very useful in identifying barrier-relevant collisions, particularly if the information coded in the crash record is not specific (e.g., manner of collision coded as “other”).

Separate the BR crashes into each traffic direction. The crash assignment to a direction is obvious if all the vehicles involved in the crash intended to move in the same direction. In the case of a head-on collision, the crash should be assigned to the direction intended by a driver who crossed the median.

(Steps 3 and 4 are conducted for each traffic direction separately.)

*Step 3. Calculate the expected annual number of BR crashes given no barrier improvement*

For each consistent road segment and each direction, calculate the annual number of BR crashes using the following SPF:

$$a = (ADT/2)^{0.6033} \cdot LEN^{0.9845} \cdot \exp\{-7.9556 + 1.6661 \cdot HSF + 0.9557 \cdot LSF\} \cdot CMF_0 \quad (9.3)$$

where:

$a$  = number of BR crashes in the implementation year (crashes/year)

$ADT$  = average daily traffic in the data period (veh/day)

$LEN$  = segment length (miles)

$HSF$  = 1 if freeway with speed limit  $\geq 65$  mph, = 0 otherwise

$LSF$  = 1 if freeway with speed limit  $\leq 60$  mph, = 0 otherwise

$CMF_0$  = crash modification factor from Table 9.1 reflecting the existing barrier scenario

Improve the estimation of the expected annual number of crashes by combining the number obtained in this step with the SPF with the number of reported BR crashes obtained in Step 2. The improved estimate should apply to the implementation year. Thus, the calculation accounts for the change in the traffic volume that occurs between the data period and the implementation year. The following equation can be used:

$$a_0 = \frac{\frac{1}{D} + A}{\frac{1}{D \cdot a} + Y} \cdot \left(1 + \frac{R}{100}\right)^{Z \cdot Y_2} \quad (9.4)$$

where:

$a_0$  = annual number of BR crashes in the implementation year (crashes/year) given no barrier improvement

$a$  = annual number of BR crashes calculated with the SPF (crashes/year)

$D$  = 0.3812, over-dispersion parameter

$A$  = number of reported BR crashes during the data period (crashes)

$Y$  = number of years in the data period (years)

$R$  = annual traffic change rate in percent (%), it is typically assumed 2%

$Z$  = 0.6033, power parameter associated with the volume in the safety performance function

$Y_2$  = number of years between the midpoint of the data period and the implementation year

*Step 4. Predict the expected annual number of BR crashes with the barrier improvement*

Select from Table 9.1 the  $CMF_1$  and predict the annual number of BR crashes in the implementation year (crashes/year) given that the barrier improvement was implemented:

$$a_1 = a_0 \frac{CMF_1}{CMF_0} \quad (9.5)$$

where:

$a_1$  = annual number of BR crashes in the implementation year (crashes/year) if the barrier improvement were implemented

$a_0$  = annual number of BR crashes in the implementation year (crashes/year) if no barrier improvement

$CMF_0$  = crash modification factor from Table 9.1 reflecting the existing barrier scenario

$CMF_1$  = crash modification factor from Table 9.1 reflecting the barrier scenario considered for implementation

*Step 5. Calculate the annual safety benefit in the implementation year*

Calculate annual safety benefit in the implementation year:

$$B = a_0 \cdot UCC_0 - a_1 \cdot UCC_1 \quad (9.6)$$

where:

$B$  = safety benefit in the implementation year in 2010 dollars

$a_0$  = annual number of BR crashes in the implementation year (crashes/year) if no barrier improvement

$a_1$  = annual number of BR crashes in the implementation year (crashes/year) if the barrier improvement were implemented

$UCC_0$  = unit crash cost under the existing barrier scenario (\$)

$UCC_1$  = unit crash cost under the barrier scenario considered for implementation (\$)

*Step 6. Calculate the total cost of barrier-relevant crashes on the study road section*

Steps 3–5 should be repeated for each direction on each design-consistent road segment and all the obtained costs then are combined.

*Remaining calculations*

Calculate the total cost of BR crashes for other barrier scenarios considered for implementation. These costs are for the implementation year. Repeating the calculations for other barrier scenarios allows estimating the differential cost of crashes, or the safety benefit. Calculating the barrier costs and annualizing the benefits and costs yields the benefit-cost ratios and the annual net benefits that may be the basis of selecting the barrier scenario.

**9.4 Example Calculations**

This example calculation is provided using the road segment near I-70 mile marker 19 (lat 39.4510995, long -87.19403) as an example to illustrate how to obtain the annual safety benefit for installing a single-run median cable barrier. The segment orientation is east/west. A median cable barrier is considered at the south edge of the median. The implementation year is 2015. The comprehensive cost is used. Details will be provided on how to select a road segment for the analysis, extract BR crashes, collect input data, and use established equations and tables to obtain the final results.

*Step 1. Identify road segments with consistent design*

The considered road segment has a length of 0.097 miles, with its west endpoint located at mile marker 18.994 (lat 39.451098, long -87.194151) and its east endpoint located at mile marker 19.091 (lat 39.451053, long -87.192331).

The parameters of the segment are consistent since:

- The traffic volume does not change.
- It is a freeway with speed limit  $\geq 65$  mph (speed limit is 70 mph).
- The depressed grass median has no barrier and the median width is consistently above 50 feet (median width is 60 feet).
- The eastbound roadside has no guardrail with a roadside hazard rating of 3–7; the westbound roadside is continuously protected by roadside guardrails.

*Step 2. Identify the BR crashes during the data period before improvement*

The existing crash records allowed selecting all the crashes that occurred on this directional segment from year 2008 through 2012 (i.e., period 2008–2012,  $Y = 2012 - 2008 + 1 = 5$  years). Using the information

found in the available crash database as well as the police reports, three crashes out of those assigned crashes were identified as BR crashes. Among the three BR crashes, two of them were eastbound (i.e.,  $A = 2$  crashes for eastbound segment) and one of them was westbound (i.e.,  $A = 1$  crashes for westbound segment).

The bi-directional segment must be divided into two separate directional segments using its median. Next, the calculations in Steps 3 to 5 are conducted for the eastbound direction and then repeated for the westbound direction.

*Step 3. Calculate the expected annual number of BR crashes given no barrier improvement*

For the eastbound segment, the SPF input values are summarized as follows:

- Two-way ADT during the data period is 36,204 veh/day.
- Segment length is 0.097 miles.
- It is a freeway with speed limit  $\geq 65$  mph,
- The existing barrier scenario identified from Table 9.1 is: wide, no barrier (median), and hazard 3–7 (roadside). The corresponding CMF for the existing barrier scenario is:

$$CMF_0 = 1.00$$

The annual number of BR crashes are calculated using the following SPR:

$$a = (ADT/2)^{0.6033} \cdot LEN^{0.9845} \cdot \exp\{-7.9556 + 1.6661 \cdot HSF + 0.9557 \cdot LSF\} \cdot CMF_0 = (36204/2)^{0.6033} \cdot 0.097^{0.9845} \cdot \exp\{-7.9556 + 1.6661 \cdot 1 + 0.9557 \cdot 0\} \cdot 1.00 = 0.0691 \text{ crashes/year}$$

The improved estimate of the expected number of crashes is calculated as follows:

$$a_0 = \frac{\frac{1}{D} + A}{\frac{1}{D} + Y} \cdot \left(1 + \frac{R}{100}\right)^{Z \cdot Y_2} = \frac{\frac{1}{0.3812} + 2}{\frac{1}{0.3812 \cdot 0.0691} + 5} \cdot \left(1 + \frac{2}{100}\right)^{0.6033 \cdot (2015 - \frac{2008 + 2012}{2})} = 0.1143 \text{ crashes/year}$$

Step 4. Predict the expected annual number of BR crashes with the barrier improvement

For the eastbound segment where a single-run cable barrier is installed near the south median edge as the barrier improvement, the identified barrier scenario from Table 9.1 is near-edge cable (median) and no guardrail (roadside), and the corresponding CMF is:

$$CMF_1 = 1.36$$

The annual number of BR crashes in the implementation year (crashes/year) given that the barrier improvement was implemented is calculated:

$$a_1 = a_0 \frac{CMF_1}{CMF_0} = 0.1143 \cdot \frac{1.36}{1.00} = 0.1554 \text{crashes/year}$$

Step 5. Calculate the annual safety benefit in the implementation year

Based on the identified existing barrier scenario and the barrier scenario considered for implementation as well as the road type, the corresponding unit crash cost in 2010 dollars are taken from Table 9.1:

$$UCC_0 = \$238,930/\text{crash}$$

$$UCC_1 = \$105,100/\text{crash}$$

The annual safety benefit for the eastbound segment in the implementation year in 2010 dollars is:

$$B = a_0 \cdot UCC_0 - a_1 \cdot UCC_1 = 0.1143 \cdot 238930 - 0.1554 \cdot 105100 = \$10,970/\text{year}$$

Step 6. Calculate the total cost of barrier-relevant cashes on the study road section

Steps 3–5 are repeated for the westbound segment and the following values are obtained:

- Two-way ADT during the data period is 36204 veh/day.
- Segment length is 0.097 miles.
- It is a freeway with speed limit  $\geq 65$  mph.
- The existing barrier scenario identified from Table 9.1 is: wide, no barrier (median) and guardrail (roadside). The corresponding CMF for the existing barrier scenario is:

$$CMF_0 = 1.00$$

$$Y = 2012 - 2008 = 5 \text{years}$$

$$A = 1 \text{crash}$$

$$a = (ADT/2)^{0.6033} \cdot LEN^{0.9845} \cdot \exp\{-7.9556 + 1.6661 \cdot HSF + 0.9557 \cdot LSF\} \cdot CMF_0 = (36204/2)^{0.6033} \cdot 0.097^{0.9845} \cdot \exp\{-7.9556 + 1.6661 \cdot 1 + 0.9557 \cdot 0\} \cdot 1.00 = 0.0691 \text{crashes/year}$$

$$a_0 = \frac{\frac{1}{D} + A}{\frac{1}{D \cdot a} + Y} \cdot \left(1 + \frac{R}{100}\right)^{Z \cdot Y_2} = \frac{\frac{1}{0.3812} + 1}{\frac{1}{0.3812 \cdot 0.0691} + 5} \cdot \left(1 + \frac{2}{100}\right)^{0.6033 \cdot (2015 - \frac{2008 + 2012}{2})} = 0.0896 \text{crashes/year}$$

The barrier scenario considered for improvement is: far-edge cable (median) and guardrail (roadside). The corresponding CMF for the scenario with improvement:

$$CMF_1 = 1.36$$

$$a_1 = a_0 \frac{CMF_1}{CMF_0} = 0.0896 \cdot \frac{1.36}{1.00} = 0.1218 \text{crashes/year}$$

$$UCC_0 = \$192,400/\text{crash}$$

$$UCC_1 = \$101,150/\text{crash}$$

$$B = a_0 \cdot UCC_0 - a_1 \cdot UCC_1 = 0.0896 \cdot 192400 - 0.1218 \cdot 101150 = \$4,911/\text{year}$$

Summing up the annual benefits for the eastbound and westbound directions yields the final total annual benefit. In the end, the final safety benefit for installing a single-run cable barrier closer to the south side of the median on this 0.097 mile long two-way segment in the

implementation year in 2010 dollars is calculated as follows:

$$B^{Final} = \$10,970 + \$4,911 = \$15,881/\text{year}$$

## 10. CONCLUSIONS

### 10.1 Study Summary

Road barriers reduce the exposure of errant vehicles to head-on collisions and roadside hazards. The recent introduction of high-tension cable barriers in medians has provided highway agencies with more viable barrier alternatives. The current guidelines for median barriers recommend conducting studies to help select the appropriate type of barrier for the conditions. The presented in-service performance study of several types of barriers under various road conditions is a result of this need for Indiana.

The study investigated the in-service performance of three types of road barriers: concrete walls, W-beam guardrails, and high-tension cable barriers installed on divided roads in Indiana. The performance for barriers on undivided roads was not analyzed in this study due to the limited crash data and the lack of embankment information. Nevertheless, the results obtained for the studied divided roads and the past research on the impact of medians on safety allowed extrapolation to include undivided multilane roads among the results for implementation. Furthermore, the obtained results for cable barriers allowed including double-run median cable barriers, which are not yet implemented in Indiana.

This in-service performance of barriers analysis focused on barrier-relevant (BR) crashes and consists of three components:

1. The effect of barriers on the BR crash frequency (segment level)
2. The effect of barriers on the probability of BR harmful events (crash level)
3. The effect of BR events on the probability of injury outcomes (occupant level)

Each component of the analysis included developing a statistical model. The three statistical models were estimated based on data obtained from existing databases of INDOT (road and traffic), ISP (crashes), and ISDH (personal injuries). A collection of detailed geometry and barrier information on selected road segments provided the Purdue University Center for Road Safety supplemented the existing data.

The developed models were used to derive the crash modification factors (CMFs) and unit crash costs (UCCs) under the studied road-barrier scenarios and presented in a table (Table 9.1). The CMFs and UCCs are the primary results of this study, which are implemented in a procedure for evaluating the safety benefits of barriers. The procedure is applicable to 51 road-barrier scenarios on new and modernized existing

roads including double-run cable barriers and undivided multilane roads.

### 10.2 Conclusions

A negative binomial regression analysis of BR crashes on paired directional roadway segments (pairing of barrier presence with barrier absence) indicated that all three types of median barriers were associated with an increase in the number of BR crashes. Median concrete barrier walls produced the largest increase, followed by median guardrails, and median cable barriers. The analysis could not confirm this increase for roadside guardrails.

A multinomial logit model with variable outcomes estimated the effects of barriers on the probability of BR harmful events: cross-median head-on collision, cross-median non-head-on crash, collision of vehicle redirected to traffic with another vehicle, median barrier collision, roadside barrier collision, non-cross-median high-risk event (rollover, collision with a strong fixed object, etc.), and non-cross-median moderate-risk event (collision with a weak fixed object, running over a ditch, etc.).

The results indicated that wider medians reduced cross-median events. No such events occurred on the studied segments with barriers during the study period in spite of 557 collisions with median barriers. This result confirms the good performance of all median barriers in preventing cross-median crashes. On the other hand, past studies indicated that approximately up to five percent of head-on collisions are not prevented by cable barriers or guardrails. Our studies included 104 reported collisions with cable barriers and 59 reported collisions with guardrails with no cross-median events, indicating that the performance of median cable barriers and median guardrails might be slightly better than reported in the past studies.

Concrete walls and guardrails increased median barrier collisions and collisions of redirected vehicles with other vehicles. At the same time, median barriers and roadside guardrails seemed to reduce high-risk and moderate-risk events in the median or on the right-hand roadside.

The transferability testing indicated that a standard multinomial logit model was suitable for analyzing the probabilities of KABCO injury outcomes. Collisions with any of the studied types of barriers, regardless of their offset to the travelled way, had the probability of severe injury outcomes lower than non-barrier collisions, particularly cross-median crashes, rollovers, and crashes with fixed strong objects. The risk of severe injury varied strongly across barrier types. Both the nearside median cable barriers (lateral offset 30 feet or less) and the far-side median cable barriers (lateral offset more than 30 feet) were superior to median concrete barriers and guardrails. The lower performance of the far-side median cable barrier compared to the nearside counterpart was attributed to crossing median open drains and other surface features.

The average costs of crashes (unit crash costs) on the roads with barriers, particularly median barriers, were generally lower than crashes on the roads without barriers. Among the median barrier scenarios, the nearside cable barrier scenarios experienced the lowest costs of BR crashes. Next in ranking were the concrete barrier walls, followed by the far-side cable barriers and median guardrails. This order of performance was determined by the probability of high-risk events in the medians and on the right-hand roadside. A 60% reduction of comprehensive unit costs was attributed to cable barriers in wide medians and a 50% reduction to its far-side counterparts. Similar reductions in the comprehensive unit costs were attributed to median concrete barriers and guardrails in narrow medians. The reduction attributed to the roadside guardrails was 20% to 30%.

Overall, the study found that median cable barriers exhibited considerably better overall safety performance than the other two types of barriers. They should be considered as a viable alternative to concrete barrier walls and guardrails where they are allowable by the median and traffic conditions. As expected, the two-run cable barriers were superior to single-run cables because they prevent a vehicle from entering the median from both sides and were much more effective protection against cross-median high-risk events.

### 10.3 Contributions

This is the most comprehensive and in-depth study of longitudinal barrier performance in improving road safety. The alternative paths of events during a crash involving a vehicle leaving the road were identified as well as all the most harmful events relevant to barriers and thereby, all barrier-relevant (BR) crashes where barriers could somehow affect the crash outcome. The BR crash is a crash where at least one vehicle leaves the travelled way, even temporarily, before the most harmful event occurs. This definition includes all run-off-road single vehicles crashes, head-on collisions, and collisions after a vehicle returns to the roadway after being redirected by a driver, an obstruction, or a barrier.

Unlike in past studies, the BR harmful events were included in the BR events model to link the onset of a BR crash with its outcome. This addition brought more insight to the crash process and better captured the effects of barriers, medians, and roadsides. This improvement led to three models specified from three perspectives: road, crash, and person.

This introduction of BR harmful events to this study's analysis allowed using two samples which helped reduce the demand for costly detailed road information. A rather small sample with the detailed road information was sufficient to build the BR crash frequency and BR events models. A large BR injury sample to estimate the outcome severity of BR harmful events was extracted solely from crash data. This approach provided an opportunity to properly estimate the probabilities of a

fatality, which is the most consequential and infrequent event. Reducing the risk of fatality and other serious outcomes is the essence of barriers, thus this improvement helped increase the accuracy of the results.

Another considerable improvement of the results quality was achieved by analyzing the injury outcome of each person involved in a BR crash separately rather than only the most severe crash outcome, which was the common practice in the past studies. Furthermore, the average costs of KABCO injuries from BR events were estimated using own linked police-hospital data instead of using "generic" costs provided by NHTSA.

This study investigated three types of median barriers and roadside guardrails arranged in 19 scenarios, which together with three types of roads, produced 51 valid road-barrier scenarios (six invalid road-barrier scenarios were excluded). These scenarios included 38 scenarios in Indiana, and represented in the samples were four double-run median cable barrier scenarios on freeways, which are not yet installed in Indiana, but produced firm results. Nine scenarios were also obtained for non-freeway roads by extrapolation through the models of this study or past studies. This is the most comprehensive and consistent comparison of various types of barriers obtained in one study to date.

The results include a table with a complete set of CMFs and UCCs and a description of an applied procedure to estimate the safety benefit of any of the 51 scenarios using either comprehensive or economic costs.

### 10.4 Future Study

An in-depth analysis of the in-service performance of barriers on undivided roads should be included in future research. Only roadside barriers are under consideration and their use depends largely on the embankment height and slope. More data collection efforts should be made for collecting enough road segments and relevant crashes as well as accessing accurate embankment information.

Future research could investigate expanding the use of cable barriers. This study concluded that nearside cable barriers performed better than far-side cable barriers. It was further inferred that double-run cable barriers should perform even better. It would be interesting to verify if the double-run cable barriers can perform as expected using the actual crashes that occurred on the road segments where those barriers were actually installed. In addition, the possible use of cable barriers on narrower medians or on roadsides is also worth investigating.

A future study could include a life-cycle cost-effectiveness analysis with consideration of the costs of the installation, maintenance, and repair of different barriers that vary considerably across the barrier types. Concrete barriers have the highest installation cost but very little maintenance and repair cost. Cable barriers have much lower installation costs, but repairs after a crash are very common. Thus, a life-cycle cost-

effectiveness analysis would be beneficial in this regard as well in the final justification of the use of a certain barrier.

Advanced models, such as random effect models, random parameter models, Bayesian networks, etc., which recently have been widely applied in modeling crash data and have demonstrated better performance than traditional models, also could provide more insight into the effects of barriers.

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## APPENDIX A: MANUAL FOR SEGMENT SELECTION IN GOOGLE EARTH

### 1. Job Objectives

1. Obtain homogeneous roadway segments with and without concrete barrier wall/guardrail/cable road barriers.
2. Obtain qualitative and quantitative information on the relevant roadway and roadside features.

*Q1: What is a homogeneous roadway segment?*

**A:** A homogeneous roadway segment is a roadway segment where the roadway and roadside characteristics remain the same over the entire length of the segment under given traffic and weather conditions.

*Q2: Why is there a need to obtain homogeneous roadway segments?*

**A:** The ROR crashes are potentially influenced by roadway and roadside features. To further understand which of those features actually influence the ROR crashes and by how much, it is necessary to find roadway segments with different roadway and roadside features and then conduct a comparison of their crash counts among different segments.

*Q3: What are the important characteristics of homogeneous roadway segment?*

**A:** Worthy of note is that the roadway and roadside features within each segment should be consistent. Although some of the features of interest may not be exactly constant over the segment (e.g., the position of trees), they can be deemed as “homogenous” to a reasonable and acceptable level in some cases, which is where engineering judgment comes into play.

*Q4: Why roadside hazard ratings need to be assessed?*

**A:** The roadside hazard rating (0–7 scale) also will be used to assist the expert’s opinion. The roadside hazard rating is presented in the following sections. For a homogeneous segment, the difference between the maximum rating and the minimum rating for one direction should be no larger than 2. The job listed here is to select those “homogenous” roadway segments and record information using the Google Earth software for our further analysis.

### 2. Job Description

The required job is divided into the following tasks:

1. Use Google Earth to select homogeneous segments which are close to the assigned spot. The segment selection and the homogeneity check are achieved by visual inspection on the Google Earth images of the roadway and roadside features.

2. Collect information for the roadway and roadside features of the selected segments in Google Earth. Information for both traffic directions is required. Carefully fill in the data entry form, which is available in an Excel spreadsheet.
3. Check the data input errors and make sure the standard for judging the segment homogeneity holds constant and reasonable over selected segments.

### 3. Work Procedure

Each student is assigned to a certain type of barrier and several sets of spots in Google Earth. Whatever the assigned type of barrier is, two types of spots are assigned in Google Earth and they are classified by the presence of a physical mile post. A “milepost spot” (yellow pin in Google Earth) designates a spot which is located exactly or very closely to a physical integer milepost, while a “boundary spot” (red rectangle in Google Earth) designates a spot which is located approximately 0.5 mile away from the physical mile post. Data collectors should start their segment selection by zooming into a milepost spot. For each milepost spot, its closest two boundary spots define the boundary within which the finally selected segment should fall. The finally selected segment should only contain the milepost spot.

The data collectors assigned to collect information about the guardrail barriers also must select a homogeneous segment without any barrier as the “control group” after a guardrail segment is selected. For the control group segment selection, instead of starting from the assigned milepost spot, data collectors should select the corresponding milepost spot by their own judgment based on the nearby roadway and roadside information. The selected control group segments should have similar roadway and roadside characteristics as their corresponding guardrail segments except for the presence of barrier.

Below is a detailed procedure for selecting homogeneous segments.

**i. Check the presence of barriers.** In Google Earth, zoom into the assigned milepost spot and start to work under the “street view.” Determine if there is a required type of barrier (barrier wall/guardrail/cable/non-barrier) around the spot. If so, continue to the next step. If not, fill in the data entry form and add a note such as “no guardrail found.” Then, move on to the next assigned milepost spot.

**ii. Set the “reference direction.”** Under the “street view,” there is at least one solid yellow line that shows the approximate path followed by the camera car. If there are two solid yellow lines, choose one of them. The direction in which the camera car was driving along the selected yellow line is the “reference direction,” and the other direction is the “opposite direction.” It should be noted that those two directions are determined and recorded based on the **entire route direction**. For the most part, the interstates, U.S. highways, and state and

county roads follow the pattern of odd numbers corresponding to north-south routes and even numbers corresponding to east-west routes. So whichever the local direction may be, the final recorded direction should be interpreted under the larger context of the entire route and could be only one of the following: E/W/N/S or CW/CCW (for beltways or loops such as I465, I469, etc.). Furthermore, the reference direction also should be interpreted in terms of whether it is in the milepost increasing direction or the milepost decreasing direction.

**iii. Check the consistency in roadway geometry and roadside hazard for both directions.** Move upward along the “reference direction” and examine the roadway features **for both directions** by slowly rotating the scroll wheel of the mouse under “street view” and then glancing from the “satellite view.” Keep moving upward until any one of the following situations occur:

- Beginning/end of a primary barrier (barrier wall/guardrail/cable).

NOTE: when the segments for a required type of barriers are selected, this type of barriers is of primary interest and is defined as the “primary barrier,” and then the other two types of barriers are the “secondary barriers.”

- Beginning/end of a horizontal curve.
- Beginning/end of a rumble strip.
- Presence of a boundary spot.
- Presence of an intersection or interchange.
- Presence of a major road construction area.
- Presence of a bridge.
- Change of the number of lanes.
- Change of the lane width
- Change of the median width.
- Change of the shoulder width.
- Other abrupt changes on roadside characteristics such as:

- Secondary barriers
- Embankments
- Curbs
- Culverts
- Ditches
- Density and distance from the edge of the travelled lanes to trees
- Other rigid and fixed objects such as utility poles, buildings, retaining walls, cliffs, noise barriers etc.

**iv. Record the downstream endpoint of the homogeneous segment.** Once the search is stopped because one or more of the aforementioned consistencies are violated, record the longitude and latitude of a point around 50 feet (use 500 feet only when the changed feature is the presence of intersections) ahead of where the search stop occurs as the “end latitude” and “end longitude.” This point is the downstream endpoint of the homogeneous segment.

**v. Record the upstream endpoint of the homogeneous segment.** Go back to the assigned milepost point and move backward toward the upstream of the solid yellow line until the consistency of any roadway and roadside characteristics is violated or a boundary point is reached. The point around 50 feet (use 500 feet only when the changed feature is the presence of an intersection) ahead of where the search stop occurs is the upstream endpoint of the homogeneous segment. Record the longitude and latitude of this point as the “start latitude” and the “start longitude,” respectively. Selecting one homogeneous segment is now completed.

**vi. Check the location of the assigned spot in the selected segment.** The selected segment should contain the milepost spot and fall into the region between the two boundary spots. If so, go to the next step. If not, record the milepost spot ID, “start latitude,” “start longitude,” “end latitude,” and “end longitude,” and add a note such as “spot not contained in the segment” or “segment exceeds boundaries.” Then move on to the next assigned milepost spot.

**vii. Check the temporal consistency of roadway and roadside characteristics.** Use the “time slider” in Google Earth to determine if the roadway and roadside characteristics on the selected segment have experienced significant changes over the years. If so, record the most recent year that those changes could be seen in Google Earth.

**viii. Measure and collect information in Google Earth “satellite view.”** Use the “show ruler” tool provided in satellite view to help measure the distance of certain features. The items required to measure or record are listed below:

- Observers’ Information
  - Observer Name
  - Computer No. (1/2/3/4/5)
  - Work Date (e.g., May-6)
  - Work Start Time (e.g., 14:00)
  - Work End Time (e.g., 4:30)
- Assigned Barrier Type (Barrier Wall/Guardrail/Cable/Non-Barrier)
- Assigned Milepost Spot
  - Spot ID (e.g., BW14\_I 465\_14)
  - Route Name (e.g., I 65)
  - Milepost (e.g., 26)
  - Latitude (e.g., 30°37’40.72”N)
  - Longitude (e.g., 96°20’3.87”W)
- Reference Direction
  - E/W/N/S or CW/CCW
  - Milepost Increasing (1-Yes; 0-No)
- Segments’ Information
  - Start Latitude (i.e., latitude of the upstream endpoint in the reference direction)
  - Start Longitude (i.e., longitude of the upstream endpoint in the reference direction)

- End Latitude (i.e., latitude of the downstream endpoint in the reference direction)
- End Longitude (i.e., longitude of the downstream endpoint in the reference direction)
- Segment Length
- Primary Barriers
  - Primary Barrier Type (Concrete/Guardrail/Cable)
  - Reference Direction
    - Left Offset
    - Right Offset
  - Opposite Direction
    - Left Offset
    - Right Offset
- Secondary Barriers
  - Secondary Barrier Type (Concrete/Guardrail/Cable)
  - Reference Direction
    - Left Offset
    - Right Offset
  - Opposite Direction
    - Left Offset
    - Right Offset
- Roadway Geometry
  - Shoulder Width
    - Reference Direction
      - Left Shoulder Width
      - Right Shoulder Width
    - Opposite Direction
      - Left Shoulder Width
      - Right Shoulder Width
  - Median
    - Median Width
    - Median Traversable (1-Yes; 0-No)
  - No. of Lanes
    - Reference Direction
    - Opposite Direction
  - Presence of Horizontal Curves (1-Yes; 0-No)
- Roadside Features (for both reference direction and opposite direction)
  - Non-traversable objects
    - Type (1-trees; 2-utility poles; 3-buildings; 4-culverts; 5-ditches; 6-retaining walls; 7-cliff; 8-noise barrier; 9-luminare supports; 10-others)
    - Continuity: (1-Continuous; 0-Intermittent)
    - Offset from Edge of Traveled Way
    - Density of Non-traversable Objects (or the Gap Length)

- No. of Driveways
  - Reference Direction
  - Opposite Direction
- Embankment
  - Embankment Slope (Steep/Medium/Flat)
  - Embankment Width (Wide/Medium/Narrow)
- Road Hazard Rating (1–7)
  - With Barrier
  - Without Barrier
- Presence of Ramble Strips (1-Yes; 0-No)
  - Reference Direction
    - Left Side
    - Right Side
  - Opposite Direction
    - Left Side
    - Right Side
- Image Data
  - Satellite View Date (e.g., 12/2007)
  - Street View Date (e.g., 08/2011)

**ix. Check for possible typos and errors.** Check for possible typos and errors for the entered information. Students assigned to guardrail barriers should continue to the next step to select a matched non-barrier segment. For other students, move to the next assigned milepost spot for barriers, and repeat Steps i to ix until the required number of segments have been selected. Make sure the standard for judging the segment's homogeneity holds constant and reasonable over the selected segments.

(NOTE: The following step applies only to students assigned to guardrail barriers.)

**Select the homogeneous segment for the non-barrier segment.** The objective of this step is to select a non-barrier homogenous segment to pair with its corresponding barrier segment already selected and recorded in the previous steps. Use the measure tool to help search for a spot one mile away from the assigned milepost for guardrail segment selection. Zoom into the spot and check for the presence of a barrier. If no barrier is found, then this spot is the milepost spot for the non-barrier homogeneous segment, for which Steps iii to ix are completed to finish the segment selection and recording procedure. Finally, move on to another assigned milepost spot for selecting a new set of barrier and non-barrier segments. If there is any barrier in this surrounding one-mile, then increase the searching distance by another one mile and check the barrier presence. Repeat the above procedure until a milepost spot without any barrier is found.

#### 4. Pictures for Roadside Hazard Rating



Clear zone greater than or equal to 30 ft; sideslope flatter than 1V:4H, recoverable.

**Figure A.1** Typical roadway with roadside hazard rating of 1 (Highway Safety Manual, 2010).

(Top: original picture; bottom: reproduced picture in Google Earth).



Clear zone between 20 and 25 ft; sideslope about 1V:4H, recoverable.

**Figure A.2** Typical roadway with roadside hazard rating of 2 (Highway Safety Manual, 2010).

(Top: original picture; bottom: reproduced picture in Google Earth).



Clear zone about 10 ft; sideslope about 1V:3H, marginally recoverable.

**Figure A.3** Typical roadway with roadside hazard rating of 3 (Highway Safety Manual, 2010).  
(Top: original picture; bottom: reproduced picture in Google Earth).



Clear zone between 5 and 10 ft; sideslope about 1V:3H or 1V:4H, marginally forgiving, increased chance of reportable roadside crash.

**Figure A.4** Typical roadway with roadside hazard rating of 4 (Highway Safety Manual, 2010).

(Top: original picture; bottom: reproduced picture in Google Earth).



Clear zone between 5 and 10 ft; sideslope about 1V:3H, virtually non-recoverable.

**Figure A.5** Typical roadway with roadside hazard rating of 5 (Highway Safety Manual, 2010).  
(Top: original picture; bottom: reproduced picture in Google Earth).



Clear zone less than or equal to 5 ft; sideslope about 1V:2H, non-recoverable.

**Figure A.6** Typical roadway with roadside hazard rating of 6 (Highway Safety Manual, 2010).

(Top: original picture; bottom: reproduced picture in Google Earth).



Clear zone less than or equal to 5 ft; sideslope about 1V:2H or steeper, non-recoverable with high likelihood of severe injuries from roadside crash.

**Figure A.7** Typical roadway with roadside hazard rating of 7 (Highway Safety Manual, 2010).

(Top: original picture; bottom: reproduced picture in Google Earth).

## APPENDIX B: VARIABLES EXTRACTED FROM CRASH REPORT

**No.Lanes.** The number of lanes in the vehicle travelling direction.

**Curve.** The indicator variable for the presence of a horizontal curve.

- 1 – A horizontal curve is present
- 0 – A horizontal curve is not present

**Intersection.** The indicator variable for the presence of any type of road junctions such as a four-way intersection, a T-intersection, a roundabout, and a ramp.

- 1 – An intersection is present
- 0 – An intersection is not present

**BarrierMS.** The collided barrier is in the median or along the roadside.

- M – The collided barrier is in the median
- S – The collided barrier is along the roadside

**BarrierLR.** The collided barrier is on the left or right to the vehicle.

- L – The collided barrier is on the vehicle's left
- R – The collided barrier is on the vehicle's right

**BarrierType.** The type of the collided barrier.

- BW – Barrier wall
- CB – Cable barrier
- G – Guardrail

**VehROR.** The indicator variable for whether or not the vehicle leaves the roadway at some point.

- 1 – The vehicle leaves the roadway
- 0 – The vehicle does not leave the roadway

**EventBefore.** The coded event that the vehicle is involved in BEFORE it leaves the roadway. See the event codes that followed.

**VehLR1.** The vehicle goes to the left or right side (relative to its travelling roadway) after it leaves the roadway.

- L – The vehicle goes to the left side relative to its travelling roadway.
- R – The vehicle goes to the right side relative to its travelling roadway.

**VehCM1.** The vehicle crosses the median and reaches the roadway in the opposite direction.

- 1 – The vehicle crosses the median
- 0 – The vehicle does not cross the median

**ROREvent1.** The category of event in which the vehicle is involved after it leaves the roadway.

- 1 – Hit a roadside barrier

- 2 – Hit a fixed roadside object
- 3 – Hit a moving roadside object (pedestrian, bicycle, another vehicle, etc.)
- 4 – Roll over and does not hit anything
- 5 – Does not roll over or hit anything on the roadside
- 6 – Other, please specify

**EventCode1.** The coded event that the vehicle is involved in AFTER it leaves the roadway. If there are multiple events involved, use blank space to separate those event codes. See the event codes that follow.

**State1.** The state of the vehicle after its run-off-road event.

- a – Comes to a stop on the roadside or in the median in its travelling direction
- a1 – Comes to a stop on the OPPOSITE roadside
- a2 – Comes to a stop on the OPPOSITE roadway
- b – Penetrates or rolls over the collided object
- c – Redirects back to the roadway and hits another vehicle
- d – Redirects back to the roadway and does not hit anything
- e – Other, please specify

**VehLR2, VehCM2, ROREvent2, EventCode2** and **State2** are required to be filled out only when the vehicle leaves the roadway again after it returns to roadway from the last run-off-road event.

### Entries for Event Coding

- 01 – Another Motor Vehicle
- 02 – Pedestrian
- 03 – Bicycle
- 04 – Railway Vehicle/Train/Engine
- 05 – Deer
- 06 – Animal Other Than Deer
- 07 – Animal Drawn Vehicle
- 15 – Overturn/Rollover
- 16 – Fire/Explosion
- 17 – Immersion
- 18 – Jackknife
- 19 – Cargo/Equipment Shift or Loss
- 20 – Off Roadway
- 21 – Fell from Vehicle (Non Collision)
- 30 – Impact Attenuator/Crash Cushion
- 31 – Bridge Overhead Structure
- 32 – Bridge Pier or Abutment
- 33 – Bridge Parapet End
- 34 – Bridge Rail
- 35 – Guardrail Face
- 36 – Guardrail End
- 38 – Highway Traffic Sign Post
- 39 – Overhead Sign Post
- 40 – Light/Luminaire Support
- 41 – Utility Pole
- 42 – Other Post/Pole or Support
- 43 – Wall/Building/Tunnel
- 44 – Work Zone Maintenance Equipment
- 45 – Embankment

46 – Curb  
47 – Ditch  
48 – Culvert  
49 – Fence  
50 – Mailbox  
51 – Tree  
52 – Other – Explain in Narrative

54 – Equipment/Mechanical Failure  
55 – Downhill Runaway  
56 – Separation of Units  
57 – Thrown or Falling Object  
58 – Parked Motor Vehicle  
60 – Cable Barrier  
61 – Concrete Traffic Barrier

## About the Joint Transportation Research Program (JTRP)

On March 11, 1937, the Indiana Legislature passed an act which authorized the Indiana State Highway Commission to cooperate with and assist Purdue University in developing the best methods of improving and maintaining the highways of the state and the respective counties thereof. That collaborative effort was called the Joint Highway Research Project (JHRP). In 1997 the collaborative venture was renamed as the Joint Transportation Research Program (JTRP) to reflect the state and national efforts to integrate the management and operation of various transportation modes.

The first studies of JHRP were concerned with Test Road No. 1—evaluation of the weathering characteristics of stabilized materials. After World War II, the JHRP program grew substantially and was regularly producing technical reports. Over 1,500 technical reports are now available, published as part of the JHRP and subsequently JTRP collaborative venture between Purdue University and what is now the Indiana Department of Transportation.

Free online access to all reports is provided through a unique collaboration between JTRP and Purdue Libraries. These are available at: <http://docs.lib.purdue.edu/jtrp>

Further information about JTRP and its current research program is available at: <http://www.purdue.edu/jtrp>

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