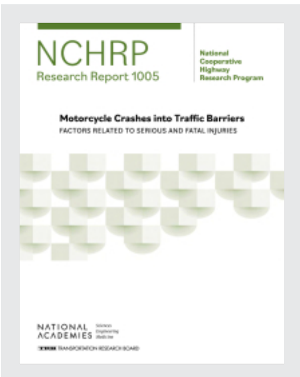

Motorcycle Crashes into Traffic Barriers: Factors Related to Serious and Fatal Injuries (2022)

DETAILS

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 1005

Motorcycle Crashes into Traffic Barriers

FACTORS RELATED TO SERIOUS AND FATAL INJURIES

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2022

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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FOREWORD

By David M. Jared
Staff Officer
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NCHRP Research Report 1005 provides support for implementation of motorcyclist protection systems (MPS) in the United States. MPS are traffic barriers specifically designed to mitigate the consequences of a motorcycle-barrier impacts and typically fall into two categories: (1) devices that reduce the severity of impacts with barrier posts through post redesign or shielding, and (2) devices that prevent impact with barrier posts by the addition of a lower rail element or redesign of the rail element. While MPS are used internationally, only a small number of MPS pilot installations are currently present in the United States. The findings of this report confirm an elevated injury risk for motorcyclists in collisions with traffic barriers and support implementation of MPS via the following: (a) development of a motorcycle-barrier crash test that considers rider orientation and injury; (b) conducting a motorcycle-barrier test with roadside hardware; (c) evaluating MPS using four-wheeled vehicles; (d) evaluating the performance of existing MPS pilot installations; and (e) developing methods to determine where to locate MPS.

Guidelines on how to reduce the risk of injury for motorcyclists in collisions with traffic barriers do not currently exist. MASH crash test procedures, which have been successful in ensuring safer barrier designs for cars and light trucks, do not prescribe a crash test procedure for motorcycles. Most research on MPS or motorcycle-barrier crash testing has been conducted outside the United States, and little has been published in recent years on the characteristics of motorcycle-barrier crashes in the United States or on potential solutions.

Under NCHRP Project 22-26, "Factors Related to Serious Injury and Fatal Motorcycle Crashes with Traffic Barriers," Virginia Tech was asked to identify factors that contribute to serious and fatal injury in motorcycle-barrier collisions. A focus was on guardrail, concrete, and cable barrier collisions, and factors that influence injury. Data analyzed included national and state crash data, state crash data matched with hospital records or roadway data, and 22 in-depth motorcycle-barrier crashes collected during the project. The available data was used to investigate national motorcycle fatality risk by object struck, injury risk by barrier type, rider post-impact trajectory, associated roadway characteristics, specific injuries sustained, and injury mechanisms. The findings confirm an elevated injury risk for motorcyclists in collisions with traffic barriers and support implementation of MPS in the United States.

The conduct of research report is provided in *NCHRP Research Report 1005* and the report appendices in *NCHRP Web-only Document 327: Serious and Fatal Motorcycle Crashes into Traffic Barriers: Injury Information*. These materials are available on the National Academies Press website (www.nap.edu) and can be found by searching for *NCHRP Research Report 1005: Motorcycle Crashes into Traffic Barriers: Factors Related to Serious and Fatal Injuries.*

CONTENTS

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

SUMMARY

Motorcycle Crashes into Traffic Barriers: Factors Related to Serious and Fatal Injuries

Research Findings

Motorcycle riders account for more fatalities than the passengers of any other vehicle type involved in a guardrail collision. In 2018, motorcycle riders accounted for 40% of all fatalities resulting from a guardrail collision. Following motorcycle riders, car occupants accounted for 31% of all fatalities in this crash mode. This is particularly surprising as cars compose approximately half of the vehicle fleet (46%), while motorcycles comprise only 3% of the registered vehicles (Figure S-1). In terms of fatalities per registered vehicle, motorcycle riders are overrepresented in the number of fatalities resulting from guardrail impacts.

There are currently no guidelines available to U.S. transportation agencies, policymakers, or engineers for how to reduce the risk of injury to motorcyclists who strike traffic barriers. MASH crash test procedures, which have been so successful in ensuring safer barrier designs for cars and light trucks, do not prescribe a crash test procedure for motorcycles. Most research in the area of motorcyclist-friendly barrier or motorcycle-barrier crash testing has been conducted in either Europe or Asia. Little has been published in recent years on the characteristics of motorcycle-barrier crashes in the United States or on potential solutions.

The objective of this research program was to identify factors that contribute to serious and fatal injury in motorcycle collisions with traffic barriers. The focus of this project was on collisions with guardrails, concrete barriers, and cable barriers, and the factors that influence injury, given that a crash has occurred. The longer-term goal is to establish priorities for U.S. transportation agencies and roadside safety engineers seeking to remediate the injury and fatality risk of motorcyclist-barrier collisions.

Constraints on Injury Mitigating Strategies

It is important to emphasize that motorcyclist-barrier fatalities should not be reduced at the expense of passenger car occupants who are involved in barrier collisions. Guidelines such as MASH and *NCHRP Report 350: Recommended Procedures for the Safety Performance Evaluation of Highway Features* (1993) have described ways of safely redirecting errant vehicles onto the road without undue occupant risk. Cable barrier or any other type of barrier should not be removed just to protect motorcyclists. Rather what is needed are barrier designs, safety programs, and research that can extend the safety record of barrier performance in car collisions to also encompass motorcyclists. The goal is to develop methods that can better protect motorcyclists without reducing the benefits of traffic barriers for passenger vehicle occupants.

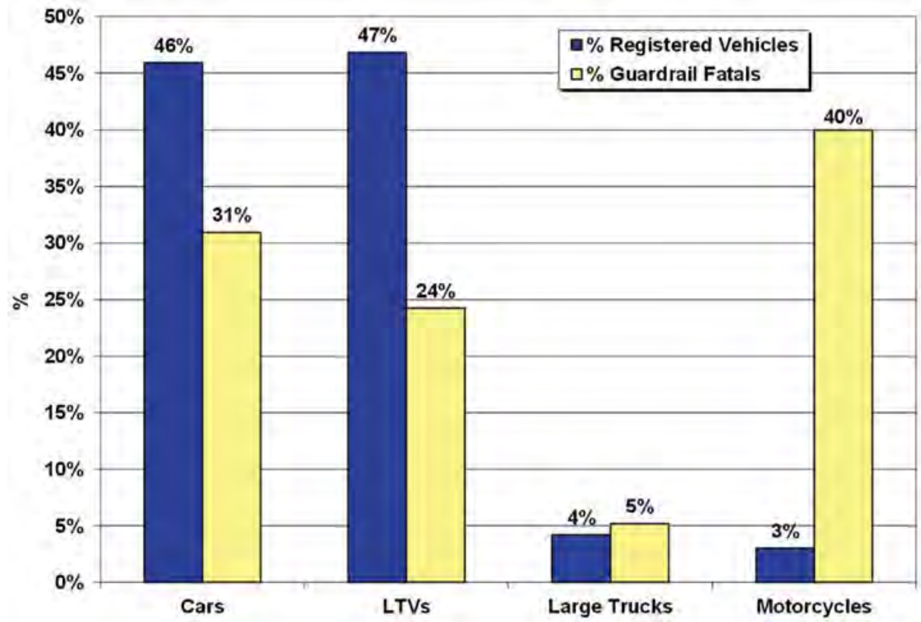


Figure S-1. Guardrail fatalities by vehicle type (FARS 2018).

Analysis of Fatal Motorcycle-Guardrail Crashes in the United States

Fatal crash trends in the United States were investigated to determine where fatal guardrail crashes were most likely to occur as compared to all fatal motorcycle crashes. For this study, data from the Fatality Analysis Reporting System (FARS) from 1999 to 2008 were analyzed. Over this time period, there were 38,276 fatal motorcycle crashes involving 39,468 fatally injured motorcycle riders and passengers. There were 1,759 fatal motorcycle-guardrail crashes over the same time period, fatally injuring 1,803 motorcycle riders and passengers, an average of 180 fatalities each year.

Fatality Risk in Roadside Motorcycle Crashes in the United States

Guardrails and other barriers are not the only obstacles on the roadside. Although this study focused primarily on barrier collisions, other roadside objects also pose a great risk to motorcyclists. This component of the study investigated the national risk of fatality in collisions with trees, signs and poles, guardrails, and concrete barriers. The FARS data from 2004 to 2008 was used to determine the number of fatalities in each collision mode, and the National Automotive Sampling System (NASS) General Estimates System (GES) data was used to estimate the total number of crashes in each collision mode. This analysis was based on more than 3,600 fatal motorcycle crashes with roadside objects and an estimated total of nearly 20,000 crashes with roadside objects. Risk of motorcycle collision with roadside objects was compared to that of single-vehicle motorcycle collisions where the motorcycle did not strike anything except for the ground.

Motorcycle crashes with roadside objects resulted in a greater risk of fatal injury than collisions with the ground. Based on the most harmful event reported in the crash, motorcycle collisions with a guardrail were 7.2 times more likely to be fatal than collisions with the ground. Collisions with a concrete barrier were 4.1 times more likely to be fatal than collisions with the ground. This is an early indication of the importance of barrier design. The risk of fatality in a guardrail collision is nearly double that of a collision with a concrete barrier.

A crucial point to consider is the potential consequences of collisions with what the barrier was shielding. Collisions with trees had a fatality risk nearly 15 times greater than the fatality risk in collisions with the ground. Thus, if a motorcyclist crashes into a barrier in place to protect users from roadside trees, the barrier is likely to have reduced injury severity. Though there is no way to determine what the injury severity would have been had the motorcyclist struck the tree, a collision with a tree may have been a more severe crash than if the rider struck the guardrail.

Serious Injury Versus Barrier Design

One key aspect of this research program was to determine whether some barrier designs are safer than others. Are cable barriers more dangerous than other barrier types? The initial study of fatality risk showed the importance of design: guardrail barrier collisions carried a greater risk of fatality than concrete barrier collisions. This question was further investigated by analyzing barrier crashes of all injury severities in three states: North Carolina, Texas, and New Jersey. The analysis dataset contained 1,000 riders involved in barrier crashes in the three states. Of these, 581 cases were involved in W-beam crashes, 367 cases were involved in concrete barrier crashes, and 52 cases were cable barrier crashes.

This study found that W-beam guardrails had significantly higher odds of serious (K+A) injury than concrete barriers. This is consistent with the earlier analysis of fatality risk. The odds of serious injury in crashes with a W-beam guardrail were about 1.4 times greater than those in crashes with a concrete barrier. There was no evidence to show that cable barrier posed an increased risk to motorcyclists than either W-beam or concrete barrier. However, the sample of cable barrier crashes was small compared to the sample of W-beam and concrete barrier crashes. This initial analysis showed no elevated risk of serious injury in cable barrier crashes. However, further investigation is needed to demonstrate if this finding is a result of the dataset used or is representative of most crashes.

Rider Post-Impact Trajectory and Injury Outcome in Barrier Crashes

The objective of this study was to characterize the rider orientation and post-impact trajectory in a barrier collision and determine how this orientation influences the injury outcome. The international literature is not consistent on this basic question. Far from being an academic issue, resolution of this question is needed both to design a representative crash test (should the rider slide into the barrier or be upright?) and to determine priorities for countermeasure design (is post padding or reducing the sharp upper edge of the W-beam more important?).

Rider trajectories in barrier collisions were determined through an analysis of police accident reports (PARs) of motorcycle-barrier crashes in New Jersey from 2007 to 2011. In a motorcycle-barrier collision, the rider will frequently separate from the motorcycle and the two may follow different trajectories. Post-impact trajectory is defined as the trajectory taken by the rider after the motorcycle collides with or contacts the road, barrier, or other object. Seven different trajectory types were identified: upright, sliding, vaulting, ejected (same side landing), ejected (side unknown), ejected into barrier, and separated prior to barrier impact. Of the 442 single-vehicle, motorcycle-barrier collisions reported in New Jersey, the PAR was analyzed for 430 crashes and the barrier was identified for 342 of these crashes (77.4% of all crashes).

The majority of riders in this study (68.0%) in single-vehicle barrier crashes collided with the barrier while upright. Another 20.0% of riders slid into the barrier. The findings show a higher prevalence of upright collisions and lower estimates for the prevalence of sliding collisions compared to studies in Europe and Australia. Some of the differences may be regional in nature since this study looks at U.S. crashes, whereas previous studies have analyzed crashes in Europe and Australia.

Analysis of Injuries from Roadside Collisions in Maryland

Motorcycle-to-barrier collisions were characterized through retrospective studies of national and state crash databases. These studies can quantify the number of motorcyclists seriously or fatally injured, but do not directly answer the question of how motorcyclists are being injured. To identify the opportunity for design improvements to the roadside to reduce the severity of these crashes, the injuries incurred must first be better understood.

To determine the type, relative frequency, and severity of injuries incurred in motorcycle roadside crashes, the Crash Outcome Data Evaluation System (CODES) was used to analyze motorcycle crashes in Maryland from 2006 to 2008. CODES links police-reported crashes to hospital data, providing detailed information about injuries incurred during collisions. This study focused on four types of motorcycle crash modes: single-vehicle barrier crashes, single-vehicle fixed-object crashes, multi-vehicle crashes, and single-vehicle overturn-only crashes. The analysis was based on injury and crash data for 1,707 motorcyclists involved in these four crash modes.

The thorax was the most frequently seriously injured body region in all types of motorcycle crashes, with the exception of multi-vehicle crashes. Additionally, motorcyclists involved in barrier crashes were about two times more likely to suffer a serious injury to the thoracic region than motorcyclists not involved in barrier collisions. The most common injury for motorcyclists involved in barrier collisions was a lung contusion, whereas the most common injury for motorcyclists not involved in barrier collisions was a hemothorax or pneumothorax. The most commonly injured regions for all motorcycle crashes were the upper and lower extremities. Over 70% of motorcyclists involved in the crashes analyzed suffered an injury to the upper and/or lower extremities. Though extremities were the most commonly injured region, they were less likely to be seriously injured compared to other body regions.

Roadway Characteristics Associated with Motorcycle Crashes into Longitudinal Barriers and the Influence on Rider Injury

This study provides an analysis of roadway and specific geometric characteristics associated with motorcycle-to-barrier crashes in two states based on 1,511 crashes occurring in Washington and Ohio. Motorcycle impacts with barriers were found to be overrepresented on horizontal curves and on sections with grade in excess of 3% in comparison to all single-vehicle motorcycle and all multiple-vehicle motorcycle crashes. Similar to previous studies, these crashes also were found to be overrepresented on ramp sections. Based on the available curvature data, however, the sole recommendation in the available published literature to place potential motorcycle-to-barrier crash countermeasures on curves with a radius less than 820 ft may not be prudent in U.S. states as less than 40% of these crashes occur on these curves. Although there were a number of similarities in motorcycle-to-barrier roadway characteristics between the two analyzed states, large differences were found in areas, including roadway configuration (e.g., divided or undivided) and posted speed limit.

Rider characteristics, such as helmet usage and alcohol involvement, were found to have a larger influence on injury severity in comparison to associated roadway characteristics. Whether or not the roadway was divided was found to be the roadway characteristic having the largest influence on rider injury. The developed models suggest that horizontal curves, vertical grades less than 3%, posted speed limits greater than 45 mph, and traffic volumes less than 10,000 vehicles per day increase rider injury risk, although these results were not statistically significant.

In-Depth Investigation of Injury Mechanisms

To determine injury mechanisms in motorcycle-to-barrier crashes, Virginia Tech collaborated with Wake Forest Baptist Medical Center (Winston-Salem, NC) to conduct a series of in-depth crash investigations of motorcyclist-barrier collisions. Cases in this study were identified and enrolled by Wake Forest Baptist Medical Center (Winston-Salem, NC) from patients involved in single-vehicle motorcycle crashes with roadside barriers who were admitted to their Level 1 trauma center.

The study investigated 21 serious motorcycle-to-barrier crashes, involving 22 riders. In these crashes, the most common regions to suffer the most serious injury were the head, lower extremities, and thorax. The thorax suffered the greatest number of serious injuries. The extremities suffered the most injuries; however, these tended to be less severe than injuries in other body regions. These findings are consistent with those presented in the Maryland CODES study and Australian research.

In most of the crashes investigated, the guardrail prevented the rider from a potentially more hazardous collision with trees. As found in the earlier study on fatality risk, collisions with trees carry a higher fatality risk than collisions with guardrail. Additionally, in several of the cases, the guardrail likely prevented the rider from traveling over a cliff or embankment. Though guardrail collisions are severe, removing the barriers is not the solution to the problem.

The study has shown that the primary injury mechanisms in the sample were (1) rider entanglement with posts; (2) lacerations from top of posts – both W-beam and cable barrier; and (3) laceration from the top of W-beam rail. Of note are the observations on cable barrier (i.e., wire-rope barrier) collisions. Despite the concern of laceration injuries by motorcyclists contacting wire-rope barriers, we found no evidence of laceration injuries from the wire rope in these systems. Injuries were found in collisions with wire-rope barrier, but the injuries resulted from contact with the posts rather than with the wire rope. This clinical finding is consistent with the conclusions from the bulk accident study conducted using state crash data that found no statistically significant difference between the injury risk of W-beam and cable barrier, both systems supported by unprotected posts.

Existing Motorcyclist Protection Systems for Motorcycle-Barrier Crashes

Several potential countermeasures currently exist to mitigate the consequences of a motorcycle-barrier impact. These devices, typically referred to as motorcyclist protection systems (MPS), generally fall into two categories: (1) devices that reduce the severity of post impact through post redesign or shielding, and (2) devices that prevent impact with the post by the addition of a lower rail element or redesign of the rail element. These MPS have been installed in multiple locations in both Europe and Australia.

Publications on testing experience with these devices are relatively limited. This was especially true for evaluating the effect that these countermeasures might have on passenger vehicle impacts. The publications available on the performance of these devices indicate that they are likely to reduce the severity of motorcycle-barrier crashes.

Two pilot tests of MPS have been conducted to date in the United States. California Department of Transportation (Caltrans) conducted the first and North Carolina Department of Transportation (NCDOT) conducted the second. Both pilot tests used Lindsay Transportation System's DR-46 Barrier Attenuator system.

Crash Tests Options for MPS

There are currently four crash test procedures for evaluating MPS: the French LIER procedure, the German BASt procedure, the Spanish UNE 135900 procedure, and the European Technical Specification CEN TS 1317-8. The most widely accepted procedure is the European Technical Specification CEN TS 1317-8, which specifies a full-scale crash test to evaluate the performance of MPS affixed to a longitudinal barrier. The CEN TS 1317-8 test is designed to emulate the situation in which a rider leaves the motorcycle and slides along the ground into a barrier. In this test, an anthropomorphic test dummy (commonly referred to as a crash test dummy) is slid at an angle into the barrier at either 60 or 70 km/h. The test prescribes limits on loads to the head and neck of the dummy. Currently, CEN TS 1317-8 does not prescribe a test for motorcyclists who strike the barrier in an upright position, which is estimated to account for more than 50% of all collisions.

Next Steps

This study is one of the first in the United States to investigate the factors leading to serious injury in motorcycle collisions with a roadside barrier. The United States currently does not provide transportation agencies or the roadside safety community any guidelines on how to reduce the risk of injury for motorcyclists in collisions with traffic barriers. This report has discussed the elevated risk faced by motorcyclists who experience these collisions, the efforts undertaken by regulators in Europe and Australia to address this issue, the design of production MPS, and potential crash tests to evaluate the crash performance of these countermeasures.

Based on these findings, this study suggests the following next steps:

- Evaluate the field performance of U.S. pilot tests of MPS. Two pilot tests of MPS have been conducted to date in the United States. Caltrans conducted the first test and NCDOT the second. Both pilot tests used Lindsay Transportation System's DR-46 Barrier Attenuator system. Evaluation of the field performance of these pilot programs should be conducted in terms of motorcycle and four-wheeled vehicle safety, installation experience, and the practicality and costs of maintaining these systems.
- Evaluate the EN 1317-8 test in the United States. The most widely accepted motorcycle-barrier crash test procedure is the European Technical Specification CEN TS 1317-8. This test simulates the crash performance of MPS affixed to a longitudinal barrier. This test should be conducted on U.S. roadside hardware that has been evaluated using MASH test procedures, to check the performance of U.S. hardware in this crash mode and to evaluate the test procedure itself.
- Evaluate the crash performance of MPS for four-wheeled vehicles. One obstacle to widespread retrofit of MPS to existing barrier systems is the crash performance of these retrofit systems for four-wheeled vehicles has not been determined. It is important that the successful crash performance of traffic barriers should not be reduced by the installation of retrofits to protect motorcyclists. The suggestion is to evaluate the performance of

MPS-equipped barriers in standard MASH crash tests using four-wheeled vehicles (e.g., small cars and pickup trucks).

- Develop a MASH motorcyclist crash test. MASH currently does not prescribe a crash test for motorcyclists striking roadside hardware. Adoption of the European EN 1317-8 test is one option. There may be regional differences, however, that may require that other crash test options should be considered as well. For example, this NCHRP project has estimated that riders striking a barrier upright occurs much more frequently in the United States than what is suggested by studies in Europe. An MPS test that uses an upright rider should be developed. Development of a new test should consider an enhanced MPS test that evaluates the risk to the thorax and lower extremities, which this study has shown to be the most frequently seriously injured body regions.
- Considerations for the AASHTO Roadside Design Guide. Potential additions to the AASHTO Roadside Design Guide should be considered for how to locate longitudinal barriers that incorporate the differences between the road departures of four-wheeled vehicles and motorcyclists. Factors in the development of these guidelines would be differences in trajectories, departure angle, departure speed, and the magnitude of evasive maneuvers (e.g., braking). NCHRP Project 17-88, which is characterizing motorcycle roadside departures in comparison to four-wheeled vehicle departures, may provide useful guidelines for this evaluation.
- Develop methods to determine where to locate MPS. The installation of MPS carries a cost, and should be considered where it would be more beneficial. Potential methods for determining suitable MPS locations include traditional hot-spot methods or the empirical Bayes methods used in the FHWA Highway Safety Manual. Cost-benefit methodologies for MPS location should be developed.

This study has important implications for U.S. federal and state transportation agencies seeking ways to reduce the risk of serious-to-fatal injury for motorcyclists. The findings show the need for the adoption of MPS that either pad or shield the posts to prevent motorcyclist entanglement and protect riders from laceration from the tops of rails and posts. MPS implemented in Europe and Australia have tremendous potential to mitigate injuries in barrier collisions. This research program has shown the need for MPS in the United States, the feasibility of these systems, and their potential safety benefit for U.S. motorcyclists. After a thorough evaluation of MPS in crash testing and pilot testing in the United States, MPS could be considered for implementation on U.S. roadways.

CHAPTER 1

Introduction

Motorcyclists are vulnerable highway users. Unlike passenger vehicle occupants, motorcycle riders have neither the protective structural cage nor the advanced restraints commonplace in passenger cars and light trucks. Motorcyclists are at particular risk in collisions with traffic barriers. Approximately one out of every eight motorcyclists who strike a guardrail and one in 12 who collide with a concrete barrier are killed. By contrast, one in 20 motorcyclists who collide with passenger vehicles are fatally injured (Gabler 2007).

Motorcycle riders account for more fatalities than the passengers of any other vehicle type involved in a guardrail collision. In 2018, as shown in Figure 1-1, motorcycle riders accounted for 40% of all fatalities resulting from a guardrail collision. Following motorcycle riders were car occupants, with 31% of all fatalities in this crash mode. This is particularly surprising as cars compose approximately half the vehicle fleet (46%) while motorcycles comprise only 3% of registered vehicles. In terms of fatalities per registered vehicle, motorcycle riders are over-represented in the number of fatalities resulting from guardrail impacts.

1.1 Consideration of Barrier Types

The three most common types of traffic barriers in the United States are depicted in Figure 1-2. W-beam guardrail is the most common type of barrier used in the United States. Concrete barriers are the second most commonly used barrier in the United States, often used to divide highways, particularly when there is little to no room for a median. Since they do not deflect great distances, concrete barriers can retain vehicles without allowing encroachment of the barrier or vehicle into opposing traffic. Lastly, cable barrier is being installed at a rapid rate in the United States. Cable barrier presents a relatively inexpensive option for shielding medians and is highly effective at preventing cross-median crashes.

Although these barrier systems have been highly effective at protecting the occupants of cars and trucks, examination of both U.S. accident and international crash data has shown barrier collisions to be the source of serious to fatal injuries for motorcyclists. New barrier designs are being implemented in Europe to reduce this risk for motorcyclists while retaining the life-saving benefits for occupants of four-wheeled vehicles.

Need for In-depth Motorcycle-Barrier Crash Data

Before the motorcycle-barrier problem can be addressed, there is a critical need to better understand the nature of the problem. Unlike passenger cars, however, there is virtually no in-depth crash investigation data describing motorcycle crashes. The most in-depth study, the Hurt report (Hurt, Ouellet, and Thom 1981a), is based upon crash data more than 25 years old

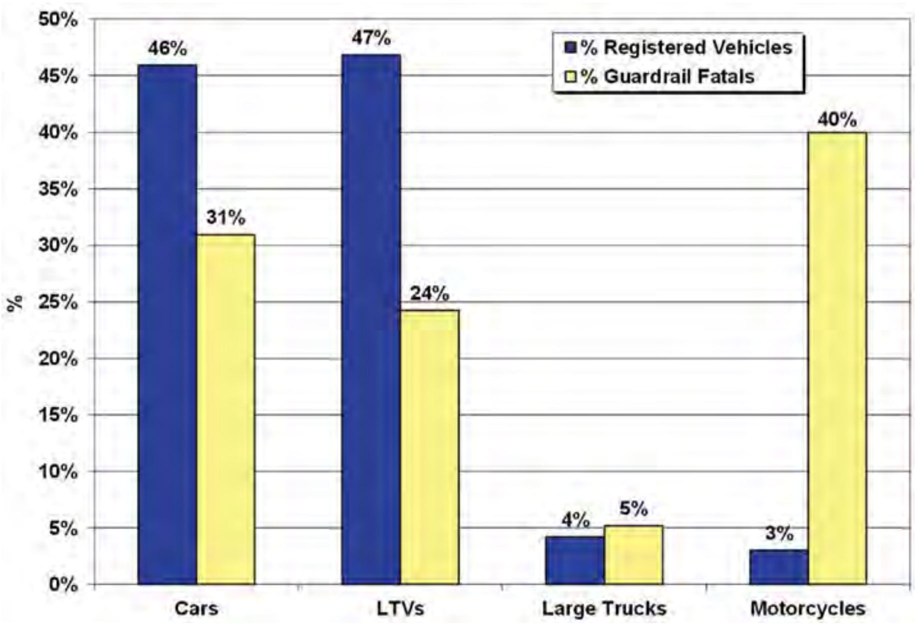


Figure 1-1. Guardrail fatalities by vehicle type (FARS 2018).

and no longer adequately reflects either the motorcycles or barriers currently on the highways. Needed is a new in-depth investigation of serious and fatal motorcycle crashes into roadside barriers that determines the characteristics of the operator, barrier, motorcycle, and roadway that control the incidence and outcome of motorcycles crashes.

Cable barrier provides an effective barrier system (Grzebieta et al. 2009; McClanahan et al. 2003; Sposito and Johnston 1998) that is sometimes questioned due to this lack of in-depth accident data. Cable barrier has been perceived as a particular laceration threat to motorcyclists (Hammond and Batiste 2008). In the United States and overseas, groups have actively lobbied for a ban on this type of barrier. To date, however, there is little evidence to support or refute the claims that cable barrier is more dangerous than W-beam barrier.

Likewise, the lack of accident data prevents any understanding of injury mechanisms in motorcycle-barrier collisions. Impacts into guardrail have been found to be much more dangerous than impacts into concrete barrier. It has been theorized that this difference in fatality risk may be due to the fact that guardrail posts carry an extra risk to motorcyclists. Under

(A) (B) (C)

Figure 1-2. Barrier types: (A) W-beam guardrail, (B) concrete barrier, and (C) cable barrier.

this theory, there is a need to pad or otherwise protect the motorcyclist from the posts. Without in-depth crash investigations, it is not possible to determine whether this theory is correct.

Constraints on Injury-Mitigating Strategies

It is important to emphasize that motorcyclist-barrier fatalities should not be reduced at the expense of passenger car occupants involved in barrier collisions. Guidelines such as MASH and *NCHRP Report 350* have described ways of safely redirecting errant vehicles onto the road without undue occupant risk. Cable barriers or any other type of barrier should not be removed just to protect motorcyclists. Rather, what is needed are barrier designs, safety programs, and research that can extend the safety record of barrier performance in car collisions to encompass motorcyclists. This research program will develop recommendations for methods that can better protect motorcyclists without reducing the benefits of traffic barriers for passenger vehicle occupants.

Theories on Motorcycle-Barrier Crash Injury Mechanisms

There are many theories about the injury mechanisms in motorcycle-barrier crashes, but little data to check the validity of these theories. Following is a list of the questions this research project seeks to answer and better understand.

- FARS analysis indicates that motorcyclist collisions with concrete barriers are significantly less lethal than collisions with metal guardrail. The theory is that this is due to entanglement with the posts. Is this true?
- Are guardrail fatalities caused by motorcyclists vaulting over the barrier or sliding into the barrier? One theory is that injuries are caused by entanglement in posts. What evidence is there for this theory?
- How does fatality and injury risk vary by barrier type?
- Motorcyclists are particularly concerned about injuries from cable barriers. How does the risk of cable barrier injury compare with other traffic barriers (e.g., guardrail or concrete barriers)? Is there a difference in risk? If so, why? If not, why not?
- What types of injuries occur in motorcycle-barrier crashes: head, chest, lower extremity?
- In traffic barrier crashes, is the motorcyclist already seriously or fatally injured by contact with the ground or other objects prior to impact with the barrier? Is the barrier actually the most harmful event?
- Changes in the post shape have been proposed as an injury countermeasure. Is there any evidence of the I-beam edges cutting the rider?
- What roadway geometries are associated with the incidence of motorcycle crashes with traffic barriers?

1.2 Research Problem Statement

The research problem statement, as outlined in the Statement of Work for the project, states

> Although limited, research appears to indicate that motorcycle riders are overrepresented in the number of serious injuries and fatalities resulting from guardrail impacts. Not much is known about impacts with other types of traffic barriers (e.g., concrete barriers, cable barriers, bridge rails, crash cushions, and end terminals). Many factors related to motorcycle crashes make analysis difficult, for example:
>
> - Motorcycle usage, roadway design, and crash data collection practices differ among states.
> - Typical coding on crash reports may not reflect the actual sequence of events and cause of injury. It may be unclear if both the motorcycle and the motorcyclist impacted the barrier or if the motorcyclist separated from the motorcycle prior to striking the barrier.
> - Impact with the barrier may not have been the most harmful event.

There is virtually no in-depth analysis of data describing motorcycle crashes involving traffic barriers in the United States. This lack of crash data analysis prevents understanding injury mechanisms in motorcycle-barrier crashes. As such, an in-depth investigation is needed of serious injury and fatal motorcycle crashes involving traffic barriers.

1.3 Objectives and Scope

The objective of this research project was to identify factors that contribute to serious and fatal injury in motorcycle collisions with traffic barriers. The focus of this project was on collisions with the following types of traffic barriers: guardrails, concrete barriers, and cable barriers. The study focused on factors that influence injury, given that a crash has occurred. The focus was not on operator behavior, training, or human factors that lead to the crash.

To accomplish these objectives, the study was delineated into two phases containing the following seven tasks:

Phase I

1. Conduct a relevant literature review including current and ongoing international research in the European Union, New Zealand, and Australia.
2. Develop a list of crash characteristics for all reportable crashes (may include all severity levels: property damage, injury, and fatal crashes) involving motorcycles and/or motorcyclists and traffic barriers. For each characteristic, identify potential data source(s).
3. Develop a revised work plan for Phase II that will quantify the factors contributing to serious injury and fatal motorcycle collisions with traffic barriers.
4. Submit an interim report that provides the results of Tasks 1 through 3.
5. Meet with the NCHRP panel to review the Task 4 interim report approximately 1 month after its submittal. Submit a revised interim report addressing the panel's review comments.

Phase II

6. Execute the approved Phase II work plan to quantify factors contributing to serious injury and fatal motorcycle collisions with traffic barriers. Quarterly progress reports shall include incremental reports of technical progress.
7. Submit a final report documenting the entire research effort. The final report should document limitations on analysis and sources of data. It should also suggest recommended injury-mitigating strategies and cite needs for future research.

CHAPTER 2

Research Approach

The objective of this research program was to identify factors that contribute to serious and fatal injury in motorcycle collisions with traffic barriers. The research approach was composed of three components: (1) synthesis of current U.S. and international literature on serious injury and fatal motorcycle crashes into traffic barriers, (2) analysis of national and state crash databases, and (3) in-depth investigations of motorcycle-barrier crashes. This chapter describes each of these three components. Detailed findings are presented in the chapters that follow in this report.

2.1 Synthesis of Current U.S. and International Literature

This task synthesized national and internationally published literature on the characteristics of serious injury and fatal motorcycle crashes into traffic barriers. The literature review was divided into the following subtasks: (1) international literature review, (2) U.S. literature review, (3) analysis of published reports on international motorcycle crash data, e.g., the Motorcycle Accidents In-Depth Study (MAIDS) database, and (4) survey of ongoing research on motorcycle-barrier crashes.

To date, motorcycle crashes have received greater attention in Europe, Australia, and New Zealand than in the United States. The research team performed a comprehensive literature review of existing international literature pertaining to the characteristics of serious injury and fatal motorcycle crashes into traffic barriers. During this task the research team reviewed the U.S. literature on the motorcycle-barrier crash issue to compare and contrast the extent of the issue in the United States with international experience. The literature review focused on published studies of the motorcycle-barrier collision problem, injury mechanisms, data collection methodologies, and potential countermeasures that have been conducted internationally and in the United States.

The literature review was supplemented with published crash data analysis from MAIDS. MAIDS is the most comprehensive in-depth data currently available for powered two-wheelers (PTWs) accidents in Europe. The investigation was conducted during 3 years on 921 accidents from five countries using a common research methodology.

2.2 Analysis of National and State Crash Databases

This subtask will analyze U.S. accident databases to determine the characteristics of the motorcycle-barrier collision problem in this country. Included will be (1) the FARS fatal crash database, (2) state accident data, and (3) the CODES database, which links state accident data with hospital injury records. The research team analyzed these databases to refine the understanding of the motorcycle-barrier crash characteristics that lead to serious injury or fatality. Each database is briefly described below.

- FARS is a census of all traffic related fatalities in the United States from 1975 to the present (NHTSA 2018a). FARS is maintained by the NHTSA, and includes records of the approximately 30,000–40,000 fatalities that occur on U.S. highways each year. FARS contains records of traffic fatalities in all vehicle types and crash modes (i.e., cars, light trucks, heavy trucks, bicyclists, motorcyclists, and pedestrians). In this research program, FARS was used to determine the characteristics of fatal crashes.
- NASS GES contains information on approximately 60,000 randomly sampled police-reported crashes each year (NHTSA 2018b). Cases from GES are assigned weights that can be used to estimate the number of similar non-sampled crashes that may have occurred that year. GES was used in this research to obtain an estimate of the national exposure of motorcyclists to barrier crashes across all severities from property damage only to fatal injury.
- State accident databases contain a complete record of all police-reported crashes. For this research, several different state databases were used to analyze risk of severe injury. Motorcycle crashes in six different states were investigated: (1) New Jersey, (2) Texas, (3) North Carolina, (4) Maryland, (5) Ohio, and (6) Washington. Data from New Jersey, Texas, and Maryland were obtained directly from each state. The data from North Carolina, Ohio, and Washington were obtained through the Highway Safety Information System (HSIS). HSIS is a multi-state database that contains information about crashes and roadways.
- CODES collects and combines crash and medical data from the crash scene and the emergency department, hospital, or trauma center. CODES was used to analyze 3 years of motorcycle collisions, from 2006 to 2008. Data sources for the Maryland CODES included police records, emergency medical services, emergency departments, and toxicology reports (NHTSA 2010). CODES data is the result of linking datasets using a probabilistic method. Injury data was reported in CODES using the International Classification of Disease 9th Revision Clinical Modification (ICD-9-CM) (NCHS 2008). The ICD-9-CM codes were converted to their respective Abbreviated Injury Scale (AIS) 90 codes to obtain measures of threat to life. CODES was used in this research to investigate the distribution of motorcyclist injuries on a body-region basis.

2.3 In-Depth Investigations of Motorcycle-Barrier Crashes

2.3.1 Overview

The preceding components of the research were conducted to determine the factors associated with the risk of serious-to-fatal injury in motorcycle-barrier crashes. Although these crash databases were invaluable to explore crash injury risk factors, none of these datasets contained sufficient information needed to elucidate detailed injury causation mechanisms. The final component of the research was to conduct in-depth investigations of motorcycle-barrier crashes that involved serious injuries in motorcycle collisions with a roadside barrier. The second objective was to determine the causes of those serious-to-fatal injuries. In collaboration with the Level 1 trauma center at the Wake Forest Baptist Medical Center, the approach was to identify and investigate cases of seriously injured motorcyclists admitted to the trauma center after experiencing a collision with a roadside barrier.

The Wake Forest Baptist Medical Center is located in North Carolina. With over 500 miles of cable barrier, North Carolina is one of the heaviest users of cable barrier in the United States, and an ideal real-world "laboratory" to evaluate the outcome of motorcyclist-cable barrier crashes. Because North Carolina has even more miles of W-beam barrier, collection of crash data from cable and W-beam barrier collisions will allow the research to directly evaluate whether cable barrier poses an elevated risk in a motorcycle-barrier collision.

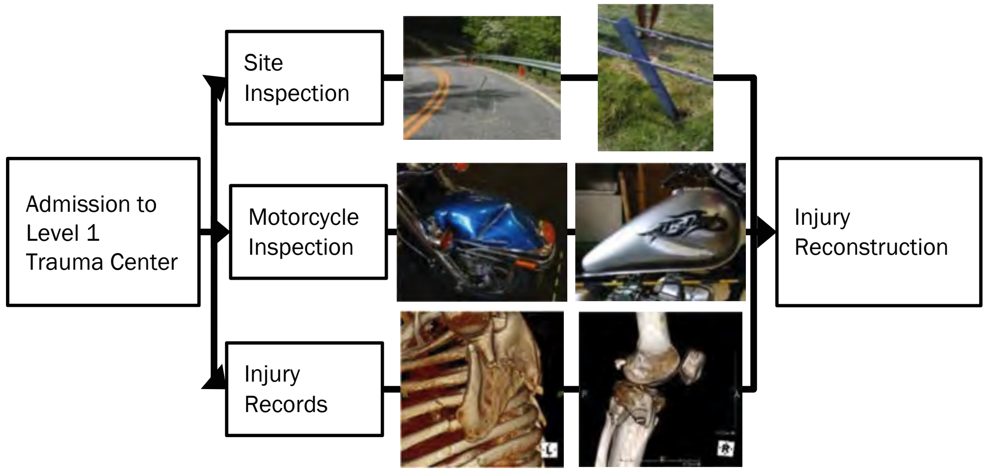


Figure 2-1. Methodology for in-depth investigation of motorcycle-barrier collisions.

Figure 2-1 presents a schematic of the methodology for in-depth investigation of cases for this study. After identifying a potential case, the Wake Forest University (WFU) research team sought informed consent from the subject to participate in the study. After receiving consent, the WFU crash investigator visited the scene to take detailed measurements and photographs of the roadway geometry and the barrier itself, including barrier dimensions and any evidence of contact between the barrier and either the motorcycle or the rider. The investigator then performed a detailed inspection of the motorcycle, which included extensive photographs of the vehicle and any evidence of interaction between the barrier and the vehicle. Finally, the WFU research team obtained the record of injuries suffered by the rider, including computed tomography (CT) scans and external photographs of the subject. The severity of all injuries was coded using the AIS (AAAM 2001; AAAM 2008). In selected cases, the team was able to obtain photographs of the rider's clothing and helmet. To protect the identity of the subject, all personally identifying information was removed from all case materials prior to the case review.

After assembly of the case documentation, the research team at Virginia Tech and the crash investigation team at WFU met to conduct a review of each case. The goal was to review the circumstances of each case and the nature of the injuries, and then to reconstruct the likely injury contact sources that led to each injury. The team used the Crash Injury Research Engineering Network (CIREN) BioTab method of coding injuries and likely injury contact source (Schneider et al. 2011) for this task.

2.3.2 Data Collection Protocol

The following summarizes the procedure followed by the crash investigation team. The protocol for crash investigation and data collection was reviewed and approved by the WFU Institutional Review Board under agreement IRB00010000.

Notification

The most challenging aspect of crash data collection is crash notification. Because of the fleeting nature of motorcycle crash evidence, prompt notification and site visits are essential in order to reconstruct the crash. The research obtained notification of a potential case when an injured motorcyclist was admitted to the Level 1 trauma center at the Wake Forest Baptist Medical Center. Research staff reviewed the hospital trauma registry each day for motorcycle crash victims reported to have collided with a traffic barrier. Only motorcycle crashes involving collisions with traffic barriers were eligible for enrollment in the research program.

Subject Consent

Names of the potential case subjects were provided to the study coordinator for follow-up and consent. In instances where the subject was unable to provide consent, the Legal Authorized Representative (LAR) was approached. Once informed consent was obtained, a case file was opened and assigned a case number.

Data Collection

The investigation of the crash included: detailed documentation of the motorcycle involved, a copy of the crash report filed by the responding police agency, and the collection of medical data relevant to the case subject's injuries and acute care. The compilation of the medical record consisted of a review of the case subject's medical records, including but not limited to the radiology, radiology reports, operative notes, and images of external injuries. The human factors, general information, and pre-crash events data for the motorcycle rider were collected during an interview following the signing of the consent form. Also, information on personal protective equipment was collected, when possible. The severity of all injuries was coded using the Abbreviated Injury Scale AIS-90, 1998 Update.

After receiving consent, the WFU crash investigator visited the crash site to take detailed measurements and photographs of the roadway geometry and the barrier itself, including barrier dimensions and any evidence of the contact between the barrier and either the motorcycle or the rider. The investigator then performed a detailed inspection of the motorcycle, which included extensive photographs of the vehicle and any evidence of interaction between the barrier and the vehicle. In selected cases, the team was able to obtain photographs of the rider's clothing and helmet.

Case Review

The collected crash and medical data was collated and sanitized by the crash investigator, study and data coordinators, and the project manager before being presented to the principal investigator (PI) at a case review meeting. To protect the identity of the subject, all personal identifying information was removed from all case materials prior to the case review. The crash investigation team presented the case to the PI and research team at Virginia Tech. During the case review meeting, the vehicle dynamics, occupant kinematics, and mechanisms of injury were evaluated and documented. The coded data was amended if required and forwarded to Virginia Tech. After a final quality check and confirmation that all personal identifiers had been removed, Virginia Tech stored the case in the project dataset.

Quality Control

Selected cases were examined by crash reconstruction experts at Harley-Davidson to check for the accuracy of the case review conclusions and to recommend any needed modifications. The results of these independent case reviews are described in the appendices of this report published as *NCHRP Web-Only Document 327: Serious and Fatal Motorcycle Crashes into Traffic Barriers: Injury Information*

Motorcycle-Barrier Crash Database

Each case was documented in a sanitized summary that provides details of the crash, injuries, and selected photos. All personal identifiers have been removed in these summaries. The detailed materials for each case generated by Wake Forest, e.g., medical records, patient photos, the scene and vehicle photos, PAR, and field notes were stored digitally on a secure network folder at WFU and physically in a paper folder in a locked file cabinet also at WFU. These materials will not be released in order to protect the privacy of the subjects. The sanitized summaries of each case received by Virginia Tech are included in *NCHRP Web-Only Document 327*.

2.4 Injury Scoring

The system used to score the severity of injuries incurred by a rider is largely a function of the database. Following is a description of the systems used in the analyses.

Abbreviated Injury Scale

The AIS is an injury coding lexicon established by the Association for the Advancement of Automotive Medicine (AAAM 2001; AAAM 2008; Gennarelli and Wodzin 2006). It is the most advanced trauma-specific, anatomically based coding lexicon and was first conceived as a system to define the type and severity of injuries arising from motor vehicle crashes (MVCs). To calculate AIS scores, medical records of traumatic incidents are transcribed into specific codes that capture individual injuries. Each injury incurred by a person or subject is coded on a six-point scale that ranges from 1 for minor injuries to 6 for unsurvivable injuries (Table 2-1). The AIS system is based on the assessment of threat to life, which was developed by a consensus of trauma surgeons, for an extensive compendium of injuries. The AIS system is widely used in in-depth crash investigation databases including NASS/CDS and CIREN. The maximum AIS (MAIS) can be used as an AIS measure of the overall severity of a patient's injuries.

Injury Severity Score

The Injury Severity Score (ISS) is another metric of overall injury severity and is calculated using AIS severity scores for body regions (Baker et al. 1974). The highest AIS severity scores in each of the three most severely injured body regions are squared and summed together (Equation 2.1). The six body regions used in the ISS calculation are (1) head and neck, (2) face, (3) chest, (4) abdomen, (5) extremities, and (6) external. The ISS scores range from 1 to 75. If any of the three AIS severity scores is a 6, the score is automatically set at 75. A patient with an ISS greater than 15 is used by many sources to designate a "major trauma" or "seriously injured" patient that needs treatment at a Level I or II trauma center. The greatest AIS score included in computing the ISS is 5 (Baker et al. 1974).

$$ISS = \sum_{i=1}^{3} \left[\max\left(AIS\right)^2 \right]_{Body\ Region\ i} \tag{2.1}$$

KABCO Scale

In many crash databases, this level of detailed injury information is not available. Instead, injury severity of the crash is reported by the police using the KABCO scale. The KABCO scale is a

Table 2-1. Abbreviated injury scale.

AIS Score	Injury Severity
1	Minor
2	Moderate
3	Serious
4	Severe
5	Critical
6	Unsurvivable

Table 2-2. KABCO injury scale.

KABCO Code	Injury Severity
K	Killed
A	Incapacitated
B	Moderate Injury
C	Complaint of Pain
O	Property Damage Only

five-point scale commonly used by law enforcement to code injury severity for PARs. As shown in Table 2-2, the KABCO scale ranges from "K" for killed to "O" for property damage only, i.e., not injured. Police officers would typically provide a code for each person involved in a crash. Crash databases that rely on PARs typically code injury severity using the KABCO scale. This would include FARS, GES, and state accident databases. Because KABCO is not a medically based scale and is coded by non-medical personnel, KABCO has been found to not accurately conform to medically based systems such as AIS (Compton 2005). In this research, seriously injured riders were defined as those whose injury severity was either a "K" or "A."

2.5 Description of Anticipated Results

The objective of this research is to determine the factors associated with serious and fatal motorcycle crashes associated with traffic barriers. Following is a list of the questions that were pursued during the research.

- Determine the risk of fatality and injury by barrier type to include W-beam, cable barrier, concrete, bridge rails, and crash cushions. Are some barrier designs safer than others?
- For each barrier type, determine the distribution of injury by body region and injury by barrier component. For W-beam barrier, for example, does the risk of injury from the posts differ from the risk of injury from impact with the rail?
- Establish the frequency and severity of injuries in motorcycle-barrier crashes by body region (head, chest, lower extremity). What should the priorities be for rider protection?
- Estimate the ratio of fatalities caused by the motorcyclist vaulting over the barrier versus sliding into the barrier. Which crash mode should be the priority for a motorcycle-barrier crash test?
- Find the ratio of motorcyclist already seriously or fatally injured by contact with the ground or other objects prior to impact with the barrier. Is there any evidence for the hypothesis that the life-threatening injuries occur from ground impact before riders collide with the barrier?
- Changes in the post shape have been proposed as an injury countermeasure. Is there any evidence of the I-beam edges cutting the rider?
- What roadway geometries are associated with the incidence of motorcycle crashes with traffic barriers?
- What are the options for dynamic crash testing of motorcycles into traffic barriers?
- What countermeasures are available to protect motorcyclists in collisions with barriers?

CHAPTER 3

Synthesis of Current U.S. and International Literature on Serious Injury and Fatal Motorcycle Crashes into Traffic Barriers

3.1 Approach

The purpose of this chapter is to summarize U.S. and international research relating to motorcycle crashes into traffic barriers. The focus is on the characteristics of these crashes as well as existing countermeasures. This literature review focuses on the available literature pertinent to the following three areas:

- Characteristics of fatal and serious injury in motorcycle-to-barrier crashes.
- Potential countermeasures that have been developed with the intent of mitigating these crashes.
- Use and effectiveness of existing motorcycle crash data collection protocols.

3.2 Motorcycle-Barrier Crash Characteristics

The following section summarizes the published research on the characteristics of motorcycle-barrier crashes. The majority of the published literature on motorcycle-barrier crash characteristics describes the frequency of these crashes, the severity of the resulting rider injuries, and the severity of these crashes in comparison with all motorcycle crashes. Most of the data presented is from real-world crash studies, which have been categorized by study location (i.e., conducted in the United States or conducted outside of the United States). Note that the vast majority of these studies were limited to only police-reported motorcycle crashes and do not include crashes not reported to the police. To augment the data from the real-world crash data studies, data are presented from available full-scale motorcycle-barrier crash tests as well as computer simulations of motorcycle-barrier crashes. Observations regarding observed or postulated rider/passenger injury mechanisms in these crashes have been assembled in a separate section. Due to the limited amount of information on motorcycle-to-cable-barrier crashes, this information has been presented in a separate section.

3.2.1 International Crash Data Studies

Domham (1987) presents German motorcycle crash statistics from a study conducted by the Federal Highway Research Institute (BASt) in 1984. In one German region, there were a total of 2,793 motorcycle crashes resulting in 44 fatalities. Those riders impacting objects off the road were overrepresented by a factor of 5 in terms of fatalities: there were 52 cases (2% of the total crashes) where the rider impacted an object off the road, but these crashes resulted in 11 fatalities (25% of the fatalities). A total of 22 of these 52 crashes involved the rider striking a guardrail, and 7 of these resulted in rider fatality. In another similar German region over a 2-year period, 207 motorcyclists were injured or killed due to an impact with an object off the road. Approximately one-fourth impacted a guardrail (50 of 207), resulting in three fatalities and 31 severely injured persons. Domham also notes that none of these crashes occurred on a horizontal curve with the smallest radii, suggesting that there may not be a strong correlation between roadway horizontal geometry and motorcycle-barrier crash risk. The author, however, did not report the proportion of motorcycle-barrier crashes occurring on any radius curve in tandem with the proportion of these crashes occurring on straight sections.

Quincy, Vulin, and Mounier (1988) presented the results of two French motorcycle crash data collection efforts in the late 1970s and early 1980s. The first study focused on characterizing motorcycle crashes on urban roadways in France, while the second focused only on rural roads. For the urban roadways, a 2-year study (1978–1979, inclusive) was conducted on 70 km (44 miles) of roadway near Paris. The roads were fully equipped with a median barrier and equipped with roadside barrier for 62% of the study section length. The urban roadways were primarily six- or eight-lane divided highways with speed limits ranging between 70 and 80 km/h (44–50 mph). For the rural roads, a 3-year observational study (1980–1982, inclusive) was conducted on 940 km (580 miles) of highway. Similar to the urban roads, the rural roads in this study section were equipped with a median barrier for the entire length and equipped with a roadside barrier for 40% of its length.

The 2-year urban road study revealed a much higher proportion of motorcycle crash fatalities (compared to all crashes) than what was found in the rural road study. Motorcycle crash fatalities represented approximately 25% of total fatalities occurring on urban roads (6 of 25 fatalities) compared with approximately 5% of total fatalities on rural roads (19 of 439 fatalities). Crashes where the barrier was the first impact (38 raw cases) represented 28% of the total number of crashes but accounted for two-thirds of the corresponding fatalities. In approximately 16% of the urban motorcycle crashes (21 raw cases), the authors noted that a guardrail was impacted after an impact with a vehicle. Motorcycle-barrier crashes were found to be overrepresented at access roads, with 54% of the crashes occurring at these locations but only representing 5% of the roadway length. The remainder of the motorcycle-barrier crashes (e.g., not at an access road location) occurred either in the median (32%) or along the roadside (14%).

The 3-year rural road study investigated 283 motorcycle crashes resulting in 206 injuries and 19 fatalities. Motorcycle crashes were found to account for 2.3% of all crashes but account for 4.7% and 4.3% of all injuries and fatalities, respectively. Rural motorcycle crashes were classified into one of four categories based on crash type: (1) fell off motorcycle alone on road, (2) crashed into another vehicle, (3) ran off road with no guardrail impact, and (4) ran off road with guardrail impact. The majority of the crashes were in categories 1, 2, and 3, with 32% (90 crashes), 38% (109 crashes), and 20% (57 crashes), respectively. Approximately 10% of motorcycle crashes (27 crashes) were found to involve a guardrail impact. Despite this relatively low frequency, however, these crashes accounted for more than 40% of the fatalities observed. Conversely, a total of 47% of motorcycle fatalities on rural roadways (9 fatalities of 19 total motorcycle fatalities) were attributed to crashes with a passenger vehicle, but these crashes represented almost 40% (109 crashes out of 283) of all rural roadway motorcycle crashes observed.

Using data from real-world motorcycle crash investigations, Hell and Lob (1993) examined rider injury in different motorcycle crash types as well as the effectiveness of protective devices such as safety clothing and helmets. An interdisciplinary investigation team collected in-depth data for 173 motorcycle crashes (210 motorcyclists involved) occurring within a 50-km (31-mile) radius around Munich between 1985 and 1990. Crashes were selected from those reported by the Bavarian State Police where the rider had at least minor injuries resulting in a data sample skewed toward higher-severity crashes. A large portion of the crashes resulted in fatal injury [50 of 210 users (24%)]. Examining the injuries by body region, the authors found that the highest injury risk was for the head and lower extremities (all collision types). With respect to crash types, head-on crashes with a second vehicle, impacts with the side of a vehicle (with head contact to vehicle), and collisions with fixed objects were noted as especially severe. These three crash types represented 34% of collisions (71 of 210 crashes) but 82% of fatalities (41 of 50 fatalities). Impacts with objects were characterized by head, thorax, and abdomen injury. Injury data was only presented with respect to all objects (i.e., not categorized by object struck). No other information was presented with respect to motorcycle-barrier crashes.

Bly (1994) reported the findings of an ad hoc group formed by the European Experimental Vehicles Committee (EEVC) tasked with examining the engineering aspects of motorcycle safety. A particular focus was on how the design of the motorcycle, the rider's clothing, and the road environment can be improved; operator behavior, education, and training were not considered. A summary of motorcycle crash data was presented for 19 countries from 1980 through 1990 as well as a short discussion on collision and injury types. Based on the available data, two-thirds of motorcycle crashes were found to involve a collision with another vehicle, while the remaining third were single-vehicle crashes. The primary crash configuration noted was frontal. Although some rider injury distribution data by body region was presented, it pertained to all crashes and was not classified by object struck. The author did note, however, that single-vehicle crashes involving contact with objects tended to produce more severe injuries. For the road environment, crash barriers were identified as obvious obstacles to motorcyclists and the author noted that there was insufficient data for motorcycle impacts with concrete and wire rope barriers.

Gibson and Benetatos (2000) provided a comprehensive review of previous international motorcycle-barrier studies and findings from fatal motorcycle crashes occurring in New South Wales (NSW) from 1998 through 1999. Coroner files for a total of 102 motorcycle crash fatalities were examined, with 39 fatalities involving a motorcycle impacting a fixed object. Of the 39 fixed object fatalities, there were a total of eight crash barrier fatalities, seven impacts with a W-beam guardrail, and a single impact with a concrete barrier. A majority of the fatal impacts, five of the eight fatalities, had an impact angle of 45 degrees or less. Most frequent fatal barrier impacts (four of eight) involved a rider losing control on a right-hand bend and exiting the roadway to the left (passenger side) and impacting a barrier located on the roadside. Based on the police speed estimate and the speed limit in the area of the crash, the authors note that motorcycle-barrier crashes occurred at speeds above 60 km/h (38 mph).

Stefan, Hoglinger, and Machata (2003) used the Community database on Accidents on the Roads in Europe (CARE) to investigate motorcycle crash trends in 13 European countries from 1991 through 2001. Data was available for Austria, Belgium, Denmark, Spain, France, Finland, Greece, Italy, Luxembourg, Netherlands, Portugal, Sweden, and the United Kingdom. All data presented refers only to motorcycles (mopeds excluded), but does not distinguish between types of motorcycles due to a lack of common motorcycle definitions across the European countries included in the analysis. A majority of the analysis was focused on all motorcycle crash types and included age trends, gender trends, crash timing, and collision type. Although data was presented for motorcycle collision type, the authors abstained from making any conclusions regarding this facet, indicating that data acquisition on collision type is still too inconsistent across European countries. Data presented for impacts with an obstacle suggest that Luxembourg, Belgium, and Netherlands have a higher proportion of motorcycle-to-object crashes, each with motorcycle-to-object crash rate in excess of 10%. Note that this observation was based only on 4 years of the data available (1992–1995). Also, for this study "obstacles" included all objects with the exception of animals; traffic barriers were not isolated. No other information relevant to motorcycle-barrier crashes was presented.

The Association of European Motorcycle Manufacturers (ACEM 2004) reported findings from MAIDS. A total of 921 in-depth motorcycle/moped crashes were collected during 1999–2000 in five sampling areas in Europe: France, Germany, Netherlands, Spain, and Italy. These five countries were selected as they were thought to be representative of motorcycle crashes in all of Europe. Detailed crash data, approximately 2,000 data elements per case, were collected using the Organization for Economic Cooperation and Development (OECD) methodology (OECD 1999) and associated case-control exposure data were collected for an additional 923 cases. The objectives of the study were threefold: (1) identify the causes of motorcycle crashes, (2) determine how contributory crash factors affect motorcycle crash risk, and (3) use the findings to develop effective motorcycle crash countermeasures. A brief description is provided of the methodology of the data collection (a separate report outlines the data collection in further detail) followed by results split into the following categories: general crash characteristics, crash causation, vehicle factors, environmental factors, human factors, conspicuity, and rider protection.

With respect to barrier impacts, the researchers noted 60 rider injuries as a result of barrier contact. The total number of crashes causing these 60 injuries was not noted, and data on the distribution of barrier impact location (e.g., posts, rail, etc.) or types of barriers impacted were not presented. The researchers noted that the roadside barrier impacts were infrequent but presented a “substantial danger” to PTW riders. The MAIDS study defines PTWs as all motorcycles and mopeds. Figure 3-1 shows the distribution of the severity of the 60 injuries resulting from motorcycle-barrier crashes in the MAIDS study. For the MAIDS study, as well as most in-depth crash studies, injury was ranked using the AIS scale (AAAM 2008). The AIS scale was used to methodically rank each injury based on threat to life, where 0 corresponds to no injury and 6 corresponds to maximum or fatal injury.

The majority of these injuries were to the spine (27%; 16 raw cases), lower extremities (23%; 14 raw cases), and head (20%; 12 raw cases) although the most prevalent, the spinal injuries, were mostly minor in nature (15 of 16 were AIS 2 or lower). Injuries to the head were

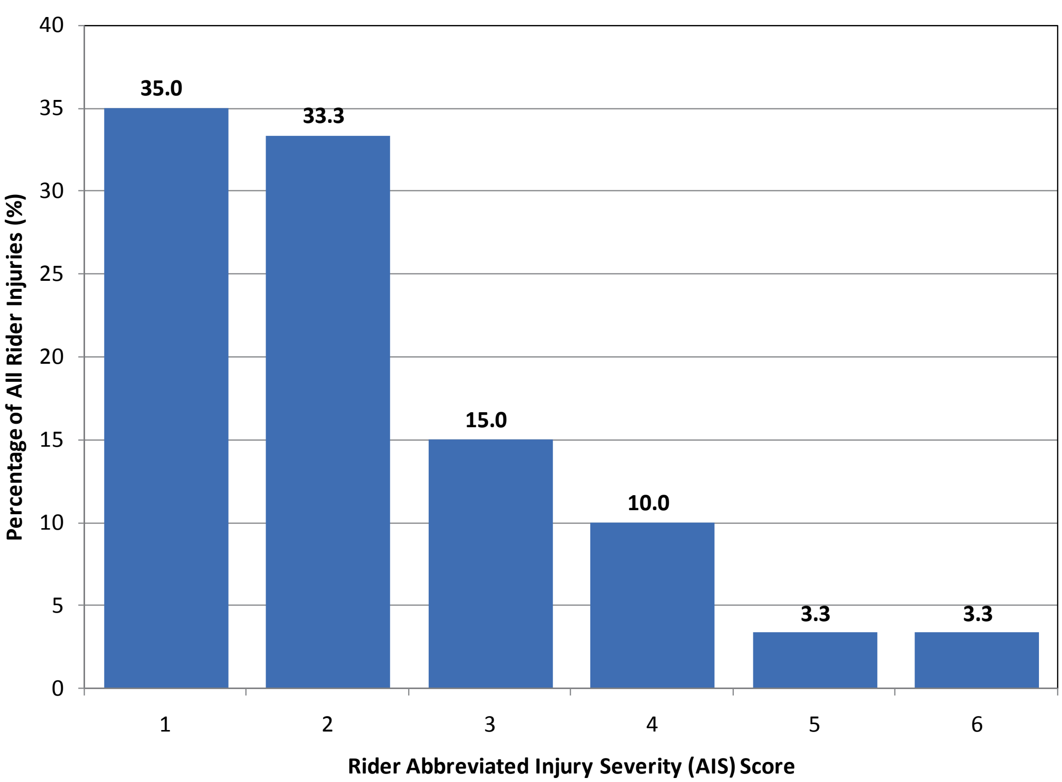


Figure 3-1. Distribution of rider injury severity in motorcycle-barrier crashes (n = 60 injuries) [developed from data reported in the MAIDS study (ACEM 2004)].

much more severe with eight of 12 at the AIS 3 level or greater. It should also be noted that both the AIS 6 injuries and half (one of two) of the AIS 5 injuries were head injuries; the other AIS 5 injury was to the upper extremity. Note that it was unclear whether the AIS 5 upper extremity injury was misreported since the highest AIS score possible for an upper extremity is an AIS 3. Approximately one-third of the lower extremity injuries were serious (AIS 3). Of all 60 barrier contact injuries, 19 of 60 were at the serious (AIS 3) level or greater.

The distribution of injury severity by body region was found to be different for all crash-involved PTW riders and those riders impacting traffic barriers. Figure 3-2 shows the distribution of serious occupant injuries (AIS 3+) by body region for all motorcycle crashes and motorcycle-barrier crashes based on data reported in the appendices of the MAIDS report (ACEM 2004). Compared to all motorcycle crashes, motorcycle-barrier crashes result in a much larger proportion of serious head and upper extremity injuries. Serious lower extremity injuries are overrepresented in motorcycle-barrier crashes, but to a lesser extent than serious head and upper extremity injuries. Based on the available data, serious spine and abdomen injuries are found to be underrepresented in motorcycle-barrier crashes. The thorax has not been included in Figure 3-2 as the thorax category was missing for the motorcycle-barrier data presented in the report. It is unclear whether there were no rider thorax injuries reported in this crash mode or the data was omitted in error. For all motorcycle crashes, however, there were a total of 180 thorax injuries noted with 45% of them serious (AIS 3+) injuries.

In conjunction with motorcycle-barrier crash testing and computer simulation, Berg et al. (2005a) reported on 57 motorcycle-barrier crashes that were investigated in Germany. The majority (63%) of the 57 cases investigated involved sigma post steel barriers (ESP) with

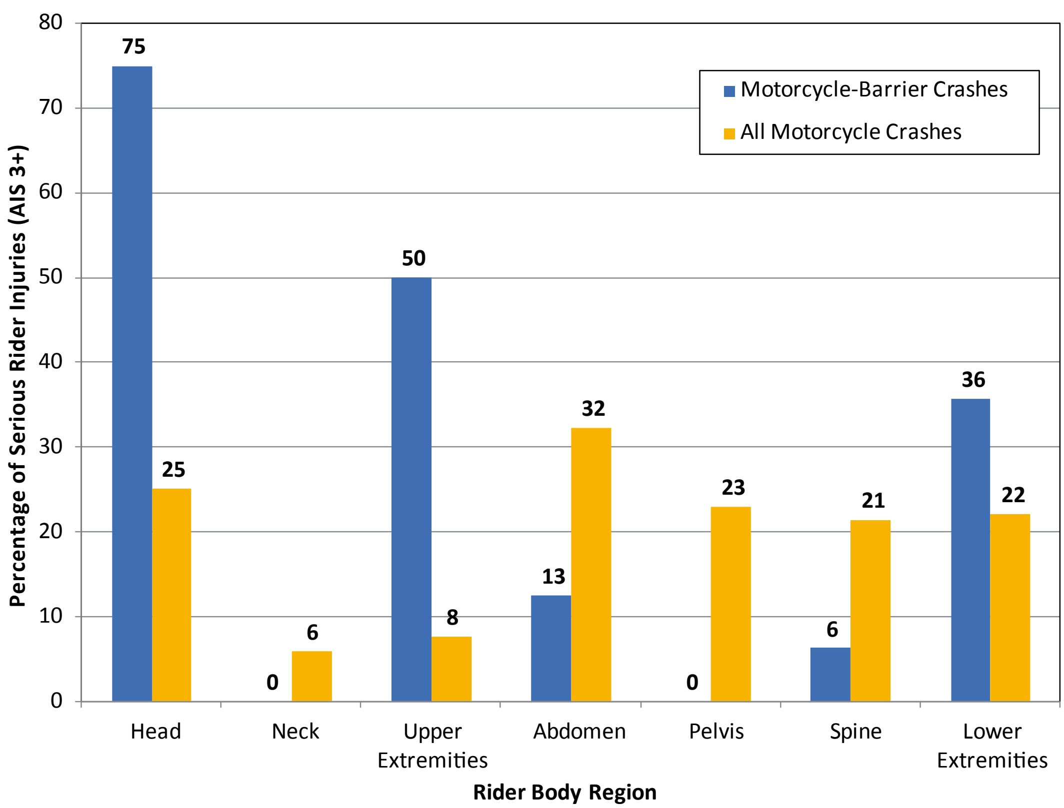


Figure 3-2. Comparison of the distribution of serious injury in all motorcycle crashes and motorcycle-barrier crashes ($n_{motorcycle\text{-}barrier\ injuries}$ = 60, $n_{all\ motorcycle\ injuries}$ = 1,930) [developed from data reported in the MAIDS study (ACEM 2004)].

the second most frequent barrier struck (18%) also a steel barrier system (EDSP). Based on the information provided by the authors, the German EDSP barrier appears to be the most closely related to the U.S. strong post W-beam barrier. With regard to impact configuration, 51% of the crashes were found to involve a motorcyclist impacting the barrier in an upright position, while 45% of the crashes were found to involve a motorcycle sliding on its side prior to impact. The remaining 4% of crashes involved a motorcyclist impacting the barrier in an inclined position. For road geometry, the majority of crashes occurred within curves (53% left, 7% right). The remaining 40% (although reported as 50% in the paper) occurred on straight roadway sections.

Selby (2006) reported on 3,767 police-reported motorcycle crashes occurring in New Zealand between 2001 and 2005. A total of 57 of these crashes involved a motorcycle impacting a barrier. In terms of fatality rate, these crashes were more severe compared to all motorcycle crashes. The fatality rate for all motorcycle crashes was reported as 4.3% (164 fatalities) while the fatality rate for motorcycle-barrier crashes was 5.3% (three fatalities). Considering only open-road crashes (non-urban roadways), however, this trend was reversed: 8.6% of all reported open-road motorcycle crashes resulted in a fatality, whereas 6.4% of reported open-road motorcycle-barrier crashes resulted in fatality. For comparison, the author notes that 7.3% of reported open-road motorcycle crashes involved a fatality and no impact with any roadside object. For nearly half of the motorcycle-barrier crashes, barrier type was unknown. A total of 28 crashes had known barrier type: 64% (18 cases) involved metal barriers, 29% (8 cases) involved concrete barriers, and 7% (2 cases) involved wire rope barriers. Selby also noted that the available data did not have information regarding the hazard that each barrier is intended to shield and that it was not clear whether the barrier, although perhaps causing an injury, prevented a more-severe injury.

To support the development of a motorcycle-barrier test standard, Peldschus et al. (2007) examined motorcycle crashes from European in-depth crash databases. Approximately 1,000 crashes were analyzed from four different sources: the German In-Depth Accident Study (GIDAS), the European Co-operation in the Field of Scientific and Technical Research (COST) 327 database, the DEKRA accident database, and the Dutch portion of the MAIDS database. Similar to other motorcycle crash studies, motorcycle-barrier impacts were found to result in more severe injuries than other motorcycle crash modes. For the crashes into road infrastructure, the median primary impact speed was above 50 km/h (31 mph) in all four databases. Note that this was based on 96 motorcycle-to-road infrastructure cases available between the four databases. Impact angles were shallow based on 18 impacts to road infrastructure from the GIDAS database.

More recently, Perandones et al. (2008) developed a methodology to select appropriate locations for potential motorcycle-barrier crash countermeasures based on historical crash data coupled with detailed roadway characteristics to estimate motorcycle run-off-road crash risk. As part of the study, the authors note collecting in-depth crash data for 16 motorcycle run-off-road crashes over a 1-year period. While there is significant mention of data collection efforts throughout this paper, including police-level motorcycle crash data and in-depth data, the authors present almost none of the data. With respect to the in-depth cases, the authors distinguish between "prospective" (e.g., collected immediately) and "retrospective" (e.g., collected after the crash occurred), but do not report the portion of crashes collected using either method. The authors do note, however, that the 16 in-depth crashes investigated involved a total of 19 injuries and two fatalities, that the 20-km study section was in a mountainous area, and that a vast majority of the cases (90%) were speed-related.

The Federation of European Motorcyclists' Associations (FEMA 2000) conducted a review of previous motorcycle safety studies with the hopes of raising awareness for the motorcycle-to-barrier crash problem and providing road authorities with effective guidelines to reduce fatalities due to this crash type. The authors summarize a number of European motorcycle studies mentioned previously. FEMA also presents results from several studies that appear to be available only in non-English versions, including Brailly (1998) and a study by Schnuell et al. (1993) at the University of Hannover. Brailly (1998) investigated 418 motorcycle crashes into barriers in France. From 1993 through 1995, there were 188 fatalities resulting from motorcycle impacts to metal barriers (800 motorcycle fatalities per year on average for all motorcycle crashes). When compared to all motorcycle crashes, the risk of fatality was found to be five times greater for motorcyclists impacting crash barriers. Brailly identifies the outside of curves as especially dangerous and suggests that the use of a screen on the barrier could reduce the number of motorcycle fatalities by a factor of two. A study by Schnuell et al. (1993) also indicated that motorcycle-to-barrier crashes result in more severe injuries compared to all other motorcycle crash types. The research concludes that protection of crash barriers where these crashes have occurred previously could reduce the number of motorcycle-barrier fatalities by one-fourth. Ellmers (1997) also cites this study by Schnuell et al. (1993) and indicates that motorcyclists contacting guardrails were found to be overrepresented in fatalities compared to crashes with no guardrail contact (21.3% versus 15.6% for no guardrail contact). Mountainous rural primary and secondary roads were identified as critical to motorcycle safety. Motorcycle crashes with guardrail contact were found to produce twice as many seriously injured persons and five times the persons killed.

Grzebieta et al. (2009) examined fatal motorcycle-barrier crashes in Australia and New Zealand. The study was conducted as a component of a major project research project at the University of NSW investigating motorcycle collisions with roadside safety barriers. In 2006, there were 238 motorcycle-related fatalities in Australia. During the period 2001–2006, approximately 5.3% of all motorcycle fatalities were known to have been associated with a roadside barrier. W-beam barriers were involved in 80.6% of the roadside barrier fatalities while 4.5% were involved with wire-rope barriers and 3% with concrete barriers. Using pedestrian fatality risk versus impact speed relationships, the authors point out the odds of rider survivability become quite low at impact speeds over 40 km/h. The paper emphasizes the important benefit that barrier systems such as wire rope barrier have provided in reducing the number of highway fatalities in all vehicle types in the United States and Europe.

Jama et al. (2011) analyzed 77 fatal motorcyclist-roadside crashes that occurred in Australia and New Zealand. The roadside barriers were primarily W-beam guardrail (72%). Most cases occurred on a curve in the roadway. In nearly half (47%), the motorcycles were estimated to have been driven at inappropriate speeds for conditions. Most fatally injured riders were male (92%). The study stated that it could not be determined whether any design modifications to the barriers could have prevented any of these fatalities as nearly half of the motorcycles were being operated at inappropriate speeds. The concern also was expressed that potential design modifications must consider the effect on other road safety objectives.

Bambach et al. (2013) investigated the relative risk of motorcyclist collisions with barriers in comparison with the roadside obstacles that these barriers shield. The study used a dataset that linked PARs and hospital admission records from NSW, Australia, from 2001 to 2009. The resulting dataset was comprised of records of 1,364 motorcyclists who struck roadside objects including traffic barriers, trees, and utility poles. The odds of serious injury in a collision with these roadside objects was compared with the odds of serious injury in a collision with a guardrail. The odds of serious injury in a collision with posts increased by a factor of 1.55 times for posts, 1.77 times for trees, and 2.15 times for utility poles, relative to guardrail, and was found to be statistically significant. No statistical difference in the odds of serious injury could be determined between guardrail and concrete barrier. The study concludes that traffic barriers provide a protective effect for motorcyclists when compared with the outcomes that could occur if collisions were not prevented with other roadside fixed objects that guardrail may be installed to shield.

3.2.2 U.S. Crash Data Studies

To date, the Hurt study (Hurt, Ouellet, and Thom 1981a) represents the most comprehensive in-depth motorcycle crash data available in the United States. A particular focus of this study was on the cause(s) of the crash and subsequent rider injuries; the effectiveness of protective equipment such as helmets; and determination of appropriate countermeasures to prevent these crashes and/or reduce injuries. Data was collected primarily from 1976 through 1979 in a 470-square mile area in Los Angeles, California. Data collected for the study can be categorized into one of four categories:

1. On-scene, in-depth (OSID) crash investigations
2. Police-reported crash records
3. Exposure site data
4. Motorcycle rider exposure interview data

A total of 900 OSID cases were investigated, with approximately two-thirds of the investigations occurring immediately after the crash and the remaining third investigated within 24 hours. The investigations were conducted by multidisciplinary teams consisting of engineers, psychologists, medical doctors, and data processing specialists. All team members were required to have motorcycle riding experience and had a minimum of 6 months of motorcycle crash investigation training. For each OSID crash, approximately 1,000 data elements were recorded. A total of 3,600 PARs were collected from the study area for the same time period, including most but not all of the 900 OSID crashes. Exposure data was collected at 505 of the 900 OSID crash sites and included traffic counts and interviews of 2,310 non-crash involved motorcycle riders. To collect the exposure data, the investigators returned to the crash scene at the same time of day and approximate weather conditions present for the crash and recorded data for 30 minutes before and 30 minutes after the time of the crash. Based on the collected data, the authors presented findings from the following six categories:

1. Accident and environmental factors
2. Vehicle factors
3. Rider and passenger characteristics
4. Injuries
5. Protection systems
6. Exposure data

Although the Hurt study was not specific to motorcycle-barrier crashes, additional data in the appendices of the Hurt report (Hurt, Ouellet, and Thom 1981b) provide some insight into motorcycle-barrier crashes. A total of 98 rider contacts with some type of barrier were noted in the Hurt study report. The most frequent rider body regions making contact with barriers is summarized in Table 3-1 based on this data. Throughout the Hurt report, data for head/neck injury and body injury only (excluding head/neck injury) is presented independently; this data has been combined for barrier impacts to generate Table 3-1.

Note that the researchers defined contact surfaces by material type (e.g., wood, metal, concrete, asphalt, etc.) and object/geometry type (e.g., curb, barrier, embankment, blunt edge, sharp edge, etc.). Based on the data available in the report, it is unclear whether rider contact with a sharp end of a guardrail would be coded as "metal-barrier/guardrail" or "metal-sharp edge." It was also unclear whether a cable barrier would be classified under the "metal-barrier/guardrail" category or be coded as "metal-cable/wire." The values in Table 3-1 and the remainder of this

Table 3-1. Summary of top four rider body contact regions for barrier impacts [developed from data reported in the Hurt study (Hurt, Ouellet, and Thom 1981b)].

Barrier Type	Body Region Contacting Barrier (Percentage of Contacts for Respective Barrier Type)				Number of Contacts Recorded
	1	2	3	4	
Metal	Head (38%)	Chest (15%)	Wrist/Hand (12%)	Upper Arm (7%)	69
Concrete	Head (64%)	Lower Leg (18%)	Wrist/Hand (9%)	Forearm (9%)	11
Wood	Chest (39%)	Head (11%)	Lower Leg (11%)	Forearm (11%)	18

discussion include only those codes specifically relating to barrier contacts. For the "wood-barrier/guardrail" category, it is presumed that the rider impacted a wooden post of a barrier, but it is possible that these figures include other objects such as wooden fences and fence posts.

For all barrier types, head and chest are the most frequent body regions to impact barriers based on the Hurt study data. The top four body regions contacted represent all of the recorded contacts for concrete barriers and nearly three-fourths of contacts with metal and wood barriers. For metal barriers, the remaining contact body regions included the shoulders (7%), knees (6%), thigh (6%), and forearm (4%). For wooden barriers, the remaining contact regions included the upper arm, knee, shoulder, pelvis/hip, and thigh, in roughly equal proportion (5.6% each).

Injury severity by contact surface was tabulated in the Hurt study (Hurt, Ouellet, and Thom 1981b) for bodily injury and head/neck injury. Table 3-2 summarizes the proportion of serious (AIS 3+) injuries by barrier type contacted. Compared with bodily injury observed for all contact surfaces (data not shown in Table 3-2), bodily contact with a metal barrier resulted in approximately twice the incidence of serious occupant injury (AIS 3 or greater). A similar trend was observed for the concrete barriers, although there only four body contacts were noted; the remaining seven contacts were to the head/neck. For head/neck injuries, barrier contacts were found to be more severe than all contact surfaces. Approximately 3% of all rider contacts resulted in fatal head and neck injury, while nearly 30% of concrete barrier contacts (two of seven) and 15% of metal barrier contacts (four of 26) resulted in fatal head and neck injury. This data was not cross-tabulated with helmet use, so whether or not these riders used a helmet is not known.

Figure 3-3 provides a comparison of injury severity distribution for motorcycle-barrier crashes between the U.S.-based Hurt study and the European MAIDS study. For this plot, rider injury severity data from the Hurt study was combined for all barrier types (e.g., metal, concrete, and wood). The injury severity distributions are relatively similar for barrier crashes in the Hurt

Table 3-2. Summary of serious rider injury by barrier type [developed from data reported in the Hurt study (Hurt, Ouellet, and Thom 1981b)].

Injury Region	Percentage of Serious (AIS 3+) Rider Injury By Barrier Type Contact				Total Raw Cases
	Concrete	Metal	Wood	All Types	
Bodily Injury Only	25.0	23.3	50.0	30.16	63
Head Injury Only	42.9	34.6	0.0	34.3	35
All Injury	36.4	27.5	44.4	31.6	98
Total Raw Cases	11	69	18	98	

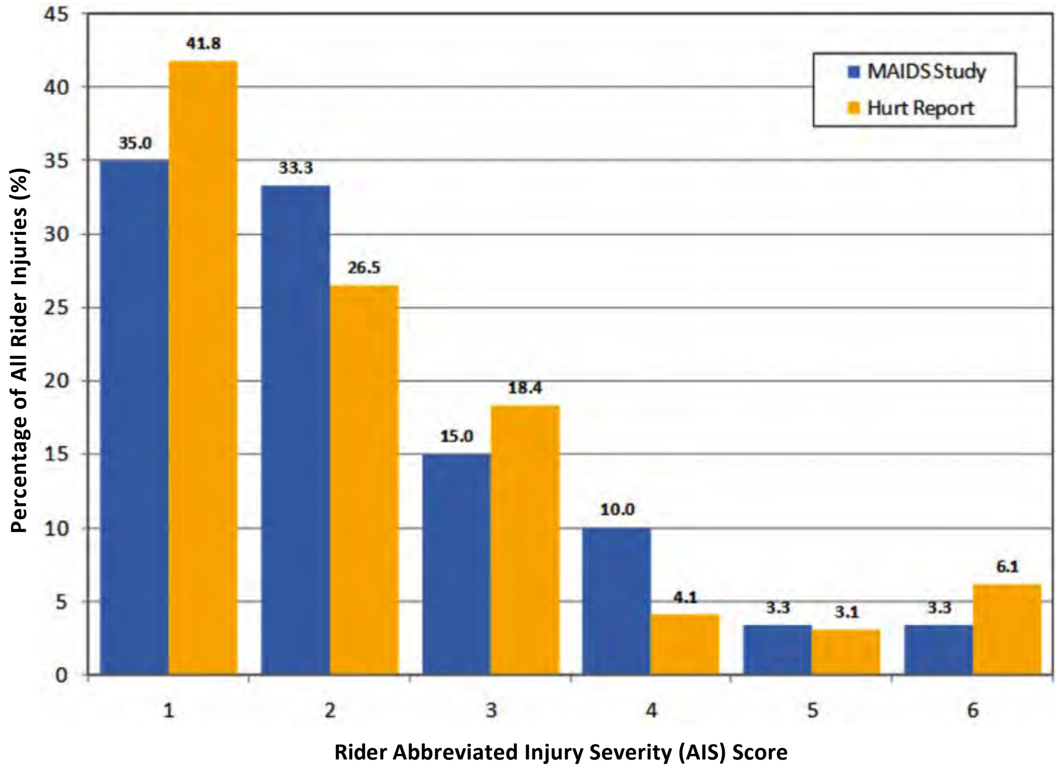


Figure 3-3. Comparison of rider injury severity distribution in motorcycle-barrier crashes: MAIDS study (n = 60) and Hurt report (n = 98) [developed from data reported in ACEM (2004) and Hurt, Ouellet, and Thom (1981b)].

and MAIDS studies. Although there are some differences, most notably in the percentage of fatal injuries, the proportion of serious injuries was nearly identical: 31.6% for the MAIDS study and 31.7% for the Hurt study.

Ouellet (1982) conducted follow-on research using the data from the Hurt study with a focus on motorcycle-specific environmental hazards. One of the recurring themes of this research was highlighting how a focus on passenger vehicle safety while designing a roadway/roadside may adversely affect motorcyclist crash risk. In terms of rider bodily injury (excluding head and neck), the pavement surface was found to be the most frequently impacted surface (82.9%) but 4% of these impacts resulted in serious rider injury (AIS 3 or greater). In contrast, rider contact with fixed objects was found to occur less frequently (9.2% of all contacts) but to result in a higher frequency of serious rider injury. Approximately 46% of tree and pole contacts resulted in serious rider injury (AIS 3 or greater), while nearly one-third of barrier impacts resulted in serious injury, which was consistent with the data shown earlier, if data from all barrier types were combined. Findings for head and neck injury were similar for body injuries except there was a higher proportion of serious injuries for all contact surface categories. Serious head and neck injury was observed in nearly 60% of contacts with trees/poles and nearly two-thirds of contacts with barriers.

Bryden and Fortuniewicz (1986) reported on a field investigation of 3,302 barrier crashes that occurred on New York state highways between July 1982 and June 1983. The objective of the research was to determine how barrier performance was affected by vehicle size and weight as well as barrier type and mounting height. Barrier performance was assessed according to resulting occupant injury, containment of the impacting vehicle, and secondary collisions. Although the primary focus was on passenger cars, the authors present injury data on 83 motorcycle-barrier crashes. For this crash type, there were seven fatalities (8.43%) and 33 incapacitating injuries (40%). These rates were found to be much higher than other vehicle types impacting traffic barriers; passenger cars had a fatality rate of 0.96% (27 in 2,818 crashes) and a serious injury rate of 8.13% (229 in 2,818 crashes), while light trucks had a fatality rate of 2.17% (7 in 322 crashes) and a serious injury rate of 13% (42 in 322 crashes). The motorcycle-barrier crash data was not shown by barrier type, but a majority of the barriers (57%) were light post barriers including cable barriers, weak post W-beam, and box beam barriers.

More recently, Savolainen and Mannering (2007) investigated rider injury severity in police-reported motorcycle crashes using nested and standard multinomial logit models. The dataset included 2,273 single vehicle motorcycle crashes and 2,213 multi-vehicle motorcycle crashes occurring in Indiana over a 34-month period between January 2003 and October 2005. In addition to the police-reported data, the authors merged in rider training data available from Indiana. The authors also indicate that the motorcycle fatality trends in Indiana have followed the national motorcycle trends closely, but no data substantiating this is presented. Motorcycle crash problem areas identified by the authors included visibility (alignment as well as lighting condition), speeding, alcohol use, lack of a helmet, right-angle and head-on crashes, and crashes with fixed objects. Another key finding was that older motorcyclists were more likely to be involved in severe injury crashes, despite controlling for other crash elements in the model.

With respect to single-vehicle crashes, approximately 21% of the single-vehicle motorcycle crashes were run-off-road crashes and 3.9% were collisions with guardrails. The authors did not provide any details on barrier type. Run-off-road motorcycle crashes were found to be 137% more likely to result in operator fatality than crashes that do not involve leaving the travel way. Collisions with curbs, culverts, and guardrails were found to decrease the probability of a minor or no-injury crash by 15%, 35%, and 17%, respectively. Collisions with trees and poles, however, were found to have a much more significant effect on fatality risk, with trees increasing fatality risk roughly five-fold and poles increasing fatality risk more than three-fold. Results were presented with respect to roadway characteristics and rider characteristics, but these results pertained to all single-vehicle motorcycle crashes; motorcycle-barrier crashes were not presented in isolation. The main findings about roadway characteristics were that a crash occurring either on a horizontal curve or on a roadway with a speed limit over 50 mph was approximately 10% less likely to result in minor or no rider injury. With respect to rider characteristics in single-vehicle motorcycle crashes, riders that had taken the Motorcycle Safety Foundation's Beginning Rider Course more than 2 years prior were found to be 171% more likely to be fatally injured and riders that were speeding were 212% more likely to be fatally injured.

Using data from a 13-year dataset from NASS/GES, Samaha et al. (2007) examined motorcycle crash trends in the United States relative to crash configuration and motorcycle, rider, and environmental characteristics. The entire dataset consisted of just over one million riders (weighted; operators and passengers) with all-terrain vehicles (ATVs) excluded from the study. Throughout the study, the authors compared motorcycle crash trends from two groupings: (1) 1992–1997 and (2) 1999–2004. Other comparison studies include the Hurt study and the more recent study completed by Savolainen and Mannering (2007).

One primary finding of the study was motorcycle crashes are becoming increasingly more severe with respect to 1992 levels. From 1992 to 2004, the risk of a motorcycle rider being involved in a fatal crash increased by 18% and risk for being in a nonsevere crashed decreased by 13% (per registered motorcyclist). The two primary motorcycle crash modes, frontal and road departures, accounted for 75% of motorcycle fatalities in crashes between 1992 and 2004. Both crash modes were found to have more severe results in recent years, with frontal crash fatality rate increasing from 2.5 to 4.3 (per hundred) and road departure crash fatality rate increasing from 4.3 to 6.5 (per hundred). Motorcycle road departure crashes were found to be particularly dangerous, accounting for 38% of all motorcycle fatalities and 19% of all motorcycle crashes. These findings were consistent with Savolainen and Mannering (2007). With respect to operator characteristics, the primary finding was that the proportion of older riders involved in crashes has increased, following suit with the trend of increased motorcycle owner age. In general, helmet use was found to be declining and the involvement of alcohol increasing. With respect to roadway characteristics, motorcycle crashes occurring away from a junction were found to be 1.7 times more likely to be fatal than those crashes occurring within an intersection. This finding seemed to be consistent with the Savolainen and Mannering study. Also, fatal crashes occurring at night were found to be overrepresented, accounting for 43% of the fatalities and 30% of the total number of crashes.

Using data from FARS and GES, Gabler (2007) investigated motorcycle-to-barrier crashes in the United States with a focus on recent trends and fatality risk compared to other types of motorcycle collisions. Two datasets were used: an overall dataset including 15 years of FARS and a more recent dataset including FARS and GES from 2000 to 2005. Fatality risk was computed using the number of fatalities from FARS and riders exposed to this collision type based on GES. For this study, a guardrail collision was defined as a crash where the most harmful event was a guardrail. As only the most recent 2 years of crash data available distinguished between the end terminal and length of need portions of the barrier, this study aggregated both into a single guardrail grouping.

Results indicated that although motorcycles only accounted for approximately 2% of the vehicle fleet, motorcycle riders accounted for 42% of all fatalities involving a guardrail collision (2005 data). Motorcycles now account for more guardrail fatalities than any other vehicle type. The motorcycle-guardrail fatality issue also was found to be a growing problem. Between 2000 and 2005, motorcycle-guardrail fatalities grew by approximately 75%, from 129 to 224 fatalities. During the same time period, car-guardrail fatalities declined by roughly one-third from 251 to 171 deaths. Nearly one-tenth of motorcyclists who impacted guardrails were fatally injured (data from 2000–2005), which is a fatality risk approximately 100 times higher than that of a car occupant involved in a guardrail collision. The author stresses that current barrier design and testing in the United States does not accommodate motorcyclists and there is a critical need to develop countermeasures to protect these vulnerable road users.

3.3 Motorcycle-Barrier Injury Mechanisms

Several researchers, primarily those who have investigated real-world motorcycle-barrier crashes, have commented on observed or postulated injury mechanisms in these crashes. This section summarizes those comments found in the published literature and has been divided into four subsections based on the available literature: (1) posts, (2) crash configuration, (3) cable barriers, and (4) current motorcycle-barrier data status and data needs. As there is only limited information on motorcycle-to-cable barrier crashes, the cable barrier section includes crash study data and injury mechanism hypotheses.

3.3.1 Posts

Ouellet (1982) provides a short discussion on injury mechanisms in motorcycle-to-barrier crashes and notes the severe nature of “perpendicular” elements (e.g., guardrail posts and the potential for the sharp edges of metal posts or the W-beam rail) to exacerbate rider injuries. He notes that all riders who struck a W-beam guardrail or metal mesh fence obtained at least multiple extremity fractures. Barrier design suggestions to reduce motorcycle crash injuries are to ensure a smooth barrier surface (e.g., solid concrete barrier) and to ensure proper barrier height to keep riders from vaulting the barrier into oncoming traffic or falling (i.e., from an elevated on-ramp). Domhan (1987) echoes this concern over the posts, indicating that motorcycle-barrier crashes are "extremely severe" when the guardrail posts are impacted. Based on their investigation of coroner files from eight fatal motorcycle-barrier impacts, Gibson and Benetatos (2000) seem to support the notion of the post-impact injury mechanisms. Contact with the barrier posts was determined to be the cause of fatality in two of the eight barrier fatality cases. They conclude that most fatal injuries occur as a result of an impact with an object other than the crash barrier beam. These objects would include the barrier posts, other posts or poles, a vehicle, or a heavy impact with the ground. It was not clear from the available data what portion of the remaining six cases involved impacts with other posts or poles, a vehicle, or a ground impact. Other researchers indicated that posts become "formidable obstacles" to motorcyclists (Candappa et al. 2005) and that the posts are the "primary aggressors" (Bly 1994).

Similarly, Koch and Schueler (1987) implicate aggressive I-beam guardrail posts as the primary injury-causing mechanism in motorcycle-barrier crashes based on the findings of Schueler et al. (1984). The authors note a 1985 crash where a motorcyclist with passenger impacted a guardrail. The rider was thrown over the guardrail and suffered severe injuries while the passenger slid over the pavement before striking a guardrail post. The passenger was fatally injured as a result of a spinal fracture. Berg et al. (2005a) also presented a single case anecdote of a motorcyclist impacting a sigma post steel barrier at approximately 85–95 km/h (53–60 mph). After losing control of the motorcycle and sliding along the road surface, the rider's neck directly impacted a sigma post of the barrier, resulting in AIS 5 injuries (fractured C1 vertebrae) and other internal injuries (not specified in detail). The injuries were ultimately fatal to the motorcycle rider.

The crash tests conducted as part of this research by Berg et al. (2005a) also provide some insight to potential injury mechanisms in these crashes. In a test with an upright Anthropomorphic Test Device (ATD) motorcyclist impacting a steel I-beam barrier, significant potential for rider snagging on the exposed top elements of the post was observed. Even a sliding test into a barrier with less aggressively shaped sigma posts resulted in a broken shoulder joint of the ATD. While the concrete barrier presented a relatively smooth and snag-free surface compared to the steel barriers, the authors note a diminished potential to absorb the impact energy of the rider as well as an increased potential for the rider to be deflected back into adjacent traffic.

Bambach et al. (2012) examined the injury characteristics of 78 fatally injured motorcyclists who struck longitudinal barrier in Australia and New Zealand from 2001 to 2006. Detailed injury records were available for 70 of these riders. Injury severity was coded using the AIS. For these riders in the dataset, multiple injuries were common. However, in most cases (46%), the most severely injured body region was the thorax. The second most common body region to be the most severely injured was the head (27%). In 34 of the 78 cases, there was evidence of rider contact with the posts.

3.3.2 Crash Configuration

For the 83 motorcycle-barrier crashes occurring in New York, Bryden and Fortuniewicz (1986) tallied barrier "function." While this categorization of barrier performance was aimed primarily at the barrier performance in passenger vehicle impacts (e.g., whether or not the vehicle penetrated, vaulted, or went underneath the barrier), it may provide some insight into crash configuration and injury mechanisms in U.S. motorcycle-barrier crashes, albeit somewhat dated. The data is summarized in Table 3-3. Note that the researchers categorized these crashes based on a review of the police-reported narratives only.

Although the categories do not clearly relate to possible motorcycle-barrier impact configurations, the data appears to suggest that at least 5% of these motorcycle-barrier crashes involved

Table 3-3. Summary of barrier performance in motorcycle-barrier crashes [developed from data reported in Bryden and Fortuniewicz (1986)].

Barrier Function Description	Raw Cases Observed	Percentage of all MC-Barrier Crashes (%)
Redirected	50	60.2
Stopped in contact with the barrier	22	26.5
Snagged	0	0.0
Penetrated	1	1.2
Ran under	4	4.8
Broke through	1	1.2
Went over	4	4.8
Unknown	1	1.2

riders sliding into the barrier (e.g., went under) with potentially more included in the "stopped in contact with the barrier." There was a small proportion, approximately 5%, of riders that "went over" the barrier.

In contrast, Quincy, Vulin, and Mounier (1988) noted that in more than half of the motorcycle-barrier crashes (58%), the rider/motorcycle combination or the rider alone was sliding along the ground. The remaining 42% were a barrier impact with no sliding. The authors also noted an increase in injury severity associated with the occurrence of sliding prior to barrier impact as opposed to those crashes where no sliding was present. Berg et al. (2005a) made similar but slightly different observations with respect to rider orientation. Based on 57 motorcycle-barrier crashes investigated in Germany, 51% of the crashes were found to involve a motorcyclist impacting the barrier in an upright position while 45% of the crashes were found to involve a motorcycle sliding on its side prior to impact. The remaining 4% of crashes involved a motorcyclist impacting the barrier in an inclined position. The authors made no mention of which configuration produced more severe rider injuries. Gibson and Benetatos (2000) had somewhat different findings, albeit based on a much smaller number of cases. Rider kinematics were able to be determined in six of the eight motorcycle-barrier fatalities examined. In half of the cases (three of six), the rider was still riding the motorcycle at impact with the barrier. One-third of the cases (two of six) involved riders who were airborne prior to barrier impact. A single rider slid into the barrier.

Selby (2006) reported on crash configuration based on 56 police-reported motorcycle-barrier crashes. A total of 32 impacts (57%) involved a barrier hit while the rider remained upright. The remaining 24 (435) involved the bike or the rider sliding into the barrier. These results were in good agreement with the findings of Berg et al. (2005a). It should be noted that Selby (2006) relied solely on a detailed analysis of traffic crash reports, not in-depth motorcycle crash data.

Peldschus et al. (2007) indicates a higher proportion of impacts (75%) with the rider/motorcycle upright prior to collision and a smaller proportion (21%) where the rider separated from the motorcycle prior to impact. A small portion of the crashes (4%) was found to involve sliding with no rider separation. Note that these findings were based on a total of 56 crashes from the DEKRA, COST, and Dutch MAIDS databases and included impacts with trees and poles as well as crash barriers. Hell and Lob (1993) indicated collisions where the rider slides along the pavement with no fixed object contact were found to be associated with a relatively low injury risk, even at relatively high speeds. No numerical values were presented to substantiate this statement, however.

Even less data is available regarding impact angle for motorcycle-barrier crashes. Gibson and Benetatos (2000) found that a majority of the impact angles were shallow; five of the eight fatalities had an impact angle of 45 degrees or less. The findings of Peldschus et al. (2007) similarly were based on 18 cases of motorcycles impacting road infrastructure from the GIDAS database. All impact angles were less than 45 degrees, with a majority (725) between one and 15 degrees.

Bambach et al. (2013) investigated 78 fatally injured riders in Australia and New Zealand and found that in approximately half (47%) of the cases the rider was upright at impact. In a similar proportion of cases (44%), the rider slid into the barrier. In these cases, the median impact angle with the barrier was 15.4 degrees.

3.3.3 Cable Barriers

MacDonald (2002), presumably based on a synthesis of the current literature, suggests that while wire cables tend to be perceived as the most dangerous portion of a steel barrier, it is much more likely that the posts are the actual cause of injury in motorcycle-barrier crashes. Using this rationale, the author indicates that concrete barriers and steel post/beam barriers present different levels of hazard to impacting motorcyclists. Candappa et al. (2005) highlights the concern of the motorcyclist community with the potential of being "sliced" by the wire ropes.

Mathematical dynamic model (MADYMO) (a software package used to analyze occupant safety systems for the transportation industry) simulations reported by Berg et al. (2005a) suggest a significant snagging potential of the rider limbs between the cables and the posts, resulting in high occupant decelerations and high predicted injury risk, regardless of impact angle or speed.

Mulvihill and Corben (2004) review the literature involving motorcycle impacts to wire rope and other roadside barriers. In addition to the review of the literature, the authors contacted a number of organizations working in a related field for additional information. Based on the available information, the authors conclude there is no reliable evidence to indicate that wire rope barriers are a greater or lesser risk to an impacting motorcyclist than any other barrier or no barrier at all.

Based on a detailed assessment of police-reported motorcycle crashes in New Zealand, Selby (2006) reported two motorcycle impacts to wire rope barrier. Both crashes occurred on state highways and involved an upright rider impacting the barrier. The exact wire rope barrier type and the rider helmet status were not indicated for either case. According to the police, one crash resulted in serious injury while the other resulted in minor injury; no fatalities were reported. The author does note, however, that the minor injury case involved a concussion, which would increase the severity to "serious" based on New Zealand guidelines.

As part of an evaluation of the Swedish 13-meter 2+1 "collision-free" roads, Carlson (2009) provides an analysis of motorcycle fatalities and serious injuries on these roadways that typically employ a cable median barrier to separate opposing traffic. A total of nine motorcycle fatalities were reported on the entire "collision-free" road network, with four of the fatalities involving cable barrier. No additional details on those four fatalities were provided. Carlson also notes that the proportion of motorcycle fatalities on these "collision-free" roads is 16%, compared to 11.5% for all roads. A slightly lower proportion of fatal + serious injury rate, normalized to a measure of traffic volume, was found for motorcyclists on these roads (7.8% compared to 9.3% on all roads). The author, however, does not indicate whether the traffic volume data used for this analysis included only motorcycles or all vehicles. Although Carlson concludes that there is no evidence to suggest that these "collision-free" roads are more dangerous for motorcyclists, it is not clear from the data presented whether there is an increased risk of cable barrier contact on these roadways or if there are differences in motorcycle usage of these roadways.

Pieglowski (2005) provides additional data, albeit older than that presented by Carlson, on the motorcycle-cable barrier issue. On the approximately 400 km of semi-motorway 2+1 roads, a total of 15 motorcycle crashes were noted between 1998 and 2004. Seven of these crashes involved an impact with a wire rope barrier, resulting in one fatality, five severe injuries, and two minor injuries; no additional details were provided on injury mechanisms or injured body regions. Nearly half of the 15 crashes occurred in the first 6 months of 2004. Although the rate of fatal/serious motorcycle crashes was very high for these semi-motorway roads, Pieglowski indicates that a similar 2+1 roadway with only road markings (no cable median barrier) had a slightly higher rate of fatal/serious injury motorcycle crashes. One large limitation of this study was a lack of motorcycle traffic data; an assumption was made that the motorcyclist traffic volume was 1% of the total roadway traffic for each roadway type. Unless motorcycle traffic data became available after this study, it is likely that Carlson (2009) made a similar assumption when computing motorcycle crash rates.

3.3.4 Current Motorcycle-Barrier Data Status and Data Needs

With respect to the biomechanics of motorcycle-barrier crashes, MacDonald (2002) indicates it is important to study real-world crashes to understand the conditions of contact and resulting injuries to the motorcyclist. The author suggests that comparative data on single-vehicle and single-motorcycle crashes into barriers is necessary and should focus on the impact conditions (speed, angle, and attitude), type and design of the barrier, area of the barrier contacted, and performance of the barrier (differing criteria depending on if a vehicle or motorcycle impacts the barrier). The overarching theme expressed by the author is there is currently insufficient information regarding the extent and nature of motorcycle impacts with traffic barriers.

Several other researchers have reached the same or a similar conclusion. Bly (1994) indicated there is "inadequate" information with respect to the effects of motorcyclists impacting wire rope and concrete barriers. The Federation of European Motorcyclists' Associations (FEMA 2000) notes although there are more than 20 papers on the subject, the studies are often "ancient" and few are truly relevant to the motorcycle-barrier crash issue. Candappa et al. (2005) notes the lack of crash data to adequately address the safety concerns of motorcycle-barrier impacts. An international workshop on motorcycle safety (OECD 2008) suggested that more research is needed to investigate the effects of the road environment on road users.

3.4 Motorcycle-Barrier Crash Testing

3.4.1 Research Tests

Quincy, Vulin, and Mounier (1988) developed two modified barrier designs intended to reduce the severity of crashes involving motorcyclists by reducing the potential for interaction with the posts. Four tests were conducted with an ATD sliding into the barrier at 55 km/h (34 mph) and 30 degrees. Although the ATD type was not specified by the authors, the ATD was likely a Hybrid II based on the publication time frame. Three tests were conducted with the modified steel barriers and one with a concrete barrier for comparison purposes. Based primarily on the measured ATD head acceleration, the authors conclude that both modified steel barrier designs are acceptable for restraining motorcyclists.

Ellmers (1997) presents background on the development of standardized procedures used to certify guardrail post protecting devices prior to installation on German roadways. The primary test involves a round wooden body impacting the protected post at an angle of 45 degree. The original test speed selected was 35 km/h (21.8 mph) based on the available crash data, but this was deemed not practical under the current state of the art. As a result, two speed classes were created: a 20 km/h (12.4 mph) low-speed test and a future 35 km/h high-speed test. Evaluation of the test hinged on the deceleration of the wooden body with a 40-g limit for a 3-ms peak and 70-g maximum. In addition to the impact test, other considerations for post protectors included winter functioning, recycling, ease of installation, and connection strength (if device consists of multiple parts). Criteria for installation of these protectors, as suggested by the German Ministry of Transport, are the frequency of motorcyclists, crash rate, and roadway alignment.

Berg et al. (2005a) used real-world motorcycle-barrier crash data to select two motorcycle-barrier crash test configurations: a motorcycle impacting the barrier upright and a motorcycle impacting the barrier while sliding on its side. Six tests were conducted, four with traditional barrier designs and two with a modified barrier design. The modified barrier design consisted of a closed box profile top rail and a lower rail below the primary rail element. For the existing barriers, a sliding and upright test were conducted with the concrete barrier as well as an upright test with a steel I-beam post barrier (EDSP) barrier and a sliding test with a steel sigma-shaped post (ESP) barrier. Impact velocity was 60 km/h (37 mph) with impact angles of 12 degree and 25 degree for the upright and sliding tests, respectively. Note that the sliding test is initiated by a rig that maintains the rider/motorcycle combination at a 45 degree angle just prior to impact with the barrier. All tests used a 180-kg Kawasaki ER 5 Twister motorcycle and a helmeted Hybrid III 50th-percentile male ATD. High-speed video and the measured ATD loads/accelerations were used to assess the test.

For the upright EDSP test, the ATD responses were well within the NHTSA-prescribed limits, but the ATD slid along the top of the barrier and aggressively snagged on the open profile of the barrier. For the upright concrete barrier test, the ATD responses were well within the limits, but the author's note the barrier fails to dissipate much of the kinetic energy of the motorcycle/motorcyclist, which increases the risk of the rider being deflected into oncoming traffic. For the sliding ESP test, the head injury criterion (HIC) for the initial impact was in excess of the limit, 1,074 compared to 1,000, and the left shoulder joint of the ATD was broken as a result of the impact. The results of the sliding test into the concrete barrier also resulted in high ATD-based injury criteria values with the HIC value of 1,346. For the modified barrier upright test, the ATD-based injury criteria values in most cases were well below the limits (with the exception of the femur compression), and the ATD did not excessively snag on the top of the barrier. For the modified barrier sliding test, the ATD injury criteria were much less than the prescribed limits (with the exception of the 3-ms head acceleration). Although the modified barrier shows improved performance with respect to ATD injury criteria, it is unknown whether the Hybrid III ATD is appropriate to predict the human response in motorcycle-barrier impacts. A summary of this crash test series is presented by Berg, Rucker, and Konig (2005), but in much less detail than Berg et al. (2005a).

3.4.2 French INRETS/LIER Test Procedure

The INRETS/LIER test procedure [as described by Peldschus et al. (2007)] is similar to tests conducted by Quincy, Vulin, and Mounier (1988). While the impact angle remains at 30 degrees, a slightly higher impact speed of 60 km/h (37 mph) is noted. Also, the authors note two different ATD sliding configurations (both impacting at 30 degrees): (1) the top of the ATD head pointed in the impact direction and (2) the ATD parallel to the barrier installation. The ATD used in this test procedure consists of the following components: (1) a Hybrid II thorax, limbs, and shoulders; (2) a pedestrian pelvis to provide a standing posture; (3) a Hybrid III head and neck; and (4) motorcyclist equipment including a suit, gloves, boots, and a helmet. The ATD-based biomechanical thresholds used to evaluate these tests include a resultant head acceleration of 220 g, a HIC value of 1,000, a neck flexion moment of 190 N-m, and a neck extension moment of 57 N-m.

3.4.3 German BASt Test Procedure

The German (BASt) tests were conducted with the goal of developing a new motorcyclist-barrier test procedure (Peldschus et al. 2007). The test series was a continuation of the Berg et al. (2005b) tests. The impact scenarios were the same as previously described, but the more recent tests used a motorcycle anthropometric test device (MATD). The primary differences from a Hybrid III ATD include nine uni-axial accelerometers in place of a single tri-axial accelerometer in the head; potentiometers to measure x- and y-direction intrusion and intrusion rate in the upper and lower chest; frangible femurs and tibias; and shear pins coupled with elastic-plastic knee elements to better reproduce twisting of the knee. There also was an effort to separate primary impacts (i.e., with the barrier) from secondary impacts (i.e., with the ground after separation from the barrier) in the more recent tests.

3.4.4 Spanish UNE 135900 Standard Crash Test Procedure

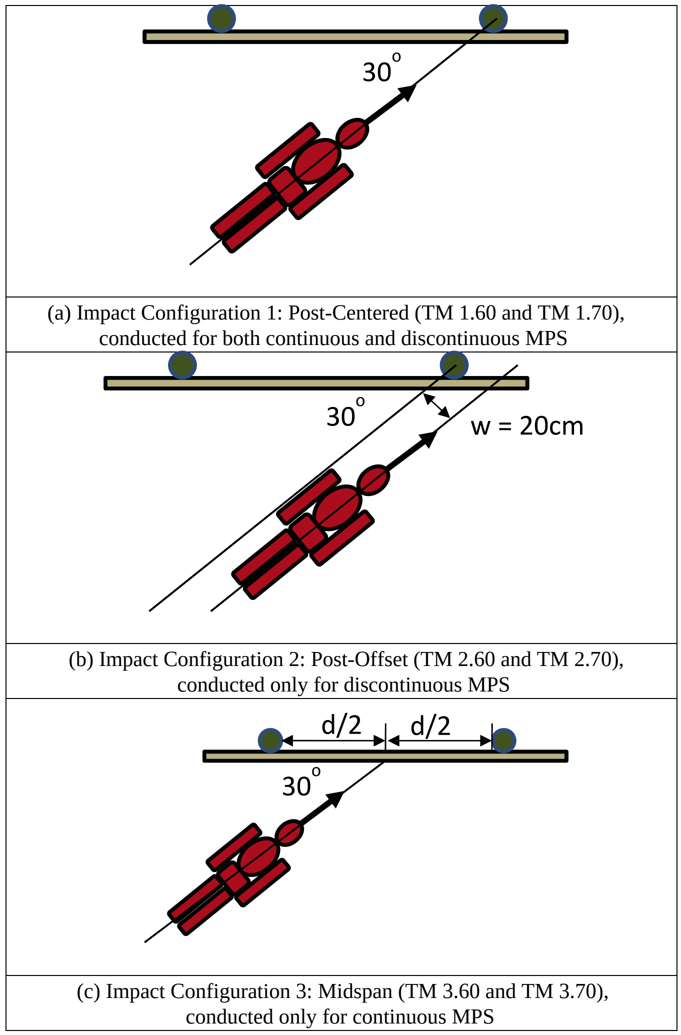
In 2005, a motorcycle-barrier test procedure, Standard UNE 135900, was developed by Centre for Automotive Research and Development (CIDAUT) under the requirements of the Spanish Transport Ministry (Peldschus et al. 2007; Garcia et al. 2009). For all tests, the rider is separated from the motorcycle and sliding face-up into the barrier at 60 km/h (37 mph) and 30 degrees. Unlike the INRETS/LIER procedures, the CIDAUT procedures prescribe that the ATD always impacts headfirst with the spine aligned with the 30-degree line. The following three impact scenarios are prescribed under the standard:

1. Centered post impact – trajectory of ATD would result in head impact with the center of the post.
2. Eccentric post impact – offset of centered post impact trajectory by a specified perpendicular distance.
3. Centered rail impact – trajectory of ATD resulting in an impact halfway between two posts.

Scenario 1 is applicable to continuous motorcycle protection systems (e.g., a continuous lower rail element) and punctual motorcycle protection systems (e.g., post protection only). Scenario 2 is intended for punctual systems only, while Scenario 3 is for continuous systems only. A Hybrid III ATD is required and must be equipped with a Regulation ECE R22 compliant helmet and an EN-1621 compliant leather motorcycle suit. Impact severity is evaluated using HIC (36-ms version), neck forces (F_x, F_y, and F_z), and neck moments (M_x and M_y only). Compared to the INRETS/LIER procedures, these procedures specify a more stringent limit on HIC (650 compared to 1,000) as well as neck extension (42 N-m compared to 57 N-m). Both procedures specify a neck flexion limit of 190 N-m. Other performance requirements include no ATD dismemberment, no cuts to the ATD clothing, no breakage of the ATD (with the exception of the clavicle), and no snagging of the ATD on any part of the safety device. This standard also specifically states that the motorcycle protection device must guarantee that it will not negatively affect performance for vehicle impacts based on the European EN-1317 crash test standards.

3.4.5 European CEN TS 1317-8 Crash Test Procedure

European Technical Specification CEN TS 1317-8 specifies a full-scale crash test to evaluate the performance of MPS affixed to a longitudinal barrier (CEN 2012). CEN TS 1317-8 was adapted from the earlier Spanish UNE-135900-2008 standard (Garcia et al. 2009). The CEN TS 1317-8 test is designed to emulate the situation in which a rider leaves the motorcycle and slides along the ground into a barrier. In this technical specification (TS), an ATD is placed on the ground in a face-up supine position as shown in Figure 3-4, and propelled into the barrier in a series of tests.



(a) Impact Configuration 1: Post-Centered (TM 1.60 and TM 1.70), conducted for both continuous and discontinuous MPS

(b) Impact Configuration 2: Post-Offset (TM 2.60 and TM 2.70), conducted only for discontinuous MPS

(c) Impact Configuration 3: Midspan (TM 3.60 and TM 3.70), conducted only for continuous MPS

Figure 3-4. CEN TS 1317-8 impact configurations.

The specific test matrix is dependent upon the design of the MPS as shown in Table 3-4. Separate tests are prescribed for continuous MPS (CMPS) and discontinuous MPS (DMPS). An example of a DMPS would be a post-padding system. The ATD can be propelled at an impact speed of either 60 or 70 km/h. Three impact locations are prescribed: the post-centered and post-offset impact locations reflect the concern that posts are the principal source of rider injury; and the midspan impact location is chosen to check whether a CMPS can prevent a rider from sliding between posts and striking some potentially injurious object (e.g., a utility pole) that is located behind the barrier system.

Table 3-4. CEN TS 1317-8 test matrix.

Test	MPS Design	Impact Configuration	Speed (km/h)
TM 1.60	CMPS and DMPS	Post-Centered	60
TM 2.60	DMPS	Post-Offset	60
TM 3.60	CMPS	Midspan	60
TM 1.70	CMPS and DMPS	Post-Centered	70
TM 2.70	DMPS	Post-Offset	70
TM 3.70	CMPS	Midspan	70

The ATD is a modified 50th-percentile Hybrid-III dummy equipped with a pedestrian kit that allows the dummy to be situated in a standing position. The ATD is equipped with a prescribed motorcycle helmet and motorcyclist protective clothing. The head of the ATD is instrumented with an array of accelerometers. The neck of the ATD is instrumented with a multi-axis load cell. The TS prescribes maximum acceptable values for the HIC and neck loads in compression, tension, shear, and bending.

The performance of a subject MPS is determined by the speed class at which the device passes all minimum biomechanical injury criteria prescribed in CEN TS 1317-8. The test is currently not mandatory across Europe. An MPS approved in one country may not receive approval in another country.

Grzebieta et al. (2013) evaluated the applicability of CEN TS 1317-8 to real-world crashes. The authors noted that the standard only considers head and neck injuries, despite evidence from injury studies that the thorax is the most commonly injured body region in rider collisions with guardrail. The authors also expressed concern that MPS performance is only tested in the sliding configuration, despite evidence that approximately half of collisions occur with the rider upright. They proposed a thoracic injury criterion be included in the test and an additional upright test be added to the standard.

3.5 Potential Motorcycle-Barrier Crash Countermeasures

Potential countermeasures developed to mitigate motorcycle-barrier crashes, sometimes called MPS, can be categorized into one of two categories based on the intent of the design.

- DMPS are designed to reduce the severity of the post impact through redesign of the post cross section or use of an energy-absorbing post cover; and
- CMPS are designed to prevent post impact with the addition of a lower rail element or redesign of the barrier rail. These systems can also prevent riders from sliding between posts and striking an injurious fixed object behind the barrier system.

3.5.1 Discontinuous MPS (DMPS)

Alternative Post Designs

Several alternative post designs have been developed that consist of less aggressive edges compared to traditional I-beam type guardrail posts. The three most common alternatives are shown in Figure 3-5 (FEMA 2000) from the final report of the Motorcyclists and Crash Barriers Project.

Post Padding Systems

Table 3-5 presents examples of post padding systems that can be retrofit to existing longitudinal barrier posts.

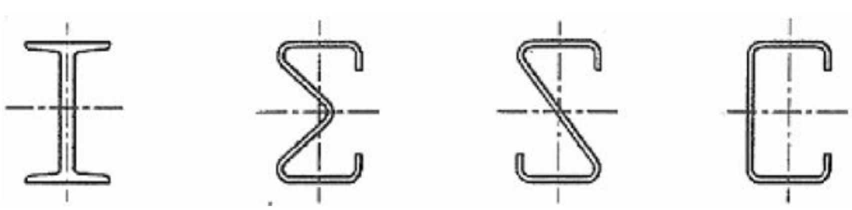
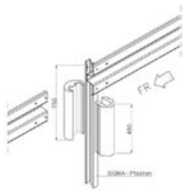


Figure 3-5. Traditional I-Beam Post* (left) *and less aggressive Sigma* (left center)*, Z-shape* (right center)*, and C-shape* (right) *barrier posts [figure adapted from FEMA (2000)].

Table 3-5. Examples of DMPS.

Device Name	Company	Description
SPU 	Firma ADV (Anpralldämpfer Vertriebsgesellschaft)	The SPU, or Schutzplankenpfostenummantelung, from Firma ADV consists of two half shells that are designed to encase the guardrail post (MacDonald 2002).
Rectangular CBP 	Salzer Formtech	The Rectangular CBP (crash barrier protector) is a singular three-fourths shell designed to cover the front and sides of the guardrail post and distribute and absorb the forces from a motorcyclist impact (FEMA 2000).
SPU Crash Absorber 	Volkman & Rossbach	The SPU Crash Absorber is a polypropylene energy-absorbing device intended to protect impacting motorcyclists from the barrier posts. The SPU is cited as having resistance to environmental conditions, the ability to accommodate numerous types of guardrail posts, and the ability to install the device without any tools (Vieira et al. 2008).
Stack Cushion 	Ingal Civil Products	Similar in design to the SPU, the Stack Cushion is designed to be attached to the posts of wire rope barriers and intended to reduce the impact severity in the event a motorcyclist impacts the post. The device is 200 mm in diameter and can accommodate a post up to 100 mm × 50 mm. This system can be installed without dismantling the existing barrier. Reprinted with permission from Ingal Civil Products. .
ProMBS 	Research concept only	The ProMBS (Protection-Motorcycle and Bicycle Safety), a countermeasure developed in Italy, is constructed of high-density polyethylene foam and is intended to prevent impact with the sharp edges of the post and absorb a portion of the rider impact energy (Janssen et al. 2005).

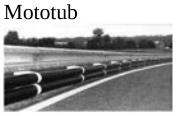
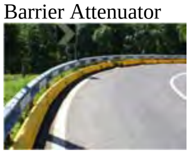
3.5.2 Continuous MPS (CMPS)

Table 3-6 presents examples of continuous systems that can be retrofit to existing longitudinal barriers. CMPS are designed to prevent post impact with the addition of a lower rail element or redesign of the barrier rail. These systems also can prevent riders from sliding between posts and striking an injurious fixed object behind the barrier system.

Countermeasure Testing

Jessel (1986) as summarized by FEMA (2000), evaluated impact attenuators fitted to crash barrier posts and found that these devices reduced chest deceleration to a level below the human tolerance threshold level. Based on a review of previous literature, Jessel suggests that the typical injuries for motorcycle-barrier crashes are fractures, open fractures, serious internal injuries, and amputations. Schmidt et al. (1985), as summarized by FEMA (2000), conducted post-mortem human subject (PMHS) tests into unprotected and protected crash barrier posts. The tests simulated a crash where a motorcyclist slides on his back at 32 km/h (20 mph) and an angle of 15 degree into a barrier post. For posts fitted with impact attenuators, injury was reduced to the AIS 1 or 2 levels compared to AIS 4 level injuries for an unprotected post under the same impact conditions.

Table 3-6. Examples of CMPS.

Device Name (Image if available)	Company	Description
Ecran Motard 	SEC-Envel	The Ecran Motard, developed by SEC-Envel, is a metal shield designed to be attached below the W-beam and prevent riders from impacting the barrier posts. According to FEMA (2000), this device has been in use in France since 1997 and approximately 500 kilometers were installed across France by the year 2000 (Mehta et al. 2009).
Plastrail 	Sodilor	Sodilor's Plastrail (Mehta et al. 2009) is another design intended to be retrofit to existing guardrails. It is constructed from plastic and designed to enlarge the surface area of the post, distributing impact forces over a larger area to reduce injury risk.
Mototub 	Sodirel	The Mototub by Sodirel is similar to the Plastrail but is fabricated from 70% recycled material (FEMA 2000). This system may be adaptable to cable barrier systems.
Ecran-Moto 	Solosar	The generic motorcyclist protection, Ecran-Moto is an underrun protection device similar to the SEC-Envel device. A secondary rail is attached to an existing W-beam barrier via suspension lugs. The turned-in edges create minimally aggressive geometry. Reprinted with permission from Solosar.
DR-46 Motorcycle Barrier Attenuator 	Lindsay Transportation	The DR-46 is a polyethylene device installed below the beam of a standard guardrail to prevent a motorcyclist from impacting the barrier posts. The standard color for this device is yellow to better warn riders of the barrier presence. The device is flexible and can follow a curve radius as small as 50 ft. Reprinted with permission from Lindsay Transportation.
CuStoM Road Safety Barrier 	Centro Sviluppo Materiali	The CuStoM (Containment urban SysTem fOr Motorcyclists) Road Safety Barrier has been designed to address motorcycle-barrier crash concerns and passenger vehicle performance. It is constructed of thin sheets of high-strength steel of differing thickness to absorb the kinetic energy of an impacting rider and provide a snag-free surface. Successful full-scale crash testing with vehicles and motorcyclists is noted, but detailed information was not presented (Janssen et al. 2005).
Basyc 	Cegasa International	The Basyc system was developed in Spain and consists of a continuous mesh attached to a modified W-beam guardrail. The mesh, consisting of polyethylene, polyester, Teflon, and paraffin, spans from the lower protrusion of the W-beam to the ground. Tension in the mesh absorbs some of the energy of an impacting motorcyclist and prevents impact with the posts. Other properties of the mesh are it is UV resistant, fireproof, recyclable, and contains perforations on the lower portion to allow snow and rain runoff to pass through (Cegasa International 2009). Modifications to the standard strong post W-beam barrier include a different blockout mechanism and a lower shoe, mounted on the post near the ground, allowing the mesh to be connected at the ground line. These barrier systems have been installed in several locations in Spain and one location in South Australia.
Lifeguard (Photo N/A)	Santedge	The Santedge Lifeguard is a cover designed to protect a motorcyclist from impacting the posts or cables of a wire rope barrier system (Mulvihill and Corben 2004). Two-meter sections of the cover are linked together to provide continuous coverage of the cable barrier. According to the manufacturer, the cover does not interfere with the functionality of the wire rope barrier. According to Mulvihill and Corben (2004), this barrier has not yet been tested for a vehicle or motorcycle impact.

An Austrian study conducted by Hofbauer in 1995 (summarized by Janssen et al. 2005) indicated that post protection decreases the impact force by 50% and roughly doubled the impact time in comparison to an unprotected post. Other stated benefits include a lifespan of at least 5 years, ability to be recycled, and ability to perform under more than a single impact (e.g., it returns to its original shape). It is noted that the post protectors do not adversely affect the performance of the barrier with respect to passenger car impacts, although no substantiating crash testing was noted.

The Basyc system was the only countermeasure to have crash test data available for passenger vehicle impacts and motorcycle impacts. Two motorcycle tests were conducted under the Standard UNE 135900 (CIDAUT 2005a-b). In CIDAUT (2005a), the ATD was slid head first into a barrier post location at 60 km/h and 30 degrees. In CIDAUT (2005b), the impact conditions remained the same, but the ATD impacted midspan between two posts. Both tests resulted in redirection of the ATD and no impact with the barrier posts. The reported HIC was 472 for the first test and 59 for the second test, well below the HIC limit of 1,000. Two tests, EN1317 TB11 and EN1317 TB32, also were performed to determine the crash performance of this barrier with respect to passenger vehicles (CIDAUT 2006a-b). EN1317 is the document prescribing the European crash test standards for passenger vehicle impacts to barriers. For test TB11, a 900-kg passenger car impacts the barrier at 100 km/h and a 20-degree angle. For test TB32, a 1,500-kg passenger car impacts the barrier at 110 km/h and a 20-degree angle. In both vehicle tests, the Basyc barrier successfully redirected the vehicle with all the occupant risk parameters falling within acceptable limits. Note that analogous U.S. barrier crash test procedures also specify a large pickup truck test; it is currently unknown how the Basyc system would perform if impacted by a large pickup.

3.6 Pilot Tests of MPS in the United States

Two pilot tests of MPS have been conducted to date in the United States, the first conducted by California Department of Transportation (Caltrans) and the second by NCDOT. Both pilot tests used the Lindsay Transportation System's DR-46 Barrier Attenuator system.

- Caltrans pilot test. The Caltrans system was installed on Highway 49 near Auburn, California, on a sharp turn in the road, a canyon road popular with motorcyclists. A length of 260 ft of the MPS was installed. To our knowledge, there has not been a published evaluation of the performance of this system.
- NCDOT pilot test. The DR-46 system was installed at several curves along NC 143 where numerous crashes into the barrier had occurred, including collisions resulting in two fatalities. The MPS was installed on a total length of 4,500 ft of barrier for an estimated cost of $135,000 (NCDOT 2018). A press release by NCDOT reported that no motorcyclists had impacted this system to date (NCDOT 2018)]. Once at least 2 years of data have been collected after installation, the performance of the MPS will be analyzed to determine the effect on crashes and motorcyclist injuries.

3.7 Data Collection Methodology

Smith et al. (2001) reported on the development of a methodology to collect on-scene in-depth data for motorcycle crashes in Thailand. This data collection methodology was developed from the procedures used in the Hurt motorcycle crash study conducted in the Los Angeles area in the late 1970s (Hurt, Ouellet, and Thom 1981a). A particular focus of the study was how the Hurt study, now several decades old, was adapted to Thailand with the expectation that some of the solutions and adaptations developed can be applied to future in-depth motorcycle crash research efforts. With respect to the methodology, the authors focused on the identification of a suitable research partner, training of investigators, data collection, crash notification challenges, and crash reconstruction.

The primary criterion for a research partner was access to both engineering consultants and qualified medical personnel. Training for research teams was reduced to 3 months (compared to 6 months for the Hurt study investigators) and focused on crash reconstruction methodology, motorcycle dynamics, interviewing methods, photography, rider injury mechanisms, human factors, team field relations, and motorcycle systems. As with the Hurt study, timely motorcycle crash notification was deemed a critical factor. To ensure timely crash notification, the Thai investigation teams monitored communications at the ambulance dispatch centers at large hospitals. In the Hurt study, the investigators monitored the fire department ambulance dispatch center communications with supplemental telephone communication from the police department dispatchers. Another primary difference in data collection methods stemmed from the increased speed at which police conducted investigations in Thailand, which afforded the Thai researchers half an hour or less at the crash scene (compared to an hour for the Hurt study investigators). As a result, the Thai study employed investigation teams of four to six (instead of the two- or three-member teams used in the Hurt study) to ensure efficient collection of crash data. A complication of using these larger teams was the increased communication between team members to ensure a coordinated data collection effort. Overall, the effort to adapt the Hurt methodology in Thailand was successful; the methodology may be adaptable for future U.S. or international motorcycle crash studies.

In the context of existing in-depth crash data available, Ouellet (2006) examines how on-scene versus follow-up investigation methods affect the sample of data collected. The focus is on three primary in-depth motorcycle crash data: (1) the Hurt study near Los Angeles in the late 1970s, (2) a Thailand study near Bangkok and "upcountry" in the late 1990s, and (3) MAIDS in France, Italy, Germany, Spain, and Netherlands in the late 1990s. The on-scene, or "hot," investigations were defined as those conducted immediately following the crash (during the police investigation), while the follow-up, or "warm," investigations were those investigated several hours (up to 24 hours) after the crash.

In the Hurt study, approximately two-thirds of the crashes were hot, while the remaining third were warm. Riders in warm crashes had significantly higher chance of fatality or hospitalization compared to riders in hot crashes. Riders in hot crashes were more likely only to need first aid at the scene of the crash compared to riders in warm crashes. The differences in warm crashes are attributed (at least in part) to differences in logistics; warm investigations are much easier if the vehicle has been impounded and/or the rider hospitalized, biasing the collected cases toward the more serious crashes. In the Thailand study, almost all of the cases were hot due to the perfunctory nature of the police reports and the lack of riders with telephones. Despite the difference in warm crashes among the two studies, there was only a slight difference in the distributions of injury in the data. In lower-severity crashes, Thailand riders were more likely to go to the emergency room or be admitted for less than a day than riders in Los Angeles. By comparison, the MAIDS study was much more limited, as the MAIDS study did not report the proportion of hot and warm cases. Although an examination of the MAIDS data appear to point toward warm investigations, Ouellet notes that differences could be attributed not only to sampling methods but to region, or both factors.

The hot cases appear to be more representative of the overall motorcycle accident population and had approximately three-fourths of riders involved in relatively minor crashes. Ouellet suggests that it may be undesirable to collect this large number of minor crashes. In such a case, a larger proportion of warm cases may be warranted. The noted disadvantages of the warm cases were the time required to complete them and the likelihood of missing data. Ouellet suggests, at a minimum, that researchers distinguish between hot and warm investigations to allow for post hoc analysis.

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Lin and Kraus (2008) provided a critical review of current motorcycle crash research focusing on methodological issues in current and past study approaches, such that future studies avoid generating biased results, and, ultimately, the development of ineffective intervention programs. There were six primary areas of focus: (1) measurement of the population at risk of motorcycle crash injuries, (2) completeness of injury data across the spectrum of all motorcycle crashes, (3) validity of crash and injury data sources, (4) exposure data issues, (5) concerns with injury severity scales, and (6) analysis of correlated injury data.

Although this paper focused on all motorcycle crashes, there were several observations made by the authors that may be applicable to the motorcycle-barrier crash subset. With respect to estimating the at-risk population, the authors cite several instances where the use of registered motorcycles may over- or underestimate the true at-risk population, such as the presence of unlicensed riders, presence of registered but unused motorcycles, or certain area-specific analyses (i.e., in tourist areas). The authors suggest that vehicle miles traveled (VMT) is a better measure but person miles traveled is likely the most accurate (but most difficult to acquire). A recurring theme with the examined data sources (death certificates, hospital records, and police reports) was the inability to capture all motorcycle crashes, especially those resulting in minor injury. The authors stress the importance of a representative sample (including the minor injury crashes) for estimating the incidence and patterns of motorcyclist injuries. The authors also note that, compared to occupants of other motor vehicles, injuries to motorcyclists are consistently less likely to be reported to the police (and that the portion reported to police has been as low as 30%). With respect to the measurement of injury severity, the authors caution that the AIS scale cannot be treated as a linear scale (i.e., the difference between AIS 1 and AIS 2 is not the same as the difference between AIS 4 and AIS 5). Also, it is not known how the same injury severity values compare for differing body regions.

Hurt, Ouellet, and Thom (1981a) noted that the Hurt study originally planned to collect OSID data for all crashes occurring in the study area, but only succeeded in collecting OSID data from 20% of the total crashes (900 of 4,500 crashes). The authors indicated that the difficulty was primarily in maintaining the notification process, which had to operate without conflict with the EMS and law enforcement personnel priorities (i.e., the care for the injured and control of the crash scene).

In general, data for the MAIDS study (ACEM 2004) was collected in a manner very similar to the Hurt study with the exception of the exposure data. Due to legal reasons, it was not always possible to stop uninvolved riders passing by the crash scene (some time after the crash occurred). Instead, the investigating teams conducted motorcycle rider interviews at randomly selected gas stations within the sampling area to obtain the relevant motorcycle and rider information.

3.8 Conclusions

Based on a focused review of available literature relevant to motorcycle-barrier crashes, several conclusions can be drawn about each of the three focus areas of this literature review. These conclusions are summarized below.

3.8.1 Motorcycle-Barrier Crash Characteristics

- Especially in the United States, there is little information available specific to motorcycle-barrier crashes, and the information that is available is more than 25 years old. Numerous researchers have indicated the need to collect more data relative to this crash mode, especially impacts with cable and concrete barriers.

- Compared to all motorcycle crashes, motorcycle-barrier crashes are consistently noted as resulting in more severe injuries. The extent to which these crashes are more severe, however, varies by study.
- For researchers conducting real-world studies, as well as those conducting simulations and/or crash tests, there is strong consensus among the published literature that unprotected guardrail posts are the primary injury-causing element in this crash mode.
- From the motorcycle-barrier crash data available, head, chest, and the lower extremities appear to be the primary rider body regions injured.
- Little has been published on the crash configuration in this crash mode in the United States (i.e., the proportion of riders sliding into the barrier versus those impacting the barrier while upright). Further, in the international data available, there are only five studies differentiating crash configuration for less than 250 total motorcycle-barrier crashes (combined), and there is some discrepancy between the findings.
- There is very little evidence on how roadway geometric characteristics influence motorcycle-barrier crashes. At least one study, however, has identified the outside of curves as problem areas for these crash types.

3.8.2 Existing Motorcycle-Barrier Crash Countermeasures

- For locations where barrier removal is not feasible or not prudent, several potential countermeasures currently exist to mitigate the consequences of a motorcycle-barrier impact. These devices generally fall into two categories: (1) devices that reduce the severity of post impact through post redesign or shielding, and (2) devices that prevent impact with the post by the addition of a lower rail element or redesign of the rail element.
- Despite the existence of a number of potential countermeasures, the published testing experience with these devices is relatively limited; this is especially true for evaluating the effect that these countermeasures might have on passenger vehicle impacts. The limited biomechanical testing, however, does indicate that these devices are likely to reduce the severity of motorcycle-barrier crashes.

3.8.3 Data Collection Methodology

- In-depth motorcycle crash data has been collected almost exclusively by medical experts coupled with experts in traffic safety research.
- The approach used to collect data in the Hurt study has successfully been adapted more recently in Thailand.

3.8.4 Crash Tests of MPS

- There are currently four crash test procedures for evaluating MPS: the French LIER procedure, the German BASt procedure, the Spanish UNE 135900 procedure, and the European Technical Specification CEN TS 1317-8.
- The most widely accepted procedure is the European Technical Specification CEN TS 1317-8, which specifies a full-scale crash test to evaluate the performance of MPS affixed to longitudinal barrier. The CEN TS 1317-8 test is designed to emulate the situation in which a rider leaves the motorcycle and slides along the ground into a barrier.

3.8.5 Pilot Tests in the United States

- Two pilot tests of MPS have been conducted to date in the United States: first by Caltrans and the second by NCDOT. Both pilot tests used the Lindsay Transportation System's DR-46 Barrier Attenuator system.

3.9 Gaps and Research Needs

This literature review has identified a number of gaps in the literature and research needs for U.S. motorcyclists.

- There are currently no guidelines available to U.S. transportation agencies, policymakers, or engineers for how to protect motorcyclists who strike traffic barriers.
- On U.S. roadways, the trade-offs between colliding with traffic barriers versus the fixed objects (e.g., utility poles) that may exist behind these barriers are unknown.
- There is only limited information on U.S. roads of rider impact configuration (i.e., sliding or upright) when striking a longitudinal barrier.
- There is no recent information of rider injury patterns in U.S. motorcyclist-barrier collisions. These injury causation mechanisms are needed to prioritize longitudinal barrier design or selection of MPS.
- It is unknown how barriers certified in MASH crash tests would perform if retrofit with MPS.
- The current most widely accepted crash test, CEN TS 1317-8, tests only riders who slide into a barrier, and only considers head and neck injuries. Missing is a test for the approximately half of all riders who strike barriers while upright, and/or at risk of thoracic injuries, the most common serious injury mode.

CHAPTER 4

Characteristics of Fatal Motorcycle-to-Guardrail Crashes

4.1 Introduction

Motorcycle rider fatalities exceeded car occupant fatalities in guardrail crashes for the first time in 2004 (Figure 4-1). Motorcycle-guardrail crashes account for more fatalities than any other vehicle type, but motorcycles comprise only 3% of all registered vehicles in the United States. This chapter investigates factors associated with fatal motorcycle-guardrail crashes. Three categories of factors were analyzed: roadway, rider, and motorcycle characteristics. Additionally, trends in fatal motorcycle-guardrail crashes were compared to trends for all fatal crashes.

4.2 Objective

This study seeks to determine the factors that influence fatal motorcycle-guardrail crashes in the United States. This study seeks to answer three specific questions:

- What road conditions are associated with fatal motorcycle-guardrail crashes?
- Who are the people involved in fatal motorcycle-guardrail crashes?
- What types of motorcycles are involved in these crashes?

These three questions will be evaluated in the context of all fatal motorcycle crashes. This allows for an understanding of characteristics unique to fatal guardrail crashes as compared to the characteristics of all fatal motorcycle crashes.

4.3 Methods

FARS data from 1999 to 2008 were used to complete the analysis of the similarities and differences between fatal motorcycle-guardrail crashes and all fatal motorcycle crashes. Guardrail crashes were determined using the most harmful event for the crash, and included collisions with both the guardrail face and the guardrail end. Each comparison was tested using a χ^2 goodness-of-fit test to determine if trends were significantly different between all fatal motorcycle crashes and fatal motorcycle-guardrail crashes.

The set of all fatal motorcycle crashes included these fatal motorcycle-guardrail collisions. To determine the characteristics of riders involved in crashes, operators and passengers who were fatally injured were included in the analysis. People who were involved in a fatal crash, but not fatally injured, were not included in the analysis of characteristics of riders. Environmental characteristics were based on the number of crashes as opposed to the number of motorcycles involved in crashes. Hence, crashes that involved multiple motorcycles were only included once in the analysis of environmental characteristics. All motorcycles involved in fatal crashes were included for analyses of vehicles.

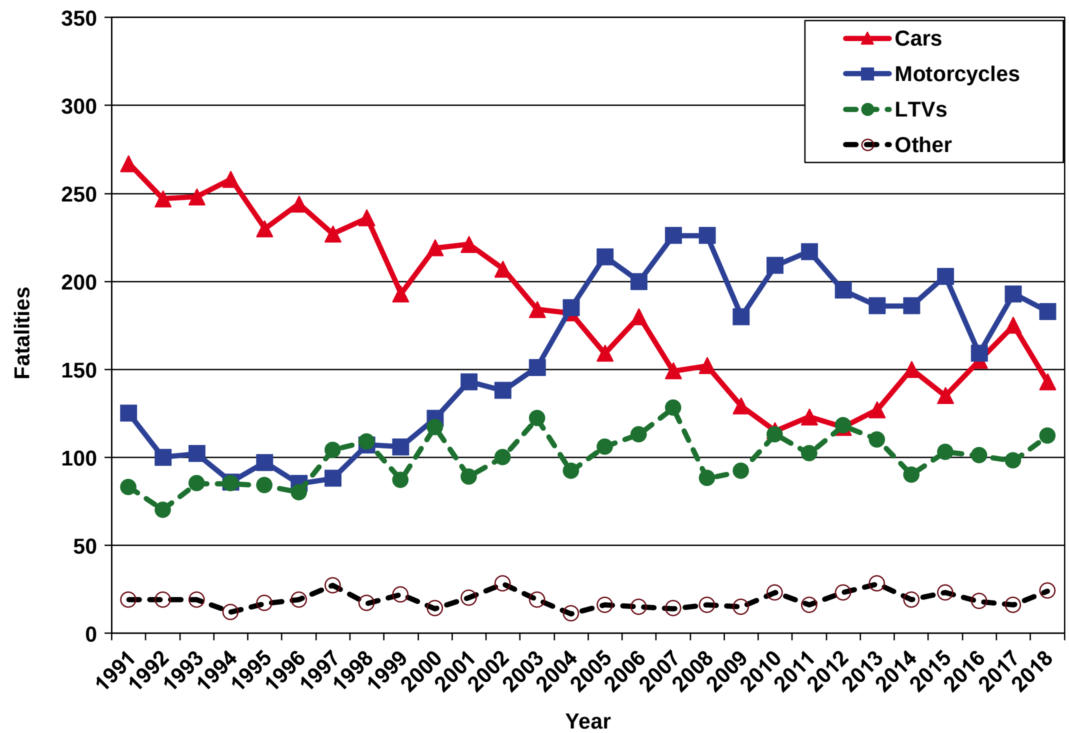


Figure 4-1. Motorcycle rider fatalities exceeded car occupant fatalities in guardrail crashes for the first time in 2004 (FARS 1991–2018).

4.4 Results

From 1999 to 2008, there were 38,276 fatal motorcycle crashes and 1,759 fatal motorcycle-guardrail crashes. These crashes are summarized in Table 4-1.

The number of fatal motorcycle crashes increased over the time period analyzed (Figure 4-2). Likewise, the number of fatal motorcycle-guardrail crashes increased at a similar rate. In the past decade, the number of fatal motorcycle crashes has been increasing at an average rate of 9% per year, and the number of fatal motorcycle-guardrail crashes has been increasing at an average rate of 10% per year.

In 1999 there were 5.8 fatal crashes per 10,000 registered motorcycles and in 2008 there were 6.6 fatal crashes per 10,000 registered vehicles. However, the rate peaked above 7.0 fatal crashes per 10,000 registered vehicles in 2005. Figure 4-3 shows the crash rate for all fatal motorcycle

Table 4-1. Summary of fatal motorcycle crashes (FARS 1999–2008).

	Fatal Motorcycle Crashes	Fatal Motorcycle-Guardrail Crashes
Number of Crashes	38,276	1,759
Total Vehicles Involved	62,056	1,867
Motorcycles Involved	38,434	1,759
Number of Motorcyclists Involved	43,530	1,945
Number of Motorcyclists Fatally Injured	39,468	1,803

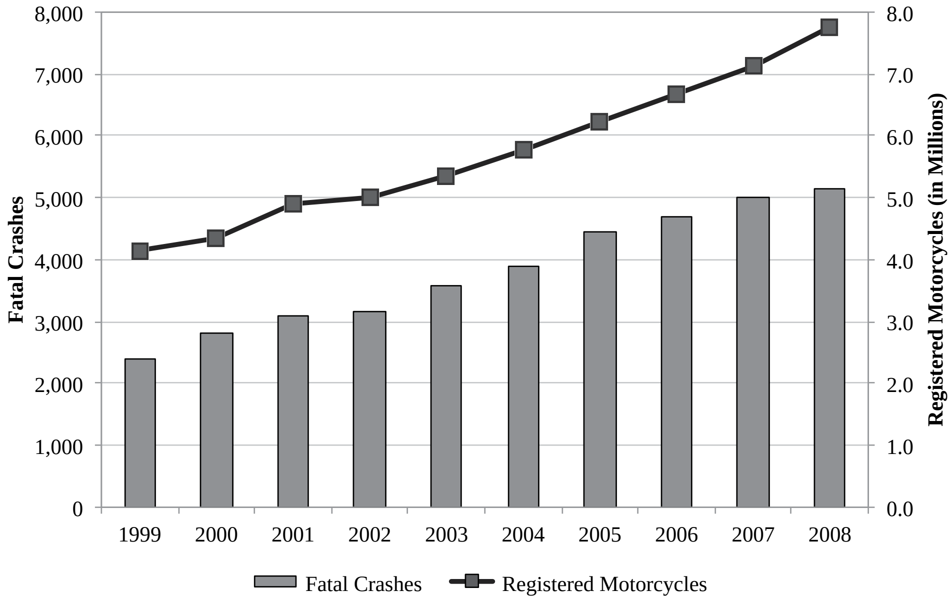


Figure 4-2. Fatal crashes and registered motorcycles (FARS 1999–2008, Traffic Safety Facts 2009).

crashes and fatal motorcycle-guardrail crashes. As shown, the rates of fatal guardrail crashes generally follow those of all fatal motorcycle crashes; however, the magnitudes of the rates are very different.

From 1999 to 2008, 62,056 vehicles (of all types) were involved in fatal motorcycle crashes, 64% motorcycles. As shown in Figure 4-4, the overwhelming majority (95%) of fatal motorcycle-guardrail collisions were single-vehicle crashes. As might be expected, most (94%) of the 1,867 vehicles involved in fatal motorcycle-guardrail crashes were motorcycles. However, there is no evidence to show the indirect involvement of other vehicles in these crashes. The trends in vehicle involvement between all fatal crashes and fatal guardrail crashes were found to be significant ($\chi^2 = 1631.1$, $p < 0.001$).

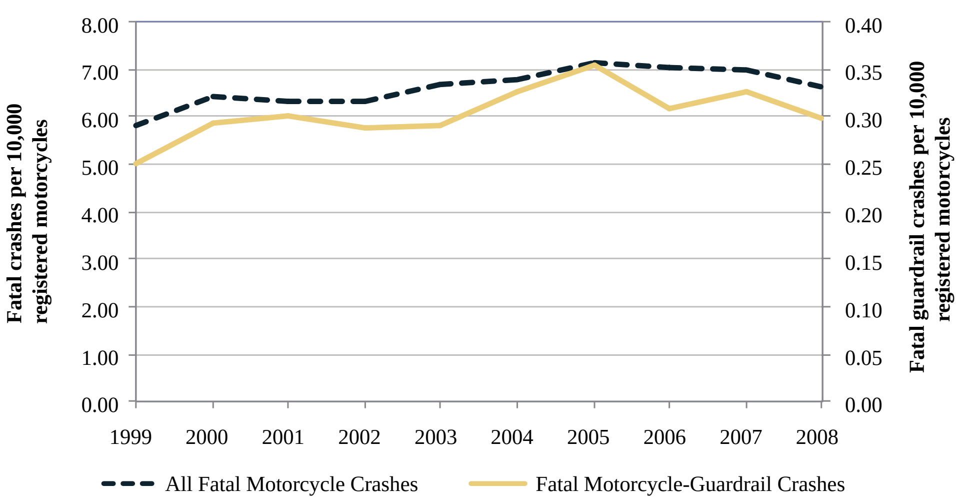


Figure 4-3. Fatal crash rate per 10,000 registered motorcycles (FARS 1999–2008, Traffic Safety Facts 2009).

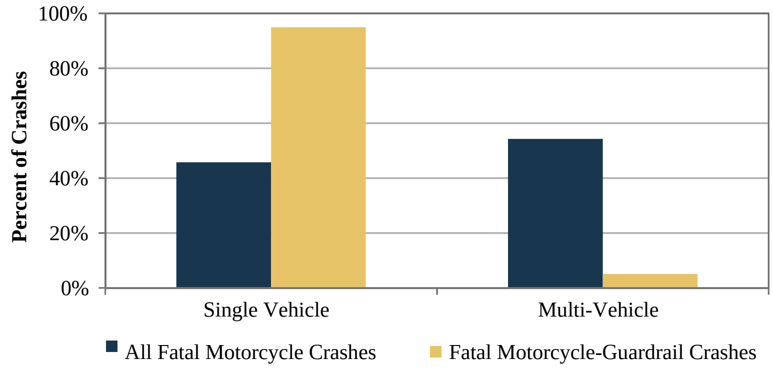


Figure 4-4. Distribution of single- and multi-vehicle crashes (1999–2008).

4.4.1 Crash Conditions

The conditions under which fatal motorcycle-guardrail crashes occurred were compared to conditions of all fatal motorcycle crashes. First, the trends in the time of the crashes were compared, including season and time of day. Next, environmental conditions of the crashes were compared, including the weather and the lighting at the time of the crash.

The season when a crash occurred was determined based on the month of the crash. Each season included three full months. Months that incorporate two seasons were divided as follows: crashes in June were classified as summer crashes, in September as autumn crashes, in December as winter crashes, and in March as spring crashes. The highest percentage of crashes occurred during the summer for all fatal motorcycle crashes (38.9%) and fatal motorcycle-guardrail crashes (42.7%), as shown in Figure 4-5. The differences in seasonal crash trends were found to be significantly different between the types of crashes considered ($\chi^2 = 21.388$, $p < 0.001$).

Next, the times of day when crashes occurred were compared through an analysis of the hour when crashes occurred. Figure 4-6 shows the percentage of crashes that occurred during each hour of the day. Crashes in which the time was "unknown" or reported as occurring during hour

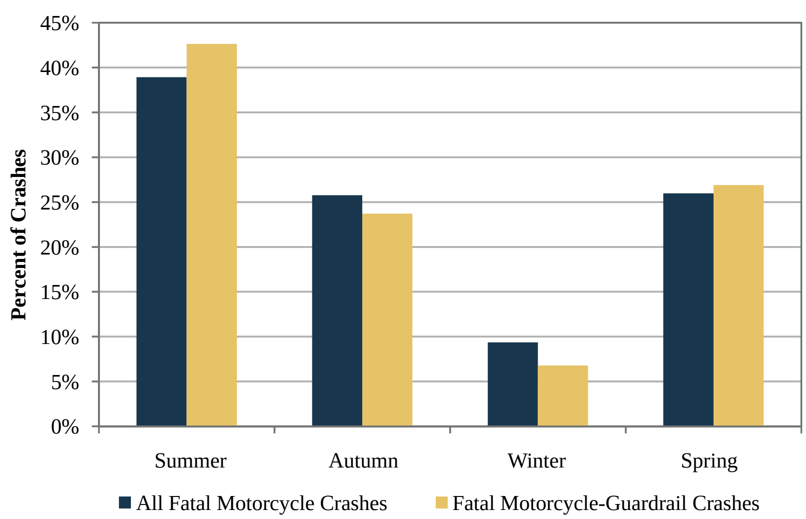


Figure 4-5. Time of year during which crashes occurred (1999–2008).

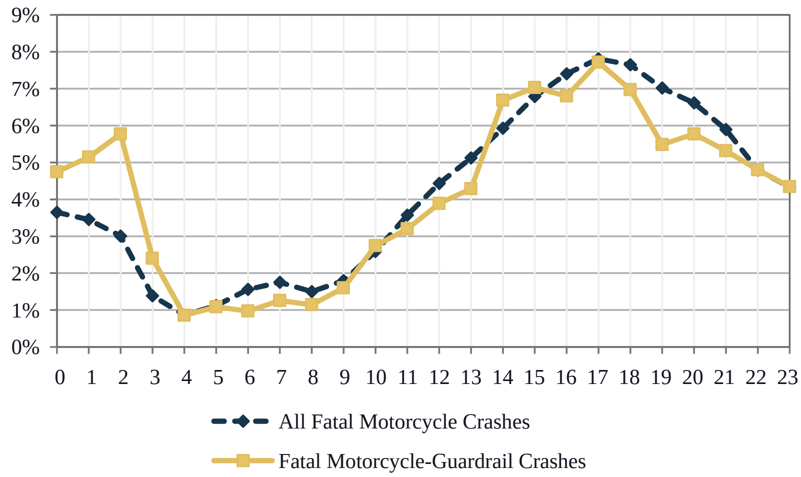


Figure 4-6. Distribution of crashes by time of day (1999–2008).

"24" were omitted from this figure for consistency. This only accounted for 0.9% of all crashes and 0.5% of guardrail crashes.

Generally, guardrail crashes followed a similar trend to all fatal crashes. However, a higher percentage of guardrail crashes occurred from midnight to 3:59 a.m. than all fatal crashes. This is most exaggerated from 2:00–2:59 a.m.; 5.8% of guardrail crashes occurred during this hour as compared to 3.0% of all fatal crashes. There were significantly different trends for the time of the day that the crash occurred between all fatal crashes and fatal guardrail crashes ($\chi^2 = 98.990$, $p < 0.001$).

Lastly, the environmental conditions under which crashes occurred were compared. As shown in Figure 4-7, the overwhelming majority of fatal guardrail crashes and all fatal crashes occurred under normal weather conditions. There was no significant difference between the weather conditions in all fatal crashes when compared to fatal guardrail crashes ($\chi^2 = 6.093$, $p = 0.637$).

The roadway alignment and profile at the location of fatal motorcycle crashes were analyzed. As shown in Figure 4-8, three-quarters of fatal motorcycle-guardrail crashes occurred on curves. Comparatively, 38% of all fatal crashes occurred on curves. These trends were found to be significantly different ($\chi^2 = 995.6$, $p < 0.001$).

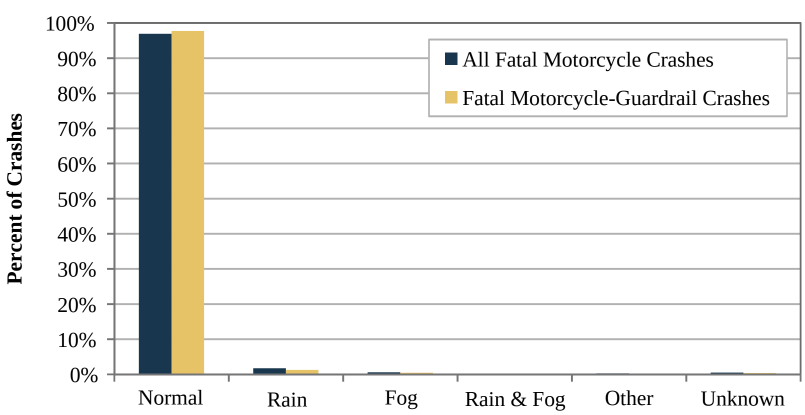


Figure 4-7. Distribution of weather conditions: all fatal crashes and fatal guardrail crashes (1999–2008).

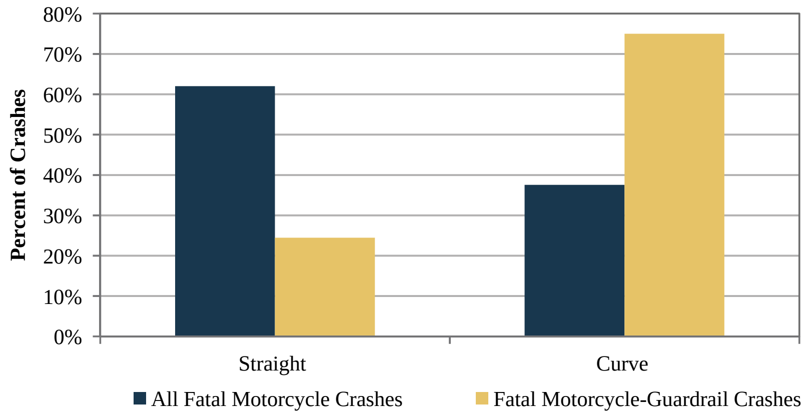


Figure 4-8. Roadway alignment during fatal crashes (1999–2008).

Entrance and exit ramps have a different method of negotiation than highway curves. The distribution of fatal crashes on curves in relation to roadway junctions was compared to how often fatal guardrail crashes occurred in relation to entrance/exit ramps, as compared to those that occurred on curves in the road. As shown in Figure 4-9, the majority of crashes that occurred on curves did not occur at a roadway junction. However, there was a higher percentage of fatal guardrail crashes on curves that occurred in relation to entrance and exit ramps as compared to all fatal crashes, and these trends were found to be significantly different ($\chi^2 = 263.2$, $p < 0.001$).

Also, approximately the same percentage of fatal guardrail crashes occurred on level and sloped roads (Figure 4-10). Comparatively, all fatal crashes more often occurred on level roads, and these trends were found to be significantly different ($\chi^2 = 378.9$, $p < 0.001$). Therefore, guard-rail impacts on roads with a grade may have an increased fatality risk. However, this may also be a function of guardrail placement.

One other characteristic analyzed was roadway functional classification. The greatest percentage (17.5%) of fatal guardrail collisions occurred on urban interstate roadways. However, 5.4% of all fatal motorcycle crashes occurred on these roads (Table 4-2). These trends in roadway function class were found to be significantly different between all fatal crashes and fatal guardrail crashes ($\chi^2 = 1034.0$, $p < 0.001$).

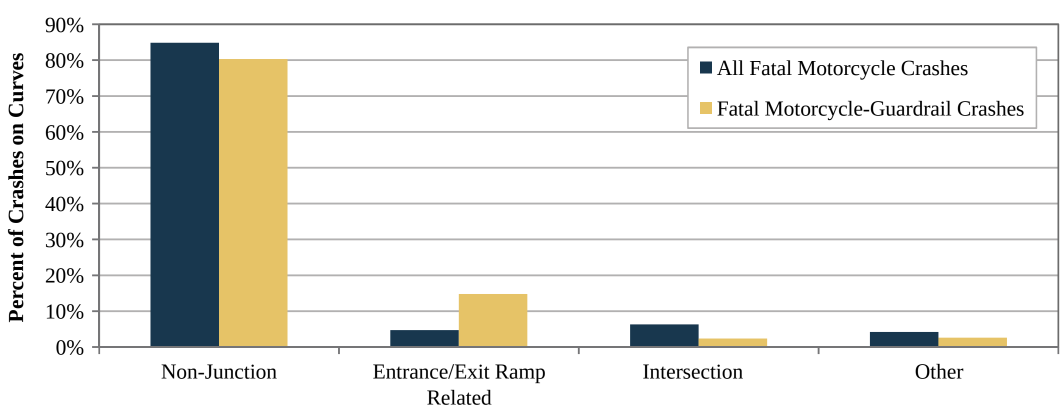


Figure 4-9. Roadway junction type in fatal crashes on curves (1999–2008).

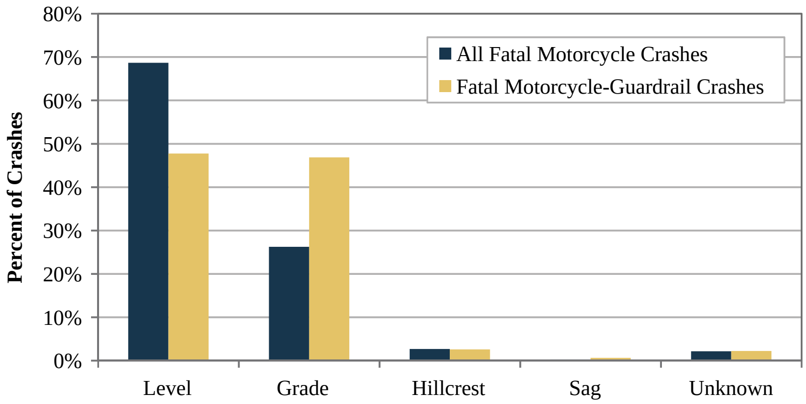


Figure 4-10. Distribution of roadway profile (1999–2008).

4.4.2 Rider Demographics

The demographics of motorcycle riders and passengers involved in fatal guardrail crashes were compared to the demographics of motorcycle riders and passengers involved in all crashes. There were 1,945 people on a motorcycle involved in a fatal guardrail crash. Of these people, 7.3% survived (142 people). These people were excluded from the analysis of the demographics of riders. The overwhelming majority (95%) of the people on a motorcycle and fatally injured in a guardrail crash were operating the vehicle; the remaining 5% were passengers on the motorcycle.

Overall, 54% of people on a motorcycle and fatally injured in a crash were properly using a helmet. Likewise, 62% of all people fatally injured in a motorcycle-guardrail crash were using a helmet at the time of the crash. Helmet laws differ by state; 19 states and the District of Columbia

Table 4-2. Roadway function distribution in fatal motorcycle crashes (1999–2008).

Roadway Function	All Fatal Motorcycle Crashes (%)	Fatal Motorcycle-Guardrail Crashes (%)
Urban- Principal Artery	13.9	8.1
Rural-Major Collector	13.5	12.4
Urban-Local Street	12.4	4.8
Rural-Local Road	11.1	4.4
Urban-Minor Artery	10.4	6.8
Rural-Minor Artery	9.5	11.4
Rural-Principal Artery	7.9	10.3
Urban-Interstate	5.4	17.5
Urban-Collector	4.1	2.4
Rural-Minor Collector	4.0	2.3
Urban-Freeway/Expressway	3.7	10.8
Rural-Interstate	2.3	6.9
Unknown	0.8	1.3
Unknown Rural	0.6	0.6
Unknown Urban	0.3	0.1

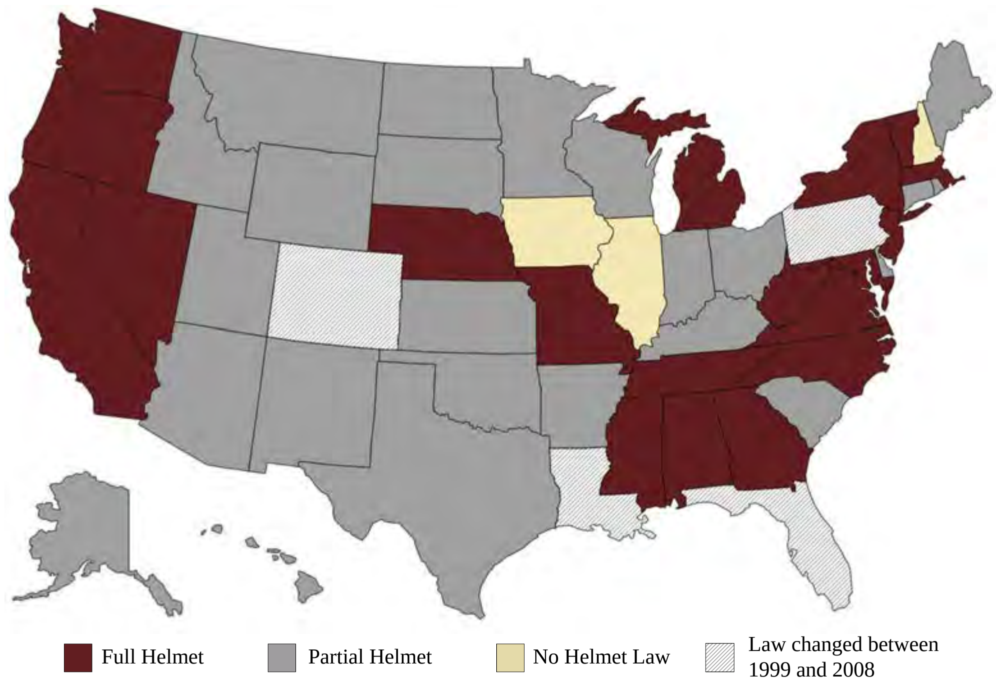


Figure 4-11. Helmet laws by state (1999–2008).

had a full helmet law from 1999 to 2008, requiring riders to wear a helmet at all times. Twenty-four states had a partial helmet law, requiring riders under a certain age, new license, and/or without medical insurance to wear a helmet, and three states had no helmet law. In the remaining four states, the helmet law changed during the time period investigated (IIHS 2013). The helmet use laws for each state are shown in Figure 4-11.

The distribution of helmet usage by helmeting law is shown in Figure 4-12 for those fatally injured in all motorcycle crashes and those fatally injured in motorcycle-guardrail crashes. This chart accounts for the changes in helmet laws in the four states previously discussed. A small percentage of riders whose helmet usage was unknown (3% of all riders) were excluded from this component of the analysis. As shown, those in fatal guardrail collisions had a slightly higher

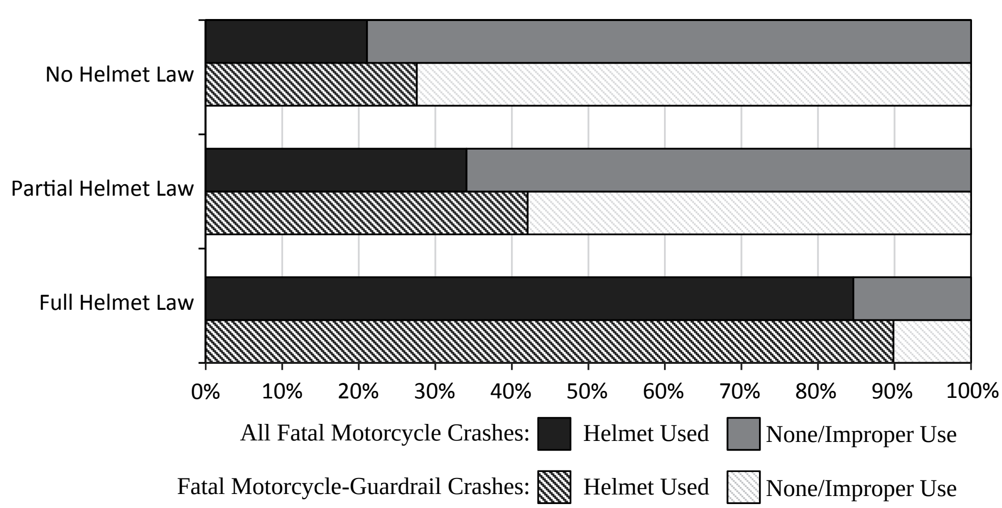


Figure 4-12. Helmet usage by state helmet law (1999–2008).

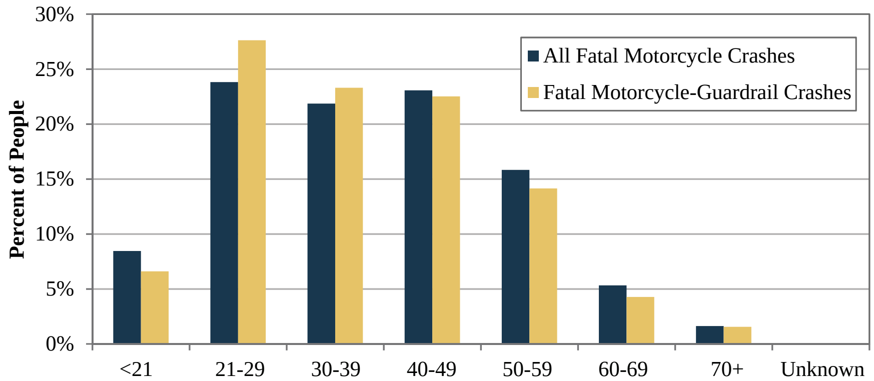


Figure 4-13. Age distribution of people fatally injured in a motorcycle crash (1999–2008).

rate of helmet usage in all cases. Trends in helmet usage by helmeting law were not found to be significantly different between riders in all fatal crashes and those in fatal guardrail crashes ($\chi^2 = 0.460$, $p = 0.794$).

As shown in Figure 4-13, a higher percentage of people between the ages of 21 and 39 was involved in fatal motorcycle-guardrail crashes than the percentage of people the same age involved in all fatal motorcycle crashes. Forty-six percent of people involved in a fatal crash and 51% of people involved in a fatal guardrail crash were in this age range. Differences in age group trends were found to be significantly different ($\chi^2 = 2.961$, $p < 0.001$).

The gender distribution of both motorcycle operators and passengers fatally injured in guardrail crashes follows the distribution of all people fatally injured in all fatal motorcycle crashes (Figure 4-14). These trends were not significantly different ($\chi^2 = 1.823$, $p = 0.402$).

Motorcycle operators involved in guardrail crashes had a higher tendency to be drinking than those involved in all crashes (Figure 4-15), and differences in these trends were found to be significant ($\chi^2 = 65.694$, $p < 0.001$). FARS classifies alcohol involvement based on either positive blood alcohol concentration or police-reported alcohol involvement (NHTSA 2009a). As previously mentioned, a higher percentage of guardrail crashes occurred during the first hours of the day as compared to all crashes. The finding that riders involved in guardrail crashes are more likely to be intoxicated may coincide with this finding, as intoxicated riders may be returning home at this time.

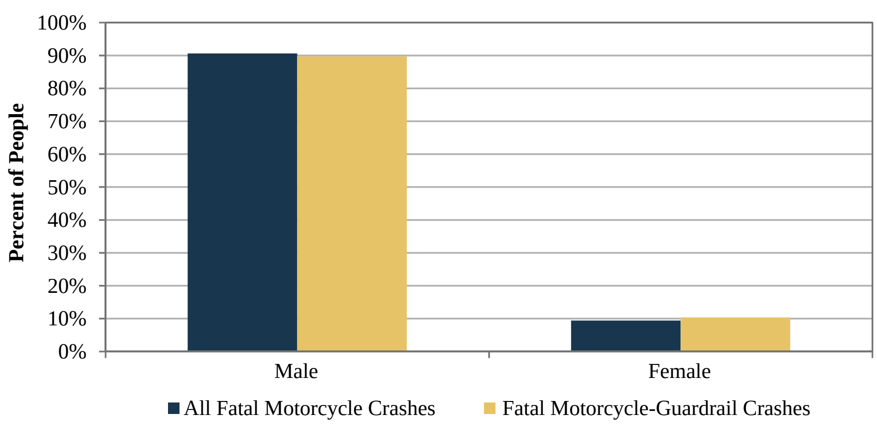


Figure 4-14. Gender distribution of people fatally injured in a motorcycle crash (1999–2008).

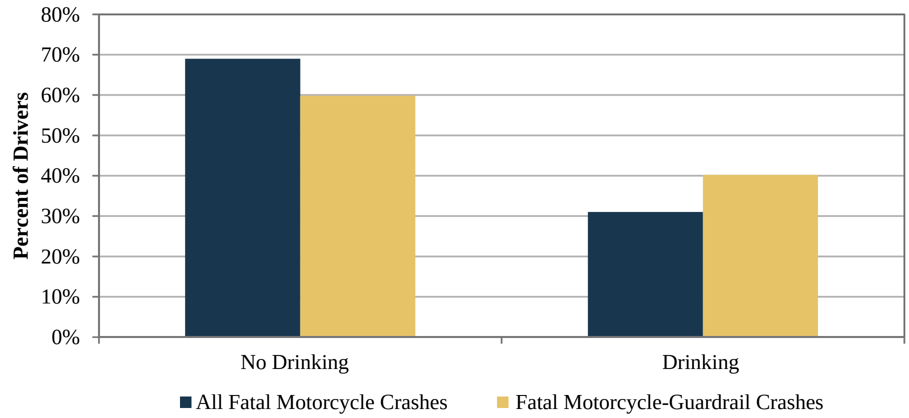


Figure 4-15. Distribution of drinking status of riders in a motorcycle crash (1999–2008).

Lastly, the license status of riders involved in all fatal motorcycle crashes was compared to the license status of those involved in fatal motorcycle-guardrail crashes. Approximately three-quarters of riders held a valid license in both crash scenarios (Figure 4-16). Trends in license status varied between operators in all fatal crashes and fatal guardrail crashes ($\chi^2 = 18.625$, $p < 0.001$).

4.4.3 Motorcycle Characteristics

The characteristics of motorcycles involved in fatal guardrail crashes were compared to the characteristics of motorcycles involved in all fatal crashes. Based on a visual inspection, the motorcycles in fatal guardrail collisions had approximately the same distribution of engine displacements as those involved in all fatal crashes (Figure 4-17). The motorcycles involved in each crash category had a median motorcycle displacement of 997 cubic centimeters.

4.4.4 Discussion

The number of fatal motorcycle-guardrail crashes has been increasing at approximately the same rate as the number of all fatal motorcycle crashes. However, fatal motorcycle-guardrail

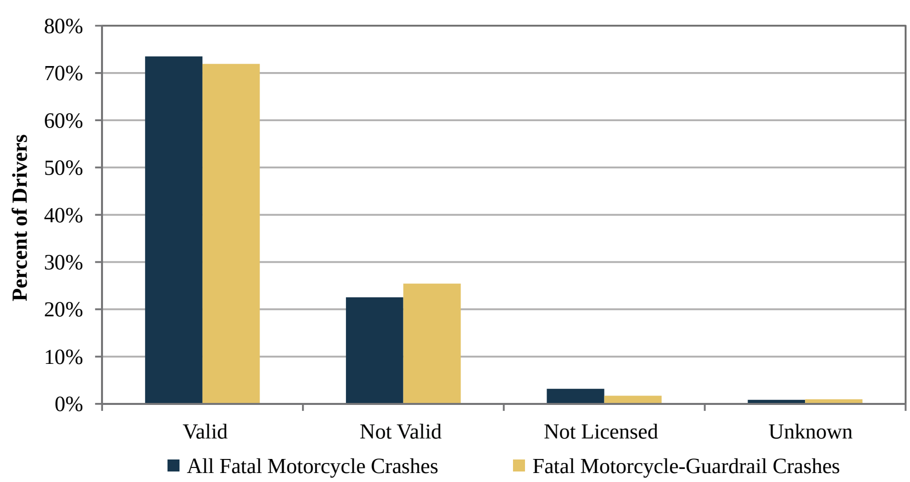


Figure 4-16. License status of riders involved in a fatal motorcycle crash (1999–2008).

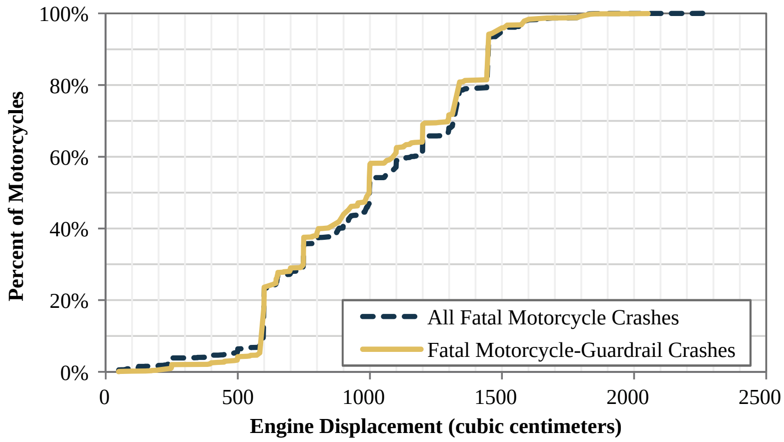


Figure 4-17. Distribution of engine size of motorcycles in fatal crashes (1999–2008).

collisions were almost exclusively single-vehicle crashes (95%), whereas less than half (46%) of all fatal motorcycle crashes were single-vehicle crashes. Additionally, 38% of all fatal motorcycle crashes occurred on curves, whereas 75% of fatal motorcycle-guardrail collisions occur on curves. Therefore, curves pose a particular hazard to motorcyclists in fatal motorcycle-guardrail collisions. The majority of the crashes that occurred on curves did not occur on entrance/exit ramps, though fatal crashes on entrance/exit ramps were more likely to involve a guardrail.

The age distribution of riders involved in fatal motorcycle-guardrail crashes tended to be younger than riders involved in all fatal motorcycle crashes; 51% of riders in fatal guardrail crashes were aged 21 to 39, whereas 46% of people involved in all fatal crashes were in the same age range. Riders involved in fatal motorcycle-guardrail crashes were more likely to be intoxicated at the time of the crash than riders involved in all fatal motorcycle crashes. Lastly, motorcycles involved in fatal guardrail crashes had approximately the same engine displacement as motorcycles involved in all fatal crashes.

4.5 Conclusions

The conclusions of the analysis of fatal motorcycle-guardrail crashes are as follows:

- Fatal motorcycle-guardrail crashes were almost exclusively single-vehicle crashes, whereas less than half of all fatal motorcycle crashes were single-vehicle crashes.
- Most fatal motorcycle-guardrail crashes occurred under normal weather conditions and in daylight. Also, the highest percentage of these crashes occurred during the summer months.
- Three-quarters of fatal motorcycle-guardrail collisions occurred on curves. The number of fatal motorcycle-guardrail crashes that occurred on level and graded roads was approximately the same.
- Riders involved in fatal motorcycle-guardrail crashes tended to be younger than those involved in all fatal motorcycle crashes; most people fatally injured in motorcycle-guardrail crashes were between the ages of 21 and 39.
- Approximately 60% of people fatally injured in motorcycle-guardrail crashes were wearing a helmet at the time of the crash. Helmet usage was correlated with state helmet laws. Riders fatally injured in states with a full helmet law were more likely to be wearing their helmet.

CHAPTER 5

Fatality Risk in Motorcycle Collisions with Roadside Objects in the United States

5.1 Introduction

Guardrails and other barriers are not the only obstacles that exist on the roadside. This chapter investigated injury risk in all types of roadside object collisions for motorcyclists. The aim is to place guardrail fatality risk in the context of fatality risks in collisions with other roadside objects. However, as discussed earlier in this report, the motorcyclist may be fatally injured before a collision with a roadside object. This risk analysis will specifically address this question by comparing risk in collisions with the ground to risk in collisions with a roadside object.

The assessment of fatality risk is complicated by the fact that motorcycle crashes frequently involve multiple impacts. For example, in a motorcycle-guardrail crash during which the rider falls onto the pavement after losing control of the cycle, the motorcyclist suffers two impacts: the first from the ground impact and the second after sliding into the barrier. In this type of crash, the question arises whether the most harmful event was from the impact with the ground or from the subsequent impact with the guardrail. Similar questions arise in multi-event crashes involving other roadside objects (e.g., trees, utility poles, concrete barriers, and passenger vehicles).

In FARS, a census of all fatal crashes in the United States, the most harmful event in a crash is determined by specially trained FARS analysts based on review of PARs. Many studies have based their estimates of risk assessment on the most harmful event. However, the concern has been raised about whether the guardrail actually was the most harmful event in these crashes. Although the FARS analysts are highly trained, the assessment of most harmful event includes some degree of subjectivity. Perhaps, in a ground-guardrail, two-event crash, the motorcyclist had already received fatal injuries from the ground impact prior to hitting the guardrail. Certainly, both events would contribute to the injury severity, but what is needed is a non-subjective method to determine which event posed the greater risk in these crashes.

Much of this chapter is provided in Daniello and Gabler (2011a). Text and figures are reproduced largely verbatim from this work and are © 2011, Elsevier.

5.2 Objective

The goal of this chapter is to determine the fatality risk in motorcycle collisions with various roadside objects and investigate how these risks compare to one another. One specific objective is to determine whether a collision with a roadside object is more likely to be harmful to a motorcyclist than the collision with the ground.

5.3 Methods

The roadside objects included for analysis in this chapter were guardrails, concrete barriers, trees, signs, and utility poles. The FARS database was used in conjunction with the GES database to analyze motorcycle crashes from 2004 to 2008. In this chapter, three independent methods were pursued to determine relative risk in roadside object collisions and collisions with the ground. The FARS and GES cases were combined to determine the fatality risk of particular motorcycle-fixed object crashes. These were based on the most harmful event and the sequence of events. GES reports all events that occurred in the crash to each vehicle. Beginning in 2004, FARS was enhanced to report up to six events suffered by each vehicle in a crash.

5.3.1 Relative Fatality Risks Based on the Most Harmful Event

The most harmful event (MHE) as coded by the FARS or GES analysts was used to compare the fatality risk of fixed-object collisions to that of collisions with the ground. The fatality risks of collisions with the various fixed objects were compared to the fatality risks of overturning or colliding with another motor vehicle. Cases with the MHE coded as an overturn or rollover collision were interpreted as equivalent to a collision with the ground. The sequence of events during the crash was not taken into account for this component of the analysis. All crashes in which the MHE was reported as either a fixed object or a collision with the ground were used in the analysis.

The number of fatal crashes was determined using the FARS data and the total number of crashes was determined using the GES data. The fatality risk of each collision event was computed using Equation (5.1)

$$Risk\ of\ fatal\ injury = \frac{Number\ of\ Fatally\ Injured\ Riders}{Number\ of\ Riders\ Exposed\ to\ Crashes} \tag{5.1}$$

Confidence bounds on data from the GES were found using the methods described in the GES Analytical User's Manual (NHTSA 2009b). These were then used to determine the confidence bounds on the fatality risk ratios. Next, the relative fatality risk of a fixed-object collision to a collision with the ground was computed for each fixed object using Equation (5.2)

$$Relative\ Risk = \frac{Risk_{Scenario\ A}}{Risk_{Scenario\ B}} \tag{5.2}$$

5.3.2 Relative Fatality Risks based on the Sequence of Events

Next, a similar analysis was conducted using the sequence of events. This provided a method for determining fatality risk independently of the FARS and GES analysts' assessments of the MHE. All analyses utilizing the sequence of events were based on the total number of motorcycles involved in crashes, as opposed to the number of crashes. Also, the FARS data reported a more detailed set of events than the GES data, including non-collision events such as "run off road, right" and "cross median." There were 13 such non-collision events included in FARS that were not included in the GES sequence of events.

This analysis compared single-event collisions with the ground to collisions with roadside objects. A crash during which the only events were those with the specified roadside object, an overturn, or one of the aforementioned non-collision events was included. For example, a crash whose reported sequence of events was (1) run off road, right, (2) guardrail face, and (3) overturn was considered a guardrail collision. However, a crash whose reported sequence of events was

(1) run off road, right, (2) tree, (3) guardrail, and (4) overturn was not included in the analysis since there was more than one object struck. Overturn events were included since it is assumed that most motorcycles will overturn in a crash due to their unstable nature. These overturn events were assumed equivalent to a rider colliding with the ground.

The fatality risk for collisions with each fixed object and the ground was computed using Equation (5.1). Next, the relative fatality risk of fixed-object collisions as compared to collisions with the ground was computed using Equation (5.2).

5.3.3 Distribution of MHE in Fatal Fixed Object-Ground Crashes

The last component of the analysis specifically explored the question of whether the ground impact or the fixed-object impact was more likely to be designated as the MHE in a fatal crash reported to involve an overturn *and* a collision with a fixed object. This analysis was limited to fatal, two-event crashes where one event was a collision with the fixed object and the other was a collision with the ground. The fraction of crashes in which overturn was designated as MHE or the given object was designated as MHE was computed and compared. This analysis will show how FARS analysts judged the relative risk of collision with a fixed object or ground for all motorcycles that experienced both collisions exclusively. Confidence bounds were computed based on a Gaussian distribution since FARS contains a census of all fatal crashes. The standard error of each proportion was computed as

$$SE = \sqrt{\frac{p\ (1-p)}{n}} \tag{5.3}$$

where p is the proportion of crashes of interest and n is the total number of crashes. The 95% confidence interval was then computed as $p \pm 1.96 \cdot SE$.

5.4 Results

The three methods of determining the more harmful component of multi-event crashes all yielded similar results. The first component of the analysis utilized the MHE as reported in the database. The number of fatal crashes and total crashes in which a fixed object, another motor vehicle, or the ground was reported as the MHE is given in Table 5-1.

Table 5-1 shows that the most common type of motorcycle crash of those analyzed was either a collision with the ground (rollover/overturn) or with a motor vehicle. However, it also shows that roadside objects are overrepresented in fatality risk. For all roadside-object collisions analyzed, the fatality risk of fixed-object collisions was found to be greater than the risk of overturn or ground collisions. Motorcycle-tree collisions had the highest fatality risk, followed by collisions with signs

Table 5-1. Motorcyclist fatality risk by most harmful object struck (FARS, GES 2004–2008).

Object Struck	Fatal Crashes	Total Crashes	Fatality Risk	95% Confidence Interval	
				Lower	*Upper*
Guardrail	1,078	7,448	0.145	0.110	0.211
Concrete Barrier	246	2,978	0.083	0.057	0.148
Signs and Utility Poles	1,191	5,424	0.220	0.163	0.338
Tree	1,178	4,001	0.294	0.211	0.485
Motor Vehicle	11,513	231,309	0.050	0.043	0.059
Rollover/Overturn	4,219	209,415	0.020	0.017	0.024

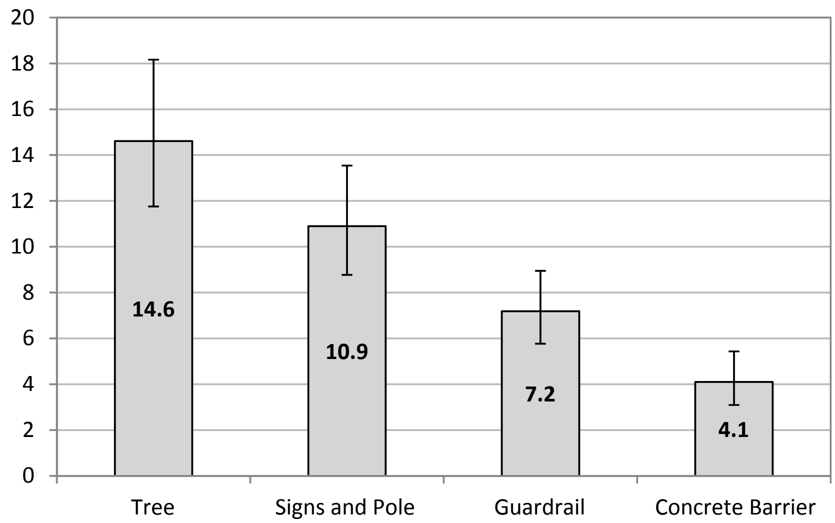


Figure 5-1. Relative fatality risk of fixed-object collisions to ground collisions based on MHE (FARS, GES 2004–2008).

and utility poles. For this analysis, crashes with utility poles and signs were grouped into one category since they were combined in the GES database.

The fatality outcome of fixed-object collisions was then directly compared to the outcome of collisions with the ground using relative fatality risk (Equation 5.2). Figure 5-1 shows the relative risks for each collision type analyzed based on the MHE. Based on this analysis, a collision with a guardrail is 7.2 (95% CI: 5.8-8.9) times more likely to be fatal than a collision with the ground. Comparatively, concrete barrier collisions are 4.1 (95% CI: 3.1-5.4) times more likely to be fatal than collisions with the ground. Even more severe are tree collisions, which are 14.6 (95% CI: 11.8-18.2) times more likely to be fatal.

Next, a similar analysis was conducted using the crash sequence of events, which removes the subjectivity of determining the MHE in the collision. As described in Section 5.3.2, this method compared crashes where the only collision event was with the ground with collisions involving roadside objects and the ground. The fatality risk of collision with each fixed object is shown in Table 5-2.

The relative fatality risk between the roadside object and a collision with the ground was computed (Figure 5-2). The relative fatality risks computed using this method were not statistically different from those computed based on the MHE.

The final component of the study addressed the question of which event was likely to be designated as the MHE in a two-event crash reported to involve a roadside object and a collision

Table 5-2. Motorcyclist Fatality Risk by Sequence of Events (FARS, GES 2004–2008).

Object Struck	Fatal Crashes	Total Crashes	Fatality Risk	95% Confidence Interval	
				Lower	*Upper*
Tree	701	3,829	0.183	0.131	0.305
Signs and Poles	1,014	9,759	0.104	0.081	0.146
Guardrail	693	6,677	0.104	0.078	0.154
Concrete Barrier	206	4,116	0.050	0.036	0.082
Rollover/Overturn	1,909	174,026	0.011	0.009	0.013

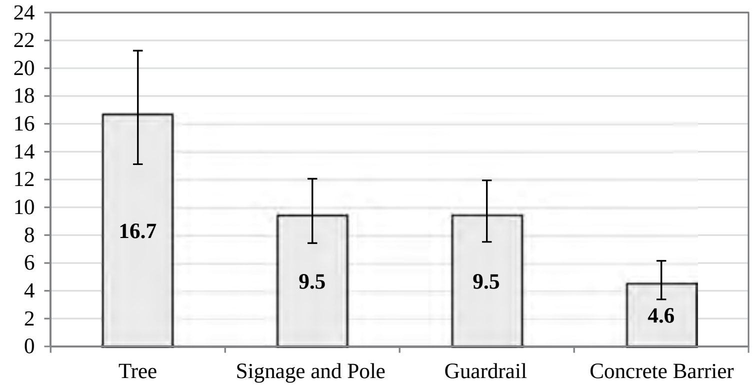


Figure 5-2. Relative fatality risk of fixed-object collisions to ground collisions based on the sequence of events (FARS, GES 2004–2008).

with the ground. Since this analysis was completed using only FARS data, signs and utility poles were divided into separate categories. Figure 5-3 shows the distribution of MHE for motorcycles in two-event crashes that collided with one of the fixed objects analyzed and the ground.

For all fixed-object collisions but signs, FARS identified the fixed object as the more harmful event than a collision with the ground. FARS designated guardrails as the MHE in 69.2% (95% CI: 61.7%-76.8%) of the two-event collisions that involved a guardrail. Likewise, utility poles were the MHE in 80.3% (95% CI: 71.0%-89.5%) of two-event crashes involving a utility pole.

For all two-event fatal crashes involving only collisions with a fixed object and the ground, the collision with the ground was designated as the MHE in less than 37% of the crashes. With the exception of signs, the fixed object was reported to be the MHE more frequently than the overturn in all fatal overturn-fixed object collisions analyzed. Sign posts are often designed to be breakaway devices and deform more easily than the other types of fixed object analyzed in this study. The lower percentage of cases where the signs were reported to be the MHE is likely attributed to this design difference. The findings of this component of the study are consistent with the relative risk studies (Figure 5-1 and Figure 5-2) in that the collision with the roadside object is most often more harmful than the collision with the ground.

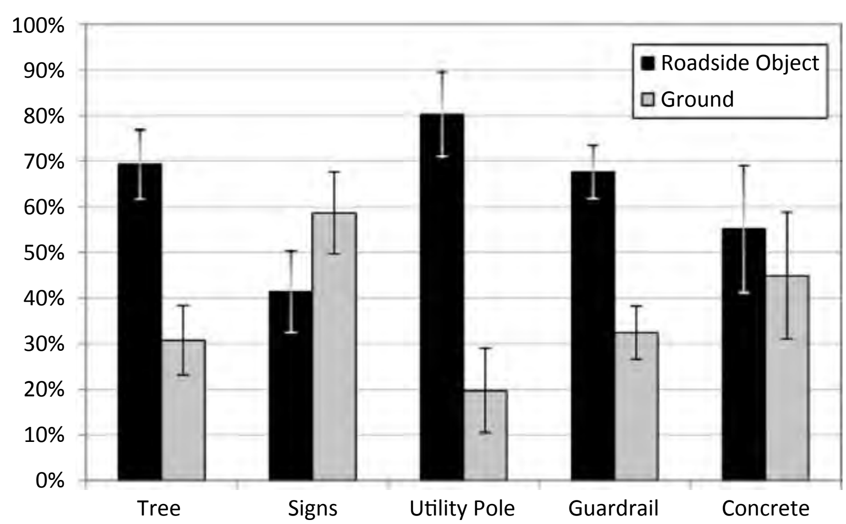


Figure 5-3. Distribution of MHE in two-event fatal crashes involving a fixed object and ground (FARS 2004–2008).

5.5 Discussion

The findings of this chapter were based on police-reported event sequences in the databases. For the time period analyzed, the FARS and GES databases coded events using different categories, making FARS and GES challenging to directly compare. There were fewer types of collisions reported in the GES data; therefore, relative risks of some collisions could not be explored. Additionally, the FARS data used in this study was limited to reporting six events, whereas no limit was placed upon the number of events per cases in GES.

The events included in the sequences are those reported in the PARs, and therefore depend upon how thoroughly police recorded all events that occurred during a crash. For example, an overturn might not have always been reported even if one had occurred during the crash. Lastly, the analyses do not include the influence of additional confounding factors, such as roadway geometry. The effects of these factors may be examined for further information about fatality risk in crashes.

5.6 Conclusions

This chapter investigated all roadside obstacles, comparing guardrails to other roadside objects such as trees and utility poles. As shown, the most hazardous roadside objects for motorcyclists were trees. The greater fatality risk for trees as compared to guardrail is consistent with the findings of Tung et al. (2008), who determined that narrow objects had a greater fatality rate than guardrails. They also found that guardrail collisions were more likely to cause serious injury than non-object collisions (Tung et al. 2008), which is consistent with the findings of this study.

This chapter also investigated the validity of the hypothesis that the rider was already fatally injured before striking the guardrail. This study has shown that motorcycle collisions with guardrail have a greater fatality risk for motorcyclists than collisions with the ground using three different methods. Based on the MHE, collisions with guardrail were seven times more likely to be fatal than collisions with the ground. Likewise, all the roadside objects analyzed in this study had a relative fatality risk greater than four as compared to collisions with the ground. The fatality risk of colliding with a tree was almost 15 times greater than the fatality risk of an overturn collision. These ratios also were confirmed by determining the relative risk based on the sequence of events; there was no statistical difference found between the relative risk ratios computed using the two methods.

The fixed object was almost invariably designated as the MHE in two-event fatal crashes that exclusively included collisions with a fixed object and the ground. Utility poles, guardrails, and trees were reported as the MHE in more than 50% of fatal collisions involving each fixed object. Therefore, with the exception of signs, it was more likely that the roadside object was the MHE in crashes including a collision with both a roadside object and the ground.

This study refutes the hypothesis that it is the ground rather than the barrier that fatally injures the rider in a multi-event crash involving a motorcycle that both overturns and strikes a guardrail. The fatality risk of striking a guardrail was seven times greater than the risk of striking the ground. Therefore, on average, a motorcycle-guardrail collision is more harmful than a motorcycle-ground collision. However, the fatality risk of colliding with a guardrail or concrete barrier was significantly lower than that of a collision with the object they may be protecting, such as a tree or utility pole. Though guardrails have demonstrated to be more harmful to motorcyclists than passengers of other vehicles, they still provide some protection against other roadside objects such as trees and utility poles.

CHAPTER 6

Relationship Between Barrier Type and Injury Severity

6.1 Introduction

Motorcyclists have a much higher fatality risk in collisions with traffic barriers than other road users (Gabler 2007). From 2003 to 2008, there were 1,604 motorcyclist fatalities from collisions with barriers in the United States, accounting for approximately 5.8% of all motorcyclist fatalities. During the same time period in the United States, there were 1,723 car fatalities from collisions with barriers, which comprised 1.6% of all car occupant fatalities. In terms of fatalities per registered vehicle, motorcycle riders are dramatically overrepresented in the number of fatalities resulting from guardrail impacts. In the United States, motorcycles comprise only 3% of the vehicle fleet but account for 40% of all fatalities resulting from guardrail collisions, and approximately one-fourth of the fatalities from concrete barrier collisions.

Much of this chapter is provided in Daniello and Gabler (2011b). Text and figures are reproduced largely verbatim from this work.

6.2 Objective

The goal of this chapter is to determine the influence of barrier design on the risk of serious injury in motorcycle-barrier crashes. A specific objective is to determine whether collisions with cable barriers carry a higher risk than collisions with W-beam guardrail or concrete barrier.

6.3 Methods

An analysis of motorcycle barrier crashes in three states—North Carolina, Texas, and New Jersey—was conducted to determine which type of barrier carries the greatest risk for motorcyclists. Both North Carolina and Texas have installed large amounts of cable barrier, a barrier type that is becoming increasingly popular in the United States. Texas has more cable barrier than any other state in the United States. However, barrier in New Jersey is only comprised of guardrail and concrete barrier. This study was based on state databases of police-reported crashes, which contain all crashes regardless of injury severity. Crashes from 2003 to 2008 in these three states were analyzed for this study.

None of the databases clearly specified which type of barrier was struck by the motorcyclist. To determine barrier type, crash locations were identified in Google Earth. The process for obtaining the location of a crash differed for each state as described. Once the crash site was identified, the "Street View" feature of Google Earth was used to determine barrier type.

6.3.1 North Carolina Crash Locations

The North Carolina HSIS database identified crash locations using the state milepost system. Information about this system was contained in the Linear Referencing System (LRS) shapefile available from the NCDOT (NCDOT 2010). The LRS maps each road segment in North Carolina and reports the associated start and end mileposts of the segment. These segments were related to the crash data based on the route identification number, which combines the route number and the county. Crash locations were then identified based on the segments. Using the "Path" tool in Google Earth, the appropriate distance from the start or end milepost was measured to the crash location. Crashes reported as containing a collision event with either a guardrail, shoulder barrier, or median barrier were examined. The analysis of North Carolina crashes was limited to interstate highways, U.S. routes, and some state routes. On many state roads, crash locations could not be accurately identified, and these roads were excluded from the analysis.

6.3.2 Texas Crash Locations

The Texas Crash Records Information System (CRIS) databases identified crash locations based on latitude and longitude coordinates. These were directly imported into Google Earth for analysis. There was a small percentage of crashes that did not report geographic coordinates. These crashes were excluded from the analysis since the location could not be identified. All motorcycle crashes that reported a guardrail, median barrier, guard post, or concrete barrier were examined.

6.3.3 New Jersey Crash Locations

The NJCRASH database reports latitude and longitude coordinates of crash locations. As described for the analysis of the Texas crashes, the latitude and longitude coordinates were input into Google Earth for further analysis. Not all crashes reported latitude and longitude locations, and these crashes were excluded from the analysis since their location could not be identified. All motorcycle crashes that reported a collision with a guardrail face, guardrail end treatment, and concrete barrier were included in this study.

6.3.4 Determination of Barrier Type Using Google Earth

The barrier type at each crash site was determined using the "Street View" feature of Google Earth. Once the crash was located, the imagery available of the area was used to view the barrier. In several cases, there was no barrier located at the measured or given crash site. For these locations, roads were scanned for approximately 0.1 miles (0.2 km) upstream and downstream of the crash site. A previous study, for which motorcycle-barrier crash site analyses were conducted, found that the actual crash site is sometimes offset from the reported latitude and longitude coordinates (Daniello et al. 2009b). If there was still no barrier identified near the crash site, the crash was excluded from the analysis. The barrier type at some crash sites was miscoded. Rather than guardrail, for example, inspection of the site photos sometimes showed another object such as a curb or fence. These miscoded cases were also excluded from the study. Though the Google Earth Street View pictures used to determine barrier type were typically taken after the crash, it is likely that the barrier type seen in the imagery was the same as that with which the rider crashed. Once barriers are installed, they are typically not changed from one barrier type to another (e.g., W-beam guardrail to concrete barrier) due to traffic considerations. If the crash occurred after the imagery was taken and barrier was later installed, these cases were excluded from the analysis since a barrier type could not be identified. It was hypothesized that this exclusion would not affect the results since it would likely be a systematic exclusion.

For several locations, Street View photographs were not available. These crashes were also excluded from the analysis since the barrier type could not be confirmed. However, for one mountainous, unusually winding road in North Carolina, 35 motorcycle-barrier crashes were reported. There was no Street View available for this road. Due to the geometry and location, it was assumed that the barrier on this road was W-beam guardrail, and these crashes were included in the analysis.

The Texas data did not specify whether the motorcyclist ran off the road to the left or right. Therefore, to determine the barrier type in cases where there were multiple barriers present, the object struck was used as the first indication. For instance, if there was W-beam guardrail and concrete barrier present and the crash record indicated a collision with concrete barrier, the barrier was recorded as a concrete barrier. The North Carolina and New Jersey data, on the other hand, indicated which side of the road the motorcyclist ran off. For divided highways, running off the road to the left was assumed to be a median crash.

6.3.5 Comparison of Barrier Types by Severity of Crashes

A binary logit model was constructed to predict serious injury as a function of barrier type, helmet usage, and other road characteristics, such as horizontal alignment and speed limit. Roadway characteristics were included since the crash risk may vary by roadway (Daniello et al. 2010). The effect of helmet usage on injury severity in barrier crashes also was analyzed since many riders were not wearing helmets at the time of the crash. Both New Jersey and North Carolina have full helmet laws. Texas, however, only requires riders under the age of 20 to wear a helmet (IIHS 2013). All statistical analyses were conducted using SAS 9.2. The logistic procedure was used to construct the binary logit model, and the Fisher's scoring method was used.

Speed limit was not available in the Texas CRIS database. Instead, speed limits were mapped throughout the state using FARS crashes that included location and speed limit. The speed limit for each crash was estimated to be either low speed (< 45 mph) or high speed based on proximity to these fatal crashes. For cases not in proximity to fatal crashes, high- and low-speed roads were estimated based on speed limit signs visible in Google Earth Street View (when available) or road type. Generally, residential areas were listed as low speed and highways were estimated as high speed.

6.4 Results

There were 2,198 motorcycle-barrier collisions reported to have occurred in the years 2003–2008 in North Carolina, Texas, and New Jersey. Of these crashes, 1,400 were examined in Google Earth, and barriers were identified for 951 crashes. As discussed previously, reasons for exclusion included (1) no barrier present at the crash site, (2) the site could not be accurately determined, or (3) there was no imagery available for the crash site. There were 286 barrier crashes without geographic coordinates in Texas, and 325 crashes where geographic coordinates were not reported in New Jersey. Locations for 113 crashes in North Carolina could not be identified from the data available. Table 6-1 shows the distribution of barrier types in crashes that were examined by state.

6.4.1 North Carolina Barrier Crashes

There were a total of 323 motorcycle-barrier crashes in North Carolina from 2003 to 2008. The barrier type of 172 of these crashes was identified using Google Earth, involving 199 riders and passengers. Table 6-2 shows the distribution of injury severity by barrier type.

Table 6-1. Crashes examined by state and barrier type.

	New Jersey	North Carolina	Texas	Total
Barrier Type				
W-beam Guardrail	168	134	244	546
Concrete Barrier	87	23	248	358
Cable Barrier	0	15	32	47
Subtotal	255	172	524	951
No Barrier	21	10	347	378
Indeterminate	1	6	5	12
No Imagery Available	5	22	32	59
Total	**282**	**210**	**908**	**1,400**
Road Alignment				
Straight	94	66	346	506
Curved	161	106	172	439
Not Reported	0	0	6	6
Total	**255**	**172**	**524**	**951**
Road Functional Class				
Interstate Highway	48	63	209	320
U.S. and State Highway	132	109	187	428
Other	75	0	128	203
Total	**255**	**172**	**524**	**951**
Helmet Usage				
Helmet	241	192	328	761
No Helmet	12	5	190	207
Unknown	15	2	62	79
Total	**268**	**199**	**580**	**1047**

There were 60 riders fatally or severely injured in the barrier crashes examined in North Carolina. There were three people reported to have been involved in a motorcycle-barrier collision whose injury severity was unknown. These riders were excluded from the analyses that follow. The majority of the motorcycle-barrier crashes in North Carolina were collisions with W-beam guardrail. Figure 6-1 compares the injuries sustained by each type of barrier based on the percentage of injuries in each category.

The majority of the crashes resulted in moderate injury for all barrier types. There was a higher percentage of concrete barrier crashes resulting in moderate injury than the other barrier types. The percentage of fatalities for each barrier type was approximately equal. However, in absolute terms, there were a larger number of collisions with W-beam guardrail than collisions with cable barrier and concrete barrier.

Table 6-2. Injury severity by barrier type in North Carolina.

Barrier Type	Injury Severity						Total
	Fatality	Incapacitating Injury	Moderate Injury	Complaint of Pain	Property Damage	Unknown	
W-Beam	15	34	76	20	10	2	157
Cable Barrier	1	4	9	2	0	0	16
Concrete Barrier	2	4	16	2	1	1	26
Total	18	42	101	24	11	3	199

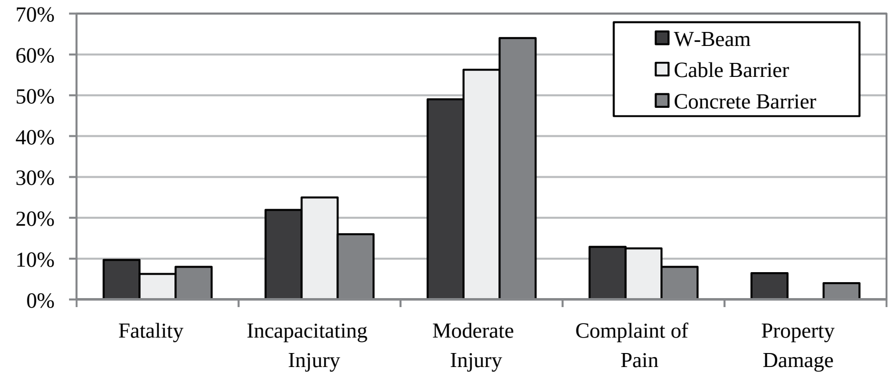


Figure 6-1. Distribution of injury severity in North Carolina motorcycle-barrier crashes (2003–08).

6.4.2 Texas Barrier Crashes

There were 1,268 motorcycle-barrier crashes in Texas from 2003 to 2008, and barrier types were identified for 524 of these crashes. The lower percentage of barrier identification may be attributed to two factors. First, no coordinates were given for 286 crashes, so these could not be examined. Second, 151 of the crashes identified as "hit median barrier" did not contain one of the studied barriers in the median. These medians were often raised islands dividing the traffic without a barrier.

As shown in Table 6-3, there were 580 riders and passengers involved in the 524 crashes with identified barriers. There were 83 fatalities and 168 incapacitating injuries. The injury severity for 26 riders remained unknown, and these riders were excluded from the analysis. The distribution of injury severity for each barrier type is shown in Figure 6-2.

In Texas, there was a lower percentage of cable barrier crashes with a K injury severity compared to W-beam and concrete barrier. However, there was also a higher percentage of riders in cable barrier crashes with incapacitating injury severity level as compared to W-beam and concrete barrier collisions. Though this dataset was larger than that for North Carolina, there were still relatively few cable barrier crashes compared to the number of W-beam guardrail and concrete barrier crashes analyzed.

Overall, there was a higher percentage of incapacitating injuries for W-beam guardrail and concrete barrier in Texas than in North Carolina. Additionally, there was a higher percentage of fatalities in collisions with W-beam guardrails in Texas as compared to North Carolina.

Table 6-3. Injury severity by barrier type in Texas.

Barrier Type	Injury Severity						Total
	Fatality	Incapacitating Injury	Moderate Injury	Complaint of Pain	Property Damage	Unknown	
W-Beam	44	87	87	26	14	12	270
Cable Barrier	2	14	13	3	4	1	37
Concrete Barrier	37	67	94	43	19	13	273
Total	83	168	194	72	37	26	580

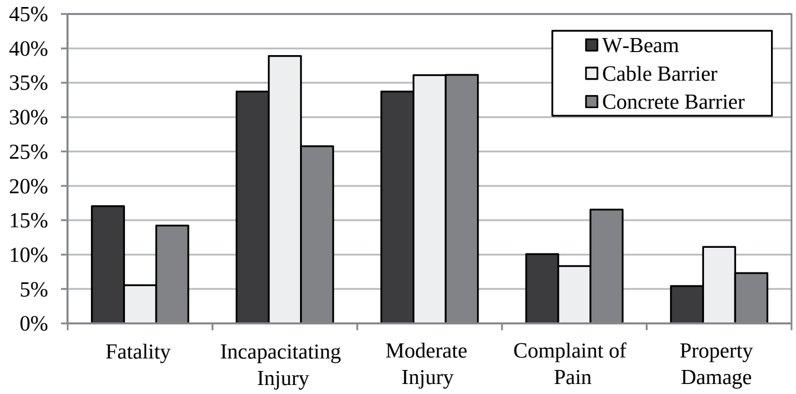


Figure 6-2. Distribution of injury severity in Texas motorcycle-barrier crashes (2003–2008).

6.4.3 Barrier Crashes in New Jersey

There were 607 motorcycle-barrier crashes in New Jersey between 2003 and 2008, inclusive. The barrier type of 255 of these crashes was identified using Google Earth. There was no cable barrier installed in New Jersey, thus the crashes included in this analysis were collisions with either with W-beam guardrail or concrete barrier.

As shown in Table 6-4, there were 268 riders and passengers involved in the 255 crashes for which the barrier was identified. There were 77 people either fatally or severely injured in these crashes. The injury severity for 18 riders was not known, and these riders were excluded from the analysis. The distribution of injury severity for each barrier type is shown in Figure 6-3.

There were approximately twice as many W-beam guardrail collisions as there were concrete barrier collisions. The majority of injuries sustained by riders were moderate for W-beam guardrail and concrete barrier. For both barrier types, there were no crashes resulting in no injury. There was a slightly higher percentage of fatal and severe injuries in collisions with W-beam guardrail than in collisions with concrete barrier.

Next, the location of the barrier in the context of the barrier type was examined. For the motorcycle to W-beam guardrail crashes analyzed, 92.3% (155) occurred in the shoulder and 7.1% (12) occurred in the median. The location of one W-beam guardrail crash could not be determined. Contrarily, 85.1% (74) of concrete barrier crashes occurred in the median, and 12.6% (11) occurred in the shoulder. The location of two (2.3%) motorcycle-concrete barrier crashes analyzed could not be determined. These findings are likely a reflection of where the various barrier types are typically installed.

Table 6-4. Injury severity by barrier type in New Jersey.

Barrier Type	Injury Severity						Total
	Fatality	Incapacitating Injury	Moderate Injury	Complaint of Pain	Property Damage	Unknown	
W-Beam	32	21	85	30	0	11	179
Cable Barrier	0	0	0	0	0	0	0
Concrete Barrier	12	12	48	10	0	7	89
Total	44	33	133	40	0	18	268

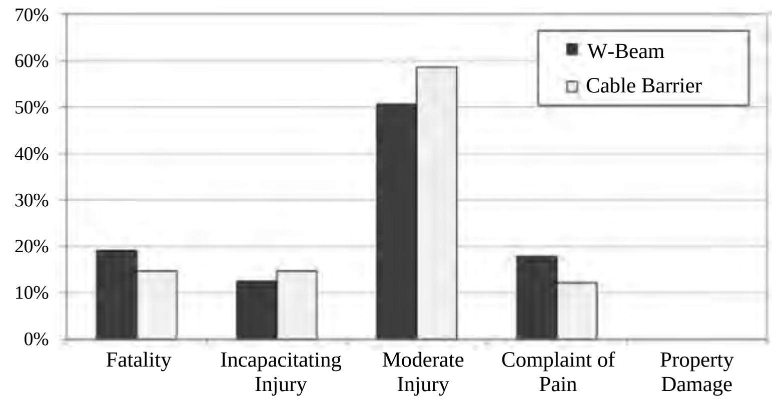


Figure 6-3. Distribution of injury severity in New Jersey motorcycle-barrier crashes (2003–2008).

6.4.4 Analysis of Dataset

Between the three states, there were over 1,000 riders involved in the analyzed barrier collisions whose injury severity was known. The injury severity by barrier type of all riders involved in the analyzed crashes is shown in Table 6-5.

As carried out for each individual state, the percentage of each injury severity by barrier type was computed. The distribution of injury severity by barrier type is shown in Figure 6-4.

For each barrier type, the percentage of moderate injuries was the same. The risk of serious (K+A) injury for concrete barrier collisions was 0.365. Comparatively, the risks of serious injury in W-beam and cable barrier collisions were 0.401 and 0.404, respectively. However, there were a small number of cable barrier crashes examined compared to the number of W-beam guardrail and concrete barrier collisions examined.

Point estimates of the odds ratio (OR) of serious injury in cable barrier crashes as compared to W-beam guardrail and concrete barrier crashes showed no difference in likelihood of serious injury between the two barrier types. The ORs of serious injury between these different barrier types are shown in Table 6-6. As shown, the confidence limits are large relative to the point estimate. One likely reason for this is the small number of cable barrier crashes observed. Based on these data, the odds of serious injury were not found to be significantly different between collisions with cable barrier and the other barrier types considered for both helmeted and unhelmeted riders.

A binary logit model was constructed to determine which road characteristics, if any, have an influence on injury severity. Dependency of severity on barrier type, horizontal alignment,

Table 6-5. Injury severity by barrier type for combined dataset.

Barrier Type	Injury Severity						Total
	Fatality	Incapacitating Injury	Moderate Injury	Complaint of Pain	Property Damage	Unknown	
W-Beam	91	142	248	76	24	25	606
Cable Barrier	3	18	22	5	4	1	53
Concrete Barrier	51	83	158	55	20	21	388
Total	145	243	428	136	48	47	1,047

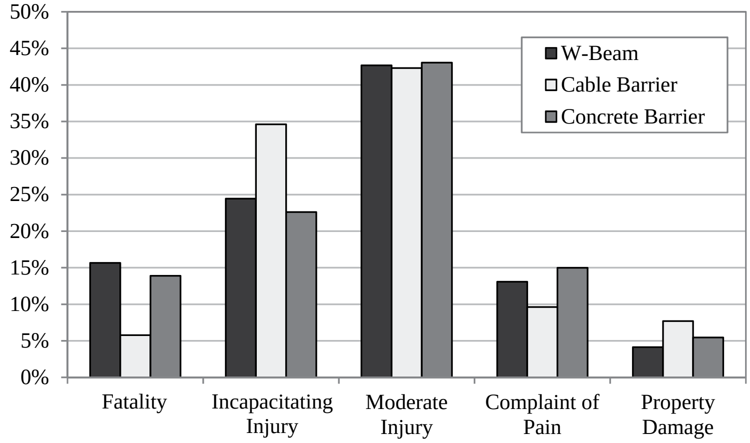


Figure 6-4. Injury severity by barrier type (North Carolina, Texas, and New Jersey, 2003–2008).

helmet usage, and speed limit were all tested. Speed limit was divided into two categories: low speed (< 45 mph) and high speed (≥ 45 mph). Since there were so few cable barrier crashes, only W-beam and concrete barrier cases were included in this component of the analysis. Additionally, the effect of helmet usage was included, since injury risk is likely a function of helmet use (Figure 6-5).

There were 705 riders that crashed with either W-beam barrier or concrete barrier in New Jersey, North Carolina, and Texas that had a complete record of horizontal alignment, speed limit, and helmet usage information. Of these, 455 were seriously injured (K+A) and 250 were either not injured or not seriously injured (B+C+O). The binary logit model was first constructed without selection using these crashes, incorporating the effects of barrier type, horizontal alignment, speed, and helmet use. This analysis showed that, though barrier placement was correlated with horizontal alignment, horizontal alignment was not a significant predictor for serious injury ($\chi^2 = 1.613$, $p = 0.204$). Posted speed limit was also not found to be a significant predictor for serious injury ($\chi^2 = 0.343$, $p = 0.558$). However, barrier type was a significant predictor for serious injury ($\chi^2 = 5.178$, $p = 0.023$). Even after controlling for the horizontal alignment, speed limit, and helmet usage, the model showed that the odds of serious injury in crashes with W-beam barriers were 1.484 (95% CI: 1.056–2.084) times greater than the odds of serious injury in concrete barrier crashes. The binary logit model was also constructed using stepwise selection, and the only significant predictor of serious injury was barrier type. The OR of serious injury was 1.404 (95% CI: 1.011–1.950) for W-beam crashes as compared to concrete barrier crashes.

Next, odds of injury in collisions with different barrier types were computed. For this component, all police-reported injuries were considered (K+A+B), and non-injury was defined as C+O. The binary logit model was constructed to predict injury as a function of barrier type, horizontal alignment, speed limit, and helmet usage. None of these were significant predictors of injury,

Table 6-6. OR of serious injury in cable barrier crashes compared to other barriers.

Helmet Usage	Barrier Type	OR of Serious Injury	95% Confidence Interval (CI)	
			Lower Bound	Upper Bound
Helmeted	Cable Barrier: W-beam	0.847	0.399	1.799
	Cable Barrier: Concrete Barrier	1.202	0.553	2.613
Unhelmeted	Cable Barrier: W-beam	1.283	0.434	3.796
	Cable Barrier: Concrete Barrier	0.905	0.301	2.718

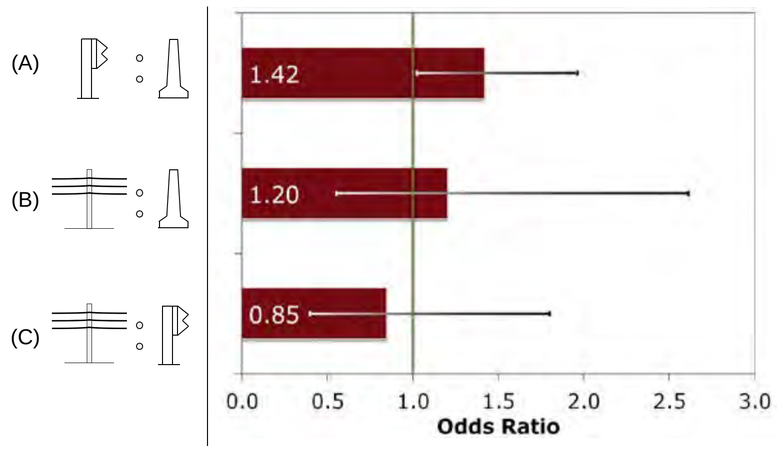


Figure 6-5. OR of severe injury for helmeted riders; comparison by barrier type (A) W-beam barrier compared to concrete barrier, (B) cable barrier compared to concrete barrier, and (C) cable barrier compared to W-beam barrier).

including barrier type. However, the point estimate of the OR showed an elevated risk of injury in W-beam crashes as compared to concrete barrier crashes. The odds of injury in guardrail crashes were 1.139 (95% CI: 0.759–1.708) times greater than the odds of injury in concrete barrier crashes, though this was not found to be significant. Due to the small number of cable barrier crashes observed, these crashes were not included in this component of the analysis.

6.5 Discussion

There are several limitations associated with this study. To identify the barrier using Google Earth, several assumptions about the barrier location needed to be made. Many crashes needed to be excluded since the location could not be identified. Additionally, ambiguity in the datasets about the events during the crash also resulted in crashes being excluded. Second, there were a limited number of motorcycle-barrier collisions, which may have affected the statistical significance of the conclusions drawn from this study. The small number of motorcycle to cable barrier crashes observed over the 6-year period is anticipated to be due to the low collision rate with this type of barrier, rather than these crashes being excluded from the data analyzed.

The KABCO scale is an approximate measure of injury severity that varies by state and over time (Becker et al. 2003; Council et al. 2005). Specifically, there has been variation in the A level of the KABCO scale between states (Council et al. 2005). In the states investigated for this study, a greater percentage of riders in crashes in Texas was designated as having an incapacitating injury (A) than those who crashed in New Jersey and North Carolina.

In the binary logit model, speed limit was not found to be a significant predictor of serious injury. Speed limit was used as a surrogate for other road factors, such as roadway type. Generally, highways and interstates have higher speed limits and local roadways have a lower speed limit. Likewise, winding roads generally have lower speed limits than straight roads. Lastly, the speed limit does not indicate the speed at which the rider was traveling at the time of the crash. Therefore, crashes on low-speed roads (< 45 mph) may have occurred at high speeds (≥45 mph). Rider travel speed was not known, though this would likely influence the likelihood of serious injury.

There are factors other than those included in the model that may influence injury outcome. Weather conditions may influence the likelihood of serious injury; however, motorcycles are typically ridden under fair weather conditions. Additionally, work zones may increase the likelihood of a motorcycle crash. Motorcycles are more sensitive to slight changes in pavement than other motor vehicles, which are more prevalent in work zones (Stekleff et al. 2013). Lastly, the offset of the barrier from the road may influence the likelihood of serious injury. If the barrier is farther off the road, the rider has more time to reduce speed and potentially steer away from the barrier.

A small number of cable barrier crashes were captured in this study, particularly for fatal crashes. Three fatal cable barrier crashes were observed. Additionally, for this dataset, there was a lower percentage of fatal crashes in cable barrier collisions than in W-beam and concrete barrier collisions. There may be a different risk of fatality in cable barrier crashes; however, there were too few fatal cable barrier crashes to investigate this further. Alternatively, the fewer number of crashes observed, compared to guardrail or concrete barrier, may be influencing the lower percentage of fatalities.

6.6 Conclusions

This study has presented an analysis of the injury risk in 951 motorcycle-barrier collisions, involving over 1,000 riders, in North Carolina, Texas, and New Jersey. The barriers examined included W-beam guardrail, cable barrier, and concrete barrier. Injury severity patterns in collisions with each barrier type were analyzed. Overall, 40.1% of people involved in motorcycle collisions with W-beam guardrail were seriously injured (K+A). Similarly, 40.4% of people involved in a motorcycle collision with cable barrier were seriously injured. A lower percentage (36.5%) of people in motorcycle-concrete barrier collisions were seriously injured.

Overall, the odds of serious injury were found to be 1.4 times greater in W-beam guardrail collisions as compared to concrete barrier collisions. From this sample of crashes, there was no significant difference seen in odds of serious injury between W-beam guardrail or concrete barrier collisions and cable barrier collisions. This finding also supports the results from the national study presented in the previous chapter, which showed that riders had a greater risk of fatality in W-beam crashes as compared to concrete barrier crashes.

CHAPTER 7

Relationship Between Rider Trajectory and Injury Outcome in Motorcycle-to-Barrier Crashes

7.1 Introduction

Previous European studies have identified two main modes of motorcycle-to-barrier impact: sliding and upright impacts (Berg et al. 2005a; Peldschus et al. 2007). Bambach et al. (2012) investigated rider orientation in fatal collisions in Australia. Few studies have focused on the rider trajectory in non-fatal and fatal crashes in the United States. One hazard identified in many studies is the guardrail posts (Domham 1987). Sliding can cause rider entanglement in the posts, while an upright collision could cause the rider to vault over the barrier.

This chapter aims to determine how the post-impact rider trajectory influences the injury outcome and compare the risk of severe injury for different trajectories. Here post-impact trajectory is defined as the trajectory taken by the rider after the motorcycle collides with or contacts the road, barrier, or other object. This study builds on previous research by investigating fatal and non-fatal crashes with a greater sample size.

Rider trajectory and crash severity are likely correlated. At the higher speeds associated with severe or fatal injuries, riders will likely follow a different trajectory than riders subjected to barrier impacts at lower speeds. One challenge for this study is to differentiate between rider and vehicle trajectory. Large-scale accident databases (e.g., FARS and GES) assume that the vehicle and occupants follow the same trajectory. This is, however, unlikely to be true for motorcyclists since, in a crash, the motorcycle and rider are more likely to disengage and follow separate trajectories. It is not known to what degree this separation takes place since this is not clearly specified in the accident databases, further complicating large-scale study of rider trajectory.

Much of this chapter is provided in Daniello, Cristino, and Gabler (2013). Text and figures are reproduced largely verbatim from this work.

7.2 Objective

The objective of this chapter is to determine the distribution of post-impact rider trajectories in motorcycle-to-barrier crashes. Additionally, this chapter aims to determine the relationship between trajectory and injury outcome in these crashes.

7.3 Methods

In the FARS and GES national databases, as well as most state crash databases, the sequence of events describes the objects struck by the motorcycle rather than the rider. The data collection protocol is vehicle-centric and assumes that vehicle occupants were subjected to the same sequence of events as the vehicles. While this is largely true for car occupants, it is not always true for motorcyclists. In motorcycle crashes, the rider and motorcycle frequently separate after collision and may follow completely different trajectories.

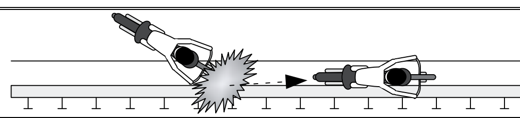
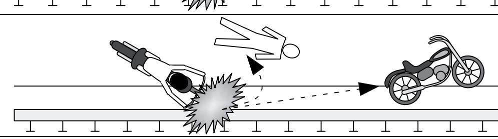
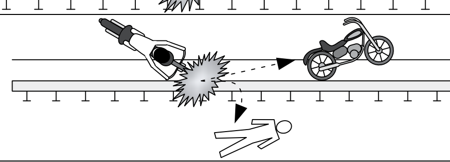
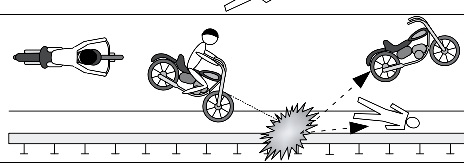
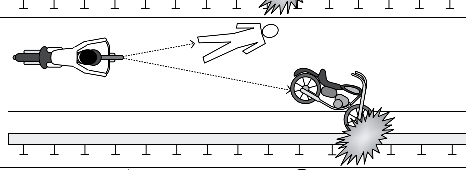
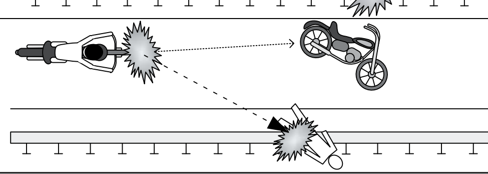
In most accident databases (including FARS), rider trajectories are not available. In this study, rider trajectories in motorcycle-to-barrier collisions were determined through an analysis of the hard copy of PARs from New Jersey. Trajectories were obtained by manual inspection of scene diagrams and narrative descriptions of each crash. The results of this analysis were merged with NJCRASH, the New Jersey state crash database, to couple the resulting set of rider trajectories with other crash factors, such as injury severity and road alignment. This study specifically analyzed single-vehicle crashes into W-beam guardrail or concrete barrier. Multi-vehicle crashes were excluded from the analysis to focus the study on injury caused by the barrier.

7.3.1 Identifying Rider Trajectories

Rider trajectories were classified into one of seven categories: upright, no ejection; ejected, same side landing onto the roadway; vaulting; sliding; separated prior to barrier impact; ejected, side unknown; and rider ejected into barrier. These are shown pictorially in Table 7-1. Two additional classifications were included to account for crashes where the trajectory could not be determined: no barrier in description and unknown. The "unknown" crashes were those where either the PAR was illegible or there was no clear trajectory.

Upright crashes were defined as those where the rider remained on the same side of the barrier after collision and the PAR description did not specify that the rider was ejected onto the roadway.

Table 7-1. Description of rider trajectories.

Rider Trajectory	Description
Upright (no stated ejection in PAR)	
Ejected (same side landing onto roadway)	
Vaulted (opposite side landing)	
Sliding	
Separated prior	
Ejected into barrier	

Vaulting crashes were defined as those where the rider was ejected from the motorcycle after impact with the barrier and came to rest on the other side of the barrier. Likewise, crashes where the rider was ejected on the same side were those where the rider was ejected into the roadway (i.e., over the handlebars). For crashes where the ejection side could not be identified, the trajectory was defined as ejected, side unknown. The rider did not contact the barrier for crashes identified as the motorcycle and rider separating prior to collision. In many of these crashes, the rider chose to jump from the vehicle to avoid the barrier. In cases where the rider was ejected into the barrier, there was a crash event prior to the collision that caused the separation. An example of a prior crash event is striking a curb, which caused the rider to become airborne and then be flung into the barrier.

All PARs were examined by two different reviewers and rider trajectory results were compared. Crashes with conflicting trajectories were reviewed again to determine which trajectory was most likely.

7.3.2 Identifying Barrier Type

Because the NJCRASH electronic database did not always correctly differentiate between barrier types, the barrier type was examined for all crashes. The barrier type was identified using Google Earth Street View based on the methods described earlier in this report. The crash location was found using the crash street and cross street names, or, when available, the latitude and longitude coordinates. The actual crash site was located using Google Earth, and the Google Street View photographs were used to examine the barrier in the area. Barriers that could not be identified and crashes where no Street View was available were excluded from the rest of the analysis. Additionally, crashes with concrete barriers in toll plazas were excluded.

The distribution of injury severity by barrier type was examined using the KABCO scale. New Jersey has a full helmet law, requiring riders to wear a helmet at all times (IIHS 2013). Odds of serious injury were investigated for helmeted riders only, since there were few unhelmeted riders, and injury outcome is likely dependent on helmet usage.

7.3.3 Road Characteristics

This study hypothesized that several road characteristics would have an influence on rider trajectory. For example, negotiating an entrance/exit ramp to or from a highway requires different handling than traveling straight on a roadway. Four main roadway characteristics were controlled for in the analysis: horizontal alignment, occurrence on an entrance/exit ramp, the side of the road where the barrier was located, and the speed limit.

Crashes on entrance/exit ramps were identified through inspection of the PARs. Though the NJCRASH data coded whether or not the crash occurred on a ramp, these were not found to be accurate in comparison to the PARs. The study combined entrance and exit ramps into one category since, in many cases, the rider was exiting one highway to enter another. Therefore, the difference between exit and entrance could not be identified.

Additionally, the side of the road where the barrier was placed was identified through the PAR crash descriptions and diagrams. NJCRASH coded a sequence of events, with variables including which side of the vehicle ran off; however, this was not coded for all cases. Therefore, the PARs were used to develop a complete picture where the rider collided with the barrier. Cases were identified as either "Right," "Median," or "Opposite Side." Opposite side crashes were those where the rider traversed the oncoming lanes and collided with the barrier on the left of the road.

Chi square analyses were used to determine which factors influenced the distribution of rider trajectory. For these analyses, all cases were included regardless of injury severity. The χ^2 test describes if the distributions of rider trajectories are the same for all instances of the characteristic analyzed in the test. For example, to determine if roadway alignment (straight vs. curved roads) influences rider trajectory, the hypothesis that straight and curved roads result in the same distribution of trajectories is tested. If the χ^2 value is sufficiently high, this hypothesis is rejected and it can be concluded that straight and curved roads result in different distributions of rider trajectories.

7.3.4 Odds of Serious Injury

A binary logit model was constructed to predict the probability of serious injury while controlling for rider trajectory and roadway characteristics. Roadway characteristics included were entrance/exit ramp, horizontal alignment, barrier type, and posted speed. Stepwise elimination was used to include only variables that had a significant effect on severity outcome. All statistical analyses were conducted using SAS 9.2. The logistic procedure was used to construct the binary logit model, and the Fisher's scoring method was used.

7.4 Results

From 2007 to 2011, there were 442 single-vehicle, motorcycle-barrier collisions reported in New Jersey. Of these crashes, the PAR was available for 430 crashes (97.3%), and the barrier was identified for 342 of these crashes, involving 361 riders and passengers. In the other 88 crashes with the PAR available, the barrier could not be identified using the methods described. Additionally, some crashes with PARs were excluded due to conflicting information between the PAR and the electronic NJCRASH database. In these cases, the crash identification numbers were the same, but several crash characteristics were not consistent between NJCRASH and the PAR. The PARs were not available for the remaining crashes. The final dataset consisted of 77.4% of all single-vehicle motorcycle-to-barrier crashes in New Jersey. All crashes included in the analysis are summarized in Table 7-2.

Table 7-2. Summary of all barrier crashes (New Jersey, 2007–2011).

	Riders	Percent of Riders
Total Crashes	430	--
Riders Involved	455	
Barrier Type		
Guardrail	265	58.2%
Concrete	96	21.1%
Other/Unknown	94	20.7%
Injury Severity (Guardrail and Concrete Only)		
K	35	9.7%
A	43	11.9%
B	181	50.1%
C	73	20.2%
O	0	0.0%
Unknown	29	8.0%
Helmet Use (Guardrail and Concrete Only)		
Helmeted	322	89.2%
Unhelmeted	20	5.5%
Unknown	19	5.3%

Table 7-3. Summary of trajectory by injury severity in New Jersey crashes (2007–2011).

Rider Trajectory	Injury Severity						Total
	Fatal	Incapacitating	Moderate	Complaint of Pain	Property Damage	Unknown	
Upright	2	11	49	29	0	6	97
Ejected (same side)	5	11	28	5	0	1	50
Vaulted	7	5	26	6	0	0	44
Sliding	6	4	31	15	0	4	60
Separated prior	0	4	13	4	0	3	24
Ejected into barrier	6	0	5	1	0	0	12
Ejected (unknown)	0	2	7	3	0	1	13
No barrier described	0	4	8	2	0	2	16
Unknown	9	2	14	8	0	12	45
Total	35	43	181	73	0	29	361

There were 265 riders involved in 248 guardrail collisions, and 96 riders involved in 94 concrete barrier collisions. Additionally, four riders were involved in collisions with concrete barriers in toll plazas ("Other" barrier type). The distribution of injury severity by trajectory is summarized in Table 7-3. For the majority of cases where a passenger was involved, the operator and passenger experienced the same trajectory, though they did not necessarily have the same injury severity. For the one case where operator and passenger trajectory differed, trajectory was coded uniquely for each person.

Table 7-4 shows the different highway characteristics investigated by barrier type. Only crashes with information available for all roadway characteristics were included in the model.

Approximately 1 in 10 riders were fatally injured in the barrier crashes investigated, which is consistent with the national fatality risk in motorcycle-to-barrier collisions found by Gabler (2007). For comparison to the other chapters presented in this dissertation, the OR of serious injury for helmeted riders was computed between guardrail and concrete barrier crashes. The odds of serious injury in guardrail crashes were 1.497 (95% CI: 0.780–2.874) times greater than those in concrete barrier crashes. This was not significant at the 0.05 level, though the point estimate is approximately equal to that presented in the previous chapter.

Table 7-4. Roadway characteristics of crashes investigated.

	Guardrail Crashes	Concrete Barrier Crashes
Horizontal Alignment		
Straight	65	42
Curve	183	52
Occurrence on Entrance/Exit Ramp		
On Ramp	45	77
Not on Ramp	196	17
Unknown	7	0
Speed Limit		
< 45 mph	102	45
≥ 45 mph	141	77
Unknown	5	3
Side of Road		
Right	180	36
Median	31	57
Opposite Side	20	0
Unknown	17	1

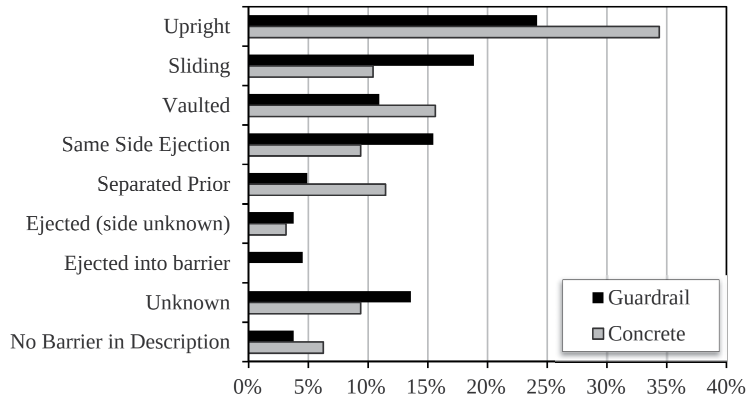


Figure 7-1. Rider trajectory in guardrail and concrete barrier collisions.

The distribution of trajectories by barrier type is shown in Figure 7-1. Most riders collided with the barrier in an upright position without vaulting over the barrier, for both guardrail and concrete barrier crashes. Overall, 16.6% of riders slid into the barrier during the crash, and sliding into the barrier occurred more frequently than vaulting over the barrier. Additionally, more riders became separated from their motorcycle prior to colliding with a concrete barrier as compared to a metal barrier. In several of these cases, riders reported jumping from the motorcycle prior to impact. Also, more riders slid into guardrail as compared to the concrete barrier. These trends in rider trajectory were significantly different between guardrail and concrete barrier crashes ($\chi^2 = 19.695$, $p = 0.012$).

7.4.1 Effect of Roadway Characteristics on Rider Trajectory

This study hypothesized that the rider trajectory may be a function of road characteristics including horizontal alignment (straight vs. curved roads), roadway versus entrance/exit ramp, posted speed limit, and the road the barrier was placed on (median, roadside, opposite roadside). These characteristics were first tested independently using χ^2 analyses. For this component of the analysis, only crashes where the rider struck the barrier were used. Additionally, crashes were limited to those where all road characteristic information was available; 36 riders were excluded due to the crash missing at least one of these key pieces of information. Lastly, the seven unhelmeted riders were also excluded. The final dataset for this analysis consisted of 234 riders, 176 in guardrail collisions and 58 in concrete barrier collisions.

Table 7-5 gives the results of each independent χ^2 analysis. Crashes occurring on an entrance/exit ramp, as compared to those not occurring on a ramp, had a significantly different distribution of rider trajectories at the 0.05 level. Distributions in trajectories were found to be different for straight and curved roads, though this was only significant at the 0.10 level. However, there was no significant difference in trajectory trends on high-speed (speed limit ≥ 45) versus

Table 7-5. Comparison of rider trajectory for roadway characteristics.

Characteristic	Levels			χ^2	*p*
Horizontal Alignment	Straight	Curve		10.092	0.073
Entrance/Exit Ramp*	Not on Ramp	On a Ramp		11.792	0.038
Posted Speed Limit	< 45 mph	≥45 mph		1.219	0.943
Side of Road	Median	Right Side	Opposite Side	10.842	0.370

* Significant difference in rider trajectory distributions at the 0.05 level.

low-speed roads. Likewise, no significant differences in rider trajectories were seen for side of road. There were 14 riders who collided with a barrier on the opposite side of the road (i.e., crossing oncoming travel lanes), which resulted in a small number of cases for the analysis. However, in comparing only median and right side crashes, there was also no significant difference in trajectory trends observed ($\chi^2 = 4.727$, $p = 0.450$).

Sliding and vaulting were more common in crashes on horizontal curves as compared to straight roads. Nearly 25% of riders slid into the barrier on curved roads, whereas 15% slid into the barrier on straight roads. Likewise, 20% of riders included in the study who crashed on curved roads vaulted over the barrier after impacting the barrier. Comparatively, 9% of riders in the study who crashed on straight roads vaulted over the barrier after impact. In collisions on exit ramps, a greater percentage of riders were thrown into the barrier compared to those who did not crash on a ramp; 13% of riders who crashed on a ramp and 2% of riders who were not on a ramp were ejected into the barrier.

7.4.2 Effect of Rider Trajectory on Injury Severity

The odds of serious injury were computed by barrier type and rider trajectory for helmeted riders (Figure 7-2). The number of serious to non-serious crashes is also given in Figure 7-2. For guardrail crashes, being ejected into the barrier had the highest odds of serious injury. However, there was no significant difference in distribution of serious injury by rider trajectory for the guardrail cases observed ($\chi^2 = 5.973$, $p = 0.309$).

In concrete barrier crashes, vaulting resulted in the greatest odds of serious injury. There were crashes observed where riders were ejected into concrete barriers. Since there were small numbers of concrete barrier crashes observed, Fisher's exact test was used to determine if there was a significant difference in distributions of serious injury by rider trajectory in these crashes. Differences in serious injury distributions in concrete barrier crashes were trending toward significance at the 0.05 level ($p = 0.052$) but did not reach it.

A binary logit model was constructed to directly compare the odds of serious injury for different rider trajectories while controlling for roadway characteristics. Rider trajectories were combined into broader categories to reduce the amount of variation in the model. All modes of ejection after a collision with the barrier (vaulted, same side ejection, and unknown side ejection) were combined to form an "ejected" rider trajectory category. The "ejected into barrier" trajectory was not included in this larger category since collision with the barrier did not cause the rider to

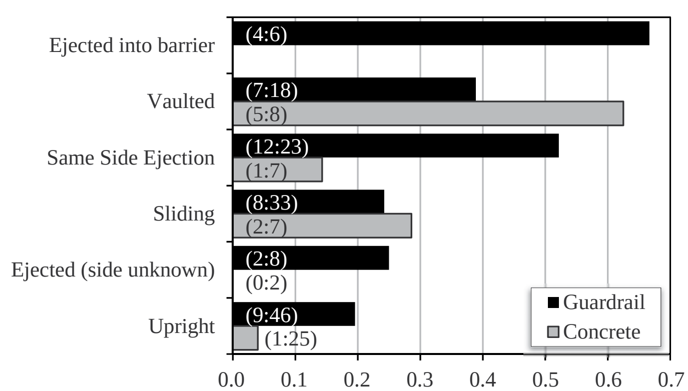


Figure 7-2. Odds of serious injury by rider trajectory (number of seriously injured: non-seriously injured riders).

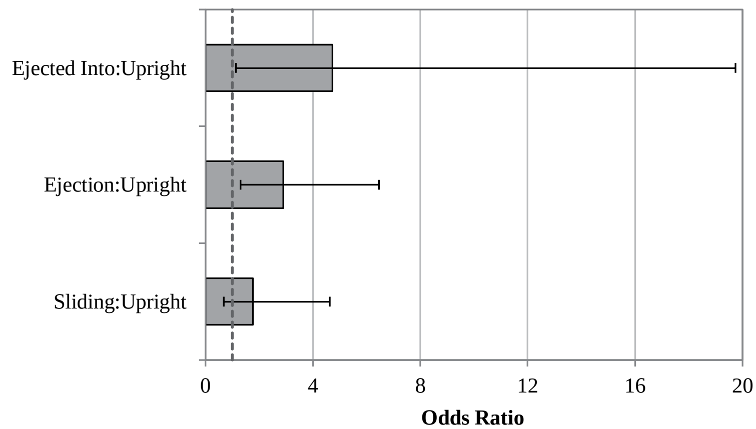


Figure 7-3. OR of serious injury compared to upright crashes.

be thrown from the motorcycle. Upright collisions were used as the dependent variable, and ejection, ejection into barrier, and sliding were all independent variables. Stepwise elimination was used to include variables into the model. The only variable significant at the 0.05 level was rider trajectory. From these analyses, it is evident that, though rider trajectory was correlated with horizontal alignment and travel on an entrance/exit ramp, these factors did not significantly influence injury outcome.

Odds ratios were computed to compare sliding, ejection, and ejection into barrier to upright collisions. As shown in Figure 7-1, upright collisions were the most common collisions observed. The odds ratios of serious injury are shown in Figure 7-3 with 95% confidence intervals. Being ejected from the motorcycle significantly increased the odds of serious injury as compared to colliding upright without being ejected. Likewise, being ejected into the barrier significantly increased the odds of serious injury 4.73 times (95% CI: 1.14–19.74). Based on the cases observed, sliding also increased the odds of serious injury as compared to striking upright without being ejected, though this elevated risk was not found to be significant at the 0.05 level.

7.5 Discussion

Several limitations are associated with this study. First, the determination of the rider trajectory relied heavily on the level of detail provided in the PAR. To reduce the influence of the reviewer, each case was independently reviewed by two people. Additionally, the level of detail of the crash description varied greatly depending on the circumstances surrounding the crash. In some cases, the crash descriptions did not include sufficient information to determine rider trajectory. Based on the level of detail incorporated in the PARs, this type of study may not be feasible for all states. There was also insufficient information in the descriptions to determine if the collision was a low-side or high-side crash. For the vaulting cases, the object that the rider struck, if any, after vaulting was unknown and not considered for the analysis. Injury outcome would likely vary by object struck. The number of crashes analyzed was greatly reduced from the original PAR sample since the barrier type could not be identified for many crashes (20.5%). It was assumed that the sample of crashes with PARs and barrier type was representative of all crashes because PARS were available for the vast majority of crashes.

Previous studies have typically identified two types of barrier collisions: upright and sliding. This study further divided upright collisions based on the trajectory of the ejected rider. In order to compare upright and sliding crashes, all modes of ejection (vaulted, same side, and side unknown) were combined with upright crashes. The majority of riders (68.0%) in single-vehicle, barrier crashes collided with the barrier while upright. Another 20.0% of riders slid into the barrier. The findings show slightly higher prevalence of upright collisions and lower estimates for the prevalence of sliding collisions compared to the previous literature. Berg et al. (2005a) also found that 51% crashed upright and 45% crashed while sliding. Likewise, Bambach et al. (2012) found that 44% of fatally injured riders in W-beam crashes crashed into the barrier while upright. In this dataset, 52% of all fatally injured riders in W-beam crashes were upright, which is consistent with the findings of Bambach et al. (2012). However, Quincy et al. (1988) found that in 58% of crashes, riders slid into the barrier. Also, Peldschus et al. (2007) found that approximately 75% of riders were upright at the time of impact, though their dataset included tree and pole impacts in addition to barrier crashes. Some of the differences may be regional in nature. This study looks at U.S. crashes, whereas previous studies have analyzed crashes in Europe and Australia.

7.6 Conclusions

The rider trajectory and barrier type were determined for 342 motorcycle-to-barrier crashes in New Jersey from 2007 to 2011. Of the crashes analyzed, riders most often struck the barrier upright without being ejected from the motorcycle. In concrete barrier crashes, vaulting over the barrier occurred more frequently than sliding into the barrier. However, in guardrail collisions, the opposite was observed: riders more frequently slid into the guardrail than vaulted over it. Several road characteristics were investigated to determine influence of the environment on rider trajectory in barrier crashes. Crashes on straight roads had different trajectory trends than crashes on curved roads, though this was not significant at the 0.05 level. A significant difference in trajectory distributions was seen for crashes that occurred on entrance/exit ramps compared to those that did not. Lastly, barrier type was also found to have a significant difference in rider trajectory trends. However, while these factors influenced trajectory type, they were not found to be significant in predicting serious injury crashes.

The findings of this study suggest that injury outcome is a function of rider trajectory. The odds of serious injury were 2.91 times (95% CI: 1.31–6.46) greater for crashes where the rider was ejected from the motorcycle after impacting the barrier as compared to crashes where the rider struck upright and was not separated from the vehicle. Additionally, being ejected into the barrier also increased the odds of serious injury.

One theory advanced by some groups is that the rider is dead before striking the barrier. In the majority of cases, the rider did not separate from the motorcycle prior to impacting the barrier. Thus, it is unlikely that the rider is typically fatally injured before striking the barrier. Likewise, striking the barrier is likely the cause of the rider becoming airborne and vaulting over the barrier, which was shown to increase injury risk.

FARS and GES follow the vehicle when reporting the sequence of events. As shown, the sequence of events that the rider experienced was similar to that experienced by the motorcycle in the majority of the crashes. Therefore, assuming the rider follows the same trajectory as the vehicle in these databases is valid.

Lastly, exit ramps had a greater percentage of riders who were ejected into the barrier, and being ejected into the barrier has a greater risk of serious injury. Likewise, more riders who crashed on horizontal curves were ejected from the motorcycle as compared to those who crashed on straight roads (41% to 35%). Though horizontal alignment is not shown to significantly affect injury outcome, it influenced the distribution of rider trajectories. Road alignment therefore has an indirect connection to injury severity.

CHAPTER 8

Characteristics of Injuries in Motorcycle-to-Barrier Collisions in Maryland

8.1 Introduction

One of the challenges in investigating motorcycle crash injury mechanisms is the lack of detailed injury descriptions for U.S. motorcycle crashes. The analysis of crash databases in the previous chapters had to rely on the reported injury severity, which is a relatively rough scale (Compton 2005). Unlike passenger car crashes, there is currently no nationally representative in-depth investigation database for motorcycle crashes in the United States. A promising alternative, however, is CODES, which links crash records to hospital records and merges injury information with crash information. This allows for a detailed analysis of injuries during crashes to paint a more complete picture of motorcycle collisions with roadside objects. Previous studies have used this dataset to investigate injury outcome in motorcycle crashes with respect to helmet use (Shankar et al. 1992) and rider age (Dischinger et al. 2006; Dischinger et al. 2007).

Previous studies on motorcyclist injuries focused on fatal crashes using European, Australian, and United Arab Emirates data. Head injuries were found to be the most common cause of fatality in all motorcycle crashes (Bambach et al. 2012; Hefny et al. 2011; Lin and Kraus 2009). Bambach et al. (2012) found that the most frequently injured region in fatal collisions was the thorax, and the head was the second most commonly injured region. There are anecdotal reports that motorcycle-to-barrier crashes may result in a very different pattern of injuries, such as amputations or severe lacerations, which are rarely observed in collisions with other objects. It is important to understand these injury patterns in order to identify the potential need for design improvements to traffic barriers.

Much of this chapter is provided in Daniello and Gabler (2012). Text and figures are reproduced largely verbatim from this work.

8.2 Objective

The objective of this chapter was to determine the type, relative frequency, and severity of injuries incurred in motorcycle-to-barrier crashes. Injury distributions were compared to motorcyclist injury distributions in other crash modes to identify how barrier collisions differ from other collision modes.

8.3 Methods

The Maryland CODES was used to analyze 3 years of motorcycle collisions, from 2006 to 2008. Data sources for the Maryland CODES include, but are not limited to, police records, EMS, emergency department, and toxicology reports (NHTSA 2010). The CODES data is the result of linking these datasets using a probabilistic method (NHTSA 2010).

Injury data is reported in CODES using the International Classification of Diseases, Ninth Revision, Clinical Modification (ICD-9-CM). The ICD-9-CM codes provide detailed injury information, but do not give a measure of injury severity. However, as discussed earlier in this report, the AIS reports injury severity in terms of threat to life (AAAM 2001). AIS ranks injury severity from AIS = 1 (minor) to AIS = 6 (not survivable). For this chapter, the ICDMap-90 Program (1998) was used to convert the ICD-9-CM codes to their respective AIS-90 codes. In a small number of cases, ICD-9-CM codes did not map directly to AIS codes. When not enough information was provided in the ICD-9-CM code to identify a unique AIS code, the AIS code with the lowest potential severity was used (Johns Hopkins and Tri-Analytics 1998).

Four categories of motorcycle crashes were analyzed in this chapter: crashes with traffic barriers, crashes with fixed objects, multi-vehicle crashes, and overturn crashes. Traffic barrier crashes involved a collision with a guardrail, construction barrier, or crash attenuator. Fixed-object crashes included collisions with bridges, buildings, culverts, embankments, fences, poles, and trees. The barrier and fixed-object crashes included in this study were limited to single-vehicle crashes. If a motorcycle struck multiple objects, for example a barrier followed by a tree, the object that caused the injury could not be determined. Multi-event collisions were therefore excluded from the barrier and fixed-object analysis. The multi-vehicle crash category included crashes between motorcycles and cars, but excluded crashes where there also was a collision with a barrier or fixed object. Overturn crashes analyzed were restricted to single-vehicle crashes. All motorcyclists included in this study were operators of the vehicle.

Severity of all crashes was analyzed using MAIS, and serious injuries were defined as those with an AIS greater than or equal to 3. In addition, injuries were analyzed by body region to determine whether injury patterns of motorcyclists involved in barrier collisions differed from other collision types. Serious lacerations and amputations were tabulated separately to investigate concerns that the sharp edges of metal barrier posts and rail edges may lead to these types of cutting injuries. The relative risk of specific injuries in different collision modes was also investigated. Cochran-Mantel-Haenszel statistics were used to determine the 95% confidence interval for these relative risks. Lastly, as a quality check, the number of fatally injured riders in Maryland CODES was compared with the number of riders fatally injured in Maryland using the FARS database.

8.4 Results

There were 5,586 motorcycle crashes of all severity in Maryland from 2006 to 2008. The CODES data linked 2,357 of these crashes with hospital inpatient or emergency department data. The injury data associated with these crashes was for the motorcycle operator. No motorcycle passengers were included in this study. Seven of the linked cases did not have any injury codes associated with them. There were 1,707 motorcyclists included in this study, which were divided into four crash categories: single-vehicle barrier crashes, single-vehicle fixed-objects crashes (excluding collisions with barriers), multi-vehicle crashes (excluding multi-vehicle collisions with barriers and fixed objects), and overturn only crashes. The number of crashes of each collision type is shown in Table 8-1. The majority of riders with linked hospital data excluded from the final dataset were in a crash that did not fall into one of the four analysis categories, as shown in the "Other" crash designation in Table 8-1. These were often multi-event collisions, such as a collision into a barrier and a fixed object.

Data linkage between two dissimilar datasets (e.g., police-reported crashes and hospital data) is seldom perfect. When using linked datasets, one question is how representative is the linked dataset of the overall dataset. Table 8-2 presents the distribution of police-reported injury severity for all cases and for the linked subset of these cases. Only 42% (2,357 of 5,586) of police-reported crashes could be linked with hospital data. However, as the linked cases required

Table 8-1. Distribution of motorcycle crashes in Maryland (2006–2008).

Crash Type	MD CODES		% Successfully Linked Crashes	Fatality Comparison	
	Linked Crashes	All Crashes		MD CODES	FARS
Single Vehicle Barrier	107	242	44.2	41	34
Single Vehicle Fixed Object[+]	260	654	39.8	44	57
Multi-Vehicle	1,103	2,601	42.4	119	152
Single Vehicle Overturn Only	242	452	53.5	1	9
Other	645	1,637	39.4	37	32
Total Crashes	2,357	5,586	42.2%	242	284

[+]Not including barrier collisions

hospital admission, we expected that the linked crashes would not include property damage only cases, most minor injury cases, and many fatal cases. Table 8-2 confirms that the linked cases are biased toward injury and disabled cases, and almost entirely exclude property damage only cases. Only 27.7% of the fatal cases were linked to hospital records. Indeed, a χ^2 test showed that there is a significant difference in the injury distributions of the linked and unlinked datasets ($p < 0.0001$).

However, when the seriously injured riders likely to have been hospitalized ("Disabled" and "Injured") are compared as shown in Table 8-3, the linked and unlinked datasets are remarkably similar. A χ^2 test showed there was no significant difference in the injury distributions of the linked and unlinked datasets ($p = 0.908$) in the "Injured" and "Disabled" groups. We concluded that using the linked CODES data to analyze the injury distributions of the A+B crashes is representative of the serious injuries in the entire dataset.

General characteristics of the crashes included in this analysis are given in Table 8-4. All levels of injury severity were included for this analysis. The gender distributions were approximately the same for all collision types. Overall, 93% of motorcyclists included in this analysis were male. Maryland has a full helmet law, which requires riders to wear a helmet at all times. Police reported that 81% of all motorcyclists were helmeted at the time of the crash. The distribution of helmet usage was also approximately the same across all collision types.

Distributions of crashes in the collision categories were significantly different between each of the different road characteristics listed in Table 8-4 (horizontal alignment, occurrence on entrance/exit ramp, and speed limit). Multi-vehicle and overturn only crashes tended to occur more frequently on straight roads, whereas barrier and other fixed-object crashes occurred more frequently on curved roads. Additionally, fixed-object and multi-vehicle crashes tended to occur more frequently on low-speed roads (speed limit < 45 mph). However, barrier and overturn only crashes occurred approximately as frequently on low-speed roads as they did on high-speed roads.

Table 8-2. Police-reported injury severity in MD CODES data for the entire dataset.

KABCO	Police-reported Injury Severity	% Linked Cases	% Unlinked Cases
O	Not Injured	5.94	33.01
C	Possible Injury	18.16	16.01
B	Injured	48.88	30.54
A	Disabled	24.18	15.02
K	Fatal	2.84	5.42

Table 8-3. Seriously injured riders in MD CODES data.

KABCO	Police-reported Injury Severity	Number of Linked Cases	Number of Un-Linked Cases	% Linked Cases	% Unlinked Cases
B	Injured	1,152	986	66.90	67.03
A	Disabled	570	485	33.10	32.97
A + B	Injured + Disabled	1,722	1,471	100	100

The vast majority of ICD-9-CM codes were successfully mapped onto AIS codes. The maximum injury severity could not be determined in fewer than 2% of cases (27 of 1,707). When mapping the ICD-9-CM scores to AIS scores, these 27 cases had at least one injury for which the severity could not be determined.

The most common body regions to be injured regardless of severity were the upper and lower extremities. Approximately 70% of all motorcyclists analyzed in this study suffered at least one injury to the upper and/or lower extremities. One in five riders (19.5%) suffered injuries to both the upper and lower extremities. For all collision modes analyzed, with the exception of overturn crashes, the lower extremities were most often the region of principal diagnosis (Figure 8-1). The region of principal diagnosis corresponds to the first ICD-9 code (Johns Hopkins and Tri-Analytics 1998), but does not provide a measure of severity. The upper extremities were the second most frequent body region for the principal diagnosis for all collision modes analyzed except overturn crashes.

Figure 8-2 presents the distribution of MAIS 3+ injuries by body region. For all crash modes analyzed except multi-vehicle crashes, the thorax was the most common region for an AIS 3+ injury. For multi-vehicle crashes, the lower extremities suffered AIS 3+ injuries most often.

Table 8-4. Composition of the dataset.

	Barrier Crashes	Fixed Object Crashes	Multi-Vehicle Crashes	Overturn Only Crashes	Total
Total Crashes	106	260	1,101	240	1,707
Horizontal Alignment					
Straight	26	117	978	180	1,301
Curve	72	138	106	56	372
Unknown	8	5	17	4	34
Entrance/Exit Ramp					
On Ramp	13	14	11	7	45
Not on Ramp	93	246	1,090	233	1,662
Speed Limit					
Low Speed (<45 mph)	52	181	742	129	1,104
High Speed (≥ 45 mph)	51	78	343	110	582
Unknown	3	1	16	1	21
Gender					
Male	98	234	1,041	215	1,588
Female	8	26	58	25	117
Unknown	0	0	2	0	2
Helmet Usage					
Helmet Used	86	225	870	202	1,383
Eye Shield Used	1	1	6	2	10
None Used	7	16	71	15	109
Unknown	12	18	154	21	205

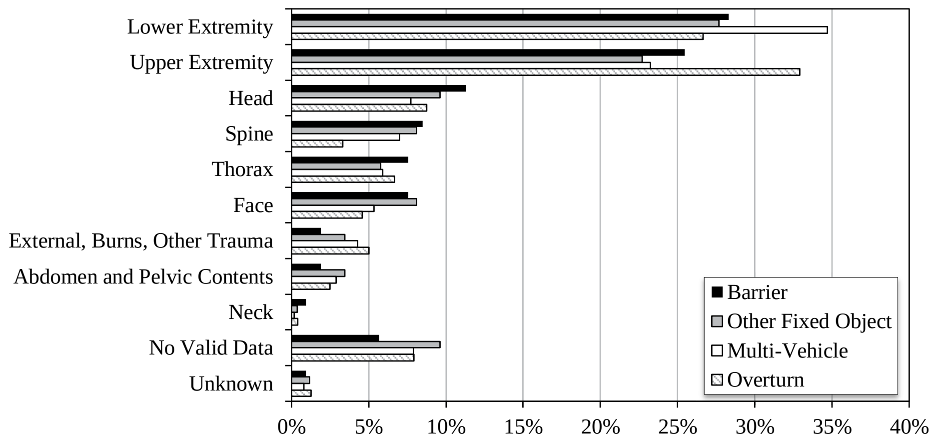


Figure 8-1. Region of principal diagnosis.

8.4.1 Extremity Injuries and Amputations

There were 1,206 motorcyclists who suffered an upper or lower extremity injury from the crashes analyzed for this study. As noted earlier, extremities were the most frequently injured body regions. To investigate reports of amputations in barrier crashes, the CODES dataset was searched for this type of injury. In this dataset, four motorcyclists suffered an amputation. None of these motorcyclists collided with a barrier. The amputations were incurred either in a collision with another type of fixed object or in a collision with another vehicle. However, this dataset excludes many of the fatal crashes; therefore, any amputations suffered during these crashes could not be determined based on this dataset.

8.4.2 Lacerations

One concern about collisions with the guardrail is that the sharp edges of the guardrail posts and the upper and lower rail edges might pose a serious laceration hazard to motorcyclists. The MD CODES dataset was examined for this type of injury. Over half of the motorcyclists (55.7%) involved in barrier collisions included for analysis suffered at least one laceration injury. In contrast, approximately one-third of riders in fixed-object and multi-vehicle collisions (33.8% and 30.9%, respectively) and 22.9% of riders in overturn collisions suffered at least one laceration injury.

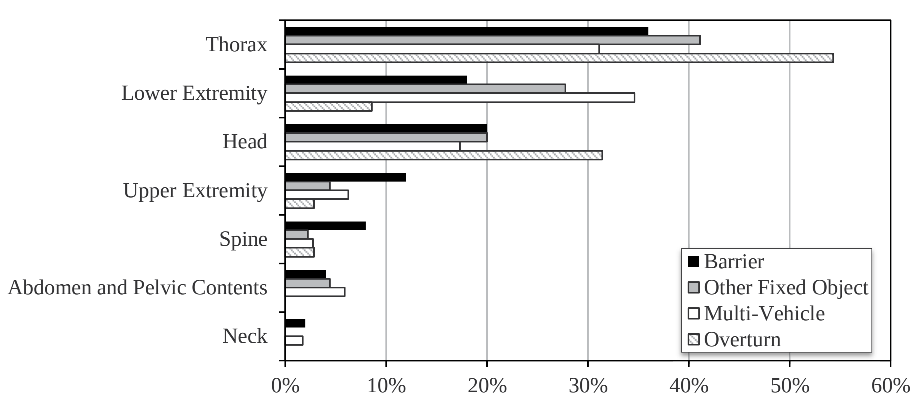


Figure 8-2. Distribution of AIS 3+ injuries by body region.

Focusing on higher severity lacerations, riders in barrier collisions were 2.26 times (95% CI: 0.75–6.86) more likely to suffer at least one AIS 2+ laceration injury than those in overturn collisions. However, this higher risk was not statistically significant. Similarly, motorcyclists involved in fixed-object collisions and those involved in multi-vehicle crashes were 1.54 (95% CI: 0.57–4.17) and 1.60 (95% CI: 0.69–3.71) times more likely to suffer an AIS 2+ laceration than motorcyclists in overturn collisions, respectively. Again, the risk of laceration in these types of collisions was not found to be significantly different from the risk of laceration in overturn collisions.

For barrier collisions, the most common body regions to suffer a laceration were the face and the lower extremities (Figure 8-3). In overturn collisions, motorcyclists were more likely to have lacerations on the upper extremities. For lacerating injuries of all crash modes analyzed, the majority of these injuries were incurred to either the face or extremities.

Different barrier post and rail designs exist that may affect the risk of laceration. Barrier type was not recorded in the CODES database. Figure 8-4 shows some common cross sections for W-beam guardrail post designs and a cable barrier post design. These are representative of posts used in the United States. As shown, all these posts have small faces, which may increase the risk of laceration. However, it was unlikely that all barriers included in this study had posts, and there was no way to differentiate between barriers with posts and barriers without posts (e.g., concrete barriers).

8.4.3 Clavicle Injuries

Clavicle fractures do not pose a large threat to life (AIS = 2); however, the implications of the injury may be serious. Loss of functionality is associated with this injury, short-term and long-term (Kemper et al. 2009). Of the 1,707 people included in the study, 111 (6.5%) suffered a clavicle fracture. The distribution of these injuries by collision type is shown in Table 8-5.

The distribution of these injuries was similar across collision types. The frequency of riders with clavicle fractures ranged from 5.0% to 10.4% in each type of collision. On average, 8% of riders in each collision type (barrier, other fixed object, multi-vehicle, and overturn only) suffered a clavicle fracture.

The odds of clavicle fracture in overturn collisions were 1.92 (95% CI: 1.15-3.21) times greater than that in multi-vehicle collisions. Kemper et al. (2009) demonstrated that clavicle fractures

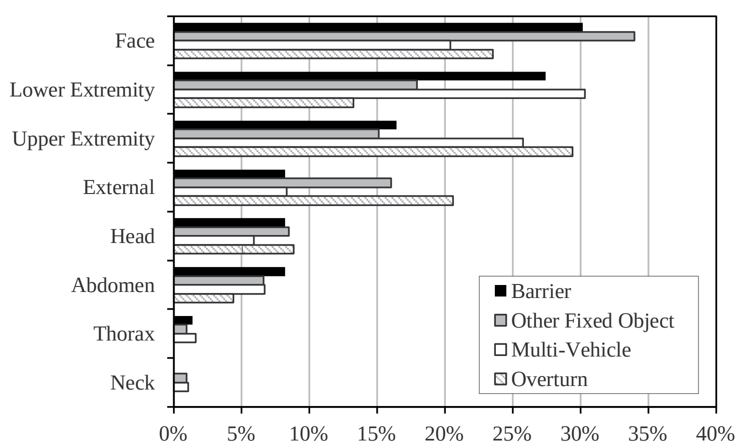


Figure 8-3. Distribution of lacerations by body region.

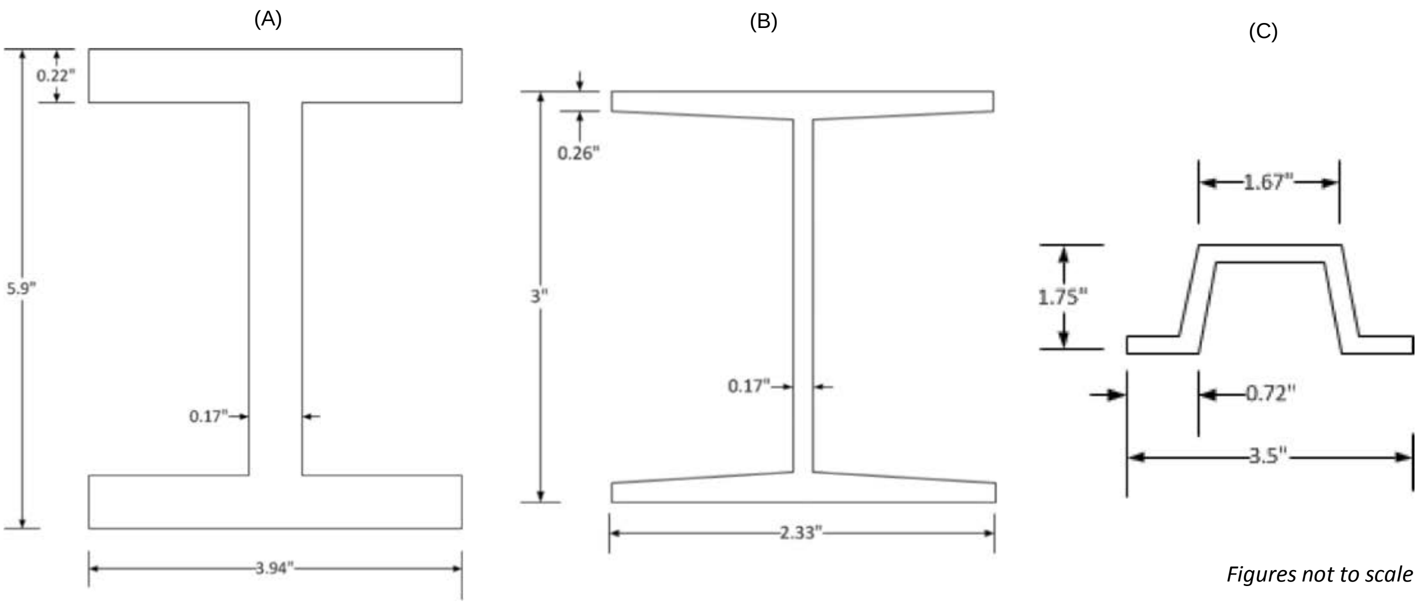


Figure 8-4. Various post designs: (A) strong-steel post for W-beam guardrail; (B) weak-steel post for W-beam guardrail; and (C) flanged-channel post for cable barrier dimensions based on AASHTO Task Force 13 Committee guidelines.

are directional, and it is likely that the loading patterns in overturn-only collisions are very different than those in multi-vehicle collisions. Significant differences in risk of clavicle fracture were not seen between the other collision types analyzed, though this may be due to a small sample size.

8.4.4 Injuries to the Thoracic Region

The thoracic region was next analyzed in further detail due to the large risk of thoracic injury in the event of a barrier collision. Of the motorcyclists included in this study, 23.5% involved in barrier collisions and 16.7% involved in overturn collisions suffered at least one injury to the thorax. Table 8-6 shows the distribution of the number of injuries to the thoracic region. Multiple thoracic injuries were common: 39% of riders with a thoracic injury suffered two or more thoracic injuries. Motorcyclists involved in a barrier collision were 2.15 times (95% CI: 1.17–3.92) more likely to suffer a serious thoracic injury than riders in overturn collisions, which was found to be significant at the 0.05 level. There were elevated relative risks of serious thoracic

Table 8-5. Distribution of clavicle fractures by collision type.

Collision type	Riders with at least one clavicle injury	Total riders analyzed	Percentage with clavicle injury (%)
Barrier	7	106	6.6
Other Fixed Object	27	260	10.4
Multi-Vehicle	55	1,101	5.0
Overturn	22	240	9.2
Total	111	1,707	6.5

Table 8-6. Distribution of people injured in the thoracic region.

Number of Thoracic Injuries	Barrier	Fixed Object	Multi-Vehicle	Ground	All
1	13	26	105	27	171
2	7	18	36	10	71
3	3	11	17	2	33
4	2	0	2	1	5
5	0	0	1	0	1
6	0	1	0	0	1
Total People Injured	25	56	161	40	282
Total Injuries	44	101	241	57	443
% People with 1+ Thoracic Injuries	23.6%	21.5%	14.6%	16.7%	16.1%

injury for motorcyclists involved in fixed object and multi-vehicle collisions as compared to overturn collisions; however, these risks were not found to be significant.

Figure 8-5 presents the types of thoracic injuries occurring in motorcycle crashes. The most common type of thoracic injury for motorcyclists who collided with a barrier was a lung contusion. The risk of lung contusion for those involved in barrier collisions was 1.87 times (95% CI: 1.04–3.36) higher than that in overturn collisions for motorcyclists who suffered at least one thoracic injury. Chest wall contusions were the most common injury for riders involved in an overturn collision. The most common injury for motorcyclists involved in a fixed-object or multi-vehicle collision was a hemothorax or pneumothorax (blood or air in the pleural cavity, i.e., the space between the chest wall and the lung).

Nearly one-third (31%) of riders involved in a barrier collision suffered a lung contusion. In contrast, 18% of riders who did not strike a barrier suffered a lung contusion. Additionally, 33% of the motorcyclists analyzed suffered at least one rib fracture, 43% of whom also suffered a hemothorax or pneumothorax associated with the fracture.

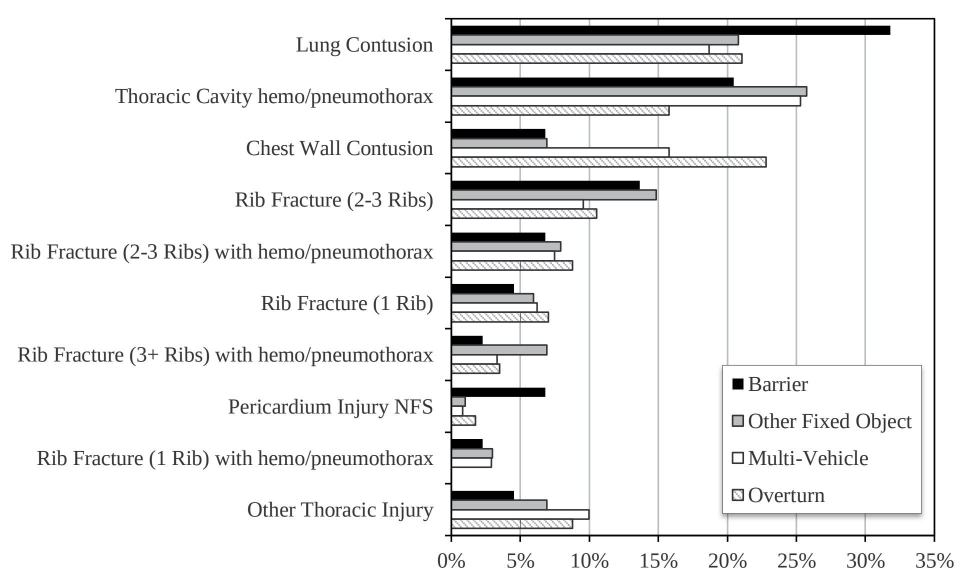


Figure 8-5. Distribution of injuries to the thoracic region.

8.5 Limitations

There were several limitations associated with this analysis conducted for this chapter. First, the CODES data only listed the injuries incurred by the rider. Hospital teams, however, had no way to determine either the injury mechanism or the component that caused the injury. Second, the Maryland CODES data did not report the type of the barrier struck by the rider. As discussed in Chapters 4 and 5, risk of fatal or serious injury was a function of barrier type, and findings from Berg et al. (2005a) suggest the same conclusion. Injury risk is likewise a function of barrier type; however, there was not enough detail in the dataset to determine the barrier type. Additionally, the sequence of events typically describes what happened to the vehicle during the crash, not the people in the crash. Based on the analysis in Chapter 6, the majority of riders also contacted a barrier when a barrier was reported. Therefore, it was assumed that the rider followed the same path as the motorcycle, effectively having the same sequence of events.

Lastly, the dataset used in this chapter is limited to those crashes that could be linked to the injury information, and is not necessarily representative of all motorcycle crashes in Maryland. The dataset did not include most property-damage-only crashes, minor non-hospitalized riders, and many fatally injured riders, and showed a significantly different distribution of police-reported injury severity than all Maryland motorcycle crashes. The injury distributions of those fatally injured may be different than those who suffered serious injuries. The dataset is therefore most appropriately used to compare the types of injuries suffered by riders who were admitted to a hospital after a crash.

8.6 Conclusions

This chapter examined the risk of injury by body region in motorcycle-barrier crashes using linked PARs and hospital data from Maryland from 2006 to 2008. The most commonly injured regions for all motorcycle crashes were the upper and lower extremities. Over 70% of motorcyclists involved in the crashes analyzed suffered an injury to the upper and/or lower extremities. This finding is consistent with that of Lin and Kraus (2009), who found that lower-extremity injuries most commonly occur in motorcycle crashes, and Hefny et al. (2011) who found that upper and lower limbs were the two most common causes of injury in motorcycle collisions in the United Arab Emirates. Extremities were the most commonly injured region, but not the most common seriously injured body region. Serious injuries are defined as those with AIS 3 or greater; however, maximum level of severity in upper extremities on the AIS scale is 3 and in the lower extremities is 4 (Benton 2000). Though extremity injuries with an AIS 2 certainly have a large impact on quality of life, this study focused on injuries with a greater threat to life (as given by the AIS scale).

The thorax was the most frequently seriously injured body region. This is consistent with the findings of Bambach et al. (2012) who examined fatal crashes. Motorcyclists involved in barrier crashes were 2.15 times (95% CI: 1.17–3.92) more likely to suffer a serious injury to the thoracic region than motorcyclists not involved in barrier collisions. The most common injury for motorcyclists involved in barrier collisions was a lung contusion, whereas the most common injury for motorcyclists not involved in barrier collisions was a hemothorax or pneumothorax.

Riders impacting a barrier had a higher risk of AIS 2+ laceration than riders in other types of collisions based on the point estimate, though this was not found to be significant. One hypothesis is that the lacerations are caused by rider impact with the edges of the guardrail posts and the upper and lower edges of the W-beam. However, the contact source for these lacerations could not be determined from the CODES data. When practical, further information about the crash should be acquired and retained so that retrospective studies can be conducted more thoroughly.

Approximately 7% of riders analyzed in this study suffered at least one clavicle fracture. This is consistent with the findings of Wick et al. (1996) and Valey et al. (1993) who found that approximately 10% of riders suffered a clavicle fracture.

This dataset showed no evidence of amputations in barrier crashes, which has been a concern to riders. However, we could not rule out if this is a problem in fatal crashes. Fatal injuries are underrepresented in the dataset since only hospital data is available to describe injuries. Injury data for fatal crashes is crucial in understanding many severe crashes. There is a need to document fatal injuries in motorcycle crashes, as is done for passenger vehicle crashes through the NASS Crashworthiness Data System. These data would provide useful insight into the most severe motorcycle crashes.

CHAPTER 9

Roadway Characteristics Associated with Motorcycle Crashes into Longitudinal Barriers and the Influence on Rider Injury

9.1 Introduction

Motorcyclists in the United States are more than 30 times more likely than passenger car occupants to be fatally injured in traffic crashes (NHTSA 2013). As early as 1981 in the seminal Hurt study (Hurt, Ouellet and Thom 1981a), motorcycle impacts with fixed objects have been implicated as posing an especially high risk to motorcycle riders. These fixed object crashes include impacts into longitudinal traffic barriers such as W-beam guardrails and concrete barriers. Although a motorcyclist impacting a barrier is a relatively infrequent event, previous research indicates that these crashes often result in severe injury consequences, even compared to other motorcycle crash types (Daniello and Gabler 2011a). In the United States, motorcycle-to-guardrail crashes account for more than 40% of all vehicle-to-guardrail fatalities, more than any other single vehicle type, despite motorcycles representing only 2% of the vehicle fleet (Gabler 2007).

Several researchers have described the development, implementation, or evaluation of motorcycle-to-barrier crash countermeasures to mitigate the injury consequences of these crashes (Koch and Schueler 1987; Ellmers 1997; Mulvihill and Corben 2004; Janssen et al. 2005). These countermeasures include specially designed longitudinal traffic barriers as well as products intended to retrofit existing barriers (e.g., guardrail post protection). Previous research suggested that installation of these countermeasures is only cost effective at locations susceptible to this crash type (Koch and Schueler 1987; Domham 1987). Little is known regarding the specific roadway conditions and roadway alignment, such as horizontal curve radius, most frequently associated with this crash type. A better understanding of the roadway characteristics associated with motorcycle-to-barrier crashes is needed and would aid designers in determining the most effective locations to implement motorcycle-to-barrier crash countermeasures.

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9.2 Objective

The purpose of this study was to examine police-reported motorcycle impacts into longitudinal traffic barriers to (1) determine specific roadway and roadway alignment characteristics associated with these crashes and (2) investigate the influence of these characteristics on resulting rider injury.

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9.3 Background and Previous Research

9.3.1 Motorcycle-to-Barrier Impacts, Rider Injury, and Related Crash Test Procedures

A majority of previously published literature regarding motorcycle impacts into barriers has focused on characterizing the resulting occupant injuries (Ouellet 1982; Bryden and Fortuniewicz, 1986; Koch and Brendicke, 1988; Hell and Lob 1993; Gibson and Benetatos 2000; ACEM 2004; Bambach et al. 2012; Daniello and Gabler 2012). On the whole, these studies suggested that motorcycle-to-barrier crashes result in more severe rider injury and an increased rider fatality risk when compared to all motorcycle crashes or motorcycle crashes involving only an impact with the ground. A study by Savolainen and Mannering (2007) provided a quantification of this increased injury risk, finding that guardrail impact decreases the probability of a minor or no-injury crash by 17%. A smaller number of researchers investigated the influence of barrier type on injury risk (Gabler 2007; Mulvihill and Corben 2004; Candappa et al. 2005; Daniello and Gabler 2011b) and generally found a slightly increased injury risk associated with metal beam barriers compared to concrete barriers.

Full-scale crash test procedures in the United States (Ross et al. 1993; AASHTO 2009), in Europe (CEN 2010), and in Australia/New Zealand (Standards Australia 1999) are used to assess the crashworthiness of longitudinal barriers prior to field installation. Since motorcyclists have traditionally represented a small portion of the overall vehicle fleet, the current U.S. procedures address only passenger vehicle (e.g., car and light truck) impacts to longitudinal barriers. Researchers have developed motorcycle-to-barrier crash test procedures (Duncan et al. 2000; Berg et al. 2005a; Peldschus et al. 2007; Garcia et al. 2009), and a testing standard currently exists in Spain (UNE 2008) and in the European Union (CEN 2012). These existing motorcycle test procedures generally specify two impact configurations: an upright rider/motorcycle impacting a barrier at an angle and a sliding rider impacting the barrier headfirst, also at an angle. Injury risk in these tests is based primarily on the measured response of an ATD.

9.3.2 Roadway Characteristics Associated with Motorcycle-to-Barrier Impacts

Several previous studies provided an indication of roadway characteristics associated with motorcycle impacts into longitudinal barriers. Using French crash data from the late 1970s and early 1980s, Quincy et al. (1988) found that motorcycle impacts into barriers occurred more frequently on urban roadways and were overrepresented at entrance and exit ramps. Approximately 54% of these crashes occurred on ramps, but this location type represented only 5% of the total roadway length. Of 22 motorcycle-barrier crashes in Germany, Domham (1987) notes that not one of these crashes occurred on a horizontal curve with the smallest radii. Ellmers (1997) indicated that mountainous rural primary and secondary roads were critical to safety for this crash type. Gibson and Benetatos (2000) presented findings from fatal motorcycle crashes occurring in NSW from 1998 through 1999. Based on eight barrier impact fatalities, the most frequent scenario (4 of 8) was the rider losing control on a right-hand bend and exiting the roadway to the left, followed by an impact to the barrier located on the roadside. Using the police speed estimate and the speed limit in the area of the crash, the authors noted that motorcycle-to-barrier crashes occurred at speeds above 60 km/h (38 mph). Berg et al. (2005a) reported on 57 motorcycle-barrier crashes that were investigated in Germany and found that the majority of crashes occurred within curves (53% left, 7% right) with the remaining 40% occurring on straight roadway sections. More recently, Jama et al. (2011) investigated 77 fatal motorcycle-to-barrier crashes in Australia and New Zealand. A vast majority (81%) of these crashes involved a horizontal curve with an approximately equal distribution of right and left curves.

While the studies summarized earlier provided some insight into roadway characteristics of motorcycle-to-barrier crashes, the findings tended to be general in nature (e.g., horizontal curve presence versus horizontal curve radius) and primarily anecdotal. A single recommendation was found with respect to horizontal curvature (Elliot et al. 2003) that suggests potential motorcycle-barrier countermeasures are appropriate on horizontal curves with a radius less than 250 meters (820 ft). No other quantitative roadway geometric data was found in the available literature specific to the motorcycle-to-barrier crash mode.

9.3.3 Effects of Roadway Geometry and Characteristics on Motorcycle Crash Frequency and Severity

Other previous motorcycle crash research, primarily focused on either single-vehicle motorcycle or all motorcycle crashes, provides additional insight regarding the influence of roadway geometric characteristics. Similar to the previous motorcycle-to-barrier research, however, a majority of these studies include only generic roadway geometry characteristics. The majority of these studies support the notion that single motorcycle crashes are more likely to occur in locations with horizontal curvature, vertical curvature, and vertical grade as summarized in Table 9-1 below.

At least two studies provided detailed roadway alignment for motorcycle crashes, although not specific to motorcycle-to-barrier impacts and focused on rural two-lane highway crash locations. Schneider et al. (2009) examined various roadway, operator, environmental, and vehicle factors affecting the severity of horizontal curve crashes on Texas rural two-lane highways. Data included 5 years of police-reported crash data coupled with roadway data, a total of

Table 9-1. Summary of previous motorcycle crash study findings related to roadway alignment.

Author [Reference]	Location/Data Years/Data Type	Roadway Alignment-Related Findings
Li et al. (2009)	Taiwan/2000–2002/Police-reported crashes linked to hospital and death records	Fatality risk on non-level, non-straight roadways was significantly increased for motor vehicle occupants but not for motorcycle occupants. Motorcycle crash victims had a higher odds of fatality (OR: 1.09), but this was not statistically significant.
Savolainen and Mannering (2007)	Indiana/2003–2005/Police-reported crashes with rider training data	Single motorcycle crashes on horizontal curves decrease the probability of a minor or no-injury crash by 8%. For multi-vehicle motorcycle crashes, horizontal and vertical curve presence increased incapacitating injury by 45 and 81%, respectively.
Preusser et al. (1995)	U.S./1992/FARS	Approximately 70% of run-off road fatal motorcycle crashes occurred on curves compared to 21% for all other fatal motorcycle crashes.
Kim et al. (2002)	HI/1986–1995/Police-reported crashes with linked hospital records	Single motorcycle crash > 5 times more likely when horizontal curve present and ~1.4 times more likely when vertical curve present. Serious and fatal injuries 1.5 times and nearly 2 times more likely on curved roads.
Quddus et al. (2002)	Singapore/1992–2000/ Police-reported crashes	Probability of fatality increases by ~72% when a bend is present. Narrow roads, sharp turns, and blind corners not found to be statistically significant with respect to injury severity. Sharp turns are found to increase motorcycle damage levels. No numerical values are indicated to define a "sharp" curve.
ACEM (2004)	5 European countries/1999–2000/In-depth crash investigations	All motorcycle crashes were found to be overrepresented in curves (30% occurring on horizontal curves) compared to passenger vehicle crashes (21% on horizontal curves).
Samaha et al. (2007)	U.S./1992–2004/Weighted sample of police-reported crashes	Motorcycle crashes occurring away from a junction were found to be 1.7 times more likely to be fatal than those crashes occurring within an intersection.

10,029 motorcycle crashes. Horizontal curves were split into three categories based on radius: "small" curves with radius less than 500 ft, "large" curves with radius greater than 2,800 ft, and "medium" curves with radius between the small and large ranges. There were a total of 354 motorcycle crashes with 62 occurring on "small" curves, 241 occurring on "medium" curves, and 51 occurring on "large" curves. Compared to all other vehicle types, fatal and incapacitating motorcycle injuries were 604%, 628%, and 568% more likely on "small," "medium," and "large" horizontal curves, respectively. Non-incapacitating injuries were 73 to 98% more likely than for operators of all other vehicle types, and "large" curves had the highest increase in non-incapacitating injury risk. Schneider et al. (2010) investigated roadway geometry effects on single-vehicle motorcycle crash occurrence using crash and roadway inventory data from Ohio. Data included 225 single-vehicle motorcycle crashes occurring on Ohio rural two-lane highways between 2002 and 2008. Roadway characteristics found to have a statistically significant effect on motorcycle crashes were (1) horizontal curve length, (2) horizontal curve radius, (3) distance relative to the curve end-points, (4) roadway shoulder width, and (5) total segment average daily traffic (ADT). Longer, higher speed curves and smaller radius curves were found to increase the frequency of motorcycle crashes on a particular segment. Curves were found to influence crash risk on adjacent tangent sections for up to 300 ft, but crash risk decreased as a motorcyclist moved further from a curved section. For every percentage point increase in total ADT, motorcycle crash frequency was estimated to increase by 0.43%. In addition, roadway sections with shoulders less than 6 ft in width were found to increase motorcycle crash risk by approximately 50%.

In addition to these alignment-related findings, researchers have also identified several other roadway factors that affect the occurrence and/or severity of motorcycle crashes. Shankar and Mannering (1996) found that single-vehicle motorcycle crashes occurring on interstates increase the likelihood of disabling and possible injury, and that wet pavement increases the likelihood of property damage and possible injury. Kim et al. (2002) found that single-vehicle motorcycle crashes were approximately three times more likely when an oily/wet road surface was present, 1.5 times more likely in rural areas, and approximately five times more likely when a roadway surface defect was present. For single-vehicle motorcycle crashes, Savolainen and Mannering (2007) found wet pavement and intersection crashes less likely to result in no injury, with a 77% and 29% higher chance of no injury, respectively. Similarly, posted speed limits over 50 mph were found to decrease the probability of a minor or non-injury single-vehicle motorcycle crash by 10%. Li et al. (2009) noted that motorcycle fatality risk decreased in urban areas and on city streets while it increased on highways.

9.4 Methodology

The overall approach for this study was to use state-level police-reported crash data linked with roadway data to investigate the characteristics of crashes involving a motorcycle impacting a longitudinal barrier. Two additional data subsets, all single-vehicle motorcycle crashes and multiple-vehicle motorcycle crashes, were used as comparison groups for the motorcycle-to-barrier cases. Statistical models were developed to examine the influence of various roadway characteristics, particularly alignment, on resulting rider injury while accounting for other potential confounding factors. All data processing and statistical analyses for this study were performed using SAS V9.2.

9.4.1 Data Sources and Case Selection Procedures

Data for the study was obtained from HSIS, a nine-state database maintained by the FHWA that contains linked crash, roadway inventory, and traffic volume data (FHWA 2011). Of the nine U.S. states with HSIS data available, only five have roadway information that includes both horizontal curvature and vertical grade information: Michigan, Utah, Washington, Ohio, and Illinois. For the present study, data was selected only from Washington and Ohio. Michigan (Council et al. 2001) and Utah (FHWA 2000) participation in HSIS ended in 1997 and 2000, respectively. For both of these states, detailed roadway alignment data is available until 1994 and has been excluded from further analysis due to the age of the limited data available. Illinois has more recent data available, but the alignment information is only collected for "potentially substandard" curves (Council and Mohamedshah 2009a). As the alignment information represents an incomplete dataset, Illinois data also was excluded.

Ohio HSIS Case Selection and Data Preparation

HSIS data from Ohio used in this study includes all motorcycle crashes occurring from 2000 through 2011. Data was available from 1997 through 1999 but was excluded from analysis as a new crash reporting form was introduced in Ohio in 2000 that represented major changes from the previous Form 46. An initial analysis of the 2000 through 2011 data indicated that a small portion, less than 1.2% of all motorcycle crashes, involved motorized bicycles. Due to the small number of motorized bicycle crashes, these cases were excluded from further analysis.

To prepare the data for analysis, accident and vehicle data tables were first merged by crash year (ACCYR) and case number (CASENO). The available crashes were then divided into three data subsets:

1. Single-vehicle motorcycle crashes involving one or more longitudinal barrier impacts (SVLB)
2. All single-vehicle motorcycle crashes (SV)
3. Multi-vehicle crashes involving at least one motorcycle (MV)

The SVLB subset is of primary interest, while SV and MV crashes primarily serve as comparison groups. The vehicle type variable (VEHTYPE) was used to exclude motorized bicycles, and the number of vehicles variable (NUMVEHS) was used to distinguish between single- (NUMVEHS = 1) and multi-vehicle (NUMVEHS > 1) crashes. Longitudinal barrier crashes were selected using all of the available sequence of event variables (EVENT1 through EVENT4). For the purpose of this study, a longitudinal barrier crash was defined as one or more impacts into a guardrail face, guardrail end, or median barrier (EVENT = 30, 31, or 32). This barrier impact could occur in any one (or more) of the four event sequences recorded. Note that MV subset was limited to data only on the crash-involved motorcycles and may include crashes where a longitudinal barrier was impacted.

For each data subset and crash year combination, PROC SQL was used to merge the combined accident and vehicle data with the associated roadway, curve, and grade tables by matching the county route variable (CNTY_RTE) and ensuring that the milepost was between the beginning and end of the road/curve/grade segment. A similar procedure was used to merge the accident/vehicle data with the angle point table except that the milepost equaled the angle point milepost; Ohio DOT defines an "angle point" as any sharp angle horizontal curve with degree of curvature exceeding 90 degrees (Council and Mohamedshah 2007). This data was then merged with the available occupant data by ACCYR, CASENO, and vehicle number (VEHNO).

Washington State HSIS Case Selection and Data Preparation

Data provided from HSIS included all motorcycle, scooter, and moped crashes occurring in Washington from 1993 through 1996 and 2002 through 2011. A complete set of data from Washington was not available between 1996 and 2002 primarily due to state budgetary constraints during that time (Council and Mohamedshah 2009b). For consistency with the Ohio data available, only the 2002 through 2011 Washington data were used in the analysis. Initial analysis of this data indicated that scooters and mopeds represent approximately 1.7% of all Washington crashes available and, as a result, have been excluded from further analysis.

Preparation of the Washington data was nearly identical with that of the Ohio data, including merging of the accident and vehicle data tables followed by dividing the data into the same three subsets. The only difference is the presence of a ramp file and the absence of an angle point file. Longitudinal barrier crashes were selected using the available object struck variables (OBJECT1 and OBJECT2). The Washington barrier-related object struck codes differ somewhat from those present in the Ohio data and generally separate barriers by type (guardrail or concrete barrier) and impact location (barrier end, barrier face). Any impact to either a concrete barrier or guardrail was considered a longitudinal barrier impact (OBJECT = 31, 32, 33, 34, 35, or 36). PROC SQL was then used to merge the crash, vehicle, roadway, curve, grade, and ramp information into a single table by matching the road inventory variables (RD_INV, ROAD_INV, CURV_INV, and GRAD_INV) and ensuring that the milepost was between the beginning and end of the road/curve/grade segment. This data was then merged with the available occupant data by ACCYR, CASENO, and VEHNO.

9.4.2 Data Analysis and Model Development

Characterization of Motorcycle Crashes into Longitudinal Barriers

For both states, descriptive statistics related to the roadway, crash, and rider were generated for all three crash subsets. Roadway characteristics included horizontal curvature, vertical grade, number of lanes, median presence/width, shoulder width, posted speed limit, functional classification, and average annual daily traffic (AADT). Mean values were reported for horizontal curve radius, vertical grade, speed limit, median width, and AADT. Non-tangent sections were categorized into two groups (radius ≥ 820 ft or < 820 ft) based on the sole recommendation for motorcycle-to-barrier crash countermeasures found in Elliot et al. (2003). Although the mean grade was reported for both states, Ohio reports only data on grades greater than or equal to 3%. Two vertical grade categories were created using the 3% grade stipulation present in the Ohio data. Number of lanes was used to group the data into three categories: two lanes or less, greater than two but less than four, and more than four lanes. Roads were classified as either divided or undivided; Ohio had a separate variable indicating this while the left shoulder data (LSHL_WD2) was used in Washington. Shoulder width was grouped into three categories: less than 2 ft, greater than or equal to 2 ft but less than 10 ft, and greater than or equal to 10 ft, based loosely on the AASHTO (2011) shoulder width guidelines. Posted speed limit was divided into two groups based on the AASHTO (2011) distinction between high- and low-speed design. Functional classification was reported in aggregate for urban and rural areas, and the area type distribution was reported separately. Crash characteristics included location and roadway surface condition. Crash location was categorized into three categories: intersection or intersection-related, non-intersection, or other. The "other" category included driveways, private property, and unknown location types. Roadway condition included dry, wet, and other, which included snow, ice, and sand, among others. Occupant characteristics included helmet usage, gender, mean age, and police-reported injury severity. The distributions of these characteristics are compared to all state-specific HSIS data where appropriate. Data was also provided on the number of MV crashes involving a barrier impact and the distribution of barrier type struck for the Washington data.

Box and whisker plots were generated to further investigate numeric roadway characteristics such as horizontal curve radius, vertical grade (Washington only), and AADT. Plots were generated for each data subset as well as all HSIS available data for the most recent year of data for a particular state. As AADT tends to change more frequently than roadway alignment, the distribution of AADT for all years and all roads in the state was reported. *T*-tests were used to compare the means of the independent sample combinations within each state (e.g., SV compared to MV crashes and SVLB compared to MV crashes).

Statistical Model Development

Using the suitable HSIS SVLB cases from both states, a binary logistic regression model was developed to predict rider injury severity based on roadway alignment characteristics, while accounting for potential crash and occupant confounding factors. Injury was categorized as either severe (fatal or incapacitating) or nonsevere (non-incapacitating, possible, and no injury). Unknown, missing, or non-traffic fatalities were excluded. Two different horizontal curve variables were used in the model development. The first categorized curved sections based on radius as described above: tangent section, radius ≥ 820 ft, or radius < 820 ft. The second normalized the radius using the recommended minimum horizontal curve radius based on Ohio (ODOT 2012) or Washington (WSDOT 2012) geometric design standards. The minimum radius was selected using a design speed equal to the posted speed limit and using the largest permissible superelevation, as superelevation data was not universally available in the HSIS roadway data. For curves with posted speed less than that of the tangent sections of the same road, the lesser speed was used in the normalized radius calculation. Vertical grade was categorized as either less than 3% or greater than 3%. AADT was divided into four categories: < 2,500 vehicles per day (vpd); 2,500 to 9,999 vpd; 10,000 to 49,999 vpd; and > 50,000 vpd. Other explanatory roadway characteristics included shoulder width (< 2 ft; ≥ 2 and < 10 ft; and 10+ ft), posted speed (≤ 45 mph and > 45 mph), and divided/undivided. Confounding occupant and crash factors included occupant age (≤ 25 and > 25 years), helmet usage (worn, not worn, or unknown), and road surface condition (dry, wet, or other). ORs were used to determine the influence of roadway characteristics on injury severity in this crash type as well as to quantify the effects of the possible confounding factors.

9.5 Results

9.5.1 Characterization of Motorcycle Impacts to Barriers

Of the 30,454 motorcycle crashes available for analysis, there were 1,511 single-vehicle motorcycle-to-barrier crashes involving 1,691 occupants. These crashes represented approximately 5% of all available motorcycle crash cases, 4.5% of Ohio crashes, and 6.2% of Washington crashes. All single-vehicle motorcycle crashes comprised 43% of all motorcycle crashes (41% of Ohio crashes and 48% of Washington crashes). Table 9-2 provides a more detailed summary of the available data. Note that Table 9-2 only includes crashes with matching roadway data. There was a small portion, less than 1% of all cases, excluded from further analysis as no matching roadway data was available.

There were differences in mean horizontal curve radius and vertical grade between states. Mean horizontal curve radius for crashes in Washington State was higher than in Ohio across all data subsets. For all reported roadway data, the mean horizontal curve radius was 2,494.7 ft and 664.5 ft for Washington and Ohio, respectively. Excluding ramps, approximately 63% of Washington SVLB crashes occurred on curved sections compared to 41% of SV crashes and 21% of MV crashes. In Ohio, approximately 19% of SVLB crashes occurred on curved sections compared to 12% of SV and 3.6% of MV crashes. Of the horizontal curve crashes, 61% of Washington SVLB and 74% of Ohio SVLB crashes were on curves with radius less than 820 ft. Approximately 45% of SVLB crashes in Washington occurred on vertical grades in excess of 3% compared to 29% and 22% for Washington SV and MV crashes, respectively. A similar trend is observed in Ohio with 20, 15, and 7% of SVLB, SV, and MV crashes occurring on grades in excess of 3%. For all roadway sections, the mean grade was 7.1% in Ohio and 1.8% in Washington. Considering only the grades equal or greater than 3%, the mean vertical grade in Washington was 4.6%. Approximately 20% of Washington SVLB crashes occurred on horizontal curve sections with a 3% grade or higher compared to 10.9% of SV crashes and 5.3% of MV crashes. In Ohio, 8.7% of

Table 9-2. Summary of Washington (2002–2011, inclusive) and Ohio (2000–2011, inclusive) HSIS data.

Variable	Available Data	Washington			Ohio		
		SVLB	SV	MV	SVLB	SV	MV
All	Vehicles	556	4372	4659	955	8856	12,567
	Occupants	599	4415	4703	1092	10,229	14,432
Geometric, Roadway and Crash Characteristics (by involved vehicle)							
Horizontal Alignment	Mean radius [ft]	1157	2235	3450	668	694	810
	Radius < 820’	162	632	197	135	799	268
	Radius ≥ 820’	102	801	706	48	296	189
	Tangent Section	157*	2094*	3355*	772	7761	12,110
Vertical Alignment	Mean grade [%]	2.72	2.02	1.65	7.7†	7.7†	6.3†
	< 3%	240	2469	3135	766	7549	11,699
	≥3%	195	999	865	189	1307	868
Lanes	1 – 2 lanes	262	1935	1565	473	5349	5815
	3 – 4 lanes	225	1852	2103	264	2481	5539
	More than 4 lanes	69	585	991	218	1026	1213
Median	Undivided	363*	3009*	3769*	493	6192	9850
	Divided	58*	550*	489*	462	2664	2717
	Mean Width [ft]	14.1	16.4	12.4	34	38.5	32.2
Shoulder Width	Less than 2 ft	65	935	1740	105	1626	5132
	≥2 and < 10 ft	360	2415	1759	466	4746	4745
	10+ ft	131	1022	1158	336	1950	1880
	Unknown/Missing	0	0	2	48	534	810
Posted Speed	Mean [mph]	51.3	50.3	46.4	53.8	50.7	42.9
	≤ 45 mph	243	1959	2499	181	2463	7571
	> 45 mph	313	2412	2160	759	6259	4650
	Not Stated	0	1	0	15	134	346
Area Type	Rural	247	1883	1212	478	4930	3673
	Urban	309	2489	3445	476	3912	8862
Roadway Functional Class	Principal Arterial	238	2263	3239	501	3893	7025
	Minor Arterial	124	828	788	139	1676	3368
	Collector	59	468	229	314	3269	2137
	Local Road	0	0	0	0	4	5
Traffic	Mean ADT [vpd]	34,925	34,021	45,971	33,396	20,929	21,298
Location	Intersection	49	950	2007	83	1499	6548
	Non-Intersection	504	3261	2005	860	7166	4742
	Other/Unknown	3	161	647	12	191	1277
Road Surface	Dry	505	3812	4285	886	8057	11,964
	Wet	37	407	350	60	581	493
	Other	14	153	21	8	160	47
Rider and Injury Characteristics (by involved occupant)							
Helmet	Helmet worn	498	3947	4100	509	4630	5347
	Helmet not worn	1	38	53	500	4862	7304
	Unknown/Missing	57	387	506	83	737	1781
Gender	Male	486	3898	4249	899	8250	11,671
	Female	104	424	308	185	1877	2307
	Unknown/Missing	9	93	146	8	102	454
Age	Mean [years]	38.8	40.8	41.5	38.9	40.9	41.2
Injury	Fatal	39	136	164	101	369	517
	Incapacitating	137	722	689	435	2731	3038
	Non-Incapacitating	257	2023	1481	411	4665	4743
	Possible Injury	113	957	1122	57	927	1864
	No Injury	43	473	1070	60	1293	3654
	Unknown	10	104	177	28	244	616

† Ohio only reports vertical grades equal to or greater than 3%, * Ramp crashes excluded.

SVLB crashes occurred on curved sections with grades at 3% or higher compared to 4.4% of SV and 0.85% of MV crashes.

Approximately half of SVLB crashes in both states occurred on roadways with two lanes or less. A higher percentage of Washington SVLB crashes (40%) occur on roadways with more than four lanes compared to Ohio SVLB crashes (23%). Of all Washington roadways, 55% were two lanes or less and 11% were more than four lanes. For Ohio, 65% of roads were two lanes are less and 6% were more than four lanes. Average median width was larger for all Ohio data subsets compared to Washington. For all divided roadways, the average median width was 37.2 ft in Ohio and 16 ft in Washington. A larger portion of Washington SVLB crashes (86%) occurred on undivided roadways compared to 52% of Ohio SVLB crashes. Note that the Washington median data in Table 9-2 does not include any ramp crashes. There were 135, 813, and 401 ramp SVLB, SV, and MV crashes, respectively. The right shoulder width distribution was similar between states for corresponding data subsets. Washington did have a higher proportion (65%) of SVLB crashes that occur on roadways with shoulders between 2 and 10 ft wide compared to Ohio (49%). Mean posted speed limit was slightly higher for SVLB crashes in both states. A smaller portion (56%) of Washington SVLB crashes occurred on roadways with a speed limit greater than 45 mph compared to 80% for Ohio SVLB crashes. Approximately half of SVLB crashes in both states occur in rural areas. For SVLB crashes, Washington minor arterials were over-represented (20% of road sections but 29% of SVLB crashes) as were Ohio principal arterials (42% of road sections but 53% of SVLB crashes). SVLB crashes occurred on higher AADT roadways in Ohio, while MV crashes had the highest AADT values in Washington. The road surface and location distributions were similar for corresponding data subsets. The vast majority of SVLB crashes in both states occurred at non-intersection locations and on dry roadways.

A small portion of the MV crashes contain longitudinal barrier impacts not included in the SVLB data subset. In Ohio, 162 MV crashes had at least one barrier impact, which represents approximately 1.35 of MV crashes and 0.8% of all Ohio motorcycle crashes. Washington was similar with 116 MV crashes that involved at least one barrier impact, representing approximately 2.5% of MV crashes and 1.3% of all Washington motorcycle crashes. With the Washington data, it was possible to discern barrier type; approximately 62% of SVLB crashes involved one or more metal barrier impacts compared to 37% impacting one or more concrete barriers. Less than 1% struck both a metal and concrete barrier.

In terms of rider characteristics, almost all of the Washington SVLB occupants were helmeted, while less than 50% of Ohio SVLB riders were helmeted. The mean age across the data subsets was similar in both states, with SVLB crashes having a lower mean age. Distribution of gender was approximately equal for all data subsets with male occupants generally more than 80% of involved occupants. A total of 6.5% of Washington SVLB and 9.2% of Ohio SVLB involved occupants were fatally injured. Fatal injury rates for the SV and MV crashes were between 3% and 3.6%. SVLB crashes also had the lowest proportion of no injury reported (7% in Washington and 5.5% in Ohio).

Figure 9-1 and Figure 9-2 show the distribution of horizontal curve radius and AADT, respectively, for the SVLB, SV, and MV crashes in each state. Figure 9-3 shows the vertical grade distribution for each Washington data subset; Ohio was excluded since the available data does not differentiate grades less than 3%. *T*-tests indicate a statistically significant difference ($p < 0.0001$ in all cases) in mean AADT, horizontal curve radius, and grade between Washington SVLB and MV crashes and between Washington SV and MV crashes. *T*-tests for the Ohio data indicate statistically significant differences in curve radius ($p < 0.001$) between SVLB and MV crashes and SV and MV crashes. The difference in mean AADT was statistically significant ($p < 0.0001$) between Ohio SVLB and MV crashes but not significant ($p = 0.391$) between Ohio SV and MV crashes.

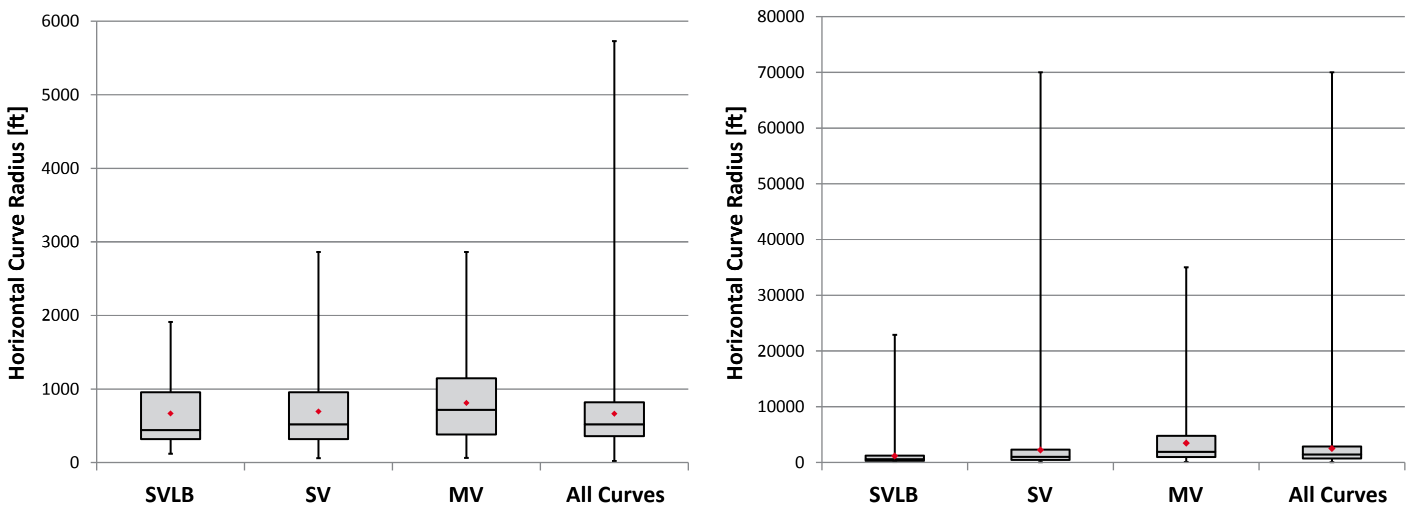

Figure 9-1. Distribution of horizontal curve radius by data subset for Ohio* (left) *and Washington* (right)*.

9.5.2 Statistical Model Results

A binary logistic regression model was developed to predict rider injury using the 1,170 cases with data available for all variables of interest. The developed model had a C-statistic value of 0.69, which provides a single numerical value of how well the model distinguishes between the response variable, in this case, presence of severe rider injury. The OR values obtained from the binary logistic regression, along with the 95% confidence bounds, are summarized in Table 9-3. Note that the OR shown is with respect to the group indicated in the comparison group column. Statistically significant effects are those where the 95% confidence bounds do not bracket the value of 1.0.

Rider helmet use, age, and alcohol involvement were found to have a statistically significant effect on rider injury severity. Not wearing a helmet was found to increase the odds of severe injury by a factor of 2, while the involvement of alcohol increased the odds of severe injury by a factor of 3. Aside from the road surface condition at the time of the crash, the only statistically

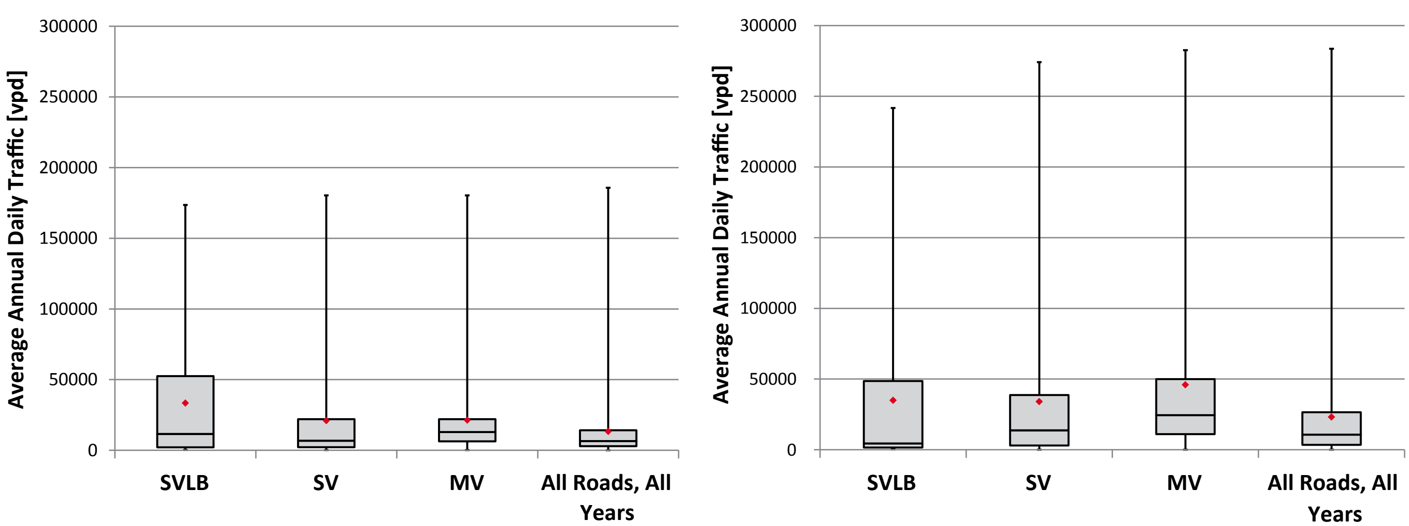

Figure 9-2. Distribution of AADT by data subset for Ohio* (left) *and Washington* (right)*.

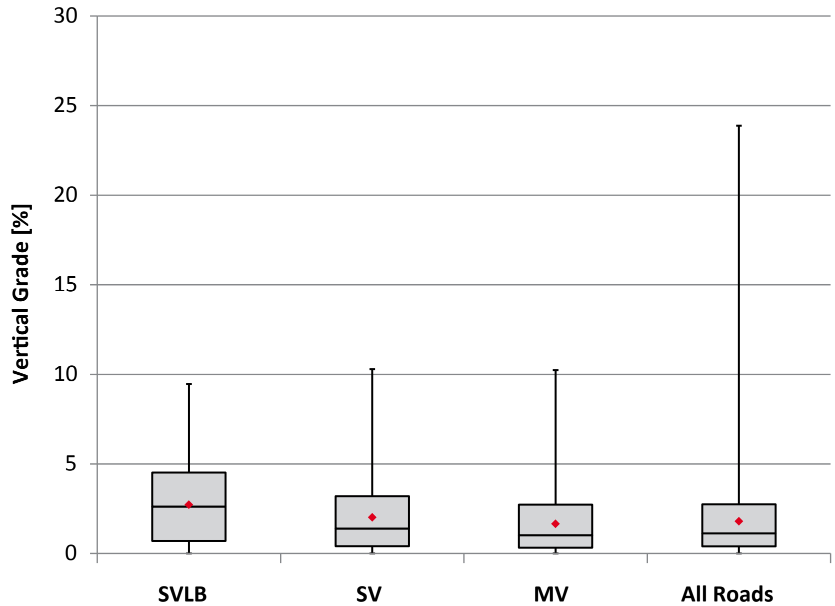

Figure 9-3. Distribution of vertical grade by data subset for Washington.

significant roadway characteristic was whether the roadway was divided. Motorcycle-to-barrier crashes occurring on a divided road were nearly 2 times as likely to result in a severe injury as those occurring on undivided roadways. There was some evidence of increased rider injury risk in curves where the radius was less than the recommended minimum, grades were less than 3%, posted speeds were greater than 45 mph, shoulder widths were between 2 and 10 ft, and AADT was less than 10,000 vpd; these results, however, were not found to be statistically significant. A nearly identical model (full results not shown) was developed using the horizontal curve radius categories in place of the normalized curve radius shown in Table 9-3. In this model, horizontal curves with radius less than 820 ft were found to increase the odds of severe rider injury by a factor of 1.2 (95% CI: 0.82–1.64) when compared to tangent sections. A similar increased odds

Table 9-3. Summary of OR results for the rider injury binary logistic regression model.

Variable Type	Parameter	Value	Comparison Group	Odds Ratio	95% CI
Roadway	Normalized horizontal curve radius	< 1	Tangent Section	1.31	0.92 – 1.9
		≥ 1	Tangent Section	0.96	0.63 – 1.5
	Vertical grade	< 3%	≥ 3%	1.28	0.95 – 1.7
	Posted speed	>45 mph	≤ 45 mph	1.32	0.97 – 1.8
	Roadside shoulder width	≥2 and < 10 ft	< 2 ft	1.11	0.72 – 1.7
		10+ ft	< 2 ft	0.91	0.53 – 1.6
	AADT	< 2,500 vpd	> 50,000 vpd	1.09	0.62 – 1.9
		2,500 - 9,999 vpd	> 50,000 vpd	1.55	0.89 – 2.7
		10,000 - 49,999 vpd	> 50,000 vpd	1.00	0.67 – 1.5
	Configuration	Divided	Undivided	1.81	1.16 – 2.8
Crash	Surface condition	Dry	Wet	3.78	2.09 – 6.8
		Other	Wet	2.86	0.80 – 10.2
Rider	Helmet use	No	Yes	2.04	1.56 – 2.7
		Unknown	Yes	1.45	0.81 – 2.6
	Age	> 25 years	≤ 25 years	1.43	1.03 – 2.0
	Alcohol	Yes	No	2.99	2.10 – 4.3

was noted for curves with radius of 820 ft or greater (OR: 1.26, 95% CI: 0.82–1.95). The odds ratios for the remainder of the effects remained nearly unchanged as well as the C-statistic (C = 0.692).

9.6 Discussion

Based on the data available from both states, SVLB crashes accounted for approximately 5% of all motorcycle crashes, which is consistent with previous studies using Maryland (Daniello and Gabler 2012) and Australian (Jama et al. 2011) data. The proportion of fatal SVLB for these crashes varied from 6.5% in Washington to 9.25% in Ohio, which is comparable to previous studies, albeit on the lower end. A study (Daniello and Gabler 2011b) using data from North Carolina, Texas, and New Jersey reported a 9%, 14%, and 16% fatality percentage, respectively, for motorcycle-to-barrier crashes. For the current study, the SVLB fatality percentage was between 2 and 2.5 times that of SV and MV crashes. A vast majority of the motorcycle-to-barrier impacts were single-vehicle events, with less than 20% involving an impact with another vehicle prior to or after barrier impact.

With respect to roadway alignment, SVLB crashes were found to occur on smaller radii horizontal curves and higher mean grades compared to MV crashes. For horizontal curves, this difference was more prominent in Washington. While differences in horizontal curve radius and vertical grade means existed between the two states, it appears that these differences were in part due to road network differences. The mean horizontal curve radius for all HSIS roadways reported in Ohio was approximately 25% of the mean reported in Washington. Likewise, the mean grade in Ohio was higher than that for all reported Washington roadways even after correcting for the reporting differences. Note that the mean grade reported, however, did not incorporate grade length. Similar to Quincy et al. (1988), ramp crashes in Washington were found to be overrepresented, although to a lesser extent. Approximately 24% of SVLB crashes occurred on ramps while these ramps represented 13.5% of HSIS-reported road mileage compared to Quincy et al. (1988), which found 54% of crashes occurring on ramps representing 5% of road mileage. No HSIS data was available to discern ramp crashes in Ohio.

Although the general trend in both states was that SVLB crashes were overrepresented on curved sections, there were large differences between states. A majority (63%) of the SVLB crashes in Washington occurred on curves, while 19% of SVLB crashes in Ohio occurred on curved sections. Strictly applying the 820-foot curve radius recommendation (Elliot et al. 2003), motorcycle-to-barrier crash countermeasures would only be present in 38% and 14% of motorcycle-to-barrier crashes in Washington and Ohio, respectively. The combination of horizontal curvature and vertical grade does appear to influence the occurrence of SVLB crashes as SVLB crashes occurred at least twice as frequently in these areas compared to SV and MV crashes. Despite this overrepresentation, less than one-fourth of Washington SVLB and less than one-tenth of Ohio SVLB crashes occurred on these sections.

Several other roadway characteristic differences were notable and further suggested differences between states for this crash mode. While a vast majority of Washington SVLB crashes occurred on undivided roadways, Ohio SVLB crashes were split approximately evenly among divided and undivided roadways. Also, more than three-fourths of Ohio SVLB crashes were on roads with speed limits greater than 45 mph compared to roughly half in Washington. SVLB crashes in both states occurred on higher AADT roadways compared to all SV crashes, but in Washington MV crashes occurred on the highest AADT roadways. Note that the AADT represents all vehicle types, not just motorcycles. Similarities did exist, however, in several roadway and crash characteristics. A vast majority of the SVLB crashes available in this study occurred at non-intersection locations in dry roadway conditions. More than two-thirds of these crashes occurred on roadways with four lanes or less and roughly half occurred on arterial roadways with an approximately even split between rural and urban areas.

In terms of rider characteristics, the gender distribution was consistent between states and across the data subsets. The difference in helmet usage between states was likely an indication of the differences in helmet laws in each state; Washington has a mandatory helmet law while Ohio does not. The mean age of riders involved in SVLB crashes was lower than those involved in either SV or MV crashes.

Based on the results of the logistic regression models, rider characteristics were found to be the most important in predicting injury severity. Not wearing a helmet, alcohol involvement, and older occupants significantly increased the risk of serious injury by factors of 2, 3, and 1.5, respectively. The only statistically significant roadway characteristic found was roadway configuration, with divided roadways increasing rider serious injury risk by a factor of nearly 2. In contrast to the Savolainen and Mannering (2007) findings for single-vehicle crashes, the current study finds wet pavement SVLB crashes less severe than those occurring on dry or other roadway conditions. There was evidence that the presence of a horizontal curve increased the risk of serious rider injury, although this risk was approximately the same for curve radii greater than or less than 820 ft. Curves with normalized radius less than 1 also demonstrated an increase in rider severe injury risk but this increase was not present for curves where the normalized radius was greater than or equal to 1. None of the horizontal curve results, however, were statistically significant. AADT less than 10,000 vpd, shoulder widths between 2 and 10 ft, posted speed limits greater than 45 mph, and vertical grades less than 3% were found to mildly increase severe rider injury risk, although these effects were not statistically significant.

9.7 Conclusions

This study provides an analysis of roadway and specific geometric characteristics associated with motorcycle-to-barrier crashes in two states based on a total of 1,511 crashes occurring in Washington and Ohio. Motorcycle impacts with barriers were found to be overrepresented on horizontal curves and on sections with grade in excess of 3% in comparison to all SV motorcycle and all MV motorcycle crashes. Similar to previous studies, these crashes were found to be overrepresented on ramp sections. Based on the available curvature data, however, the sole recommendation for placing motorcycle-to-barrier crash countermeasures on curves with radius less than 820 ft may not be prudent in U.S. states as less than 40% of these crashes occur on these curves. Although there were a number of similarities in motorcycle-to-barrier roadway characteristics between the two analyzed states, large differences were found in areas, including roadway configuration (e.g., divided/undivided) and posted speed limit.

Rider characteristics, such as helmet usage and alcohol involvement, were found to have a larger influence on injury severity in comparison to associated roadway characteristics. Whether or not the roadway was divided was found to be the roadway characteristic having the largest influence on rider injury. The developed models suggest that horizontal curves, vertical grades less than 3%, posted speed limits greater than 45 mph, and traffic volumes less than 10,000 vpd increase rider injury risk, although these results were not statistically significant.

CHAPTER 10

In-Depth Investigation of Injury Mechanisms in Motorcycle-to-Barrier Crashes

10.1 Objective

In the previous chapters, motorcycle-to-barrier collisions in the United States were characterized through retrospective studies. However, these studies do not directly answer the question of how motorcyclists are injured in collisions with traffic barrier. This chapter describes a study developed to determine injury mechanisms through in-depth investigations of motorcycle crashes. This chapter also presents an analysis of injuries in these crashes to identify specific injury mechanisms in motorcycle-to-barrier crashes.

The objective of this chapter is to present the results of a series of in-depth motorcycle crash investigations of the injury mechanisms in motorcycle-barrier collisions through clinical studies and crash investigations.

10.2 Methods

10.2.1 Identification of Cases

Cases in this study were identified and enrolled by the Wake Forest Baptist Medical Center (Winston-Salem, NC) from patients involved in motorcycle crashes who were admitted to their Level 1 trauma center. Wake Forest is part of the CIREN. Through this network, Wake Forest has established a screening system to identify potential candidates to be incorporated in the CIREN database. Wake Forest expanded their screening system to identify cases for this research. Inclusion criteria were:

- SV motorcycle crash;
- Collision with guardrail, concrete barrier, or cable barrier; and
- Admission to Level 1 trauma center.

These inclusion criteria are similar to those from previous chapters. Cases were limited to SV crashes as the focus of this study is on injuries resulting from barrier crashes, not from collisions with other vehicles. In a MV crash, it is difficult to discern which injuries are caused by barriers or other vehicles. Additionally, only cases with barriers in the median or on the roadside were included. If a patient entered the trauma center for injuries in a motorcycle-to-barrier crash matching these criteria, he/she was asked to participate in the study. Consent was obtained before the investigation, and patients who did not consent were not included in the study.

10.2.2 Crash Investigation

There were three main components of each crash investigation in this study: (1) environment and barrier, (2) motorcycle, and (3) rider. An investigator visited the crash site soon after the crash to collect the environmental data elements. Additionally, the investigator inspected the motorcycle and recorded the damage to the vehicle. When possible, the investigator visited the site within a week of the crash. Due to this short time frame, there would typically still be evidence of the crash remaining (e.g., skid marks, fabric transfers, etc.) at the scene. Both the site and the motorcycle were photographed, with particular attention paid to factors associated with the crash, such as fabric transfers, blood, scrapes, or skid marks.

Detailed injury data was also gathered from medical records for each patient in the study. WFU tabulated all injuries and assigned an injury score using the AIS. They also provided the imagery for each injury, including CT scans, x-ray images, and patient photos showing external injuries. Additionally, WFU developed 3-D reconstructions for several severe injuries, a useful tool for visualizing the nature of these injuries. If available, photographs of the helmet were taken as evidence of what happened to the motorcyclist's head during the crash.

Lastly, the Wake Forest team interviewed each rider. These interviews provided background about the rider's driving and motorcycling history, as well as what the rider remembered from the crash. Information about motorcycle training and education was also incorporated since the benefits of rider training are debated (Daniello, Gabler and Mehta 2009). Additionally, information about personal protective gear usage was gathered through the interview.

10.2.3 Case Review

The team at Virginia Tech next combined evidence from the crash investigations with the injury data from the patient and reconstructed a description of each crash (Figure 10-1). For these reconstructions, we reviewed the evidence from the scene, motorcycle, helmet, and injuries and determined potential crash scenarios. These scenarios focused on how each injury could have been incurred. Crash causation was discussed in the case reviews, but was not a focus of these reconstructions, as the main goal was to determine injury mechanisms given that a crash had occurred. After thorough review of the case, the team determined the most likely crash scenario based on all the evidence provided on the crash and injuries.

From this reconstruction, the team at Virginia Tech determined the injury contact source (ICS) for each injury. The ICS is the impact point that caused the injury (e.g., ground, guardrail post, motorcycle handlebar, etc.). We typically identified ICS based on markings or transfers,

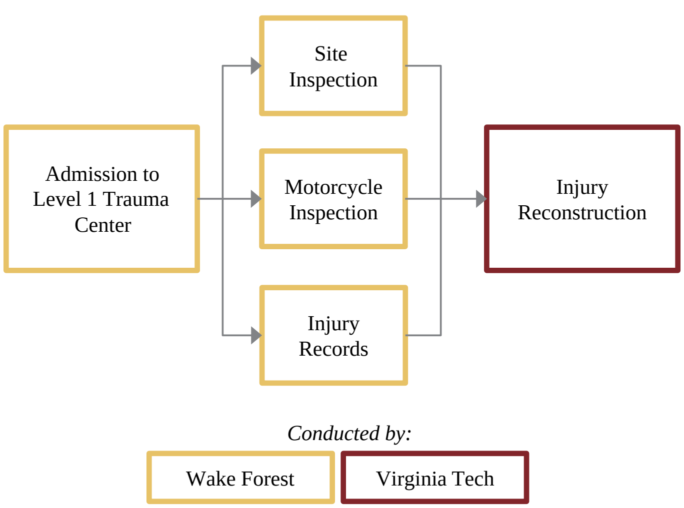

Figure 10-1. Crash Reconstruction Methodology.

injury patterns, or damage to either the motorcycle or environment. Each ICS was assigned a "Certainty" value, representing how confident the team was in determining the ICS. The certainty values were either "Certain," "Probable," or "Possible" with "Possible" being the lowest level and "Certain" being the greatest level of confidence. The ICS and confidence values were developed based on the BioTab methodology developed for the CIREN database (Schneider et al. 2011).

10.2.4 Example Crash Descriptions

As an example of the methodology, two of the crashes and the ICS for the most serious injuries are described. Contact points for the most severe injuries are included in the descriptions. A summary of all crashes is provided in the Results section of this chapter. Additional details on each crash, the barrier, the rider, and associated injuries are included in the appendices.

Cases MC-001-D and MC-001-P

This first case involved a male operator and a female passenger traveling on a 2006 Harley-Davidson Electra Glide Ultra Classic Touring motorcycle. Both the 58-year-old operator and the 61-year-old passenger were wearing DOT-approved half-helmets. The motorcycle was traveling in a southwesterly direction on a two-lane rural roadway, and negotiating an "S" curve on a downhill slope. The roadway was bordered to the north by a W-beam guardrail, and to the south by steep hill banks. It was daylight, with no adverse weather conditions, and the roadway was dry. On exiting the left curve segment into the straight away, the operator leaned the motorcycle left, and allowed the left crash bar/foot peg to contact the asphalt pavement. Subsequent control loss redirected the vehicle toward the right (north) pavement edge.

As shown in Figure 10-2, as the vehicle departed the north pavement edge, the right aspect of the front wheel/fender impacted a W-beam guardrail. The impact resulted in moderate damage to the motorcycle. At this point, both riders were ejected and the motorcycle rebounded off the guardrail. The motorcycle re-entered the road, as the left side struck the ground. The vehicle slid along the pavement to final rest (on its left side) in the westbound lane, facing southeast. The helmeted 58-year-old male operator and 61-year-old female passenger were reported by police to have come to rest on the north shoulder near the vehicle's final rest position. The operator reported paying full attention to driving at the time of the collision.

The operator (Case MC-001-D) suffered three AIS-3 injuries to his torso: multiple rib fractures, a spleen laceration with hematoma, and a pneumothorax on the left side. All three of these injuries were postulated to be caused by his torso contacting the ground as he fell from the motorcycle. He also suffered an open mid-shaft radius fracture in his left forearm (AIS-3), thought to be caused by impacting either the handlebar or the guardrail. Lastly, he had a hemoperitoneum (AIS-3), which was postulated to be caused by his shoulder hitting the guardrail. Each of these injury contact sources were thought to be "Possible."

The passenger (Case MC-001-P) suffered two AIS-3 injuries to her head: a right occipital condyle fracture and a subarachnoid hemorrhage. She also suffered two AIS-3 injuries to her spine: a C7 lamina fracture and a T6 spinal burst fracture with 50% height loss. All of these injuries were postulated to have been caused by her head contacting the ground; her helmet was severely scratched and the face mask was cracked. These contact sources were determined with "Probable" certainty.

The guardrail struck during this crash successfully redirected the riders and prevented them from what would have likely been a more severe crash. The guardrail was shielding a steep cliff and retained the operator, passenger, and motorcycle, preventing them from going over the cliff.

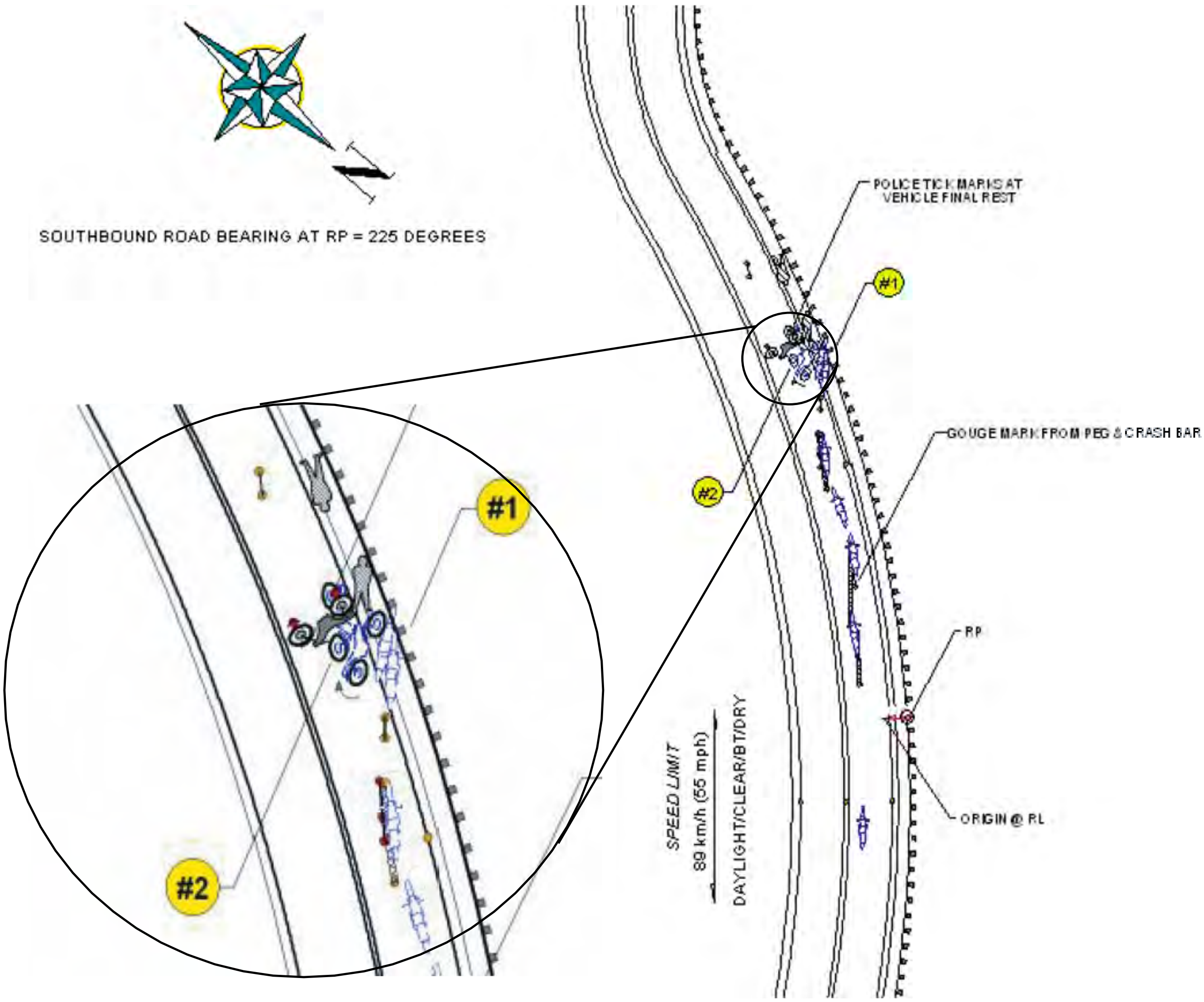

Figure 10-2. Crash diagram for Case MC-001.

Case MC-007-D

This case involved a 33-year-old male wearing a DOT-approved half-helmet. He was riding a 2003 Harley-Davidson Electra Glide Classic. It was dark, with no lighting on the street. The rider was traveling northbound on a four-lane arterial with a continuous left-turn lane. After exiting a curve, the rider ran off the road to the right and contacted the W-beam guardrail that was placed at the road edge. As shown in Figure 10-3, the motorcycle was redirected and followed along the guardrail for 78 ft, where the vehicle came to rest. The rider remained on the motorcycle for approximately half that distance (42 ft) and was subsequently ejected from the motorcycle. The right side of the rider was in contact with the rail for an extended period during the crash. Based on damage to the guardrail blockouts and possible skin transfers, the rider's chest was likely dragged along the tops of the rail and posts during the crash.

The rider suffered multiple rib fractures on the posterior and anterior side. This injury was coded as an AIS-5 injury. Additionally, he suffered multiple other soft tissue injuries in his chest and abdomen, including bilateral lung contusions (AIS-4), bilateral hemopneumothoraces with large anterior mediastinal hematoma (AIS-4), liver lacerations (AIS-4), and a small spleen

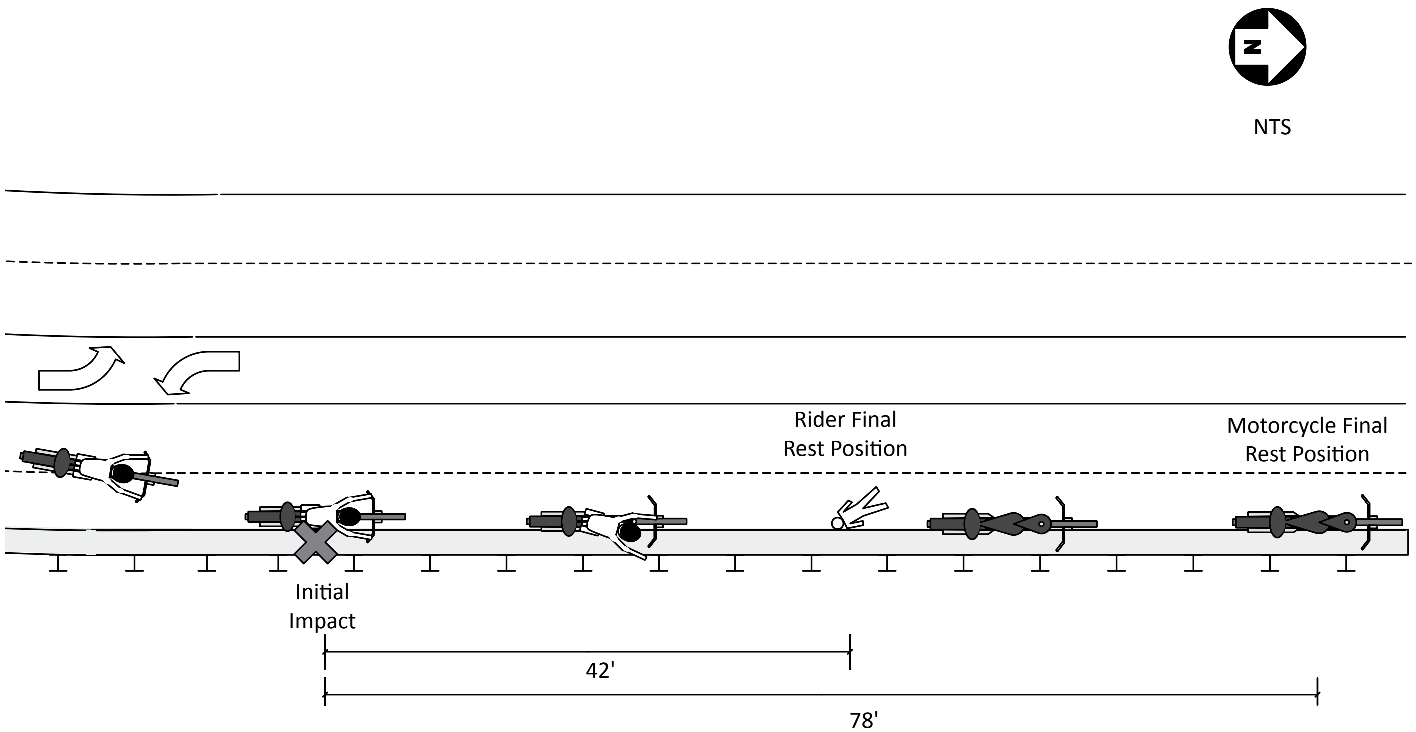

Figure 10-3. Crash scenario for Case MC-007.

laceration (AIS-2). The "probable" cause of these injuries was multiple impacts to the top of the rail and posts while partially seated on the motorcycle. Two of the blockouts between the posts and the rail were rotated, and a potential skin transfer was observed on one post top. This injury pattern and likely rider position were consistent with the rider being dragged along the rail.

10.3 Results

The research program investigated a total of 21 cases involving 22 riders striking roadside barriers. All cases were collected from the WFU catchment area, either in the states of North Carolina or Virginia, and date from 2010 to 2016. Table 10-1 resents the composition of the resulting dataset by crash. As shown in Table 10-1, most collisions were with W-beam barrier (19), the most common form of barrier in the United States. Three (3) cases involved collisions with cable barrier, a barrier type typically installed in the median of divided highways to prevent cross-median crashes. Only one case involved concrete barrier, the least common barrier in the United States. Most crashes in the sample (81%) involved either large touring or cruiser motorcycles.

Most departures were to the right side of the road (76%). The roadway alignment was almost evenly split between curves (9 of 21) and straight runs (8 of 21). Two cases occurred on entrance ramps. A portion of the WFU catchment area is near the Appalachian Mountains on roadways popular with motorcyclists. Reflecting the nature of this area, in many cases the barrier was intended to shield motorists from a steep drop-off or embankment. As these areas were typically heavily forested, the barrier also was intended to prevent collisions with trees.

Table 10-2 describes the riders involved in the investigated crashes. Of the riders included in this study, 18 were male and four were female. As a group, the riders were older than the general population. The average age of the riders was 50.1 years old, with a standard deviation

Table 10-1. Summary of in-depth crashes investigated.

Case Number	Motorcycle Type	Barrier Type	Road Alignment	Side of Road	Barrier Shielded
MC-001	Touring	W-Beam	Curve	Right	Steep drop-off
MC-002	Cruiser	W-Beam	Entrance Ramp	Right	Embankment
MC-003	Touring	W-Beam & Cable	Straight	Median	Opposing Traffic
MC-004	Cruiser	Cable	Straight	Median	Opposing Traffic
MC-005	Cruiser	W-Beam	Straight	Right	Trees and Stream
MC-006	Sport	W-Beam	Curve	Right	Embankment and Wooded Area
MC-007	Touring	W-Beam	Straight	Right	Embankment
MC-008	3-Wheel Touring	W-Beam	Curve	Right	Steep Cliff
MC-009	Sport	W-Beam	Curve	Left	Embankment and Wooded Area
MC-010	Cruiser	W-Beam	Curve	Right	Steep drop-off
MC-011	Cruiser	W-Beam	Curve	Right	Embankment
MC-012	Cruiser	W-Beam	Straight	Right	Steep drop-off
MC-013	Cruiser	Cable	Straight	Median	Opposing Traffic
MC-014	Cruiser	W-Beam	Straight	Right	House
MC-015	Cruiser	W-Beam	Curve	Right	Steep drop-off
MC-016	Cruiser	W-Beam	Entrance Ramp	Right	Embankment
MC-017	Motocross	W-Beam & Concrete	Curve	Right	Bridge
MC-018	Cruiser	W-Beam	Curve	Right	Steep drop-off
MC-020	Cruiser	W-Beam	Straight	Median	Opposing Traffic
MC-021	Touring with tri-wheel retrofit	W-Beam	Straight	Right	Embankment
MC-022	Touring	W-Beam	Curve	Right	Embankment

of 12.4 years. All riders were helmeted. With the exception of the one passenger in case MC-001, all subjects were the operator of the motorcycle.

Injuries varied in severity from maximum AIS (MAIS) = 2 to 5 (median = 3). AIS = 3 corresponds to serious injury. The ISS varied from ISS = 8 to ISS = 45 (median = 22). A total of 15 of 22 riders had an ISS of 16 or greater, the threshold for major trauma. There were no fatalities in the sample. Figure 10-4 presents the distribution of serious injuries (MAIS 3+) injuries by body region. When a subject suffered multiple AIS 3+ injuries to a single body region, only the highest severity injury was counted in this tabulation. The most common serious injuries were to the thorax and the lower extremities. Together these two body regions accounted for nearly two-thirds of all injuries (60%).

Figure 10-5 presents the distribution of contact sources associated with AIS 3+ injuries. Examination of the contact sources showed that most AIS 3+ injuries resulted from impact of the rider with the posts supporting either the W-beam rail or the cable barrier (32%). Ground impacts resulting after a rider was ejected from the motorcycle comprised 27% of all AIS 3+ injury body regions. Guardrail and cable barrier posts are designed to deform upon contact with cars and trucks, but crash site inspection showed that these posts deformed very little under loading from a motorcycle or rider. A substantial number of the AIS 3+ injuries (11%) resulted when riders fell across the top of a barrier system while still seated and were then dragged down the length of the barrier before falling off the bike. Crash site inspection combined with examination of injury extent showed that rider contact with top of the W-beam rail and striking the unprotected tops of the posts resulted in laceration-type injuries to the riders.

Table 10-2. Summary of rider demographics and injuries.

Case Number	Age	Gender	MAIS	ISS	Number of injuries	Region of Most Serious Injury
MC-001-D	58	Male	3	27	11	Thorax Upper Extremity Abdomen
MC-001-P	61	Female	3	27	11	Thorax Spine Head
MC-002-D	58	Male	3	22	14	Thorax Upper Extremity
MC-003-D	49	Male	2	8	5	Head Lower Extremity
MC-004-D	31	Male	5	45	29	Head
MC-005-D	51	Female	3	9	4	Lower Extremity
MC-006-D	46	Male	3	22	4	Thorax Spine
MC-007-D	33	Male	5	45	20	Thorax
MC-008-D	63	Male	3	14	7	Lower Extremity
MC-009-D	19	Male	4	26	8	Thorax
MC-010-D	59	Male	3	10	10	Lower Extremity
MC-011-D	74	Male	4	29	16	Head
MC-012-D	50	Female	4	25	5	Thorax
MC-013-D	53	Male	3	17	12	Lower Extremity
MC-014-D	43	Male	2	9	9	Spine Upper Extremity
MC-015-D	48	Female	4	29	10	Lower Extremity
MC-016-D	67	Male	3	17	9	Lower Extremity
MC-017-D	39	Male	3	11	10	Upper Extremity
MC-018-D	43	Male	3	10	8	Lower Extremity
MC-020-D	52	Male	5	38	29	Head
MC-021-D	55	Male	3	22	15	Thorax
MC-022-D	51	Male	3	17	12	Head

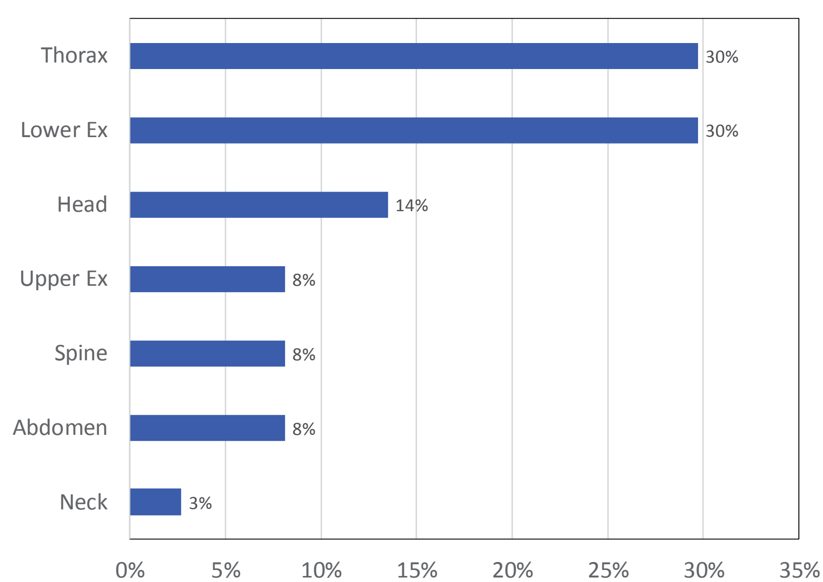

Figure 10-4. Distribution of AIS 3+ injuries by body region.

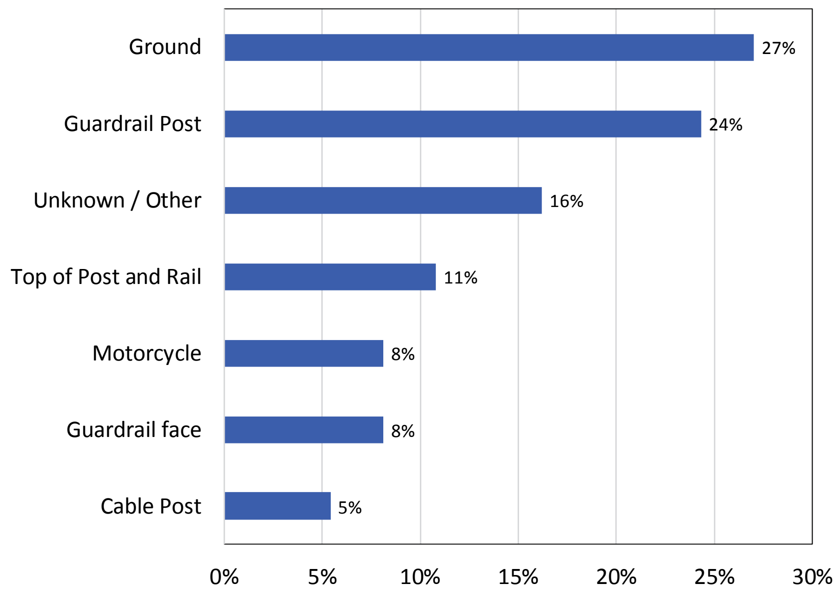

Figure 10-5. Distribution of AIS 3+ injuries by ICS.

Nearly half of all serious injuries were the result of impact with some component of the barriers; however, the distribution of serious injuries was not uniform across barrier components. Nearly two-thirds of the serious injuries from barrier impact (60%) resulted from contact with the posts. Almost one-quarter of the serious injuries (23%) from barrier impact were caused by being dragged over the tops of the posts, top of the rail, or top cable. The balance was due to blunt impact with the barrier face.

10.3.1 Personal Protective Equipment

Personal protective equipment (PPE) may prevent or mitigate motorcyclist injuries in all types of crashes. Table 10-3 presents the distribution of PPE worn by the riders in the WFU motorcycle-barrier dataset. All riders were helmeted. Both North Carolina and Virginia require that riders wear helmets. All helmets were DOT-certified. Only one rider (MC-006-D) was wearing body armor. Half of all riders (11 of 22 riders) wore motorcycle jackets. All jackets and chaps were made of leather unless otherwise noted in Table 10-3. However, with the exception of helmets, none of this PPE is intended to prevent or mitigate impact injury, but rather to prevent or mitigate abrasions from the road surface (i.e., “road rash”). The severity of abrasion injuries would typically not rise to the level of serious injury (AIS 3+).

10.3.2 Human Factors

The focus of this research program was on injury mechanisms and injury severity given that a crash has occurred, rather than on factors that may have caused the crash. However, through interviews with the operator and witnesses, our investigations did collect a limited amount of information on the human factors associated with each crash. Table 10-4 presents these human factors for each operator. In general, the operators were older than the U.S. population. The average age of the operators was 49.7 years. The median age of operators was 50 years old. In general, the operators had many years of experience operating motorcycles. The average number of years riding was 18 years. The median number of years riding was 11 years. However, two riders were novices and had only been riding for a few days. Speeding did not appear to be

Table 10-3. Distribution of rider PPE.

Case Number	MAIS	ISS	Helmet	Face Mask	Goggles	Jacket*	Gloves	Chaps*	Boots
MC-001-D	3	27	×			×	×		×
MC-001-P	3	27	×	×		×			×
MC-002-D	3	22	×			×			
MC-003-D	2	8	×						
MC-004-D	5	45	×						
MC-005-D	3	9	×	×					
MC-006-D	3	22	×			× (1)	×	×(1)	
MC-007-D	5	45	×						
MC-008-D	3	14	×		×	×	×	×	
MC-009-D	4	26	×						
MC-010-D	3	10	×			× (2)			
MC-011-D	4	29	×			×	×		
MC-012-D	4	25	×		×	×	×	×	×
MC-013-D	3	17	×			× (3)	×	×	×
MC-014-D	2	9	×						
MC-015-D	4	29	×	×					
MC-016-D	3	17	×			×		×	×
MC-017-D	3	11	×				×		
MC-018-D	3	10	×						×
MC-020-D	5	38	×		×				×
MC-021-D	3	22	×						×
MC-022-D	3	17	×		×	×	×	×	×

* Material is leather unless otherwise noted.
1 Jacket made out of Kevlar w/ built-in elbow and shoulder armor; pants made out of Kevlar as opposed to leather chaps.
2 Jacket made out of neoprene.
3 Vest as opposed to a full jacket

a contributing crash causation factor. Police-estimated travel speed exceeded the posted speed limit in three of the 19 crashes in which the posted speed limit was known. Alcohol involvement was noted in two of the 21 operators.

10.4 Discussion

This study is one of the first in the United States to investigate factors leading to serious injury in motorcycle collisions with roadside barriers. This chapter presented the results of a study on the injury mechanisms in motorcycle-to-guardrail collisions. The study investigated 21 serious motorcycle-to-barrier crashes, involving 22 riders. In these crashes, the most common regions to suffer the most serious injury were the head, lower extremities, and thorax. The thorax suffered the greatest number of serious injuries. The extremities suffered the most injuries; however, these tended to be less severe than injuries in other body regions. These findings are consistent with those presented in our Maryland CODES study and the Bambach et al. (2012) study.

In most of the crashes investigated, the guardrail prevented the rider from a potentially more hazardous collision with trees. In the earlier discussion on fatality risk, collisions with trees were more likely to be fatal than collisions with guardrail. Additionally, in several of the cases, the guardrail likely prevented the rider from traveling over a cliff or embankment.

Table 10-4. Distribution of operator human factors.

Case Number	Age	Gender	Toxicology	Time Since Departure	Riding Experience (years)	Police-estimated, Travel Speed (mph)	Posted Speed Limit (mph)
MC-001-D	58	Male	None	30 min.	8	30	55
MC-002-D	58	Male	None	25 min.	40	35-40	45
MC-003-D	49	Male	Alcohol Use, BAC unknown	40 min.	3	65	65
MC-004-D	31	Male	None	30 min.	3	65	65
MC-005-D	51	Female	None	1 min.	2	5	35
MC-006-D	46	Male	None	8 hr.	7	50*	Unknown
MC-007-D	33	Male	None	30 min.	-	55	45
MC-008-D	63	Male	None	Full day	40	40	55
MC-009-D	19	Male	None	30 min.	10	50	55
MC-010-D	59	Male	None	Unknown	Unknown	25	55
MC-011-D	74	Male	None	Unknown	53	50	55
MC-012-D	50	Female	None	2 hr.	Unknown	Unknown	Unknown
MC-013-D	53	Male	BAC: 0.184 at hospital	5-10 min.	Unknown	65	65
MC-014-D	43	Male	None	5 min.	-	15	55
MC-015-D	48	Female	None	8 hr.	13	55	55
MC-016-D	67	Male	None	Unknown	15	65	55
MC-017-D	39	Male	None	5 min.	20	70	55
MC-018-D	43	Male	None	Unknown	5	40	55
MC-020-D	52	Male	None	10 min.	36	55	55
MC-021-D	55	Male	None	Unknown	35 years	45	45
MC-022-D	51	Male	None	Unknown	Unknown	45	45

*Not police reported. Estimated by rider.

Therefore, though guardrail collisions are severe, removing the barriers is not the solution to the problem.

Additionally, all components of the guardrail were associated with injury causation. However, they varied in severity. Nearly two-thirds of the serious injuries thought to be caused by the barrier were postulated to be caused by rider entanglement with the posts supporting the barrier. In approximately one-quarter of the crashes investigated, riders were believed to interact primarily with the top of the rail or top cable, as opposed to going under the barrier. Providing a protective covering to the top edge of the rail and the upper faces of the posts may mitigate these injuries. Finally, not all of the recorded injuries were thought to be caused by contact with the barrier. An estimated 27% of serious injuries were believed to be caused by blunt impact with the ground.

The study has shown that the primary injury mechanisms in our sample were (1) rider entanglement with posts; (2) lacerations from top of posts, both W-beam and cable barrier; and (3) laceration from the top of W-beam rail. Of note are our observations on cable barrier (i.e., wire-rope barrier) collisions. Despite the concern of laceration injuries to motorcyclists contacting wire-rope barriers, we found no evidence of laceration injuries from the wire rope in these systems. Injuries were found in collisions with wire-rope barrier, but the injuries resulted from contact with the posts rather than with the wire rope. This clinical finding is consistent with the conclusions from our bulk accident study conducted using state crash data (Chapter 6), which

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found no statistically significant difference between the injury risk of W-beam and cable barrier, both systems supported by unprotected posts.

This study has important implications for U.S. federal and state transportation agencies seeking ways to reduce the risk of serious-to-fatal injury for motorcyclists. The findings show the need for the adoption of MPS that either pad or shield the posts to prevent motorcyclist entanglement. MPS have been implemented in Europe and Australia that have tremendous potential to mitigate injuries in barrier collisions (Corben et al. 2010; La Torre et al. 2012). To date, these systems have not been adopted in the United States.

10.5 Limitations

This study has several limitations: (1) the findings are based on a small sample of cases; (2) the findings are based on a convenience sample of cases admitted to a Level 1 trauma center; and (3) the sample was collected from only a single region of the United States. The sample did, however, include all major barrier types encountered in the United States. Even though both states in the catchment area for data collection have mandatory helmet laws, only 20 states in the United States have mandatory helmet laws. The results should not be interpreted as nationally representative of the United States. Rather, the findings should be used as a means to identify opportunities for countermeasure development and the need to prioritize the development and implementation of MPS for barriers.

CHAPTER 11

Conclusions

11.1 Research Findings

Motorcycle riders now account for more fatalities than the passengers of any other vehicle type involved in a guardrail collision. In 2018, motorcycle riders accounted for 40% of all fatalities resulting from a guardrail collision. Following motorcycle riders were car occupants, with 31% of all fatalities in this crash mode. This is particularly surprising as cars compose approximately half of the vehicle fleet (46%) while motorcycles comprise only 3% of the registered vehicles. In terms of fatalities per registered vehicle, motorcycle riders are overrepresented in the number of fatalities resulting from guardrail impacts.

There are currently no guidelines available to U.S. transportation agencies, policymakers, or engineers for how to protect motorcyclists who strike traffic barriers. MASH crash test procedures, which have been successful in ensuring safer barrier designs for cars and light trucks, do not prescribe a crash test procedure for motorcycles. Most research in the area of motorcyclist-friendly barrier or motorcycle-barrier crash testing has been conducted in either Europe or Asia. Little has been published in recent years on the characteristics of this issue in the United States or on potential solutions.

The objective of this research program was to identify the factors that contribute to serious and fatal injury in motorcycle collisions with traffic barriers. The focus of this project was on collisions with guardrail, concrete barrier, and cable barrier, and the factors that influence injury given that a crash has occurred. The longer term goal is to establish priorities for U.S. transportation agencies and roadside safety engineers seeking to remediate the injury and fatality risk of motorcyclist-barrier collisions.

11.1.1 Constraints on Injury Mitigating Strategies

It is important to emphasize that motorcyclist-barrier fatalities should not be reduced at the expense of passenger car occupants involved in barrier collisions. Guidelines such as MASH and *NCHRP Report 350* have described ways of safely redirecting errant vehicles onto the road without undue occupant risk. Cable barriers or any other type of barrier should not be removed just to protect motorcyclists. Rather what is needed are barrier designs, safety programs, and research that can extend the safety record of barrier performance in car collisions to encompass motorcyclists. The goal is to develop methods that can better protect motorcyclists without reducing the benefits of traffic barriers for passenger vehicle occupants.

11.1.2 Anticipated Research Results

The objective of this research program is to determine the factors associated with serious and fatal motorcycle crashes associated with traffic barriers. Following is a list of the research questions pursued in this program:

- Determine the risk of fatality and injury by barrier type to include W-beam, cable barrier, concrete, bridge rails, and crash cushions. Are some barrier designs safer than others?
- For each barrier type, determine the distribution of injury and injury by barrier component. For W-beam barrier, for example, does the risk of injury from the posts differ from the risk of injury from impact with the rail?
- Establish the frequency and severity of injuries in motorcycle-barrier crashes by body region (head, chest, lower extremity). What should the priorities be for rider protection?
- Estimate the ratio of fatalities caused by motorcyclists vaulting over a barrier versus sliding into a barrier. Which crash mode should be the priority for a motorcycle-barrier crash test?
- Find the ratio of motorcyclists already seriously or fatally injured by contact with the ground or other objects prior to impact with the barrier. Is there any evidence for the hypothesis that the life-threatening injuries occur from ground impact before riders collide with the barrier?
- Changes in the post shape have been proposed as an injury countermeasure. Is there any evidence of the I-beam edges cutting the rider?
- What roadway geometries are associated with the incidence of motorcycle crashes with traffic barriers?
- What are the options for dynamic crash testing of motorcycles into traffic barriers?
- What countermeasures are available to protect motorcyclists in collisions with barriers?

11.1.3 Gaps and Research Needs

The literature review identified a number of gaps in the literature and research needs for U.S. motorcyclists. Following is a summary:

- There are currently no guidelines available to U.S. transportation agencies, policymakers, or engineers for how to protect motorcyclists who strike traffic barriers.
- On U.S. roadways, the trade-offs between colliding with traffic barriers versus the fixed objects (e.g., utility poles) that may exist behind these barriers are unknown.
- There is only limited information on U.S. roads of rider impact configuration (i.e., sliding or upright) when striking a longitudinal barrier.
- There is no recent information on rider injury patterns in U.S. motorcyclist-barrier collisions. These injury causation mechanisms are needed to prioritize longitudinal barrier design or selection of MPS.
- It is unknown how barriers certified in MASH crash tests would perform if retrofit with MPS.
- The current most widely accepted crash test, CEN TS 1317-8, only tests riders who slide into a barrier, and only considers head and neck injuries. Missing is a test for the approximately half of all riders who strike barriers while upright and/or at risk of thoracic injuries, the most common serious injury mode.

11.1.4 Analysis of Fatal Motorcycle-Guardrail Crashes in the United States

Fatal crash trends in the United States were investigated to determine where fatal guardrail crashes were most likely to occur as compared to all fatal motorcycle crashes. For this study, data from FARS from 1999 to 2008 were analyzed. Over this time period, there were 38,254 fatal motorcycle crashes involving 39,468 fatally injured motorcycle riders and passengers. There were 1,759 fatal motorcycle-guardrail crashes over the same time period, fatally injuring 1,803 motorcycle riders and passengers, an average of 180 fatalities each year.

Fatal motorcycle-guardrail crashes were almost exclusively single-vehicle crashes, though over 50% of all fatal motorcycle crashes are multi-vehicle crashes. About three-quarters of fatal guardrail crashes occurred on curves. Riders fatally injured in motorcycle-guardrail crashes tended to be younger than the overall population of fatally injured motorcyclists.

11.1.5 Fatality Risk in Roadside Motorcycle Crashes in the United States

Guardrails and other barriers are not the only obstacles that exist on the roadside. Although this study focused primarily on barrier collisions, other roadside objects pose a great risk to motorcyclists. This component of the study investigated the national risk of fatality in collisions with trees, signs and poles, guardrails, and concrete barriers. The FARS data from 2004 to 2008 was used to determine the number of fatalities in each collision mode, and the NASS GES data was used to estimate the total number of crashes in each collision mode. This analysis was based on over 3,600 fatal motorcycle crashes with roadside objects and an estimated total of nearly 20,000 crashes with roadside objects. Risk of motorcycle collision with roadside objects was compared to that of single-vehicle motorcycle collisions where the motorcycle did not strike anything except for the ground.

Motorcycle crashes with roadside objects resulted in a greater risk of fatal injury than collisions with the ground. Based on the MHE reported in the crash, motorcycle collisions with guardrail were 7.2 times more likely to be fatal than collisions with the ground. Collisions with concrete barrier were 4.1 times more likely to be fatal than collisions with the ground. This is an early indication of the importance of barrier design. The risk of fatality in a guardrail collision is nearly double that of a collision with concrete barrier.

A crucial point is to consider the potential consequences of collisions with what the barrier was shielding. Collisions with trees had a fatality risk nearly 15 times greater than the fatality risk in collisions with the ground. Thus, if a motorcyclist crashes into a barrier in place to protect users from roadside trees, the barrier is likely to have reduced injury severity. Though there is no way to determine what the injury severity would have been had the motorcyclist struck the tree, a collision with a tree may have been a more severe crash than if the rider struck the guardrail.

11.1.6 Risk of Serious Injury in Barrier Crashes

One key aspect of this research program was to determine whether some barrier designs are safer than others. Are cable barriers more dangerous than other barrier types? The initial study on fatality risk showed the importance of design: guardrail barrier collisions carried a greater risk of fatality than concrete barrier collisions. This question was further investigated by analyzing barrier crashes of all injury severities in three states: North Carolina, Texas, and New Jersey. The analysis dataset contained 1,000 riders involved in barrier crashes in the three states. Of these, 581 cases were involved in W-beam crashes, 367 cases were involved in concrete barrier crashes, and 52 cases were cable barrier crashes.

This study found that W-beam guardrail had significantly higher odds of serious (K+A) injury than concrete barrier. This is consistent with the earlier analysis of fatality risk. The odds of serious injury in crashes with W-beam guardrail were about 1.4 times greater than those in crashes with concrete barrier. There was no evidence to show that cable barrier posed a greater risk to motorcyclists than either W-beam or concrete barrier. However, we caution that the sample of cable barrier crashes was small compared to the sample of W-beam and concrete barrier crashes. This initial analysis showed no elevated risk of serious injury in cable barrier crashes. However, further investigation is needed to demonstrate if this finding is a result of the dataset used or is representative of most crashes.

11.1.7 Relationship Between Rider Post-Impact Trajectory and Injury Outcome in Barrier Crashes

The objective of this study was to characterize the rider orientation and post-impact trajectory in a barrier collision, and determine how this orientation influences the injury outcome. The international literature is not consistent on this basic question. Resolution of this question is needed to design a representative crash test (should the rider slide into the barrier or be upright?) and to determine priorities for countermeasure design (is post padding or reducing the sharp upper edge of W-beam more important?).

Rider trajectories in barrier collisions were determined through an analysis of PARs of motorcycle-barrier crashes in New Jersey from 2007 to 2011. In a motorcycle-barrier collision, the rider will frequently separate from the motorcycle, and the two may follow different trajectories. We defined post-impact trajectory as the trajectory taken by the rider after the motorcycle collides with or contacts the road, barrier, or other object. Seven different trajectory types were identified: upright, sliding, vaulting, ejected (same side landing), ejected (side unknown), ejected into barrier, and separated prior to barrier impact. Of the 442 single-vehicle, motorcycle-barrier collisions reported in New Jersey, the PAR was analyzed for 430 crashes, and the barrier was identified for 342 of these crashes (77.4% of all crashes).

The majority of riders in our study (68.0%) in single-vehicle barrier crashes collided with the barrier while upright. Another 20.0% of riders slid into the barrier. Our findings show a higher prevalence of upright collisions and lower estimates for the prevalence of sliding collisions compared to previous literature. Using German data, Berg et al. (2005a) found that 51% crashed upright and 45% crashed while sliding. Using Australian data, Bambach et al. (2012) found that 44% of fatally injured riders in W-beam crashes crashed into the barrier while upright. In our dataset, 52% of all fatally injured riders in W-beam crashes were upright, which is consistent with the findings of Bambach et al. (2012). However, using French data, Quincy et al. (1988) found that in 58% of crashes riders slid into the barrier. Some of the differences may be regional in nature. Our study looks at U.S. crashes, whereas previous studies have analyzed crashes in Europe and Australia.

Rider post-impact trajectory, however, was found to be a significant predictor for serious injury. Being ejected from the motorcycle after impacting the barrier was found to increase odds of serious injury compared to crashes striking the barrier upright. Additionally, being ejected into the barrier also increased the odds of serious injury (4.7 times higher than non-ejected).

11.1.8 Analysis of Injuries from Roadside Collisions in Maryland

Motorcycle-to-barrier collisions were characterized through retrospective studies of national and state crash databases. These studies can quantify the number of motorcyclists who are seriously or fatally injured, but do not directly answer the question of how motorcyclists are being injured. To identify the opportunity for design improvements to the roadside to reduce the severity of these crashes, the injuries incurred must first be better understood.

To determine the type, relative frequency, and severity of injuries incurred in motorcycle roadside crashes, CODES was used to analyze motorcycle crashes in Maryland from 2006 to 2008. CODES links police-reported crashes to hospital data, providing detailed information about injuries incurred during collisions. This study focused on four types of motorcycle crash modes: single-vehicle barrier crashes, single-vehicle fixed object crashes, multi-vehicle crashes, and single-vehicle overturn-only crashes. The analysis was based on injury and crash data for 1,707 motorcyclists involved in these four crash modes.

The most commonly injured regions for all motorcycle crashes were the upper and lower extremities. Over 70% of motorcyclists involved in the crashes analyzed suffered an injury to the upper and/or lower extremities. Though extremities were the most commonly injured region, they were not the most commonly seriously injured body region. The thorax was the most frequently seriously injured body region in all types of motorcycle crashes, with the exception of multi-vehicle crashes. Additionally, motorcyclists involved in barrier crashes were about two times more likely to suffer a serious injury to the thoracic region than motorcyclists not involved in barrier collisions. The most common injury for motorcyclists involved in barrier collisions was a lung contusion, whereas the most common injury for motorcyclists not involved in barrier collisions was a hemothorax or pneumothorax.

In the study of injuries in Maryland crashes, riders that impacted a barrier had a higher risk of AIS 2+ laceration than riders in other types of collisions based on the point estimate, though this was not found to be significant. One hypothesis was that the lacerations were caused by rider impact with the edges of the guardrail posts and the upper and lower edges of the W-beam.

11.1.9 Roadway Characteristics Associated with Motorcycle Crashes into Longitudinal Barriers and the Influence on Rider Injury

This study provides an analysis of roadway and specific geometric characteristics associated with motorcycle-to-barrier crashes in two states based on a total of 1,511 crashes occurring in Washington and Ohio. Motorcycle impacts with barriers were found to be overrepresented on horizontal curves and on sections with grade in excess of 3% in comparison to all single-vehicle motorcycle and all multiple-vehicle motorcycle crashes. Similar to previous studies, these crashes also were found to be overrepresented on ramp sections. Based on the available curvature data, however, the sole recommendation in the available published literature to place potential motorcycle-to-barrier crash countermeasures on curves with a radius less than 820 ft may not be prudent in the United States, as less than 40% of these crashes occur on these curves. Although there were a number of similarities in motorcycle-to-barrier roadway characteristics between the two analyzed states, large differences were found in areas, including roadway configuration (e.g., divided/undivided) and posted speed limit.

Rider characteristics, such as helmet usage and alcohol involvement, were found to have a larger influence on injury severity in comparison to associated roadway characteristics. Whether or not the roadway was divided was found to be the roadway characteristic having the largest influence on rider injury. The developed models suggest that horizontal curves, vertical grades less than 3%, posted speed limits greater than 45 mph, and traffic volumes less than 10,000 vpd increase rider injury risk, although these results were not statistically significant.

11.1.10 In-Depth Investigation of Injury Mechanisms

To determine injury mechanisms in motorcycle-to-barrier crashes, Virginia Tech collaborated with the Wake Forest Baptist Medical Center (Winston-Salem, NC) to conduct a series of in-depth crash investigations of motorcyclist-barrier collisions. Cases in our study were identified and enrolled by Wake Forest Baptist Medical Center (Winston-Salem, NC) from patients involved in single-vehicle motorcycle crashes with roadside barriers who were admitted to their Level 1 trauma center.

The study investigated 21 serious motorcycle-to-barrier crashes, involving 22 riders. In these crashes, the most common regions to suffer the most serious injury were the head, lower extremities, and thorax. The thorax suffered the greatest number of serious injuries. The extremities suffered the most injuries; however, these tended to be less severe than injuries in other body regions. These findings are consistent with those presented in our Maryland CODES study and the Bambach et al. (2012) study.

In most of the crashes investigated, the guardrail prevented the rider from a potentially more hazardous collision with trees. As found in the earlier study on fatality risk, collisions with trees carry a higher fatality risk than collisions with guardrail. Additionally, in several of the cases, the guardrail likely prevented the rider from traveling over a cliff or embankment. Therefore, though guardrail collisions are severe, removing the barriers is not the solution to the problem.

The study has shown that the primary injury mechanisms in our sample were (1) rider entanglement with posts; (2) lacerations from top of posts, both W-beam and cable barrier; and (3) laceration from the top of W-beam rail. Of note are our observations on cable barrier (i.e., wire-rope barrier) collisions. Despite the concern of laceration injuries by motorcyclists contacting wire-rope barrier, we found no evidence of laceration injuries from the wire rope in these systems. Injuries were found in collisions with wire-rope barrier, but the injuries resulted from contact with the posts rather than with the wire rope. This clinical finding is consistent with the conclusions from our bulk accident study conducted using state crash data, which found no statistically significant difference between the injury risk of W-beam and cable barrier, both systems supported by unprotected posts.

11.1.11 Existing MPS for Motorcycle-Barrier Crashes

Several potential countermeasures currently exist to mitigate the consequences of a motorcycle-barrier impact. These devices, typically referred to as MPS, generally fall into two categories: (1) devices that reduce the severity of post impact through post redesign or shielding, and (2) devices that prevent impact with the post by the addition of a lower rail element or redesign of the rail element. These MPS have been installed in multiple locations in both Europe and Australia.

Publications on testing experience with these devices are relatively limited. This was especially true for evaluating the effect that these countermeasures might have on passenger vehicle impacts. The publications that were available on the performance of these devices indicate that they are likely to reduce the severity of motorcycle-barrier crashes.

Two pilot tests of MPS have been conducted to date in the United States. The first was conducted by Caltrans and the second by NCDOT. Both pilot tests used the Lindsay Transportation System's DR-46 Barrier Attenuator system.

11.1.12 Crash Tests Options for MPS

There are currently four crash test procedures for evaluating MPS: the French LIER procedure, the German BASt procedure, the Spanish UNE 135900 procedure, and the European Technical Specification CEN TS 1317-8. The most widely accepted procedure is the European Technical Specification CEN TS 1317-8, which specifies a full-scale crash test to evaluate the performance of MPS affixed to longitudinal barrier. The CEN TS 1317-8 test is designed to emulate the situation in which a rider leaves the motorcycle and slides along the ground into a barrier. In this test, an ATD (commonly referred to as a crash test dummy) is slid at an angle into a barrier at either 60 or 70 km/h. The test prescribes limits on loads to the head and neck of the dummy. Currently, CEN TS 1317-8 does not prescribe a test for motorcyclists who strike barrier in an upright position, which is estimated to account for over 50% of all collisions.

11.2 Recommendations

This study is one of the first in the United States to investigate the factors leading to serious injury in motorcycle collisions with roadside barriers. The United States currently does not provide transportation agencies or the roadside safety community any guidelines on how to reduce the risk of injury for motorcyclists in collisions with a traffic barrier. This report has discussed the elevated risk faced by motorcyclists who experience these collisions, the efforts undertaken by regulators in Europe and Australia to address this issue, the design of production MPS, and potential crash tests to evaluate the crash performance of these countermeasures.

Based on these findings, this study suggests the following next steps:

- *Evaluate field performance of U.S. pilot tests of MPS.* Two pilot tests of MPS have been conducted to date in the United States. The first was conducted by Caltrans and the second by NCDOT. Both pilot tests used the Lindsay Transportation System's DR-46 Barrier Attenuator system. Evaluation of the field performance of these pilot programs should be conducted in terms of motorcycle and four-wheeled vehicle safety, installation experience, and the practicality and costs of maintaining these systems.
- *Evaluate EN 1317-8 test in the United States.* The most widely accepted motorcycle-barrier crash test procedure is the European Technical Specification CEN TS 1317-8. This test simulates the crash performance of MPS affixed to a longitudinal barrier. This test should be conducted on U.S. roadside hardware that has been evaluated using MASH test procedures, both to check the performance of U.S. hardware in this crash mode, and to evaluate the test procedure itself.
- *Evaluate crash performance of MPS for four-wheeled vehicles.* One obstacle to widespread retrofit of MPS to existing barrier systems is that the crash performance of these retrofit systems for four-wheeled vehicles has not been determined. It is important that the successful crash performance of traffic barriers should not be reduced by the installation of retrofits to protect motorcyclists. The recommendation is to evaluate the performance of MPS-equipped barriers in standard MASH crash tests using four-wheeled vehicles (e.g., small cars and pickup trucks).
- *Develop a MASH motorcyclist crash test.* MASH currently does not prescribe a crash test for motorcyclists striking roadside hardware. Adoption of the European EN 1317-8 test is one option. There may be regional differences, however, which may require that other crash test options be considered as well. For example, this NCHRP project has estimated that riders striking a barrier upright occurs much more frequently than suggested by studies in Europe. An MPS test that uses an upright rider should be developed. Development of a new test should consider an enhanced MPS test that evaluates the risk to the thorax and lower extremities, which our study has shown to be the most frequently seriously injured body regions.
- *Considerations for the AASHTO Roadside Design Guide.* Potential additions to the AASHTO *Roadside Design Guide* should be considered for how to locate longitudinal barrier that incorporates the differences between the road departures of four-wheeled vehicles and motorcyclists. Factors in the development of these guidelines would be differences in trajectories, departure angle, departure speed, and the magnitude of evasive maneuvers (e.g., braking). NCHRP Project 17-88, which is characterizing motorcycle roadside departures in comparison to four-wheeled vehicle departures, may provide useful guidelines for this evaluation.
- *Develop methods to determine where to locate MPS.* The installation of MPS carries a cost, and should be considered where it would be more beneficial. Potential methods for determining suitable MPS locations include traditional hot-spot methods or the empirical Bayes methods used in the FHWA Highway Safety Manual. Cost-benefit methodologies for MPS location should be developed.

This study has important implications for U.S. federal and state transportation agencies seeking ways to reduce the risk of serious-to-fatal injury for motorcyclists. The findings show the need for the adoption of MPS that either pad or shield the posts to prevent motorcyclist entanglement and protect riders from laceration from the tops of rails and posts. MPS have been implemented in Europe and Australia that have tremendous potential to mitigate injuries in barrier collisions. This research program has shown the need for MPS in the United States, the feasibility of these systems, and their potential safety benefit for U.S. motorcyclists. After a thorough evaluation of MPS in crash testing and pilot testing in the United States, our recommendation is that MPS should be considered for implementation on U.S. roadways.

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Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
GHSA	Governors Highway Safety Association
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

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