INJURY MECHANISMS IN ROADSIDE MOTORCYCLE COLLISIONS

Allison Daniello

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Hampton C. Gabler, Chair
Stefan M. Duma
Shane B. McLaughlin
Michael L. Madigan
Joel D. Stitzel

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INJURY RISK IN ROADSIDE MOTORCYCLE COLLISIONS

Allison Daniello

(ABSTRACT)

More motorcyclists are fatally injured each year in guardrail crashes than passengers of any other vehicle, while only accounting for three percent of the vehicle fleet. Since motorcyclists account for a high percentage of these fatalities, the goal of zero deaths on the road cannot be achieved without addressing the safety of motorcyclists. The objective of this research was to determine the factors that lead to serious or fatal injury in motorcycle barrier crashes, given that a crash occurred.

The likelihood of serious or fatal injury in barrier crashes was significantly influenced by both barrier type and rider trajectory after striking the barrier. A national study of motorcyclist fatality risk using the Fatality Analysis Reporting System (FARS) and General Estimates System (GES) showed that crashes with guardrail than crashes were about 7 times more likely to be fatal than those with the ground, based on the most harmful event reported. An analysis of 1,000 riders in barrier crashes in three states showed that the odds of serious injury were 1.4 times greater in guardrail crashes than in concrete barrier crashes. These analyses did not take into account the trajectory of the rider after striking the barrier, since this was unknown. The police accident report for 350 barrier crashes in New Jersey was used to determine the rider trajectory in those crashes. Being ejected from the motorcycle after impacting the barrier significantly increased the odds of serious injury over crashes where the rider was not ejected.

While providing insight into factors influencing injury severity, these analyses do not provide an understanding of the nature of injuries incurred in these crashes. To further understand how injuries were caused in motorcycle-barrier crashes, we developed a methodology for determining injury mechanisms in motorcycle-barrier collisions. Using this methodology, we investigated 9 serious motorcycle-to-barrier crashes. In these crashes, as well as in an analysis of 106 barrier crashes in Maryland, the thorax and lower extremities most commonly suffered serious injury. Of particular concern are the posts and top of the rail, both of which can lead to lacerations and blunt trauma.

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1 INTRODUCTION

The risk of fatal injury for motorcyclists greatly increases when motorcyclists depart the roadway and collide with roadside objects such as trees, poles, or traffic barriers [*1-3*]. The elevated risk of fatal injury in motorcycle-barrier collisions [*4, 5*] has been a major motivating factor in the growing concerns over the crash compatibility of traffic barriers and motorcycles.

Though motorcyclists account for a small percentage of vehicles on the road, they are growing in popularity in the United States. With the rising number of motorcycles on the roads, motorcycle fatalities also increased. As shown in Figure 1.1, motorcyclist fatalities have doubled between 1998 and 2008 [*6*]. One particular hazard for motorcyclists is roadside crashes. Roadside safety systems, e.g. guardrail, are typically designed to reduce injuries in passenger cars, but typically do not consider the safety of motorcyclists.

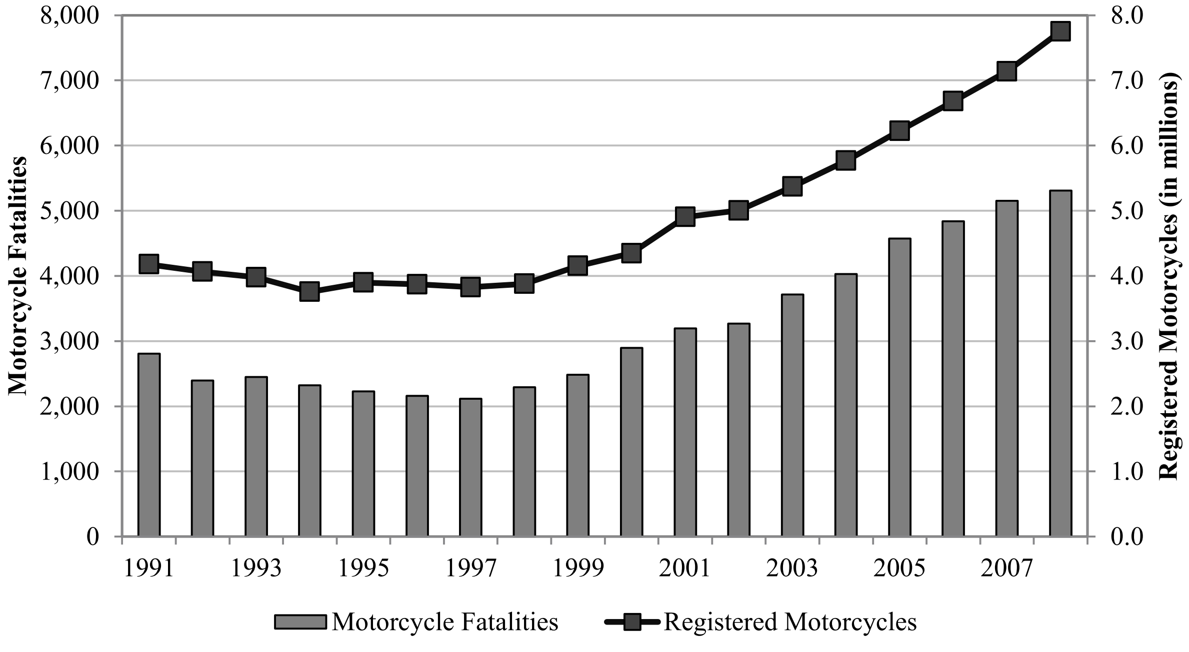


Figure 1.1. Fatal Crashes and Registered Motorcycles (FARS 1991-2008, Traffic Safety Facts 2009)

The number of registered motorcycles in the United States has been rapidly increasing. Also shown in Figure 1.1, the number of registered motorcycles nearly doubled between 1998 and 2008. By 2008, there were 7.8 million registered motorcycles, as compared to 3.9 million registered motorcycles in 1998. The number of light trucks and vans (LTVs) increased at a similar rate. Comparatively, the number of registered passenger cars only increased by ten percent over the same time period.

There have been recent efforts in the United States and around the world to move towards zero deaths on the roads [*7, 8*]. Significant research has been done for other road users to improve highway safety by evaluating vehicle and airbag performance in different collisions modes [*9-14*], pre-crash notification systems [*15-17*], guardrail performance [*18-21*], and accuracy of crash reconstruction methods and event data recorders [*22-27*]. Many of the efforts to move towards zero deaths focus on barrier design and safety [*8, 25-27*]. However, motorcyclists are rarely considered in design and testing. Only recently was a standard of motorcycle testing in barrier collisions developed [*28*] for use in Europe. There are no standards, however, for barrier testing specific to motorcyclists in the United States. Additionally, there is a philosophy that the roadside should be forgiving to drivers who make mistakes; one small error should not result in a serious or fatal injury [*29, 30*]. This philosophy is generally applied to passengers of other vehicles, but not motorcyclists. Though, if this holds true for other vehicles, it should also hold true for motorcyclists.

Motorcyclists currently account for about half of guardrail fatalities in the United States (Figure 1.2). Without addressing this issue, the zero deaths goal cannot be achieved. Moreover, motorcycle crashes into guardrail now account for more fatalities in barrier crashes than crashes of any other vehicle type, even though they only comprise of about 3% of the vehicle fleet [*6*].

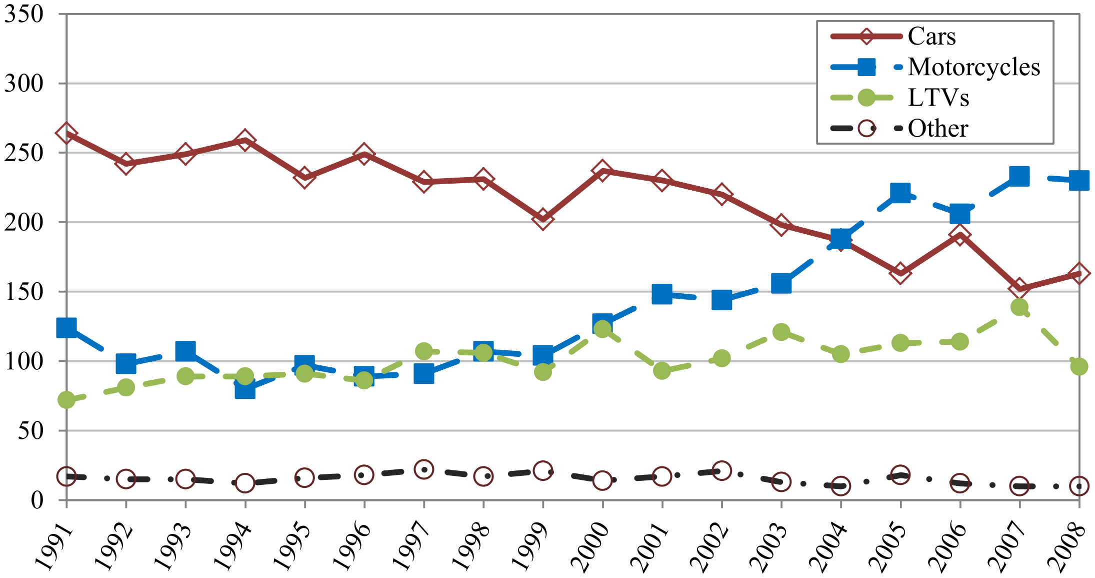


Figure 1.2. Fatal Vehicle-Guardrail Crashes by Vehicle Type (FARS 1991-2008)

The rate of motorcyclist fatality in guardrail collisions per registered vehicles has generally increased since 1991. By comparison, the fatality rate for passenger cars and LTVs has generally been decreasing over the same time period (Figure 1.3). Additionally, the fatality rate in guardrail crashes is drastically higher for motorcyclists than that for passengers of cars and LTVs.

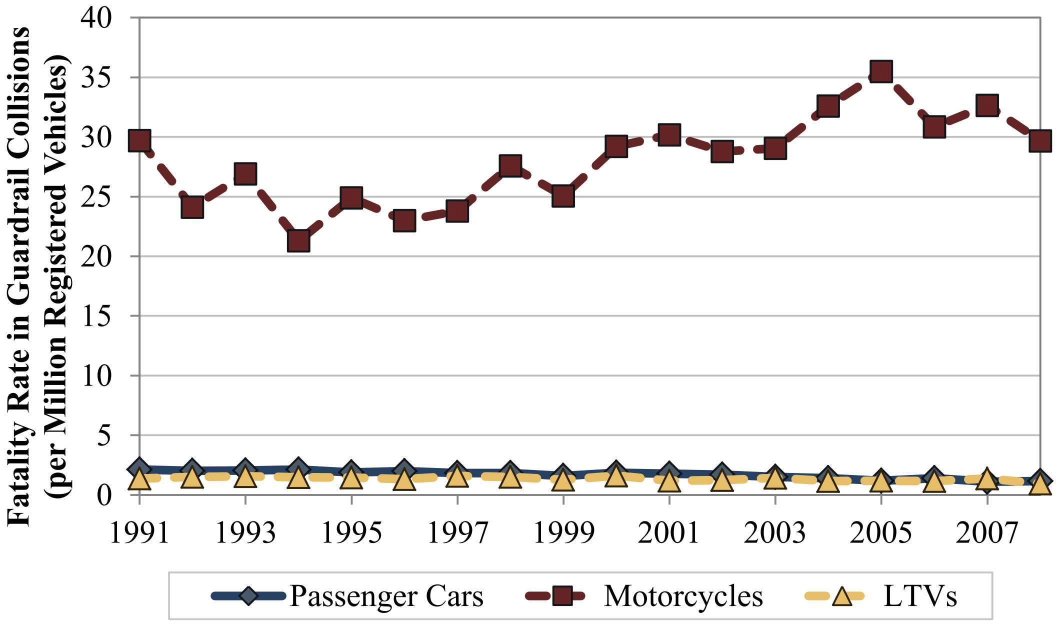
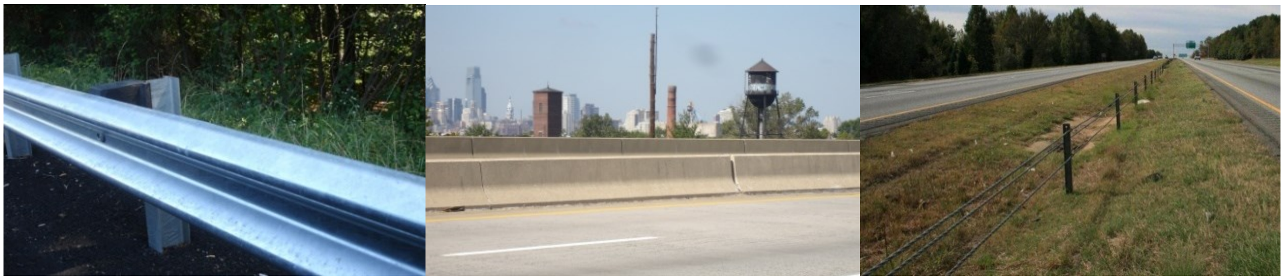


Figure 1.3. Fatality Rate in Guardrail Collisions (FARS 1991-2008 and Traffic Safety Facts, 2009)

This research has focused on three main types of barriers: guardrail, concrete, and cable barrier. These are depicted below in Figure 1.4. 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. Concrete barriers are often used to divide highways, particularly when there is little to no room for a median. Since they do not deflect great distances, they retain vehicles without causing encroachment into opposing traffic. Lastly, cable barrier is being installed at a rapid rate in the United States. Cable barrier presents a relative inexpensive option for shielding medians, and is highly effective at preventing cross-median crashes.



(A) (B) (C)

Figure 1.4. Barrier Types. (A) W-beam Guardrail, (B) Concrete Barrier, (C) Cable Barrier

These barrier systems are highly effective for vehicles, though they have shown to cause more severe injuries for motorcyclists. However, there is no recent in-depth information available to determine how these systems are affecting motorcyclists in the United States.

There are several theories regarding motorcycle collisions with barriers that have many supporters, though there is a lack of research to support these theories. These theories threaten the installation of engineering methods that may potentially save lives. This research will address these theories and seek either supporting or refuting evidence for each argument:

***Theory 1*:** Barriers are a hazard for motorcyclists and should be removed.

Roadside barriers are designed to retain cars and other large vehicles such as vans and trucks. Motorcyclists are usually thrown from their motorcycle in the event of a collision, leaving them at the mercy of the surrounding environment, including roadside barriers, as they come to a stop. However, guardrails and other barriers have been effective in saving the lives of occupants of cars and trucks, and cannot simply be removed to protect motorcyclists.

Theory 2: Cable barriers pose a unique hazard to motorcyclists compared to other barrier types; they are human "cheese-cutters."

There has been a growing concern about the elevated risk of motorcycle collisions with cable barrier [*31*]. Cable barriers have been very effective at protecting motorists from cross-median crashes [*32-34*]. Motorcycle activist groups, however, perceive cable barrier as a particular threat to motorcyclists, referring to this barrier design as a 'cheese cutter'. Both in the U.S. and overseas, these groups have actively lobbied for a ban on this type of barrier. In Norway, these groups have succeeded in exerting sufficient political pressure to have cable barrier banned. Several studies have been conducted in the Australia, Europe, and the United States to examine the effects of motorcycle crashes into barriers [*1, 32, 35*]. To date, however, there is little evidence to either support or refute the claims that cable barrier is more dangerous than W-beam barrier.

Theory 3: The barrier is not causing injuries: the motorcyclist has already been fatally injured before striking the barrier.

Motorcycle collisions are complex events, often involving multiple impacts. Additionally, unlike passengers of other vehicles, the motorcyclist is not restrained to the motorcycle. Prior to impacting the barrier, the motorcyclist may fall from the motorcycle and be fatally injured upon impact with the ground. Again, there is a lack of research on where and how injuries are incurred during these crashes. This theory influences where the research should be focused in order to reduce the most fatalities, and determining its validity will impact the direction of research.

1.1 OBJECTIVE

The goal of this research is to determine the factors that lead to serious or fatal injury in motorcycle barrier crashes. This study has focused on factors that influence injury, given that a crash has occurred. The focus was not on driver behavior, training, or human factors that lead to the crash.

This research has addressed the aforementioned theories in the context of this broader goal. Theory 1 will be addressed in Chapter 4 by comparing injury risk in barrier collisions with injury risk in other types of collisions. The second theory regarding cable barriers will be addressed in Chapter 5 by comparing injury risk in different collision types. Lastly, the theory that motorcyclists are fatally injured before striking the barrier will be addressed in Chapters 4, 6, and 7 by comparing injury severity, rider trajectory, and injuries incurred between different collision types.

2 RESEARCH APPROACH

2.1 DATA SOURCES

The analyses for this research focused both on national and state-specific crash trends. The two data sources that were used for national characteristics are the Fatality Analysis Reporting System (FARS) and the National Automotive Sampling System (NASS) General Estimates System (GES). FARS is a comprehensive census of all US traffic related fatalities that occur within 30 days of a traffic crash [*36*]. GES contains information on approximately 60,000 randomly sampled police reported crashes each year [*37*]. 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. FARS was used in Chapter 3 to investigate characteristics of fatal motorcycle-guardrail crashes. Both of these national databases were used in Chapter 4 to investigate fatality risk in roadside and median crashes.

State databases contain a complete record of all police-reported crashes. This allows for an analysis of serious and non-serious crashes without estimating the total number of crashes. Additionally, having a record of all crashes allows for investigation of the specific circumstances around each crash.

For this research, several different state databases were used to analyze risk of severe injury. Motorcycle crashes in four different states were investigated: (1) New Jersey, (2) Texas, (3) North Carolina, and (4) Maryland. These databases were obtained from each of the states, with the exception of North Carolina. North Carolina crash data was obtained through the Highway Safety Information Systems (HSIS). HSIS is a multi-state database that contains information about both crashes and roadways. Chapters 5 - 7 were state-based studies and used these databases. Due to the limited availability of data and the need for specific data elements for each study, not all states were included in each study.

Lastly, this research project developed a new database of in depth motorcycle-to-barrier crash investigations. Motorcycle-to-barrier crashes were investigated to determine injury mechanisms in these crashes. The development of this dataset is described in Chapter 8.

2.2 INJURY SCORING

The Abbreviated Injury Scale (AIS) is one metric used to rank the threat to life an injury [*38*]. AIS scores range from 1 (minor injury) to 6 (not survivable). An AIS score of 3 is considered a serious injury. The maximum, or highest, AIS score (MAIS) was used to describe the injury severity of a person with multiple injuries.

Though the AIS scale provides a good metric for comparing individual injuries, it does not consider the overall condition of a person. The Injury Severity Score (ISS) provides a means for comparing injury severity for persons with multiple injuries by combining multiple AIS scores into a single score. The ISS is computed by summing the squares of the three highest AIS scores in 3 different body regions, as shown in the Equation (2.1). The greatest AIS score included in computing the ISS is 5 [*39*].

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

Six body regions are classified for the ISS: (1) head or neck, (2) face, (3) chest (4) abdominal or pelvic contents, (5) extremities or pelvic girdle, and (6) general [*39*]. This differs slightly from the body regions defined by AIS. Though grouped for the computation of ISS, the head and neck body regions are defined separately in AIS. Likewise, upper and lower extremities are defined as separate body regions by AIS but combined for computing ISS. Lastly, spinal injuries are divided into two categories based on the location of the injury.

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. This is a five-level scale for which

‘K’ indicates killed, ‘A’ indicates incapacitating injury, ‘B’ indicates moderate injury, ‘C’ indicates complaint of pain, and ‘O’ indicates property damage only. There is one injury level assigned to each person in the crash; thus, this describes his/her overall injury severity, as compared to the severity of each injury as defined in the AIS scale. For this research, seriously injured riders were defined as those whose the injury severity was either a ‘K’ or ‘A’.

2.3 COMPUTATION OF INJURY METRICS

Two means of comparing severity in different scenarios (e.g. collisions with different roadside objects) were used for this research study: risk and odds. First, the risk of serious injury was defined as

$$Risk\ of\ serious\ injury = \frac{Number\ of\ Seriously\ Injured\ Riders}{Number\ of\ Riders\ Exposed\ to\ Crashes} \tag{2.2}$$

This is the probability of being seriously injured, given that the specific crash scenario has occurred. For this research, exposure was based on the number of riders involved in a given crash type. There are other metrics of exposure, though, that can be used to investigate crash risk, such as vehicle miles traveled (VMT). However, the VMT data for motorcycles may not be accurate. Though motorcycle registrations have been increasing, the VMT for motorcycles has remained relatively constant. The small size of motorcycles compared to other road users makes them difficult to detect by traffic counting sensors [*40*]. Additionally, unlike for other vehicles, VMT changes by day of week and by season for motorcycles [*40*]. Lastly, the number of miles of each barrier type installed across the US is largely unknown. Therefore, using VMT may not accurately capture motorcyclist exposure to different potential crash scenarios with roadside barriers.

The risk in two different crash scenarios can be compared using the relative risk, which is the ratio of the risk from each scenario, as calculated by Equation (2.2). Thus, relative risk was defined as

$$Relative\ Risk = \frac{Risk_{Scenario\ A}}{Risk_{Scenario\ B}} \tag{2.3}$$

If the relative risk is greater than 1, Scenario A poses a greater risk of serious injury than Scenario B. Vice versa, if the relative risk is less than 1, Scenario B poses a greater risk of serious injury than Scenario A.

Different crash scenarios were also compared using the odds of serious injury, defined as

$$Odds\ of\ serious\ injury = \frac{Seriously\ Injured\ Riders}{Non - Seriously\ Injured\ Riders} \tag{2.4}$$

As with the relative risk, two scenarios can be compared using the odds ratio (Equation (2.5)).

$$Odds\ Ratio = \frac{Odds_{Scenario\ A}}{Odds_{Scenario\ B}} \tag{2.5}$$

Though similar in concept, the odds ratio (OR) and relative risk (RR) are not equal. If serious injuries occur as more than 10% of outcomes in the crash scenarios being compared then the OR will be greater than the RR. Likewise, the OR will be less than the RR if the RR is less than 1 and more than 10% of the outcomes are serious injuries [*41*]. For scenarios where less than 10% of the outcomes are serious injury, the OR and the RR will be approximately equal.

3 CHARACTERISTICS OF FATAL MOTORCYCLE-TO-GUARDRAIL CRASHES

3.1 INTRODUCTION

The fact that motorcycle-guardrail crashes result in nearly half of all vehicle-guardrail fatalities is particularly surprising since motorcycles comprise only 3% of all registered vehicles in the U.S. This chapter investigates the 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.

3.2 OBJECTIVE

This study seeks to determine the factors which 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 also 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 characteristics of all fatal motorcycle crashes.

3.3 METHODS

The Fatality Analysis Reporting System (FARS) data from 1999-2008 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, both drivers 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.

3.4 RESULTS

From 1999-2008, there were 38,254 fatal motorcycle crashes and 1,757 fatal motorcycle-guardrail crashes. These crashes are summarized in Table 3.1.

Table 3.1. 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

The number of fatal motorcycle crashes has been increasing over the time period analyzed (Figure 1.1). Likewise, the number of fatal motorcycle-guardrail crashes has been increasing 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.

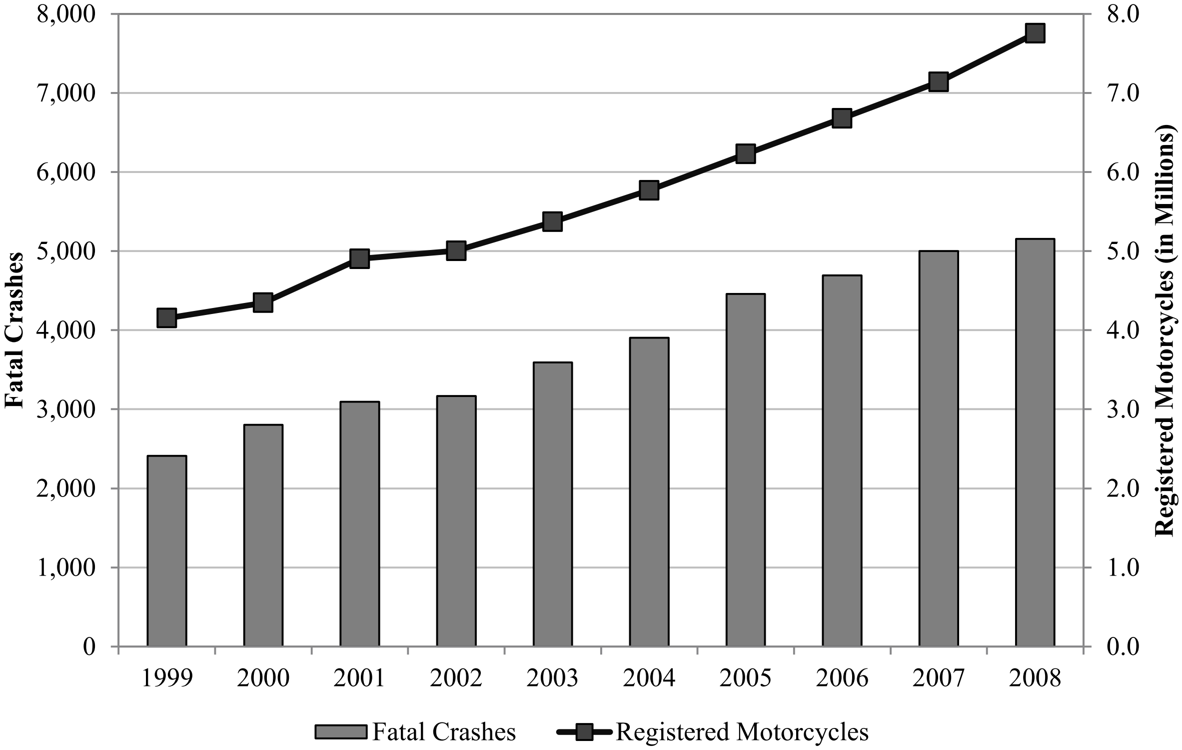


Figure 3.1. Fatal Crashes and Registered Motorcycles (FARS 1999-2008, Traffic Safety Facts 2009)

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 3.2 shows the crash rate for all fatal motorcycle crashes and fatal motorcycle-guardrail crashes. As shown the rates of fatal guardrail crashes generally followed those of all fatal motorcycle crashes; however, the magnitudes of the rates are very different.

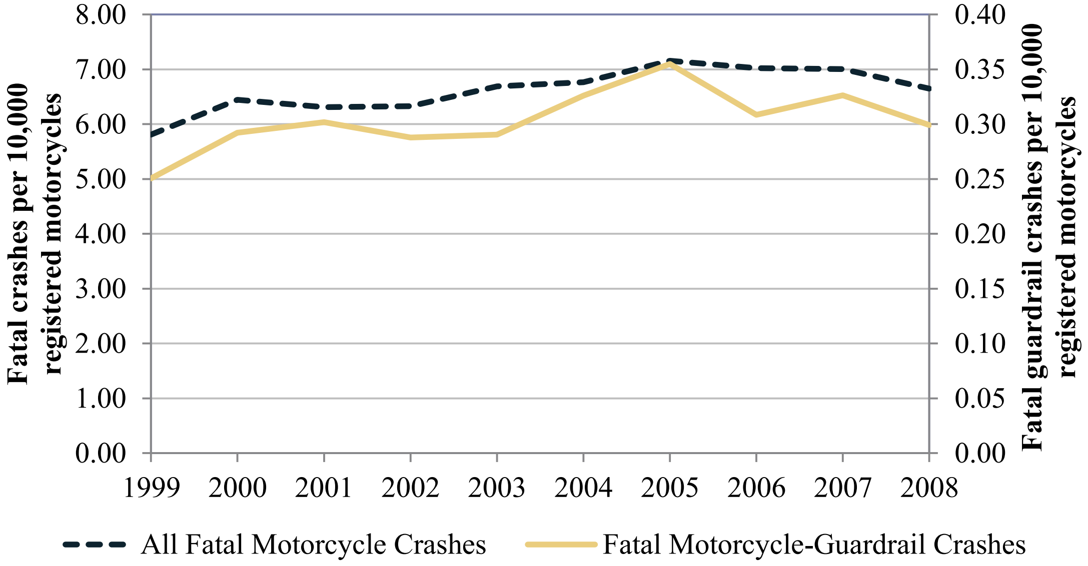


Figure 3.2. Fatal crash rate per 10,000 registered motorcycles (FARS 1999-2008, Traffic Safety Facts 2009)

From 1999-2008, 62,056 vehicles (of all types) were involved in fatal motorcycle crashes, 64% of which were motorcycles. As shown in Figure 3.3, 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 ($\chi^2 = 1631.1$, $p < 0.001$).

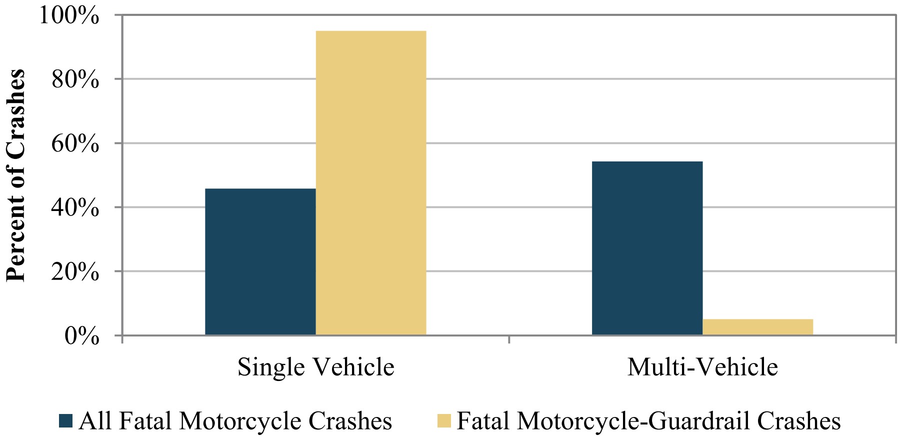


Figure 3.3. Distribution of Single- and Multi- Vehicle Crashes (1999-2008)

3.4.1 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 during which 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 was 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 3.4. The differences in seasonal crash trends were found to be significantly different between the types of crashes considered ($\chi^2 = 21.388$, $p < 0.001$).

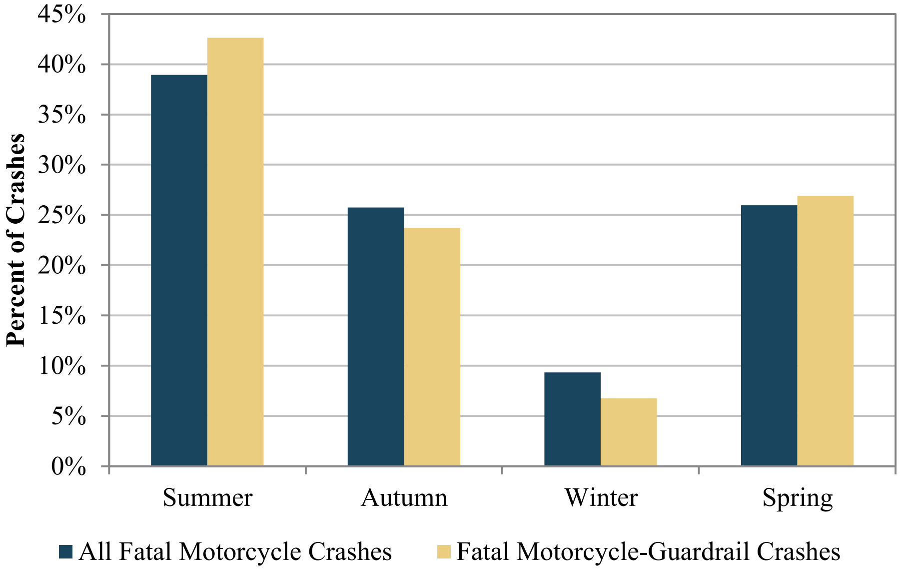


Figure 3.4. Time of year during which crashes occurred (1999-2008)

Next, the time of day during which crashes occurred were compared through an analysis of the hour during which crashes occurred. Figure 3.5 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 "24" were omitted from this figure for consistency. This only accounted for 0.9% of all crashes and 0.5% of guardrail crashes.

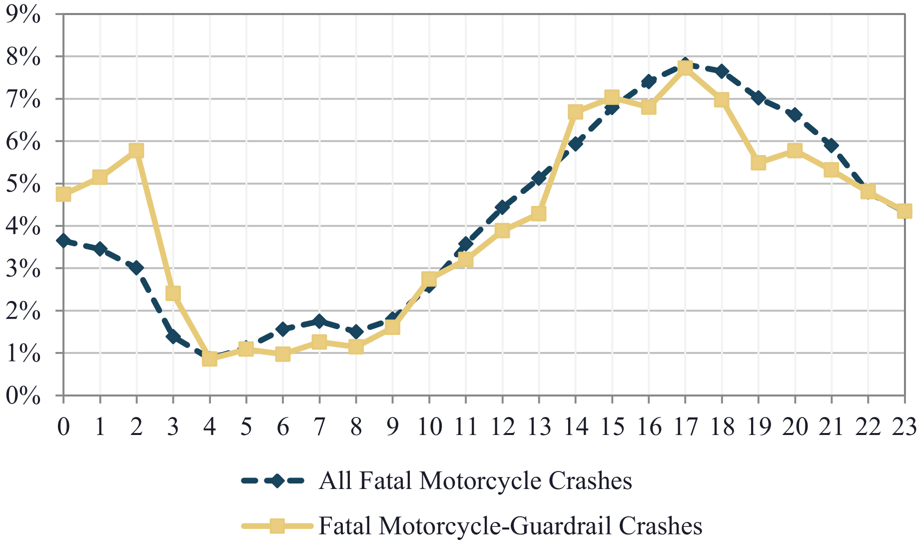


Figure 3.5. Distribution of crashes by time of day (1999-2008)

Generally, guardrail crashes followed a similar trend to all fatal crashes. However, a higher percentage of guardrail crashes occurred from midnight to 3:59 AM than all fatal crashes. This is most exaggerated from 2:00-2:59 AM; 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 3.6, 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 ($\chi^2 = 6.093$, $p = 0.637$).

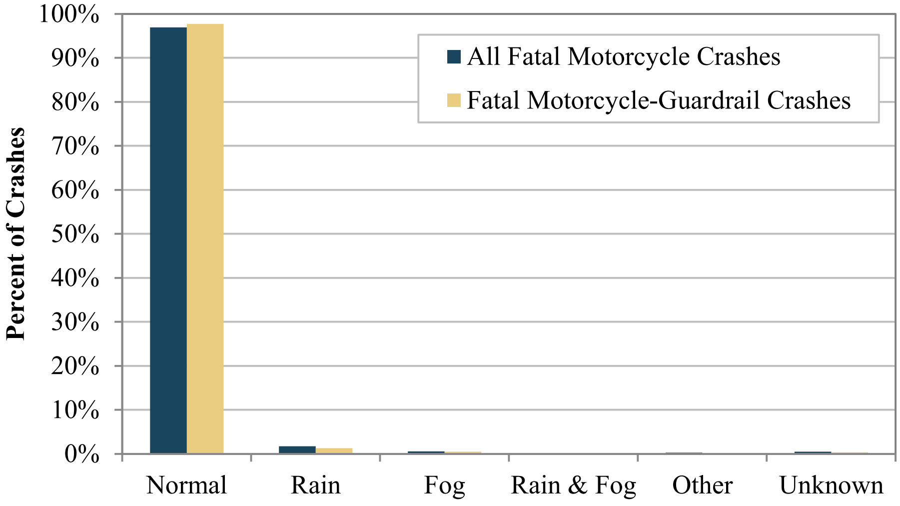


Figure 3.6. Distribution of weather conditions: all fatal crashes and fatal guardrail crashes (1999-2008)

The roadway alignment and profile at the location of fatal motorcycle crashes were analyzed. As shown in Figure 3.7, three-quarters of fatal motorcycle-guardrail crashes occurred on curves. Comparatively, only 38% of all fatal crashes occurred on curves. These trends were found to be significantly different ($\chi^2 = 995.6$, $p < 0.001$).

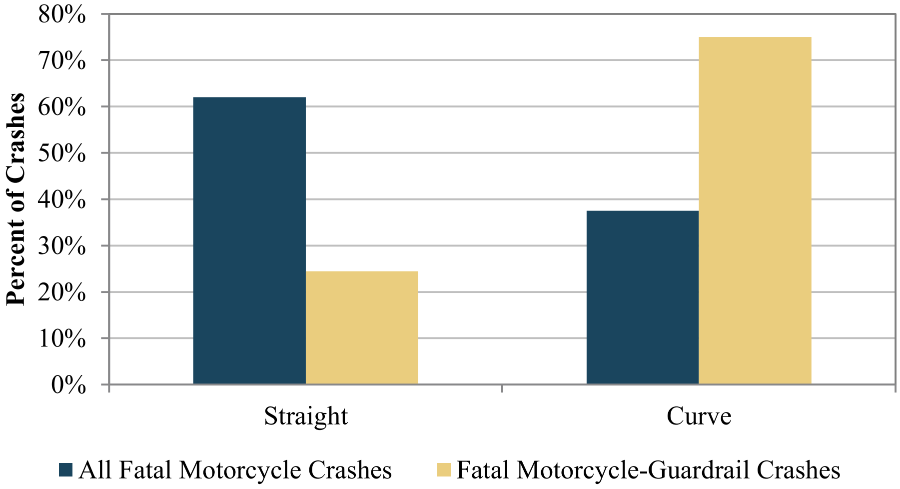


Figure 3.7. Roadway alignment during fatal crashes (1999-2008)

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 investigate 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 3.8, 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 ($\chi^2 = 263.2$, $p < 0.001$).

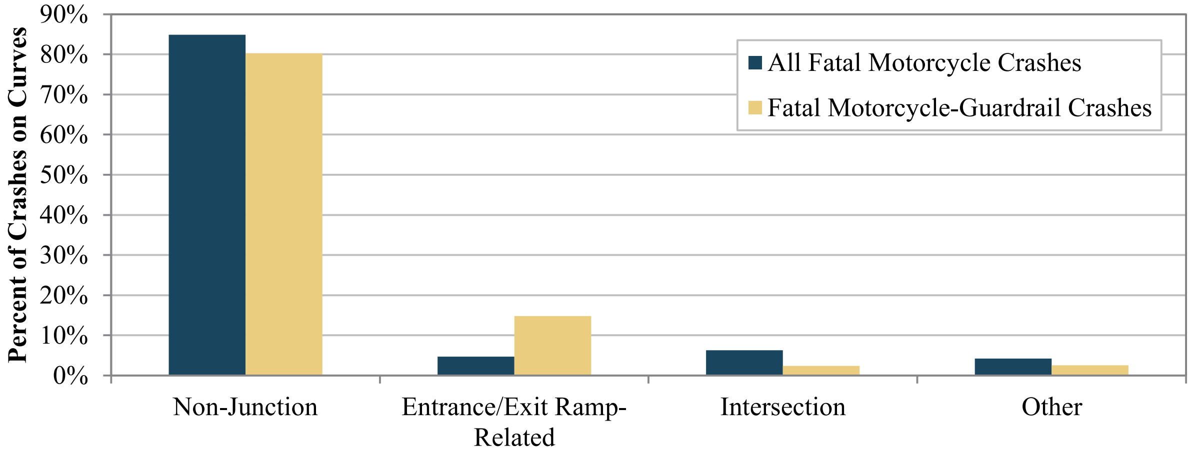


Figure 3.8. Roadway Junction Type in Fatal Crashes on Curves (1999-2008)

Also, there were approximately the same percentage of fatal guardrail crashes that occurred on level and graded roads (Figure 3.9). 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, graded roads may pose a particular hazard in guardrail crashes. However, this may also be a function of guardrail placement.

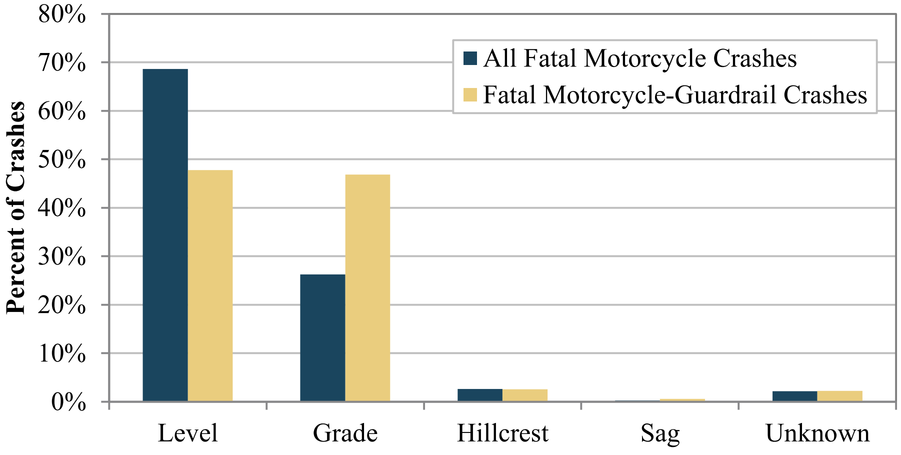


Figure 3.9. Distribution of roadway profile (1998-2008)

One other characteristic analyzed was roadway functional classification. The greatest percentage (17.5%) of fatal guardrail collisions occurred on urban interstate roadways. However, only 5.4% of all fatal motorcycle crashes occurred on these roads (Table 3.2). These trends in roadway function class were found to be significantly different between all fatal crashes and fatal guardrail crashes (χ^2 = 1034.0, $p < 0.001$).

Table 3.2. 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-Min Collector	4.0%	2.3%
Urban-Frwy/Xprwy	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%

3.4.2 RIDER DEMOGRAPHICS

Second, 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 that was involved in a fatal guardrail crash. Of these people, only 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, and 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 had a full helmet law from 1999-2008, 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 [*42*]. The helmet use laws for each state are shown in Figure 3.10.

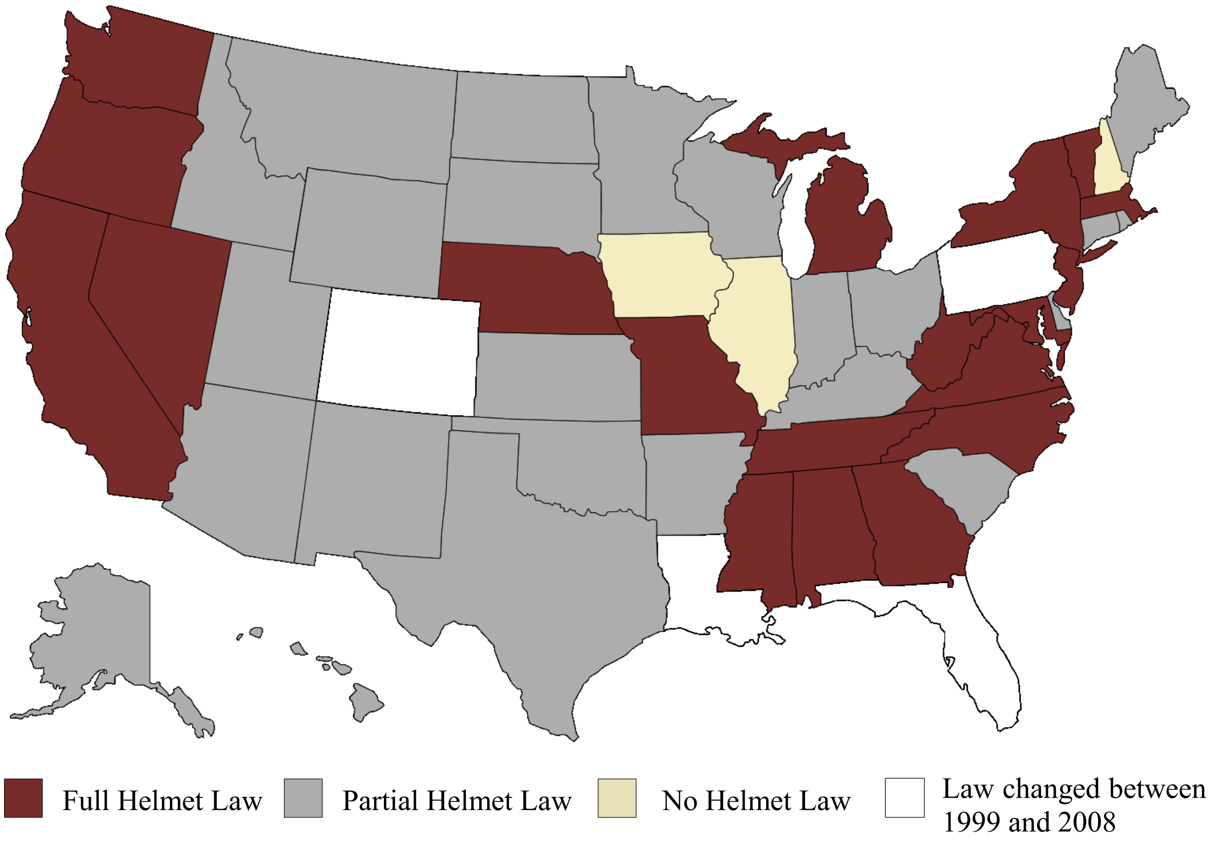


Figure 3.10. Helmet Laws by State (1999-2008)

The distribution of helmet usage by helmeting law is shown in Figure 3.11 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. There were a small percentage of riders whose helmet usage was unknown (3% of all riders), who were excluded from this component of the analysis. As shown, those in fatal guardrail collisions had a slightly higher 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 ($\chi^2 = 0.460$, $p = 0.794$).

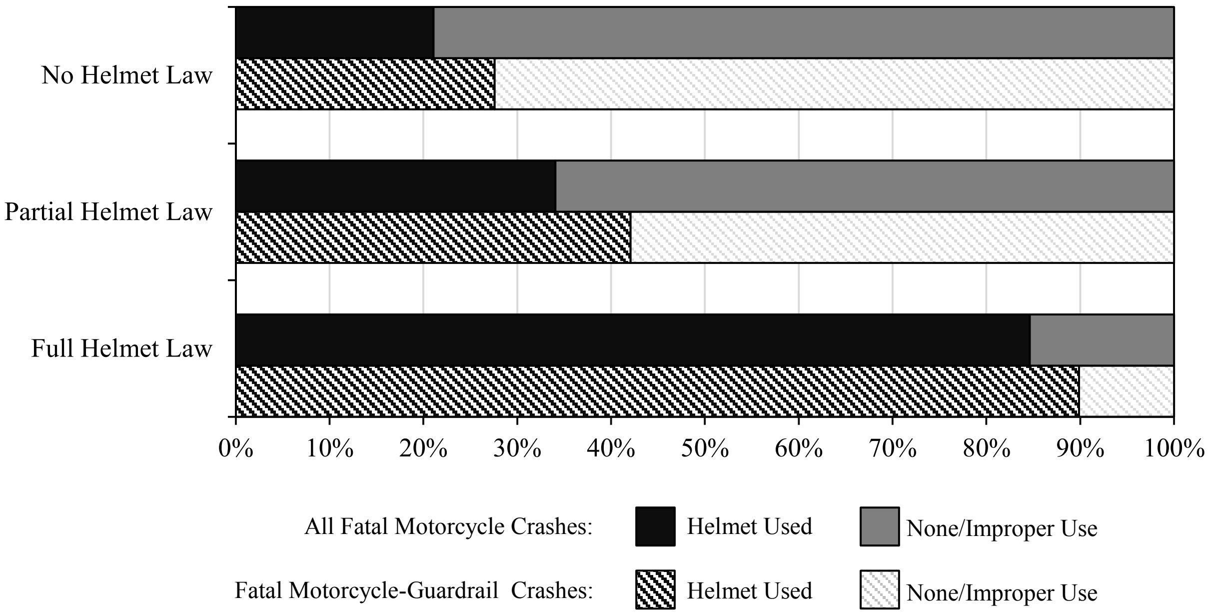


Figure 3.11. Helmet Usage by State Helmet Law (1999-2008)

As shown in Figure 3.12, there were a higher percentage of people between the ages of 21 and 39 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 ($\chi^2 = 2.961$, $p < 0.001$).

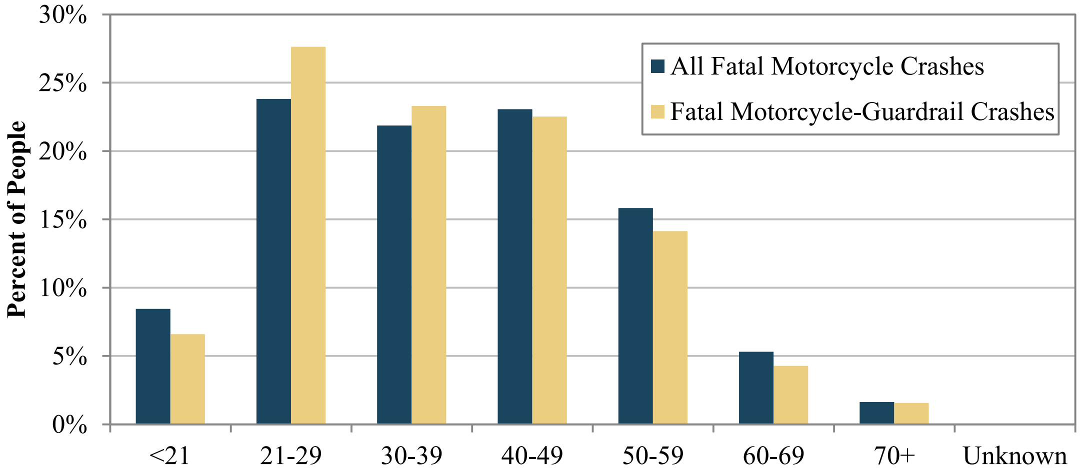


Figure 3.12. Age distribution of people fatally injured in a motorcycle crash (1999-2008)

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 3.13). These trends were not significantly different ($\chi^2 = 1.823$, $p = 0.402$).

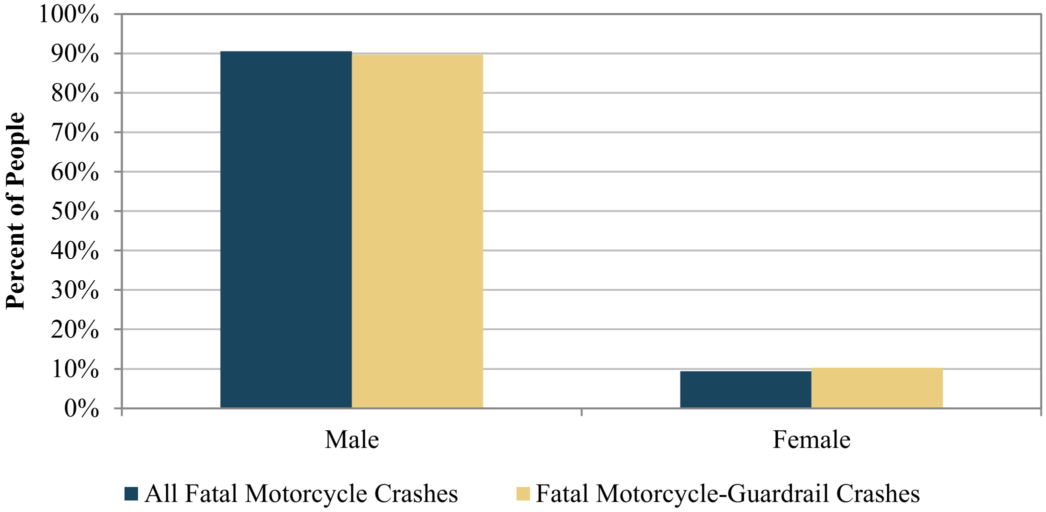


Figure 3.13. Gender distribution of people fatally injured in a motorcycle crashes (1999-2008)

Motorcycle operators involved in guardrail crashes had a higher tendency to be drinking than those involved in all crashes (Figure 3.14), 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 BAC or police-reported alcohol involvement [*36*]. 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.

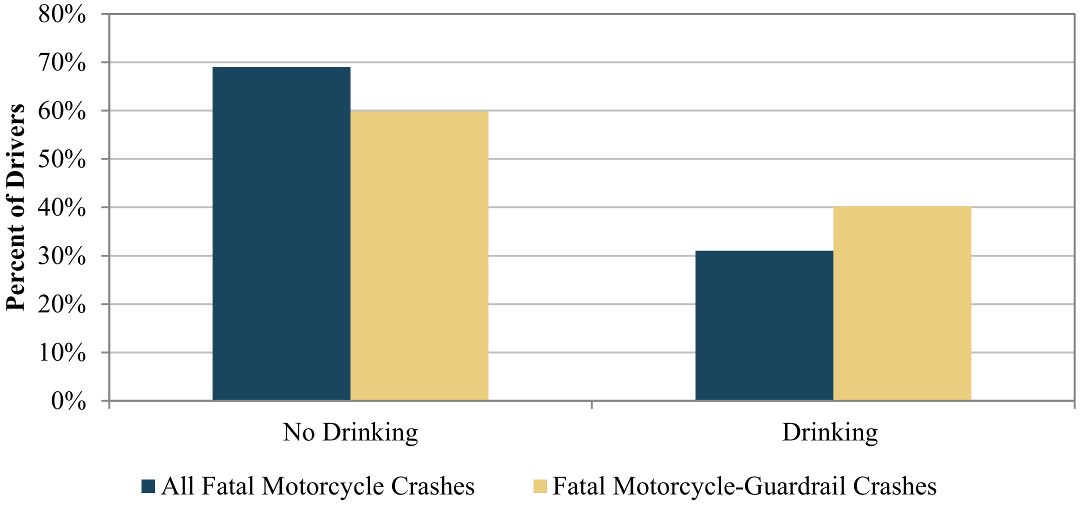


Figure 3.14. Distribution of drinking status of riders in a motorcycle crash (1999-2008)

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 3.15). Trends in license status varied between drivers in all fatal crashes and fatal guardrail crashes ($\chi^2 = 18.625$, $p < 0.001$).

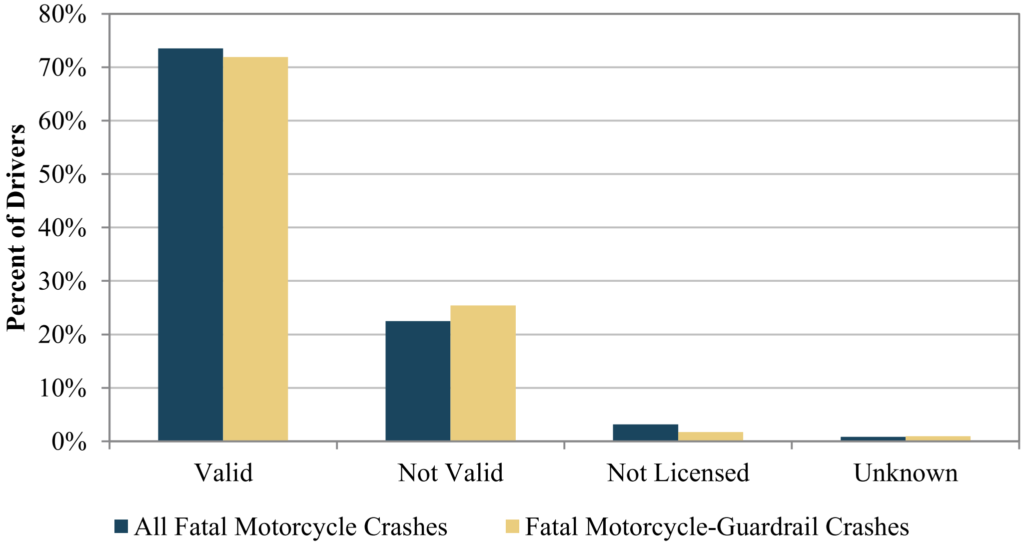


Figure 3.15. License status of riders involved in a fatal motorcycle crash (1999-2008)

3.4.3 *Motorcycle Characteristics*

Lastly, 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 3.16). The motorcycles involved in each crash category had a median motorcycle displacement of 997 cubic centimeters.

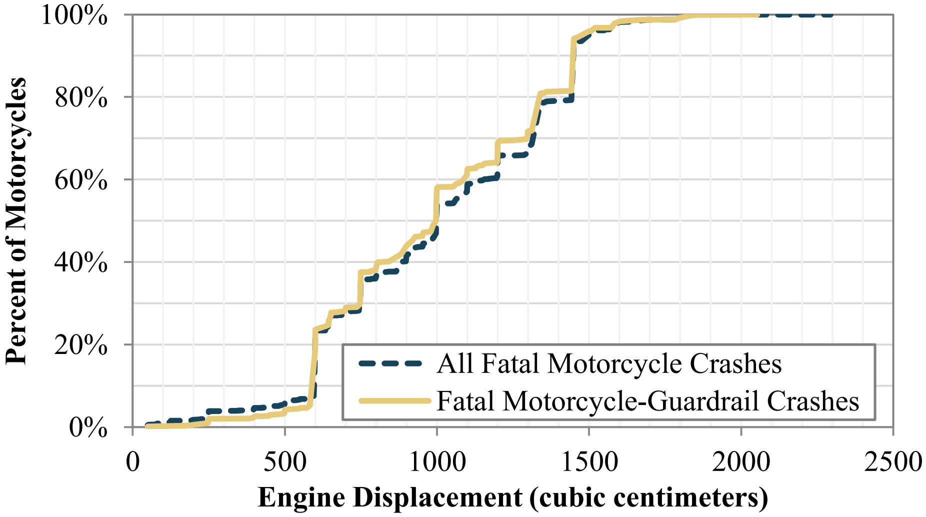


Figure 3.16 Distribution of engine size of motorcycles in fatal crashes (1999-2008)

3.4.4 *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 collisions were almost exclusively single vehicle crashes (95%), whereas less than half (46%) of all fatal motorcycle crashes were single vehicle crashes. Additionally, only 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 21-39 whereas only 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.

3.5 CONCLUSIONS

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

1. Fatal motorcycle-guardrail crashes were almost exclusively single vehicle crashes, whereas less than half of all fatal motorcycle crashes were single vehicle crashes.

2. 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.

3. 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.

4. 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.

5. 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.

4 FATALITY RISK IN MOTORCYCLE COLLISIONS WITH ROADSIDE OBJECTS IN THE UNITED STATES

4.1 INTRODUCTION

Guardrails and other barriers are not the only hazards that exist on the roadside. This chapter investigated injury risk in all types of roadside object collisions for motorcyclists. The aim was to place guardrail fatality risk in the context of fatality risks in collisions with other roadside objects. However, as discussed in Chapter 1, 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 the Fatality Analysis Reporting System (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 police accident reports. 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.

4.2 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 to address Theory 3.

4.3 METHODS

The roadside objects included for analysis in this chapter were guardrails, concrete barriers, trees, signs, and utility poles. The Fatality Analysis Reporting System (FARS) database was used in conjunction with the General Estimates System (GES) database to analyze motorcycle crashes from 2004-2008. 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 both 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.

4.3.1 RELATIVE FATALITY RISKS BASED ON THE MOST HARMFUL EVENT

First, 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 (2.2). Confidence bounds on data from GES were found using the methods described in the GES Analytical User's Manual [*37*]. 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 (2.3).

4.3.2 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 most harmful event. 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 thirteen 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, (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.

The fatality risk for collisions with each fixed object and the ground was computed using Equation (2.2). Next, the relative fatality risk of fixed object collisions as compared to collisions with the ground was computed using Equation (2.3).

4.3.3 DISTRIBUTION OF MOST HARMFUL EVENT 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 most harmful event 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

$$SE = \sqrt{\frac{p \cdot (1-p)}{n}} \qquad (4.1)$$

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 +/- 1.96·SE.

4.4 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 most harmful event 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 most harmful event is given in Table 4.1.

Table 4.1. 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
Rollover/Overturn	4,219	209,415	0.020	0.017	0.024

Table 4.1 shows that the most common type of motorcycle crash of those analyzed was either a collision with the ground or with a motor vehicle. However, it also shows that roadside objects are dramatically 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 for either overturn or motor vehicle collisions. Motorcycle-tree collisions had the highest fatality risk, followed by collisions with signs and utility poles. For this analysis, crashes with utility poles and signs were grouped into one category since they are 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 (2.3)). Figure 4.1 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 only 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.

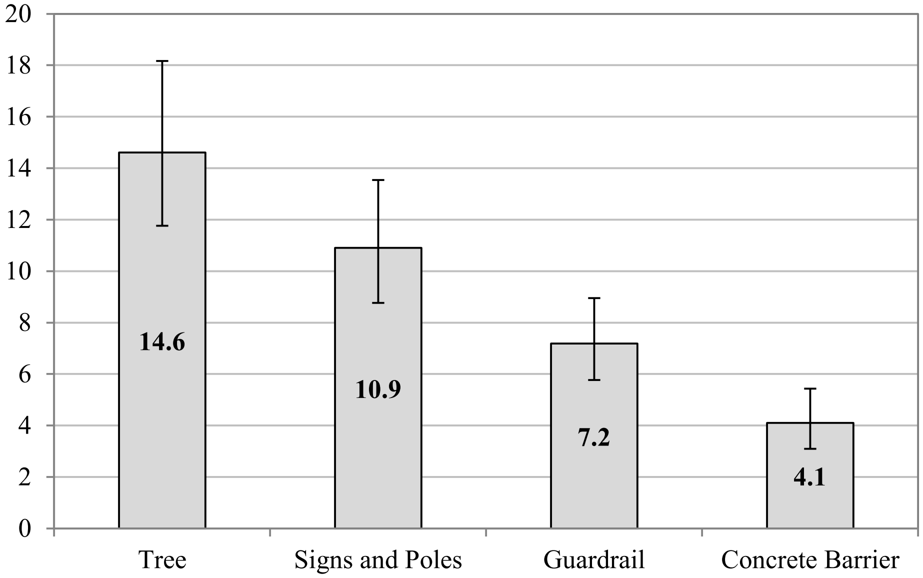


Figure 4.1. Relative fatality risk of fixed object collisions to ground collisions based on MHE (FARS, GES 2004-2008)

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 4.3.2, 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 4.2.

Table 4.2. 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

The relative fatality risk between the roadside object and a collision with the ground was computed (Figure 4.2). The relative fatality risks computed using this method were not statistically different from those computed based on the MHE.

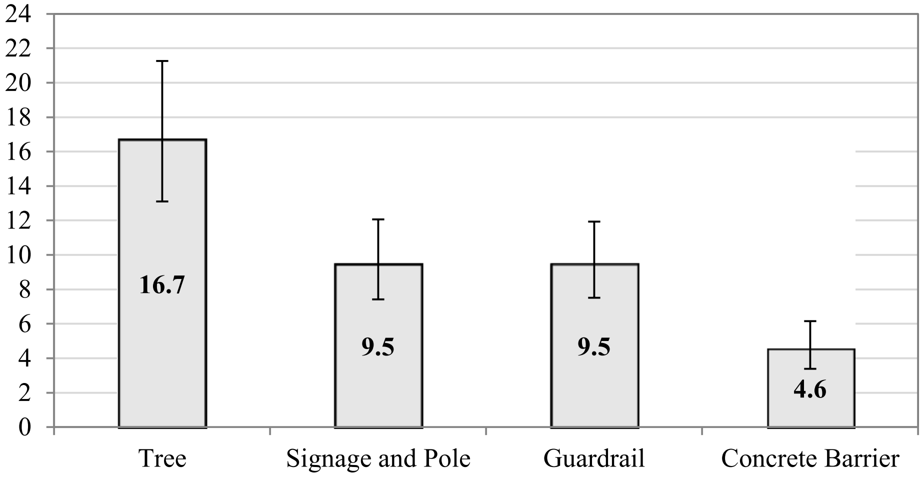


Figure 4.2. Relative fatality risk of fixed object collisions to ground collisions based on the sequence of events (FARS, GES 2004-2008)

The final component of the study addressed the question of which event was likely to be designated as the most harmful event in a two-event crash reported to involve a roadside object and a collision with the ground. Since this analysis was completed using only FARS data, signs and utility poles were divided into separate categories. Figure 4.3 shows the distribution of most harmful event for motorcycles in two-event crashes that collided with one of the fixed objects analyzed and the ground.

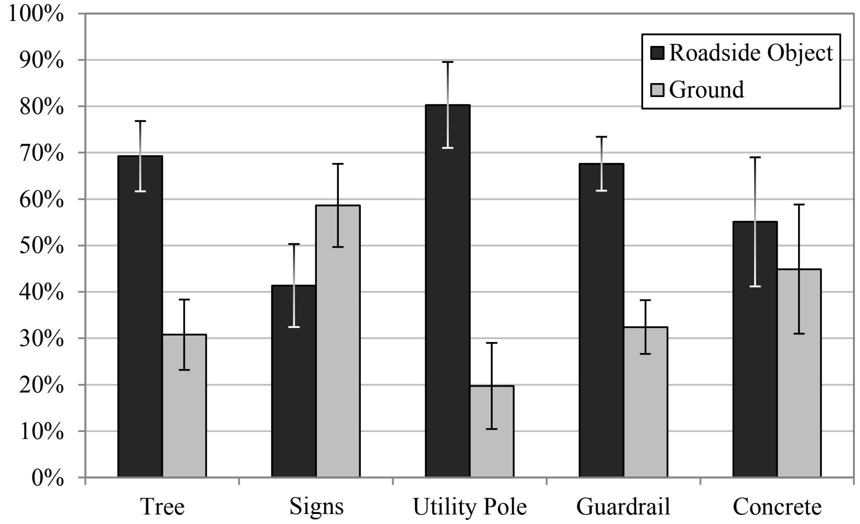


Figure 4.3. Distribution of most harmful event in two-event fatal crashes involving a fixed object and ground (FARS, 2004-2008)

For all fixed object collisions but signs, FARS identified the fixed object as the most harmful event in the majority of the crashes. FARS designated guardrails as the most harmful event in 69.2% (95% CI: 61.7%-76.8%) of the two-event collisions that involved a guardrail. Likewise, utility poles were the most harmful event 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 most harmful event in less than 37% of the crashes. With the exception of signs, the fixed object was reported to be the most harmful event 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 most harmful event is likely attributed to this design difference. The findings of this component of the study are consistent with the relative risk studies (Figure 4.1 and Figure 4.2) in that the collision with the roadside object is most often more harmful than the collision with the ground.

4.5 LIMITATIONS

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 6 events, whereas no limit was placed upon the number of events per cases in GES.

Starting in 2010, FARS included a separate event table. As of 2011, FARS and GES were standardized [*43*]. Therefore, an analysis using these later FARS years would have fewer limitations. However, these later years of data were not included since some of the variable definitions had changed compared to previous years.

The events included in the sequences are those reported in the police accident reports, 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.

4.6 DISCUSSION

Several other methods were considered to analyze which aspect of a collision was more likely to cause harm to the motorcyclists. First, the fatality risk was computed based on the sequence of events. Single-event roadside object collisions were compared to crashes where both the collision with the ground and the collision with the roadside object were reported. In a brief analysis of police accident reports from one state, the overturn was often not coded, though it was described in the synopsis of the crash. Since the overturn was omitted in some cases, the data was not consistent enough to conduct this analysis of single event versus two-event crashes. A second proposed analysis was to determine the fatality risk based on the number of crash events. However, since overturn was not coded for some crashes, the number of events in a crash could not be consistently determined.

The relative risk analyses presented in this study did not directly consider whether or not a collision with the ground was reported. Therefore, these analyses were not subject to this potential bias. The distribution of most harmful event was based on crashes where the overturn is reported, since the sequence of events in these crashes was assumed to be complete. The aforementioned analyses that were considered would provide more insight into the research question. These types of large scale studies may be possible in Europe using in-depth motorcycle crash databases, e.g. MAIDS [*44*]. Chapter 6 presents a small scale study that uses narrative descriptions from police accident reports to investigate how crash configuration and rider trajectory affects injury outcome.

4.7 CONCLUSIONS

This chapter investigated all roadside hazards, 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. [*3*], 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 [*3*], which is also consistent with the findings of this study.

This chapter also investigated the validity of Theory 3, which hypothesizes that the rider is already fatally injured before striking 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 most harmful event, collisions with guardrail were 7 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 4 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 were also 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 most harmful event 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 most harmful event 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 most harmful event 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 (Theory 3). The fatality risk of striking a guardrail was 7 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.

5 RELATIONSHIP BETWEEN BARRIER TYPE AND INJURY SEVERITY

5.1 INTRODUCTION

Motorcyclists have a much higher fatality risk in collisions with traffic barriers than do other road users [*4*]. From 2003-2008, 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 U.S., 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 over-represented in the number of fatalities resulting from guardrail impacts. In the U.S., motorcycles comprise only 3% of the vehicle fleet, but account for nearly half of all fatalities resulting from guardrail collisions, and 22% of the fatalities from concrete barrier collisions.

5.2 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.

5.3 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 which is becoming increasingly popular in the United States. Texas has more cable barrier than any other state in the U.S. 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 2003-2008 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 location of a crash differed for each state as described below. Once the crash site was identified, the "Street View" feature of Google Earth was used to determine barrier type.

5.3.1 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 North Carolina Department of Transportation (NCDOT) [*45*]. 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, US routes, and some state routes. On many state roads, crash locations could not be accurately identified, and these roads were excluded from the analysis.

5.3.2 TEXAS CRASH LOCATIONS

The Texas CRIS databases identified crash locations based on latitude and longitude coordinates. These were directly imported into Google Earth for analysis. There were 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.

5.3.3 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.

5.3.4 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. Our 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 [*46*]. 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. We hypothesized that this exclusion would not affect the results since it would like be a systematic exclusion.

There were several locations where there were no Street View photographs 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, there were 35 motorcycle–barrier crashes 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.

5.3.5 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 for may vary by roadway [*47*]. The effect of helmet usage on injury severity in barrier crashes was also analyzed since many riders were not helmeted 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 [*42*]. All statistical analyses were conducted using SAS 9.2 (SAS Institute Inc., Cary, NC). 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 both location and speed limit. The speed limit for each crash was then 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.

5.4 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 5.1 shows the distribution of barrier types in crashes that were examined by state.

Table 5.1 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***

Table 5.1 (continued)

	New Jersey	North Carolina	Texas	*Total*
Road Functional Class				
Interstate Highway	48	63	209	*320*
US & 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***	***1,047***

5.4.1 NORTH CAROLINA BARRIER CRASHES

There were a total of 323 motorcycle-barrier crashes in North Carolina from 2003-2008. The barrier type of 172 of these crashes was identified using Google Earth, involving 199 riders and passengers. Table 5.2 shows the distribution of injury severity by barrier type.

Table 5.2. 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*

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 5.1 compares the injuries sustained by each type of barrier based on the percentage of injuries in each category.

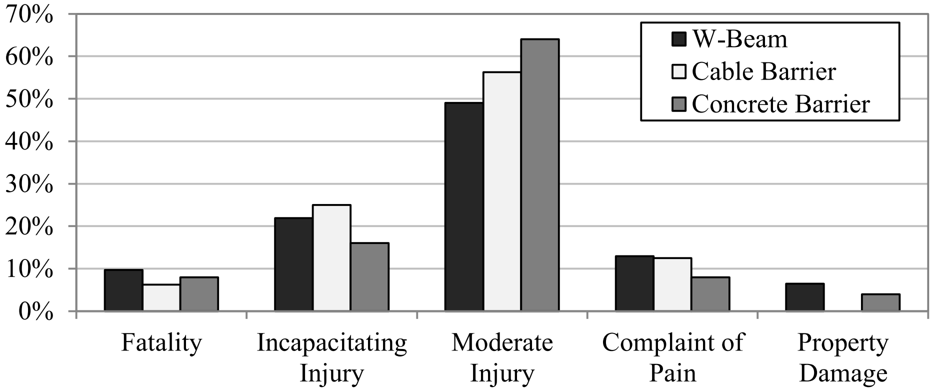


Figure 5.1. Distribution of Injury Severity in North Carolina Motorcycle-Barrier Crashes (2003-08)

The majority of the crashes resulted in moderate injury for all barrier types. There were 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.

5.4.2 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.

Table 5.3 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*

As shown in Table 5.3, there were 580 riders and passengers involved in the 524 crashes for which the barrier was identified. 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 5.2.

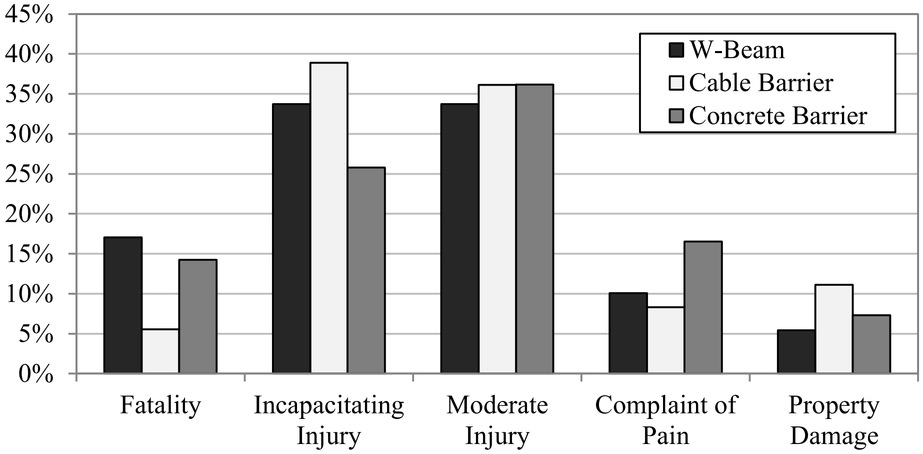


Figure 5.2 Distribution of Injury Severity in Texas Motorcycle-Barrier Crashes (2003-2008)

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 data set 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 were a higher percentage of fatalities in collisions with W-beam guardrails in Texas as compared to North Carolina.

5.4.3 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 is 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.

Table 5.4 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*

As shown in Table 5.4, 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 5.3.

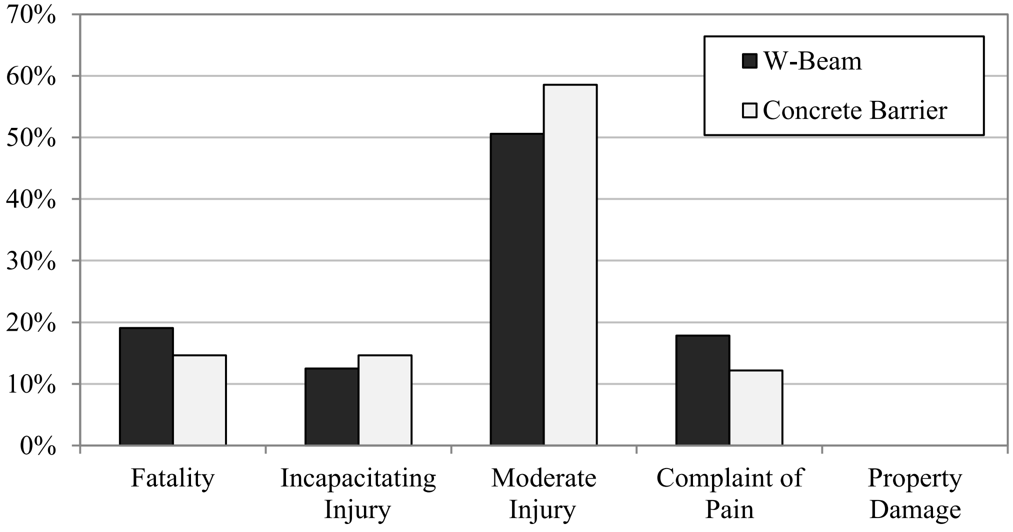


Figure 5.3 Distribution of Injury Severity in New Jersey Motorcycle-Barrier Crashes (2003-2008)

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 both 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. 92.3% (155) of the motorcycle to W-beam guardrail crashes analyzed 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 2 (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.

5.4.4 *ANALYSIS OF DATA SET*

Between the three states, there were 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 5.5.

Table 5.5 Injury Severity by Barrier Type for Combined Data Set

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*

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 5.4.

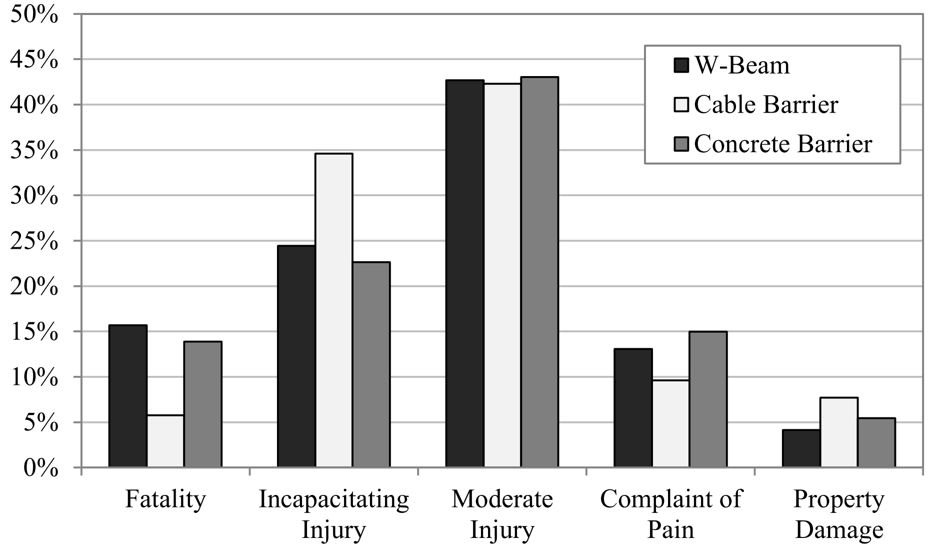


Figure 5.4. Injury Severity by Barrier Type (North Carolina, Texas, and New Jersey, 2003-2008)

For each barrier type, the percentage of moderate injuries was the same. The risk of serious (K+A) injury in for concrete barrier collisions was 0.365. Comparatively, the risk of serious injury in W-beam and cable barrier collisions was 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 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 odds ratio of serious injury between these different barrier types are shown in Table 5.6. 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 un-helmeted riders.

Table 5.6. Odds Ratio of Serious Injury in Cable Barrier Crashes Compared to Other Barriers

Helmet Usage	Barrier Type	OR of Serious Injury	95% 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
Un-Helmeted	Cable Barrier: W-beam	1.283	0.434	3.796
	Cable Barrier: Concrete Barrier	0.905	0.301	2.718

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, helmet usage, and speed limit were all tested. Speed limit was divided into 2 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.

There were 705 riders that crashed with either W-beam barrier or concrete barrier in New Jersey, North Carolina, and Texas that also 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 (χ^2=1.613, p=0.204). Posted speed limit was also not found to be a significant predictor for serious injury (χ^2=0.343, p=0.558). However, barrier type was a significant predictor for serious injury (χ^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 odds ratio of serious injury was 1.404 (95% CI: 1.011-1.950) for W-beam crashes as compared to concrete barrier crashes.

The odds of injury in collisions with different barrier types were next 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, including barrier type. However, the point estimate of the odds ratio 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.

5.5 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-cable barrier crashes observed over the six 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 relatively rough and injury severity scores vary by state and over time [*48, 49*]. Specifically, there has been variation in the 'A' level of the KABCO scale between states [*49*]. In the states investigated for this study, there were a greater percentage of riders in crashes in Texas 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 travelling at the time of the crash. Therefore, crash on low speed roads (< 45 mph) may have occurred at high speeds (≥45 mph). Unfortunately, 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 [*50*]. Lastly, the offset of the barrier from the road may influence the likelihood of serious injury. If the barrier is further off the road, the rider has more time to reduce speed and potentially steer away from the barrier.

There were a small number of cable barrier crashes included in this study, particularly for fatal crashes. Only 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.

5.6 CONCLUSIONS

This study has presented an analysis of the injury risk in 951 motorcycle-barrier collisions, involving 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 that from the national study presented in Chapter 4, which showed that riders had a greater risk of fatality in W-beam crashes as compared to concrete barrier crashes.

6 RELATIONSHIP BETWEEN RIDER TRAJECTORY AND INJURY OUTCOME IN MOTORCYCLE-TO-BARRIER CRASHES

6.1 INTRODUCTION

Previous European studies have identified two main modes of motorcycle-to-barrier impact: sliding and upright impacts [*51, 52*]. Bambach et al. [*53*] investigated rider orientation in fatal collisions in Australia. Few studies have focused on the rider trajectory in both non-fatal and fatal crashes in the United States. One hazard identified in many studies is the guardrail posts [*35*]. 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 we define post-impact trajectory 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 both 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, which further complicates the large scale study of rider trajectory.

6.2 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.

6.3 METHODS

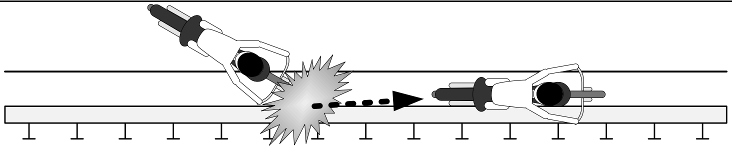
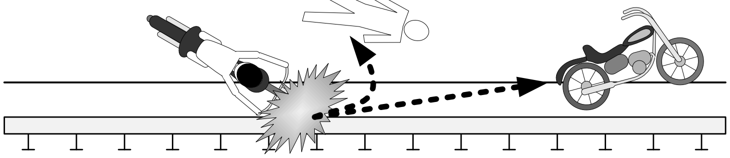
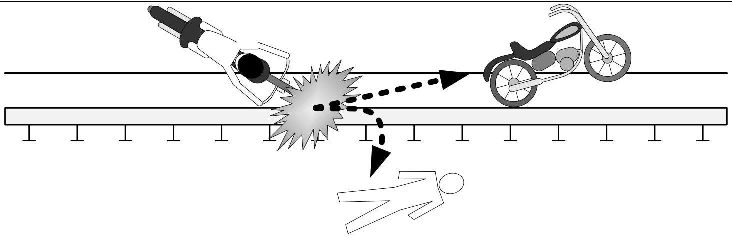
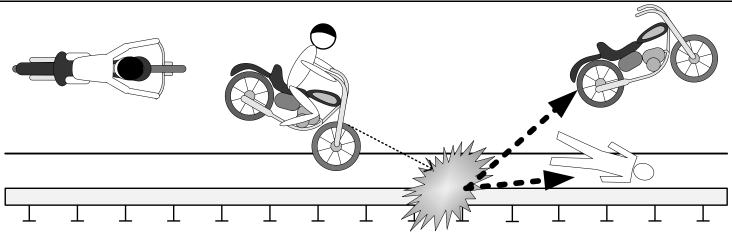
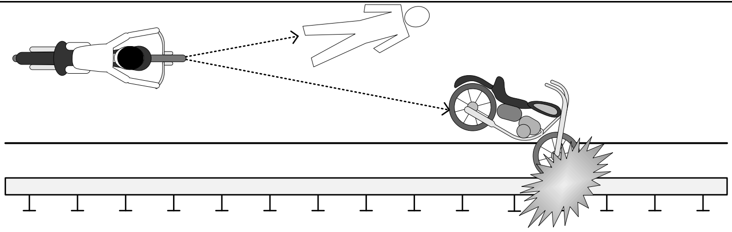
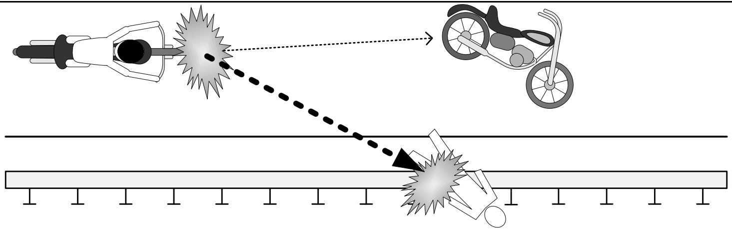
In the FARS and GES national databases, as well as most state crash databases, the sequence of events describes the objects struck by the motorcycle rather than the rider. The data collection protocol is vehicle-centric and assumes that vehicle occupants were subjected to the same sequence of events 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 police accident reports (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.

6.3.1 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 6.1. 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.

Table 6.1. 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	

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. 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 that were 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 then reviewed again to determine which trajectory was most likely.

6.3.2 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 in Chapter 5. 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 [*42*]. Odds of serious injury were investigated for helmeted riders only, since there were few un-helmeted riders and injury outcome is likely dependent helmet usage.

6.3.3 ROAD CHARACTERISTICS

Our 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. Our 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 is 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.

6.3.4 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 (SAS Institute Inc., Cary, NC). The logistic procedure was used to construct the binary logit model, and the Fisher's scoring method was used.

6.4 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 police accident report 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 6.2.

Table 6.2. 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%
Un-helmeted	20	5.5%
Unknown	19	5.3%

There were 265 riders involved in 248 guardrail collisions, and 96 riders involved in 94 in concrete barrier collisions. Additionally, 4 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 6.4. For the majority of cases where a passenger was involved, the driver and passenger experienced the same trajectory, though they did not necessarily have the same injury severity. For the 1 case where driver and passenger trajectory differed, trajectory was coded uniquely for each person. Table 6.3 shows the different highway characteristics investigated by barrier type. Only crashes with information available for all roadway characteristics were included in the model.

Table 6.3. 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

Table 6.3 (continued)

	Guardrail Crashes	Concrete Barrier Crashes
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

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 [*4*]. For comparison to the other chapters presented in this dissertation, the odds ratio 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 Chapter 5.

Table 6.4. 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*

The distribution of trajectories by barrier type is shown in Figure 6.1. 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 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 (χ^2=19.695, p=0.012).

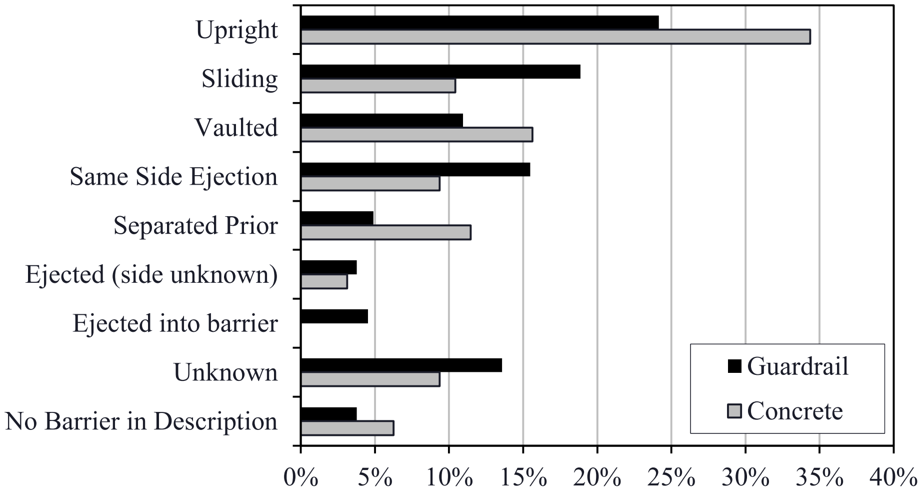


Figure 6.1. Rider Trajectory in Guardrail and Concrete Barrier Collisions

6.4.1 *EFFECT OF ROADWAY CHARACTERISTICS ON RIDER TRAJECTORY*

Our study hypothesized that the rider trajectory may also be a function of road characteristics including horizontal alignment (straight vs. curved roads), roadway vs. 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 7 un-helmeted 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 6.5 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 low speed roads. Likewise, no significant differences in rider trajectories were seen for side of road. There were only 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 (χ^2=4.727, p=0.450).

Table 6.5. 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

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.

6.4.2 *Effect of Rider Trajectory on Injury Severity*

The odds of serious injury were computed by barrier type and rider trajectory for helmeted riders (Figure 6.2). The number of serious to non-serious crashes is also given in Figure 6.2. 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 (χ^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 tending towards significance at 0.05 level (p=0.052), but did not reach it.

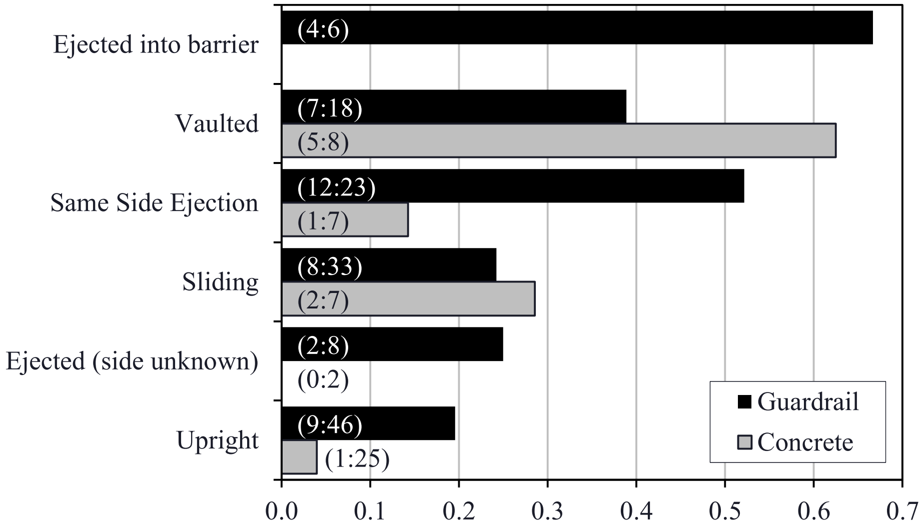


Figure 6.2. Odds of Serious Injury by Rider Trajectory
(Number of Seriously Injured: Non-Seriously Injured Riders)

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 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 6.1, upright collisions were the most common collisions observed. The odds ratios of serious injury are shown in Figure 6.3 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 (95% CI: 1.14-19.74) times. 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.

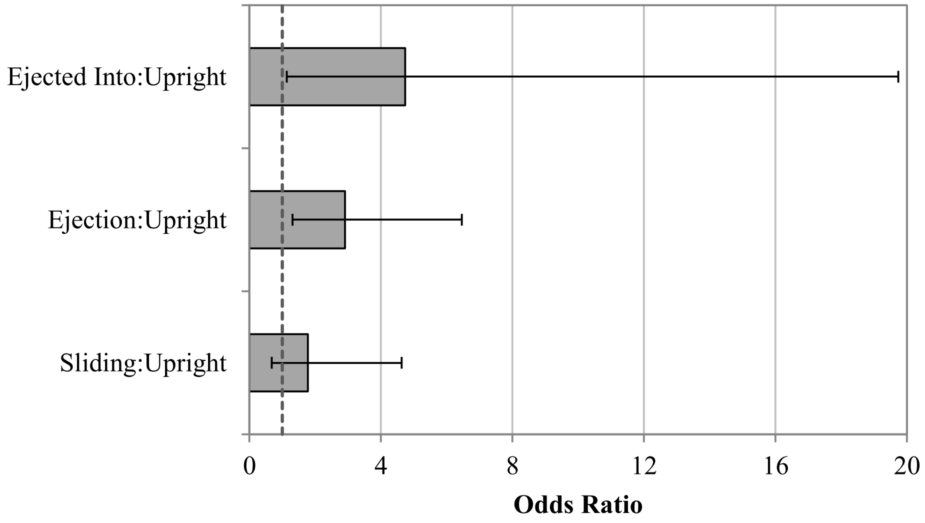


Figure 6.3. Odds Ratio of Serious Injury Compared to Upright Crashes

6.5 DISCUSSION

There are several limitations 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%). We assumed that the sample of crashes with PARs and barrier type was representative of all crashes because police accident reports were available for the vast majority of crashes.

Previous studies have typically identified two types of barrier collisions: upright and sliding. Our 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. Our findings show slightly higher prevalence of upright collisions and lower estimates for the prevalence of sliding collisions compared to previous literature. Berg et al. [*51*] also found that 51% crashed upright and 45% crashed while sliding. Likewise, Bambach et al. [*53*] found that 44% of fatally injured riders in W-beam crashes crashed into the barrier while upright. In our data set, 52% of all fatally injured riders in W-beam crashes were upright, which is consistent with the findings of Bambach et al. [*53*]. However, Quincy et al. [*54*] found that in 58% of crashes, riders slid into the barrier. Also, Peldschus et al. [*52*] 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. Our study looks at US crashes, whereas previous studies have analyzed crashes in Europe and Australia.

6.6 CONCLUSIONS

The rider trajectory and barrier type was determined for 342 motorcycle-to-barrier crashes in New Jersey from 2007-2011. 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 were 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 (95% CI: 1.31-6.46) times 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 in the motorcycle-barrier controversy 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 does not show to significantly affect injury outcome, it influenced the distribution of rider trajectories. Road alignment therefore has an indirect connection to injury severity.

7 THE CHARACTERISTICS OF INJURIES IN MOTORCYCLE TO BARRIER COLLISIONS IN MARYLAND

7.1 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 [*55*]. Unlike passenger car crashes, there is currently no in-depth investigation database for motorcycle crashes in the United States. A promising alternative, however, is the Crash Outcome Data Evaluation System (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 [*56*] and rider age [*57, 58*].

Previous studies on motorcyclist injuries have focused on fatal crashes using European, Australian, and United Arab Emirates data. Head injuries have been found to be the most common cause of fatality in all motorcycle crashes [*53, 59, 60*]. Bambach et al. [*53*] 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.

7.2 OBJECTIVE

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

7.3 METHODS

The Maryland Crash Outcome Data Evaluation System (CODES) was used to analyze three years of motorcycle collisions, from 2006-2008. Data sources for the Maryland CODES include, but are not limited to, police records, EMS, emergency department, and toxicology reports [*61*]. The CODES data is the result of linking these datasets using a probabilistic method [*61*].

Injury data is reported in CODES using the International Classification of Disease 9th 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 in Section 2.2, the Abbreviated Injury Scale (AIS) reports injury severity in terms of threat to life [*38*]. AIS ranks injury severity from AIS=1 (minor) to AIS=6 (not survivable). For this chapter, the ICDMap-90 Program (Johns Hopkins and Tri-Analytics, 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 [*62*].

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. Both the barrier and fixed object crashes included in this study were limited to single-vehicle crashes. If a motorcycle struck multiple objects, e.g., 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 was also 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 the maximum AIS severity score (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.

7.4 RESULTS

There were 5,586 motorcycle crashes of all severity in Maryland from 2006 – 2008. The CODES data linked 2,357 of these crashes with hospital inpatient or emergency department data. The injury data associated with all of 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 4 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 7.1. 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 7.1. These were often multi-event collisions, such as a collision into a barrier and a fixed object.

Table 7.1. Distribution of 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*	*250*

$^+$Not including barrier collisions

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 7.2 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 hospital admission, we expected that the linked crashes would not include property damage only cases, most minor injury cases, and many fatal cases. Table 7.2 confirms that the linked cases are biased towards 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 ($p < 0.0001$).

Table 7.2. Police Reported Injury Severity in MD CODES Data for the Entire Dataset

KABCO	Police Reported Injury Severity	% Linked Cases	% Un-Linked 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

However, when the seriously injured riders likely to have been hospitalized (‘Disabled’ and ‘Injured’) are compared as shown in Table 7.3, 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.

Table 7.3. Seriously Injured Riders in MD CODES Data

KABCO	Police Reported Injury Severity	Number of Linked Cases	Number of Un-Linked Cases	% Linked Cases	% Un-Linked 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

General characteristics of the crashes included in this analysis are given in Table 7.4. 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.

Table 7.4. Composition of the Data Set

	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	1301
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	1090	233	1662
Speed Limit					
Low Speed (<45 mph)	52	181	742	129	1104
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

Distributions of crashes in the collision categories were significantly different between each of the different road characteristics listed Table 7.4 (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.

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 7.1). The region of principal diagnosis corresponds to the first ICD-9 code [*62*], 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.

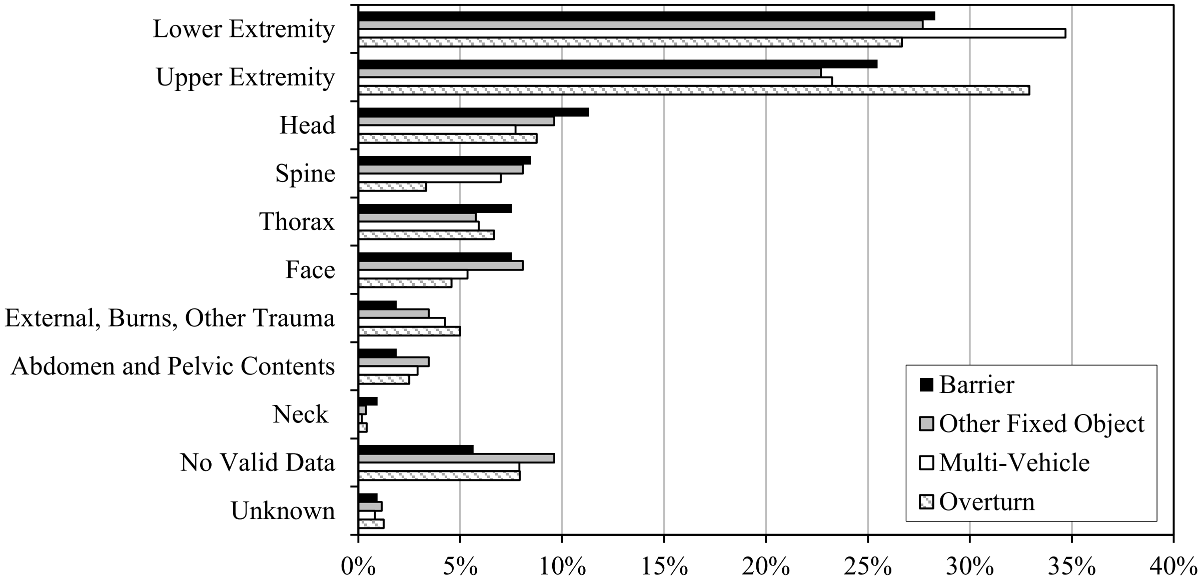


Figure 7.1. Region of Principal Diagnosis

Figure 7.2 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.

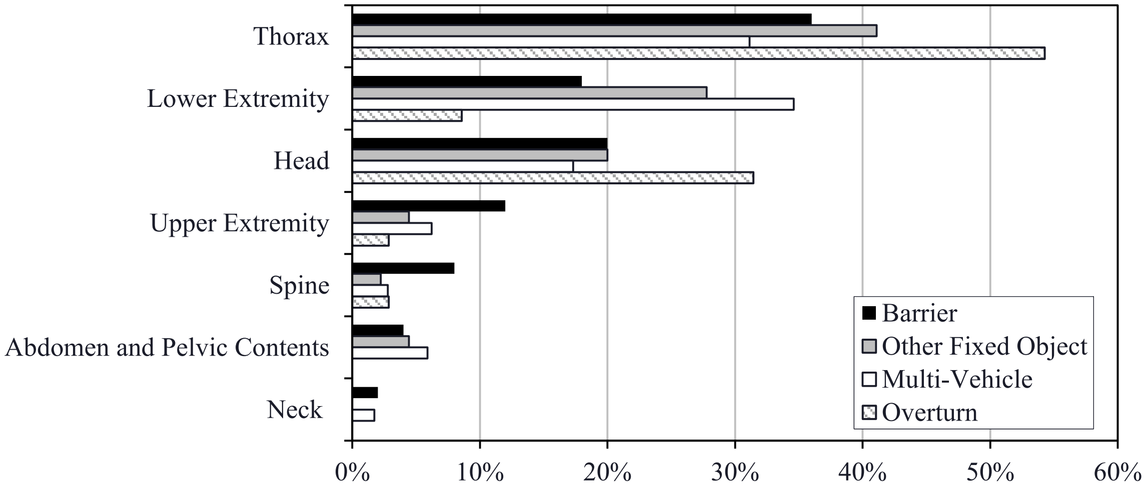


Figure 7.2. Distribution of AIS 3+ Injuries by Body Region

7.4.1 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 above, the 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 our dataset, only 4 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.

7.4.2 LACERATIONS

One concern about collisions with 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, only 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.

Focusing on higher severity lacerations, riders in barrier collisions were 2.26 (95% CI: 0.75-6.86) times 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 than 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 7.3). 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.

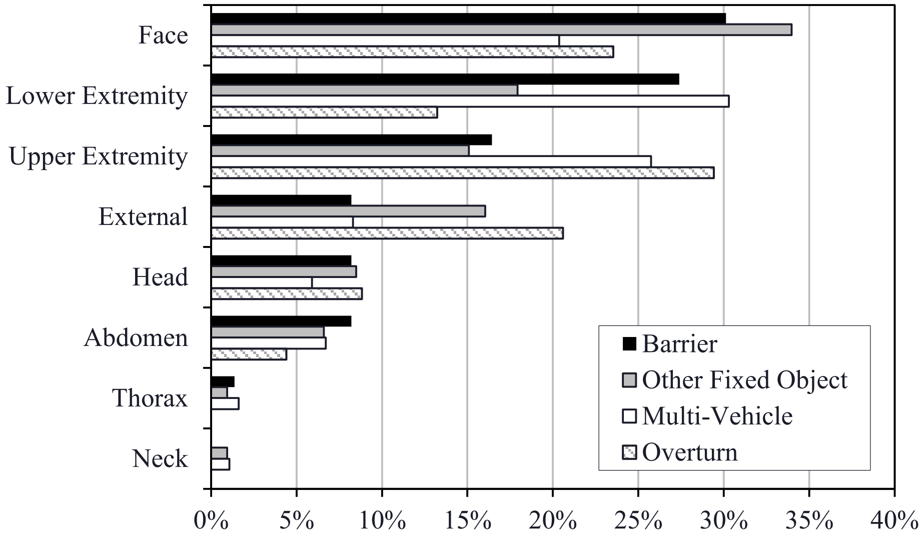
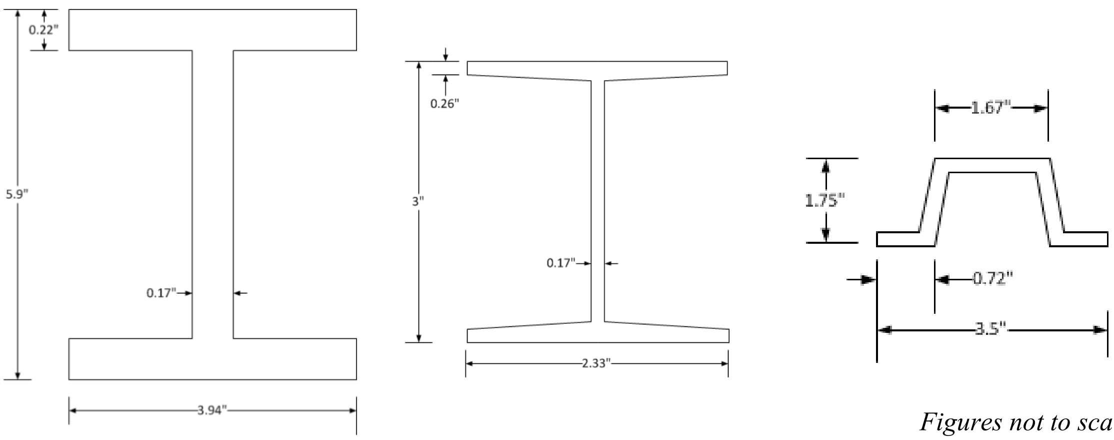


Figure 7.3. Distribution of Lacerations by Body Region

Different barrier post and rail designs exist that may affect the risk of laceration. Unfortunately, barrier type was not recorded in the CODES database. Figure 7.4 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.



Figures not to scale

Figure 7.4. Various Post Designs

(A) Strong-Steel Post for W-Beam Guardrail (B) Weak-Steel Post for W-Beam Guardrail (C) Flanged-Channel Post for Cable Barrier. Dimensions based on Task Force 13 Guidelines.

7.4.3 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, both short-term and long-term [*63*]. 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 7.5.

Table 7.5. 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%

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. [*63*] demonstrated that clavicle fractures 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 also be due to a small sample size.

7.4.4 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 7.6 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 (95% CI: 1.17-3.92) times 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 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.

Table 7.6. 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%*

Figure 7.5 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 (95% CI: 1.04 - 3.36) times 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).

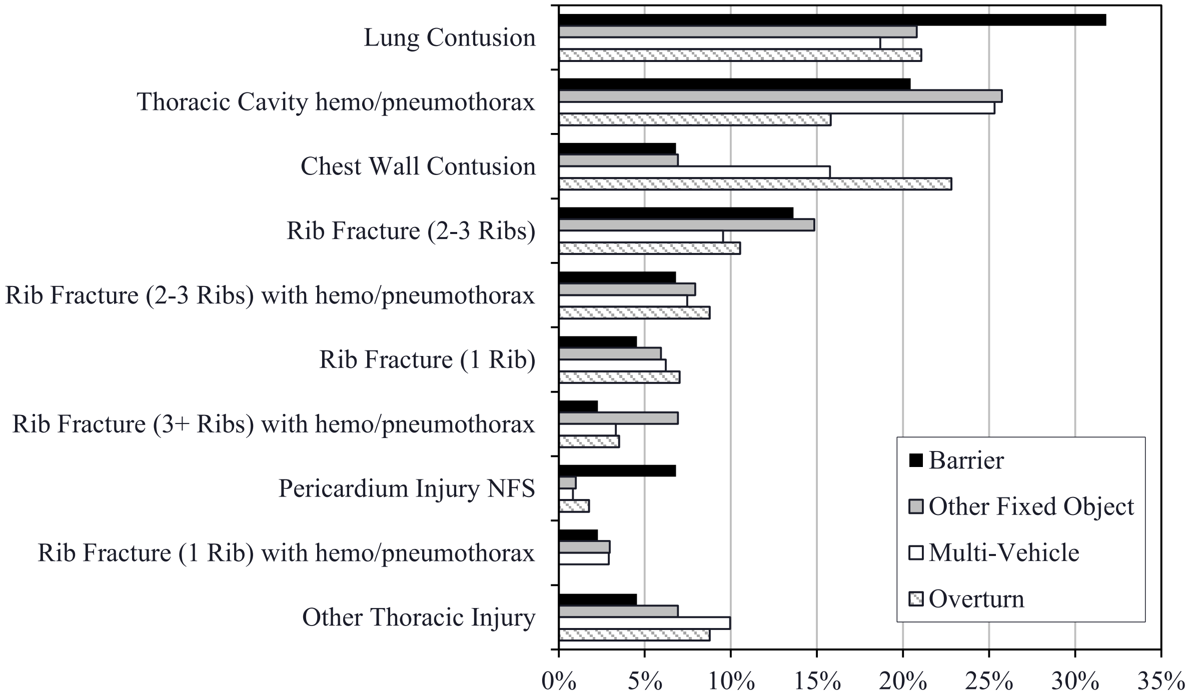


Figure 7.5. Distribution of Injuries to the Thoracic Region

Nearly one-third (31%) of riders involved in a barrier collision suffered a lung contusion. In contrast, only 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.

7.5 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 which 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. [*51*] 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 data set 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 data set 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.

7.6 CONCLUSIONS

This chapter examined the risk of injury by body region in motorcycle-barrier crashes using linked police accident reports and hospital data from Maryland from 2006-2008. 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 [*60*], who found that lower-extremity injuries most commonly occur in motorcycle crashes, and Hefny et al. [*59*], 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 commonly seriously injured body region. We defined serious injuries 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 [*64*]. 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. who examined fatal crashes [*53*]. Motorcyclists involved in barrier crashes were 2.15 (95% CI: 1.17-3.92) times more likely to suffer a serious injury to the thoracic region that 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. [*65*] and Valey et al. [*66*], who both 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.

8 IN-DEPTH INVESTIGATION OF INJURY MECHANISMS IN MOTORCYCLE-TO-BARRIER CRASHES

8.1 INTRODUCTION

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 being injured. This chapter describes a protocol developed to determine injury mechanisms through in depth investigations of motorcycle crashes. This chapter also presents a preliminary analysis of injuries in these crashes to begin to identify specific injury mechanisms in motorcycle-to-barrier crashes.

The last in-depth motorcycle study in the United States was conducted over 30 years ago by Hurt et al. [*67*]. Since this study was conducted, there have been significant changes in barrier, helmet, and motorcycle design, and these data do not accurately reflect crashes presently occurring in the United States. In the United States, there is no in-depth crash investigation data available for motorcycles, unlike that available for passenger cars through studies such National Automotive Sampling System Crashworthiness Data System (NASS-CDS) and the Crash Injury Research and Engineering Network (CIREN). To determine injury mechanisms in motorcycle-to-barrier crashes, Virginia Tech is conducting a program of in-depth motorcycle crash investigations with sponsorship from the National Academies of Science.

8.2 OBJECTIVE

The objective of this chapter is to develop a methodology of determining injury mechanisms in motorcycle-barrier collisions through clinical studies and crash investigations. Furthermore, this chapter begins to characterize injuries and injury mechanisms in motorcycle-to-barrier collisions based on crashes investigated to date.

8.3 METHODS

8.3.1 IDENTIFICATION OF CASES

Cases in our study were identified and enrolled by 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 Crash Injury Research Engineering Network (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:

- Single-vehicle motorcycle crash
- Collision with guardrail, concrete barrier, or cable barrier

In an approach similar to previous chapters, cases were limited to single-vehicle crashes since the focus research is on injuries in barrier crashes, not those with other vehicles. In a multi-vehicle 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.

8.3.2 DATA ELEMENTS COLLECTED

The data elements to be collected in our study were determined by examination of previous or on-going in-depth crash investigation programs. Data elements collected in each of these investigation programs were compared to determine data elements that were most frequently used. Additionally, these programs offered data element needs, which were incorporated into our study. After the initial list of data elements was developed, these were compared to the list of research questions for our project to ensure that the data elements collected were sufficient to answer all proposed research questions [*68*].

The list of data elements was derived from four previous studies/protocols: (1) Motorcycle: Common International Methodology for In-Depth Accident Investigation (OECD common methodology), (2) Motorcycle Accidents In-Depth Study (MAIDS), (3) Motorcycle Accident Cause Factors and Identification of Countermeasures (commonly referred to as the Hurt Report), and (4) NASS-CDS. The first three studies are motorcycle-specific, though not necessarily focused on roadside barriers [*44, 67, 69*]. Each provides detailed information about data elements to be collected in order to fully describe the motorcycle and the dynamics of the crash. Though NASS-CDS does not contain any motorcycle crashes, it provided a comprehensive list of data elements to describe the circumstances of the crash.

Next, the set of roadside data elements to be collected through this study was developed based on four roadside-specific studies/databases: (1) National Cooperative Highway Research Program (NCHRP) Project 17-22, (2) Longitudinal Barrier Special Study (LBSS), (3) NJDOT Motorcycle-Barrier Crash Database, and (4) HSIS Michigan Roadside Data. NCHRP 17-22 expanded on roadside crashes reported in NASS-CDS, collecting additional information about the roadside environment. Data elements included, but were not limited to, shoulder and roadside dimensions, barrier dimensions, and barrier performance [*70*]. Likewise, the LBSS was a study conducted from collecting further information on the roadside environment for selected NASS-CDS crashes in the 1980s. The NJDOT Motorcycle-Barrier Crash Database was selected due to its focus on motorcycle crashes. This study collected roadside through retrospective site investigations of motorcycle crashes in New Jersey [*46, 71*]. The Michigan HSIS data contains a detailed data table specific to barriers, and was therefore chosen as one of the model databases [*72*].

Lastly, data elements regarding the specific injuries were based on the BioTab method developed for CIREN [*73*]. The collection of data elements developed for the current research is included in Appendix A.

8.3.3 CRASH INVESTIGATION

There were three main components of each crash investigation in our 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 detailed the damage to it. Ideally, the investigator visited the site within a week of the crash. Due to this short time frame, there was still evidence of the crash remaining (e.g. skid marks, fabric transfers, etc.). Both the site and the motorcycle were photographed, with particular attention paid to factors altered by 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. Wake Forest tabulated all injuries and assigned an injury score using the Abbreviated Injury Scale (AIS). They also provided the imagery for each injury, including CT scans, x-ray images, and patient photos showing external injuries. Additionally, they developed 3-D reconstructions for several severe injuries, which provided 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 riders 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 [*74*]. Additionally, information about personal protective gear usage was gathered through the interview.

8.3.4 Case Review

The team at Virginia Tech next coupled evidence from the crash investigations with the injury data from the patient and determined what occurred during each crash (Figure 8.1). 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. 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.

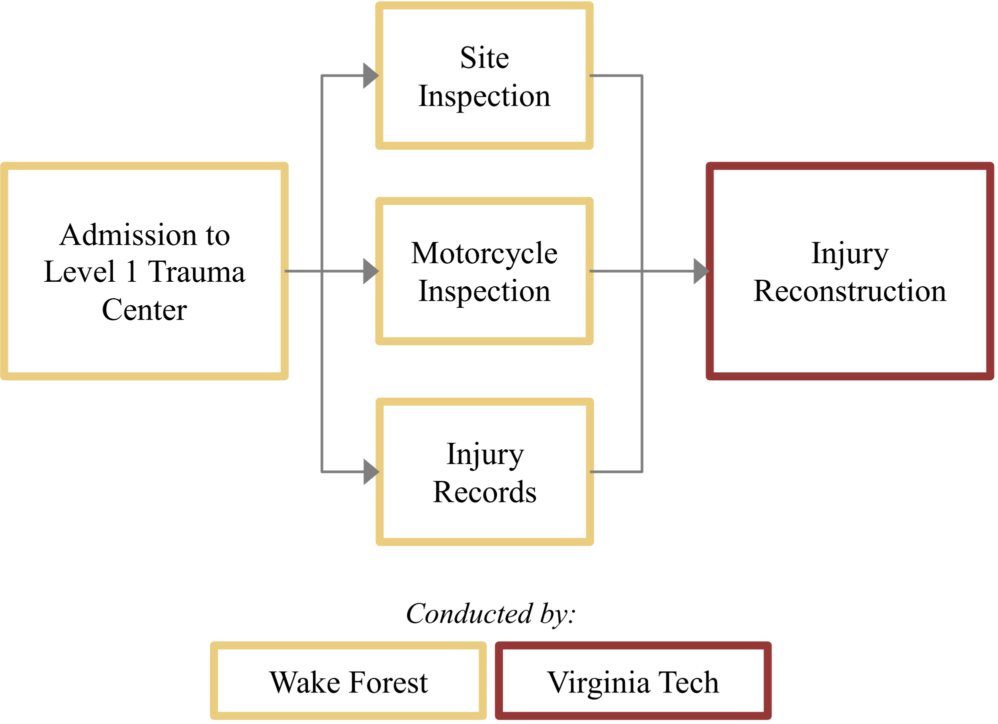


Figure 8.1. Crash Reconstruction Methodology

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, injury patterns, or damage to either the motorcycle or environment. Each ICS was also 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 injury contact source and confidence values were developed based on the BioTab developed for the CIREN database [*73*].

8.4 RESULTS

To date, the project has investigated 9 motorcycle-to-barrier collisions, involving 10 motorcyclists. As shown in Table 8.1, there were 7 crashes with W-beam guardrail, 1 crash with cable barrier, and 1 crash with both W-beam guardrail and cable barrier. With the exception of case MC-001, no passengers were present on any of the motorcycles involved in these crashes.

Table 8.1 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 Cliff
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

Table 8.2 describes the riders involved in the crashes investigated. Of the riders included in this study, 8 were male and 2 were female. The average age of the riders was 46.9, with a median age of 50. The MAIS of riders ranged from 2 to 5, and their ISS scores ranged from 8 to 45. None of the occupants involved in these crashes investigated were fatally injured. The three most common regions to suffer the most severe injury were the head, lower extremities, and thorax; three riders had at least one of their most severe injuries in these regions.

Table 8.2. Summary of Riders Involved in Crashes Investigated

Case Number	Age	Gender	Training (yrs prior)	Riding Experience (yrs)	MAIS	ISS	Region of Most Serious Injury
MC-001-D	58	Male	None	8	3	27	Upper Extremity Chest Abdomen
MC-001-P	61	Female	None	0 (Passenger experience only)	3	27	Spine Head
MC-002-D	58	Male	None	40	3	17	Upper Extremity Chest
MC-003-D	49	Male	None	3	2	8	Lower Extremity Head
MC-004-D	31	Male	Yes (2)	3	5	45	Head
MC-005-D	51	Female	No	2	3	9	Lower Extremity
MC-006-D	46	Male	No	7	3	22	Thorax Spine
MC-007-D	33	Male	Yes (0)	0	5	33	Thorax
MC-008-D	63	Male	Yes (40)	40	3	14	Lower Extremity
MC-009-D	19	Male	No	10	4	26	Thorax

8.4.1 CRASH DESCRIPTIONS AND INJURY CONTACT SOURCES

Two of the crashes and the ICS for the most serious injuries are described below. Contact points for the most severe injuries are included in the descriptions. Additionally, crash descriptions and complete injury lists are included in Appendix B.

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

This first case involved a male driver and a female passenger travelling on a 2006 Harley Davidson Electra Glide Ultra Classic Touring motorcycle. Both the 58 year old driver 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 driver leaned the motorcycle left, and allowed the left crash bar/foot peg to contact the asphalt pavement. Subsequent control loss re-directed the vehicle towards the right (north) pavement edge.

As shown in Figure 8.2, 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, the occupants 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 driver 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 driver reported paying full attention to driving at the time of the collision.

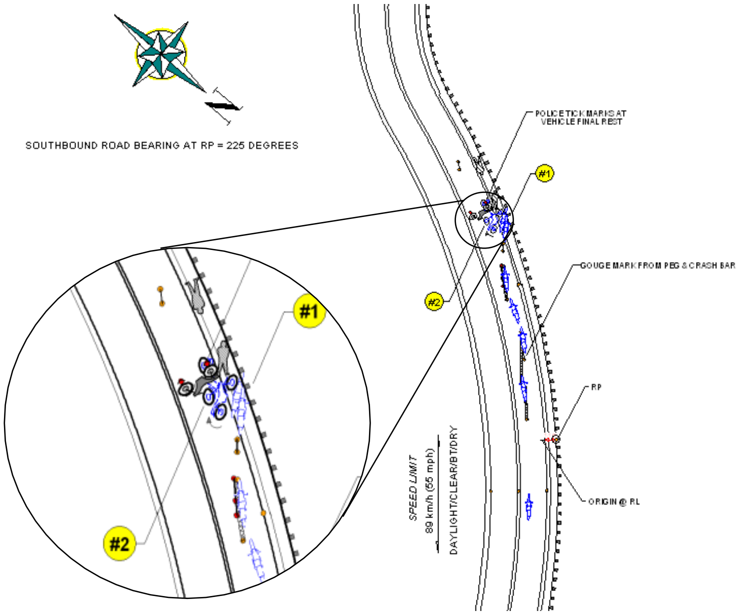


Figure 8.2. Crash diagram for Case MC-001

The driver (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 rider, passenger, and motorcycle, preventing them from going over the cliff.

8.4.1.2 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 travelling northbound down 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 8.3, the motorcycle was redirected and followed along the guardrail for 78 feet, 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.

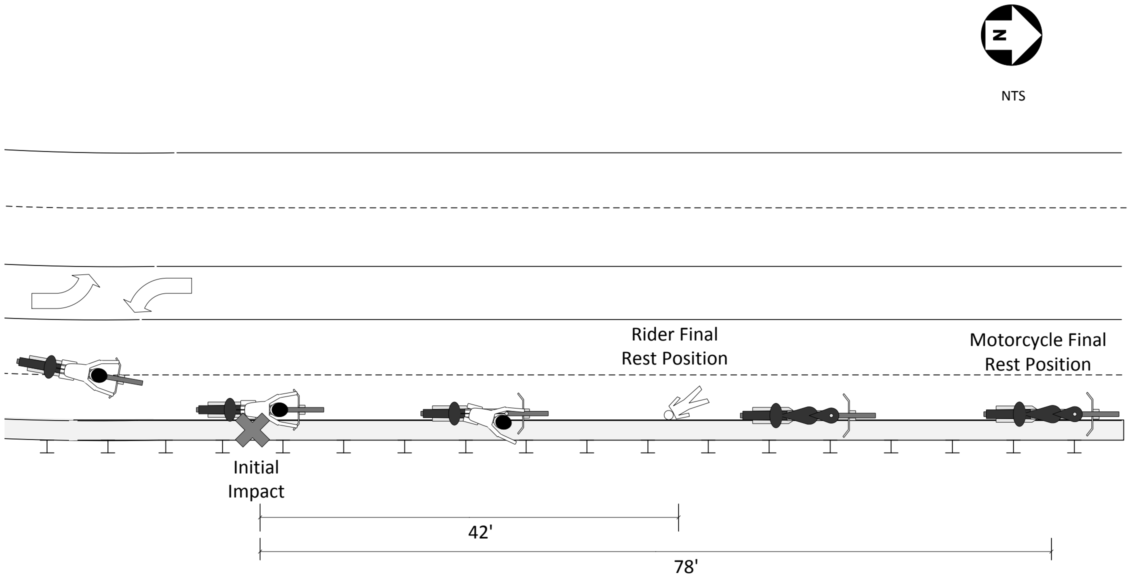


Figure 8.3. Crash scenario for Case MC-007

The rider suffered multiple rib fractures on both 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 hemo-pneumothoraces with large anterior mediastinal hematoma (AIS-4), liver lacerations (AIS-4), and a small spleen 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 was consistent with the rider being dragged along the rail.

8.4.2 SUMMARY OF INJURIES AND CONTACT SOURCES

Between the ten riders, there were 111 AIS-coded injuries. The distribution of serious and non-serious injuries by body region is shown in Figure 8.4 for all barrier types. Consistent with Chapter 7, the thorax suffered the greatest number of serious injuries (AIS 3+). However, the extremities suffered the greatest number of non-serious injuries. These early findings were consistent with those presented in Chapter 7.

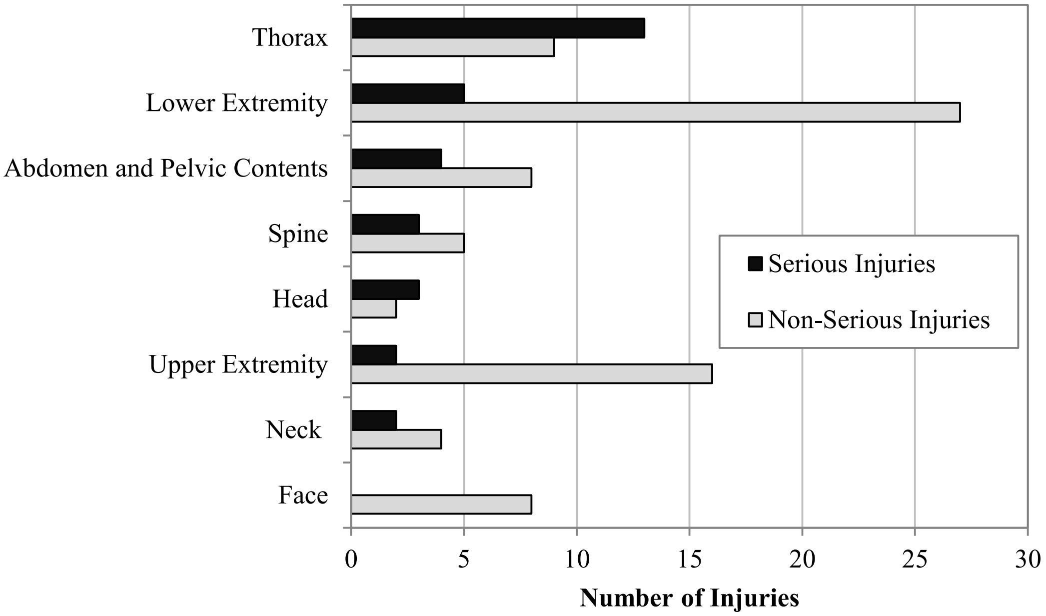


Figure 8.4. Number of Injuries Observed by Body Region

Injury severity was next analyzed as a function of barrier offset. For cases MC-001 through MC-005, the barrier offset was estimated using the scene photographs and ImageJ 1.46 Software (NIH, Bethesda, MD). The offset for Case MC-003 could not be measured; none of the photos provided enough evidence to estimate distance. Offsets for the other cases were measured at the crash site. Figure 8.5 shows the distribution of ISS by barrier offset. Generally, ISS decreased as barrier offset increased, with the exception of Case MC-004. In this case the cable barrier was offset over 10 feet from the edge of the travel line, but resulted in the greatest ISS (45). However, this was also the only cable barrier case investigated where the barrier offset was known.

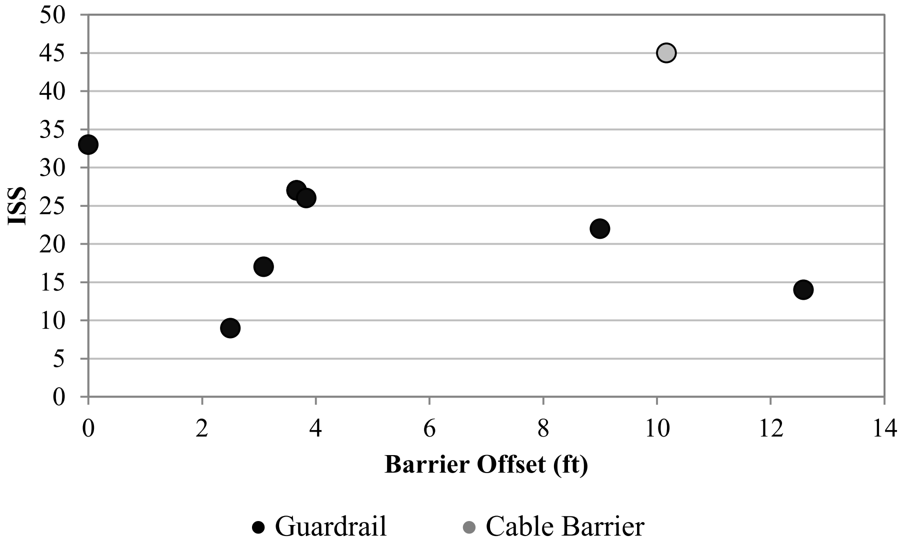


Figure 8.5. Injury Severity Score by Barrier Offset

Not all of the injuries observed were caused by the barrier. Figure 8.6 shows the distribution of serious and non-serious injuries by general injury contact source. As shown, the barrier (either W-beam or cable barrier) was postulated to have caused the greatest number of both serious and non-serious injuries. The second most common injury contact source was the ground.

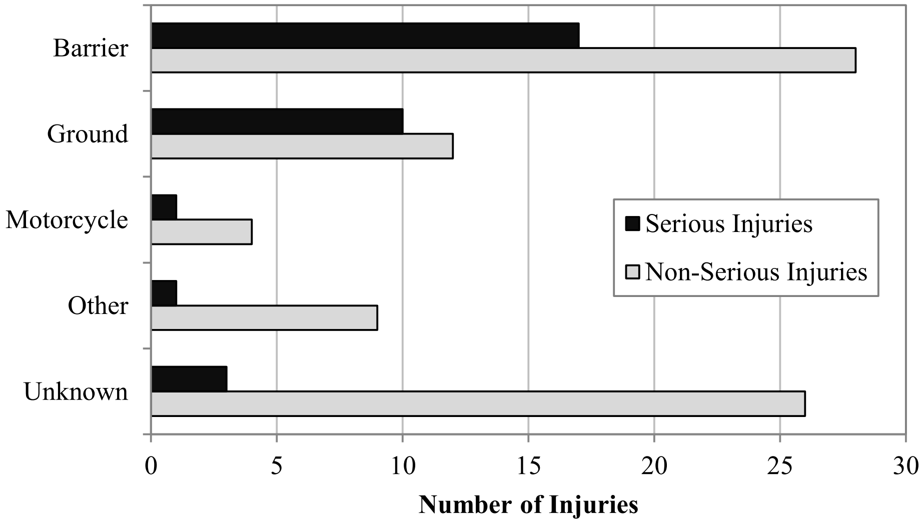


Figure 8.6. Distribution of Injury Contact Source

Five of the eight riders who were involved in a guardrail collision were postulated to have injuries caused by the guardrail. In two of the eight cases, there was evidence on the barrier of potential direct contact between the person and the barrier. In one case, a fabric pattern was present in an oily substance, likely fluid from the motorcycle. In the other case, there was a potential skin transfer observed on the upper edges of one of the posts. There were two injuries where the contact source was potentially the motorcycle or the guardrail, which were excluded in this part of the analysis. Figure 8.7 shows injury contact sources by guardrail component. The greatest number of serious injuries was postulated to be caused by the combination of hitting both the upper edge of the rail and upper edges of the posts (4 injuries). However, all these were suffered by the same person (MC-007-D). The posts caused the second greatest number of serious injuries, though overall caused fewer injuries than all faces of the rail. The rail face and edges caused 11 of the 27 injuries postulated to be caused by the guardrail, and 3 of these were AIS 3+ injuries.

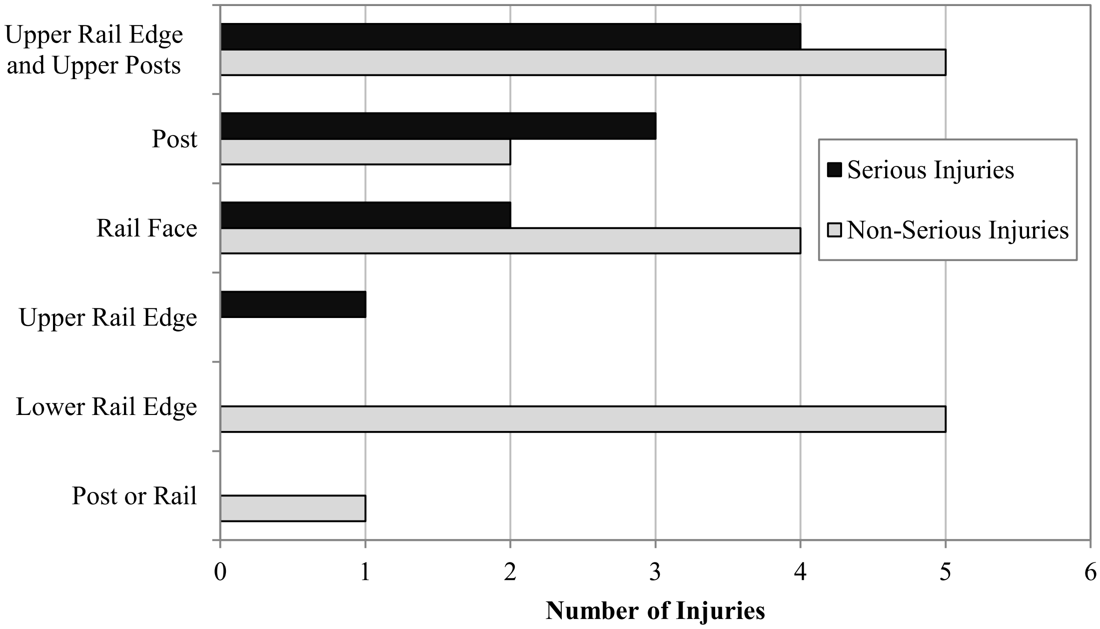


Figure 8.7. Injury Contact Sources by Guardrail Component

The posts of the cable barrier were thought to cause the majority of the injuries in Cases MC-003-D and MC-004-D. However, the contact source for eight of the fifteen injuries suffered by the rider in Case MC-004-D could not be distinguished between the cable and the post. There was evidence of skin and blood transfer onto the cable from the crash. However, there were too few cases collected thus far to begin to characterize injuries caused by cable barriers.

8.5 DISCUSSION

This chapter developed a methodology for determining injury mechanisms in motorcycle to guardrail collisions. To date, this methodology has been used to investigate 9 serious motorcycle-to-barrier crashes, involving 10 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 Chapter 7 and Bambach et al. [*53*].

Thus far, there have been too few cases to draw strong conclusions about injury causation. Nonetheless, in the cases investigated, some trends in injury sources are beginning to emerge. First, fewer serious injuries were caused by the ground in the crashes investigated, which is consistent with the findings in Chapter 4. In three of the nine cases analyzed, there was evidence of direct contact between the rider and the barrier. An analysis of the FARS dataset showed that the most harmful event was more likely to be the barrier as opposed to the ground in collisions involving contact with both the barrier and the ground. However, there are a small number of cases included in this analysis, whereas Chapter 4 was nationally representative.

In two of the crashes investigated, the guardrail prevented the rider from a potentially more hazardous collision with trees. As demonstrated in Chapter 4, collisions with trees were more likely to be fatal than collisions with guardrail. Additionally, in four of the cases, the guardrail likely prevented the rider from travelling over a cliff or embankment. Therefore, though guardrail collisions are severe, removing the barriers is not the solution to the problem, as has been suggested by some motorcycle groups.

Additionally, all components of the guardrail were associated with injury causation. However, they varied in severity. Nearly half of the injuries thought to be caused by the guardrail were postulated to be caused by the rail. However, the posts tended to cause more serious injuries in these crashes. Three of five injuries thought to be caused by guardrail post had an AIS of 3 or greater. Comparatively, only 3 of the 9 injuries likely caused by the rail had an AIS of 3 or greater.

Not all the injuries recorded were thought to be caused by contact with the barrier. Several riders suffered injuries typically incurred by blunt impact. These were generally postulated to be caused by contact with the ground. Also, there were several injuries hypothesized to be incurred from contact with the rail, which is cause to re-examine the hypothesis that barrier injuries are mainly being caused by the posts. In many of the crashes investigated, riders were believed to interact primarily with the top of the rail, 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 injuries.

Based on the cases investigated, the injury mechanisms in cable barrier and guardrail crashes are similar. Many of the injuries in the two cable barrier crashes investigated appeared to be caused by the posts. Likewise, several of the serious injuries in guardrail crashes were caused by the posts. These similarities in injury patterns may explain why the fatality risks of guardrail and cable barriers are similar, as discussed in Chapter 5.

9 SUMMARY OF RESEARCH PROGRAM AND CONTRIBUTION TO THE FIELD

9.1 RESEARCH SUMMARY

More motorcyclists are fatally injured each year in guardrail crashes than passengers of any other vehicle, while only accounting for three percent of the vehicle fleet. Since motorcyclists account for a high percentage of these fatalities, the goal of zero deaths on the road cannot be achieved without addressing the safety of motorcyclists. The roadside is designed to be forgiving to drivers of other vehicles who make a mistake and run off the road. The same notion however has not been typically applied to motorcyclists.

Detailed injury data for riders involved in crashes is crucial to understanding serious injury mechanisms in motorcycle-barrier crashes. This is also a required first step towards the design of injury countermeasures. Unfortunately, in the U.S. there is little information on serious injuries in motorcycle crashes, unlike the data available for passenger vehicle crashes in the National Automotive Sampling System Crashworthiness Data System. The factors that lead to serious or fatal injury in motorcycle barrier crashes were investigated through several retrospective studies, focusing on factors that influence injury, given that a crash has occurred. Additionally, specific injury mechanisms were identified through a prospective study of motorcycle-to-barrier crashes.

9.1.1 ANALYSIS OF FATAL MOTORCYCLE-BARRIER CRASHES IN THE U.S.

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 1999-2008 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.

Fatal motorcycle-guardrail crashes were almost exclusively single vehicle crashes, though over 50% of all fatal motorcycle crashes are multi-vehicle crashes. Additionally, about three-quarters of fatal guardrail crashes occurred on curves, whereas almost two-thirds of all fatal crashes occurred on straight roads. Lastly, people fatally injured in motorcycle-guardrail crashes tended to be younger than the population of fatally injured motorcyclists. From these findings, further analyses conducted through this research were limited to single vehicle crashes. Multi-vehicle crashes are often more complex than single vehicle crashes and injuries incurred the roadside object cannot be discerned from injuries caused by striking the other vehicle. Since single-vehicle crashes account for the majority of motorcycle-guardrail fatalities, focusing on these crashes will address the vast majority of the problem. Additionally, other studies considered tested road alignment to determine its influence on injury outcome.

9.1.2 FATALITY RISK IN ROADSIDE MOTORCYCLE CRASHES IN THE U.S.

Although this study mainly focused on barrier collisions, there are other roadside objects that 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, guardrail, and concrete barriers. The FARS data from 2004-2008 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 collisions 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 most harmful event reported in the crash, motorcycle collisions with guardrail were 7 times more likely to be fatal than collisions with the ground. Additionally, collisions with trees had a fatality risk nearly 15 times greater than the fatality risk in collisions with the ground.

As shown, trees were more likely to cause fatal injury in roadside crashes than barriers. Thus, if a motorcyclist crashes into a barrier in place to protect users from roadside trees, the barrier is likely to be reducing injury severity. Though there is no way to determine what the injury severity would be had the motorcyclist struck the tree, it is more likely that it would have been a more severe crash than if he/she struck the guardrail.

9.1.3 RISK OF SERIOUS INJURY IN BARRIER CRASHES

From the initial study on fatality risk, guardrail barrier collisions resulted in a greater risk of fatality than concrete barrier collisions. This was further investigated by analyzing barrier crashes of all injury severities in North Carolina, Texas, and New Jersey. However, the crash databases for these states did not well identify the barrier type struck by the motorcyclists. Instead, this information was incorporated by "visiting" each crash site using the "Street View" feature of Google Earth. The final dataset contained 1,000 riders involved in barrier crashes in the three states. Of these, 581 were involved in W-beam crashes, 367 were involved in concrete barrier crashes, and 52 were in cable barrier crashes.

This study showed that W-beam guardrail had significantly higher odds of serious (K+A) injury than concrete barrier. The odds of serious injury in crashes with W-beam guardrail were about 1.4 times greater than those in crashes with concrete barrier. Though injury risk varied between W-beam and concrete barrier crashes, there was no evidence to show that cable barrier poses 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 shows no elevated risk of serious injury in cable barrier crashes; further investigation is needed to demonstrate if this finding is a result of the dataset used or is representative of most crashes.

9.1.4 Relationship between Rider Post-Impact Trajectory and Injury Outcome in Barrier crashes

The national and multi-state crash studies previously described focused on the sequence of events as reported for the vehicle. However, there are likely barrier crashes where the rider and vehicle separate, and follow different trajectories. This study aimed to determine how frequently this separation occurred and how the rider post-impact trajectory influences the injury outcome. 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.

Rider trajectories in barrier collisions were determined through an analysis of police accident reports of motorcycle-barrier crashes in New Jersey from 2007-2011. There were seven different trajectories identified: upright, sliding, vaulting, ejected (same side landing), ejected (side unknown), ejected into barrier, and separated prior to barrier impact. Google Earth Street View was also used to verify the barrier type in each collision. 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).

From this analysis, the majority of riders followed a similar path to the motorcycle. Therefore, assuming the sequence of events for the motorcycle was also experienced for the motorcyclist is valid. Additionally, we found that we found that 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 rider 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. Barrier type was also found to have a significant difference in rider trajectory trends. However, while these roadway factors influenced trajectory type, they were not found to be significant in predicting serious injury crashes.

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 where striking the barrier upright. Additionally, being ejected into the barrier also increased the odds of serious injury.

9.1.5 ANALYSIS OF INJURIES FROM ROADSIDE COLLISIONS IN MARYLAND

The previous studies presented investigated general crash trends; however, these did not investigate specific injuries caused in roadside motorcycle crashes. Rather, these characterized the circumstances under which roadside crashes occurred and those that were more likely to cause injury. However, to identify the potential need for design improvements to the roadside to reduce the severity of these crashes, the injuries incurred must first be better understood.

This next study determined the type, relative frequency, and severity of injuries incurred in motorcycle roadside crashes in Maryland. The Crash Outcome Data Evaluation System (CODES) was used to analyze motorcycle crashes in Maryland from 2006-2008. 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 2 times more likely to suffer a serious injury to the thoracic region that 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 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.

9.1.6 INJURY CAUSATION IN MOTORCYCLE-BARRIER CRASHES

Motorcycle-to-barrier collisions were characterized through retrospective studies in the previous analyses. However, these studies do not directly answer the question of how motorcyclists are injured. To determine injury mechanisms in motorcycle-to-barrier crashes, Virginia Tech is conducting a program of in-depth motorcycle crash investigations with sponsorship from the National Academies of Science. 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.

To date, the methodology developed for this program has been used to investigate 9 serious motorcycle-to-barrier crashes, involving 10 motorcyclists. There were 7 crashes with W-beam guardrail, 1 crash with cable barrier, and 1 crash with both W-beam guardrail and cable barrier. In these crashes, the most common regions to suffer the most serious injury were the head, lower extremities, and thorax. The greatest number of serious injuries was suffered to the thorax. The extremities suffered the most injuries;

however these tended to be less severe than injuries in other body regions. These early findings were consistent with the trends in injuries observed in barrier crashes in Maryland.

From the in-depth investigations, similar trends in injury causation were emerging between cable barrier crashes and guardrail crashes. Many of the injuries in the two cable barrier crashes investigated were thought to be caused by the posts. Likewise, several of the serious injuries in guardrail crashes were incurred by the posts. However, there were only two cable barrier crashes investigated to date.

All components of the guardrail were associated with injury causation. Though the posts tended to cause more serious injuries in these crashes, nearly half of the injuries postulated to be caused by the guardrail were thought to be caused by the rail. This is cause to re-examine the hypothesis that barrier injuries are mainly being caused by the posts. In many of the crashes investigated, riders were believed to interact primarily with the top of the rail, 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 injuries.

In two of the crashes investigated, the guardrail prevented the rider from a potentially more hazardous collision with trees. As demonstrated in Chapter 4, collisions with trees were more likely to be fatal than collisions with guardrail. Additionally, in four of the cases, the guardrail likely prevented the rider from travelling over a cliff or embankment. Therefore, though guardrail collisions are severe, removing the barriers is not the solution to the problem, as has been suggested by some motorcycle groups.

9.2 PUBLICATION SUMMARY

The research presented in this dissertation has sought to determine the factors associated with serious injury from motorcycle to barrier crashes. The research findings have been published in several journal and conference articles. Table 9.1 presents the journal and conference articles that provided the basis for each chapter.

Table 9.1. Publication Summary

Chapter	Title	Journal (Volume, Issue)	Date
4	Fatality risk in motorcycle collisions with roadside objects in the United States	Accident Analysis and Prevention (43, 3)	2011
5	The effect of barrier type on injury severity in motorcycle to barrier collisions in North Carolina, Texas and New Jersey	Transportation Research Record (2262)	2011
6	Relationship between Rider Trajectory and Injury Outcome in Motorcycle-to-Barrier Crashes	Transportation Research Record (accepted)	2013
7	The Characteristics of Injuries in Motorcycle to Barrier Collisions in Maryland	Transportation Research Record (2281)	2012

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APPENDIX A. DATA ELEMENTS COLLECTED FOR IN-DEPTH INVESTIGATIONS

As described in Chapter 8, a list of data elements to collect for the in-depth investigations were developed based on previous studies that focused on off-road crashes and motorcycle crashes. Thanks to Dr. Doug Gabauer for his help in developing the list of data elements. These were divided in 6 different tables in a relational database. The main tables of the database are listed in Table A.1.

Table A.1 Tables in In-Depth Motorcycle Investigation Database

Table	Description
Crash	General description of crash
Motorcycle	Information about the motorcycle
Barrier	Information about each barrier struck during the crash
Event	List of events
Person	Description of case occupant
Injury	Information about each injury and injury contact sources

The database has four levels related through three variables: Crash ID, Vehicle Number, and Person ID. Additionally, the Event Table is related to the Barrier Table though the Barrier Number. These relationships are depicted in Figure A.1.

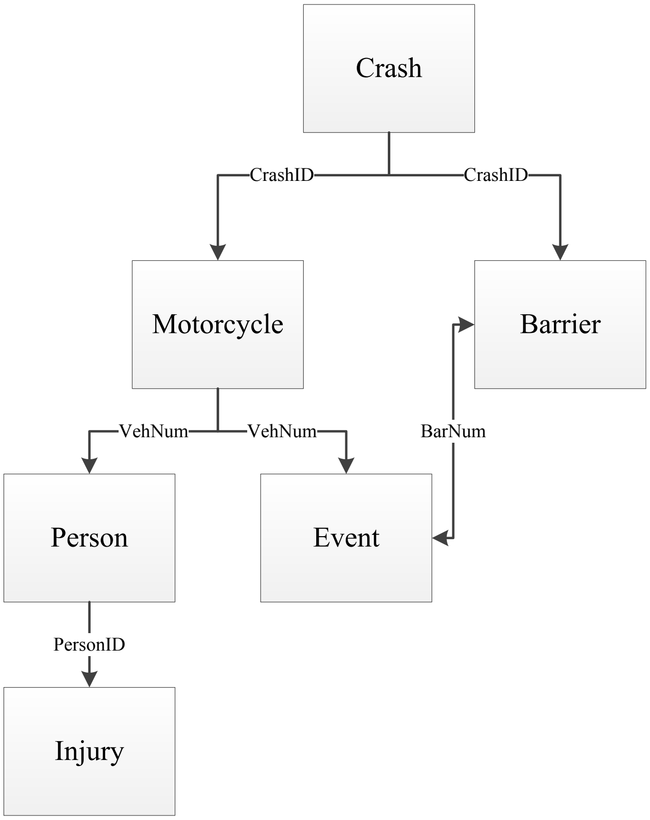

Figure A.1. Hierarchy of In-depth Motorcycle Database

The Crash table is the highest level table for each case. There is one entry per case in this table, and the list of data elements in the table is given in Table A.2. These data elements were collected from scene photographs, crash investigation forms, and police reports.

Table A.2. Data Fields in Crash Table

Field	Describes	Field	Describes
Crash ID Number	General Crash	Edge of Pavement to Barrier (m)	Roadside
Date	General Crash	Lateral Slope Offset (m)	Roadside
Time	General Crash	Rate of Slope	Roadside
Road	General Crash	Slope width (ft)	Roadside
County	General Crash	Object at end of last slope	Roadside
State	General Crash	Type of Area (Same Side)	Roadway
Day of Week	General Crash	Type of Area (Opposite Side)	Roadway
Latitude	General Crash	Illumination	Roadway
Longitude	General Crash	Intersection Type	Roadway

Table A.2 (continued)

Field	Describes	Field	Describes
Collision With	General Crash	Dir of Traffic Flow, Lane adj to MC, Right	Roadway
Number of Other Vehicles Involved	General Crash	Direction of Traffic Flow, Lane adjacent to MC, Left	Roadway
Number Pedestrians Involved	General Crash	Lane dividers, Right	Roadway
Fatal Injuries	General Crash	Lane dividers, Left	Roadway
Crash Configuration	General Crash	Traffic way	Roadway
Animal Involvement	General Crash	Posted Speed Limit (mph)	Roadway
Animal Struck	General Crash	Number of Through Lanes	Roadway
Pedestrian Involvement	General Crash	Lane Travelled	Roadway
Location of Pedestrian	General Crash	Lane Width (m)	Roadway
Stationary View Obstructions	General Crash	Roadway Width	Roadway
Temperature (deg F)	General Crash	Roadway Surface	Roadway
Weather Condition	General Crash	Roadway Defects	Roadway
Wind Condition	General Crash	Roadway Condition	Roadway
Wind direction	General Crash	Vertical Alignment	Roadway
Number of MC Involved	General Crash	Horizontal Alignment	Roadway
Number of People Involved	General Crash	Vertical Traffic Controls	Roadway
Roadside Environment, Right	Roadside	Vertical Traffic Control Functioning	Roadway
Roadside Environment, Left	Roadside	Vertical Traffic Control Visible	Roadway
Roadside Obstacles, Right	Roadside	Vertical Traffic Control Violated	Roadway
Roadside Obstacles, Left	Roadside	Traffic Condition	Roadway
Rumble Strip Presence	Roadside	Cause of limited visibility	Roadway
Curb Presence	Roadside	Radius of Curve - Point of Departure (ft)	Roadway
Curb Height (cm)	Roadside	Radius of Curve - Length of Chord (ft)	Roadway
Shoulder width (m)	Roadside	Radius of Curve - Middle Ordinate (ft)	Roadway

The next level of the database incorporates the motorcycle and the barrier. Table A.3 gives all the data fields collected that are associated with the motorcycle. This is related to the crash level by the Crash ID Number. There should only be one motorcycle entry per case since the study focuses on single vehicle crashes.

Table A.3. Data Fields in Motorcycle Table

Field	Describes	Field	Describes
Crash ID Number	Main	Tire Size (Front and Rear)	Wheels
Vehicle Number	Main	Tire Manufacturer (Front and Rear)	Wheels
Manufacturer	Main	Rim Size (Front and Rear)	Wheels
Model	Main	Rim Manufacturer (Front and Rear)	Wheels
Motorcycle Year	Main	Tread Type (Front and Rear)	Wheels
Style	Main	Tread Depth (mm) (Front and Rear)	Wheels
Number of Passengers	Main	Tire Balding (Front and Rear)	Wheels
Weight (lb)	Main	Inflation Pressure (kPa) (Front and Rear)	Wheels
VIN	Main	Braking Evidence (Front and Rear)	Wheels
Odometer Reading (mi)	Main	Front Wheel Displacement	Wheels
Registered Owner Category	Main	Pre-Crash Motion, Prior	Pre-Crash
Pedals	Body	Travel Speed (mph)	Pre-Crash
Motorcycle Modifications	Body	Travel Speed CI (mph)	Pre-Crash
Modification Description	Body	Line of sight to other vehicle	Pre-Crash
Color	Body	Pre-Crash Motion, After	Pre-Crash
Displacement (cc)	Body	Collision Avoidance 1	Pre-Crash
Number of Cylinders	Body	Collision Avoidance 2	Pre-Crash
Mechanical Problem Symptom	Body	Collision Avoidance 3	Pre-Crash
Mechanical Problem Source	Body	Collision Avoidance 4	Pre-Crash
Reduction in Wheelbase	Body	Swerve	Pre-Crash
Steering Stem Adjustment	Body	First Collision Contact	Crash
Stability Control Presence	Body	Impact Speed (mph)	Crash
Left Handlebar Height (cm)	Body	Impact Speed CI (mph)	Crash
Right Handlebar Height (cm)	Body	Roll attitude angle (deg)	Crash
Handlebar Length (cm)	Body	Roll attitude angle CI (deg)	Crash
Ride Height (cm)	Body	Barrier Impact	Crash
Braking Skid Marks	Evidence	Sideslip angle (deg)	Crash
Length of Braking Skid Mark, Front Tire (m)	Evidence	Sideslip angle CI (deg)	Crash
Length of Braking Skid Mark, Rear Tire (m)	Evidence	Relative heading angle (deg)	Crash
Braking Skid Mark Evidence	Evidence	Rollover Type	Crash
Tire Striation Evidence	Evidence	Time from precipitating event (s)	Crash
Accelerating Evidence, Rear Tire	Evidence	Time from precipitating event CI (s)	Crash
Counter Steering	Evidence	Post-Crash Motion	Crash
Cornering Skid Mark Evidence	Evidence	Distance from POI to POR (m)	Crash
Cornering Tire Striation Evidence	Evidence	Post-crash scrape marks	Crash
Pre-Crash Scrape Marks	Evidence		

The Barrier Table is on the same level of the database as the motorcycle table. There can be multiple entries per case in this table (i.e. occupant strikes W-beam and cable barriers). This table is related to the Event Table for events involving the respective barrier. The list of data elements collected for the barriers is given in Table A.4. Variables vary slightly by barrier type. However, due to the relatively small number of cases, these were incorporated into the same table.

Table A.4. Data Fields in Barrier Table

Field	Barrier Describing[1]	Field	Barrier Describing[1]
Crash ID Number	--	Crash Cushion Location	Crash Cushion
Barrier Number	--	Lateral Offset, Crash Cushion (m)	Crash Cushion
Barrier Type	All	Crash Cushion Length	Crash Cushion
Barrier Location (Roadside/Median)	All	CC Width at Nose (cm)	Crash Cushion
Barrier Description	All	CC Width at Base (cm)	Crash Cushion
Work Zone Area	All	Deformed CC Length (cm)	Crash Cushion
Lateral Offset (m)	All	CC Impact Location	Crash Cushion
Damage Length to Barrier (cm)	All	Rail Rupture	Guardrail
Contact Length (cm)	All	Distance to rail rupture (cm)	Guardrail
Deflection extent 1 (cm)	All	Blockout	Guardrail
Deflection extent 2 (cm)	All	Blockout Width (cm)	Guardrail
Deflection extent 3 (cm)	All	Blockout Depth (cm)	Guardrail
Deflection extent 4 (cm)	All	Post Type	Metal
Deflection extent 5 (cm)	All	Post width (cm)	Metal
Deflection extent 6 (cm)	All	Post depth (cm)	Metal
Maximum deflection (cm)	All	Post Spacing (m)	Metal
Delineation Markings	All	Vertical Spacing	Metal
Barrier Height (cm)	All	Rail 1 Height (cm)	Metal
Impact Location (m)	All	Rail 1 Depth (cm)	Metal
Initial Point of Contact (m)	All	Rail 2 Height (cm)	Metal
Presence of Curb	All	Rail 2 Depth (cm)	Metal
Curb Height (cm)	All	Rail 3 Height (cm)	Metal
Curb Width (cm)	All	Rail 3 Depth (cm)	Metal
Width of Shielded Hazard (cm)	All	Rail 4 Height (cm)	Metal
Number Bridge Rails	Bridge Rail	Rail 4 Depth (cm)	Metal
Number of Cables	Cable		
Concrete Barrier Shape	Concrete		
Concrete Barrier Section Length (m)	Concrete		
Barrier Width, Top (cm)	Concrete		
Temporary Barrier	Concrete		

[1] Metal Barrier refers to Guardrails, Bridge Rails, and Cable Barriers

The Person Table is a level below the Motorcycle Table and relates to the motorcycle table through the Crash ID and Vehicle Number. There may be multiple people per motorcycle (i.e. rider and passenger). The fields give a general description about the person, as well as their experience and typical use of safety equipment. Data fields are listed in Table A.5.

Table A.5. Data Fields in Person Table

Field	Describes	Field	Describes
Crash ID Number	--	Motorcycle Experience (yrs)	Experience
Vehicle ID Number	--	Crash Involved Motorcycle Experience (yr)	Experience
Person ID Number	--	Days per Year Riding	Experience
Age	General	Distance Motorcycle is Ridden per year (km)	Experience
Gender	General	Motorcycle Training Completed	Experience
Eye Correction Required	General	Motorcycle Training Type	Experience
Eye Correction Worn at Time of Crash	General	Training Month	Experience
Education Level	General	Training Year	Experience
Occupation	General	Motorcycle Recreation Usage	Experience
Position on Motorcycle	General	Motorcycle Basic Transportation Usage	Experience
Sitting Height (cm)	General	Experience with Passenger	Experience
Buttock-Knee Length (cm)	General	Experience with cargo/luggage	Experience
Sitting Knee Height (cm)	General	Alcohol/drug use prior to crash	Impairment
Motorcycle Moving Violation Convictions (5yr)	General	Alcohol/drug impairment	Impairment
Other Vehicle Moving Violation Convictions (5yr)	General	Permanent physiologic impairment	Impairment
Attire at time of Crash	Attire	Transient physiologic impairment	Impairment
Outer Wear at time of Crash	Attire	Helmet Used	Safety
Specialty Clothing	Attire	Number of other PPE Used	Safety
Footwear	Attire	Other PPE Used	Safety
Post-crash motion	Dynamics	Percent Helmet Usage	Safety
Distance from POI to POR (m)	Dynamics	Percent Other PPE Usage	Safety
Driving Experience (All Vehicles, years)	Experience	Attention to driving task	Safety
Driving Experience (All Vehicles) Units	Experience		

The Event Table is on the same level as the Person Table. There is one entry for each event that occurs during the crash. Specific details about injury mechanisms are incorporated on the Injury Table. These will likely be different than each event since these are specific instances during the crash. There is one entry on the Injury Table for each AIS-coded injury. Associated with the injury is the injury contact source (ICS) and its associated confidence level. All variables included in the Injury Table are shown in Table A.6.

Table A.6. Data Fields in Injury Table

Field	Field
Crash ID Number	AIS
Vehicle Number	Aspect
Person ID Number	Lesion
Injury Number	Source of Injury Data
Body Region	Injury Contact Source 1
Type of Anatomic Structure	Injury Contact Source 1 Confidence
Specific Anatomic Structure	Injury Contact Source 2
Injury Level	Injury Contact Source 2 Confidence

APPENDIX B. DETAILED INJURY INFORMATION FROM IN-DEPTH CRASH INVESTIGATIONS

Injury information and contact sources for three cases were described in Chapter 8. This appendix includes a brief description of the other seven cases and lists all injuries for each case. Additionally, a diagram showing the internal injuries is included for each rider. Thank you to the whole CIB group who helped in determining the injury mechanisms and crash scenarios described here and in Chapter 8.

CASE MC-001-D

The first case investigated involved a male driver and female passenger colliding with a W-beam guardrail. The 5'8" driver was 58 years old and weighed 190 lbs. He was wearing a DOT-approved half helmet at the time of the crash. As shown in Figure B.1, the majority of his serious injuries were in his upper body. The most serious injury he suffered had an AIS of 3, and his ISS was 27.

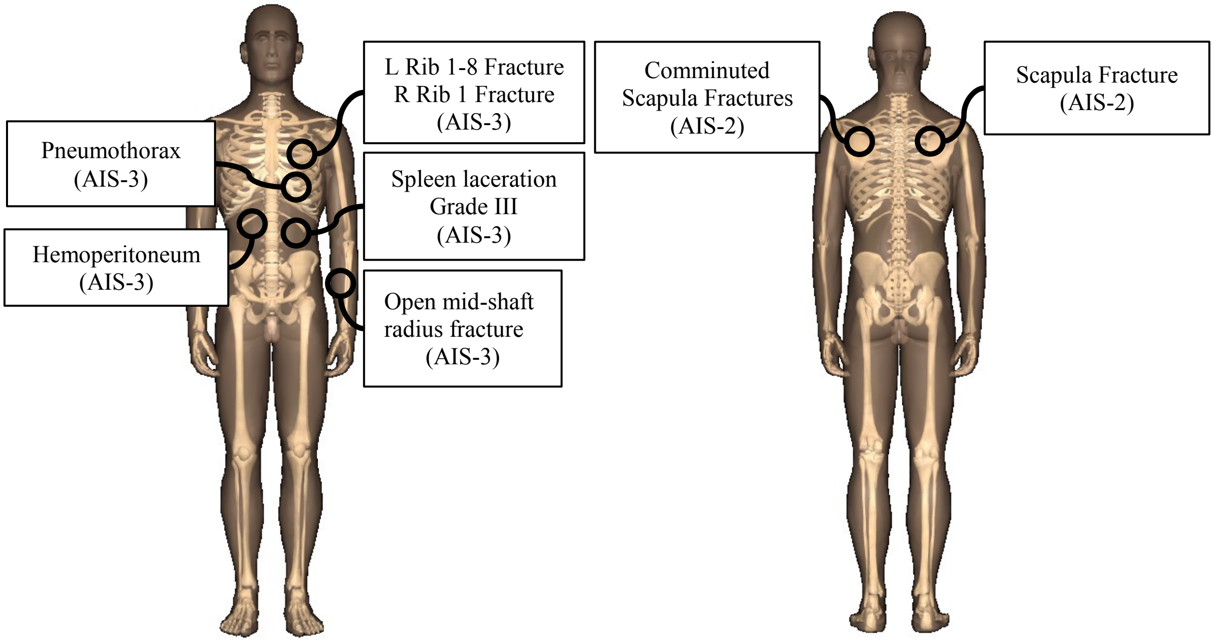

Figure B.1. Internal Occupant Injuries, MC-001-D

The majority of his thoracic injuries were postulated to be caused by contact with the ground (Table B.1). Also, the injuries to his right shoulder and scapula were likely caused by his shoulder hitting the guardrail.

Table B.1. Comprehensive Injury List for Case MC-001-D

Injury	AIS-90	Cause of Injury	Evidence	Certainty
Left open mid-shaft radius fracture	752804.3	Impact to arm – handlebar/ guardrail?	Crash scenario	Possible
Left rib 1-8 fractures, R 3rd rib fracture	450230.3	Torso loads ground	Crash scenario	Possible
Spleen laceration Grade III (w/ Perisplenic hematoma)	544224.3	Torso loads ground	Crash scenario	Possible
Left sided pneumothorax	442202.3	Torso loads ground	Crash scenario	Possible
Hemoperitoneum	543800.3	Shoulder loads guardrail	Crash scenario	Possible
Right scapula fracture – medial aspect	753000.2	Torso loads ground	Crash scenario	Possible
Left comminuted scapula fractures	753000.2	Shoulder loads guardrail	Crash scenario	Possible
Right shoulder abrasion	710202.1	Torso loads handlebar	Crash scenario	Possible
Right thoracic contusion	410402.1	Shoulder loads guardrail	Crash scenario	Possible
Right shoulder contusion	710402.1	Unknown	Unknown	Unknown
Left lower leg (shin) abrasion	810202.1	Unknown	Unknown	Unknown

CASE MC-001-P

The passenger in Case MC-001 was a 61 year old female. She was 5’2” and weighed 155 lbs. Like the driver, she was also wearing a DOT-approved half-helmet, only her helmet also had a face mask. As shown Figure B.2, her most serious injuries (AIS-3) were suffered to her spine and head.

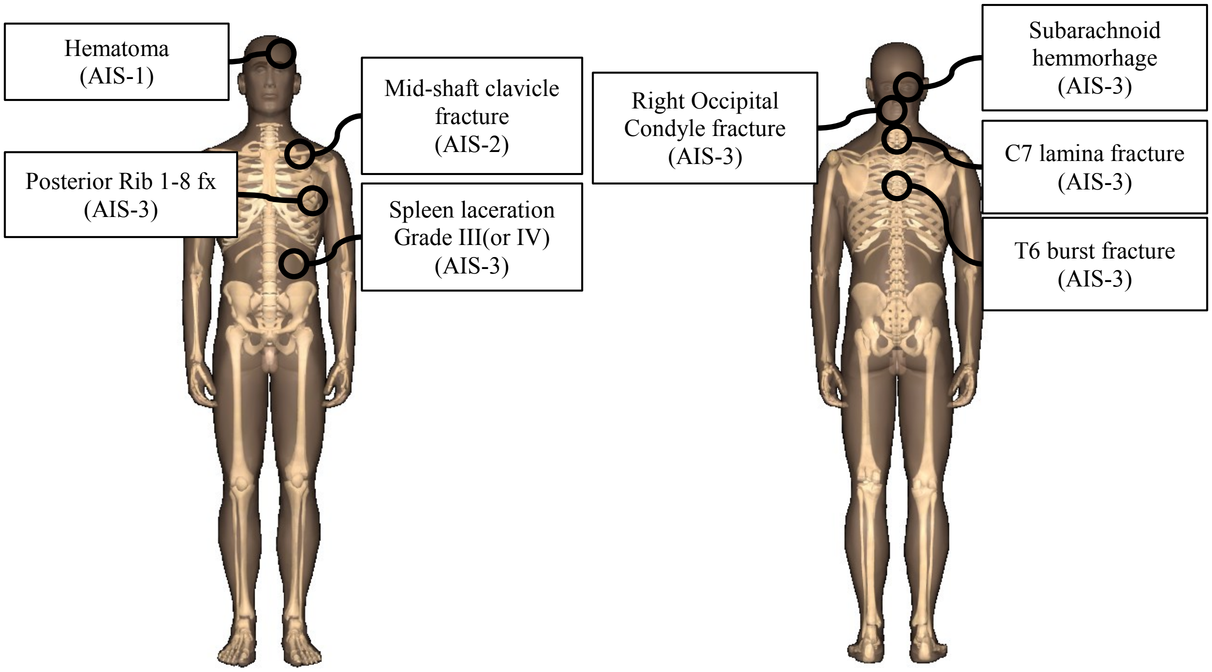

Figure B.2. Internal Occupant Injuries, MC-001-P

As described in Table B.2, the majority of her injuries were likely caused by contact with the ground. It was not likely that any of her injuries were caused by contacting the guardrail.

Table B.2. Comprehensive Injury List for Case MC-001-P

Injury	AIS-90	Cause of Injury	Evidence	Certainty
C7 lamina fracture	650224. 3	Head to ground	Helmet scratch w/ gravel	Probable
Right occipital condyle fracture	150202.3	Head to ground	Helmet scratch w/ gravel	Probable
T6 spinal burst fracture – 50% height loss	650434.3	Head to ground	Helmet scratch w/ gravel	Probable
Subarachnoid hemorrhage	140684.3	Head to ground	Helmet scratch w/ gravel	Probable
Left clavicle fracture – mid-shaft, comminuted	752200.2	Torso to ground	Helmet scratch w/ gravel	Possible
Left posterior rib fracture 4-8	450230.3	Torso to ground	Helmet scratch w/ gravel	Possible
Grade III (or IV?) spleen laceration	541814.3	Torso to ground	Helmet scratch w/ gravel	Possible
Left scalp hematoma	110402.1	Head to ground	Helmet scratch w/ gravel	Probable
Left inferior facial abrasions	210202.1	Head to ground	Helmet scratch w/ gravel	Probable
Left shoulder contusion	710402.1	Ecchemosis from clavicle fracture	Caused by other injury	Caused by other injury
Left hand abrasions	710202.1	Hand to ground	Gravel road	Possible
Left heel contusion	810402.1	Unknown	Unknown	Unknown

CASE MC-002-D

The case occupant was a 58 year old male. He was 5'6" and weighed 180 lbs. At the time of the crash, the rider was wearing a DOT approved half-helmet. His ISS was 17, with an MAIS of 3. It was reported that he had a possible heart attack prior to the crash.

The motorcycle was traveling in a northwesterly direction within an interchange area between two major state highways. The multi-lane interchange area was bordered to the north by a W-beam guardrail, and curved left for westbound traffic. Curve warning signs were present at the site. It was daylight; with no adverse weather conditions as the roads were dry. As the motorcycle approached the merge area within the westbound segment of the interchange, the driver allowed the motorcycle to continue in a forward tracking mode towards the right (north) shoulder. As shown in Figure B.3, the motorcycle departed the north shoulder, as the right side surface subsequently impacted the W-beam guardrail. The impact resulted in moderate damage. The motorcycle rebounded off the guardrail in a clockwise rotation, and re-entered the westbound (outboard) travel lane. At this point, the left side surface of the motorcycle struck the ground, resulting in minor damage. Following spinout, the motorcycle came to rest in the westbound travel lanes (on its left side), facing northeast.

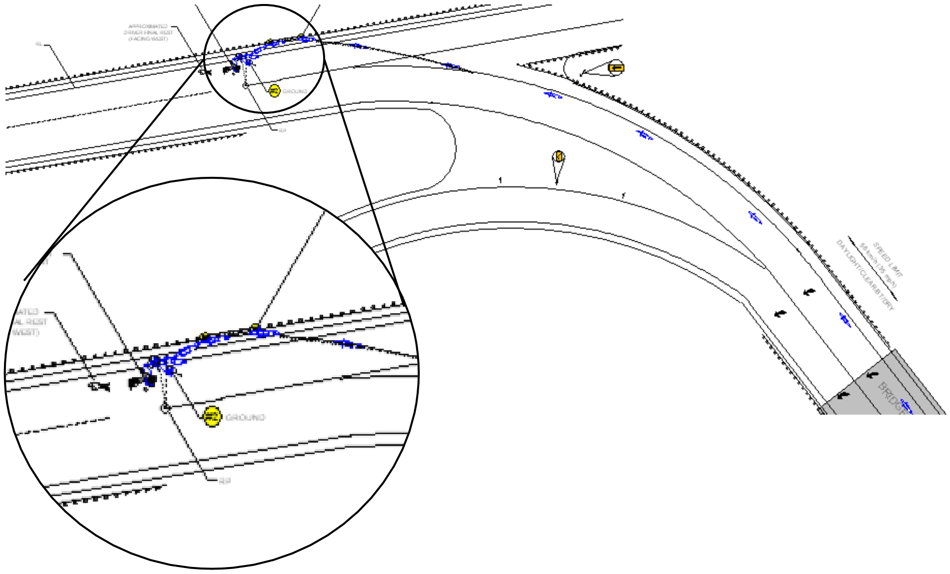

Figure B.3. Crash scenario for Case MC-002

Figure B.4 is a comprehensive list of the case occupant's internal injuries; he also suffered minor external injuries as listed in Table B.3. As shown, he mainly suffered injuries to his torso and lower extremities.

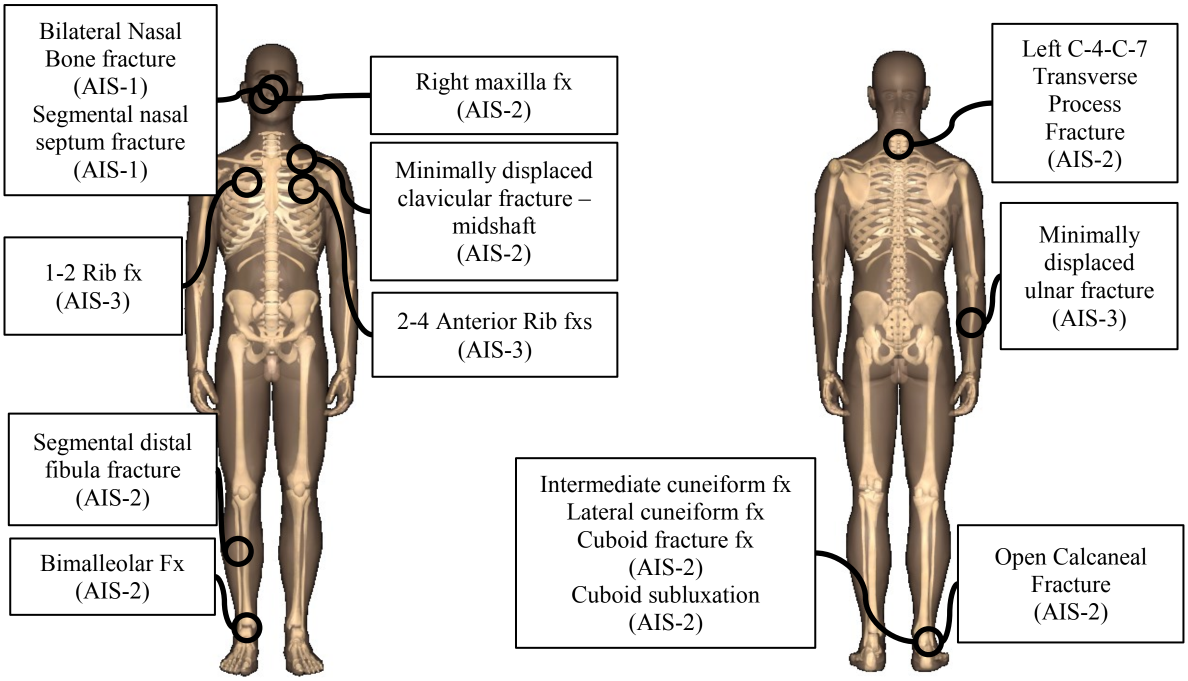

Figure B.4. Occupant Injuries, MC-002-D

Table B.3. Comprehensive Injury List for Case MC-002-D

Injury	AIS-90	ICS	ICS Evidence	Certainty
Left C-4 - C-7 Transverse Process Fx	650220.2	Possible relation to face contact	- No road rash -No damage to helmet - Nose injuries appear to be from blunt impact	Possible
Right Open Calcaneal Fx	851400.2	Contact w/lower edge of rail	- Damage to exhaust/brake pedal - Height relative to bottom edge of rail	Probable
Right intermediate cuneiform, lateral cuneiform and cuboid fxs	852000.2			
Right medial cuboid subluxation consistent w/ligamentous injury	840402.2			

Table B.3 (continued).

Injury	AIS-90	ICS	ICS Evidence	Certainty
Right minimally displaced ulnar fx	753204.3	Interaction w/ upper edge of rail	- Handlebar damage - Potential rubber transfer to rail	Possible
Left Neck Laceration	310602.1	Unknown	Unknown	--
Minimally displace Left calvicular fx - midshaft	752200.2	Collision with ground/ tumbling	- Crash scenario - Bruising on left shoulder	Probable
Right 1-2 Rib Fx and Left anterior 2-4 Rib Fxs	450230.3	Collision with ground/ tumbling	- Crash scenario	Possible
Bilateral Nasal Bone fx	251000.1	Contact with handlebar/ instruments	- Injuries/ helmet damage do not suggest facial contact with ground - Appears to be blunt impact injury	Possible
Segmental nasal septum fx	251000.1			
Right maxilla fx	250800.2			
Large soft tissue hematoma – base of the left neck w/displacement of thyroid and airway rightward.	310402.1	Unknown	Unknown	--
Segmental distal fibula fx on Right	851606.2	Contact w/lower edge of rail	- Damage to exhaust/brake pedal - Height relative to bottom edge of rail	Probable
Right bimalleolar fx	851612.2			

CASE MC-003-D

The case occupant was a 5’10”, 49 year old male who weighed 210 lbs. At the time of the crash, the rider was wearing a DOT approved half-helmet. His ISS was 8, with an MAIS of 2.

The motorcycle was travelling southbound on the inboard travel lane of a four-lane (limited access) interstate highway, on approach to a bridge overpass. The asphalt surfaced roadway sloped uphill for southbound traffic, and was divided by a grass median. Within the median, a three cable guardrail system provided a positive barrier between the travel lanes to the north and south of the bridge overpass.

The bridge supports were bordered by W-beam guardrails. There were no traffic controls present. It was dark and there were no adverse weather conditions. The road was not lit, and the surface was dry.

As the motorcycle approached the bridge, the driver allowed the motorcycle to enter the left (east) shoulder in a forward tracking mode (Figure B.5). The left side surface of the motorcycle subsequently impacted ("sideswiped") the W-beam guardrail, resulting in minor damage (event 1). Following collision with the guardrail, Vehicle 1 was reported by police to have traveled south on the shoulder an additional 68 meters (220 feet) prior to overturning. The motorcycle entered the center grass median, as the front wheel/tire struck a cable barrier (event 2). This impact resulted in moderate damage to the front wheel and fender. Engagement with the cable guardrail (front wheel under rides center cable strand) re-directed the motorcycle in a counterclockwise rotation as the right side surface impacted the ground (event 3). This final impact resulted in moderate damage to the right side frame and rear fender. During spinout, the motorcycle flipped onto its left side where it came to final rest (in the center median) south of the overpass, facing southwest.

It was unknown at which point during the crash sequence the driver was ejected from the motorcycle; however, evidence suggested it probably occurred following event 2 (over the right side surface and prior to event 3). The police reported that the driver of Vehicle 1 came to rest north of, and adjacent to, the motorcycle.

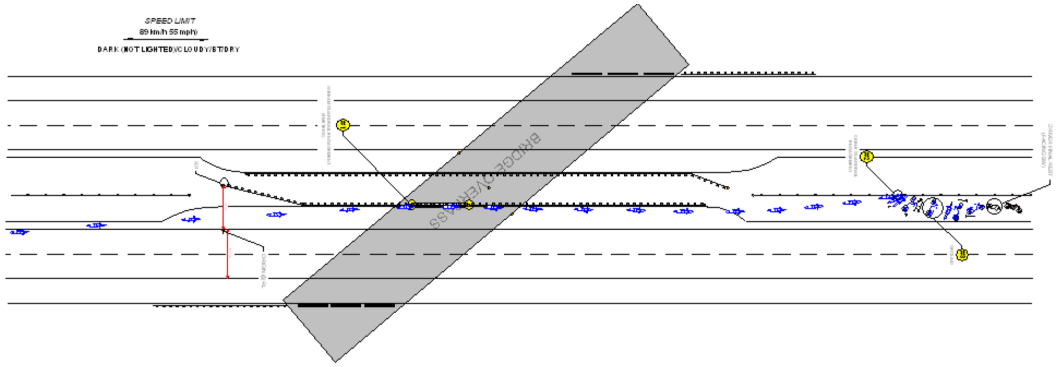

Figure B.5. Crash scenario for Case MC-003

As shown in Figure B.6, he mainly suffered injuries to his lower extremities. Table B.4 is a comprehensive depiction of the case occupant's injuries.

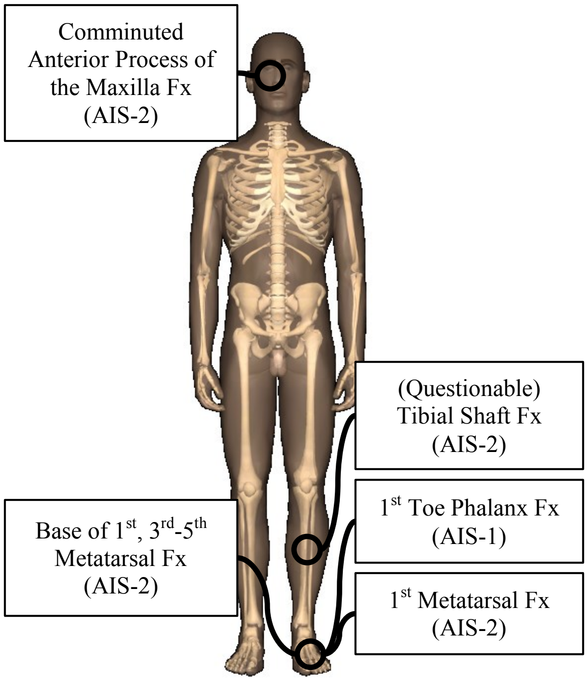

Figure B.6. Occupant Injuries, MC-003-D

As shown in Table B.4, the injuries to the lower extremities were likely caused by contact with the cable barrier post, and the head injury was likely caused by collision with the ground.

Table B.4. Comprehensive Injury List for Case MC-003-D

Injury	AIS-90	Cause of Injury	ICS Evidence	Certainty
L 1st Metatarsal fracture	852200.2	Collision with cable barrier post	- Likely position on motorcycle - Concentration of fractures on inside of foot	Probable
L 1st Toe Phalanx fracture	853602.1			
Base of L 1st, 3rd, 4th, and 5th Metatarsal fracture	852200.2			
Right comminuted anterior process of the maxilla fracture	250800.2	Collision with ground	Helmet scrapes, Road rash on face, Dirt in/on bike	Probable

CASE MC-004-D

Case MC-004-D involved a 31 year old male, who was wearing a DOT-approved half-helmet at the time of the crash. He was 5’4” and weighed 130 lbs. His ISS was 45, and his MAIS was 5. He was not fatally injured in this crash.

The motorcycle was travelling westbound on the inboard travel lane of a multi-lane (limited access) state highway on a clear day with no adverse weather conditions. The asphalt surfaced (level) roadway curved right for westbound traffic, and was divided by a grass median. Within the median, a three cable guardrail system provided a positive barrier between the east/west travel lanes. An on-ramp for westbound vehicles was located just to the east of the crash site. There were no traffic controls present. The driver of the motorcycle approached the (westbound) on-ramp and reportedly observed a non-contact vehicle abruptly merge from the right, across his path of travel. In anticipation of the impending harmful event, the driver of the motorcycle steered left and braked in avoidance.

As shown in Figure B.7, the motorcycle subsequently departed the left (south) pavement edge and entered the center median in a slight clockwise rotation (i.e. rear wheel tracking outside of front wheel). The back wheel/tire of the motorcycle initially impacted a support post for the cable guardrail, resulting in moderate damage. The left side surface (seat and frame) engaged the three horizontal cables. This continuous interaction with the guardrail re-directed the motorcycle into a counterclockwise rotation. At this point, the motorcycle flipped as the right side surface impacted the ground. The motorcycle came to final rest in close proximity to the struck guardrail (on its right side) facing northwest.

At impact with the cable guardrail, the helmeted 31 year old male driver was ejected off the left side of the motorcycle. The driver struck the top cable line, as evidenced by the blood, fabric transfers, and skin tissue identified within the strands of this component. The driver of Vehicle 1 was reported by relatives to have come to rest on the north side adjacent to the struck portion of the guardrail. Following the crash, the driver of Vehicle 1 was transported (via Air Care) to a nearby trauma center and admitted for treatment of serious injuries. Vehicle 1 was reported by police to have been towed from the crash site due to disabling damage.

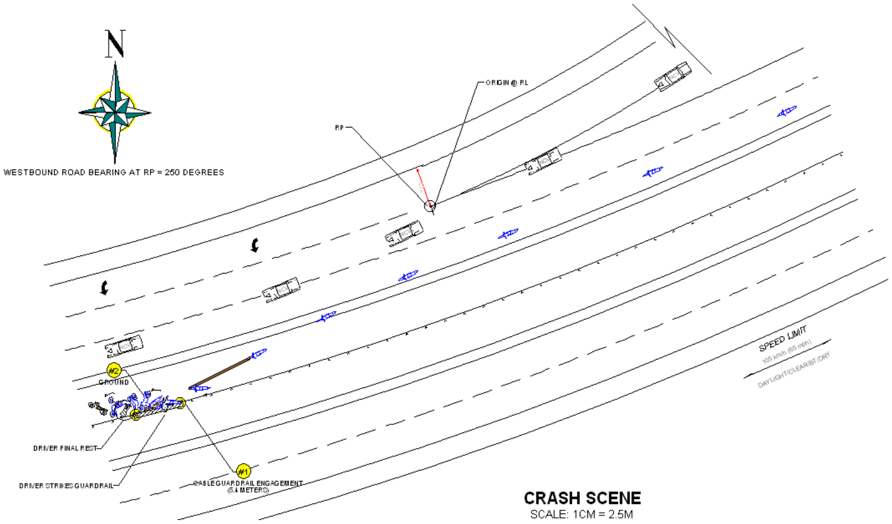

Figure B.7. Crash scenario for Case MC-005

Figure B.8 is a comprehensive depiction of his internal injuries. As described in Table B.5, he also suffered multiple contusions and lacerations.

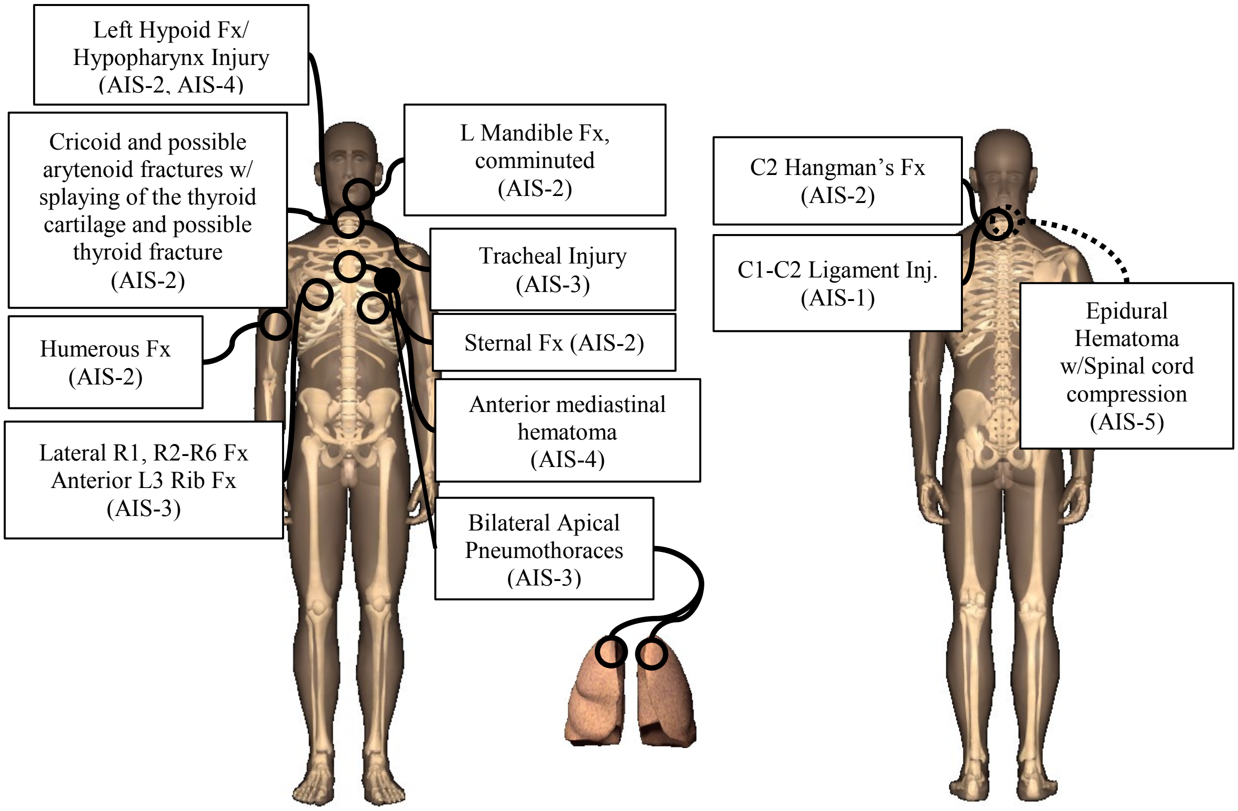

Figure B.8. Internal Occupant Injuries, MC-004-D

As shown in Table B.5, the contact source could not be determined for many of his injuries due to the chaotic nature of the crash. Based on the available evidence, contact sources for several of his main injuries were postulated. However, many of the external injuries could not be determined as there were too many possibilities for causation in the hypothesized crash scenario.

Table B.5. Comprehensive Injury List for Case MC-004-D

Body Region	Injury	AIS-90	ICS	ICS Evidence	Certainty
Head	L Mandible Fx, comminuted	250610.2			
Neck	Spinal Epidural Hematoma W/ Spinal Cord Compression	140422.5	Contact with cable and post	Pattern of injuries; patient memory(?); blood and skin tissue transfers on cable near post	Possible
	C-2 Hangman's Fx	650230.2			
	C-1—C-2 Ligament Injury	640284.1			
	Tracheal Injury	422699.3			
	Left Hyoid fracture/ Hypopharynx Injury	350200.2 340608.4			
	Cricoid and possibly arytenoid fractures with splaying of the thyroid cartilage and possible thyroid fracture	341404.2			
	Severe neck lacerations	310606.3			
Chest	Bilateral Apical Pneumothoraces	442020.3	Contact with post	Pattern of injuries; patient memory(?); blood and skin tissue transfers on cable near post	Possible
	Sternal Fx	450804.2			
	Bilateral Rib Fxs: Right lateral 1st rib, 2nd thru 6th rib fxs, Left anterior 3rd rib fx	450230.3			
	Anterior mediastinal hematoma	440206.4			
	R chest contusion	410402.1			
	Chest laceration	410602.1			
Abdomen	Abdominal laceration on R	510602.1	Unknown	Unknown	Unknown
	R hip contusion	510402.1			
	R flank contusion	510402.1			
Right Arm	R Humerus Fx	752602.2	Contact with Post	Nature of injury, crash kinematics	Possible
Left Arm	L upper arm contusion	710402.1	Unknown	Unknown	Unknown
	L forearm laceration	710602.1			
	L shoulder abrasion	710202.1			
Right Leg	R inner thigh contusion	810402.4	Unknown	Unknown	Unknown
	R knee contusion	810402.1			
	R knee lacerations	810602.1			
Right Foot	R ankle contusion	810402.1	Unknown	Unknown	Unknown
Left Leg	L upper leg abrasions	810202.1	Unknown	Unknown	Unknown

CASE MC-005-D

This case involved a 51 year old female, who was wearing a DOT-approved three-quarter helmet at the time of the crash. She was 5’0” and weighed 202 lbs. Her ISS was 9 with an MAIS of 3.

The rider was initially stopped and facing north in a business parking lot. The gravel (level) parking area bordered a connecting two-lane east/west (asphalt/level) state highway to the south. There were no traffic controls present at the site. It was daylight; with no adverse weather conditions as the road was dry. The driver of the motorcycle proceeded onto the east/west connector in an attempt to turn left (west). As shown in Figure B.9, Vehicle 1 traversed the travel lanes in a northwesterly direction, towards the north pavement edge. The motorcycle departed the north shoulder, as the right side surface impacted a W-beam guardrail. The impact resulted in minor damage to the motorcycle. Vehicle 1 was re-directed counterclockwise, and came to final rest in close proximity to the point of impact (semi-upright/leaned against the guardrail) facing west.

At impact, the rider’s right lower extremity struck the guardrail. This contact was evidenced by the fabric transfers identified on the face of the guardrail. The driver was subsequently ejected over the right side surface of the motorcycle, vaulted over the guardrail, coming to rest in an adjacent wooded area facing northwest. The driver reported to the investigator that the motorcycle was difficult to steer during her pre-impact approach, resulting in a limited turn radius. The driver also stated that no trees were struck during her post-impact kinematic trajectory.

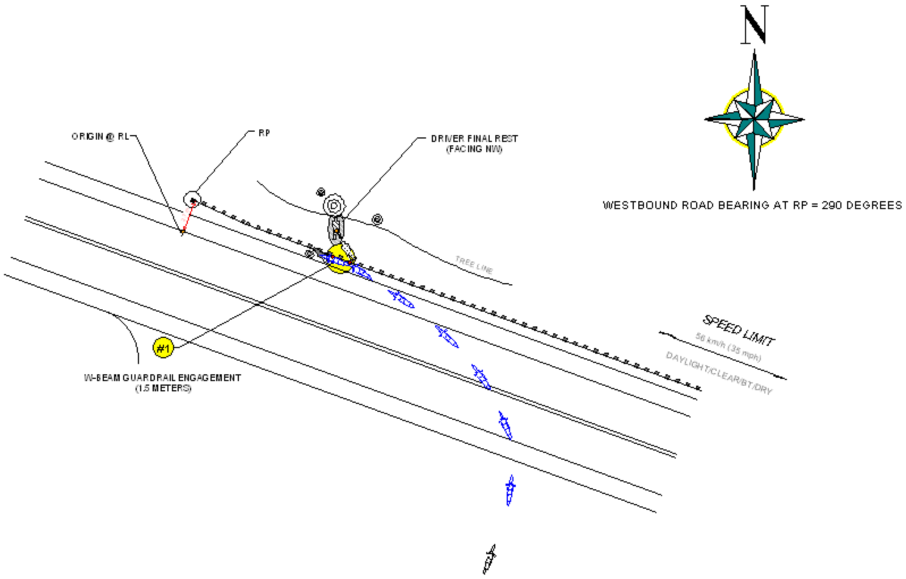

Figure B.9. Crash scenario for Case MC-005

Figure B.10 is a comprehensive depiction of her internal injuries. She also suffered abrasion and lacerations on her left knee and lower leg/ankle, respectively.

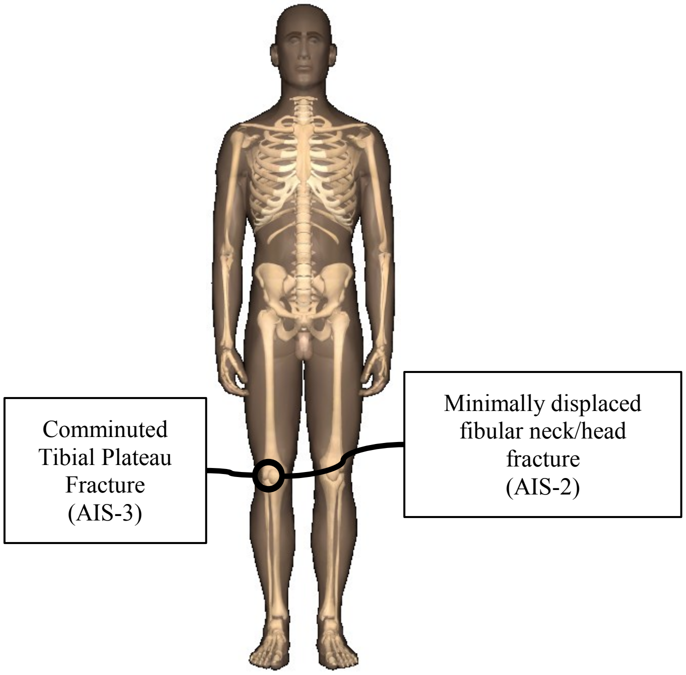

Figure B.10. Internal Occupant Injuries, MC-005-D

As described in Table B.6, her leg was likely pinned between the guardrail and the motorcycle as she vaulted over the barrier, causing these fractures.

Table B.6. Comprehensive Injury List for Case MC-005-D

Injury	AIS-90	Cause of Injury	Evidence	Certainty
Highly comminuted R tibial plateau fracture (extension to articular surface), w extensive fragmentation of lateral and medial plateaus, with 6 mm lateral tibial plateau depression	853422.3	Lateral femural condyle driven into tibial head. (Lower leg constrained b/t motorcycle and rail as pt. fell over rail)	- Bike leaned to right (fuel tank dent) - Lateral tibia plateau sheared -Occupant kinematics	Probable
Minimally displaced R fibular neck/head fracture	851606.2			
L knee abrasion	810202.1	Ground after ejection	Crash scenario, environment, final resting position	Probable
L lower leg and ankle lacerations	810602.1	Ground after ejection	Crash scenario, environment, final resting position	Probable

CASE MC-006-D

The case occupant was a 5’10” 46 year old male who weighed 175 lbs. At the time of the crash, the rider was wearing a helmet, but no additional information about the helmet was known. His ISS was 22, with an MAIS of 3.

The case occupant was travelling in a group of 9 riders on a mountainous road. The driver was cornering a turn and leaned too far to the left. His left knee and foot peg scraped along the ground. He lost control and ran off the road to the right. As shown in Figure B.11, he slid into the guardrail approximately 4 posts upstream of the end terminal. It is anticipated that the rider separated from the motorcycle prior to collision with the guardrail, but is likely that both the rider and the motorcycle collided with the guardrail. After the crash, the motorcycle was partially on the road and facing forward. The driver was lying next to the motorcycle on his back.

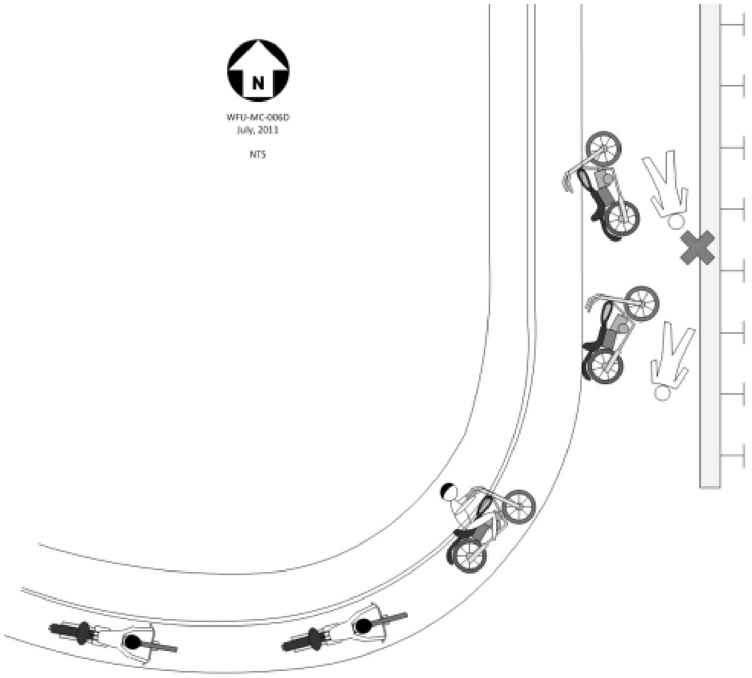

Figure B.11. Crash scenario for Case MC-006

As shown in Figure B.12, there was a concentration of injuries in his lower back.

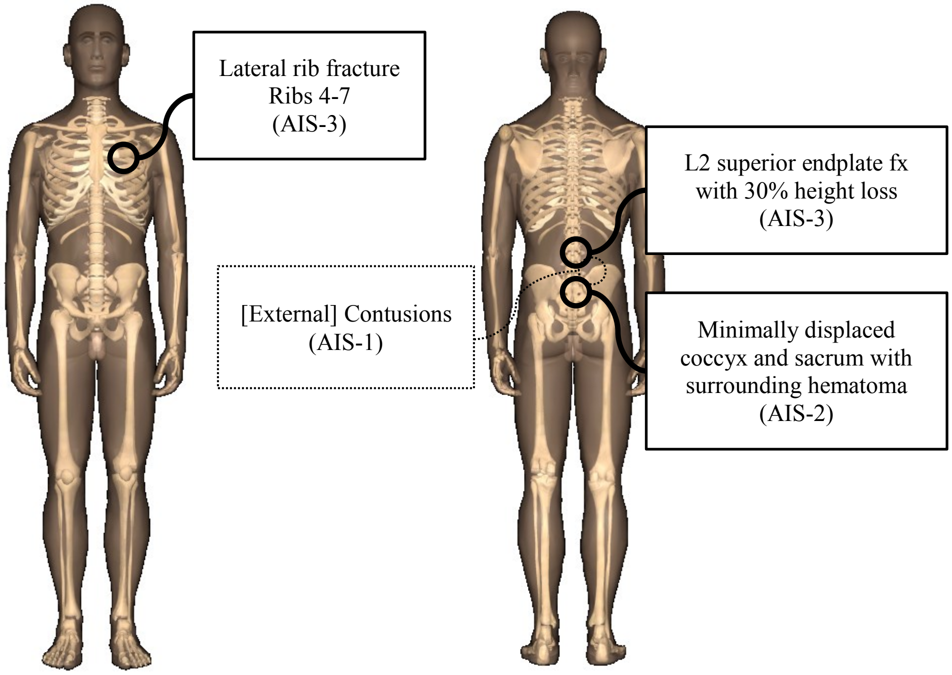

Figure B.12. Occupant Injuries, MC-006-D

The lower back injuries were likely caused by collision with the post of the guardrail, as described in Table B.7. A specific contact source for his rib fractures could not be determined due to a lack of evidence.

Table B.7. Comprehensive Injury List for Case MC-006-D

Injury	AIS-90	ICS	ICS Evidence	Certainty
Left lateral rib fractures 4-7 – some mildly displaced	450230.3	Two possible: Motorcycle Rail	- No fabric transfers - Concentrated injury, no scraping in area - No arm injuries	Possible
L2 superior endplate fracture with 30% height loss	650634.3	Post	- Injuries consistent with impact with rigid object; only rigid object was rail system - Kinematics of crash - Likely motorcycle trajectory - Likely let go of motorcycle (riding experience)	Probable
Minimally displaced coccyx fracture and sacrum fracture w/surrounding hematoma	852600.2			
Buttocks contusions	810402.1			

CASE MC-007-D

Case MC-007-D involved a 33 year old male, who was 6’5” and 175 lbs. He was wearing a DOT approved half-helmet at the time of the crash. As shown in Figure B.13, he suffered the most severe injuries to his thorax. His most severe injury, multiple rib fractures, was an AIS-5 injury, and his ISS was 33.

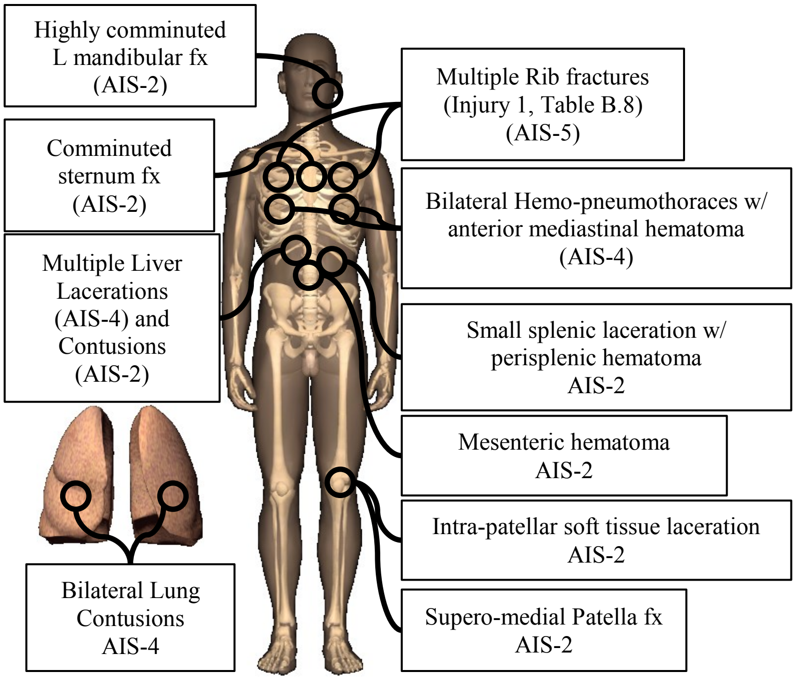

Figure B.13. Internal Occupant Injuries, MC-007-D

The injuries to the thorax were postulated to be caused by contact with the top of the posts and rail while still seated on the motorcycle (Table B.8).

Table B.8. Comprehensive Injury List for Case MC-007-D

Injury	AIS-90	ICS	ICS Evidence	Certainty
-R posterior 1st rib fx -R anterior 2nd-9th rib fx -L anterior 3rd-10th rib fx -R5,6 and L4-8 comminuted -R4 fx in 2 areas	450242.5	- Multiple impacts to top of rail and posts while on motorcycle	- Injury pattern - Likely rider position → Draped over rail, being dragged along - Rotated blockouts - Potential skin transfer - Damage to fairing - Bike leaning over rail (paint transfers, rotated blockouts)	Probable
Bilateral lung contusions	441410.4			
Bilateral hemo-pneumothoraces w/ large anterior mediastinal hematoma	441454.4			
Multiple liver lacerations	541826.4			
Comminuted sternum fx	450804.2			
Large pectoralis lacerations with associated hematomas – upper outer chest regions	410604.2			
Multiple liver contusions	541812.2			
Small splenic laceration w/small to moderate perisplenic hematoma	544222.2			
Mesenteric hematoma	542010.2			

Table B.8 (continued).

Injury	AIS-90	ICS	ICS Evidence	Certainty
Highly comminuted L mandibular fx	250612.2	- Post or rail	- Focused abrasion - High loading rate -- jaw shattered	Possible
L knee: intrapatellar soft tissue laceration	852400.2	- Contact with ground	- Presumed rider trajectory - No likely contact source with motorcycle	Possible
L superomedial patella fx w/small fx adjacent to the inferior patellar pole.	852400.2			
L cheek abrasion	210202.1	Various	--	--
Thorax abrasion	410202.1			
L foot abrasions	810202.1			
L hand and finger abrasions	710202.1			
R hip laceration	510602.1			
R ankle abrasion	810202.1			
R outer thigh abrasions	810202.1			
L flank abrasions	510202.1			

CASE MC-008-D

This case involved a 63 year old male, who was helmeted at the time of the crash. However, further details about the helmet are not known. He was 6’4” and weighed 275 lbs. His ISS was 14 with an MAIS of 3.

The rider was travelling along a mountainous road in a group of 7 motorcycles. The roadway was dry at the time of the crash. The rider lost control and ran off the right side of the road into the W-beam guardrail (Figure B.14), as evidenced by the skid marks on the road and roadside. The motorcycle continued along the guardrail, as evidenced by paint transfers downstream of the initial impact. Witnesses reported that the rider was ejected from the vehicle onto the road side of the guardrail. However, in this crash it is not believed that the motorcycle overturned since it was a 3-wheeled vehicle. Additionally, the guardrail prevented the rider and motorcycle from falling off a steep incline on the other side of the guardrail.

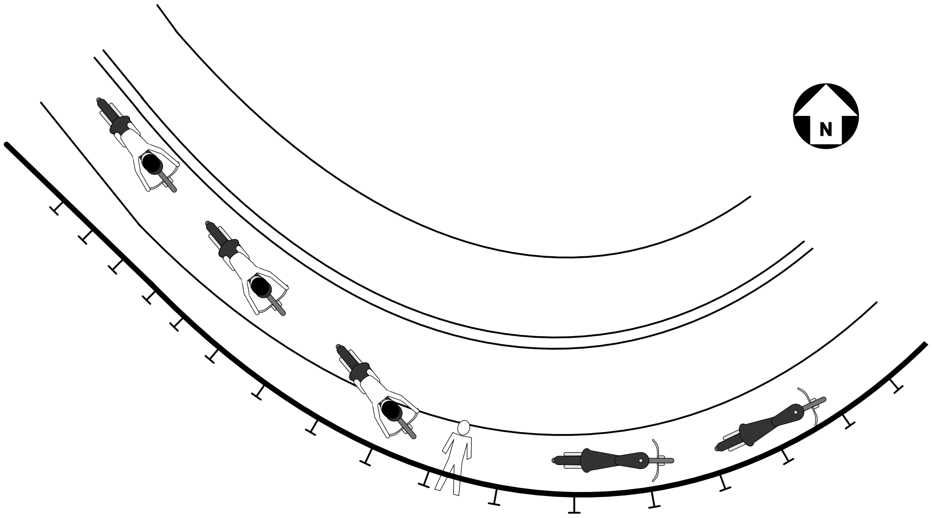

Figure B.14. Crash scenario for Case MC-008

Figure B.15 is a depiction his internal injuries; he also suffered several abrasions on his arms and knee (Table B.9).

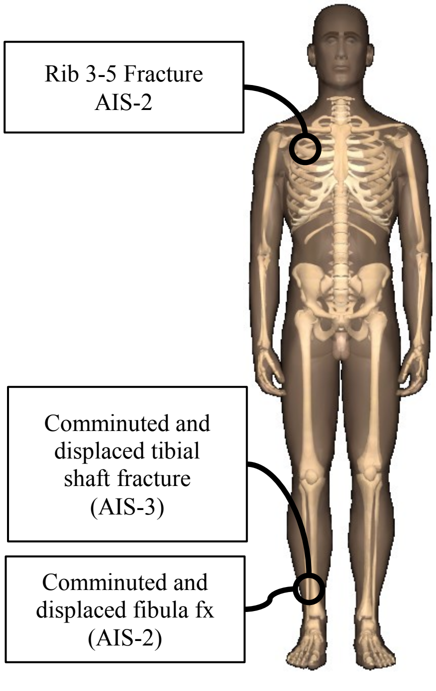

Figure B.15. Internal Occupant Injuries, MC-008-D

Unlike crashes previously described, he was riding a 3-wheeled motorcycle. His leg likely became ensnared in the motorcycle, causing the fractures in his ankle (Table B.9).

Table B.9. Comprehensive Injury List for Case MC-008-D

Injury	AIS-90	ICS	ICS Evidence	Certainty
Right comminuted and displaced distal tibial shaft fracture	853422.3	Foot/ankle/ lower leg entrapped in motorcycle while rider was being ejected after initial impact with rail	-Clean 45° angle of tibia fracture (characteristic of torsional loading) - No evidence of bone crushing (from high speed direct impact) - Unique geometry of trike limits foot proximity to guardrail - No injury to ankle or foot	Probable
Right distal comminuted displaced fibula fracture	851606.2			
Right rib 3-5 fractures	450220.2	Contact with guardrail or ground	- No evidence on motorcycle of ride-induced damage (contact with bike would have left damage i.e. on handlebar, windscreen, or mirror)	Possible
Right hand abrasion	710202.1	Miscellaneous contacts with environment after ejection	Lack of more severe injuries in areas of abrasion	Possible
Left elbow abrasion	710202.1			
Right elbow abrasion	710202.1			
Left knee abrasion	810202.1			

CASE MC-009-D

The final case investigated involved a 19 year old male with an ISS of 26. He was 6’3” and weighed 195 lbs. At the time of the crash, he was wearing a DOT-approved full-face helmet.

Approaching a curve, the rider lost control of the motorcycle and ran off the left side of the road into the guardrail as evidence by several skid marks across the road surface. About half way into the opposing lane (Figure B.16), the rider laid the bike on its right side as evidenced by a wider skid mark. The motorcycle became ensnared under the rail between 2 posts, denting both posts and ripping the blockouts. The front wheel was nearly perpendicular with the road. The motorcyclist was reported to be found 2 posts upstream with his leg around the post.

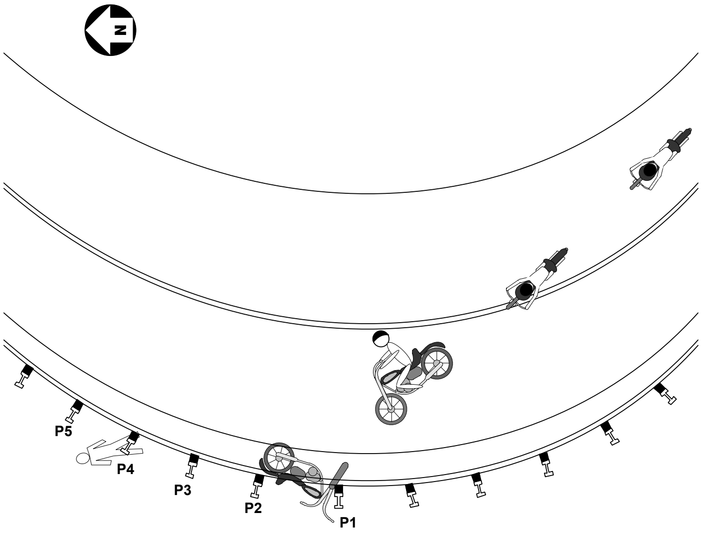

Figure B.16. Crash scenario for Case MC-009

The most severe injury he suffered had an AIS of 4 and was likely caused by impacting the guardrail face (Figure B.17 and Table B.10).

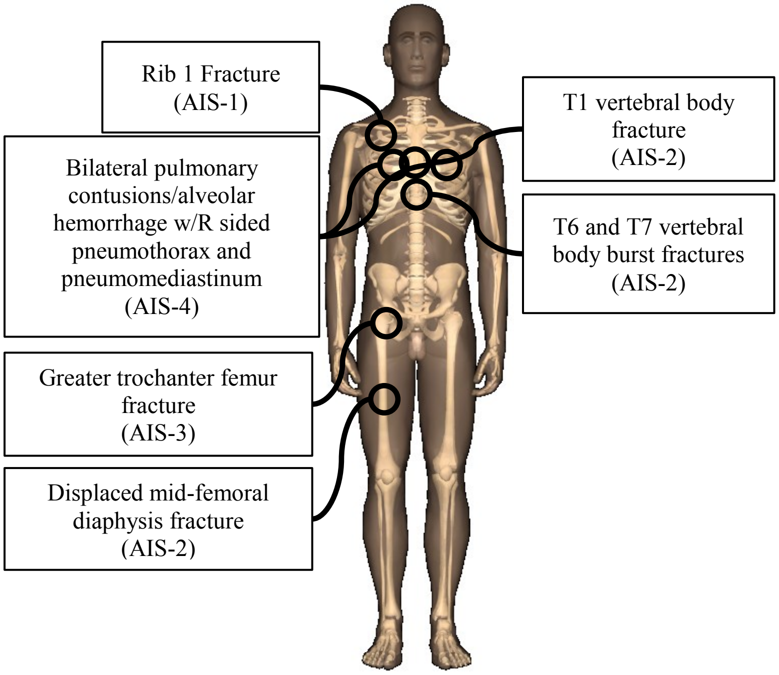

Figure B.17. Internal Occupant Injuries, MC-009-D

All of the case occupant's injuries are described in Table B.10. Many of his serious injuries were thought to be caused by the barrier.

Table B.10. Comprehensive Injury List for Case MC-009-D

Injury	AIS-90	ICS	ICS Evidence	Certainty
Bilateral pulmonary contusions/alveolar hemorrhage with right sided pneumothorax and pneumomediastinum	441452.4	Guardrail Face	- Distributed damage, not concentrated impact - Ground impact would have caused more scraping - Pulmonary contusion w/o rib fx usu. associated with distributed loading to thorax	Possible
Anterior T1 vertebral body fracture – no substantial height loss	650430.2	Guardrail face	- Vertebral body fractures from chest flexion - Fracture on anterior aspect indicates flexion	Possible
T6 and T7 vertebral body burst fractures	650432.2			
R greater trochanter femur fracture	851808.3	Guardrail posts	- Witness says leg "wrapped around post" - Possible post rotation?	Possible
Displaced R mid femoral diaphysis fracture	851814.3			
R 1st rib fracture	450212.1	Guardrail/ Ground	Crash scenario	Possible
R high frontal scalp hematoma w/no evidence of calvarial fracture	110402.1	Helmet interaction	Crash scenario	Possible
R buttocks and gluteus hematoma	840602.1	Guardrail or ground	Crash scenario	Possible