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Study on Motorcycle Safety in Negotiation with Horizontal Curves in Florida and Development of Crash Modification Factors

Final Report

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University of South Florida
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Study on Motorcycle Safety in Negotiation with Horizontal Curves in Florida and Development of Crash Modification Factors

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Disclaimer

The opinions, findings, and conclusions expressed in this publication are those of the authors and not necessarily those of the State of Florida Department of Transportation.

Metric Conversion Chart

APPROXIMATE CONVERSIONS TO SI UNITS

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
AREA				
in^2	squareinches	645.2	square millimeters	mm^2
ft^2	squarefeet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

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16. Abstract

Motorcycle crashes are overrepresented on horizontal curves, especially along rural two-lane roads. Most roadway design and traffic control strategies on horizontal curves include limited considerations for motorcycles. It is necessary to conduct a study to investigate the factors contributing to motorcycle crash risk on horizontal curves and identify effective countermeasures to improve motorcycle safety. This project aimed to fill the gap by completing the following four tasks:

1. A comprehensive literature review to summarize current practices of preventing motorcycle crashes on horizontal curves
2. A crash analysis to address relevant factors and how to influence motorcycle crash risk on horizontal curves, including crash occurrence, risk of fatalities and severe injuries, and motorcyclist-at-fault
3. A field experiment to evaluate the effectiveness of Dynamic Speed Feedback Signs (DSFS) to reduce motorcycle speed and increase motorcyclist attention on curve risk
4. A before-after crash analysis to address the effectiveness of DSFS in motorcycle crash reduction on horizontal curves
5. Recommendations to address the identified curve-related safety issues for motorcycles in Florida and prevent motorcycle injury on horizontal curves

Advanced statistical models were used to analyze 11 years (2005–2015) of motorcycle crashes data collected on curves on Florida roadways. Crash Modification Factors (CMFs) of curve radius and curve type for single-motorcycle crashes on rural two-lane highways were developed. The CMFs can be used in *Highway Safety Manual* (HSM)-compatible motorcycle safety management. Significant factors contributing to motorcycle crash frequency, severity, and motorcyclist-at-fault on horizontal curves were also identified and quantified. A field behavior experiment collected speed profile data and eye-tracking data from 10 participants with different DSFS operation modes ("OFF" – without DSFS, "STATIC" – continuously display speed limit, "DYNAMIC" – feedback scheme with flashing and "SLOW DOWN" display). The results indicate that DSFS in "DYNAMIC" mode can effectively increase motorcyclist attention on curves and intention to reduce speed. The before-after with comparison group study shows that the implementation of DSFS on rural two-lane undivided curves can reduce lane departure motorcycle crashes by 22%. Based on the analysis results, recommendations were developed for increasing awareness of curve risks, decreasing speed, roadside clearance, implementation of DSFS, and education/training.

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Executive Summary

Motorcycle crashes are overrepresented on horizontal curves. While curved segments accounted for only 5.8% of total mileage in Florida roadways, 57% of fatal single-motorcycle crashes, as well as 36% of incapacitating injury single-motorcycle crashes and 26% of non-incapacitating single-motorcycle injury crashes (in 2009 and 2010) occurred on curves. Because of the predominance of horizontal curves existing on rural roads which have relatively high speed and low safety standards, the problem of motorcycle safety is more significant on rural curves, particularly on rural two-lane roadways. According to this study, single-motorcycle crashes on horizontal curves were 4.92–1.62 times more than on tangent segments on rural two-lane roads.

Most roadway design and traffic control strategies for horizontal curve safety include limited consideration for motorcycles, especially on rural roads. Past studies and documents of horizontal curve safety focused mainly on vehicles. As the cornering characteristics of motorcycles and riding behaviors are significantly different from vehicles and driving behaviors, there is limited knowledge on how motorcyclists interact with horizontal curves and speed control treatments on curves and what factors contribute to motorcycle crashes on horizontal curves. This lack of knowledge obstructs efforts to develop effective countermeasures for preventing motorcycle crashes and injuries on horizontal curves in Florida.

Chapter 1 of this report details project backgrounds and objectives. Realizing the challenges of motorcycle safety on horizontal curves, this project aimed to (1) identify factors contributing to the risk of motorcycle crashes on Florida horizontal curves, including crash frequency, injury severity, and motorcyclist-at-fault, (2) develop Crash Modification Factors/Functions (CMFs) to quantify the impacts of horizontal curvature and/or other factors in motorcycle safety management, (3) assess the effectiveness of Dynamic Speed Feedback Signs (DSFS) to reduce motorcycle speed and increase motorcyclist attention, and (4) develop recommendations to improve motorcycle safety on horizontal curves in Florida, based on the analysis results.

Chapter 2 includes a comprehensive literature review, including motorcycle crash analysis on horizontal curves, CMFs for curve-related motorcycle crashes, motorcyclist behaviors on curves, countermeasures to improve motorcycle safety on curves, and motorcycle exposure. The chapter summarizes past studies and current practices of motorcycle safety research and management to support the objectives of this project.

Chapter 3 describes the efforts of data collection for motorcycle crash analysis. The research team identified 10,858 horizontal curves (including 2,592 rural two-lane curves) statewide from the Florida Department of Transportation (FDOT) Roadway Characteristics Inventory database. Data on curvature, geometry, pavement, and historical motorcycle crashes (2005–2015) were collected from various data resources and matched to the identified curves.

Chapter 4 provides the details of motorcycle crash analysis based on the collected crash data and advanced statistical modeling technologies, providing the analysis results and findings to answer the following research questions:

- What factors contribute to single-motorcycle crash occurrence on rural two-lane curves?
- What factors contribute to single-motorcycle crash injury severity on horizontal curves?
- What factors contribute to motorcycle making mistakes (at-fault) in two-vehicle crashes on horizontal curves?

Based on the crash analysis, the following major findings were obtained:

- Sharp curves are more likely to increase single-motorcycle crash frequency and injury severity as well as the likelihood of motorcyclist-at-fault in a two-vehicle crash. The CMF of curve radius for single-motorcycle crashes on rural two-lane curves was developed using the case-control technology:

$$\mathrm{CMF_R} = \begin{cases} 3.27 & R \leq 1{,}000\,ft \\ 2.98 & 1{,}000\,ft < R \leq 2{,}000\,ft \\ 1.82 & 2{,}000\,ft < R \leq 10{,}000\,ft \end{cases}$$

  where $\mathrm{CMF_R}$ is the CMF of curve radius for single motorcycle crash on rural two-lane roadways, R is the curve radius in feet, and the baseline is a straight segment.

  The mixed logistics model shows that sharp curves (<1,500 ft) tend to increase the risk of serious injury and/or fatality by 6.1%. If the curve radius is less than 400 ft, the probability of motorcyclists making mistakes tends to increase by 7%.

- Speed is the predominant factor causing fatality and serious injury in single-motorcycle crashes on rural curves. If operating speed (estimated impact speed, similarly hereinafter) is 50 mph, the risk of fatality and serious injury in a single motorcycle crash is 24.1% higher than that with a low operation speed (<50 mph).

  Speeding increases the risk of fatality and serious injury by 16.8% in a single motorcycle crash. If the speed is higher than the posted speed limit, the likelihood of motorcyclists making an error tends to increase by 28.7% (speed – speed limit > 15 mph) and 11.7% (15 mph ≥ speed – speed limit > 10 mph).

- Old motorcyclists (age ≥ 60) experience a 16.3% higher risk of fatality and injuries in a single motorcycle crash on rural curves than middle-aged motorcyclists (ages 30–60). They also are 7.7% more likely to make mistakes on curves than middle-aged motorcyclists.
- Use of a helmet and other safety equipment can reduce the risk of fatality and serious injury by 8.4% in a single-motorcycle crash on rural curves. Motorcyclists with proper riding behaviors experience an 11.9% lower risk of fatality and severe injury than motorcyclists with improper riding behaviors.
- The presence of trees, barriers, and other fixed objects on the roadside are dangerous to motorcyclists in curve negotiation. If a single motorcycle hits these

objects, the risk of fatality and severe injury increases by 15.6%, 20.7%, and 7.5%, respectively.

- Motorcyclists have significant safety compensation behaviors on horizontal curves—they intend to use safe riding behaviors when they are subjectively aware of risks. If they feel "safe" and "confident," they tend to take unsafe and aggressive riding behaviors. The safety compensation behaviors can explain some counterintuitive findings in the crash analysis, such as that poor pavement conditions are more likely to experience lower injury severity in motorcycle crashes on curves. Thus, increasing motorcyclist awareness of potential risks is an effective way to improve motorcycle safety on curves.

Chapter 5 illustrates the field experiment that examined the interaction between motorcyclists and DSFSs on horizontal curves along rural two-lane roads. Speed profile data and eye-tracking data of 10 participants were collected through VBox and Tobii Pro Glasses 2 at 18 curves along W Ozello Trail in Crystal River, Florida. Statistical comparisons were applied to these data to investigate the effectiveness of various DSFS operations modes in speed reduction and attention improvement, including:

- *OFF* – LED panel turned off and covered with a black plastic bag. This mode represents no DSFS activation (without DSFS); only the static curve warning sign is present.
- *STATIC* – Sign activated, but no feedback function works, sign continuously displays speed limit of curve without flashing.
- *DYNAMIC* – Sign activated, and feedback function works. Sign displays speed limit of associated curve if sign not triggered by speeding. When approaching motorcycle speed is higher than the thresholds, the sign flashes and displays a text message of "SLOW DOWN."

A before-after crash analysis was also conducted to address the effectiveness of DSFS in motorcycle crash reduction on horizontal curves and develop the Crash Modification Factor (CMF) for DSFS. Lane departure motorcycle crashes were compared in on rural road segments that implemented DSFS between the before period (2012-2014) and the after period (2015-2017). A comparison group containing 77 similar roadway segments was used to control the influence from external factors (e.g., temporal changes in traffic volume, weather, etc.).

The major findings from the field experiment were as follows:

- DSFSs in "DYNAMIC" mode (flashing plus "SLOW DOWN" display) effectively increased motorcyclist attention rate (percentage of observations that motorcyclists pay attention to DSFS) and attention distance (distance of motorcyclist firstly paying attention to DSFS) on curve presence and speed limit by 50%. As inattention is a major cause of motorcycle crashes on curves, DSFS in "DYNAMIC" mode can effectively improve motorcycle safety on curves.

- Although DSFSs in "DYNAMIC" mode reduced the speed reduction rate, they do not reduce motorcycle speed and the speeding rate to a significant degree. The average motorcycle speed when entering the curve was higher than the posted safe speed limit.

- Implementation of DSFS can reduce lane departure motorcycle crashes by 22% on rural two-lane undivided curves. The CMF is 0.78.
- DSFSs in "DYNAMIC" mode potentially may cause the risk of distraction for motorcyclists if the sign is too close to the beginning of the curve. This issue became more significant on left-hand curves.

Chapter 6 summarizes the conclusions and recommendations of this research and includes a summary of project tasks and major findings to recommend implementation strategies for improving motorcycle safety on horizontal curves. The recommended countermeasures include the following:

- Awareness of curve risk – Motorcyclist inattention to and/or misunderstanding curve risk are the critical factors contributing to motorcycle crash occurrence, crash severity, and motorcycle-at-fault on horizontal curves. To increase motorcyclist attention and awareness of potential curve risks, the following low-cost countermeasures are suggested:
  - Advance curve warning and advisory speed signs
  - Chevron alignment signs – especially for curves with a concave slope
  - Advance pavement markings for curve warning and speed advisory – supplement curve warning signs with advisory speed plaques by providing highly-conspicuous, supplementary warning information to motorcyclists
- Speed control – High speed is the most significant factor contributing to the risk of fatalities, severe injuries, and motorcyclist-at-fault. To reduce excess speed when entering a curve, the following countermeasures are suggested:
  - Combination horizontal alignment/advisory speed sign – installed at the beginning of a curve to emphasize speed reduction to motorcyclists
  - Speed reduction markings, i.e., transverse stripes spaced at gradually decreasing distances (*Manual on Uniform Traffic Control Devices* [MUTCD], Section 3B.22), to increase motorcyclist perception of speed and cause them to reduce their speed
- Implementation of Dynamic Speed Feedback Sign (DSFS) – To effectively implement DSFSs to improve motorcycle safety on rural curves, the following are recommended:
  - Feedback function with flashing + "SLOW DOWN" should be activated on DSFS in general conditions.
  - Distance between the DSFS and the curve should be long enough to provide adequate reaction time to motorcyclists and avoid distraction risk. For example, assuming a speed limit of 35 mph, the distance should be 100 ft or longer to give motorcyclists a reaction time of at least 2 seconds. If the distance between the DSFS and the curve cannot provide enough reaction time, the flashing function should be deactivated to avoid potential distraction risk.

- If the distance between the DSFS and the curve is too far (≥200 ft), a combination horizontal alignment and advisory speed sign should be installed at the beginning of the curve to reminder motorcyclists to slow down.
  - Advanced radar systems are recommended at some curves to increase the detection distance for motorcycles.
  - Periodic maintenance of DSFS is suggested to exclude dysfunctional issues, such as broken cable, not working, and obstruction by tree branch.
  - Enforcement programs are suggested to supplement the implementation of DSFS.
- Clear zone – Roadside characteristics (e.g., roadside slope, clear-zone width, coverage of fixed objects) are the dominant contributors to the risk of fatality and severe injury in a single-motorcycle crash on a curve. Clear zones are useful for providing sight distance along curves and recovery areas for motorcycles that inadvertently leave the roadway; they also decrease the risk of animals near the roadway.
- Safety education and training – Motorcyclist characteristics and behaviors are factors directly contributing to motorcycle crash risk on horizontal curves. To improve safety-related riding behaviors, the following are recommended:
  - Use of helmets and/or other safety equipment is strongly encouraged.
  - Motorcyclists, especially older motorcyclists, should take periodic health examinations to make sure they are in good condition.
  - Training courses are suggested for motorcyclists, especially for older motorcyclists, to improve their curve negotiation skills.
  - Non-local rider-friendly countermeasures such as clear risk information about curved trails should be provided to non-local motorcyclists on site or online.
  - Special education programs and campaigns related to safety on curves should be developed to advise motorcyclists of the proper behaviors with respect to horizontal curves and traffic control strategies (such as DSFS).

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Chapter 1
Introduction

1.1 Background

The motorcyclist population is growing at a very rapid rate, with motorcycle ownership increasing by 19% from 2003 to 2008; nationwide, approximately 10.4 million motorcycles were owned in 2015. Motorcycles also are being used more frequently for general transportation purposes as opposed to recreational riding. In addition, there has been a substantial influx of younger, older, and female motorcyclists. With this increase in motorcycle traffic demand, motorcycle-related traffic injuries and fatalities have become an issue that requires special attention by traffic safety officials, advocates, and researchers. As the state with the second highest number of registered motorcycles, Florida experienced an increase in motorcyclist fatalities from a record low of 246 in 2001 to 462 in 2013, as shown in Figure 1.

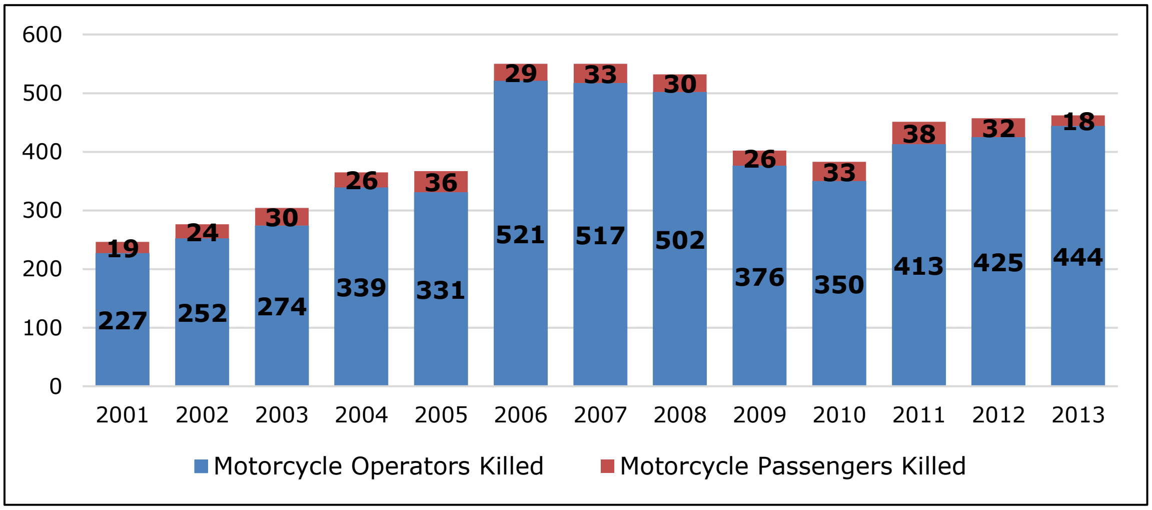


Figure 1. Florida Motorcycle Fatalities, 2001–2013

In response to these issues, various countermeasures have been developed to either prevent crash occurrences or reduce motorcyclist and side-seat passenger injuries in the event of a motorcycle crash, including improvements in conspicuity, motorcycle rider training, enforcement and licensing initiatives, helmet use, protective clothing, etc. Although the annual number of motorcycle fatalities has decreased in recent years due to the implementation of these countermeasures, fatalities of motorcyclists remain overrepresented.

The effect of horizontal curvature on motorcycle crashes is of significant interest to roadway designers. As shown in Figure 2, in Florida in 2009 and 2010, 57% of fatal single-motorcycle crashes, 36% of incapacitating single-motorcycle crashes, 26% of non-incapacitating single-motorcycle crashes, and 32% of total single-motorcycle crashes occurred on curved segments, which accounted for only 5.75% of total mileage. In addition, according to a Florida Department of Transportation (FDOT) District 7 data analysis on motorcycle crashes, 33% of all motorcycle crashes involved only a motorcyclist, and nearly one third of motorcycle fatalities related to problems negotiating a curve prior to a motorcycle crash. The paradox between the high rate of severe motorcycle crashes, especially fatal crashes, on curved segments and very low curve mileage shows that horizontal curves are a critical factor contributing to motorcycle crash risk.

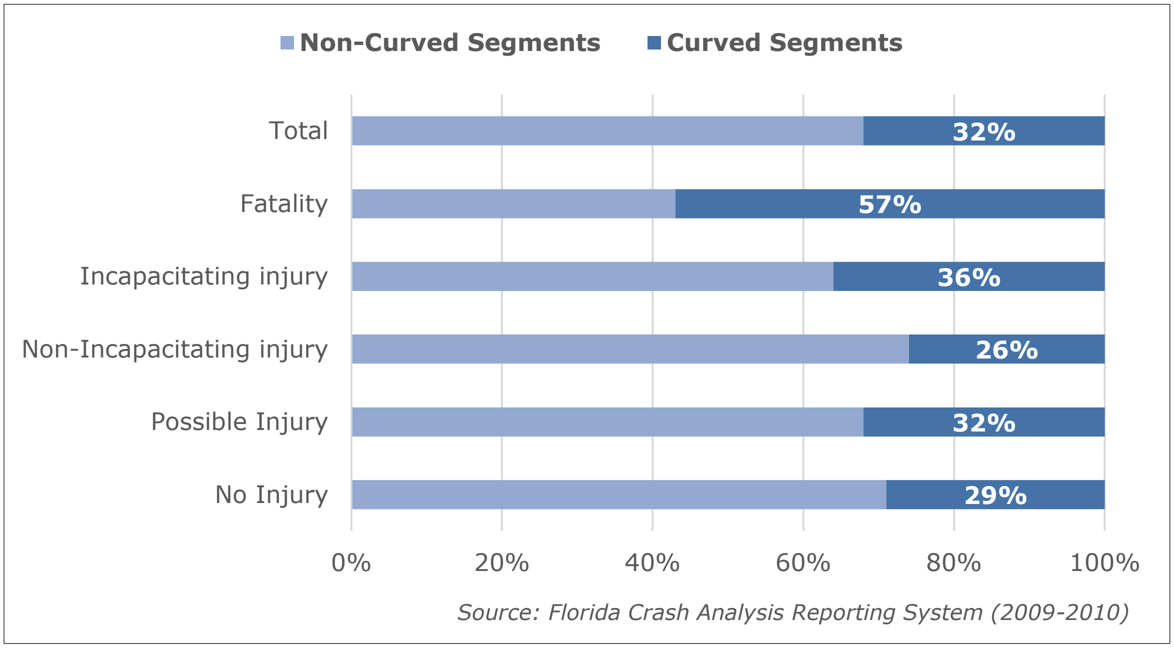


Figure 2. Motorcycle Crashes by Injury Severity, Curved vs. Non-Curved Segments, 2009–2010

Horizontal curves are likely to reduce available sight distance and adversely impact vehicle-handling capabilities, increasing the potential for traffic crashes and fatalities. These problems are particularly serious for motorcyclists for the following reasons:

- The operation of negotiating horizontal curves for motorcyclists is a complex maneuver, requiring advanced riding skills including counterintuitive tasks such as counter-steering, simultaneous application of front and rear brakes, and opening the throttle. This complexity and improper training in the intricacies of motorcycle negotiation may contribute to higher and more severe crash involvement.
- Some motorcyclists may have reflex and physical coordination limitations, including motorcyclist impairment (alcohol, medication), that significantly increases their crash risk.
- Negotiation with horizontal curves is an attraction to motorcycle motorcyclists with risk-seeking characteristics in all age and socioeconomic categories because of the dangers and challenges. Risk-seeking motorcyclists find it difficult to resist the temptation of the high performance that most motorcycles offer such that they tend to ride at a dangerous speed before and while in negotiation with curves. This unsafe motorcyclist behavior is more likely to increase crash risk.

Based on the above analysis, motorcyclist behaviors play a significant role in contributing to curved-related motorcycle crashes and are influenced by curve geometry, roadway environment, motorcycle characteristics, and traffic control treatments. Effective countermeasures such as motorcycle-friendly geometry designs and traffic controls are beneficial for reducing motorcycle frequency risk at horizontal curves and mitigating curve-related fatalities/severe injuries.

However, most roadway design and traffic control manuals include limited consideration of motorcycles, especially related to horizontal curves. This lack of knowledge on risk factors contributing to motorcycle crash risk, such as crash occurrence, injury severity, and motorcyclist-at-fault on curves, prevents development of effective safety countermeasures to mitigate motorcycle crash risk on curves. Thus, it is necessary to conduct research to investigate factors contributing to motorcyclist behavior and consequential motorcycle crashes on horizontal curves.

1.2 Research Objectives

This project aimed to identify factors contributing to motorcycle crashes on horizontal curve segments and develop effective countermeasures to reduce motorcycle crash risk. More specifically, the research objectives are to:

- Conduct a comprehensive analysis to identify risk factors that significantly contribute to motorcycle crash occurrence, risk of fatalities and severe injuries, and motorcyclist-at-fault on horizontal curve segments in Florida.
- Develop motorcycle Crash Modification Factors/Functions (CMFs) to quantify the impacts of horizontal curvature and/or other factors. The developed CMFs will be compatible with the *Highway Safety Manual (HSM)*.
- Perform an assessment on the effectiveness of selected countermeasures implemented in FDOT District 7 to reduce excess speed and increase motorcyclist attention.
- Develop recommendations to improve motorcycle safety on horizontal curves in Florida.

1.3 Report Organization

The report is organized as follows: Chapter 1 introduces the project background and research objectives. Chapter 2 presents a comprehensive review of previous studies, including CMFs for horizontal curves, contributing factors to horizontal curve-related crashes, riding behavior studies on horizontal curves, motorcycle safety countermeasures on horizontal curves, and motorcycle exposure study. The data collection and methodologies for curve-related motorcycle crash analysis and modeling are provided in Chapters 3 and 4, respectively. Chapter 5 describes a field experiment that assessed the safety effectiveness of dynamic speed advisories in speed control on horizontal curves for motorcycles, including crash analysis and riding behavior study through eye trackers. Finally, Chapter 6 presents conclusions and recommendations for preventing motorcycle crash injury on horizontal curves in Florida.

Chapter 2
Literature Review

2.1 Motorcycle Crash Modeling at Horizontal Curves

Several previous studies that explored the safety effects of horizontal curves combined with other contributing factors on motorcycle crash occurrence and injury severity using various statistical methodologies were identified from available information resources such as Google Scholar, Transportation Research Information Database (TRID), etc. Among them, only three studies (*1*–*3*) assessed the impacts of horizontal curvature parameters such as curve radius, curve length, etc., on motorcycle crash frequency and severity. Others (*4*–*6*) explored the correlation between the presence of horizontal curves and motorcycle injury severities. These studies are summarized as below.

2.1.1 Horizontal Curvature Parameters

Effects of Horizontal Curvature on Single-Vehicle Motorcycle Crashes along Rural Two-Lane Highways – Schneider et al. (*1*) assessed the impacts of horizontal curvature on the frequency of single-vehicle motorcycle crashes on rural two-lane highways. The authors collected data on 225 single-motorcycle crashes that occurred on 30,379 horizontal curves in Ohio from 2002–2008. Each curve consisted of a single curve and two 300-ft buffers at each end without any intersection or other curve (as shown in Figure 3).

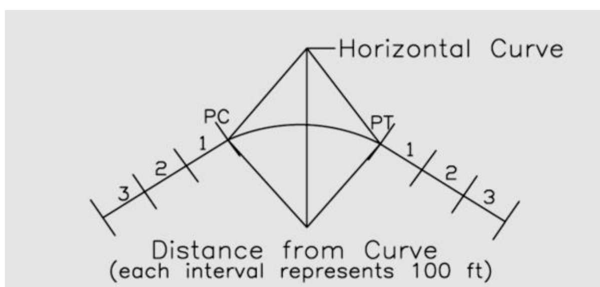


Figure 3. Horizontal Curve for Data Collection

Because many curves had zero crash observations (zero-inflated), a negative binominal model applying a full Bayesian method was used to improve model performance. Two horizontal curvature parameters—curve radius and curve length—in combination with other geometric and traffic factors were assessed by the developed model. The major conclusions included the following:

- An increasing radius, which is indicative of a smoother curve, results in a significant decrease in the frequency of motorcycle crashes. A 1% increase in the radius tends to decrease the single-motorcycle crash frequency by 0.74%.
- A 1% change in curve length results in an increase in the frequency of single-motorcycle crashes by 0.39%.

- Every 100-ft increase in distance to a curve (up to 300 ft) is more likely to reduce the single-motorcycle crash frequency on the tangent sections immediately connecting the curve by 43.48%.
- A narrow shoulder (≤ 6 ft) increases single-motorcycle crashes by 52.24%.
- For every 1% change in annual daily traffic (ADT), motorcycle crash frequency is expected to increase by 0.43%.

Modeling the Injury Severity of Single-Motorcycle Crashes on Horizontal Curves – Wang et al. (*2*) quantified the impacts of horizontal curvature on the injury severity of single-motorcycle crashes along horizontal curves. Data on 494 single-motorcycle crashes were collected from 3,320 curved roadway sections in Florida for a 10-year period (2003–2012). A heterogeneous choice model with the log-log link function was fitted to estimate the impacts. Based on the developed model, marginal effects were used to quantify the impacts of the horizontal curvature and other contributing factors. The major findings were as follows:

- An increase of 1,000 ft in curve radius decreases the likelihood of fatalities and serious injuries by 0.2% and 0.15%, respectively, in single-motorcycle crashes along a curved roadway section.
- Speeding is the most significant factor and is likely to increase the risk of fatalities in a single-motorcycle crash by 10.84%.
- Good lighting conditions are an effective factor in reducing the risk of fatalities and serious injuries on curved roadway segments because they can improve motorcyclist sight distance.
- Other significant factors include crash type, roadway surface width, speed limit, use of helmet, and motorcyclist characteristics.

Influence of Horizontally Curved Roadway Section Characteristics on Motorcycle-to-Barrier Crash Frequency – Gabauer and Li (*3*) investigated motorcycle-to-barrier crash frequency on horizontally-curved roadway sections using the negative binominal model. Data on 4,915 horizontal curved roadway sections with 329 motorcycle-to-barrier crashes were collected in Washington State between 2002 and 2011. Based on the developed model, they found the following:

- A motorcycle-to-barrier crash countermeasure placement criterion is mainly based, at the very least, on horizontal curve radius.
- Horizontal curves of 820 ft or less were found to increase crash frequency rate by a factor of 10 compared to curves not meeting this criterion.
- Curves with a radius of less than 500 ft are 40+ times more likely to experience a motorcycle-to-barrier crash than a curve with radius in excess of 2800 ft.
- Longer curves—those with higher traffic volume—and those that have no adjacent curved sections within 300 ft of either curve end likely would be better candidates for a motorcycle-to-barrier crash countermeasure.

2.1.2 Presence of Horizontal Curves

Probabilistic Models of Motorcyclists' Injury Severities in Single- and Multi-Vehicle Crashes – Savolainen and Mannering (*4*) developed two probabilistic models—a nested-logit model with the full information maximum likelihood estimation and a multinomial logit model—to provide additional insight into the factors contributing to motorcyclist injuries in single-motorcycle crashes and multi-motorcycle crashes, respectively. To develop the models, data on 2,273 single-motorcycle crashes and 2,213 multi-motorcycle crashes were collected in Indiana between January 1, 2003, and October 15, 2005. A binary variable was included in the models as the indicator of horizontal curve presence. Key findings were as follows:

- Single-motorcycle crashes on horizontal curves were less likely to result in minor or no injuries by 8%, i.e., the severity of crashes occurring on horizontal curves is more likely to be incapacitating injury or fatality.
- Horizontal curves result in a 45% increase in incapacitating injuries in multi-motorcycle crashes compared to other injury severities.
- Speeding (motorcyclists cited for unsafe speed) results in a 212% increase in the probability of a fatality in single-motorcycle crashes.
- The crash-injury severity analysis presented in this paper revealed several problem areas leading to more severe injuries, including poor visibility (horizontal curvature, vertical curvature, darkness), unsafe speed (citations for speeding), alcohol use, not wearing a helmet, and right-angle and head-on collisions.

Analysis of Motorcycle Crashes in Texas with Multinomial Logit Model – Geedipally et al. (*5*) developed multinomial logit (MNL) models to identify factors likely to affect the severity of motorcyclist injuries in urban and rural crashes. Data on 48,871 motorcycle crashes that occurred on the Texas State Highway System from 2003 through 2008 were obtained from the Texas Department of Transportation Crash Records Information System. Using a likelihood test, the authors found that rural and urban crash severities have different characteristics. Thus, the MNL models were estimated for urban and rural crashes separately. Major conclusions included the following:

- The presence of horizontal curves tends to increase the likelihood of severe injuries in a motorcycle crash in urban areas. Compared to a straight zero-grade road, an at-grade horizontal curve is likely to increase the probabilities of fatality and incapacitating injury by 79.5% and 25.9%, respectively. The combination of horizontal and vertical curve increases the probabilities by 152% and 43.6%, respectively.
- Horizontal and vertical curves were not found to have significant impacts on motorcyclist injuries on rural roads.
- Based on the findings, the authors suggested that increasing visibility on roadway segments involving horizontal and vertical curves in urban areas is an effective method for reducing motorcyclist injuries, since curves decrease the visibility and maneuverability of motorcycles. Also, enforcement of speed limits should be increased at such locations.

- The use of additional street lighting in rural locations with high motorcycle crash frequencies should be explored.

A Simplified Method for Analyzing Factors Contributing to Motorcyclists' Fatal Injuries in Ohio – Eustace and Indupuru (*6*) conducted a study to determine the significant factors contributing to the risk of a motorcyclist being fatally injured. Crash data from 2003 through 2007 containing 23,727 records were obtained from the Ohio Department of Public Safety. All motorcycle crashes were grouped based on their injury severities—fatally-injured (success group) and not fatally-injured (failure outcome). The overrepresentation factors (ORF) were calculated for all variables of interest using the following equation:

$$\text{ORF} = \frac{R_s}{R_c} = \frac{A/(A+C)}{B/(B+D)} \quad (1)$$

where:

R_s = proportion of positive (success) outcomes for set of interest

R_c = proportion of positive outcomes for complementary (comparison) set

A = number of positive (success) outcomes for set of interest

B = number of positive outcomes for complementary set

C = number of negative (failure) outcomes for set of interest

D = number of negative outcomes for the complementary set

An ORF greater than 1 indicates that the successful event (fatality) is more likely to occur in the group of interest than in the complementary group, and an ORF less than 1 indicates that the successful event is less likely in the group of interest. The analysis results showed the following:

- The presence of horizontal curves, either at-grade or graded, increases the chances of fatal risks of motorcyclists.
- Being age 65 and over, riding while speeding, riding while under the influence of alcohol or drugs, riding without a helmet, riding at night, being male, and being the operator were statistically-significant motorcyclist-related characteristics that elevated the risk of being fatally injured.
- Environmental conditions such as dark with light or dark with no light had significant effects of increasing the chances of motorcyclist fatal injuries once involved in traffic crashes.
- In terms of crash type characteristics, motorcyclists had elevated risks of being fatally injured when involved in single-vehicle crashes, especially running off the road, crossing the median, and hitting a curb.

2.2 Crash Modification Factors (CMFs) for Horizontal Curvature

A CMF is a measure of the safety effectiveness of a given treatment and can be applied to predict expected crash frequency with the treatment by multiplying CMF by expected crash frequency without treatment. A CMF could be a single value or a formula.

Previous studies that focused on the development of CMFs for evaluating the safety effectiveness of horizontal curvature were identified from various resources, including the CMF Clearinghouse, Google Scholar, TRID, etc. These CMFs are summarized in Table 1. Most CMFs are a function of horizontal curvature parameters with a baseline of tangent roadway segments. In these CMFs, the most important curve factor is radius (R), a continuous variable having a linear or non-linear negative correlation with CMFs. Curve length is also a factor in two CMFs. Other factors include presence of spiral transition, segment length, and speed limit. However, all these CMFs applied to passenger vehicles or trucks. No motorcycle-specific CMFs for horizontal curvature were found.

To understand the crash prediction model for horizontal curves, such as model structure, independent variables, samples, and methodologies, all previous studies related to the prediction models are summarized in Table 2. Most of these models were developed for passenger vehicles; only one was for motorcycles.

Table 1. Summary of Horizontal Curve-related Crash Modification Factors

CMF	Method	Dataset	Ref.	Note
For rural 2-lane highways: $CMF = 1 + 0.106\left(\frac{5730}{R}\right)^2$ R – radius of horizontal curve, ft	• Cross-sectional study • Negative binomial regression model • Empirical Bayes Technique	• In Texas • 3,514 segments • 822 crashes • 1999–2001	(*7*)	CMF focuses on injury (plus fatal) crashes
For 2-lane rural highways: $CMF = \frac{1.55L_e + \frac{80.2}{R} - 0.12S}{1.55L_e}$ L_e – Length of horizontal curve, mi R – Radius of horizontal curve, ft S – 1.0 for spiral transition, 0.5 if there is a spiral transition curve at one end of curve, or 0.0 for non-spiral transition	• Regression model	• In Washington • 10,900 curves	(*8*)	CMF based on full range of crash severities
For dynamic speed feedback signs on rural 2-lane curves: $CMF = 0.93 \sim 0.95$	• Before-and-after study • Full Bayes analysis	• In seven states • 51 viable sites (22 test sites, 29 control sites) • 1116 observations • 2005-2011	(*9*)	Specific value of CMF depends on type and direction of crash
For freeways and rural highways: $CMF = 1.0 + 0.97(0.147V)^4 \frac{(1.47V)^2}{32.2R^2}\left(\frac{L_C}{L}\right)$ V – speed limit, mph R – curve radius, ft L_C– Horizontal curve length, mi L – Segment length, mi	• Regression analysis	• In Texas	(*10*)	CMF focused on injury (plus fatal) crashes, applicable to any curve with CMF value of 2.0 or less when ratio L_c/L is set to 1.0

Table 1, continued

For freeways: $CMF = e^{0.1096(CD)}$ CD – degree of curvature, 5730/R R – curve radius, ft.	• Negative binomial regression model	• In Texas • 561 curves • 4,855 crashes • 1997–2001	(*11*)	CMF typically used on rural and urban four-lane freeways
For rural 4-lane highways: $CMF = e^{0.0831(CD)}$ CD – degree of curvature, 1747/R R – curve radius, m	• Negative binomial regression model	• In Texas • 260 curves • 1,024 crashes • 1997–2001	(*12*)	CMF applicable only for rural 4-lane divided and undivided highways
For rural multilane highways: $CMF = \begin{cases} 1, \mathrm{R} \geq 4240 \\ \frac{197.6}{R^{0.633}}, \mathrm{R} < 4240 \end{cases}$ R — curve radius, ft	• Curve fitting • Cross-sectional study	• In Washington • 3017 segments • 956 crashes • 2007–2011	(*13*)	CMF set to 1.0 when radius of curve is 4,240 ft or more

Table 2. Crash Prediction Models for Horizontal Curvature Parameters

Crash Prediction Model	Method	Dataset	Reference
Relative accident rate (RCR) on horizontal curves: $RCR = 127.1658R^{-0.7099}$ RCR – relative number of accidents per million vehicle kilometers of travel R – radius of horizontal curve, m	• Weight analysis of marginal gradient	• 10 CMFs from 10 countries	(*14*)
Crash frequencies on horizontal curves: $N = AADT^{0.9224}L^{0.8419}e^{0.0662SR-7.1977}$ N – number of accidents on horizontal curve during 3-year period L– length of horizontal curve, km SR – speed reduction on horizontal curve from adjacent tangent to curve, km/h	• Poisson regression model	• In Texas • 1,747 crashes • 5,287 curves • 1993–1995	(*15*)
Roadway departure crash frequency on 2-lane rural highways: $N = AADT^{0.7657}e^{-0.076LW-0.062SW+0.075CD-6.448}$ N – number of crashes per mile per year LW – lane width, ft SW – shoulder width, ft CD – degree of curvature	• Poisson regression model	• In Texas • Departure crashes (25%~52%) • 40,644 sections • 2003–2007	(*16*)
Crash frequency for total crashes on 4-lane median-divided highway: $N_T = e^{-0.071+0.803lnL+\frac{0.270}{R}+0.327\times AADT\times 10^{-4}}$ Crash frequency for severe crashes on 4-lane median divided highway: $N_S = e^{-1.457+0.869lnL+\frac{0.338}{R}+0.409\times AADT\times 10^{-4}}$ $N_{\frac{T}{S}}$– number of total/severe crashes per year and per carriageway L – curve length, km R – curve radius, km	• Negative multinomial regression model • Maximum likelihood method	• In Italy • 118 curves • 1,916 crashes • 1999–2003	(*17*)
Number of trucks involved in accidents per year: $N = Ve^{-0.54-0.36x_1-0.34x_2+0.04x_3+0.18x_4+0.12x_5+0.47x_6}$ V – truck travel miles or exposure in 10^6 truck-miles x_1 – dummy variable for year 1, 1 if in 1986, 0 otherwise x_2 – dummy variable for year 2, 1 if in 1987, 0 otherwise x_3 – AADT per lane in 1000s of vehicles x_4 – horizontal curvature in degrees per 100-ft arc x_5 – length of original horizontal curve in mi x_6 – length of original vertical grade in m (grade>2%)	• Linear regression model • Poisson regression model	• From HSIS • 4,983 sections • 927 trucks in crash • 1985–1987	(*18*)

Table 2, continued

Number of truck-related crashes on horizontal curve section: $N = e^{-1.5662+1.1006x_1+0.0014x_2-0.0002x_3+0.0512x_4}$ x_1 – natural log of the length of horizontal curve, mi x_2 – truck ADT, vehicles per day x_3 – passenger ADT, vehicles per day x_4 – degree of horizontal curvature, °	• Negative binomial model • Full Bayes methods	• In Ohio • 15,390 curves • 225 crashes • 2002–2006	(*19*)
Number of motorcycle-related crashes on horizontal curve: $N = e^{-3.427+0.338x_1-0.361x_2-0.001x_3+0.739x_4+0.00014x_5}$ x_1 – natural log of length of horizontal curve, mi x_2 – distance from curve segments (100-ft interval) x_3 – radius of horizontal curve, ft x_4 – shoulder width less than 6 ft x_5 – total average daily traffic (ADT), vehicles per day	• Negative binomial model • Full Bayes methods	• In Ohio • 30,379 curves • 225 crashes • 2002-2008	(*1*)
Number of vehicle crashes on horizontal curves of 2-lane rural highway: $N = Ve^{-10.561+0.109x_1+0.00084x_2+0.09626x_3-0.5842x_4-0.1970x_5}$ V – vehicle travel miles or exposure in 10^6 vehicle-mi x_1 – degree of horizontal curve, ° x_2 – total length of horizontal curve segment, m x_3 – superelevation horizontal curve, % x_4 – length of spiral curve, m x_5 – shoulder width, m	• Poisson regression model	• In Iran • 502 curves • 301 crashes • 2007	(*20*)
Number of vehicle crashes on horizontal curves of 2-lane rural highway: $N = e^{-4.137-0.00052x_1+0.00056x_2+0..448x_3+0.02x_4-0.024x_5}$ x_1 – radius of curve, ft x_2 – curve length, ft x_3 – natural log of AADT, vehicles per day x_4 – posted speed, mph x_5 – right shoulder width, ft	• Negative binomial regression	• In Wisconsin • 6 types of curve • 11,224 crashes • 2005–2009	(*21*)

2.3 Contributing Factors in Horizontal Crash Modeling

Motorcycle crash occurrence and injury severity on horizontal curves are the consequence of a combination of horizontal curvature and other factors. This section summarizes the horizontal curvature parameters and associated contributing factors that were addressed in previous studies. Because only a limited number of previous studies focused on curve-related motorcycle crash modeling, this summary extends to vehicle crashes.

The horizontal curvature parameters that influence crash experience on horizontal curves include curve radius, curve length, superelevation, spiral curve, and curve deflection angle. These curvature parameters and their safety effectiveness are shown in Table 3.

Table 3. Horizontal Curvature Factors and Safety Effectiveness

Factors	Effectiveness	Previous Studies
Radius of Curve (R) or Degree of Curve (D) $\mathrm{D} = \frac{5230}{R}, \mathrm{R\ in\ ft}$	Short radius (large degree of curve) represents sharper curve: – Decrease margin of safety against vehicle crash by rollover or slide out – Decrease sight distance – Increase crash frequency/rate at curves – Increase crash injury severity at curves	(*8*, *10*, *16*–*22*)
Length of Curve (L)	Long curve length represents more exposure – Increase crash frequency/rate at curves – No influence on crash injury severity	(*1*, *8*, *17*, *19*–*21*)
Superelevation (S)	Superelevation and friction provide centripetal force to keep vehicle from going off road. – Increasing superelevation up to 0.8% and 1% in urban and rural areas, respectively, reduces crash frequency/rate	(*20*)
Spiral Curve (Transition Curve)	– Some studies reported that presence of long spiral curves reduces crash frequency/rate – Other studies concluded that transition curves are dangerous because of driver underestimation of severity of horizontal curves	(*8*, *10*, *20*)

Other geometry-related factors contributing to crash frequency and/or severity are summarized in Table 4.

Table 4. Associated Factors Contributing to Curve-related Crashes

Factors	Effectiveness	Previous Studies
Lane Width	Wide lane width: - provides more space in negotiation with curves - provides better sight distance - reduces crash frequency on curves	(*10*, *16*, *23*)
Shoulder Width	Crash frequency/severity decreases with increase in shoulder width	(*1*, *16*, *18*, *20*, *21*)
Traffic Volume (ADT/AADT)	High traffic exposure increases crash frequency on curves	(*16*–*21*, *23*)
Speed Limit	High speed limit increases crash frequency and severity on curves	(*2*, *10*, *21*, *24*, *25*)

2.4 Motorcycle Rider Behavior Studies on Curves

In addressing motorcyclist safety, the effectiveness of a countermeasure is usually investigated through two approaches: crash analysis and proactive analysis (e.g., behavior study). Although traffic crashes (e.g., frequency, severity, fatality rates, etc.) are the direct measure of safety, there are some limitations of analyzing crash statistics for countermeasure evaluation:

- Analyzing crash data is a reactive approach to safety issues, as a safety problem can be identified only after several crashes have been recorded. This approach, therefore, does not allow *ex-ante* evaluations.
- As motorcycle crashes are (fortunately) rare, it can take quite some time before unsafe situations become apparent. Quick safety scans based on crash data are not very feasible.
- Many minor injury crashes might go underreported, as lower crash severity levels make reporting to authorities less likely, which may result in biased estimates.

Compared to crash analysis (reactive method), behavioral studies have emerged as the proactive method that can provide an *ex-ante* prediction of the safety effects of a specific measure (*26*). Studies show that in 93% of vehicle crashes, the crash was, at least partially, a result of driver behavior, which means driver behavior is the most important factor for traffic safety. An important advantage of a behavioral study is the fact that relatively unsafe driving behavior or potential conflicts occur more frequently than accidents; therefore, a shorter period of observation is required.

As a motorcyclist behavior measure, riding speed on curves is critical to motorcycle safety on horizontal curves. Negotiating curves requires that motorists anticipate the curve by adjusting their speed and lane position to accommodate the severity of the curve (*27*). According to the laws of mechanics, the force resolution for resolving the forces acting on a vehicle traversing a curve leads to the following formula (*28*):

$$f = \frac{v^2}{R * g} - e \qquad (2)$$

where f = side friction factor, v = speed of vehicle, R = radius of curvature, and e = superelevation. Equation 2 is based on the force balance for a point mass on a superelevated surface traveling at a certain speed along a circular arc. When curvature/path radius, superelevation, and side friction factors are fixed, a higher speed will increase the likelihood of slipping and rollover. Studies have found that there is a considerable difference between motorist driving speeds and paths they take on horizontal curves. The design radius and the radius driven by a motorcycle can vary considerably, which can alter the forces experienced by an individual motorcycle.

Regarding motorcycle crashes at curves, Hurt, Ouellet, and Thom (*29*) identified "slide-out and fall due to over-braking or running wide of a curve due to excess speed" as common motorcyclist errors. Clarke et al. (*30*) found that most single-vehicle crashes were caused by the rider's misjudgment of the appropriate speed when riding through a curve and that the majority of the motorcyclists are aware of this error. The authors concluded that countermeasures must address the need to make motorcyclists slowdown in relation to road hazards such as bends.

Motorcyclist riding speed is also an important factor related to injury severity, because the lack of a protective structure and differences in mass heighten their injury susceptibility in collisions with rigid objects (i.e., vulnerable road users). Researchers simulated motorcycle crashes and showed that speeds of 48 and 60 km/hr (30 and 37 mph) will cause a motorcyclist to eject form the vehicle and somersault to land on his/her back, whereas at 32 km/hr (20 mph) the speed is not enough to create a whole rotation and, thus, the motorcyclist lands on his/her head (*31*). Table 5 summarizes the safety behavior measures (e.g., speed and lane position) in motorcyclist behavior studies. Most of these studies generally examined motorcycle speed as a safety measure because the appropriate response for road hazards such as curves was to slow down at some point after the hazard was visible (*32*, *33*).

Table 5. Summary of Previous Studies on Safety-related Motorcyclist Behaviors

Reference	Behavior Measures	Method	Notes/Findings
(*34*)	• Speed • Lane position	• Motorcycle simulator • Compare experiential and behaviors • Across motorcyclist groups	• Non-advanced motorcyclists more likely to choose inappropriate lane position than inappropriate speed when entering a bend
(*35*)	• Free-flow speeds	• Instrumented motorcycle • Speed prediction model • Ordinary Least Square method	• Speed adjustment with various driving conditions • Experienced motorcyclist speeds significant more than inexperienced rider • Improvement of road conditions increase speed
(*28*)	• Mean speed	• Instrumented motorcycle • Speed prediction model • Ordinary Least Square method	• Significant variation was detected on motorcyclist behavior when carrying pillion related to experience level
(*36*)	• Longitudinal accelerations	• Testing motorcycle-equipped intelligent curve warning system • Compare actual and ideal accelerations to trigger warning	• Results prove intelligent curve warning system can provide reasonably early warning
(*37*)	• Throttle activation • Longitudinal acceleration • Speed	• Motorcycle simulator • Questionnaires	• Riding with curve warning system with haptic glove leads to reduction of critical curve events • System with force feedback throttle required increased attention
(*32*)	• Speed	• Simulator	• Experienced motorcyclists crashed less often, received better performance evaluations, and approached hazards at more appropriate speed

Table 5, continued

(*33*)	• Speed • Steering • Eye movement	• Simulator • Instrumented motorcycle • Mental workload evaluation	• Results revealed differences between experts and first-time motorcyclists and effect of training on novice group
(*38*)	• Appropriate speed Lane positioning • Overtaking • General caution • Ability to detect/avoid hazards	• Questionnaire • Simulator • Rating scores	• Simulator useful for distinguishing motorcyclists from drivers during safe periods of riding but not necessarily during hazardous periods
(*39*)	• Sight distance to stopping distance ratio • Visual gaze area • Speed • RSP circuit ride scores	Video gaze data	• Beginner-trained motorcyclists rode more quickly over curved section of closed course than other two groups • Experienced motorcyclists rode more quickly over curved section of open road than other two groups

2.5 Countermeasures to Improve Motorcycle Safety at Horizontal Curve Segments

Various countermeasures are available to improve motorcycle safety at horizontal curve segments, and three main aspects should be addressed that may improve motorcycle safety: road user, vehicle, and infrastructure. The countermeasures related to infrastructure improvements are the focus in this project, including:

- Warning signs/systems to increase motorcyclist alertness
- Ability to judge the curve sharpness
- Motorcycle-optimized horizontal curve designs (e.g., skid-resistant pavement surfaces and adding paved shoulders)

These safety countermeasures serve two functions: (1) prevent motorcycle crash occurrence (i.e., reduce crash frequency), and (2) minimize the consequences when a crash does occur (i.e., reduce the severity of an injury in the event of a crash).

2.5.1 Countermeasures to Prevent Motorcycle Crash Occurrence

Communication of Curves

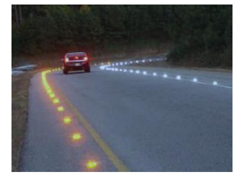
Horizontal curves are likely to reduce the available sight distance and adversely impact vehicle-handling capabilities, increasing the potential for traffic crashes and fatalities. The challenges associated with safe negotiation on horizontal curves compound with the addition of a nighttime driving environment or adverse weather. However, communicating these constraints to motorcyclists mitigates the potential for adverse traveling results. Countermeasures for warning and better delineation (for both vehicle and motorcycle) include:

- Advance curve warning and advisory speed signing
- Chevrons and enhanced chevron signs
- Vertical delineation and reflective barrier delineation
- On-pavement curve signing
- Converging chevron pavement marking pattern
- In-pavement lighting
- Flashing beacons
- Dynamic speed feedback sign
- Sequential dynamic LED-enhanced chevron signs
- Dynamic curve warning system

Table 6. Countermeasures Related to Communication of Curves

Countermeasures	Purpose	Notes	Example
Advance Curve Warning & Advisory Speed Signing	Inform drivers of a curve & recommend comfortable and safe speed	Uniformly and consistently displayed so curves with similar characteristics (e.g., radius, sight distance) have similar messages	
Chevrons & Enhanced Chevron Signs	Delineate curve so drivers are better able to gauge sharpness of curve	Larger chevrons could be particularly useful if sight distance issues exist; retroreflective signs are very useful at nighttime	
Vertical Delineation	Improve curve delineation	Flexible bollards or pylons can reduce the effects of a motorcyclist colliding with a post	
Reflective Barrier Delineation	Improve curve delineation, particularly effective at night and during wet weather	Reflectors (e.g., panels of retroreflective sheeting) can be applied when barriers (e.g., guardrails) present	
On-Pavement Curve Signing*	Indicate alignment change in advance of horizontal curves	Placing markings at same location as for advisory signs would allow driver sufficient time to react and adjust speed	

Table 6, continued

Converging Chevron Pavement Marking Pattern*	Reduce speed by creating illusionary effect of speeding up	Chevron pavement marking sets should be placed increasingly closer as driver moves into pattern	
In-Pavement Lighting*	Increase visibility of horizontal curves, particularly during nighttime and wet weather	Most appropriate for locations with large number of nighttime or adverse weather crashes	
Flashing Beacons	Provide notice to drivers that conditions are changing ahead	Used in conjunction with appropriate signing	
Dynamic Speed Feedback Sign *(ITS Application)*	Provide message (e.g., actual speed or SLOW DOWN) to drivers exceeding a speed threshold	Target drivers who are speeding rather than all drivers	
Sequential Dynamic LED-Enhanced Chevron Signs *(ITS Application)*	Typically set up via radar to flash only when driver exceeds set speed threshold	Apply selectively to high-crash curve locations	
Dynamic Curve Warning System *(ITS Application)*	Interact with individual driver; may lead to better compliance, as message appears more personalized	Changeable message sign and radar unit	

***** If large pavement markings pose a threat to motorcyclists due to a change in height or friction, other treatments should be considered. Sources: *(6, 40–42)*

Effectiveness of Speed Feedback Countermeasures

Among the countermeasures related to communication of curves in

Table 6, the effectiveness of speed feedback countermeasures have been studied in different conditions in United States and other countries, as shown in Table 7. The feedback may be the driver's actual speed, a message such as SLOW DOWN, or activation of a warning device such as beacons or a curve warning sign.

Table 7. Effectiveness of Speed Feedback Countermeasures

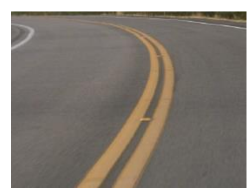
Reference	Treatments	Facility Type	Change in Speed (mph)					
			Motorcycle		***Car***		***Other (e.g., truck)***	
			All	*Week day*	*All*	*Week day*	*All*	*Week day*
(*43*)	Speed Indicator Devices	London: residential or commercial and residential mix	1.2	-1.9	-1.5	-1.9	-0.9	-1.6
(*44*)	Dynamic Speed-Activated Feedback Sign	OR: I-5 near Myrtle Creek, on a curve	/		-2.6		-1.9	
(*45*)	Speed Activated Sign	SC: on secondary highways	/		-3		/	
(*46*)	Dynamic Curve Warning Systems	CA: 5 sites in Sacramento River Canyon on I-5	/		-3.0~ -7.8 (4 sites)		-1.9~ -5.4 (3 sites)	
(*47*)	Dynamic Speed Feedback Sign	MN: 2-lane rural roadway	/		Vehicles with CURVE AHEAD–REDUCE SPEED sign more likely to negotiate curve successfully			
(*48*)	Vehicle-Activated Curve Warning Sign	UK: 3 curves on 2-lane road	/		-2.1~ -6.9		/	
(*49*)	Speed Feedback Sign	Doncaster, UK: semi-rural roadways	/		-7 (85^{th} percentile)		/	

Pavement Treatments

A vehicle will skid during braking and maneuvering through a curve when frictional demand exceeds the friction force between the roadway and the vehicle tire, which is particularly true during wet weather. Pavement grooving and high friction surface are two common treatments to improve pavement friction and increase skid resistance. However, grooved pavement may cause hazards to motorcycles. Motorcycles, with only two wheels, are more susceptible to difficulties and hazards such as edge drop-offs, curbs, uneven surface, slick pavement markings, etc. Balancing general countermeasures (e.g., pavement marking reflectivity) with motorcyclist-specific needs is a challenge requiring continued vigilance. Countermeasures related to pavement conditions typically include:

- Pavement grooving (cars only)
- High-friction surface
- Gap left in pavement marking (for motorcycles)
- Centerline rumble strips with sinusoidal cut pattern (for motorcycles)
- Raised/recessed pavement markers
- Better pavement maintenance

Table 8. Pavement Treatments

Treatments	Purpose	Applicable		Notes	Example
		Car	*MC*[*]		
Pavement Grooving	Increase skid resistance and directional control (better drainage and rougher surface)	Yes	**No**	• Create longitudinal cuts in concrete surfaces • Use motorcycle placard to alert motorcyclists	
High-Friction Surface	Increase coefficient of friction and improve skid resistance for dry and wet pavement	Yes	Yes	Binder and aggregate material (e.g., textured pavement by troweling, open-graded asphalt mixes) on asphalt or concrete pavement	
Gap Left in Pavement Marking	Allow motorcyclists to pass marking without encountering change in friction	/	Yes	Suitable for large pavement markings that can pose threat to motorcyclists because of change in height or friction	
Centerline Rumble Strips with Sinusoidal Cut Pattern	Eliminate sharp edges that pose hazards to motorcyclists	/	Yes	Create motorcycle-friendly safety edge	
Retroreflective Raised/Recessed Pavement Markers	Provide lane guidance and improved delineation at night and during wet weather	Yes	Careful	Pavement marking reflective and traction should be balanced for motorcycles	
Better Pavement Maintenance	Avoid or remove humps, bumps, and slick surfaces that are hazardous to motorcyclists	Yes	Yes	Avoid excess tar when sealing roadway cracks; remove loose material (e.g., sand and gravel)	

[*]*MC=Motorcycle; Sources:* (*40–42*, *50*)

Shoulder and Drainage

Rural roads, which often are preferred by motorcyclists, present design and construction challenges for engineers. In rural areas, narrow rights-of-way are usually available, which limits the roadway, shoulders, and proper drainage features. If water cannot drain properly, shoulder deterioration can cause pavement drop off and shoulder loss, and the uneven road surface can catch the motorcyclist off-guard. Consequently, a rider's loss of footing may cause him or her to lose control of the motorcycle. Moreover, many rural roads have narrow, unimproved, or no shoulders. The lack of a recovery area often contributes to motorcycle crashes when a motorcycle departs the roadway pavement. In addition, shoulder rumble strips often are used to alert drivers when they depart the road lanes. However, the type or pattern of rumble strips selected, and their placement should be based on a consideration of unconventional vehicle needs (e.g., motorcycle), available shoulder width, pavement age, and installation method. Countermeasures related to shoulders and drainage typically include:

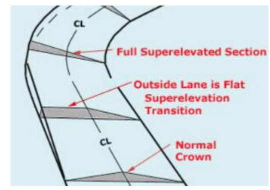
- Roadway crowns
- Widening/adding shoulders
- Shoulder drop-off elimination
- Shoulder rumble strips

In addition to all the countermeasures above, there are several large intelligent transportation system (ITS) projects in the research and development phase to improve motorcycle safety. For example, an automatic emergency notification and localization system linked to a rider's mobile phone named e-Call is underway in European. These advanced driver assistance systems and connected vehicles (e.g., vehicle-to-infrastructure, vehicle-to-vehicle communications) are promising for improving traffic safety.

2.5.2 Countermeasures to Reduce Injury Severity

Countermeasures to reduce injury severity provide a more forgiving environment if run-off-road incidents occur. Roadside hazard management consists of two key strategies: development of clear zones and modifying roadside hazards, especially trees and poles, such that any impact is either totally avoided or has reduced consequences. Table 9 shows countermeasures related to shoulders and drainage.

Table 9. Countermeasures Related to Shoulders and Drainage

Counter-measures	Purpose	Applicable		Notes	Example
		Car	*MC**		
Roadway Crowns	Great for drainage	Yes	No	Present unique challenges to motorcyclists when stopping, turning, or slowing down	
Widening/ Adding Shoulders	Provide additional space for recovery when vehicle leaves roadway	Yes	Yes	Not always practical due to right-of-way and resource constraint	
Shoulder Drop-Off Elimination	Mitigate run-off-road accidents by employing safety edge	Yes	Yes	Produce wedge-shaped edge to pavement as asphalt placed	
Shoulder Rumble Stripes	Provide audible and vibratory alerts to drivers when vehicles depart roadway	Yes	Care -ful	Consider specific needs for motorcycles	

**MC=Motorcycle; Sources:* (*40–42*, *50*)

Provision of Safe Roadsides

Provision of safe roadsides is an important measure to reduce injuries in crashes involving all road users, but it is particularly important for motorcyclists since they are vulnerable road users with less protection than drivers in four-wheeled vehicles (*42*). To provide safe roadsides, countermeasures such as a clear zone have been recommended. A clear zone is an unobstructed, traversable roadside area that allows a driver to stop safely or regain control of a vehicle that has left the roadway. For motorcycle safety, a systematic countermeasure is usually needed, including redesigned side terrains, consolidated signposts, larger clear zones, improved sight distances around curves, and motorcycle-friendly barriers. An example of a motorcycle safe roadside is shown in Figure 4.

(a) before treatment

(b) after treatment

Source: (40)

Figure 4. Norwegian Vision Zero Motorcycle before and after Treatment

Improved Barrier Design

Barriers are erected to prevent the occurrence of some of the most severe types of crashes (e.g., head-on and rollover crashes, crashes into trees, poles, and other roadside objects). There are three general categories of barriers that have different performance characteristics and use: solid concrete barriers often are placed between opposing lanes of traffic on urban freeways to prevent head-on collisions; steel W-beam guardrails are used to prevent crashes with trees, poles, and other rigid objects; and flexible barriers have four heavily-tensioned steel cables fastened in parallel between upright posts. Motorcyclists are vulnerable road users, and some motorcycle-friendly barrier designs have been developed to shield a body sliding on the pavement from a post, as shown in

Table 10.

Table 10. Countermeasures of Improved Barriers

Countermeasures	Purpose	Notes	Example
W-Beam Guardrail Equipped with Lower Motorcycle Barrier	Minimize injury to motorcyclists by adding extra piece (rub rail) that fits along bottom of the W-beam	Steel W-beam fitted with rub rail on high-speed, tight-radius curves	
Flexible Safety Barriers	Reduce effects of motorcyclist colliding with post in crash by adding post protectors	Install flexible barriers with padding around each post, on slow-speed, tight-radius curves	

Sources: (*40*, *41*)

2.6 Motorcycle Exposure Data and Methodology

Motorcycle exposure data, a measure of motorcycling activities, is important in deriving motorcycle safety statistics such as crash rates and injury rates. Vehicle Miles Traveled (VMT) is considered the best measure for exposure because it measures actual miles traveled and is US DOT's preferred method of measuring fatality rates (Middleton et al., 2013). Crash and injury rates per 100 million VMT are considered the most valid indices of risk. However, little information is available about the amount of motorcycle riding that is done and how that has changed from time to time (*51*, *52*).

In estimating motorcycle VMT, the most common method is the count-based estimates. Counting technologies include intrusive (e.g., loops, piezoelectric sensors, and road tubes) and nonintrusive technologies (e.g., video, radar, and infrared traffic logger). The details on existing technologies and procedures for counting motorcycles can be found in NCHRP Project 8-36B (Task 92) (*53*).

An alternative approach to estimate motorcycle volume and VMT is to derive estimates from registration data or insurance company records (commonly referred to as registration-based estimates). The following sources may be used for the estimation (*51*, *52*, *54*):

- Motorcycle registration data
- Motorcycle license data
- Motorcycle sales data
- Travel demand data
- Surveys of motorcyclists (according to the National Household Traffic Survey [NHTS], 5% own motorcycles and 3.6% of all vehicles are motorcycles)
- Roadside manual counts
- Insurance company data

In Australia, Haworth (*51*) found that motorcycles comprised 0.5% of vehicles and that this proportion did not differ greatly by road type, although it was generally higher during daytime (6am–6pm) and lower during night-time (6pm–6am). It is well-known that the activity of motorcycles is subject to substantially greater seasonal and day-of-week variation than the activity of other vehicles (e.g., four-wheeled vehicles). Thus, use of seasonal and day-of-week factors, which may be derived from continuous counts of motorcycles, is usually a prerequisite for producing reasonable annual average daily traffic (AADT) estimates for motorcycles.

Chapter 3
Data Collection

This report represents the efforts of data collection in Task 2. As crash modeling is a data-driving methodology to explore contributing factors to motorcycle crash frequency/ severity on horizontal curves and to develop CMFs, a comprehensive dataset was needed for this project, including crash data, curvature data, geometry data, pavement data, traffic control data, environmental data, traffic data, motorcycle data, and rider/passenger data. The needed data categories and sources are shown in Table 11.

Table 11. Needed Data Categories and Sources

Data Category	Data Sources	Purpose
Crash – Severity, type, date, time, …	• FDOT CAR	• Crash frequency analysis • Crash severity analysis • CMF development
Curvature Parameters – Radius, length, type, …	• FDOT RCI • FDOT GIS Layers • Google Earth	
Geometry – Lanes, median shoulder, …	• FDOT RCI • FDOT GIS Layers • Google Earth	
Pavement – Condition, roughness, friction, …	• FDOT CAR • FDOT RCI	
Traffic Control – Speed limit, traffic sign, pavement markers, …	• FDOT RCI • Google Earth	
Environment – Lighting, weather, …	• FDOT CAR	• Crash severity analysis
Traffic – AADT, truck %, …	• FDOT RCI • FTI	• Crash frequency analysis • Crash severity analysis • CMF development
Motorcycle – Year, movement, speed, …	• FDOT CAR	• Crash severity analysis
Rider/Passenger – Age, gender, …	• FDOT CAR	

These sources contain millions of data records. To process the large-scale data, the research team developed a stand-alone application on the Microsoft Visual Basic.Net platform (as shown in Figure 5). This application retrieved data from original sources based on given conditions and converted raw data to proper formats. The intermediate data and final data were stored in a project database hosted on CUTR’s MS SQL servers. In addition, ArcGIS 10.3 and Google Earth Pro were used to conduct spatial analysis and data review/validation.

With these computer tools, the research team implemented a procedure for data collection and processing, as shown in Figure 6. The following chapters describe the details and results of each step in the procedure.

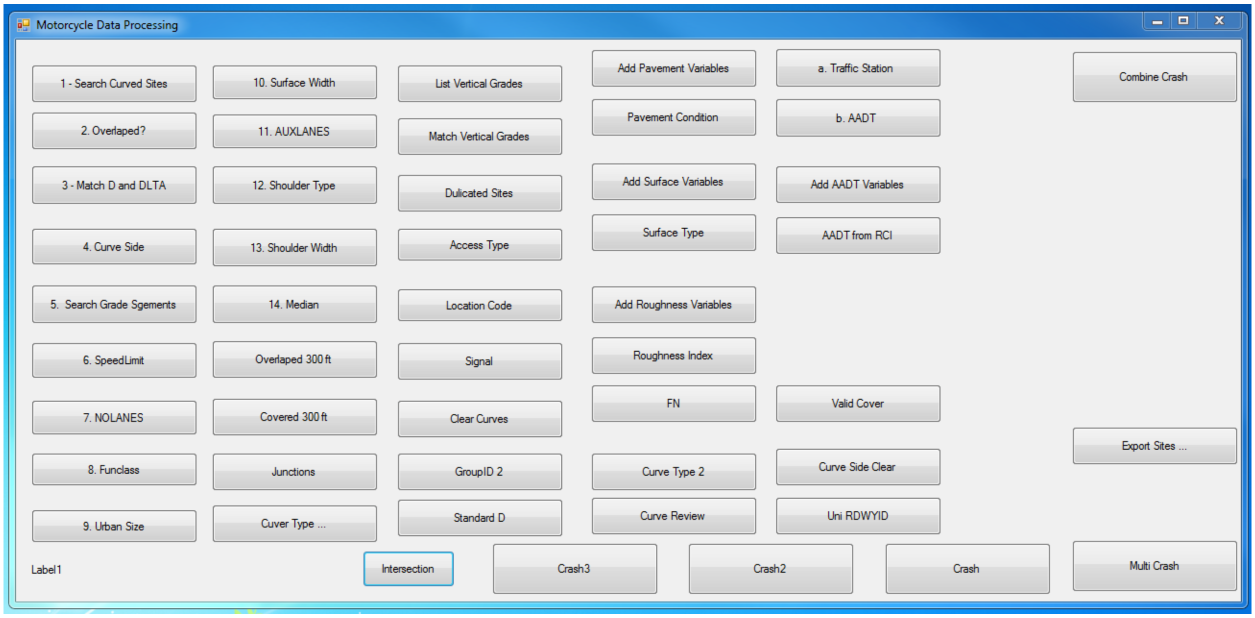


Figure 5. Stand-alone Application for Data Processing

Figure 6. Overall Procedure for Data Collection and Processing

3.1 Site Selection

The first step of data collection was to identify all horizontal curves on Florida rural two-lane roads. For comparison purposes, the straight segments with similar characteristics (RTN: rural, two-lane, no median) were also identified from the Florida roadway network. The site selection procedure and results are described as below.

3.1.1 Selection of Horizontal Curves

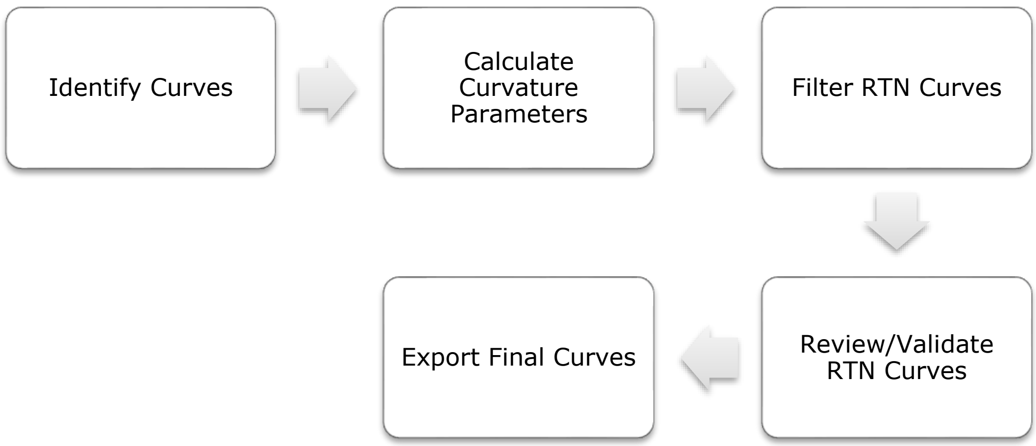


Figure 7. Procedure to Select Horizontal Curves on Rural Two-Lane Roads in Florida

Step 1 – Identify Horizontal Curves

The computer application scanned the FDOT Roadway Characteristics Inventory (RCI) database to identify any segment with the roadway characteristics of "HRZPTINT" (Horizontal Point of Intersection) as horizontal curves. "HRZPTINT" defines the milepoint number for the intersection of the back and forward tangents projected onto the roadway, as shown in Figure 8, including:

- PC – Point of Curvature –point on back tangent at which curve begins.
- PI – Point of Intersection –point at which back and forward tangents intersect.
- PT – Point of Tangency –point on forward tangent at which curve ends.

In total, 10,858 horizontal curves were identified from the FDOT RCI database.

Step 2 – Calculate Curvature Parameters

Horizontal Degree of Curve (D), represented by "HRZDGCRV" in RCI, denotes the degree of curvature per 100 feet (Figure 8). The research team scanned and matched "HRZDGCRV" for each identified curve in Step 1 based on Roadway ID and beginning/ending milepoints (PC/PT) of curves. The radius of curve was calculated by

$$\text{R in feet} = \frac{5729.6}{D \text{ in demical}} \tag{3}$$

Each curve site was extended 300 ft from its two ends (PC and PT), as shown in Figure 9. These buffer areas are significantly influenced by the curve. Two new curve ends were defined: beginning point of the curve = PC – 300 feet; ending point of the curve = PT + 300 feet. Roadway ID plus beginning/ending mileposts were used to identify a horizontal curve. The curve length was calculated as

$$\text{L in mile} = \text{Ending Milepost } - \text{Beginning Milepost} + 600 \text{ feet} \tag{4}$$

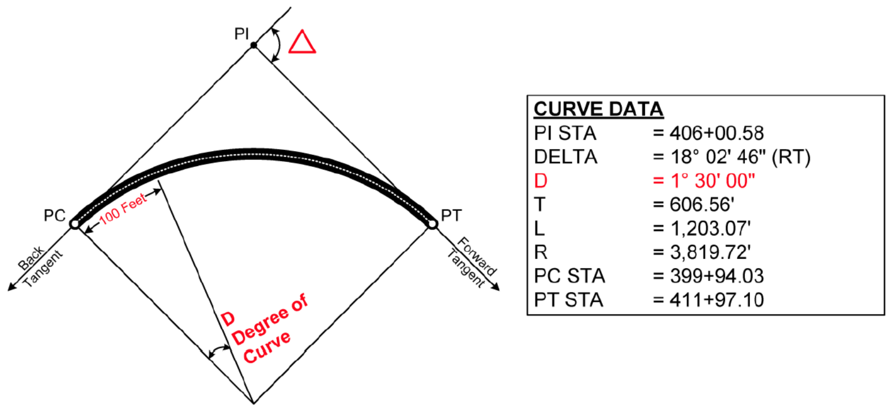


Figure 8. Horizontal Curve Parameters in RCI

Source: FDOT RCI Handbook

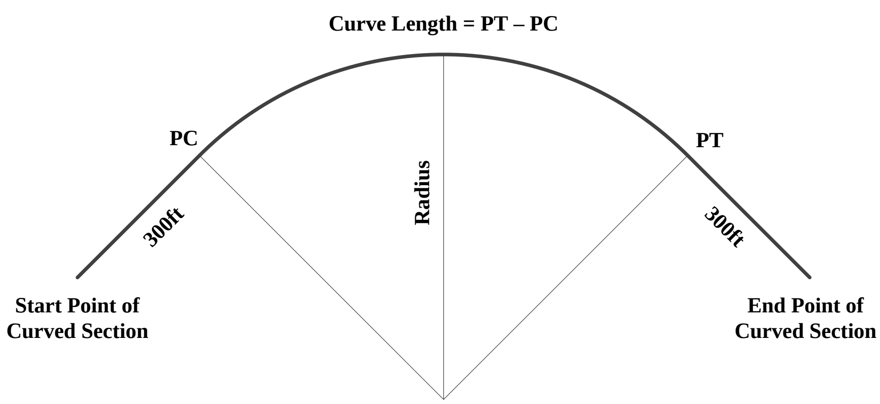


Figure 9. Extension of Horizontal Curve Sites

Step 3 – Filter Curves

This study focuses on motorcycle safety on rural two-lane roads. The identified curves were filtered by the following criteria:

- On rural roads (RCI variable "FUNCLASS" <= "09")
- Bi-directional two-lane roads (RCI variable "NOLANES" =2)
- No median or pavement median (RCI variable "RDMEDIAN" is null)

Finally, 2,540 curves on rural two-lane (no median) roads (RTN curves) were identified as the preliminary set of study sites.

Step 4 – Review Curves

The identified RTN curves were reviewed by the research team in ArcGIS and Google Earth to:

- Validate curve parameters
- Identify overlapped curves
- Identify composite curves and curve types

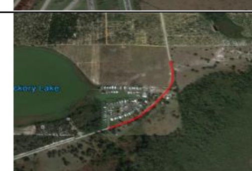
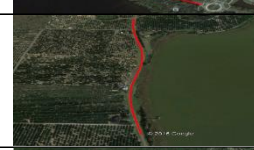
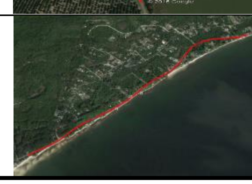
First, the side of the curve centers was retrieved from the roadside record of “HRZPTINT” in the RCI:

- Left – on left side at milepoint ascending direction
- Right – on right side at milepoint ascending direction

The research team reviewed the curves with invalid side information (center or mull) on Google Earth to determine their curve sides.

All overlapped curves also were identified in curve review. If a curve was fully covered by another curve, the duplicated curve was deleted from the list. If a curve overlapped with other curves (not fully covered), these curves constitute a composite curve. The research team reviewed these composite curves in ArcGIS/Google Earth to determine the curve type as defined in Table 12.

Table 12. Definition of Curve Types

Code	Description	Example
0	Single Curve (only one center of circle on same roadway side)	
1	Composite Curve, C-Type (two or more centers of circle on same roadway side)	
2	Composite Curve, S-Type (two centers of circle on two different roadway sides)	
3	Composite Curve, M-Type (three centers of circle on two different roadway sides)	
4	Composite Curve, X-Type (more than three centers of circle on two different roadway sides)	

Step 5 – Export Final Curves

After removing the duplicate or invalid curves, a final list consisting of 2,529 RTN curves was produced.

3.1.2 Selection of Straight Segments

In addition to horizontal curves, the research team identified straight segments with similar characteristics as the comparison baseline in crash modeling and CMF development (see Figure 10. Procedure to Select Straight Segments on Rural Two-Lane Roads):

- All rural roads were selected from the RCI database ("FUNCLASS" ⩽ "09").
- The selected rural roads were split into rural segments by signalized intersections ("SIGNALTY" = "02").
- The rural segments obtained in Step 2 were spatially matched to two-lane segments ("NOLANES" = 2).
- These segments were spatially matched to no-median segments ("RDMEDIAN" is null).
- The RTN segments may contain curves. Thus, the RTN segments were spatially matched to the identified curves. Any overlapped portions were removed from the list.

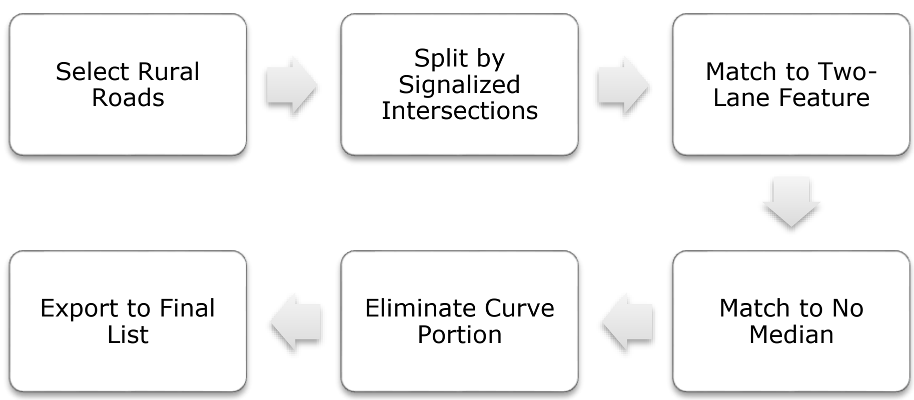


Figure 10. Procedure to Select Straight Segments on Rural Two-Lane Roads

Finally, 8,120 RTN straight segments were produced. The produced RTN curves and straight segments are shown in Figure 11.

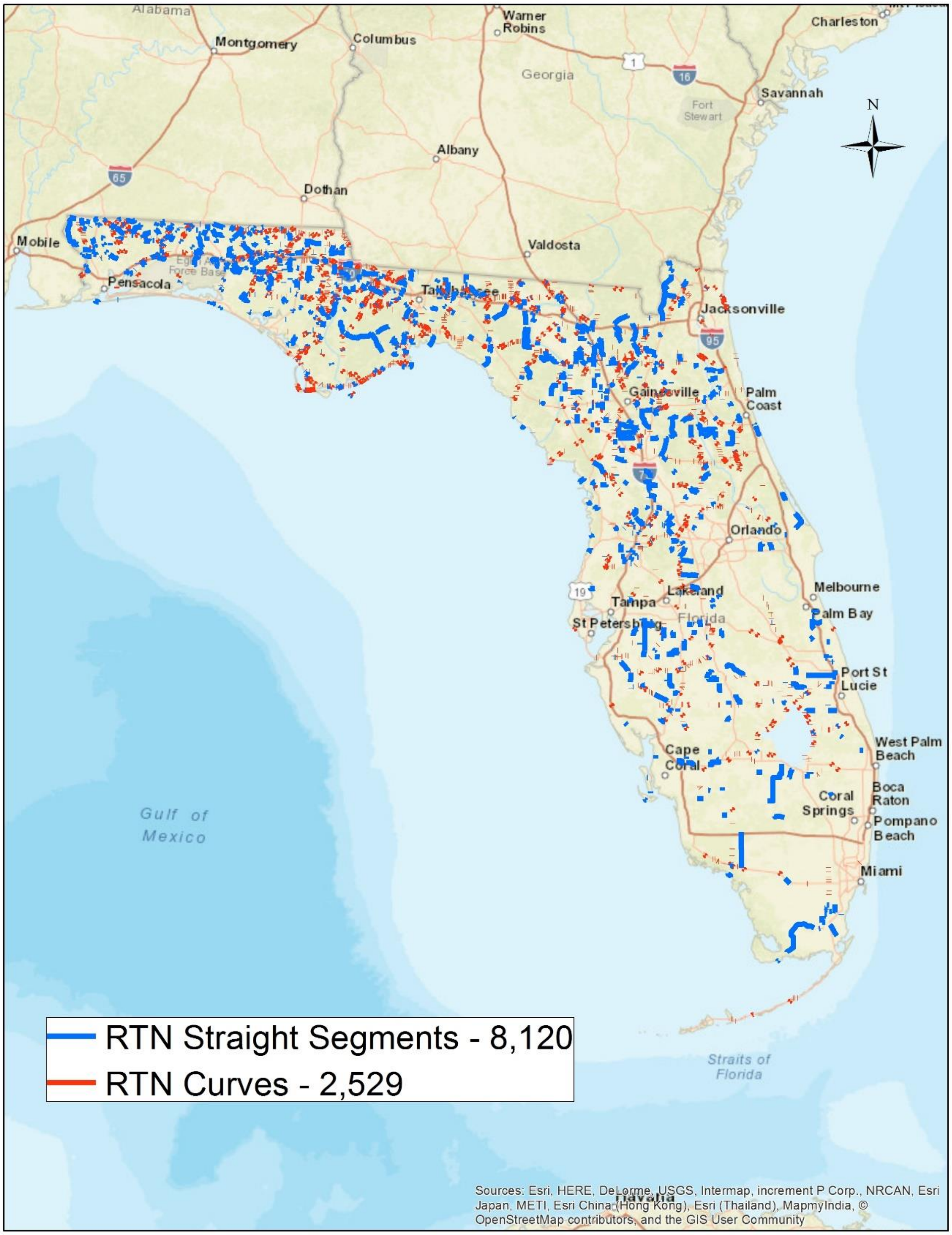


Figure 11. Selected Curves and Straight Segments on Rural Two-Lane Roads (No-Median)

3.2 Site Data Collection

Once the study sites (including curves and straight segments) were identified, the research team collected site-related data for each site, including geometry, pavement, traffic, and traffic controls. Roadway ID plus Beginning/Ending Mileposts, which describes the spatial range of a site, were used to match data features. Table 13 summarizes the site data collection.

Table 13. Summary of Site-related Data

Category	Data	Source	Original Variable	Note
Curvature	Radius	FDOT RCI	HRZDGCRV	Converted from Degree of Curve
	Length	FDOT RCI	HRZPTINT	= PT − PC + 600 feet
	Type	ArcGIS Google Earth	-	
	Grade	FDOT RCI	GRACLASF	
Geometry	Number of through lanes	FDOT RCI	NOLANES	
	Number of auxiliary lanes	FDOT RCI	AUXLNUM	
	Shoulder type	FDOT RCI	SHLDTYPE SHLDTYPx	
	Shoulder width	FDOT RCI	SLDWIDTH SHLDWTHx	
Access Management	Access density	FDOT RCI	INTSDIRx	= Number of intersections within sites / site length
Pavement	Pavement condition	FDOT RCI	PAVECOND	
	Pavement surface type	FDOT RCI	SURFNUM	
	Roughness index	FDOT RCI	ROUGHIND	
	Pavement skid number	FDOT CAR	SKTRESNM	
Traffic	AADT	FDOT RCI FTI DVD	SECTADT	2013–2015
	Truck percentage	FDOT RCI FTI DVD	AVGTFACT	2013–2015
Traffic Control	Speed limit	FDOT RCI	MAXSPEED	
	Signal	FDOT RCI	SIGNALTY	If any signal exists within site

3.3 Motorcycle Crash Data Clearance and Site Match

The research team cleared up motorcycle crash data from the FDOT Crash Analysis and Reporting (CAR) database (2005– 2015) using the following procedure.

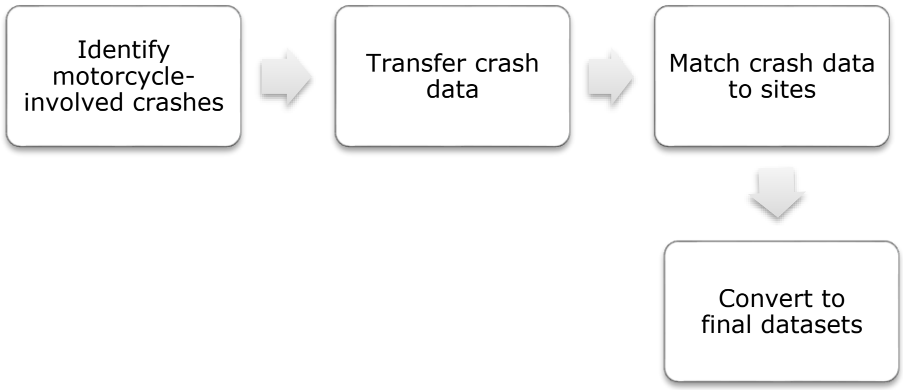


Figure 12. Procedure to Motorcycle Crash Data Clearance

- **Identify Motorcycle-involved Crashes** – Crash events with at least one motorcycle involved were defined as motorcycle-involved crashes. The research team scanned all crash records from 2005 to 2015 in the FDOT CAR system. If any vehicle involved in a crash was coded as “motorcycle” (“VEHICLETYP” = 11), the crash was labeled as a motorcycle-involved crash. In total, 105,310 motorcycle crashes were selected.
- **Transfer Crash Data** – The raw crash data in the FDOT CAR system was stored in three tables: Crash, Vehicle, and Person. One record in the crash table, representing one crash, may connect to multiple records in the Vehicle and Person tables (multiple vehicles and persons in one crash). The research team transferred the data of motorcycle crashes from different tables to one data row.
- **Match Crashes to Sites** – Roadway ID plus Beginning/Ending Mileposts represent the spatial range of a site. A crash, as a data point, also has a similar location indicator (Roadway ID plus Milepost). A motorcycle crash was linked to a site if the following criteria were satisfied:
    - Roadway ID of motorcycle crash = Roadway ID of site
    - Beginning milepost of site ≤ Milepost of crash ≤ Ending Milepost of site

  In total, 440 motorcycle crashes were found for 2,529 horizontal RTN curves (rural, two-lane, no median). Meanwhile, 1,524 motorcycle crashes were found for 8,120 control sites (straight segment with similar characteristics).
- **Export to Final Datasets** – Two kinds of datasets were produced as the final outputs:
    - Site Level – all data (site data and linked crash data) were organized for each site. One row represents one site. This dataset was used for crash frequency/occurrence analysis and CMF development.
    - Crash Level – all data were organized for each crash. One row represents one crash and its linked site. This dataset was used for injury severity analysis.

The collected crash data fields are summarized in Table 14. In total, 440 motorcycle crashes for 11 years (2005–2015) on 2,529 RTN curves were analyzed. The descriptive analysis of the collected site and crash data is given in Appendix A.

Table 14. Summary of Collected Crash Data

Data Field	CAR Table	Note
CARNUM	CRASH, VEHICLE, PERSON	Identifier for each crash
CRASHTYPE	VEHICLE	Crash type: single, motorcyclist-at-fault, other
CRASHDATE	CRASH	Crash date and time
DIRECTION	CRASH	
ACCISEV	CRASH	Injury severity
SITELOCA	CRASH	Specific site: intersection, interchange …
LIGHTCND	CRASH	Lighting condition
WEATHCND	CRASH	Weather condition
TRAFCTRL	CRASH	Traffic controls
ALCINVOLV	CRASH	Alcohol/drug involved
VHYEAR	VEHICLE	Motorcycle year
VHSPD	VEHICLE	Motorcycle speed
HARMEVN	VEHICLE	Harmful events
VHTYP	VEHICLE	Vehicle type
TRAVDIR	VEHICLE	Travel direction
CONTCAU	VEHICLE	Contributing causes
RIDER	PERSON	Rider/Driver/Passenger
AGE	PERSON	Age
GENDER	PERSON	Gender
SAFEQCD	PERSON	Safety equipment: helmet …

Chapter 4
Crash Analysis and Development of CMFs

4.1 Overview

Motorcycle crash patterns on horizontal curves on Florida rural roads were investigated. Through the crash analyses, the research team expected to achieve the following goals:

- Quantify the effects of horizontal curvature on motorcycle crash occurrence and severity.
- Identify factors contributing to motorcycle crash frequency on rural horizontal curves in Florida.
- Identify factors contributing to motorcycle crash severity on rural horizontal curves in Florida.
- Identify factors contributing to motorcyclist-at-fault in two-vehicle crashes on horizontal curves in Florida.
- Develop CMFs for motorcycle crashes on rural horizontal curves.

The systematic crash analysis was based on historical crash data collected in Florida. Two crash data types were used to address motorcycle safety issues on horizontal curves from two aspects: how horizontal curvature and other factors influence motorcycle crash occurrence (based on frequency data) and severity in a motorcycle crash (based on severity data).

- *Motorcycle crash frequency* – likelihood of motorcycle crashes, defined as the number of motorcycle crashes occurring within a given period (e.g., one year), on a roadway entity (e.g., a horizontal curve). Multiple crashes occurring at the same location over a period may be an indication of a safety issue and should be investigated and addressed appropriately.
- *Motorcycle crash severity* – outcome of a motorcycle crash; given that a motorcycle crash occurred, the most severe injury level involved in the crash. In the Florida CAR system, five crash severity levels are defined: Fatal, Incapacitating-Injury, Non-Incapacitating Injury, Possible Injury, and No Injury. The high probability of severe injuries from motorcycle crashes may imply serious safety issues and more attention to safety improvement.

To address the safety effects of a geometric design (e.g., horizontal curvature) or a countermeasure (e.g., speed advisory sign), statistical comparison between the geometric design/countermeasure and a baseline (without the geometric design/countermeasure) is the basic method to distinguish the difference in crash frequency/severity from the baseline. The data organizations for the statistical comparisons typically can be classified as either before-after or cross-sectional studies. A before-after study surveys the change of crash frequency and/or severity before and after implementation of a treatment (design or countermeasure) at the same sites. A cross-sectional study compares the difference of crash frequency or severity over different sites during the same period. This study adopted the cross-sectional design for the following reasons:

- Horizontal curvature is a constant factor. Very few curve sites in which horizontal curvature varied over time were found within the observation period (2005–2015). Thus, before-after design is not feasible for assessing horizontal curvature.
- In current FDOT databases (e.g., RCI), it is difficult to capture treatments that may influence motorcycle safety and vary over the observation period (e.g., speed control signs). For these factors, before-after design also is not feasible.
- A cross-sectional study can provide enough samples over space within the observation period to capture the difference of horizontal curvature and other factors in motorcycle safety.

The research team implemented a procedure for crash analysis, as shown in Figure 13. The following chapters describe the details and results of each step in the procedure.

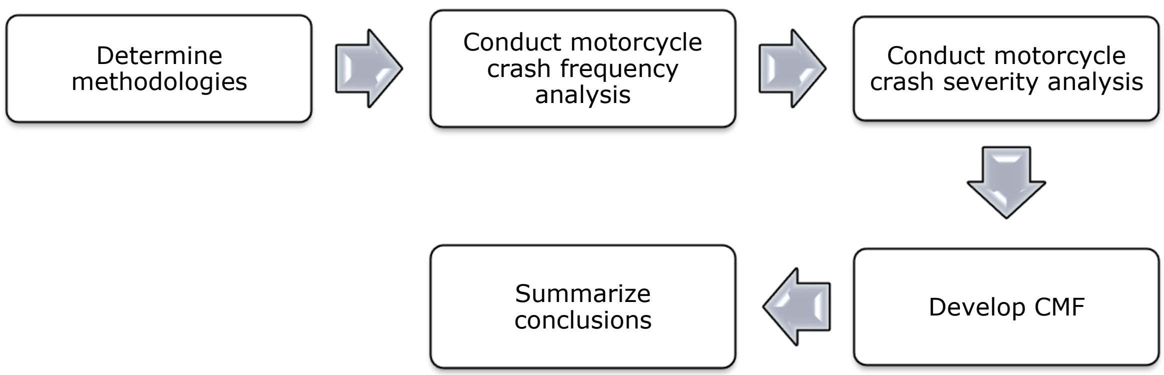


Figure 13. Overall Procedure for Data Collection and Processing

4.2 Methodologies

This section presents the efforts conducted to determine crash analysis methodologies, including considerations in motorcycle crash analysis, statistical technologies for crash frequency and severity modeling, and methodologies for CMF development.

4.2.1 Considerations in Motorcycle Crash Analysis

Traffic crashes are stochastic events; thus, statistical methodologies are a natural choice for analyzing crash data. Various statistical methodologies, such as descriptive analysis, hypothesis testing, regression model, etc., have been used widely in crash analysis. In this study, regression models were used to fit crash-frequency and crash-severity data since they can quantify the relationships between the dependent variable (crash frequency or crash severity) and explanatory variables (horizontal curvatures, geometric design, pavement conditions, motorcyclist characteristics, etc.).

Motorcycle crash data, either frequency or severity, have specific characteristics and considerations in crash modeling, as follows:

- *Unobserved heterogeneity* – The occurrence and severity of a motorcycle crash is a complicated outcome that involves complex interactions among human factors and roadway characteristics, vehicle features, traffic attributes, and environmental conditions (*55*). Sample data for crash modeling usually are retrieved from police accident reports and roadway characteristics inventory files; it is impossible to include all factors influencing the occurrence of a traffic crash in these databases over time, space, and individuals. The unobserved factors, correlated with the observed variables, potentially can cause the issue of unobserved heterogeneity—that is, differences among crash observations that are not measured. Ignoring the issue of unobserved heterogeneity may lead to biased and inconsistent parameter estimation, erroneous inferences, and predictions (*55*).
- *Confounding variables* – A confounding variable is an extraneous variable that correlates with both the dependent variable and the independent variable. Ignoring confounding variables in crash modeling, it may obtain a bias inference on the cause and degree of the change of motorcycle crashes. For example, traffic volume is a typical confounding variable related to both crash frequency (high traffic volume means a high probability of crash occurrence) and horizontal curvature (high traffic volume is more likely to occur on a high-class roadway with better geometric design, such as small curve radius). Without controlling confounding variables (match or average), the crash reduction on a curve may be caused by low traffic exposure rather than improvement of geometric design.
- *Self-selectivity/endogeneity* – The values of some factors are dependent on crash occurrence and severity. An example of this issue is that speed-warning signs are more likely placed on curves with high number of and/or severe crashes. This issue is called self-selectivity or endogeneity. If this endogeneity is ignored, an erroneous conclusion may be derived (*56*). In the example, a wrong conclusion that speed-warning signs tend to increase motorcycle crash frequency or severity may be obtained if we do not consider that the sites with speed warning controls are more likely to have high crash numbers or severe crash severity.
- *Low sample-mean and excess zero observations* – Motorcycle crashes are rare and random events. Some roadway entities may have few observed motorcycle crashes (low sample-mean and excess zeros) due to low motorcycle exposure. In this study, more than 98% of curves sites have zero observations of motorcycle crashes for the 11 years (2005–2015) of the study; the sample-mean is 0.02 crashes per 11 years. With the low sample mean and excess zeros, the traditional methodology may cause incorrect estimation and erroneous inferences (*56*).
- *Risk compensation* – Motorcyclist characteristics/behaviors are the most direct factors causing a motorcycle crash. Motorcyclist behaviors responding to a change of roadway conditions in negotiation of horizontal curves are first determined by his/her understanding on the change of roadway conditions. If a motorcyclist realizes the roadway conditions are dangerous, he/she may take some safer

behaviors (e.g., low speed, pay more attention on surrounding environment, etc.). If a motorcyclist feels safe, he/she may tend to take risk behaviors (e.g., high speed, careless riding, etc.), which may result in motorcycle crashes or increasing the crash severity. Ignoring this issue, the effects of a treatment may be over- or under-estimated (*57*).

This study addressed these issues from different aspects: good design of data collection scheme, proper modeling technologies, and careful interpretation. Mixed-effects models potentially can capture unobserved heterogeneity by allowing parameters to vary across observations (*57*). These models potentially also can give insight into other issues, such as risk compensation and endogeneity. In this study, two mixed-effects models (mixed-effects negative binomial model and mixed-effects logistic model) were used for fit crash-frequency and crash-severity data, respectively, to address unobserved heterogeneity and risk compensation. The case-control method was also used to develop CMF by controlling confounding variables and addressing low-mean sample.

4.2.2 Statistical Methodology for Crash-Frequency Data: Random Parameter Negative Binomial Model

Motorcycle crash frequency, as an indicator of the likelihood of motorcycle crash occurrence, is usually measured as a count variable with over-dispersion (variance greater than mean). The Negative Binomial regression model is an extension of the Poisson model to overcome possible over-dispersion in the crash data (*56*, *57*). In a Poisson regression model, the probability of curve segment *i* having y_i crashes per a given period is shown:

$$P(y_i) = \frac{EXP(-\lambda_i)\lambda_i^{\,y_i}}{y_i} \qquad (5)$$

where $P(y_i)$ is the probability of curve segment i having y_i crashes per a given period and λ_i is the Poisson parameter for curve segment i which is equal to curve segment $i's$ expected number of crashes per a given period, $E(y_i)$. Poisson regression models can be estimated by specifying the Poisson parameter λ_i as a function of explanatory variables by typically using a log-linear function:

$$\lambda_i = EXP(\beta X_i) \qquad (6)$$

where $X_i$is a vector of explanatory variables and β is the vector of regression coefficients (*58*). To address this over-dispersion problem, the Negative Binomial model can be derived as

$$\lambda_i = EXP(\beta X_i + \varepsilon_i) \qquad (7)$$

where $EXP(\varepsilon_i)$ is a gamma-distributed error term with mean 1 and variance α. The addition of this term allows the variance to differ from the mean as.$\mathrm{VAR}[yi] = \mathrm{E}[y_i][1 + \alpha\mathrm{E}[y_i]] = \mathrm{E}[y_i] + \alpha\mathrm{E}[y_i]^2$ The negative binomial probability density function can be described as

$$P(y_i) = \left(\frac{1/\alpha}{1/\alpha + \lambda_i}\right)^{1/\alpha} \frac{\Gamma\,(1/\alpha + y_i)}{\Gamma\,(1/\alpha) y_i!} \left(\frac{i}{1/\alpha + \lambda_i}\right)^{y_i} \qquad (8)$$

where $\Gamma(\cdot)$ is a gamma function.

To resolve the issue of unobserved heterogeneity, a random-parameters (mixed-effects) negative binomial regression model was developed to allow some parameters to vary across crash observations rather than fixed in traditional models. The equation of regression coefficients for random parameters model is given as

$$\beta_i = \beta + \phi_i \tag{9}$$

where $\phi_i$is a randomly distributed term with mean 0 and variance σ2. With this, the log-likelihood function can be shown as

$$LL(\beta) = \sum_{\forall i} ln \int_{\phi_i} f(\phi_i)\, P(y_i|\phi_i) d\phi_i \tag{10}$$

where $f(\cdot)$ is the probability function of the ϕ_i. Since Equation 6 cannot be derived to a closed form, the simulated maximum likelihood approach with a Halton sequence was used to estimate the model parameters (*59*).

4.2.3 Statistical Methodology for Crash-Severity Data: Mixed-effects Logistic Model

Motorcycle crash-severity, indicating the outcome of a motorcycle crash, is a categorical variable. In this study, the crash-severity data were aggregated into a binary variable: 1 -fatality or severe injury, and 0 - slight injury or no injury. Thus, binary choice models, such as logistic model was naturally used to fit the crash-severity data. The logistic model, also named the binary logit model, is expressed as (*60*):

$$\Pr(y_i = 1|X_i) = \phi(X_i\beta) = \frac{\exp(X_i\beta)}{1 + \exp(X_i\beta)} \tag{11}$$

where $\Pr(\cdot)$ denotes the probability of the injury severity (yi) of crash observation$i$; β is the vector of regression coefficients; X_i is the vector of explanatory variables for crash observation i; and $\Phi$is the cumulative distribution function (CDF) of the logistic distribution.

To resolve the issue of unobserved heterogeneity, mixed-effects models (also referred as random parameters models) were developed to allow some parameters to vary across crash observations, rather than fixed in traditional models. The equation of mixed-effects logistic model is given as

$$\Pr(y_i = 1|X_i) = \int \phi(X_i\beta) \,.\, f(\beta|\phi) d\beta = \int \left(\frac{\exp(X_i\beta)}{1 + \exp(X_i\beta)}\right).\, f(\beta|\phi) d\beta \tag{12}$$

where $f(\beta|\phi)$ is the density function of random parameter β with distribution parameter φ. Eq. 8 is a mix of two distributions: $\phi(X_i\beta)$ for error item and $f(\beta|\phi)$ for random parameters. The log-likelihood function for the random parameter logistic model can be derived as

$$LL(\beta) = \sum_{i} \{y_i \ln(\Pr(y_i = 1|X_i) + (1 - y_i)\ln(1 - \Pr(y_i = 1|X_i)\} \tag{13}$$

As Equation 13 cannot be derived to a closed form, the simulated maximum likelihood approach with a Halton sequence was used to estimate the model parameters (*59*).

4.2.4 Case-Control Methodology for Crash Modification Factor Development

As described in FHWA's *A Guide to Developing Quality Crash Modification Factors*, the case-control method has been employed more recently to estimate CMFs for geometric design elements (*61*). Case-control studies are based on cross-sectional data. However, unlike cross-sectional studies that select samples base the presence and absence of a specific characteristics (e.g., horizontal curve), case-control studies select samples based on outcome status (e.g., crash or no crash) and then determine the risk factor (e.g., sharp curve) within each outcome group. In case-control studies, cases are defined as those roadway entities that experience at least one crash during the observation period, and the corresponding controls are drawn from those entities that do not experience a crash during the period. A matching scheme, which randomly matches cases with controls that are similar in some potential confounding variables, provides a balanced design and automatically adjusts the estimates for the effects of variables included in the matching scheme.

The ratio of controls to cases may vary and often depends on the availability of time, budget, and other factors. As the ratio of controls to cases increases, the power of the design increases but at a decreasing rate (Figure 14).

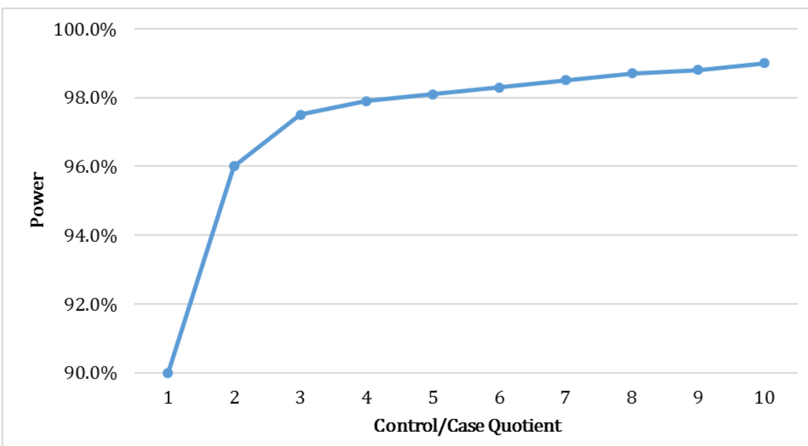


Figure 14. Power vs. Control/Case Quotient

Case-control studies assess whether exposure to a potential treatment (e.g., a sharp curve) is disproportionately distributed between the cases and controls, thereby indicating the likelihood of an actual benefit/loss from the treatment (*61*). A simple case-control analysis is shown in Table 15.

Table 15. Tabulation for Simple Case-Control Analysis

Risk Factor	Number of Cases	Number of Controls
With	A	B
Without	C	D

The odds ratio (CMF), indicating the relative risk, is expressed as the expected increase or decrease in the outcome in question due to the presence of the risk factor. An odds ratio greater than 1.0 suggests that the presence of the treatment increases risk, while a value less than 1.0 would suggest a decrease in risk. Using the notation in Table 15, the odds ratio is calculated as

$$Odds\ Ratio = CMF = \frac{A/B}{C/D} = \frac{AD}{BC} \tag{14}$$

The case-control method may be very useful for studying rare events, such as motorcycle crash-frequency data with low mean and excess zeros, because the number of cases and controls is predetermined. Another advantage of the case-control design is that multiple treatments may be investigated in relation to a single outcome using the same sample.

In this study, a complex case-control method was implemented. A conditional logit model was used to estimate the odds ratio. The conditional probability of an outcome associated with the unmatched variables (the risk factor in which we are interested) X_1, X_2, … , X_m for each member of the i^{th} matched set is given by

$$P(Y = 1) = 1 \Big/ \left\{ 1 + exp\left[-\left(\alpha_i + \sum_{j=1}^{m} \beta_j X_j \right) \right] \right\} \tag{15}$$

where:

m − number of explanatory variables

α_i − effect of matching variables for each matched set

β_j − estimated regression parameters for unmatched explanatory variables

X_j − unmatched explanatory variables included in the model

The odds ratio (CMF) for the unmatched explanatory variable β_j can be calculated as

$$Odd\ Ratio = Exp(\beta_j) \tag{16}$$

4.3 Analysis for Motorcycle Crash-Frequency

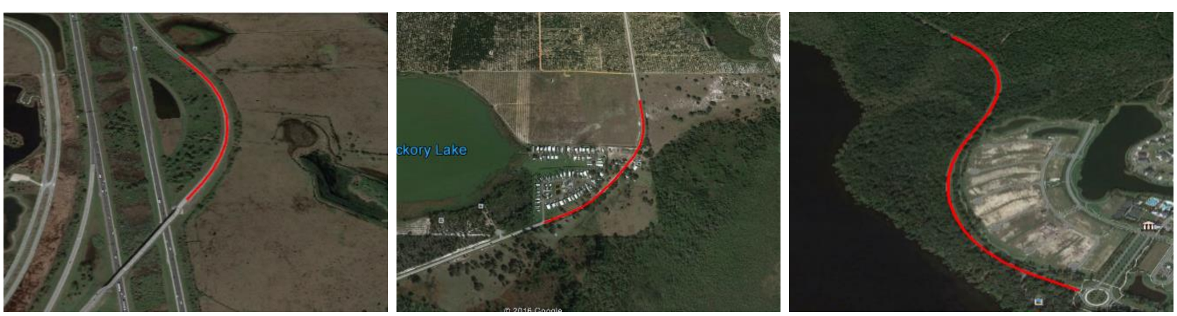
4.3.1 Descriptive Statistics of Motorcycle Crash-Frequency Data

The motorcycle crash-frequency data were organized at the site level, which means one record in the dataset represents one roadway entity (horizontal curve). In total, 2,179 horizontal curves (sites) were identified from the FDOT RCI database with the following characteristics: rural roads, two lanes, and paved median only. Information on geometry, traffic, and pavement data was extracted from the RCI database for each identified curve. In total, 439 motorcycle crashes for 11 years (2005–2015) were spatially matched to the identified horizontal curves. The descriptive statistics of the collected data are shown in Table 16.

The types of horizontal curve are classified as reverse curve and non-reverse curve. A reverse curve consists of two jointed simple curves but curving in opposite directions. A non-reverse curve could be a simple curve or a compound curve (a series of two or more simple curves with deflections in the same direction immediately adjacent to each other). The types of horizontal curves are shown in Figure 15.

Table 16. Descriptive Statistics of Motorcycle Crash-Frequency Data

Variable Description	Mean	Std. Dev	Min.	Max.
Dependent variable: number of motorcycle crashes (2005–2015)	0.198	0.581	0	8
Curve characteristics				
Logarithm value of curve radius (in log[ft.])	8.239	0.969	4.54	13.44
Reverse curve indicator (1 if curve is in reverse curves, 0 otherwise)	0.190	0.393	0	1
Curve length (in mi)	0.350	0.225	0.08	6.07
Geometric characteristics				
Shoulder width (in ft)	11.928	2.766	2	24
Auxiliary lane indicator (1 if auxiliary lane exists in curve segment, 0 otherwise)	0.024	0.153	0	1
Grade indicator (1 if vertical grade is present, 0 otherwise)	0.114	0.318	0	1
Access density: number of junctions per mile	3.026	4.731	0	48
Pavement characteristics				
Average pavement condition (scale 0–5)	3.798	0.420	2.4	5.0
Pavement roughness indicator (1 if 11-year average international roughness index (IRI) is greater than 75 in./mi, 0 otherwise)	0.309	0.462	0	1
Traffic characteristics				
Average annual daily traffic (AADT) (in 000 of vehicles/day)	4.269	2.959	0.46	25.18



1 – Single Curve 2 – Compound Curve 3 – Reverse Curve

Figure 15. Types of Horizontal Curves

4.3.2 Estimated Random Parameter Negative Binomial Model

The software package NLOGIT 5 was used to the Mixed-effects Negative Binomial model. The estimated random parameters negative binomial regression logistic model, along with average marginal effects, is presented in Table 17.

Table 17. Estimated Mixed-Effects Negative Binomial Model

Variable Description	Estimated Parameter	*t-Statistic*	Marginal Effect
Constant	-2.771	-3.78	
Curve characteristics			
Logarithm value of curve radius (in log [ft.])	-0.208	-3.29	-0.027
Standard deviation of parameter distribution	(0.047)	(6.42)	
Reverse curve indicator (1 if curve is reverse curve, 0 otherwise)	-0.490	-2.61	-0.064
Standard deviation of parameter distribution	(0.734)	(4.78)	
Curve length (in mi)	1.067	4.98	0.138
***Geometric* characteristics**			
Auxiliary lane indicator (1 if auxiliary lane is present in curve segment, 0 otherwise)	0.777	2.59	0.101
Grade indicator (1 if vertical grade is present, 0 otherwise)	0.409	2.40	0.053
Access density: number of junctions per mile	0.061	5.10	0.008
***Pavement* characteristics**			
11-year average pavement condition (scale 0–5)	0.318	2.38	0.041
Standard deviation of parameter distribution	(0.034)	(2.21)	
Pavement roughness indicator (1 if 11-year avg international roughness index (IRI) greater than 75 in./mi, 0 otherwise)	0.007	0.05	0.001
Standard deviation of parameter distribution	(0.507)	(4.86)	
***Traffic* characteristics**			
Average annual daily traffic (AADT) (in 000 vehicles per day)	0.165	8.93	0.021
***Overdispersion* parameter α**	0.745	5.29	
Number of observations	2179		
Log-likelihood with constant only	-1249.37		
Log-likelihood at convergence	-1068.38		
McFadden pseudo R-squared (ρ^2)	0.145		

4.3.3 Model Interpretation for Motorcycle Crash Frequency

Curve Radius and Type

The logarithm value of the curve radius is a random parameter that is normally distributed, with a mean of -0.208 and standard deviation of 0.047. This indicates that increasing the curve radius nearly always decrease the motorcycle crash frequency (less than 0.05% of the distribution would have a positive value) but with varying magnitude across the population of rural two-lane roadway segments. The increase of curve radius can reduce the risk factors for motorcyclists in negotiation with curves, such as speed variation, poor sight distance, and complexity of negotiation maneuvers.

The reverse curve indicator produced a normally-distributed negative parameter with a mean of -0.490 and a standard deviation of 0.734, suggesting that for 74.8% of roadway segments, the presence of reverse curve tends to result in a decrease in crash occurrences. For the remaining roadway segments, the presence of reverse curve tends to result in an increase in crash occurrences. This is perhaps because a great portion of motorcyclists (around 74.8%) would become more alert and take safety compensation behaviors (e.g., slow speed) to compensate for the difficulty of negotiating reverse curves. Other motorcyclists still suffer the risk caused by reverse curve, such as frequent adjustments of riding posture, poor sight distance, etc.

Figure 16 presents the expected motorcycle crash frequency (per 11 years) by curve radius and type, holding other factors at average over sample observations. The relationship between motorcycle crash frequency and curve radius is near-logarithmic. The expected motorcycle crash frequency decreases rapidly with an increase in radius if the curve is sharp (radius < 1,500 ft). When the radius exceeds 1,500 ft but is less than 3,000 ft, the decrease slope is smaller than sharp curves but still higher than a flat curve (radius > 4,000 ft). It is also obvious that the presence of reverse curve can significantly decrease the motorcycle crash frequency at each radius level.

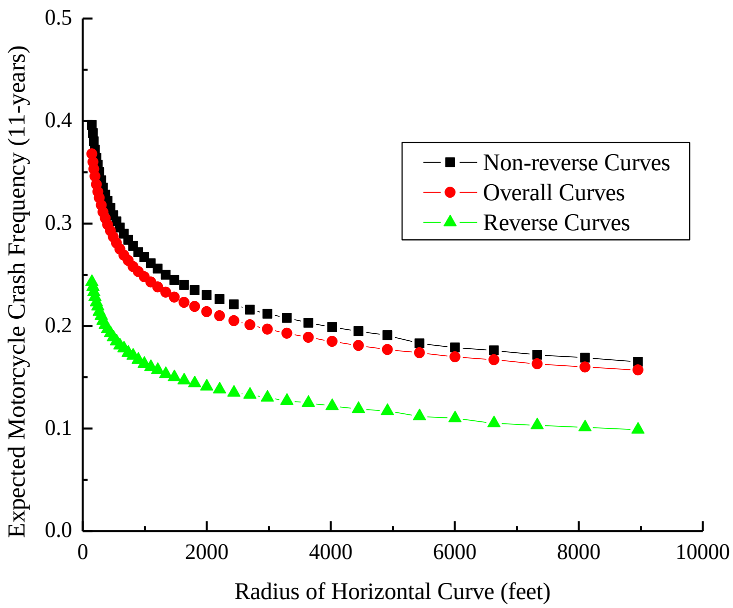


Figure 16. Expected Motorcycle Crash Frequency by Curve Radius and Curve Type

Curve Length

Since some factors (e.g., shoulder width) may vary with the increase in curve length, curve length could not be treated as an exposure variable that be assumed to have a linear relationship with expected crash frequency. The model shows that the length of horizontal curve is a positive fixed parameter, which indicates that the average number of motorcycle crashes increases with an increase in curve length because would gain more exposure time with increase of curve length. The marginal effects showed that a one-mile increase in curve length on RTU roads results in an average increase of 0.138 motorcycle crashes per 11 years.

Geometric Characteristics

Auxiliary lanes, linking access points and, consequently, increased potential traffic conflicts, were found to increase the probability of motorcycle crash occurrence on horizontal curves. Marginal effects show that the presence of auxiliary lanes would increase the average number of motorcycle crashes on RTU roads by 0.101 (per 11 years).

The vertical grade variable produced a positive fixed parameter that increases the motorcycle crash frequency by 0.053 crashes per 11 years. The interaction between horizontal curves and vertical slope can significantly decrease the sight distance and increase the complexity of riding maneuvers.

The number of access points per mile on horizontal curves is a positive fixed parameter, since high access density may increase traffic conflicts. Marginal effects show that each additional junction per mile can result in an increase of 0.008 motorcycle crashes per 11 years on RTU roads.

Pavement Characteristics

Pavement condition variable ranges from 0 (completely deteriorated) to 5 (excellent pavement condition). This variable produced a normally-distributed negative parameter with a mean of 0.318 and a standard deviation of 0.034, suggesting that for nearly all rural two-lane curves, the number of motorcycle crashes increases when the pavement conditions become better. This finding seems counterintuitive and could be related to a variety of unobserved factors. One possible unobserved factor is related to motorcyclist risk compensation behavior; that is, motorcyclists who believe pavement quality is good tend to take risky behaviors, such as higher speed and less alertness. On the other hand, if motorcyclists feel unsafe with poor pavement conditions, they may take low-risk behaviors (e.g., low speed, more attention on surrounding environment). Similar findings about the effects of good pavement condition tending to increase vehicle crash frequency were found in several previous studies (*62*, *63*).

Another measure of pavement condition is the International Roughness Index (IRI), which measures roughness of road surface. In Florida, the IRI is measured in inches per mile, with lower values indicating a smoother surface. The model shows that a rough-pavement (IRI > 75 in/mi) is a random positive parameter, with a mean of 0.007 and a standard deviation of 0.507, suggesting that 50.6% of motorcyclists tend to increase motorcycle crash frequency on horizontal curves with rough pavement and 49.4% tend to decrease motorcycle crash frequency.

Traffic Characteristics

Annual average daily traffic (AADT) results in a positive fixed parameter, indicating that a growth of 1,000 vehicles per day increases the expected number of motorcycle crashes by 0.021 per 11 years.

4.3.4 Crash Modification Function for Horizontal Curvature

The CMF function for horizontal curve radius is a mathematical function that describes the impacts of the curve radius on motorcycle crash frequency relative to a baseline. Assuming that the curve radius of 5,000 ft is the baseline, the crash modification function can be derived as

$$CMF = \frac{\lambda(R_i|X)}{\lambda(R_0|X)} = \frac{EXP\left(-0.208 \times LN(R_i) + \bar{\beta}\ \bar{X}\right)}{EXP\left(-0.208 \times LN(R_0) + \bar{\beta}\ \bar{X}\right)} = \left(\frac{R_i}{5000}\right)^{-0.208} \tag{17}$$

where $\lambda(R_i|X)$ is the expected number of crashes along curve segments with radius R_i, R_0 is 5,000 ft, the baseline of CMF; -0.208 is the estimated parameter of radius in Table 17; $\bar{X}$ represents the vector of the other variables; and $\bar{\beta}$ is the vector of estimated parameters for the other variables.

The curve of the CMF for horizontal curve radius is shown in Figure 17. The CMF curve has a similar nonlinear tendency with the curve of curve radius—expected motorcycle crash frequency. The safety performance in reducing motorcycle crashes is more significant in the low range of curve radius (radius < 2,000 ft). For example, the expected motorcycle crash frequencies for horizontal curves of 150, 500, and 1000 ft are 2.07, 1.61, and 1.40 times, respectively, as many as the frequency for the radius 5,000 ft. In other words, if decreasing the radius from 5,000 ft to 150 ft, 500 ft, and 1,000 ft, the expected motorcycle crash frequency will increase by 107%, 61%, and 40%, respectively. If increase the radius from 5,000 ft to 6,000 ft, the percent of expected motorcycle crash frequency is only decreasing by 4%.

The crash modification factor for reverse curve indicates the relative change of expected motorcycle crash frequency comparing reverse curves with non-reverse curves (simple or compound curves).

$$CMF = \frac{\lambda(Reverse|X)}{\lambda(Non - reverse|X)} = \frac{EXP\left(-0.490 \times 1 + \bar{\beta}\ \bar{X}\right)}{EXP\left(-0.490 \times 1 + \bar{\beta}\ \bar{X}\right)} = EXP(-0.490) \approx 0.61 \tag{18}$$

where $\lambda(Reverse|X)$is the expected number of crashes along reverse curves; $\lambda(Non - reverse|X)$ is the expected number of crashes along non-reverse curves; -0.490 is the estimated parameter of reverse curve in Figure 17; $\bar{X}$ represents the vector of the other variables; and β is the vector of estimated parameters for the other variables. The crash modification factor of curve type indicates that the number of motorcycle crashes would decrease 39% (=1 - 0.61) when a reverse curve is present on a rural two-lane road.

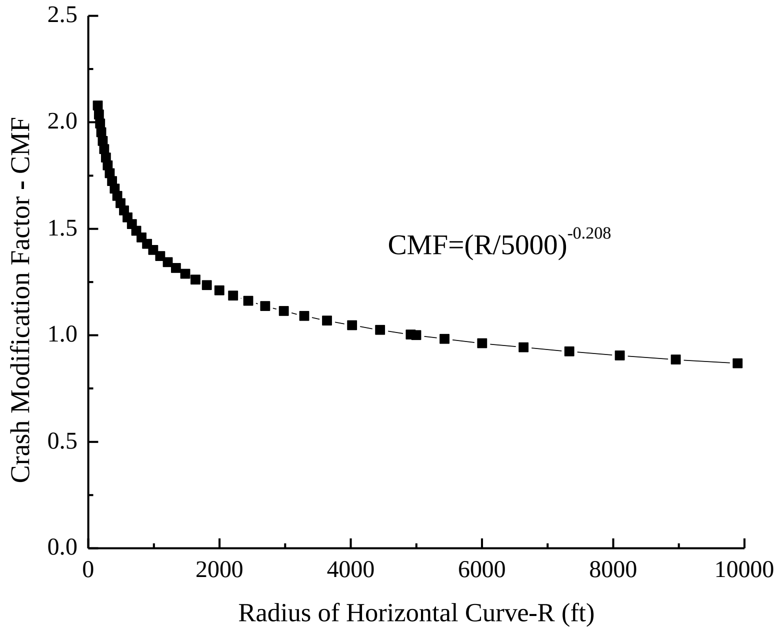


Figure 17. Crash Modification Function by Curve Radius

4.4 Analysis for Motorcycle Crash-Severity

4.4.1 Descriptive Statistics of Motorcycle Crash-Severity Data

Motorcycle crash-severity data were organized at crash-level, which means one record in the dataset represents one crash. In this study, only single-motorcycle crashes were considered to exclude the influence from other vehicles. In addition, the sample size of single-motorcycle crashes on rural two-lane curves is too small (219) to conduct a meaningful statistical analysis. Thus, this study identified 8,597 horizontal curves on both urban and rural roads. In total, 2,168 single-motorcycle crashes occurred between 2005 and 2015 and were spatially matched to the identified horizontal curves. The descriptive statistics of the collected data are shown in Table 18.

Table 18. Descriptive Statistics of Single-Motorcycle Crash-Severity Data

Variable	Mean	SD.
Crash severity (1 if crash severity is fatality or incapacitating injury, 0 otherwise)	0.385	0.487
Sharp curve indicator (1 if radius of curvature is less than 1,500 ft, 0 otherwise)	0.260	0.439
Moderate curve indicator (1 if radius of curvature is 1,500–4,000 ft, 0 otherwise)	0.377	0.485
S-curve indicator (1 if curve type is composite curve with different offset directions, 0 otherwise)	0.293	0.455
High motorcycle speed indicator (1 if motorcycle speed is more than 50 mph, 0 otherwise)	0.466	0.499
Speeding indicator (1 if motorcycle crash cause is exceeding speed limit, 0 otherwise)	0.065	0.246
Speed control sign indicator (1 if traffic control facility is speed control sign, 0 otherwise)	0.313	0.464
Auxiliary lane indicator (1 if auxiliary lane exists in crash location, 0 otherwise)	0.371	0.483
Vegetation median indicator (1 if median type is vegetation, 0 otherwise)	0.360	0.480
Paved median indicator (1 if median type is paved median, 0 otherwise)	0.827	0.378
Road access control indicator (1 if road access is full or partial control, 0 otherwise)	0.321	0.467
Poor pavement condition indicator (1 if pavement condition index is less than 3, 0 otherwise)	0.025	0.156
Roughness indicator (1 if pavement roughness index is more than 80 in./mi, 0 otherwise)	0.370	0.483
Friction indicator (1 if skid test number is larger than 40, 0 otherwise)	0.330	0.470
Dry road surface indicator (1 if road surface condition is dry, 0 otherwise)	0.883	0.321
Darkness indicator (1 if light condition is darkness without street light, 0 otherwise)	0.144	0.351
Darkness with street light indicator (1 if light condition is darkness with street light, 0 otherwise)	0.233	0.423
Tree indicator (1 if motorcycle hit tree or shrubbery, 0 otherwise)	0.012	0.111
Barrier wall indicator (1 if motorcycle hit utility concrete barrier wall, 0 otherwise)	0.041	0.197
Other-fixed object collision indicator (1 if collision with other fixed objects, 0 otherwise)	0.117	0.322
Alcohol/drugs indicator (1 if motorcycle crash is under influence of alcohol/drugs, 0 otherwise)	0.100	0.300
Helmet indicator (1 if all motorcycle occupants wear safety helmet, 0 otherwise)	0.630	0.483
Proper driving indicator (1 if crash cause is no improper driving or action, 0 otherwise)	0.239	0.427
Weekend indicator (1 if motorcycle riding is on Saturday or Sunday, 0 otherwise)	0.429	0.495
Younger motorcycle rider indicator (1 if motorcycle rider age is under 30, 0 otherwise)	0.351	0.477
Older motorcycle rider indicator (1 if motorcycle rider age is over 60 old, 0 otherwise)	0.097	0.296
Male indicator (1 if motorcycle rider is male, 0 otherwise)	0.919	0.273

4.4.2 Estimated Mixed Logistic Model

The software package NLOGIT 5 was used to estimate the mixed-effects logistic model. The estimated mixed logistic model, along with marginal effects (ME), is presented Table 19.

Table 19. Fitted Mixed-Effects Logistic Model with Average Marginal Effects

Variable	Coef.	*t*-statistic	ME (%)
Constant	-1.784	-6.83	
Sharp curve indicator (1 if radius of curvature is less than 1500 ft, 0 otherwise)	0.269	2.09	6.08
Moderate curve indicator (1 if radius of curvature is 1500–4000 ft, 0 otherwise)	0.070 (0.763)	0.65 (7.08)	1.58
S-curve indicator (1 if curve type is a composite curve with different offset directions, 0 otherwise)	0.258 (0.729)	2.50 (6.01)	5.82
Higher motorcycle speed indicator (1 if motorcycle speed is more than 50 mph, 0 otherwise)	1.068	9.91	24.11
Speeding indicator (1 if motorcycle crash cause is exceeding speed limit, 0 otherwise)	0.743	3.81	16.78
Speed control sign indicator (1 if traffic control facility is speed control sign, 0 otherwise)	0.351	3.58	7.93
Auxiliary lane indicator (1 if auxiliary lane exists in crash location, 0 otherwise)	-0.200	-2.09	-4.51
Vegetation median indicator (1 if median type is vegetation, 0 otherwise)	0.220	2.06	4.98
Paved median indicator (1 if median type is paved median, 0 otherwise)	0.326	2.35	7.36
Road access control indicator (1 if road access is full or partial control, 0 otherwise)	-0.596	-4.96	-13.47
Poor pavement condition indicator (1 if pavement condition index is less than 3 (poor), 0 otherwise)	-0.546	-1.75	-12.34
Roughness indicator (1 if pavement roughness index is more than 80 in./mi, 0 otherwise)	-0.205	-2.00	-4.64
Friction indicator (1 if skid test number is larger than 45, 0 otherwise)	0.322	3.22	7.28
Dry road surface indicator (1 if road surface condition is dry, 0 otherwise)	0.506	3.48	11.42
Darkness indicator (1 if light condition is darkness without street light, 0 otherwise)	0.368	2.78	8.32
Darkness with street light indicator (1 if light condition is darkness with street light, 0 otherwise)	0.260	2.20	5.88
Tree indicator (1 if motorcycle hit tree or shrubbery, 0 otherwise)	0.692	1.72	15.62
Barrier wall indicator (1 if motorcycle hit utility concrete barrier wall, 0 otherwise)	0.915	4.06	20.66
Other-fixed object collision indicator (1 if collision with other fixed object, 0 otherwise)	0.333	2.29	7.51
Alcohol/drugs indicator (1 if motorcycle crash is under the influence of alcohol/drugs, 0 otherwise)	0.319	2.01	7.20
Helmet indicator (1 if all motorcycle occupants wear safety helmet, 0 otherwise)	-0.370	-3.83	-8.35
Proper driving indicator (1 if crash cause is no improper driving or action, 0 otherwise)	-0.527	-4.66	-11.90
Weekend indicator (1 if motorcycle riding is on Saturday or Sunday, 0 otherwise)	0.217	2.38	4.91
Younger motorcycle rider indicator (1 if motorcycle rider age is under 30, 0 otherwise)	-0.221	-2.17	-5.00
Older motorcycle rider indicator (1 if motorcycle rider's age is over 60, 0 otherwise)	0.721 (1.382)	4.44 (6.09)	16.27
Male indicator (1 if motorcycle rider is male, 0 otherwise)	-0.206 (2.390)	-1.36 (21.24)	-4.66
Model Statistics			
Number of observations	2168		
Restricted log likelihood	-1445.03		
Log-likelihood at convergence	-1315.16		
McFadden pseudo R-squared (ρ^2)	0.086		

All random parameters are normally distributed with standard deviation in parentheses.

4.4.3 Model Interpretation for Motorcycle Injury Severity

Curve Parameters

Sharp curves (radius < 1500 ft), as a fixed parameter, are more likely to increase the probability of severe injuries in single-motorcycle crashes by 6.08%, compared to non-sharp curves (radius ≥ 1500 ft). Small radii greatly decrease negotiation space and increase the complexity of riding maneuvers. Consequently, injury-deteriorating riding behaviors (e.g., excessive speed, erroneous lean angle, flawed trajectory) on sharp curves are exceedingly significant with s small curve radius.

Moderate curves (1500 ft ≤ radius < 4000 ft) have random effects on single-motorcycle injury severities, following a normal distribution, with a mean of 0.07 and a standard deviation of 0.763. To further address the random effects, another mixed-effects logistic model was developed to exclude the disturbance of sharp curves that were included in the modeling baseline (moderate curve indicator = 0); all sharp curve crashes were rejected from the sample. Results showed that the indicator of moderate curves is still a random parameter (mean = 0.0876; SD = 0.1957; *t*-statistic for mean = 0.92, and SD = 2.16). It could be inferred that the heterogeneity of unobserved factors related to moderate curves (e.g., motorcyclist safety intentions, complexity of curve negotiation, traffic/environmental/ geometric features) is a reason for the random effect. Because the positive effect (increasing injury severity) is close to the negative effect (decreasing injury severity), the overall effect of moderate curves is insignificant (*t*-statistic for mean = 0.65, Table 19). Evidence is that there is no significant difference between the probability of a negative coefficient and a positive coefficient (46.3% vs. 53.7%).

The reverse curve (S-curve) indicator is another normally-distributed random parameter, with a mean of 0.258 and a standard deviation of 0.729. Motorcyclists traveling on a reverse curve (Figure 15) must continuously change counterweight directions for tracking the change of curve offsets. These frequent adjustments of riding posture are likely to cause loss of control and, consequently, result in 63.8% of single-motorcycle crashes being more likely to cause severe injuries on reverse curves. On the other hand, reverse curves may cause safety compensation behaviors (e.g., slow speed if motorcyclist feels unsafe) to compensate for the risk of severe injuries on reverse curves for the remaining 36.2% of single-motorcycle crashes. On average, reverse curves tend to increase the probability of severe injury by 5.82%.

As shown in Figure 18, the probability of severe injuries in single-motorcycle crashes is a deceasing function (piecewise) of curve radius by different curve types. Compared to flat curves, sharp curves increase the probability of severe injuries in single-motorcycle crashes by 7.7% (=41.1% - 33.4%) overall and 7.3% (= 41.5% -34.2%) for reverse curves.

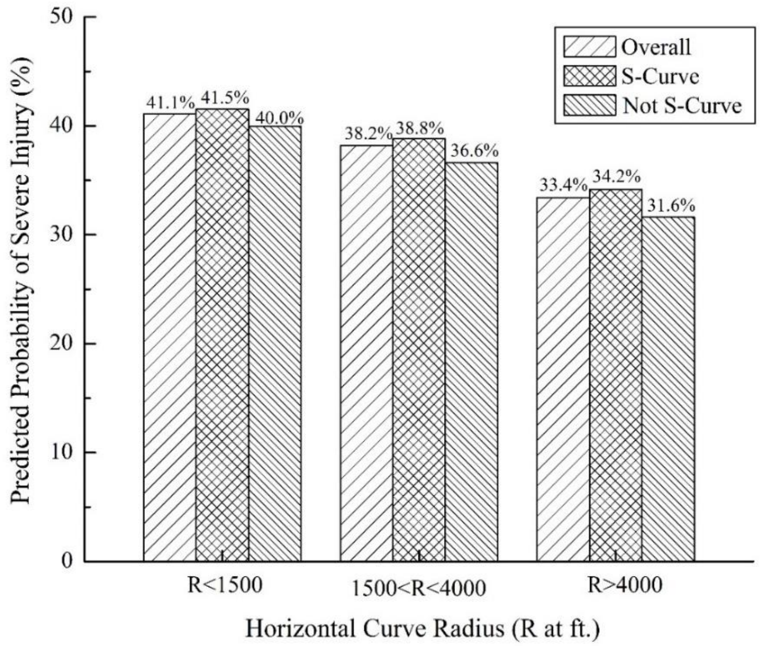


Figure 18. Predicted Probability of Severe Injuries by Curve Radius and Curve Type

Speed

Speed is the most predominant factor contributing to injury severity. Damage to motorcycle occupants is related to pressure, deceleration, change in velocity, and kinetic energy dissipation to human bodies; all these factors are the increasing function of speed (*64*). The marginal effect of the high-speed indicator (> 50 mph) denotes that high speed is likely to increase the probability of severe injuries by 24.11%.

Speeding is another dangerous factor that tends to increase the probability of severe injuries by 16.78%. These findings are consistent with previous studies (*2*, *24*, *65*–*70*).

Based on the model, speed control signs are more likely to increase the probability of severe injury in crashes on curves. This counterintuitive effect is caused by the issue of self-selected sample (endogeneity): speed control signs are more likely to be installed in zones in which high-speed issues have existed and significant crashes occurred. An analysis of the sample data indicated that the average speed in single-motorcycle crashes with speed control signs (53.7 mph) is significantly higher than the average speed without speed control signs (47.8 mph).

Roadway Characteristics

The presence of auxiliary lanes is more likely to decrease the probability of severe injuries of single-motorcycle crashes on horizontal curves by 4.51%. Auxiliary lanes extend pavement width to provide more negotiation space for motorcyclists and usually are linked to access points, which tend to cause motorcyclist safety compensation behaviors (e.g., reducing speed) for avoiding potential conflicts.

Vegetation and paved medians are more likely to result in severe injuries in curve-related single-motorcycle crashes, and motorcyclist negative safety compensation behaviors (safety compensations) may be the cause. These two kinds of medians psychologically increase the negotiation space for motorcyclists, who may feel more confident in curve negotiation and intend to use injury-deteriorating behaviors (e.g., increasing speed, careless riding). Safety compensation effects were explored by numerous studies (*5*, *24*, *68*, *71*, *72*). Based on the sample, average speeds in motorcycle crashes with vegetation and paved medians are 55.9 mph and 51.8 mph, respectively; speed values with non-vegetation and non-paved median are 46.1 mph and 39.3 mph, respectively.

Single-motorcycle crashes that occur on full-access-controlled curves tend to have a lower probability of severe injuries compared to non-access-controlled curves. However, full-access-controlled roads usually have higher running speeds, which is a significant injury-deteriorating factor. This effect is possible for several reasons. First, compared to other roads, full-access-controlled roads have a higher design standard for horizontal curves (e.g., flat curve design, wide lane width, large clearance space on medians or shoulders).

Thus, the complexity of curve negotiation on full-access-controlled roads is lower than others, and motorcyclists have more opportunities to avoid injury-deteriorating crashes (e.g., hitting on fixed objects). Second, motorcyclists traveling on full-access-controlled roads are more likely to take injury-mitigating behaviors (e.g., wear a helmet, less alcohol/drug impairment). In addition, the percentage of invulnerable motorcyclists (e.g., young, male) using full-access-controlled roads is higher than those using non-access-controlled roads. The sample data analysis supported these inferences (full-access control vs. non-access control): sharp curve, 7.6% vs. 34.7%; helmet use, 72.4% vs. 58.8%; alcohol/drug impairment, 4.7% vs. 12.4%; young rider, 42.5% vs. 32.5%; male, 94.3% vs. 90.8%). A similar discussion of safety compensation effects for motorcycle crashes on interstates was found in a previous study conducted by Shanker and Mannering (*68*).

Pavement

The effects of negative safety compensation effects are significant for the three pavement factors (pavement condition, roughness index, friction). Single-motorcycle crashes on curves with poor pavement conditions (pavement condition index < 3, roughness index > 80, or friction number ≤ 45) are more likely to have a lower probability of severe injuries compared to curves with good pavement conditions. Motorcyclists likely will use injury-mitigating riding behaviors (e.g., reduce speed, careful riding) if they psychologically lack confidence on poor pavement. Geedipally et al. (*5*) reached a similar conclusion, that good surface conditions increase the probability of fatal and incapacitating injury by encouraging vehicle speeding.

Environment

Dry road surfaces increase the probability of severe injuries in single-motorcycle crashes on curves by 11.42% because they encourage motorcyclists to use injury-deteriorating behaviors by riding at a high speed. This finding is consistent with previous studies (*24*, *67*).

Darkness is likely to increase the probability of severe injuries in single-motorcycle crashes on curves, which is in line with previous studies (*2*, *5*, *24*, *65*, *66*, *69*, *70*). This could be the result of a number of factors: (1) darkness will decrease the sight distance of motorcycle motorcyclists and increase the difficulty of looking through the horizontal curve; (2) because of the low volume of traffic at night, motorcyclists may take more risk behaviors by riding at a high speed; (3) alcohol- or drug-impaired motorcyclists typically are self-selected risk takers in darkness; and (4) motorcyclists with lower helmet use and safety awareness also typically are self-selected risk takers in darkness. Street lighting mitigates the injury of motorcyclists on curves due to improved sight distance. Darkness with lights, as shown in Figure 19, will decrease the probability of severe injuries by 2.3% (42.9% - 40.6%), compared to darkness.

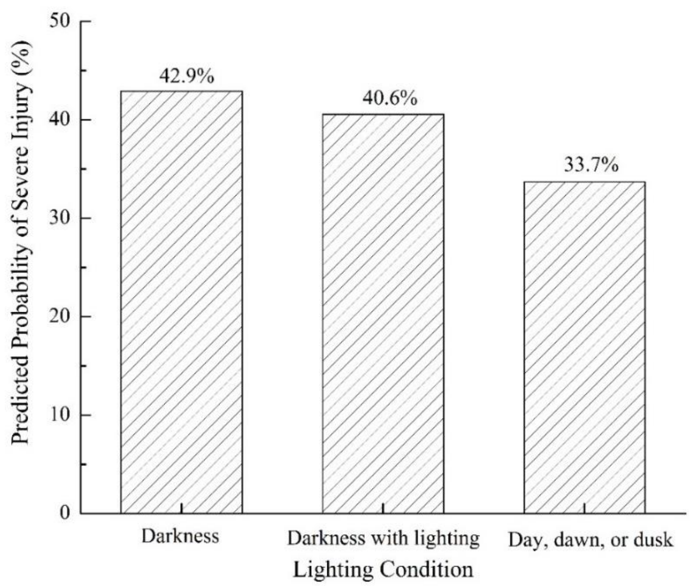


Figure 19. Predicted Probability of Severe Injury by Lighting Condition

Crash Characteristics

Collisions with a concrete barrier wall, tree, and other-fixed object are more likely to increase the likelihood of severe injuries in single-motorcycle crashes on curves by 20.55%, 15.62%, and 7.51%, respectively. Hitting fixed objects is likely to transfer more kinetic energy to motorcyclists. This finding is consistent with previous studies (*24*, *68*, *73–75*).

Alcohol or drug impairment, which degrades motorcyclist ability to safely negotiate curves and increases inherent risk-taking tendencies, increases the probability of severe injuries for single-motorcycle crashes on curves by 7.20%. This finding is in line with previous studies (*2*, *24*, *65–68*, *70*, *73*). Proper riding, which captures motorcyclist inherent safety awareness, decreases the probability of severe injury by 11.90%, and helmet use decreases the likelihood of severe injury by 8.35%. This effect is also supported by previous studies (*2*, *24*, *65*, *67*).

Single-motorcycle crashes occurring on weekends are more likely to result in severe injuries. Shaheed and Gkritza reported similar findings (*67*). Motorcyclists are more likely to drive recklessly and have less safety awareness on weekends. Based on the sample data, the percentage of helmet use on weekends is 58.99%, which is significantly lower than that on weekdays (66.02%).

Motorcyclist Characteristics

Compared to adult and older motorcyclists, young motorcyclists (age < 30) have much better perception of curves and higher tolerance to injuries. As indicated in previous studies (*2*, *5*, *67*), young motorcyclists are less likely to suffer severe injuries in single-motorcycle crashes on curves by 5%.

The parameter related to older motorcyclists (age ≥ 60) is random and normally distributed, with a mean of 0.721 and a standard deviation of 1.382. This suggests that, on average, about 69.9% of older motorcyclists involved in a curve-related single-motorcycle crash are more likely to experience severe injuries; the remaining 30.1% are less likely to suffer severe injuries (Eq. 4). The random effects of older motorcyclists could be caused by (1) unobserved heterogeneity related to older motorcyclist physiological conditions and injury tolerances and (2) unobserved heterogeneity related to older motorcyclist driving experience and familiarity with road environment. On average, older motorcyclists tend to increase the probability of incurring severe injury in curve-related single motorcycle crashes by 16.27%. The vulnerability of older motorcyclists was reported in previous studies (*24*, *68*, *73*), but it was considered a fixed parameter.

The male indicator is also normally distributed, with a mean of -0.206 and a standard deviation of 2.390, suggesting that 53.4% of male motorcyclists are less likely to experience severe injuries in curve-related single-motorcycle crashes (Eq. 4). However, 46.6% of male motorcyclists are more likely to be involved in crashes involving severe injuries. Usually, the injury tolerance of a male is higher than that of a female. In contrast, male motorcyclists are more likely to take risk-seeking behaviors than female motorcyclists. The random effects of male motorcyclists reflect the variance of male motorcyclists in physiological characteristics and risk-seeking intentions. Since the difference between the two effects are not very significant (53.4% vs. 46.6%), the overall marginal effects of male motorcyclists are insignificant (*t*-statistics = -1.36). Previous studies have contradictory insights on the impact of gender—some researchers indicated that male motorcyclists are more likely to increase the injury severity of motorcycle crashes (*5*, *65*, *69*, *70*), but others stated that male motorcyclists tend to decrease the likelihood of severe injuries in a motorcycle crash (*67*).

4.5 CMF Development using Case-Control Method

4.5.1 Data Collection and Descriptive Statistics

As described in Methodologies, the case-control method has a different data collection scheme from the cross-sectional method. In this study, the data collection procedure for the case-control study is shown in Figure 20.

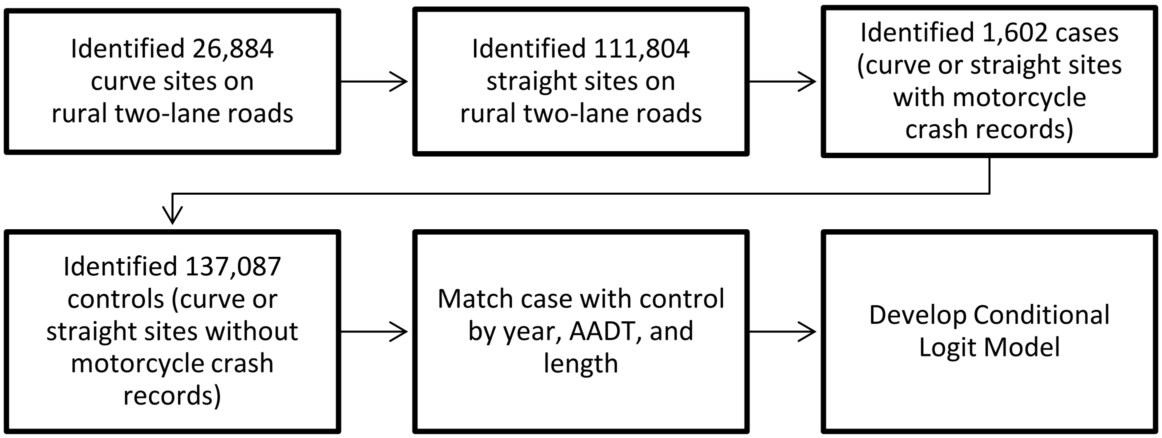


Figure 20. Procedure for Case-Control Data Collection

In total, 1,602 cases were matched to 16,020 controls with similar year, AADT, and length. The 1:10 control/case ratio can make the power of case-control study reaching 99%. The descriptive statistics of risk factors is given in Table 20.

Table 20. Descriptive Statistics of Risk Factors for Case-Control Study

Variable Description	Mean	SD.
Sharp curve indicator (1 if radius of curve is less than 1,000 ft, 0 otherwise)	0.012	0.110
Moderate curve (1 if radius of curve is between 1000 ft and 2000 ft, 0 otherwise)	0.046	0.210
Flat curve (1 if radius of curve is between 2000 ft and 10,000 ft, 0 otherwise)	0.121	0.326
Straight segment (1 if radius of curve is greater than 10,000 ft or tangent, 0 otherwise)	0.821	0.384
Vertical slope indicator (1 if vertical slope exists in the segment, 0 otherwise)	0.094	0.292
Principal arterial indicator (1 if functional classification is principal arterial, 0 otherwise)	0.368	0.482
Auxiliary lane indicator (1 if auxiliary lane exists in the segment, 0 otherwise)	0.060	0.238
Access ability indicator (1 if access density of roadway is greater than zero, 0 otherwise)	0.576	0.494
Higher speed limit indicator (1 if speed limit is greater than 50 mph, 0 otherwise)	0.735	0.441
Narrow surface width indicator (1 if surface width is less than 24 ft, 0 otherwise)	0.246	0.431
Narrow shoulder width indicator (1 if shoulder width is less than 12 ft, 0 otherwise)	0.448	0.497
Paved shoulder type (1 if shoulder type is paved or paved with warning device, 0 otherwise)	0.745	0.436
Poor pavement indicator (1 if pavement condition is less than 3, 0 otherwise)	0.266	0.442

4.5.2 Estimation of Conditional Logistic Model

The conditional logit model was estimated based on the collected case-control data. The fitted model is given in Table 21.

Table 21. Matched Case-Control Model for Motorcycle Crashes

Variable Description	Estimated Parameter	*t*-Statistic	Odds Ratio (CMF)
Sharp curve indicator (1 if radius of curve is less than 1,000 ft, 0 otherwise)	1.185	4.70	3.27
Moderate curve (1 if radius of curve is between 1000 ft and 2000 ft, 0 otherwise)	1.091	7.47	2.98
Flat curve (1 if radius of curve is between 2000 ft and 10,000 ft, 0 otherwise)	0.598	4.75	1.82
Straight segment (1 if radius of curve is greater than 10,000 ft, 0 otherwise)	-	-	-
Vertical slope indicator (1 if vertical slope exists in the segment, 0 otherwise)	0.402	4.57	1.50
Principal arterial indicator (1 if functional classification is principal arterial, 0 otherwise)	0.761	11.03	2.14
Auxiliary lane indicator (1 if auxiliary lane exists in the segment, 0 otherwise)	0.439	4.62	1.55
Access ability indicator (1 if access density of roadway is greater than zero, 0 otherwise)	0.664	10.71	1.94
Higher speed limit indicator (1 if speed limit is greater than 50 mph, 0 otherwise)	0.454	5.40	1.58
Narrow surface width indicator (1 if surface width is less than 24 ft, 0 otherwise)	-0.598	-5.75	0.55
Narrow shoulder width indicator (1 if shoulder width is less than 12 ft, 0 otherwise)	-0.140	-2.19	0.87
Paved shoulder type (1 if shoulder type is paved or paved with warning device, 0 otherwise)	1.003	8.96	2.73
Poor pavement indicator (1 if pavement condition is less than 3, 0 otherwise)	-0.277	-3.34	0.76
Model Statistics			
Number of observations	17,622		
Restricted log likelihood	-3,841.43		
Log-likelihood at convergence	-3,385.78		
McFadden pseudo R-squared (ρ^2)	0.119		

4.5.3 CMFs for Curve Radius

The probabilities of a motorcycle crash occurring on sharp curve (R<1000 ft), moderate curve (1000<R≤2000 ft), and flat curve (2000<R<10,000 ft), relative to the probability of a motorcycle crash occurring on tangent segments, increase by about 227%, 198%, and 82%, respectively.

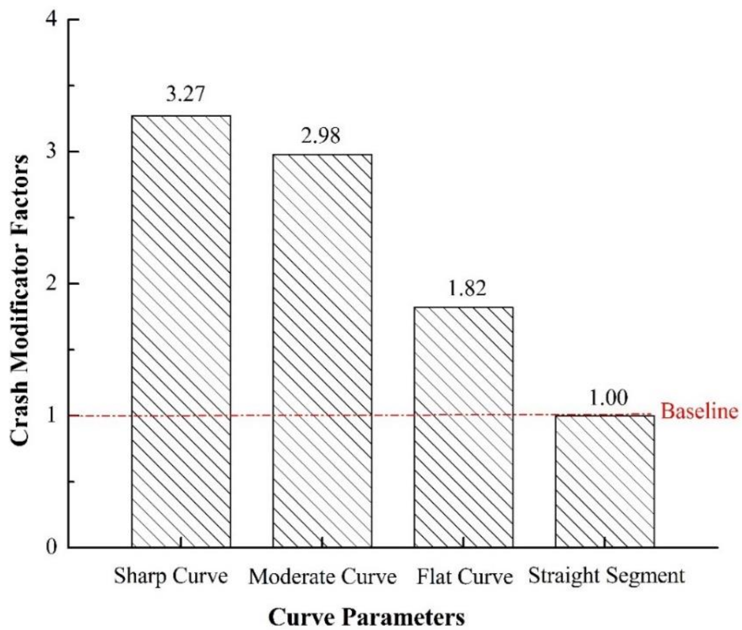


Figure 21. CMFs of Horizontal Curve Radius for Motorcycle Crashes on Rural Two-Lane Highway

4.6 Analysis of Motorcyclist-At-Fault

In addition to motorcycle crash frequency and severity, motorcyclist-at-fault—a motorcyclist making mistakes resulting in a motorcycle crash—is an important safety measure in motorcycle-involved crashes. Savolainen and Mannering (*24*) indicated that motorcyclists who are at-fault in crashes also are more likely to be killed in a multi-vehicle crash. Few studies were found that examined motorcyclist-at-fault and contributing factors. Knowledge about geometric features, motorcycle attributes, motorcyclist characteristics and unsafe behaviors, and crash-specific factors influence motorcyclists at-fault on horizontal curves is very limited, especially regarding curve parameters and curve-specific features. This absence of knowledge prevents development and/or deployment of effective countermeasures to reduce motorcyclist fatalities and injuries on horizontal curves.

Contributing factors that significantly influence motorcyclist-at-fault in a crash on a horizontal curve were investigated. A mixed logistic model was developed based on the binary response of whether the motorcyclist is at-fault in a two-vehicle crash on curves to quantify the effects of roadway characteristics, environmental factors, and rider/motorcycle characteristics on the likelihood of motorcyclist at-fault and address the unobserved heterogeneity of the sample.

4.6.1 Descriptive Statistics of Sample

In this study, crashes that involved two vehicles with at least one being a motorcycle were considered. In total, 5,316 two-vehicle motorcycle crashes that occurred between 2005 and 2015 were spatially matched to the identified 8,597 horizontal curves (including interstate, urban arterial and rural roads). These crashes were labeled as “motorcyclist-at-fault” or not based on police crash reports. Information on crash characteristics and person/vehicle factors also were collected. The descriptive statistics of the collected data are shown in Table 22.

Table 22. Descriptive Statistics of Two-Vehicle Motorcycle Crashes on Horizontal Curves

Variable Description (number of observations: 5,316)	Mean	SD
Curve Characteristics		
Sharp curve indicator (1 if curve radius is less than 400 ft; 0 otherwise)	0.021	0.143
Reverse curve indicator (1 if centers of curve are in different sides; 0 otherwise)	0.377	0.485
Long curve indicator (1 if length of curve is more than 0.8 miles; 0 otherwise)	0.036	0.185
Motorcyclist Characteristics		
Male rider indicator (1 if motorcycle rider is male; 0 otherwise)	0.927	0.260
Local rider indicator (1 if motorcycle rider is registered in Florida; 0 otherwise)	0.885	0.319
Motorcycle insurance indicator (1 if motorcycle insurance is valid; 0 otherwise)	0.763	0.425
No physical defect indicator (1 if no defects known; 0 otherwise*)	0.977	0.150
Middle age indicator (1 if motorcyclist age is 25-65; 0 otherwise)	0.696	0.069
Young age indicator (1 if motorcyclist age is under 25; 0 otherwise)	0.251	0.150
Old age indicator (1 if motorcyclist age is older than 65; 0 otherwise)	0.053	0.051
Motorcycle safety equipment indicator (1 if any safety equipment used; 0 none)	0.857	0.531
Motorcycle driver license classification indicator (1 if driver license is class E; 0 otherwise)	0.825	0.38
Riding Behaviors		
Extremely low speed indicator (1 if motorcycle speed - speed limit < -10 mph)	0.425	0.150
Low speed indicator (1 if -10 mph ⩽ motorcycle speed - speed limit < 0 mph)	0.462	0.142
Normal speed indicator (1 if 0 mph ⩽ motorcycle speed - speed limit < 10 mph)	0.055	0.052
High speed indicator (1 if 10 mph ⩽ motorcycle speed - speed limit < 15 mph)	0.017	0.019
Extremely high-speed indicator (1 if motorcycle speed - speed limit ⩾ 15 mph)	0.040	0.039
Right-handed indicator (1 if cornering direction is on right-hand, 0 on left-hand)	0.509	0.500
Same direction indicator (1 if motorcycle and another vehicle are traveling in the same direction; 0 otherwise)	0.613	0.487
Non-obstruction indicator (1 if no vision obstruction for motorcyclist in this crash; 0 otherwise)	0.927	0.260
Roadway Geometry		
Divided roadway indicator (1 if roadway is divided or one-way; 0 otherwise)	0.498	0.500
Roadway classification indicator (1 if roadway is expressway; 0 otherwise)	0.213	0.409
Shoulder width in ft	8.192	5.978
Crash Characteristics		
Motorcyclist-at-fault indicator (1 if motorcyclist is at-fault in this crash; 0 otherwise)	0.406	0.491
Adverse weather indicator (1 if it is raining or fog; 0 otherwise)	0.032	0.177
Crash location indicator (1 if crash occurs on the second half of the curve; 0 otherwise)	0.758	0.428
Fatality indicator (1 if crash severity if fatal; 0 otherwise)	0.014	0.118
Rear-end crash (1 if crash type is rear-end; 0 otherwise)	0.315	0.216
Hit-on crash (1 if crash type is hit-on; 0 otherwise)	0.032	0.031

**Physical defects include eyesight defect, fatigue/asleep, hearing defect, illness, seizure, epilepsy, blackout, and other physical defects.*

4.6.2 Estimation of Motorcyclist-At-Fault Model

Motorcyclist-at-fault is a binary variable (1 if motorcyclist is at-fault in a two-vehicle crash on curve; 0 if other). A binary choice model, such as logistic regression, was widely used to fit the two-vehicle motorcycle crash data. The riding behavior and consequent outcome (e.g., at-fault or not) are the result of a complex energy dissipation mechanism that involve direct and indirect impacts from interactions among human factors, roadway characteristics, vehicle features, traffic-related factors, and environmental conditions. Sample data for crash modeling usually are retrieved from police accident reports and roadway characteristics inventory files; it is impossible to include all factors influencing motorcyclist-at-fault status in a traffic crash. Unobserved factors, if correlated with observed variables, potentially may cause the issue of unobserved heterogeneity. Traditional statistical methods (e.g., logistic model) cannot address the issue of unobserved heterogeneity and may lead to biased and inconsistent parameter estimation, erroneous inferences, and predictions (*55*). To resolve this issue, a mixed logistic model was developed in this study to allow some coefficients to vary across crash observations rather than fixed in traditional models. The description of mixed logistic model is given in Section 4.2.3.

The software package NLOGIT 5 was used to estimate the mixed logistic model with the maximum simulated likelihood (MSL). A total of 10 normally-distributed random parameters (sharp curve, long curve, motorcycle safety equipment count, motorcyclist license classification, roadway divided indicator, reverse curve indicator, roadway shoulder width, young rider, older rider, male rider, bad weather) were identified after 300 Halton draws. The fitted mixed logistic model is shown in Table 2. Random coefficients are presented in **bold**, and associated standard deviations are given in brackets following the mean values. The t-statistics and marginal effects for independent variables are also given in Table 23.

4.6.3 Model Interpretation for Motorcyclist-At-Fault Model

Curve Parameters

Three curve parameters (radius, type, and length) were examined in this study. The model shows that a sharp curve (radius < 400 ft) tends to increase the likelihood of a motorcyclist at-fault by 7.6%, compared to other curves, at a confidence level of 90%. Reverse curves and long curves (>0.8 mile) have no significant influence on motorcyclists at-fault in a two-vehicle crash on a curve. However, all these factors are normally-distributed random parameters. The randomness might be introduced by unobserved factors that associate with the three variables and vary over crash observations. For example, some motorcyclists will increase their safety consciousness (e.g., slow down, pay more attention, etc.) when facing high-risk curves, such as sharp curves and/or reverse curves, but other motorcyclists may take risk-seeking behaviors (e.g., high speed, aggressive riding, etc.) with a similar situation. Health conditions, experience, and cornering skills that influence motorcyclists at-fault on curves also may vary by motorcyclist. The heterogeneity of the factors behind the three curve parameters was not included in the sample data and presented as the random distribution of the curve parameters.

Table 23. Fitted Motorcyclist-At-Fault Model

Variable	Coef. (SD.)	*t*-statistic (SD.)	Marginal Effects
Constant	0.738	2.64	
Curve Characteristics			
Sharp curve indicator (1 if curve radius less than 400 ft)	**0.325 (0.69)**	**1.76 (2.63)**	7.7
Reverse curve indicator (1 if centers of curve in different sides)	**0.035 (0.96)**	**0.58 (12.47)**	0.84
Long curve indicator (1 if length of curve more than 0.8 miles)	**-0.092 (1.32)**	**-0.61 (5.78)**	-2.1
Motorcyclist Characteristics			
Male rider indicator (1 if motorcycle rider male)	**-0.20 (1.06)**	**-2.01 (22.88)**	-4.78
Young age indicator (1 if motorcyclist age under 25)	**0.115 (3.31)**	**0.77 (10.30)**	2.73
Old age indicator (1 if motorcyclist age older than 65)	**0.325 (0.33)**	**5.08 (4.29)**	7.71
Local rider indicator (1 if motorcycle rider registered in Florida)	-0.361	-4.05	-8.58
Motorcycle insurance indicator (1 if motorcycle insurance valid)	-0.258	-3.98	-6.13
No physical defect indicator (1 if no defects known*)	-0.84	-4.79	-20.08
Motorcycle safety equipment indicator	**-0.307 (0.62)**	**-4.78 (13.6)**	-7.29
Motorcycle driver license classification indicator (1 if driver license class E)	**-0.179 (0.52)**	**-2.45 (11.94)**	-4.25
Riding Behaviors			
Extremely low-speed indicator (1 if motorcycle speed - speed limit < -10 mph)	-0.442	-3.72	-10.49
Low-speed indicator (1 if -10 mph ≤ motorcycle speed - speed limit < 0 mph)	-0.907	-7.56	-21.54
High-speed indicator (1 if 10 mph ≤ motorcycle speed - speed limit < 15 mph)	0.494	2.18	11.73
Extremely high-speed indicator (1 if motorcycle speed - speed limit ≥ 15 mph)	1.21	6.32	28.74
Same direction indicator (1 if motorcycle and another vehicle traveling in same direction)	0.872	13.23	20.76
Non-obstruction indicator (1 if no vision obstruction for motorcyclist in this crash)	0.468	4.12	11.11
Right-handed indicator (1 if cornering direction right-hand)	-0.097	-1.81	-2.31
Roadway Features			
Divided roadway indicator (1 if roadway divided or one-way)	-0.395	-4.58	-9.37
Expressway indicator (1 if roadway expressway)	0.40	5.26	9.49
Shoulder width in ft	**-0.0005 (0.06)**	**-0.09 (15.13)**	-0.01
Crash Characteristics			
Crash location indicator (1 if crash occurs on second half of curve)	0.146	2.27	3.47
Adverse weather indicator (1 if rain or fog)	**0.267 (1.58)**	**1.68 (6.25)**	6.35
Fatality indicator (1 if crash severity fatal)	1.33	5.63	31.5
Rear-end crash (1 if crash type is rear end)	1.15	17.58	27.27
Hit-on crash (1 if crash type is hit on)	0.65	3.57	15.48

Table 23, continued

Model Statistics	
Number of observations	5,316
Restricted log likelihood	-2,941.21
Log-likelihood at convergence	-2,953.35
McFadden Pseudo R-square (ρ^2)	0.0069

Sharp curves are accompanied by a low speed limit (usually ≤ 35 mph) and require a more significant speed reduction from normal speed to a safe entry speed. Sight distance is also decreased on sharp curves so that motorcyclists have difficulty detecting obstruction ahead. Motorcyclists need more advanced cornering skill to negotiate sharp curves. In addition, sharp curves might attract risk-taking motorcyclist behaviors for some aggressive motorcyclists (*1*). The impacts of sharp curves that tend to increase the likelihood of motorcyclist at-fault (68%) are more significant than the impacts of sharp curves that tend to decrease the likelihood of motorcyclist at-fault (e.g., increased safety consciousness) (32%), such that the overall impact of sharp curves significantly increases the risk of motorcyclist at-fault in two-vehicle crashes. The positive and negative impacts of reverse curves and long curves are close (51.3% vs. 49.7%, 47% vs. 53%, respectively); consequently, the overall impacts of the variables are insignificant.

Motorcyclist Characteristics

The male motorcyclist indicator produced a normal distribution with the mean of -0.2 and the standard deviation of 1.05. On average, male motorcyclists are less likely to be at-fault than female motorcyclists in a two-vehicle crash on curves by 4.78%. Motorcyclist gender is a random parameter that indicates unobserved heterogeneity, such as health conditions, safety consciousness, riding experience, cornering skills, familiarity with roadway conditions, etc. (*55*) The heterogeneity results in the random impact of motorcyclist gender on motorcyclist-at-fault in curve crashes. Previous studies (*76*–*78*) also indicated that the risk of motorcyclist-at-fault is not strongly associated with motorcyclist gender.

Motorcyclist age is another random parameter associated the heterogeneity of motorcyclist safety characteristics and behaviors (*55*). Compared to mid-age motorcyclists (25–65), older motorcyclists (>65) are 7.7% more likely to be at-fault in a curve-related two-vehicle crash on average. This finding is similar to the findings of a prior study (*76*). Hosking et al. (*78*) reported that more experienced motorcyclists tend to demonstrate better hazard perception skills and decreased response times to a potential crash. Nevertheless, older motorcyclists tend to decrease the at-fault likelihood in 17% of two-vehicles on curves due to their enhanced safety riding consciousness and behaviors. Young motorcyclists (<25) do not present a significant impact on motorcyclist-at-fault on curves. This finding is different from two previous studies (*76*, *77*) that reported that young motorcyclists are less likely to be at-fault in motorcycle crashes (not limit to curve-related). This result may be due to young motorcyclists having more significant heterogeneity of riding characteristics and behaviors. They are often inclined to accept risk-seeking behaviors, but they usually ride sport bikes that are easier to maneuver on horizontal curves and good physical capability including shorter response/perception time. The positive and negative impacts of young motorcyclists is close (51% vs. 49%).

The local motorcyclist and insurance indicators are two fixed parameters that tend to reduce the likelihood of motorcyclist-at-fault in two-vehicle crashes on curves. Local motorcyclists are more familiar with curve presence and roadway conditions; thus, they make fewer mistakes in negotiating curves. Haque et al. (*76*) reported a similar finding that foreign-registered motorcycles are more involved in at-fault crashes on expressways than local-registered motorcycles. Safety-oriented motorcyclists, who are more likely to take safe riding behaviors on curves, usually carry insurance. An insured motorcyclist is 25% less likely to be at-fault in a two-vehicle crash on curve. This is consistent with Schneider's finding (*1*). Motorcyclists who have no physical defects (e.g., eyesight or hearing defect, fatigue, illness, seizure, epilepsy, blackouts, etc.) are 20% less likely to be at-fault in a two-vehicle crash on a curve than motorcyclists who have physical defects.

Riding Behaviors

Speed is a predominant factor that tends to increase the likelihood and severity of motorcycle crashes (*6*, *9*, *12–16*, *18*, *27*, *28, 29*). On curves, high speed increases motorcyclist reaction time and the difficulty of negotiating curves; consequently, speed tends to increase the likelihood of at-fault for motorcyclists in two-vehicle crashes on curves. The model denotes that the probability of motorcyclist-at-fault is 28.7% more likely to increase by extremely high speed (speed – speed limit ≥15 mph) and 11.7% more likely by high speed (10 mph ≤ speed – speed limit < 15 mph) compared to normal speed (0 mph ≤ speed – speed limit < 10 mph). If speed decreases to extremely low (speed – speed limit < -10 mph) and low (-10 mph ≤ speed – speed limit < 0 mph), the likelihood of at-fault is reduced by 10.5% and 21.5%, respectively. Prior studies (*1*, *76*) also found that motorcyclists who were estimated to be traveling at higher speeds were more likely to be found at-fault .

If a motorcycle and another vehicle travel were traveling in the same direction when a crash occurred, the motorcyclist is 20.8% more likely to be at-fault than if in the other direction (opposite or crossing). Schneider et al. (*77*) found a similar result, namely, that when a motorcycle struck the side of another vehicle, the motorcycle was less likely to be at-fault . For vision obstructions present on curves, motorcyclists are more attentive and careful; consequently, they are 10% less likely to be at-fault.

Motorcyclists who take right-handed cornering are 2.3 less likely to be at-fault than those taking left-handed cornering. A possible explanation is that motorcyclists need to scan multiple objects simultaneously, such as roadside signs, surrounding vehicles, and other objects on the road or at roadside when they negotiate curves. If they negotiate a curve on the left, they need to move their head significantly to scan both the left side for traffic conditions on the opposite lane and the right side for roadside signs or crossing traffic. This double-side scan increases the complexity of the cornering task and may result in an increased likelihood of at-fault for motorcyclists. On the other hand, motorcyclists taking a right-hand negotiation can scan the opposite lane conditions (left side) and roadside conditions (right side) without a big movement of the head.

Roadway Features

A divided road and a one-way road physically separate motorcycles and opposing traffic; thus, the likelihood of motorcyclist-at-fault is decreased by 9.4%. Motorcyclists are 9.5% more likely to be at-fault on expressway curves because expressways are associated with high speed, which is more likely to increase fault for motorcyclists. Haque et al. (*76*) reported a similar finding that in multi-vehicle crashes, motorcyclists are more likely to make mistakes on expressway ramps and to implicate other road users. Shoulder width was found to be a random parameter with a mean of -0.0005 and a standard deviation of 0.06. In 50% of two-vehicle crashes on curves, an increase in shoulder width decreases the likelihood of motorcyclist-at-fault; in the other 50% of crashes, the impact of a wider shoulder increased the likelihood. Overall, the impact of shoulder width is insignificant. The heterogeneity of motorcyclist safety consciousness and behaviors might account for the randomness.

Crash Characteristics

Crashes in which a motorcyclist is at-fault are 3.5% more likely to occur on the second half of a curve compared to other locations (e.g., first half of curve, tangent segments before or after curve). Adverse weather conditions (e.g., rain or fog) are distributed with a mean of 0.27 and a standard deviation of 1.58. Overall, adverse weather tends to increase the risk of motorcyclist-at-fault by 6.35% at a confidence level of 90%. Adverse weather increases the risk for motorcyclists in curve negotiation, such as reduced sight distance, wet pavement, etc. Other the other hand, motorcyclists increase their safety consciousness with adverse weather, such as reduced speed, more attention to surrounding conditions, etc. The opposite impacts of weather conditions lead the randomness.

Motorcyclist-at-fault is strongly associated with the injury severity of two-vehicle crashes on curves. The probability of a fatality tends to increase by 31.5% if a motorcyclist makes a mistake in a two-vehicle crash on a curve. This finding is consistent with a prior study (*83*). Motorcyclists are 27.3% and 15.5% more likely to be at-fault in rear-end and head-on two-vehicle crashes on a curve, respectively, compared to other crash types. Motorcyclists might be too close to other vehicles under some situations in rear-end crashes (*1*), and motorcyclists making mistakes are likely to result in hitting opposite vehicles.

4.7 Summary and Conclusions

This study investigated the effects of horizontal curvature and associated factors (geometric, traffic, vehicle, and motorcyclists) on motorcycle crashes on horizontal curves in Florida from three aspects:

- What factors influence single-motorcycle crash occurrence (frequency) on rural two-lane curves?
- What factors influence single-motorcycle crash severity (risk of fatality and severe injury) on rural two-lane curves?
- What factors influence motorcyclists-at-fault in a two-vehicle crash on horizontal curves?

Random parameter negative binomial models and mixed logistics models were developed to investigate the relationships between motorcycle crash risk measures and various contributing factors. Important factors contributing to motorcycle crass risk on horizontal curves are summarized in Table 24.

In addition, the research team developed CMFs of horizontal curve radius for motorcycle crashes on rural two-lane roadways using two different methods: cross-sectional and case-control, as follows:

- CMFs by Cross-sectional Method

$$CMF = \left(\frac{R}{5000}\right)^{-0.208} \quad (19)$$

R is curve radius in ft.; baseline is 5000 ft.

- CMFs by Case-Control Method

$$\mathrm{CMF_R} = \begin{cases} 3.27 & R \leq 1{,}000\, ft \\ 2.98 & 1{,}000\, ft < R \leq 2{,}000\, ft \\ 1.82 & 2{,}000\, ft < R \leq 10{,}000\, ft \end{cases} \quad (20)$$

The two CMFs have the same trend, but their baselines are different. Considering the case-control method can effectively address confounding variables and low-mean sample, the CMF-developed case-control method is preferred.

Table 24. Important Risk Factors of Motorcycle Crashes on Horizontal Curve Segments

Risk Factors	Effects on Crash Risk			Cause	Suggested Countermeasures
	Crash Occurrence	**Crash Severity**	**Motorcycle At-Fault**		
Sharp Curve	⇧ High risk if R < 1,500 ft	⇧ 6.08% higher risk if R < 1,500 ft	⇧ 7.7% higher risk if R < 400 ft	• Increased speed variation • Decreased sight distance • Increased complexity of negotiation maneuver	• Increase curve radius • Advance curve warning & advisory speed signing • Chevrons & enhanced chevron signs • Dynamic curve warning system
Reverse Curve	⇩	⇧		• Promotion of safety-compensation behavior (e.g., reduce speed) • Increased complexity of negotiation maneuver (e.g., run off the road)	• Reverse curve warning & advisory speed signing • Chevrons & enhanced chevron signs • Flashing beacons
Higher Speed	⇧ 58% higher risk if speed > 50 mph	⇧ 24% higher risk if speed > 50 mph	28% higher risk if speed – speed lime > 15 mph	• Reduced time of response • Increased complexity of negotiation maneuver • Increased kinetic energy dissipation to motorcycle rider's body	• Dynamic speed feedback sign with posted speed • SLOW sign (e.g., on-pavement curve signing)
Speeding		⇧ 16% higher risk	⇧ 28% higher risk if speed – speed lime > 15 mph	• Geometric design barrier • Reduce time of response • Increase kinetic energy dissipation to motorcycle rider's body	• Dynamic speed feedback sign with posted speed • Enforcement countermeasure
Auxiliary Lane	⇧	⇩		• Increased potential traffic conflicts • Promotion of safety-compensation behavior (e.g., reduce speed)	• Longitudinal channelizers • Pavement marking
Poor Pavement Condition	⇩			• Promotion of safety-compensation behavior (e.g., reduce speed) • Increased rider alertness	• Road markings that make road look rougher • Transverse rumble stripes
Lighting		⇩		• Improved sight distance • Decreased complexity of negotiation maneuver	• Lighting installment (e.g., in-pavement lighting, reflective barrier delineation)

Table 24, continued

Vertical Slope	⇧			• Reduced sight distance	• Advanced curve warning signs • Chevrons & enhanced chevron signs
Access Density	⇧	⇧		• Introduce more conflicts from side streets	• Avoid access points within the functional area of curves • Provide good sign distance
Old Motorcyclists		⇧	⇧	• Weak detection/reaction/control ability • Weak body condition	• Regular physical examination • Special training program for senior motorcyclists
Female Motorcyclists		⇧	⇧	• Relatively weak body condition • Lack of negotiation skills	• Safety Education Program • Enhanced Training Courses
Use of Helmet		⇩	⇩	• Protect motorcyclists' heads in crash • Increase safety consciousness	• Encourage or enforce use of helmet
Non-local Motorcyclists			⇧	• Not familiar with road conditions	• Provide clear traffic signs and curve indicators • Provide information about motorcycle trails online

Chapter 5
Evaluation of Dynamic Speed Feedback Signs to Improve Motorcycle Safety on Horizontal Curves

5.1 Background

The fitted injury severity model (Table 19) also concluded that high motorcycle speed (≥ 50 mph) and speeding tend to increase the probability of fatal and severe injury by 24% and 16%, respectively, in a single-motorcycle crash on horizontal curves. As indicated in the Motorcycle Safety Foundation (MSF) naturalistic study (*84*), excess entry speed, combining inattention and weak cornering skill, are major contributors to cornering mishaps for motorcyclists on horizontal curves. Excess entry speed may be caused by workload and distraction, fatigue, sight distance, misperception of the degree of roadway curvature, and situational complexity (*85*).

A Dynamic Speed Feedback Sign (DSFS) is an ITS device consisting of a speed measuring device (e.g., radar) and a message board to display feedback (e.g., actual speed, warning text, and/or flashing beacons) to drivers/motorcyclists who exceed a predefined speed threshold. Several studies have been conducted to evaluate the effectiveness of a DSFS for speed control, as summarized in Table 7. These studies have shown that a DSFS has adequate performance in the reduction of speed and crash and improvement of driver behaviors in most situations. However, all these studies focused on vehicle drivers but not motorcyclists. Most studies were conducted on roadway segments and school zones. Limited studies explored the effectiveness of a DSFS on curves. Since motorcyclist behaviors are significantly different from vehicle driver behaviors, the existing studies presented limited knowledge on (1) how motorcycles react with DSFSs on rural two-lane curves and (2) what DSFS configuration is effective to improve motorcycle safety on curves?

The primary objective of this evaluation study was to investigate the effectiveness of a DSFS to improve motorcyclist safety-related behaviors on rural two-lane curves and identify factors (e.g., roadway features, motorcyclist characteristics) contributing to motorcyclist reactions to a DSFS. To be specific, this study aims to (1) compare motorcycle speeding reduction when entering curves due to different DSFS configurations, (2) examine motorcyclist attention on DSFSs with different configurations, and (3) model the connection between motorcyclist behaviors in curve negotiation and DSFS configurations and other factors.

To achieve the research objectives, two field experiments were designed and conducted at selected sites in Florida. The basic experiment procedure is shown in Figure 22. In addition, a before-after crash analysis was conducted to compare lane departure motorcycle crash frequencies before and after the implementation of DSFS in selected segments in FDOT District 7. The Crash Modification Factor (CMF) for DSFS was developed based on the before-after analysis.

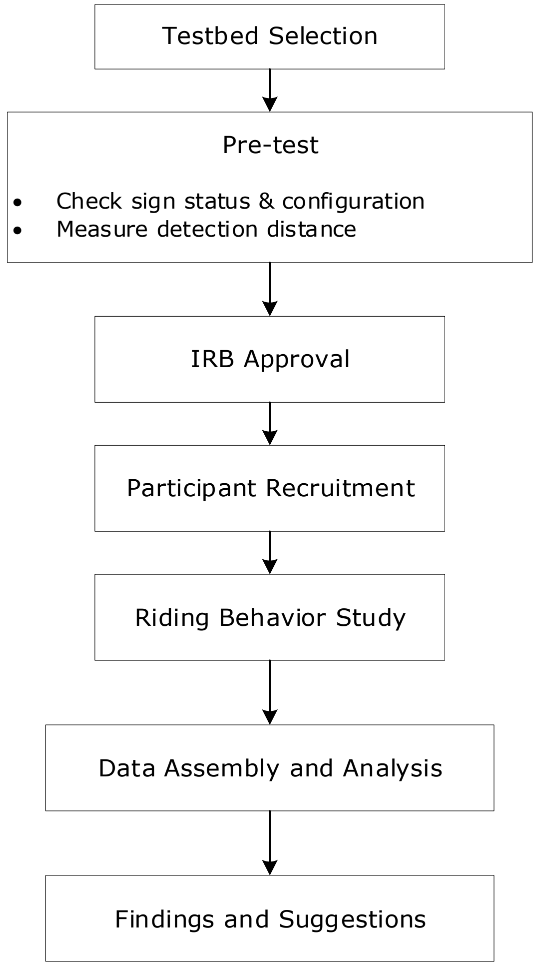


Figure 22. Flow Chart of Field Experiment for Evaluating DSFSs

5.2 Site Selection for Behavioral Study

W Ozello Trail in Crystal River, Florida, was identified by FDOT as the study site to evaluate the effectiveness of DSFSs for motorcycle safety. It is a rural two-lane road of 9.1 miles that provides excellent riding and is a popular destination for motorcycle enthusiasts in central Florida. As the trail has a relatively high-speed limit (30–40 mph on tangent sections) and many curves/bridges, there were significant safety issues related to speeding and curves. From 2005–2010, 41 motorcycle crashes, 4 of which were fatal, occurred on W Ozello Trail. A considerable proportion (61%) were caused by failure to control speed on curves (e.g., overturned, hit roadside objects, ran in ditch/culvert). To improve motorcycle safety and reduce curve-related crashes, in 2015, FDOT implemented DFSFs (produced by the Information Display Company) on 18 curves along W Ozello Trail. The test bed layout is shown in Figure 23, and site characteristics are given in Table 25.

Figure 23. Map of Testbed (W Ozello Trail, Crystal River, Florida)

Table 25. Site Characteristics along W Ozello Trail

Site	Direction	Latitude	Longitude	Location	Cornering Direction	Speed Limit on Upstream Tangent (mph)	Speed Limit of Curve (mph)
1	WB	28.852761	-82.600512	East of Winterset Ave	left	35	30
2	WB	28.847106	-82.607650	West of W Holloway Path	right	35	30
3	WB	28.843422	-82.612296		right	35	30
4	WB	28.835752	-82.622378		right	45	40
5	WB	28.837335	-82.647970	East of S Lighthouse Point	left	35	30
6	WB	28.833031	-82.663762	East of Schooner Drive	left	35	30
7	WB	28.831281	-82.668874	West of Ferndell Point	right	35	30
8	WB	28.833916	-82.672058	West of S Panther Point	right	25	20
9	WB	28.852543	-82.673682		right	25	20
10	WB	28.855839	-82.671592	East of Spangler Loop	right	15	10
11	EB	28.856266	-82.670763	East of Spangler Loop	right	15	10
12	EB	28.851942	-82.674350		left	35	30
13	EB	28.841824	-82.675693	East of S Estuary Drive	left	25	20
14	EB	28.832680	-82.664795	East of Schooner Drive	right	35	30
15	EB	28.837233	-82.649148	East of S Lighthouse Point	right	35	30
16	EB	28.835512	-82.623499		left	45	40
17	EB	28.839768	-82.613861		left	35	30
18	EB	28.845996	-82.609318		left	35	30

5.3 Pre-Test

The research team conducted a field pre-test on W Ozello Trail to check the state of the DSFSs. A set of factors, such as product mode, radar performance, upstream clearance, and detection distance for motorcycles, were examined in the field.

5.3.1 Dynamic Speed Feedback Sign

The DSFSs implemented along W Ozello Trail are produced by the Information Display Company. The sign consists of solar-powered AdvisorySpeed™ displays with bright LED speed digits and a "SLOW DOWN" message installed with standard static curve signs. Each sign can display the advisory speed continuously or can be unlit until a vehicle approaches. When drivers exceed the displayed speed, the radar-activated ViolationAlert™ feature catches their attention by flashing the speed and/or a "SLOW DOWN" message.

Figure 24. Example of DSFS on W Ozello Trail

Source: Produce catalog, Information Display Company

The DSFS can be configured onsite in DeviceManager™ software through a Bluetooth wireless link, as shown in Figure 25. The major setting operations include:

- *Speed limit* – Speed limit of horizontal curve; values range from 10–40 mph according to curve sharpness; sign displays speed limit continuously until "SLOW DOWN" display is triggered.
- *Violation alert speed* – Threshold for triggering beacon flashing; on W Ozello Trail, this value was set as 1 mph—if detected vehicle/motorcycle speed is 1mph higher than speed limit, beacon flashing is activated.

- *"Slow Down" speed* – Threshold for triggering "SLOW DOWN" displays; value was set as 1 mph on W Ozello Trail; if detected vehicle/motorcycle speed is 1 mph higher than speed limit, LED panel will display "SLOW DOWN" message. Otherwise, LED panel displays the speed limit constantly.

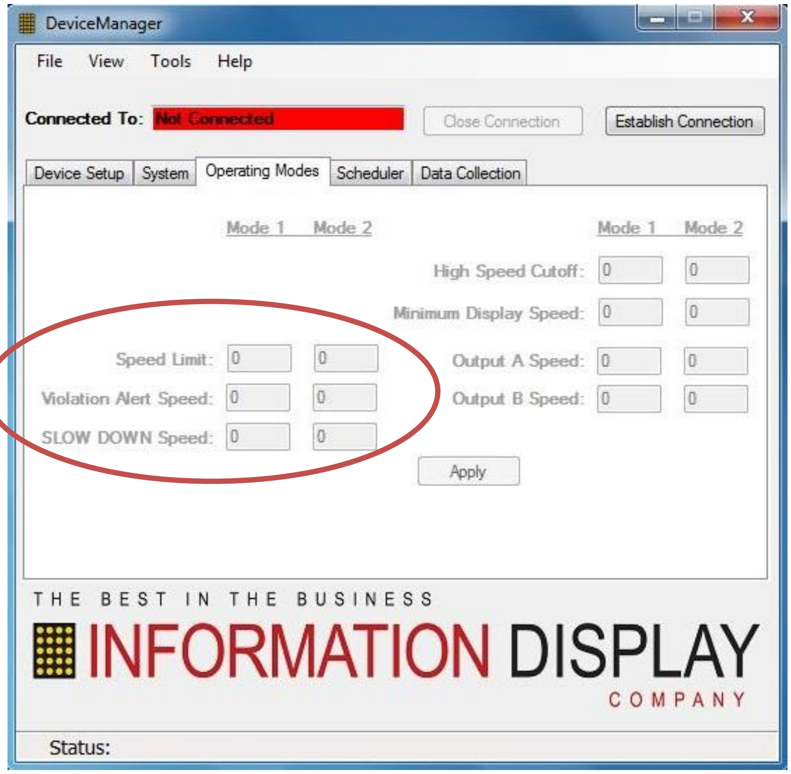


Figure 25. Configuration in Device Manager

5.3.2 Radar Detection Distance for Motorcycle

All DSFSs on W Ozello Trail are equipped with unconfigurable radars for which the detection parameters cannot be changed. A long detection distance can provide motorcyclists with an alert farther from the curve and, thus, more reaction time to reduce speed. The detection distance of the radar is influenced by several factors, such as target vehicle size, upstream clearance, and radar performance. This study examined the detection distance of DSFSs on motorcycle along the testbed.

In the test, all parameters of the DSFSs were set as their original values: violation alert speed was 1 mph above the sign speed limit, and the "SLOW DOWN" speed was 1 mph above the speed limit. In the test, a motorcyclist rode a Harley Davidson Softail motorcycle at 10 mph above the speed limit to go through all DSFSs along the trail (bi-direction) twice while an operator on the back seat took a video with a time stamp app on an iPhone. The app recorded the first flashing time at 0.01 seconds for each DSFS. The flashing time stamps were matched to the records from a VBox Sport mounted on the motorcycle to obtain a high-resolution location (GPS coordinates) of the first flashing when approaching a sign. The detection (flashing) distance of a DSFS was calculated as the spatial difference between the first flashing location and the target DSFS location along the route.

Harley Davidson Softail motorcycle and Vbox Sport

Screenshot of iPhone app to record first flashing time stamp

Figure 26. Pre-Test for Detection Distance for Motorcycles

The average detection distance of each sign for motorcycle was calculated, as shown in Table 26. The reaction time represents the time difference between the first flashing and the passing of the sign, assuming the motorcycle was running at the posted speed of the sign.

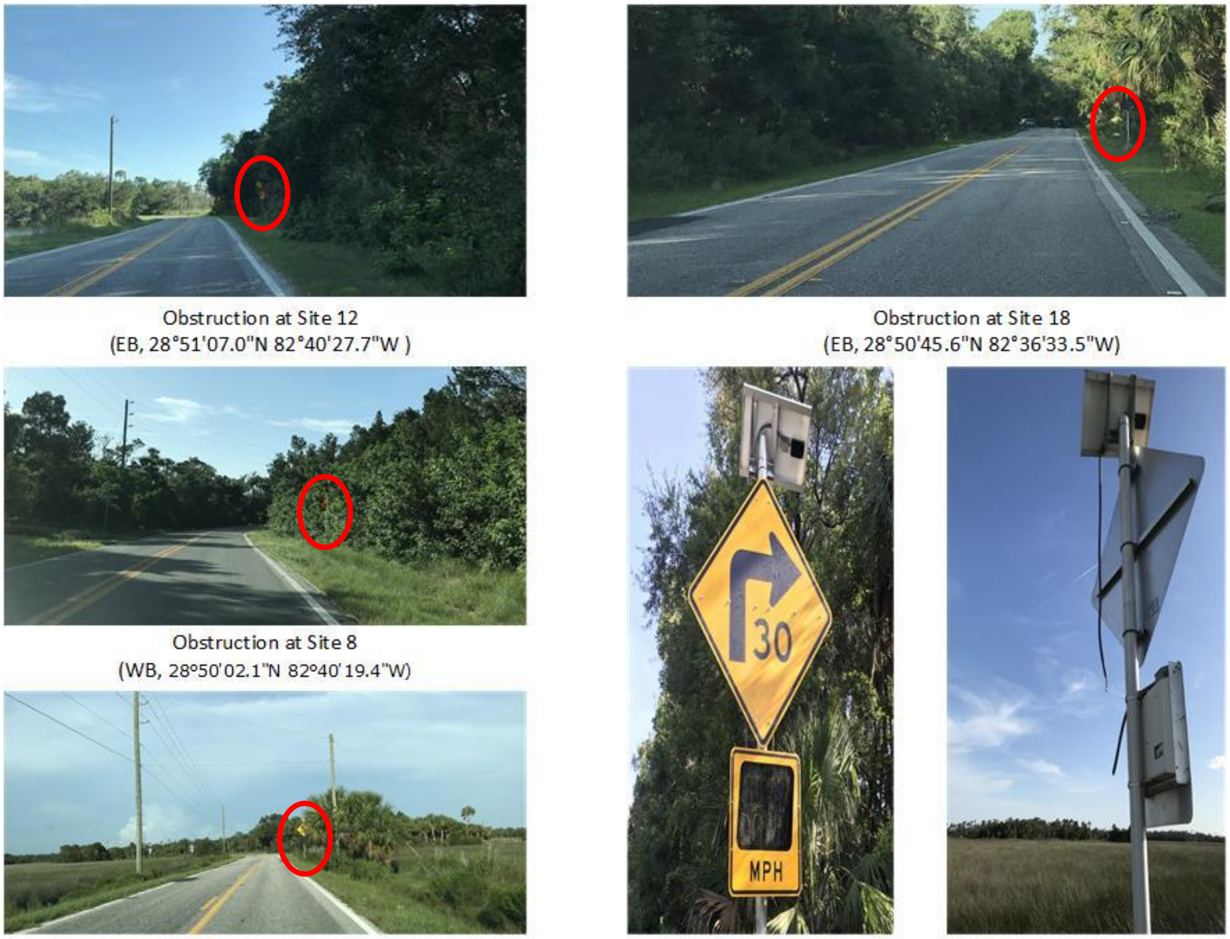
The detection (flashing) distance of a DSFS varies for different signs due to different geometric designs and upstream clearances. At several sites (4, 6, 7, 8, 12, 16, 17, 18, highlighted in Table 26), the detection distance was too short to provide enough reaction time (less than 2 seconds) for motorcyclists to reduce their speed before entering the curve. In particular, Sites 5 and 6 are left curves (curve center on left side). When a motorcyclist is approaching a curve, he/she should pay attention on the left to negotiate the curve. However, the flashing distance is very short at Sites 5 and 6, so motorcyclists are likely to be distracted by a sudden flashing on the right, which increases the risk of encroaching into the opposite lane. This concern was confirmed by the motorcyclist involved in this test.

Table 26. DSFS Detection (Flashing) Distance for Motorcycles

Sign	Run 1 (ft)	Run 2 (ft)	Average Distance (ft)	Reaction Time (sec)
1	269	207	238	5.41
2	148	105	126.5	2.88
3	*Inactive*			-
4	85	108	**96.5**	**1.65**
5	46	46	**46**	**1.05**
6	16	52	**34**	**0.77**
7	49	66	**57.5**	**1.31**
8	82	46	64	2.18
9	217	128	172.5	5.88
10	338	318	328	22.36
11	*No flash*			-
12	46	26	**36**	**0.82**
13	223	164	193.5	6.60
14	338	299	318.5	7.24
15	387	253	320	7.27
16	62	26	**44**	**0.75**
17	26	16	**21**	**0.48**
18	13	10	**11.5**	**0.26**

5.3.3 Obstruction and Other Issues

Four signs were found to be obstructed by tree branches, and two signs were found to have a physical defect. Figure 27 shows the identified issues in the pre-test.



Obstruction at Site 12
(EB, 28°51'07.0"N 82°40'27.7"W)

Obstruction at Site 18
(EB, 28°50'45.6"N 82°36'33.5"W)

Obstruction at Site 8
(WB, 28º50'02.1"N 82º40'19.4"W)

Obstruction at Site 16
(EB, 28°50'07.8"N 82°37'24.6"W)

Not working Site 3
(WB,28°50'36.3"N 82°36'44.3"W)

Broken cable at Site 16
(EB, 28°50'07.8"N 82°37'24.6"W)

Figure 27. Identified DSFS Issues in Pre-Test

5.4 Motorcycle Behavior Study

This study observed motorcyclist behaviors interacting with DSFS operations. Two motorcycle behavior measures (speed profile and attention) were examined, as high speed and inattention are the two major causes resulting in motorcycle crash occurrence on horizontal curves (*84*). The objective of the behavior study was to understand how motorcyclists interact with different DSFS operations and if a DSFS can effectively improve motorcycle safety on rural curves in Florida.

5.4.1 Participant Recruitment

This study recruited 10 motorcyclists to take a one-hour field test with their own motorcycles. All motorcycle motorcyclists met the following requirements:

- Must be age 18 or older with 5 years or more of riding experience.
- Have a motorcycle, valid motorcycle license, and motorcycle insurance.

Before the recruitment, an Institutional Review Board (IRB) application was submitted to and approved by the USF Office of Research Integrity & Compliance to protect the rights, safety, and welfare of human subjects who participated. The IRB protocol and approval letter are provided in Appendix C.

After IRB approval, a recruitment flyer (Appendix C.3) was distributed to motorcyclists in CUTR's database through email and media. A total of 10 participants were tested. Participant characteristics are shown in Table 27.

Table 27. Description of Participant Characteristics and Survey

Data Field	Value	Frequency (total = 10)
Gender	Male	6
	Female	4
Motorcycle type	Dual sport	2
	Curser	4
	Touring	4
Familiarity with trail	Not familiar	2
	Moderately familiar	5
	Extremely familiar	3
First time riding on trail	Yes	2
	No	8
Familiarity with DSFS	Not familiar	1
	Moderately familiar	6
	Extremely familiar	3
Aware of DSFS in test	Not aware	1
	Moderately aware	3
	Extremely aware	6
Response to DSFS in test	Effect on riding/speed	7
	No effect on riding/speed	3

5.4.2 Experiment Devices

This study collected motorcycle speed data and motorcyclist attention data. Two devices were used in the field experiment:

- *Tobii Pro Glasses 2* – A wearable eye tracker that can capture motorcyclist eye movement in real time. This tool gives researchers deep and objective insights into interaction between motorcyclists and DSFS operations by showing exactly what the motorcyclist is looking at as he/she is approaching selected curves with different DSFS configurations. The data could help researchers identified the impacts of a DSFS to increase motorcyclist attention on curves and, consequently, improve motorcycle safety on curves. The Tobii Pro Lab software could help researchers quickly and easily analyze large volumes of the eye-tracking data with the automated Real-World Mapping tool.

Figure 28. Tobii Pro Glasses 2

- *VBox Sport* – A lightweight and portable data logger that can measure vehicle performance measures, including velocity, acceleration, and GPS location in a high resolution (up to 20 Hz). The device was used to record motorcycle speed profile in negotiating with curves. The accurate GPS location information was matched to the eye-tracking videos by timestamps for addressing the spatial position of motorcyclist behaviors.

Figure 29. VBox Sport Performance Meter

5.4.3 Experiment Procedure

The experiment was conducted during two consecutive summer days with clear weather conditions. Before the experiment, 18 DSFSs were randomly configured in three modes:

- *OFF* – Sign turned off and covered with a black plastic bag. This mode represents no DSFS activation (without DSFS).
- *STATIC* – Sign activated, but no feedback function works. Sign continuously displays speed limit of curve without flashing.
- *DYNAMIC* – Sign activated, and feedback function works. Sign displays speed limit of associated curve if sign not triggered. When approaching motorcycle speed higher threshold, sign flashes and displays text message of “SLOW DOWN.”

The configuration of DSFS operations are shown in Table 28.

Table 28. Configuration of DSFS in Behavior Study

Site	Direction	Cornering Direction	Speed Limit of Curve (mph)	DSFS Mode	Radar Detection Distance for Motorcycle (ft)	Distance from DSFS to Curve (ft)
1	WB	left	30	DYNAMIC	269	295
2	WB	right	30	STATIC	148	131
3	WB	right	30	OFF	N/A *	135
4	WB	right	40	DYNAMIC	85	46
5	WB	left	30	STATIC	46	59
				OFF**		
6	WB	left	30	DYNAMIC	16	52
				OFF**		
7	WB	right	30	STATIC	49	246
8	WB	right	20	OFF	82	75
9	WB	right	20	DYNAMIC	217	151
10	WB	right	10	STATIC	338	82
11	EB	right	10	DYNAMIC	N/A *	23
12	EB	left	30	DYNAMIC	46	102
13	EB	left	20	STATIC	223	141
14	EB	right	30	DYNAMIC	338	72
15	EB	right	30	DYNAMIC	387	102
16	EB	left	40	OFF	62	105
17	EB	left	30	OFF	26	397
18	EB	left	30	DYNAMIC	13	187

**Not working during experiment.*
***Configuration on second day.*

Each participant took a one-hour field test with the two devices along the testbed. The testing procedure was as follows:

- *Step 1* – When a participant arrived at the start point (Figure 23), researchers asked the participant to read and sign the consent form (Appendix C.4).
- *Step 2* – If the participant agreed and signed the form, researchers mounted the VBox Sport on his/her motorcycle and calibrated the Tobii Pro Glasses.
- *Step 3* – The participant worn the Tobii Pro Glasses and rode from the start point to the check point (Figure 23), after then returned to the start point. A survey car followed the participant and kept a safety distance to prevent any following vehicles passing the participant.
- *Step 4* – When the participant returned to the start point, researchers unmount the devices and retrieved data from the devices. Researchers also recorded the participants' characteristics, as shown in Table 27.

The field test procedure was repeated for all participants. The performance data were retrieved from the two devices, including:

- *Speed* – The spot speed of motorcycle measured by the VBox Sport every 50 milliseconds (sampling rate is 20 Hz).
- *Lat, Long* – The GPS coordinates for each speed measurement point (20 Hz) from the VBox Sport.
- *Timeline* – The timeline (in millisecond) for each speed measurement point from the VBox Sport.
- *Front Video with Gaze Indicator* – The front video (25 fps) recorded by the Tobii Pro Glasses with gaze cycles indications eye's attention point.
- *Video Time Stamp* – The time stamp of the front video in 10 milliseconds.

5.4.4 Data Reduction

The collected raw data were processed in lab to produce the dataset for analysis. First, the Tobii front videos were reviewed by research staff to identify motorcyclists' attention points when they are approaching the DSFS sign and the curve. Figure 30 gives an example of eye tracking events for a motorcyclist negotiating curve. The VBox speed data were imported into ArcGIS and matched to the identified attention events by timestamps for determining the spatial position of attention events.

Figure 31 shows the data collection layout. The speed data were collected in three points: MP 1 – the speed at the location where a rider first pays attention to DSFS, MP 2 – the speed at the sign, and MP3 – the speed at the beginning of a curve. Motorcyclists' attention frequency (the number of attention points falling on the sign) and attention distance (the distance between the sign and the first attention location, D1 in Figure 31) were also collected from eye tracking videos. The collected speed and attention data were summarized in Table 29.

1. A motorcycle is approaching a DSFS; the rider pays attention to opposite vehicle

2. The DSFS is flashing; the rider pays attention to the DSFS

3. The DSFS is still flashing; the rider pays attention to front road

4. The rider is approaching the curve; he pays attention to the curve starting point

5. The rider starts to negotiate with the curve; he pays attention to opposite lane

6. The rider completes curve negotiation; he pays attention to front

Figure 30. Example of Tobii Front Video with Gaze Indicators (Site 1)

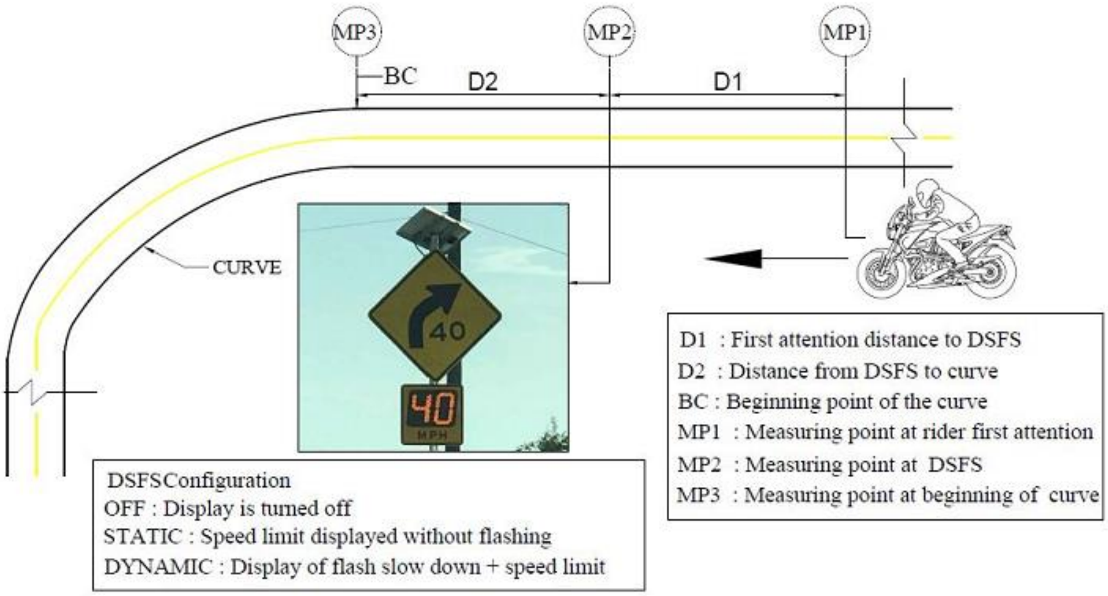


Figure 31. Data Collection Layout in Behavior Study

Table 29. Descriptive Statistics of Speed and Attention Data

Site	Average Speed (mph)						Attention Frequency		Attention Distance (ft.)	
	MP1		MP2		MP3		Mean	SD	Mean	SD
	Mean	SD	Mean	SD	Mean	SD				
1	45	3.6	42	5.2	38	4.1	4.75	3.92	239.5	138.23
2	38	6.2	39	5.3	39	4.1	2	1.20	129.2	83.42
3	36	4.6	37	7.9	37	7.3	1	1.49	158.2	60.27
4	42	6.6	38	4.9	39	4.6	2	2.45	198.8	80.60
5	35	8.5	36	7.5	37	6.8	1	1.41	129.6	78.42
6	33	5.3	31	5.4	29	3.9	0.5	1.00	162.7	77.82
7	30	4.5	30	4.5	28	5.4	1.71	1.50	176.6	113.54
8	32	6	31	5.6	32	6.8	0.5	0.76	38.5	22.09
9	34	4.1	31	3.8	27	3.7	1.38	2.13	135.9	61.37
10	30	5.2	25	4.2	21	3.6	1.4	1.52	185.3	84.40
11	36	7.3	29	5.2	27	5.6	2	0.82	160.3	56.30
12	36	9.7	33	7.8	34	6.7	1.17	1.60	80.4	31.31
13	32	7	31	6.5	26	4.2	1.88	1.64	55.1	41.90
14	34	3.7	29	4.1	28	3	1.86	1.57	220.5	88.08
15	41	8.6	38	4.4	37	3.8	2.71	2.43	190.9	78.06
16	45	5.4	42	3.3	41	4.3	0.5	0.84	74.8	43.13
17	44	5.8	43	6.2	34	7	1.17	1.60	81.2	39.45
18	41	6.3	40	6.7	40	6	1.57	2.82	90.6	52.51

5.5 Speed Data Analysis

5.5.1 Speed Analysis Method

Three speed measures (average speed, speed reduction rate, speeding rate) were examined at two locations: near sign (MP2 in Figure 31) and the beginning of curve (MP3 in Figure 31), respectively.

- *Average speed* – The arithmetic mean of all speed observations at the target location (MP2 – near sign and MP3 – at curve).

$$\overline{V_{zk}} = \frac{1}{N \cdot M}\sum_{j=1}^{M}\sum_{i=1}^{N} V_{ijzk} \quad (21)$$

where $\overline{V_k}$ is the average speed (mph) at location *z* (MP1 or MP3) with DSFS operation mode *k*; V_{ijzk} is the spot speed of *i*th participant at location *z* (MP1 or MP3) in Site *j with* DSFS operation mode *k*; *N* and *M* are the number of participants and the number of sites for location *z* and DSFS mode *k*.

- *Speed reduction rate* – Percentage of observations for which the speed at the measurement location (MP2 or MP3) was lower than the initial speed (speed at MP1, Figure 31) by 1 mph or more. A buffer of 1 mph was used to exclude motorcycle speed fluctuation.

$$P_{zk}^{SR} = \frac{N_{zk}^{SR}}{N_{zk}} \cdot 100\% \quad (22)$$

where P_{zk}^{SR} is the speed reduction rate at location *z* with DSFS mode *k*; N_{jk}^{SR} is the number of observations that the speed at location *k* of site *j* is lower than the initial speed by one mph or more; N_{zk} is the total number of observations at location *z* with DSFS mode *k*.

- *Speeding rate* – Percentage of observations that the speed at the target location (MP2 or MP3) was higher than the speed limit of the curve by 1 mph or more.

$$P_{zk}^{Speeding} = \frac{N_{zk}^{Speeding}}{N_{zk}} \cdot 100\% \quad (23)$$

where $P_{zk}^{Speeding}$ is the speeding rate at location *z* with DSFS operation mode *k*; $N_{zk}^{Speeding}$ is the number of observations that the speed at location *z* with DSFS operation mode *k* is greater than the speed limit by 1 mph or more.

A *t*-test was conducted to compare the average speed at the target location (MP1 or MP2) between a DSFS activation mode (STATIC or DYNAMIC) that represents DSFS operations and the OFF mode that represents without DSFS. The hypothesis is given as follows:

H_0: average speed with DSFS (STATIC or DYNAMIC) =
average speed without DSFS (OFF)

H_a: average speed with DSFS (STATIC or DYNAMIC) < average speed without DSFS (OFF)

If the null hypothesis (H_0) is rejected, DSFS has significant effects on reducing motorcycle speed on curves. If not, there is no evidence to support the statement.

A Chi-squared test was used to compare speed reduction rate and speeding rate between with DSFS (STATIC or DYNAMIC) and without DSFS (OFF). The hypothesis is given as follows:

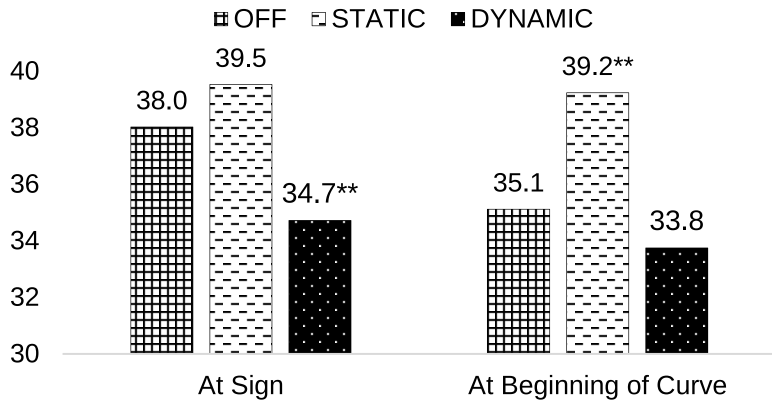
H_0: speed reduction rate (or speeding rate) with DSFS (STATIC or DYNAMIC) = speed reduction rate (or speeding rate) without DSFS (OFF)

H_a: speed reduction rate (or speeding rate) with DSFS (STATIC or DYNAMIC) ≠ speed reduction rate (or speeding rate) without DSFS (OFF)

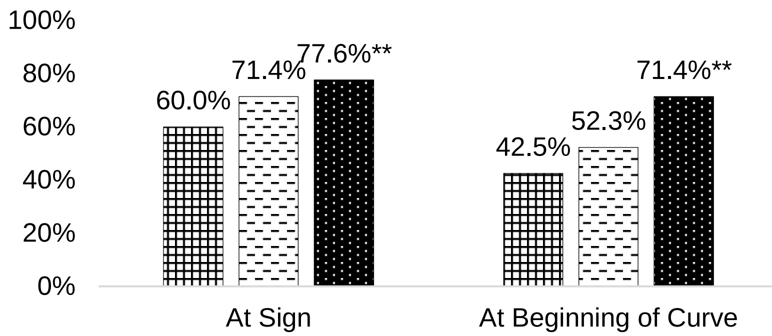
5.5.2 Speed Analysis Results

Figure 32 shows the comparisons of speed measures among the three DSFS modes (OFF is baseline). Compared to the "OFF" mode, the DSFS working in "DYNAMIC" mode significantly increased the speed reduction percentage, by 28.9% (= 71.4% - 42.5%, Figure 32B) at the beginning of the curve and by 17.6% (= 77.6% - 60%) at the sign. Motorcyclists tended to reduce their speed when they detected the DSFS flashing and the display of "SLOW DOWN."

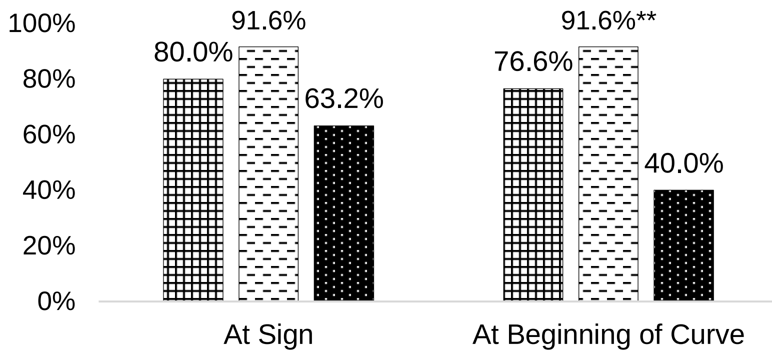
However, the difference in average speed reduction between "DYNAMIC" and "OFF" was significant only at the sign (3.3 mph = 38 mph – 34.7 mph, Figure 32A). At the beginning of the curve, the speed difference (1.3 mph) between the two DSFS modes was not significant. The speeding rates of the two modes were insignificant at either the sign or the beginning of a curve, although the mode of "DYNAMIC" experienced relatively lower speeding behaviors (Figure 32C). This result indicates that, compared to no DSFS ("OFF" mode), the feedback scheme of DSFS (flashing + "SLOW DOWN" display) can effectively result in motorcyclist speed reduction behaviors when approaching the curve. However, the degree of speed reduction (from normal speed to curve-ready speed) is limited—the average entry speed for the all three modes was higher than the speed limit of the curve.



A. Average Speed (mph)



B. Percentage of Speed Reduction



C. Percentage of Speeding

*** 95% significant in comparison with baseline (OFF)*

Figure 32.Comparison of Speed Measures

Motorcyclists usually use a speed for curve negotiation based on their prediction and judgment on the potential risk of a curve, such as curve sharpness, sight distance, surface condition, and any potential conflicts. This confidence speed often is higher than the posted speed limit, especially for experienced motorcyclists (all participants had five years or more of riding experience). When they detected a DSFS flashing and a display of "SLOW DOWN," they were more likely to increase their alertness and reduce their speed slowly. Once they felt that they understood the risk of the curve (from the displayed speed limit and by scanning the curve conditions), they stayed at the maximum speed at which they were confident to negotiate a curve. Thus, the results show that the impact of a DSFS in DYNAMIC mode has a limited effect on reducing speed rate and entry speed. However, a DSFS still has an impact on improving motorcycle safety on rural curves. Even without a significant degree of speed reduction, motorcyclists still are alerted by a DSFS and tend to slow down their speed. The flashing function of a DSFS helps motorcyclists pay attention to the sign, and the message of the speed limit and "SLOW DOWN" helps them to be aware of the presence and sharpness of a curve. Although their entry speed may be higher than the speed limit, they still pay attention to curve negotiation.

The average speed and speeding rate of the "STATIC" mode shown in Figure 32 are extremely high. This counterintuitive phenomenon might be caused by site-specific factors that influence the speed at the sign and curves. The speed reduction rate of the "STATIC" mode was higher than the "OFF" mode, but the difference was insignificant. Based on this result, a DSFS in the "DYNAMIC" mode has a more effective impact on increasing motorcyclist speed reduction rates than the "STATIC" mode.

5.6 Attention Data Analysis

5.6.1 Attention Analysis Method

This study examined motorcyclist attention to a DSFS with different DSFS operations. If the gaze of a motorcyclist falls on a DSFS, as shown in Event 2 in Figure 30, an attention event can be identified. Based on the identified attention events, three attention measures were calculated:

- *Average Attention Distance* – Distance (in ft) between the sign and the location that motorcyclists first pay attention to the sign (D1 in Figure 31):

$$\overline{D_k} = \frac{1}{N \cdot M}\sum_{j=1}^{M}\sum_{i=1}^{N} D_{ijk} \qquad (24)$$

  where $\overline{D_k}$ is average attention distance (ft) with DSFS operation mode k; D_{ijk} is attention distance (ft) for ith participant at site j with DSFS operation mode k; N and M are the number of participants and sites for DSFS operation mode k, respectively.

- *Average Attention Rate* – Percentage of motorcyclists paying attention on DSFS when they are approaching curves.

$$\overline{R_k} = \frac{1}{N \cdot M}\sum_{j=1}^{M}\sum_{i=1}^{N} C_{ijk}^{A}/C_{ijk} \tag{25}$$

where $\overline{R_k}$ is the average attention rate; C_{ijk}^{A} and C_{ijk} are the count of attention events and total events, respectively, for *i*th participant at site *j* with DSFS operation mode *k*; *N* and *M* are the number of participants and sites for DSFS operation mode *k*, respectively.

- *Average Attention Frequency* – Number of attention events during a motorcyclist approaching a curve.

$$\overline{F_k} = \frac{1}{N \cdot M}\sum_{j=1}^{M}\sum_{i=1}^{N} N_{ijk}^{A} \tag{26}$$

where $\overline{F_k}$ is the average attention frequency (number of attention events per rider) with DSFS operation mode *k*; N_{ijk}^{A} is the number of attention events for *i*th participant at site *j* with DSFS operation mode *k*; *N* and *M* are the number of participants and sites for DSFS operation mode *k*, respectively.

The one-tail *t*-test was used to compare the average attention distance between with DSFS (STATIC or DYNAMIC) and without DSFS. The hypothesis is:

H0: average attention distance with DSFS =
average attention distance without DSFS

Ha: average attention distance with DSFS >
average attention distance without DSFS

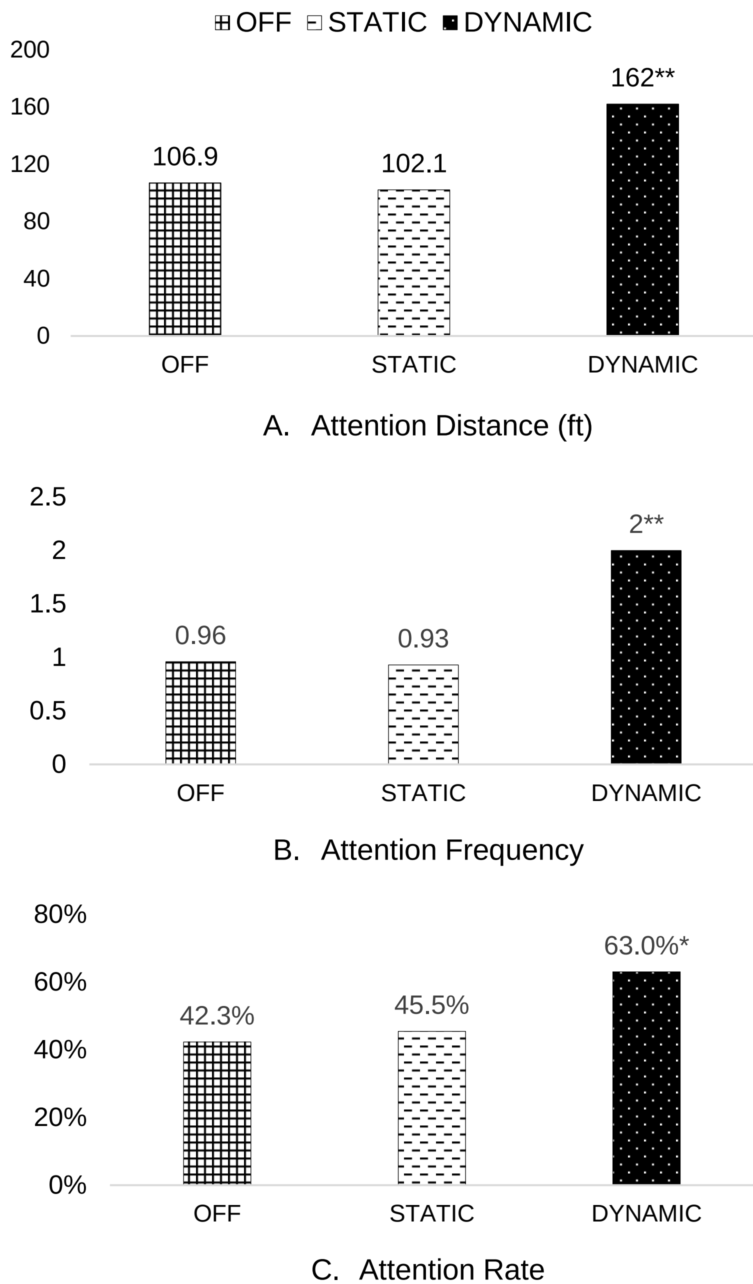
The Chi-squared test was used to compare the average attention rate between with DSFS (STATIC and DYNAMCI) and without DSFS (OFF). The null hypothesis is:

H0: average attention rate with DSFS =
average attention rate without DSFS

Ha: average attention rate with DSFS >
average attention rate without DSFS

5.6.2 Attention Analysis Results

Figure 33 shows the analysis results for attention measures. In Figure 33a, the average attention distance with "DYNAMIC" operations (162 ft) was much longer than that with "STATIC" operations (102.1 ft) and "OFF" operations (106.9 ft). The *t*-test results show that the difference of attention distance between "DYNMAIC" operations and "OFF" operations was significant at a confidence level of 95%. The difference between "STATIC" operations and "OFF" operations was insignificant. This result indicates that the flashing function of a DSFS, accompanying by a "SLOW DOWN" display, is more likely to affect motorcyclist attention at a long distance such that motorcyclists have more reaction time to recognize the potential risk of curves and prepare themselves well for curve negotiation.



** 90% significant in comparison*
*** 95% significant in comparison*

Figure 33. Comparison of Attention Measures

“DYNAMIC” operations experienced a higher attention rate than “STATIC” and “OFF” operations: 63% of motorcyclists paid attention to a DSFS when approaching a curve with a DSFS in the “DYNAMIC” mode; comparatively, only 42% and 45% of motorcyclists paid attention to the “OFF” and “STATIC” modes, respectively. A Chi-squared test indicated that this difference of attention rate between “DYNAMIC” operations and “OFF” operations was significant at a confidence level of 90%. A high attention rate means a high probability that motorcyclists receive DSFS information and understand the risk of curves. It can be concluded that “DYNAMIC” operations of DSFS can effectively increase motorcyclist attention and, consequently, improve motorcycle safety on curves.

A negative binomial model, as shown in Table 30, reported that motorcyclists significantly looked more often at the sign with “DYNAMIC” operations compared to the other two operations, at a confidence level of 95%. On average, motorcyclists looked at the sign twice with DSFS operations (Figure 33). When changing the operation mode from “STATIC” or “OFF” to “DYNAMIC,” the average attention frequency increased by approximate 1.1 per curve-negotiation event. The attraction from the flashing function of a DSFS is a major cause for high attention frequency. The model also indicates that motorcyclists who are familiar with the trail were more likely to pay less attention to the sign (confidence level is 90%).

Table 30. Fitted Negative Binomial Model for Attention Frequency

	Coef.	**Standard Deviation**	***p*-value**	**Marginal Effects**
Constant	0.0892	0.2973	0.764	
DYNAMIC mode	0.7774	0.3299	0.018	1.14
STATIC mode	-0.0589	0.3873	0.879	-0.55
OFF mode	*Baseline*			
Be familiar with trail	-0.5106	0.2842	0.072	-0.69
Overdispersion factor	1.1011	0.2920		
Model Statistics				
Number of observations	122			
Log-likelihood	-200.22			

With “DYNAMIC” operations (flashing + “SLOW DOWN”), motorcyclists were more likely to notice the DSFS information and recognize curve presence and the speed limit at a long distance, such that they had more time to react the curve and understand curve sharpness, adjust speed, and scan potential risks. Thus, a DSFS in “DYNAMIC” mode can effectively improve motorcycle safety on curves. The “STATIC” mode, which displays the speed limit continuously without feedback schemes, had no significant effect on motorcyclist attention in terms of attention rate, frequency, and distance.

However, the “DYNAMIC” mode potentially may cause a distraction issue. Motorcyclists tended to be attracted by the flashing beacon and looked more times at the sign when they were approaching the curve and may pay less attention to other potential risks, such as oncoming vehicles on opposite lane and conflicts on a roadside. This issue potentially becomes more serious when a DSFS sign is too close a left-hand curve. With this design, when the flashing beacon is on, motorcyclists are close to the curve and start to scan the opposite lane (on the left) and seek an appropriate lateral position; the flashing may attract motorcyclists to look on the right. The multiple scanning maneuvers (left and right) may lead motorcyclists to deviate from the appropriate trajectory and run into the opposite lane or onto the roadside. In the experiment, at least one participant complained that the flashing sign distracted him in a left-hand curve.

Figure 34 to Figure 37 present examples of a motorcyclist's eye-tracking data during different DSFS operation modes. Figure 34 represents eye-tracking data for "OFF" operations, in which motorcyclists looked at the DSFS (static curve symbol only) twice: Event 1 - 14:00:56:56 and Event 3 - 14:00:57:16. Except for these two events, motorcyclists continuously scanned the opposite traffic and surrounding conditions. Figure 35 shows eye-tracking data for "STATIC" operations, in which motorcyclists looked at the DSFS twice at the beginning, then continuously scanned road conditions even without opposing traffic. Figure 36 represents eye-tracking data for the "DYNAMIC" mode with opposing traffic; motorcyclists continuously paid attention to the DSFS (four times) when the sign was flashing and moved his eyes to front conditions and opposite traffic when he was close to the sign and the curve.

1. Pay first attention to DSFS

2. Scan opposite traffic

3. Pay second attention to DSFS

4. Scan front

5. Pay attention to opposite traffic

6. Continuously pay attention to opposite traffic

Figure 34. Eye Tracking with "OFF" Mode

1. Pay first attention to DSFS

2. Pay second attention to DSFS

3. Scan front

4. Continuously scan front

Figure 35. Eye Tracking with "STATIC" Mode

1. Pay first attention to DSFS

2. Pay second attention to DSFS

3. Pay third attention to DSFS

4. Pay fourth attention to DSFS

5. Scan front

6. Pay attention to opposite traffic

Figure 36. Eye Tracking for "DYNAMIC" Mode with Opposite Traffic

1. Pay first attention to DSFS

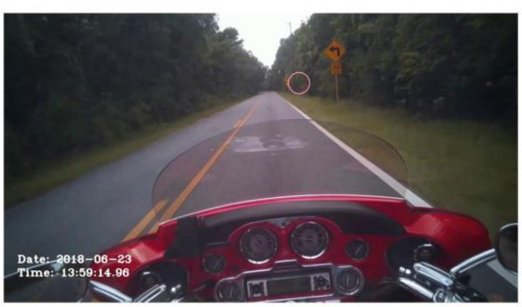
2. Pay second attention to DSFS

3. Pay third attention to DSFS

4. Pay fourth attention to DSFS

5. Pay fifth attention to DSFS

6. Pay sixth attention to DSFS



7. Pay seventh attention to DSFS

8. Scan front

Figure 37. Eye Tracking for "DYNAMIC" Mode without Opposite Traffic

5.7 Before-After Crash Analysis

In addition to the behavioral study, a before-after study was conducted to compare motorcycle crash frequency before and after the implementation of DSFS at selected roadway segments in FDOT District 7. Based on the before-after study, the CMF for DSFS was developed to quantify the effectiveness of DSFS on motorcycle safety.

5.7.1 Before-After Methodology

The before-after method is widely used in traffic crash analysis to address the effectiveness of a countermeasure (such as DSFS) on traffic crash reduction. The basic idea of a before-after study is to compare the number of crashes occurring before the improvement and the number occurring after the improvement in a same-time scale, assuming other factors have no significant changes during the study period. The safety effect is determined by the difference of crash counts between the before and after periods. The formula for deriving a CMF-based on this method is

$$CMF = \frac{N_A}{N_B} \quad (27)$$

where N_B and N_A are the crash frequencies before and after the implementation, respectively. When N_A is less than N_B, the CMF is less than 1.0, which implies that the countermeasure tends to reduce crash counts. However, such a simple before-after comparison may lead to inaccurate and biased conclusions because the method cannot distinguish the effect of the countermeasure from the effects of external factors (e.g., traffic flow, weather, economy, etc.) that may have also changed from the before period to the after period (*86*).

To resolve the issue of external causal factors, a before-after with comparison group method was used in this study. A comparison group is a group of control sites that are similar to the treated sites (with the implementation) and have no implementation of countermeasures in both the before and after periods. The comparison group is used to account for changes in crashes related to external causal factors such as time and traffic volume trends because there is confidence that the effects of external factors are similar for both treatment group and comparison group (*86*).

A guide published by FHWA provides details of the before-after with comparison group study (*61*), assuming crash counts were observed for two groups in the before and after periods, as shown Table 31.

Table 31. Summary of Notation for Before-After Study

	Treatment Group	Comparison Group
Before	$N_{T,B}$	$N_{C,B}$
After	$N_{T,A}$	$N_{C,A}$

The expected number of crashes for the treatment group that would have occurred in the after period without treatment ($N'_{T,A}$) is estimated from Eq. 28.

$$N'_{T,A} = \frac{N_{C,A}}{N_{C,B}} \times N_{T,B} \quad (28)$$

The comparison ratio ($N_{C,A}/N_{C,B}$) indicates how crash counts are expected to change in the absence of treatment. The variance of $N'_{T,A}$ is estimated approximately from Eq. 29.

$$\mathrm{Var}(N'_{T,A}) = {N'_{T,A}}^2 \times \left(\frac{1}{N_{T,B}} + \frac{1}{N_{C,B}} + \frac{1}{N_{C,A}}\right) \quad (29)$$

The CMF for the treatment of interest is estimated from Eq. 30, and its variance is estimated from Eq. 31.

$$\mathrm{CMF} = \frac{N_{T,A}}{N'_{T,A}} \Big/ \left(1 + \frac{\mathrm{Var}(N'_{T,A})}{{N'_{T,A}}^2}\right) \quad (30)$$

$$\mathrm{Var}(\mathrm{CMF}) = \frac{\mathrm{CMF}^2 \left[\frac{1}{N_{T,A}} + \frac{\mathrm{Var}(N'_{T,A})}{{N'_{T,A}}^2}\right]}{\left[1 + \frac{\mathrm{Var}(N'_{T,A})}{{N'_{T,A}}^2}\right]^2} \quad (31)$$

A confidence interval is a measure of the uncertainty of a CMF. As the confidence interval increases, there is less certainty in the estimate of the CMF. If the confidence interval does not include 1.0, it can be stated that the CMF is significant at the given confidence level. If the confidence interval includes 1.0, the estimation of CMF is insignificant and should be used with caution. The formula for the 95% confidence interval (CI) calculation is given as

$$\mathrm{CI} = \mathrm{CMF} \pm \left(1.96 \times \sqrt{\mathrm{Var}(\mathrm{CMF})}\right) \quad (32)$$

In conducting a before-after with comparison group study, the following factors should be considered:

- The lengths of the before and after periods should be the same for the treatment group and the comparison group. Hauer (*87*) recommended the use of three years for before and after periods if data are available and no significant changes occurred in external factors.

- The ratios of expected crash counts in the after period to the expected crash counts in the before period are equal for the comparison group and the treatment group, assuming no treatment. The suitability of a comparison group can be determined by comparing a time-series of target crashes for a treatment group and comparison group during a period before the treatment implementation. Eq. 33 is used to calculate the sample odds ratio (OR) by a series of paired two years:

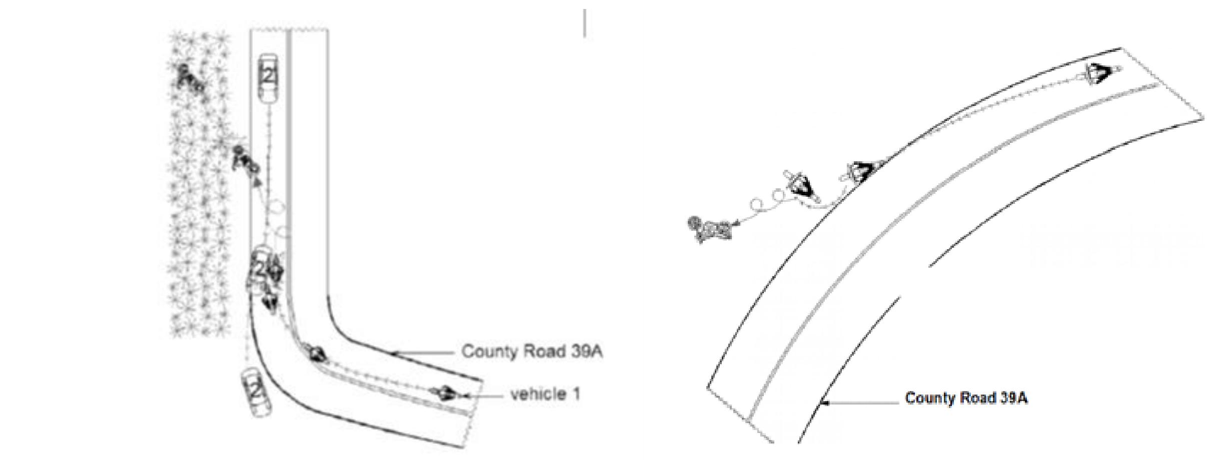
$$\mathrm{OR} = \frac{(N_{T,i} \times N_{C,i+1})/(N_{T,i+1} \times N_{C,i})}{1 + 1/N_{T,i+1} + 1/N_{C,i}} \quad (33)$$

  where $N_{T,i}$ is the number of crashes for the treatment group in year i; $N_{T,i+1}$ is the number of crashes for the treatment group in next year (i + 1); $N_{T,i}$ and $N_{T,i+1}$ are the numbers of crashes for the comparison group in year i and year i+1, respectively. If the mean of sample odds ratios is sufficiently close to 1.0 (i.e., subjectively close to 1.0 and the confidence interval includes the value of 1.0), then the comparison group is deemed suitable.

5.7.2 Crash Data Collection

The research team collected historical motorcycle crash data on 89 roadway segments in five counties in FDOT District 7 (Citrus, Hernando, Pinellas, Pasco, and Hillsborough) for eight years (2010–2017). This study considered lane departure motorcycle crashes on curves (as shown in Figure 38) only because lane departure crashes are mainly caused by excessive speed on curves and may be impacted by DSFS. The research team reviewed collected crash data (reports) and selected the crashes of interest based on the following criteria:

- Motorcycle crashes were curve related
- Motorcycle crashes were lane departure crashes, including ran off road to roadside and ran into opposite lane (hitting on an object)



A. Ran into Opposite Lane & Hit an Object B. Ran Off Road

Figure 38. Examples of Lane Departure Motorcycle Crashes

The collected motorcycle crash data are presented in Table 32 through Table 36.

Table 32. Summary of Motorcycle Crash Data Collected in Citrus County

Segment	DSFS	RTU	All		Lane Departure	
			2010–2014	*2015–2017*	*2010–2014*	*2015-2017*
E Gobbler Rd	N	Y	20	2	10	2
E Trails End Rd	N	Y	2	0	1	0
Elkcam Blvd	N	Y	0	0	0	0
Homosassa Trail	N	Y	7	2	3	1
Istachatta Rd (Tomas Rd-Atinson Ct)	N	Y	1	0	0	0
Istachatta Rd (Tomas Rd-Floral Park Dr)	N	Y	4	0	3	0
N Forest Ridge Blvd	N	N	0	1	0	1
Ozello Trail	Y	Y	29	10	27	5
Riverwood Dr	N	Y	2	1	2	1
W Cypress Dr	N	Y	1	0	1	0
W Dunnellon Rd (River Garden Dr-W Heath Ct)	N	Y	2	1	2	0
W Dunnellon Rd (US19-W Heath Ct)	N	Y	3	5	3	4
W Gulf to Lake Hwy	N	N	1	0	0	0

Table 33. Summary of Motorcycle Crashes Collected in Hernando County

Segment	DSFS	RTU	All		Lane Departure	
			2010–2014	*2015–2017*	*2010–2014*	*2015–2017*
Citrus Way	Y	Y	6	1	5	0
Cortez Blvd	N	Y	1	3	1	2
Elgin Blvd	N	N	3	1	2	0
Forest Oaks Blvd	N	Y	0	1	0	1
Fort Dade Ave	N	Y	7	5	7	5
Hayman Rd	Y	Y	1	0	1	0
Landover Blvd	N	Y	3	1	3	1
Lingle Rd	Y	Y	0	2	0	1
Osowaw Blvd	Y	Y	1	2	0	1
Powell Rd	Y	Y	0	1	0	1
Shaol Line Blvd	N	Y	5	0	2	0
Spring Hilll Dr	N	N	3	0	2	0
Weatherly Rd	N	Y	8	8	2	0

Table 34. Summary of Motorcycle Crashes Collected in Hillsborough County

Segment	DSFS	RTU	All		Lane Departure	
			2010–2014	*2015–2017*	*2010–2014*	*2015–2017*
Anderson Rd	N	N	4	1	2	1
Balm Riverview Rd	N	Y	1	0	0	0
Bears Ave - W of Lake Emerald to Ehrlich	N	N	0	0	0	0
Boyette Rd	N	Y	4	5	2	4
CR 587 (Gunn Hwy)	N	Y	0	0	0	0
E Keysville Rd	N	Y	1	0	1	0
Mcintosh Rd	N	Y	1	0	1	0
Montague St	N	N	1	0	1	0
Morris Bridge Rd - E Fletcher Ave to Lamplighter Ln	N	Y	3	0	3	0
N Lakeview Dr	N	N	1	0	0	0
Newberger Rd	N	Y	1	2	1	2
Northbridge Blvd	N	N	1	0	1	0
Old Mulberry Rd	N	N	1	0	1	0
Patterson Rd	N	Y	9	5	5	3
Race track Rd	N	Y	0	2	0	0
Riverview Dr	N	Y	4	0	2	0
S Gornto Lake Rd	N	Y	3	0	2	0
S Monley Rd	N	Y	2	1	2	1
Twin Branch Acres Rd	N	Y	1	0	1	0
W Linebaugh Ave	N	Y	2	0	1	0
Williams Rd	N	Y	1	0	0	0

Table 35. Summary of Motorcycle Crashes Collected in Pasco County

Segment	DSFS	RTU	All		Lane Departure	
			2010–2014	*2015–2017*	*2010–2014*	*2015–2017*
Baileys Bluff Rd	N	Y	13	6	12	6
Bellamy Brothers Blvd	N	Y	1	0	0	0
Collier Pkwy	N	Y	0	0	0	0
Decubellis Rd	N	Y	6	3	5	2
Ehren Cutoff	N	Y	2	1	1	0
Embassy Blvd	N	N	1	0	1	0
Golf links Blvd	N	N	0	0	0	0
Grand Blvd	N	N	1	0	1	0
Jessamine Rd	N	Y	2	0	0	0
Lake iola Rd	N	Y	2	1	1	1
Little Rd (Cypress Lakes - Plathe)	N	N	1	2	0	1
Little Rd (Hudson - New York)	N	N	0	0	0	0
Marine PKWY	N	N	1	0	1	0
Meadow Pointe Blvd	N	N	1	1	1	1
Mitchell Blvd	N	N	2	1	2	1
Morris Bridge Rd	N	Y	1	1	1	0
Old Lakeland HWY	N	Y	1	0	1	0
Parkway Blvd	N	Y	3	5	2	4
Perrine Ranch Rd (Grand Blvd and Seven Springs Rd)	N	Y	0	0	0	0
Prospect Rd	N	Y	1	0	1	0
River Rd	N	N	1	0	0	0
Sea forest Dr	N	Y	1	1	1	0
Shady Hills Rd	N	Y	6	5	3	1
Strauber Memorial HWY	N	Y	0	1	0	1
Trilby Rd (Hunter - Highpond)	N	Y	2	0	1	0
Trouble Creek Rd	N	N	2	3	1	2
Perrine Ranch Blvd (Meadowood and CR 77)	N	Y	1	0	0	0

Table 36. Summary of Motorcycle Crashes Collected in Pinellas County

Segment	DSFS	RTU	All		Lane Departure	
			2010–2014	*2015–2017*	*2010–2014*	*2015–2017*
49th st N	Y	N	0	0	0	0
Carillon PKWY (tower - lake carillon dr)	N	N	3	2	0	2
Co Rd 296 (Bryan dairy rd)	N	Y	0	0	0	0
Enterprise rd E	N	N	1	0	0	0
Fairway ave S	N	N	1	0	0	0
Forest lakes blvd	Y	Y	2	0	1	0
Indian rocks rd	N	Y	0	0	0	0
N Belcher rd	Y	N	1	0	1	0
Park pl blvd	Y	N	2	1	0	0
Pinellas\Park st N (62 - CR694)	Y	N	3	0	1	0
Pinellas\park st N (Central ave)	N	N	2	0	0	0
park st N (Dartmouth - 22)	N	N	1	0	0	0
Spring Blvd	N	N	1	1	0	0
CR 611	N	N	4	2	1	1

5.7.3 Motorcycle Crash Trend Analysis

The trends of motorcycle crashes on curves in the selected segments are presented in Figure 39. The lane departure motorcycle crashes on curves showed an increase tendency, from 18 crashes per year to 31 crashes per year in the before period (2011–2014). In 2010, the number of crashes was extremely high (43 per year) and suddenly dropped to 21 per year in the next year (2011). In the after period (2015–2017), lane departure motorcycle crashes show a consistent trend (around 20 crashes per year) that was significantly less than the annual crash counts between 2012 and 2014.

The trend of lane departure motorcycle crashes on DSFS segments is similar to the trend on all segments. In the before period, the number of lane departure motorcycle crashes on DSFS segments had a sudden drop from 2010 (14 crashes per year) to 2011 (4 crashes per year) and presented an increase trend from 2011 (4 crashes per year) to 2014 (8 crashes per year). After the implementation of DSFS, these segments experienced a lower and more consistent crash frequency (5, 4, and 4 for 2015, 2016, and 2017, respectively) than that in the before period. The number of fatal motorcycle crashes showed no significant trend over the years due to a very limited sample size.

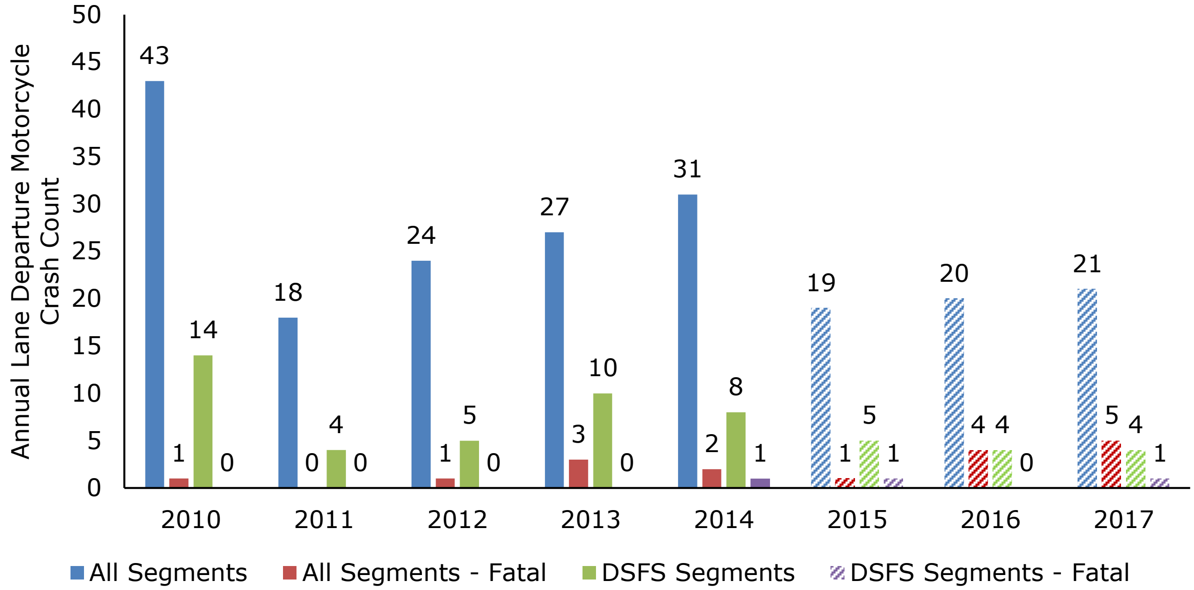


Figure 39. Trend of Lane Departure Motorcycle Crashes on Curves in Selected Segments FDOT District 7

Figure 40 presents a comparison of lane departure motorcycle crashes on curves. On DSFS segments, the average frequency was reduced from 8.6 crashes per year before implementation of DSFS (2010–2014) to 4.3 crashes per year after implementation of DSFS (2015–2017). The reduction percentage was 49.3% (= [8.6 – 4.3] / 8.6 × 100%). In comparison, the reduction percentage on non-DSFS segments was 21.6% in the same periods. Overall, the average crash frequency decreased by 28.4% (from 35.4 to 25.3) on all segments. As shown, DSFS effectively reduced lane departure motorcycle crashes on rural curves, but the reduction percent of 49.3% overestimates the effectiveness of DSFS because other factors also caused a reduction (21.6%) in lane departure motorcycle crashes on curves. A before-after crash with comparison group analysis was applied to obtain a more reasonable result, as discussed in the next section.

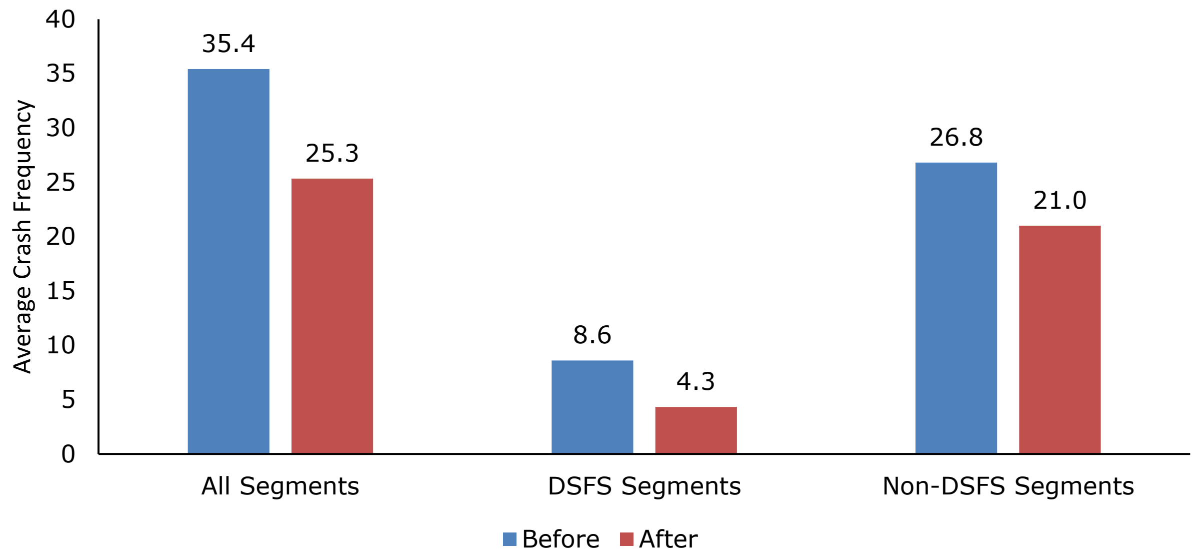


Figure 40. Comparison of Lane Departure Motorcycle Crashes in Before and After Periods

5.7.4 Analysis and CMF Development

The roadway segments were categorized into two groups: *treatment group*—roadway segments with DSFS since 2015, and *comparison group*—similar segments without DSFS before and after 2015. To ensure the similarity between the treatment and comparison groups, only two-lane undivided rural segments were included in the comparison group. The treatment group consisted of 11 segments and the comparison group consisted of 77 similar segments.

To verify the suitability of the comparison group, a series of odds ratios was calculated for lane departure motorcycle crashes over paired years (2010–2014) using Eq. 33. The analysis results, as shown in Table 37, indicate that the mean of odds ratios for paired years (2010–2011, 2011–2012, 2012–2013, 2013–2014) is 0.94 and close to 1. The 95% confidence interval of odds ratios include 1. The two values imply that the comparison group has sufficient similar trends with the treatment group over the years and is good for comparison in the before-after study.

Table 37. Suitability Analysis of Comparison Group

	2010	2011	2012	2013	2014
Treatment	12	4	5	9	8
Comparison	24	12	18	16	21
Odds Ratio		1.16	0.94	0.42	1.24
Mean of Odds Ratio					**0.94**
Variance of Odds Ratio					0.136
95% Confidence Interval of Odds Ratio					**(0.217, 1.664)**

In the trend analysis, there was a sudden drop from 2010 to 2011 caused by unknown special events. To avoid unnecessary influence from this trend, the two-year crashes were excluded from the before-after study. Hauer (*87*) suggested that the before period should be the same as the after period; thus, the before-after study adopted three years for both the before period (2012–2014) and the after period (2015–2017). The observations of lane departure motorcycle crashes for the before-after study are shown in Table 38.

Table 38. Observations of Lane Departure Motorcycle Crashes for Before-After Study

	Treatment	Comparison
Before	22	55
After	13	38

Based on Eq.28 to Eq.32, the CMF for DSFS on lane departure motorcycle crashes was calculated. The calculation procedure is shown in

Table 39. The CMF is 0.78, indicating that DSFS tends to reduce lane departure motorcycle crashes by 22% (= 1 – 78%) on rural two-lane undivided curves. The 95% confidence interval includes 1.0, indicating that this CMF is insignificant at a 95% confidence interval. This insignificance may be caused by the small sample size.

Table 39. Calculation of CMF for DSFS

Equation	Value
Comparison Ratio (Eq.8)	0.69
Expected Crashes in the After Period (Eq.8)	15.2
Variance of Expected Crashes (Eq.9)	20.78
CMF (Eq. 10)	**0.78**
Variance of CMF (Eq. 11)	0.086
95% Confidence Interval – Lower Bound (Eq. 12)	**0.2**
95% Confidence Interval – Upper Bound (Eq. 12)	**1.36**

The sample size of fatal lane departure motorcycle crashes was too small to be meaningful statistically. This study did not develop the CMF for fatal crashes.

5.8 Summary and Conclusions

The field experiment examined the interaction between motorcyclists and DSFS operations on horizontal curves along rural roads and the effectiveness of DSFSs for improving motorcycle safety on horizontal curves. Speed profile and eye-tracking data for 10 participants in negotiating curves with different DSFS operations were collected through VBox and Tobii Pro Glasses 2. Statistical comparisons were applied to these data to examine the impacts of three DSFS operation modes ("OFF" – without DSFS, "STATIC" – displaying speed limit continuously, "DYNAMIC" – flashing and displaying "SLOW DOWN" if motorcycle speed higher than thresholds) on motorcyclist behaviors.

The before-after crash analysis compared lane departure motorcycle crash frequencies between the before period (without DSFS, 2012–2014) and the after period (with DSFS, 2015–2017) to address the effectiveness of DSFS in motorcycle crash reduction. A comparison group was used to eliminate the unnecessary influence from external factors. The Crash Modification Factor (CMF) for DSFS was developed based on the before-after comparison.

Based on the analysis, the following major conclusions were obtained:

- A DSFS working in the DYNAMIC feedback scheme with flashing plus "SLOW DOWN" display effectively increases motorcyclist attention on curve information (e.g., presence of curve, speed limit of curve, excess entry speed). This improvement includes average 51% longer attention distance and 49% higher attention rate.
- A DSFS working in the DYNAMIC feedback scheme significantly results in motorcyclist speed reduction behaviors at the sign and at curve entry. This is caused by an increased attention rate with the DSFS dynamic feedback scheme. However, the reduction degree is slight (average 3.3 mph at sign and average 1.3 mph at curve entry). The average speed with a DSFS (in the DYNAMIC feedback scheme) is still higher than the posted speed limit, by around 4 mph.
- As inattention is a major cause of motorcycle crashes on curves, a DSFS in the DYNAMIC feedback scheme can effectively reduce the likelihood of inattention and can effectively increase motorcycle safety on curves.
- The before-after crash analysis supports the effectiveness of DSFS for improving motorcycle safety on rural two-lane undivided curves: the implementation of DSFS can reduce the lane departure motorcycle crashes on rural curves by 22%. The CMF for DSFS is given as

$$\text{CMF for Dynamic Speed Feedback Sign} = 0.78 \tag{34}$$

This CMF is valid for lane departure motorcycle crashes on rural two-lane undivided curves.

- However, a DSFS in the DYNAMIC mode (flashing function) may potentially increase the risk of distraction for motorcyclists, especially when the sign is close to the left-hand curve entry.
- Maintenance is important for DSFS functions. Some signs were in abnormal states (Figure 27), such as broken cable, not working, and obstruction by tree branch. All these issues may influence the functionality of a DSFS to increase motorcyclist attention on curves.
- The detection distance of a DSFS for motorcycles is very short on some curves (Table 26). Current signs are equipped with low-end radar, which cannot configure parameters to adjust detection distance.

Chapter 6
Conclusions and Recommendations

6.1 Summary

Horizontal curves, as fundamental design elements of highway systems, pose a critical issue in motorcycle safety management. Because of the predominance of horizontal curves and relatively high speed and low safety standards on rural roads, the issue of motorcycle safety is more significant on rural curves, particularly on rural two-lane roadways. This study indicates that horizontal curves experience single-motorcycle crashes 4.92–1.62 times higher than straight rural two-lane segments.

Excess entry speed, inattention, and weak cornering skills are major contributors to cornering mishaps for motorcyclists on horizontal curves. High motorcycle speed (estimated impact speed ≥ 50 mph) and speeding (operating speed > speed limit) tend to increase the probability of fatal and severe injury by 24% and 16%, respectively, in single-motorcycle crashes on rural two-lane curves. FDOT District 7 has implemented DSFSs on 148 rural and suburban highway curves to improve off-system roadway safety.

However, most roadway design and traffic control manuals include limited consideration for motorcycles, especially on horizontal curves. Meanwhile, the lack of knowledge on how DSFSs influence motorcycle safety-related behaviors prevents performance evaluation of DSFSs in safety improvement on curves and their proper implementation and operation.

To fill this gap, this project aimed to (1) identify factors that significantly increase the risk of motorcycle crashes and aggravate their injury severity on horizontal curve segments in Florida; (2) develop motorcycle CMFs to quantify the impacts of horizontal curvature and/or other factors for motorcycle safety management; and (3) assess the effectiveness of DSFSs in reducing the risk factors of curve-related motorcycle behaviors.

To achieve the research objectives, the following tasks were completed:

1. Conducted a comprehensive literature review to summarize the previous studies on the following topics:
    - Motorcycle crash analysis and modeling on curves
    - CMFs for horizontal curve parameters
    - Contributing factors to horizontal curves
    - Motorcycle behaviors on curves
    - Countermeasures to prevent motorcycle crash occurrence and severity on curves
    - Motorcycle exposure data and methodology
2. Analyzed Florida motorcycle crashes related to horizontal curves to address and quantify risk factors contributing to motorcycle crash frequency and severity. Statistical regression models were used to set up the relationship between

motorcycle crashes and contributing factors, such as horizontal curve parameters, geometric design, traffic, environmental factors, and motorcyclist characteristics. As a result, CMFs for horizontal curve parameters were developed.

3. Performed a field experiment to examine the interaction between motorcyclists and DSFSs on curves along W Ozello Trail in Crystal River. Eye-tracking and speed profile data were collected from 10 participants using Tobii Pro Glasses 2 and VBox Sport at 18 DSFSs in different scenarios (operation modes), including "OFF," "STATIC," and "DYNAMIC." The speed data and eye tracking data were statistically compared to address the effectiveness of DSFSs in speed reduction and attention improvement.

4. Conducted a before-after crash analysis to address the effectiveness of DSFS in motorcycle crash reduction on horizontal curves. Lane departure motorcycle crashes were compared in on rural road segments that implemented DSFS between the before period (2012-2014) and the after period (2015-2017). A comparison group containing 77 similar roadway segments was used to control the influence from external factors (e.g., temporal changes in traffic volume, weather, etc.).

5. Based on the results of the crash analysis and DSFS evaluation, recommendations were made to improve motorcycle safety on horizontal curves, including engineering countermeasures and education/enforcement programs.

6.2 Findings and Conclusions

6.2.1 Motorcycle Crash Analysis

Major conclusions from the motorcycle crash analysis are as follows:

- Curve radius is a significant risk factor contributing to motorcycle crash risk. Short curve radius tends to increase single-motorcycle crash risk, including frequency and injury severity, and also increases the likelihood of motorcyclist-at-fault in two-vehicle motorcycle crashes. Based on the case-control study:

$$\mathrm{CMF_R} = \begin{cases} 3.27 & R \leq 1{,}000\,ft \\ 2.98 & 1{,}000\,ft < R \leq 2{,}000\,ft \\ 1.82 & 2{,}000\,ft < R \leq 10{,}000\,ft \end{cases} \tag{35}$$

  where $\mathrm{CMF_R}$ is the CMF of curve radius for single motorcycle crash on rural two-lane roadways; R is the curve radius in feet; Baseline is straight segment. The mixed logistics model shows that sharp curves (< 1,500 ft) and intermediate curves (1,500 ft – 4,000 ft) tend to increase the risk of severe injury and/or fatality by 6.08% and 1.58%, respectively, on rural roads. In addition, if the curve radius is less than 400 ft, the probability of motorcyclists making mistakes tends to increase by 7%.

- A reverse curve (a composite of two curves with opposite center locations) has contradictory impacts on motorcycle crashes. This design experiences a lower single-motorcycle crash frequency on rural curves. The CMF of a reverse curve for single-motorcycle crashes on rural two-lane roadways ($\mathrm{CMF_T}$) is

$$\mathrm{CMF_T} = 0.61 \tag{36}$$

where the baseline is non-reversed curves. However, reversed curves tend to increase the risk of fatality and severe injury by 5.82% on rural roads.

- Speed is the most predominant factor causing fatalities and severe injuries in single-motorcycle crashes on rural curves. If operating speed is 50 mph, the risk of fatality and severe injury in a single motorcycle crash is 24.11% higher than that with a low operating speed (<50mph). Speeding—operating speeding is higher than speed limit—increases the risk of fatality and severe injury by 16.8% in a single motorcycle crash. If speed is higher than the speed limit, the likelihood of a motorcyclist making mistakes increases by 28.7% (speed – speed limit > 15 mph) and 11.7% (15 mph ≥ speed – speed limit > 10 mph), respectively.
- Older motorcyclists (age ≥ 60) experience a 16.27% higher risk of fatality and injury in a single motorcycle crash on rural curves than middle-aged motorcyclists (age 30–60). They also tend to make mistakes on curves, at 7.71% higher than middle-aged motorcyclists.
- Motorcyclists have significant safety compensation behavior on horizontal curves: they tend to use safe riding behaviors when they are subjectively aware of risks. If they feel "safe" and "confident," they use unsafe and aggressive riding behaviors. The safety compensation behavior can explain some counterintuitive findings in the crash analysis, such as that poor pavement conditions are more likely to cause lower injury severity in motorcycle crashes on curves. On the other hand, increasing awareness of potential risks is an effective way to improve motorcycle safety on curves.
- Use of a helmet can reduce the risk of fatality and severe injury by 8.35% in a single-motorcycle crash on rural curves. Motorcyclists with proper riding behaviors experience 11.9% lower risk of fatality and severe injury than those with improper riding behaviors.
- The presence of trees, barriers, and other fixed objects on a roadside are dangerous to motorcyclists in curve negotiation. If a single motorcycle hits these objects, the risk of fatality and severe injury increases by 15.6%, 20.7%, and 7.5%.
- Other factors contributing to single-motorcycle crash frequency and severity on curves, with associated causes and countermeasures, are summarized in Table 24.

6.2.2 DSFS Field Experiment and Crash Analysis

The major conclusions from the DSFS field experiment are the following:

- A DSFS with flashing plus "SLOW DOWN" display effectively increases motorcyclist awareness of curve risk by 50%. Motorcyclist intentions for reducing speed are increased; consequently, the speed reduction rate tends to increase. As inattention is a major cause for motorcycle crashes on curves, a DSFS can effectively improve motorcycle safety on curves.
- A DSFS does not reduce motorcycle speed (including speeding percentage) to a significant degree. Average motorcycle speeds were all higher than the posted speed limit with the three operations modes.

- The before-after study supports that a DSFS can improve motorcycle safety on horizontal curves. On rural two-lane undivided curves, the implementation of DSFS can reduce lane departure motorcycle crashes by 22% (CMF = 0.78).
- A DSFS with flashing potentially may introduce the risk of distraction for motorcyclists, especially when the sign is close to a left-hand curve entry.

6.3 Recommendations

6.3.1 Awareness of Curve Risk

Based on the crash and behavior analysis, motorcyclist inattention to and/or misunderstanding of curve risk are the critical factors contributing to motorcycle crash occurrence, crash severity, and motorcyclist-at-fault on curves. Making motorcyclists fully aware of the presence of curves and curve risks (e.g., sharpness, reversed curves, vertical grade, poor sign distance, access points, etc.) is an effective method to prevent motorcycle crash risk on horizontal curves.

The following engineering countermeasures are suggested for implementation on horizontal curves to increase motorcyclist awareness of curve risk.

Advance Curve Warning and Advisory Speed Signs

A horizontal alignment warning sign combined with an advisory speed plaque can call motorcyclist attention to unexpected conditions (e.g., presence of horizontal curves) on or adjacent to a roadway and advise them of the safe speed through the curve. Chapter 2C of MUTCD gives the standard of advance curve warning sign plus advisory sign for a horizontal curve. An example (W1-1L + W13-1P or W1-1R + W13-1P) is illustrated in Figure 41.

The cost for this countermeasure is low. The CMF Clearinghouse reports a 30% decrease in injury crashes and an 8% decrease in Property Damage Only (PDO) crashes when using advance static curve warning signs. No specific CMFs for motorcycles were found.

Chevron Alignment Sign

Chevron Alignment Signs (W1-8 in Figure 41) define the direction and sharpness of curve(s) and guide motorcyclists through a change in horizontal alignment. Chevron signs are more important if a concave slope presents. An example of Chevron Alignment Signs is given in Figure 42.

The cost of Chevrons is low, and the CMF Clearinghouse reports a 4–25% reduction in motorized crashes on rural curves. No CMFs for motorcycle crashes were found.

Advance Pavement Markings for Curve Warning and Speed Advisory

Pavement markings with curve warning and advisory speed in advance of horizontal curves provide highly conspicuous, supplementary warning information to motorcyclists. These markings supplement curve warning signs with advisory speed plaques by providing the information in the motorcyclist’s direct line of sight, emphasizing the message. An example of Advance Markings for Curve Warning and Speed Advisory is given in Figure 43.

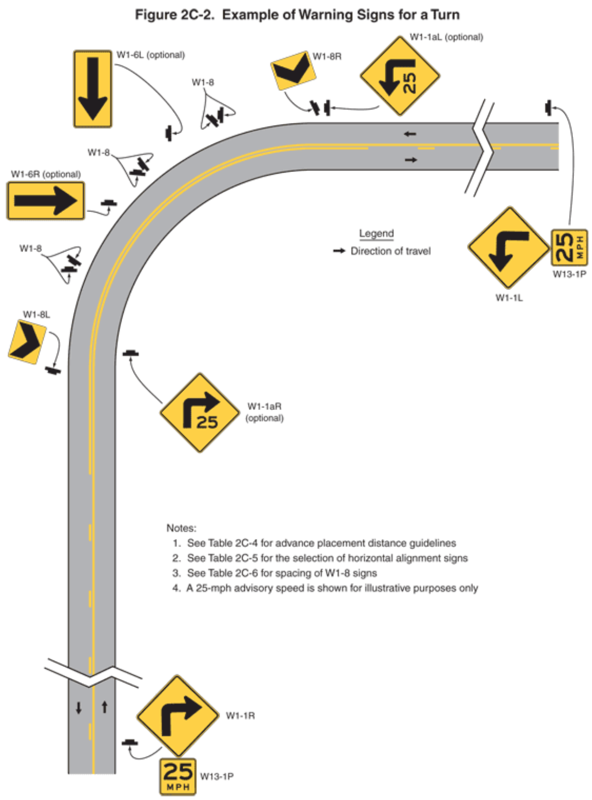


Figure 41. Warning Signs for Curve

Source: MUTCD 2009

Figure 42. Example of a Curve without Chevrons and with Chevrons

Source: FHWA, Low-Cost Treatments for Horizontal Curve Safety, 2016

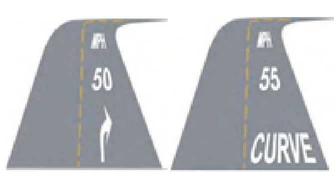


Figure 43. Advanced Pavement Markings for Curve Warning and Advisory Speed

Source: NCHRP Report 600, Human Factors Guidelines for Road Systems

6.3.2 Speed Control

As concluded in the crash analysis, high speed, including speeding behaviors, is the most significant factor contributing to the risk of fatalities and severe injuries and motorcyclists-at-fault. Reducing excess speed to enter a curve has been recognized as an effective way to improve motorcycle safety on curves. Static advisory speed signs (Figure 41) and DSFSs have been widely used to reduce motorcycle speed. This study concluded that DSFS (usually accompany by static signs) can reduce motorcyclist attention on curve risk and increase the speed reduction rate, but entry speed is still higher than the posted safe speed. As supplements for advisory speed signs and DSFSs, the following countermeasures are suggested.

Combination Horizontal Alignment/Advisory Speed Sign

If the distance between a DSFS (and other speed advisory signs) is too long, motorcyclists may increase their speed after passing the signs. To emphasize speed reduction to motorcyclists, a combination of a combination Curve/Advisory Speed (W1-a, Figure 41) sign could be installed at the beginning of the curve.

Speed Reduction Markings

Speed reduction markings are transverse stripes spaced at gradually decreasing distances (*MUTCD*, Section 3B.22). This design is increases motorcyclist perception of speed and causes them to reduce their speed. As spacing between bars gradually narrows, motorcyclists sense that they have increased speed and will slow down to maintain the same time between each set of bars.

Figure 44. Example of Speed Reduction Markings
Source: FHWA, Low-Cost Treatments for Horizontal Curve Safety, 2016

6.3.3 Implementation of DSFS

As noted, DSFSs could increase motorcyclist awareness of curve presence and risks, and reduce lane departure motorcycle crashes on rural two-lane curves by 22%. To implement DSFSs for improving motorcycle safety on rural curves, the following recommendations were developed:

- The feedback function with flashing + “SLOW DOWN” should be activated on DSFSs.
- The distance between a DSFS and a curve should be long enough to provide adequate reaction time to motorcyclists and avoid distraction risk. For example, assuming a speed limit of 35 mph, the distance should be 100 ft or longer to give motorcyclists a reaction time of at least 2 seconds.
- If the distance between a DSFS and a curve cannot provide enough reaction time, the flashing function should be deactivate to avoid potential distraction risk.
- If the distance between a DSFS and a curve is too far (≥ 200 ft), the combination of horizontal alignment and advisory speed sign should be installed at the beginning of the curve to remind motorcyclists to slow down.
- Advanced radar systems are suggested at some curves to increase the detection distance for motorcycles.
- Periodic maintenance on DSFSs is suggested to exclude dysfunctional issues (as shown in Figure 27) such as broken cable, not working, and obstruction by tree branch.
- Enforcement programs are suggested to supplement the implementation of DSFSs.

6.3.4 Clear Zone

Roadside characteristics (e.g., roadside slope, clear-zone width, and coverage of fixed objects) are the dominant contributor to the risk of fatality and severe injury in a single-motorcycle crash on curves. Clear zones are useful for providing sight distance along curves and recovery areas for motorcycles that inadvertently leave the roadway. Clear zones also decrease the risk of having animals near the roadway.

6.3.5 Safety Education and Training

This study confirmed that motorcyclist characteristics and behaviors are significant factors contributing motorcycle crash risk on curves. To increase safety intentions and improve riding behaviors, the following are recommended:

- Use of helmets and/or other safety equipment is strongly encouraged.
- Motorcyclists, especially for older motorcyclists, should take periodic health examinations to make sure they are in good condition.
- Training courses are suggested for motorcyclists, especially older motorcyclists, to improve their curve negotiation skills.
- Non-local motorcyclist-friendly countermeasures such as clear risk information for curved trails should be provided to non-local motorcyclists on site or online.
- Special education programs and campaigns for safety on curves should be developed to advise motorcyclists about the proper behaviors with respect to horizontal curves and traffic control strategies (such as DSFSs).

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Appendix A
Descriptive Analysis of Curve Data

A.1 Descriptive Analysis of RTN Curve Sites

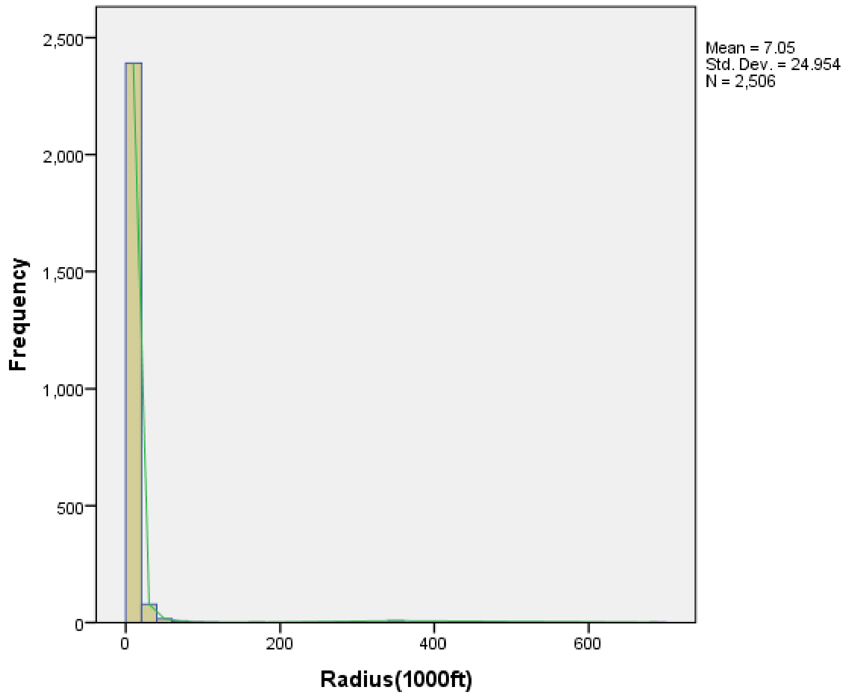

Figure 45. Distribution of Curve Radius of RTN Site

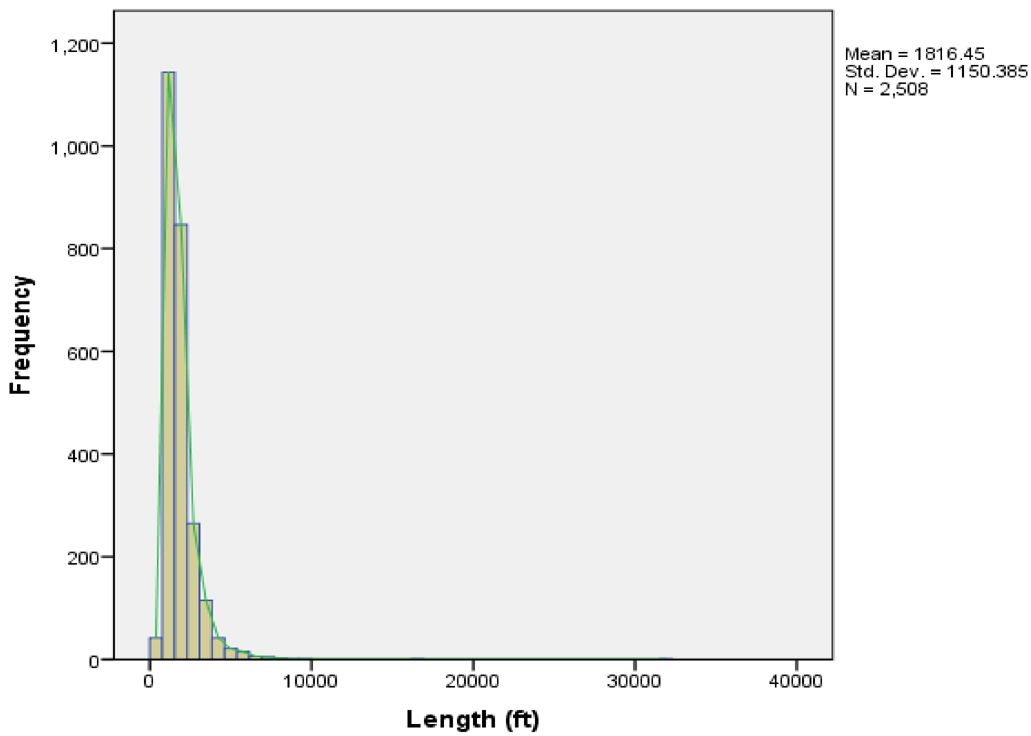

Figure 46. Distribution of Curve Length of RTN Sites

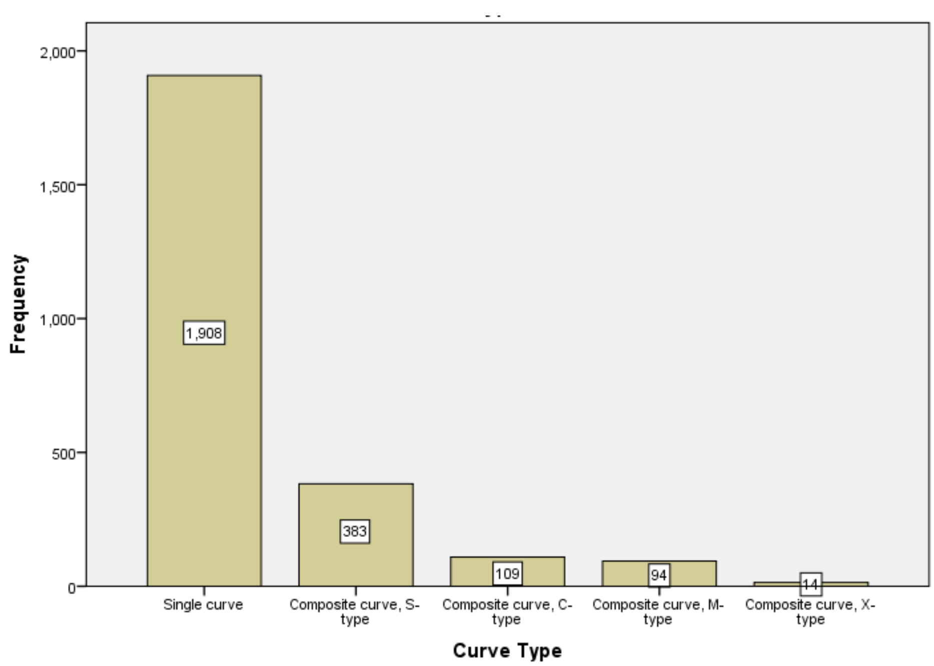

Figure 47. Distribution of Curve Type of RTN Sites

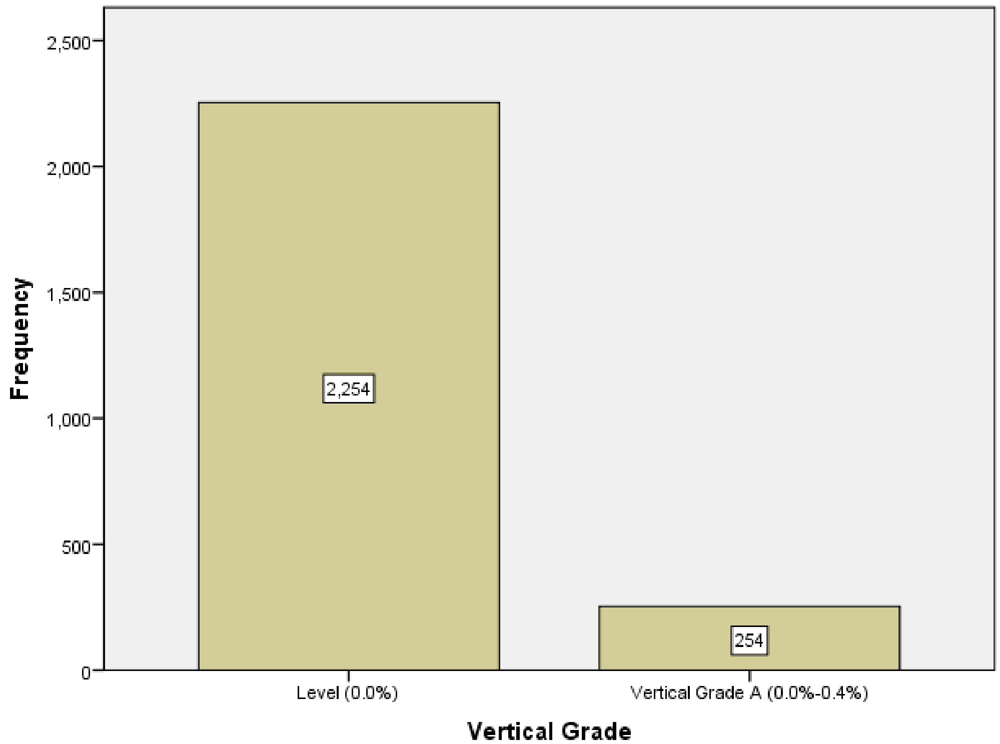

Figure 48. Distribution of Vertical Grade of RTN Sites

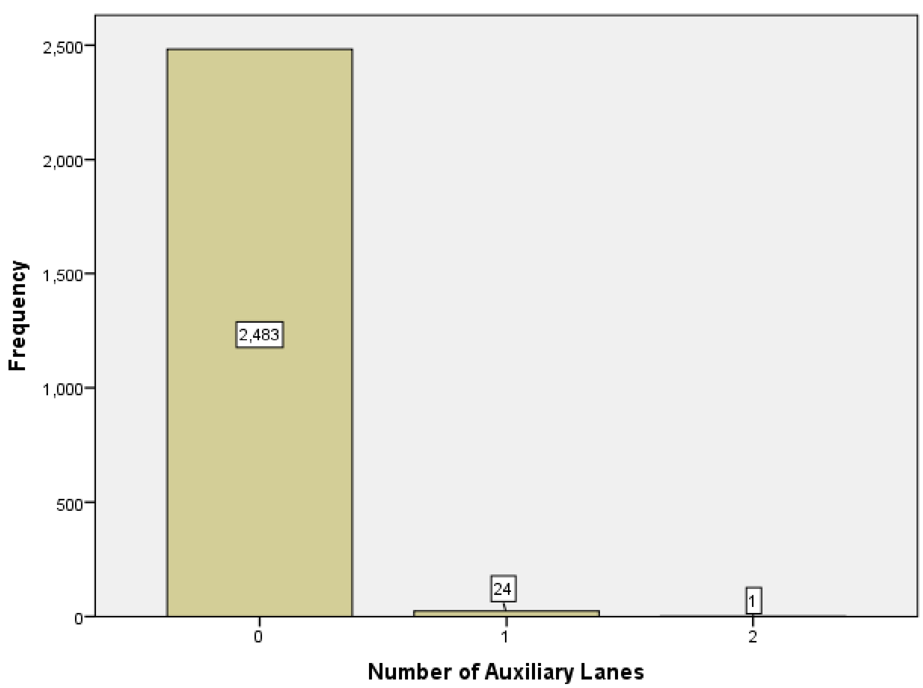

Figure 49. Distribution for Number of Auxiliary Lanes of RTN Sites

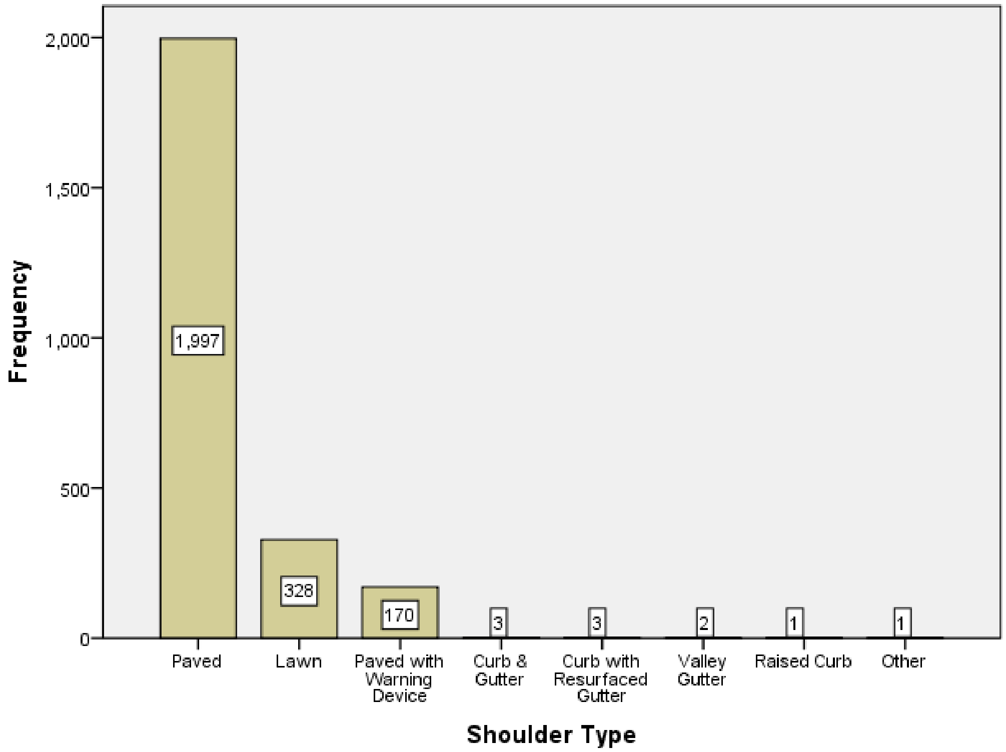

Figure 50. Distribution of Shoulder Type of RTN Sites

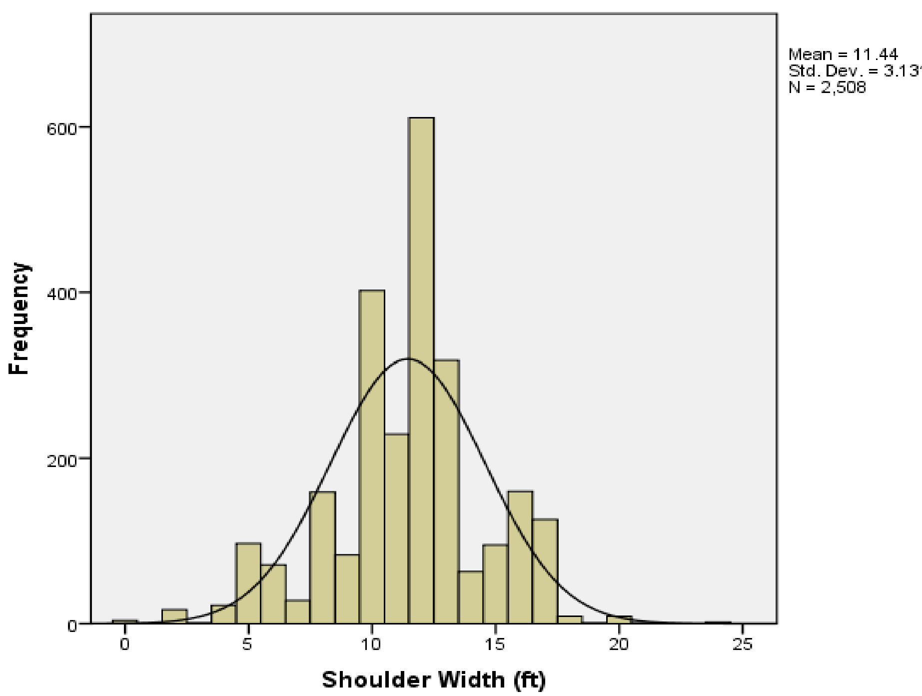

Figure 51. Distribution of Shoulder Width of RTN Sites

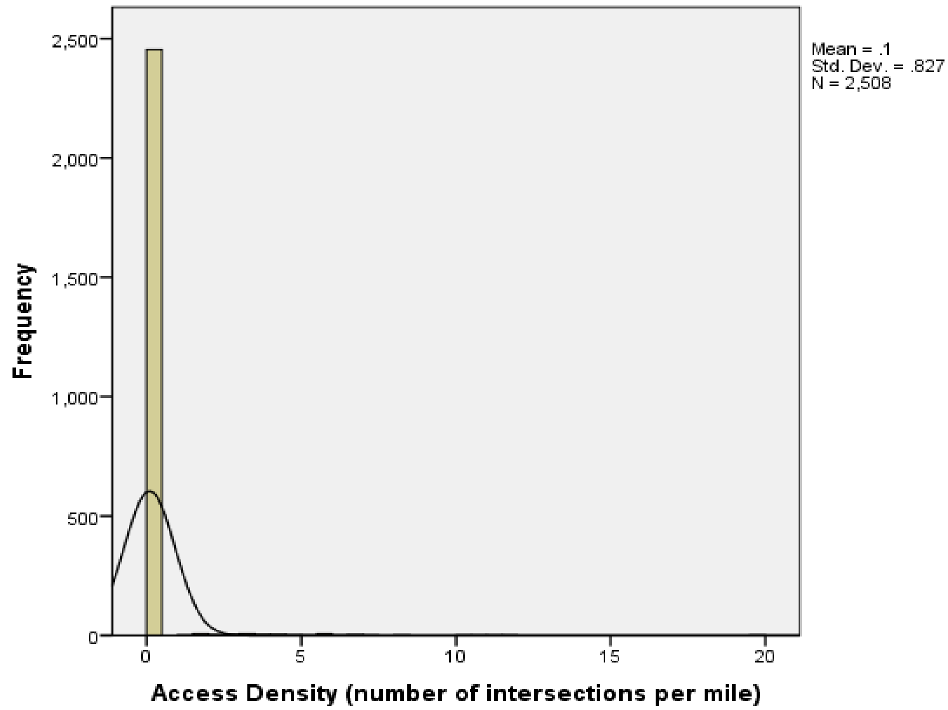

Figure 52. Distribution of Access Density of RTN Sites

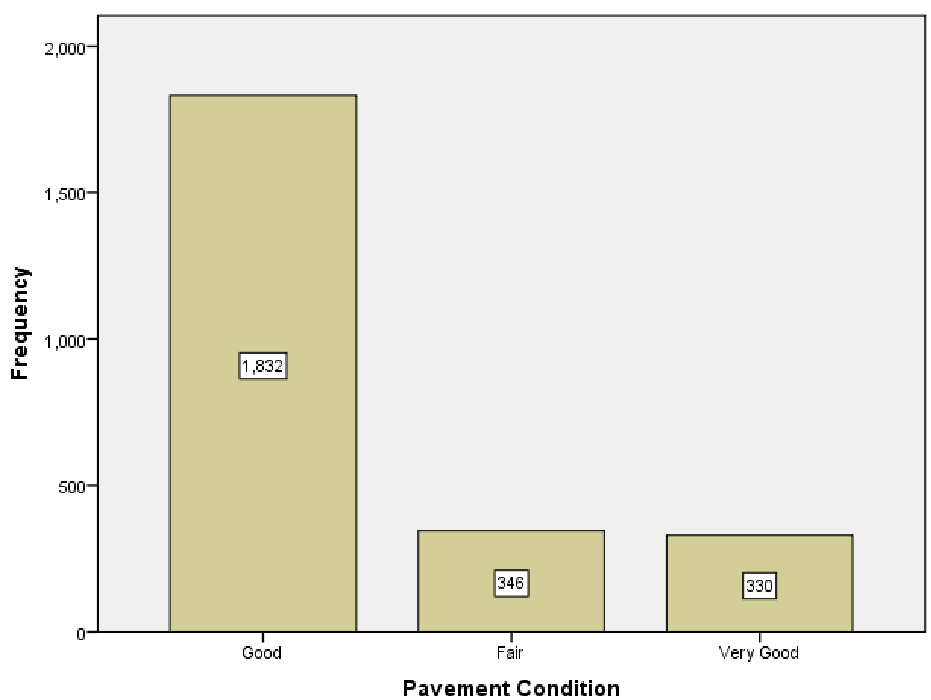

Figure 53. Distribution of Pavement Condition of RTN Sites

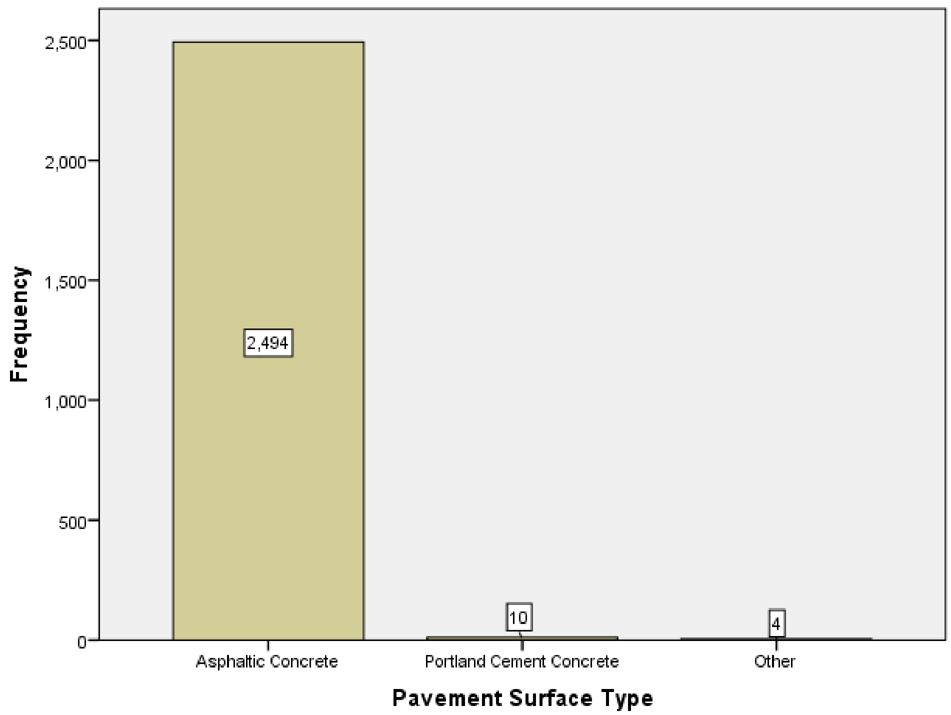

Figure 54. Distribution of Pavement Surface Type of RTN Sites

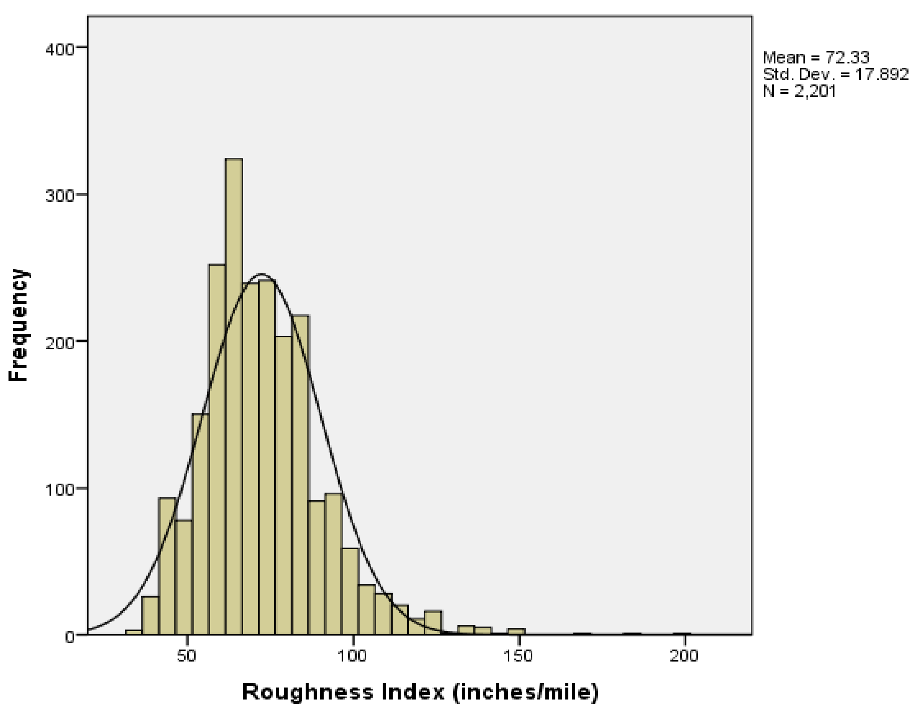

Figure 55. Distribution of Pavement Roughness Index of RTN Sites

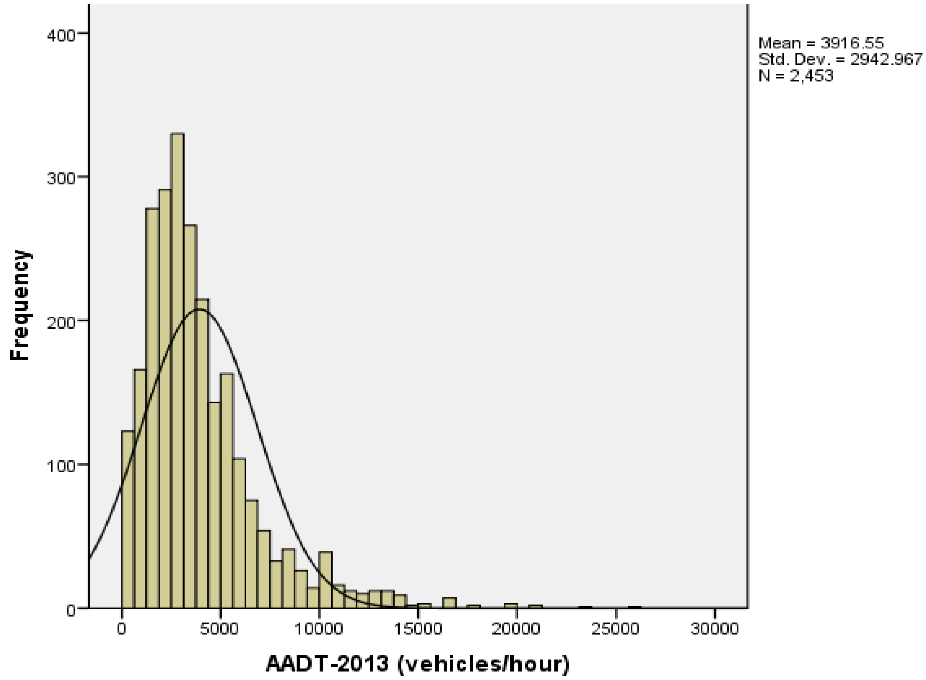

Figure 56. Distribution of Traffic Volume of RTN Sites

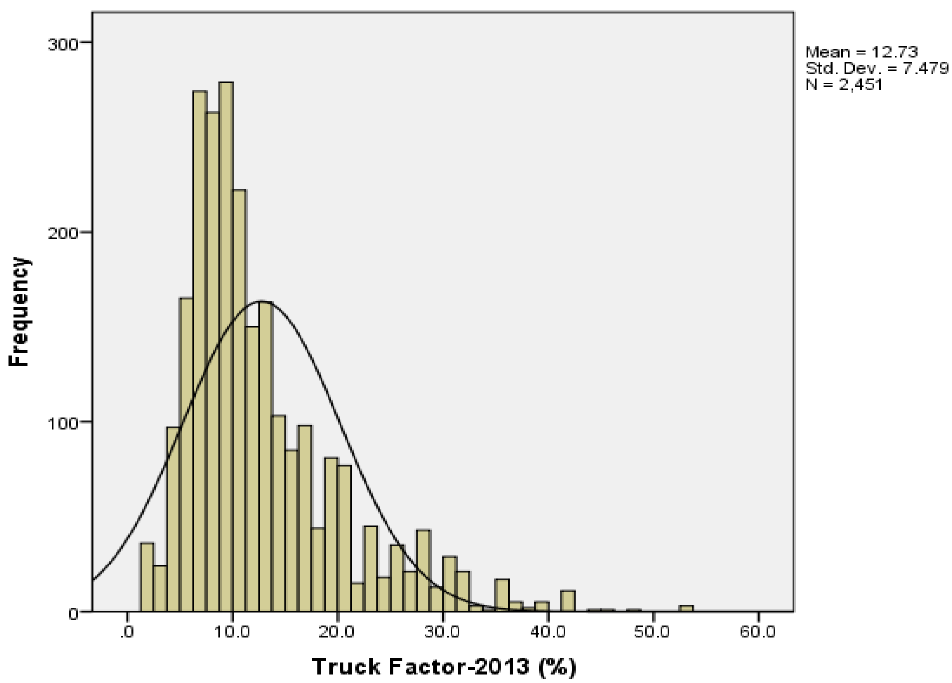

Figure 57. Distribution of Average Truck Factor of RTN Sites

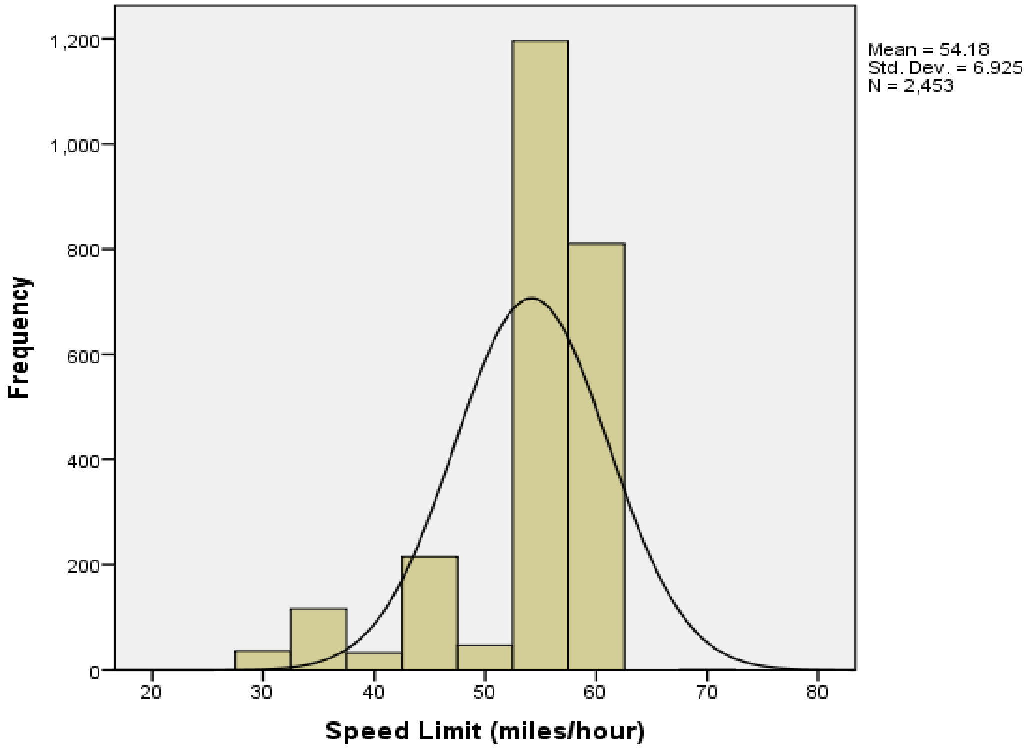

Figure 58. Distribution of Speed Limit of RTN Sites

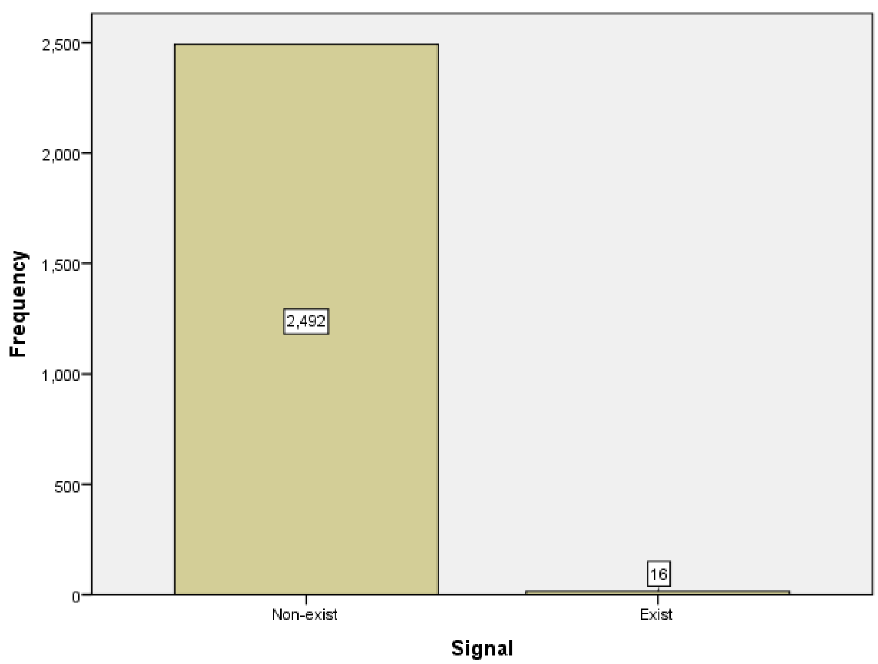

Figure 59. Distribution of Signal Control of RTN Sites

A.2 Descriptive Analysis of Motorcycle Crashes on RTN Curve Sites

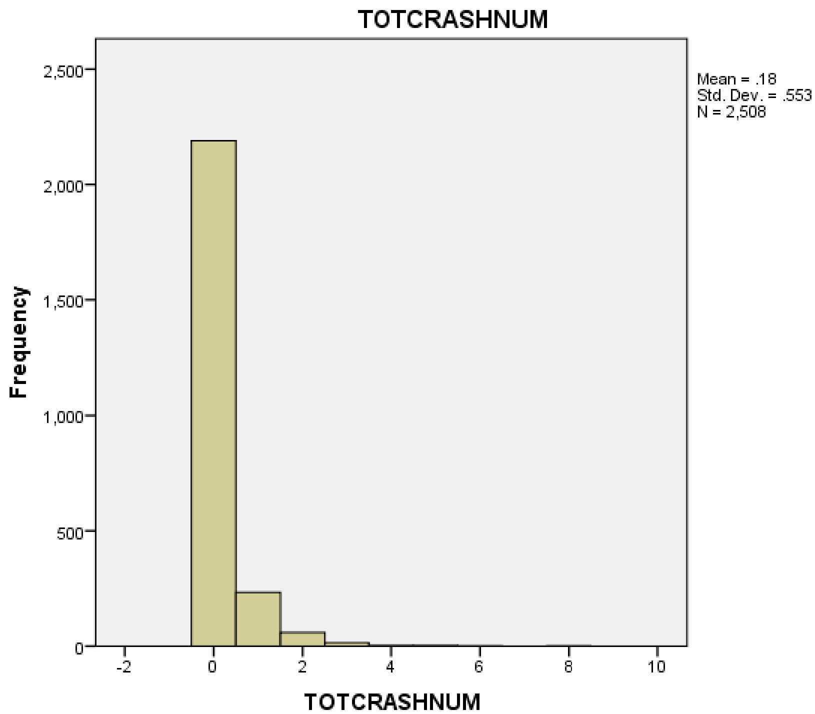

Figure 60. Distribution of Curve Sites by Total Number of Motorcycle Crashes

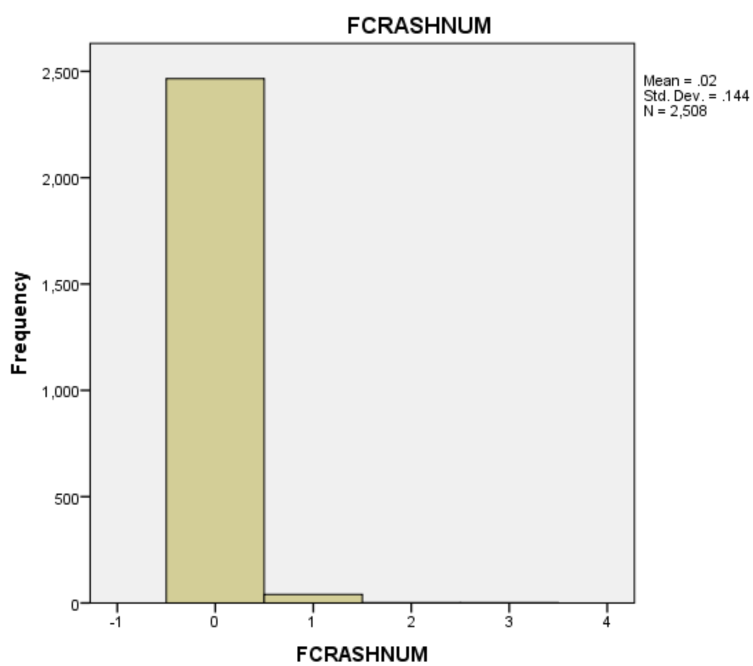

Figure 61. Distribution of Curve Sites by Number of Fatal Motorcycle Crashes

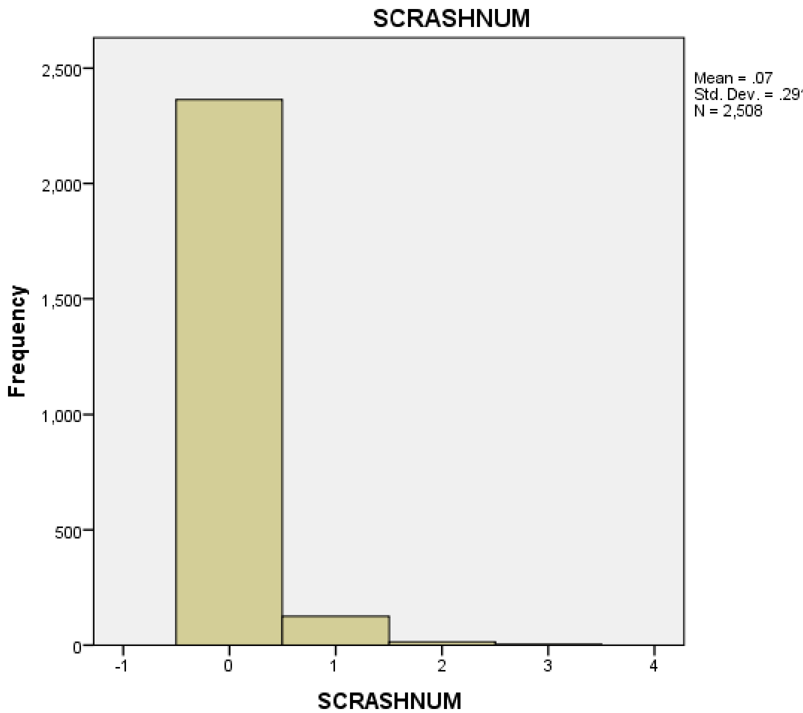

Figure 62. Distribution of Curve Sites by Number of Serious Injury Motorcycle Crashes

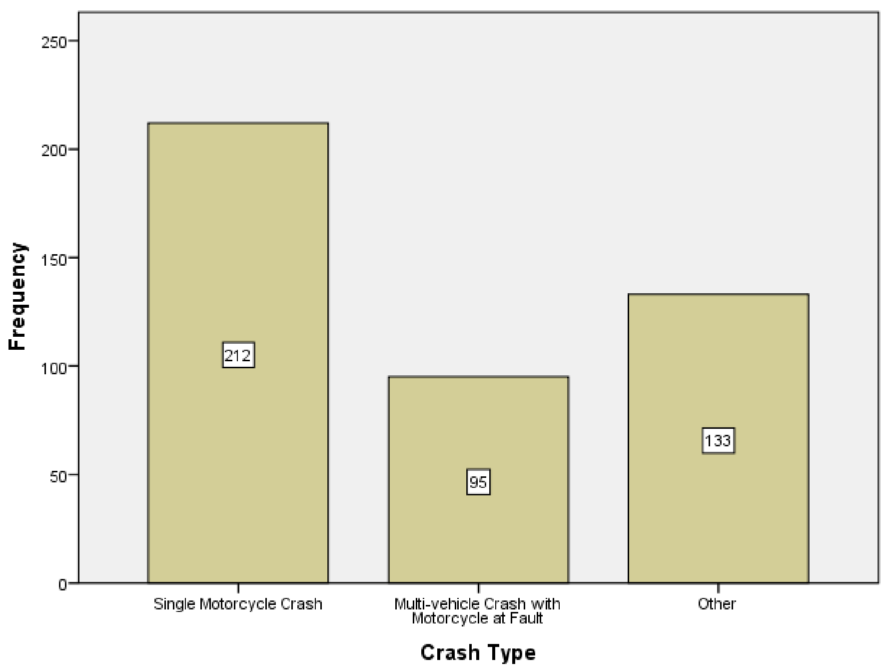

Figure 63. Distribution of RTN Motorcycle Crash Types

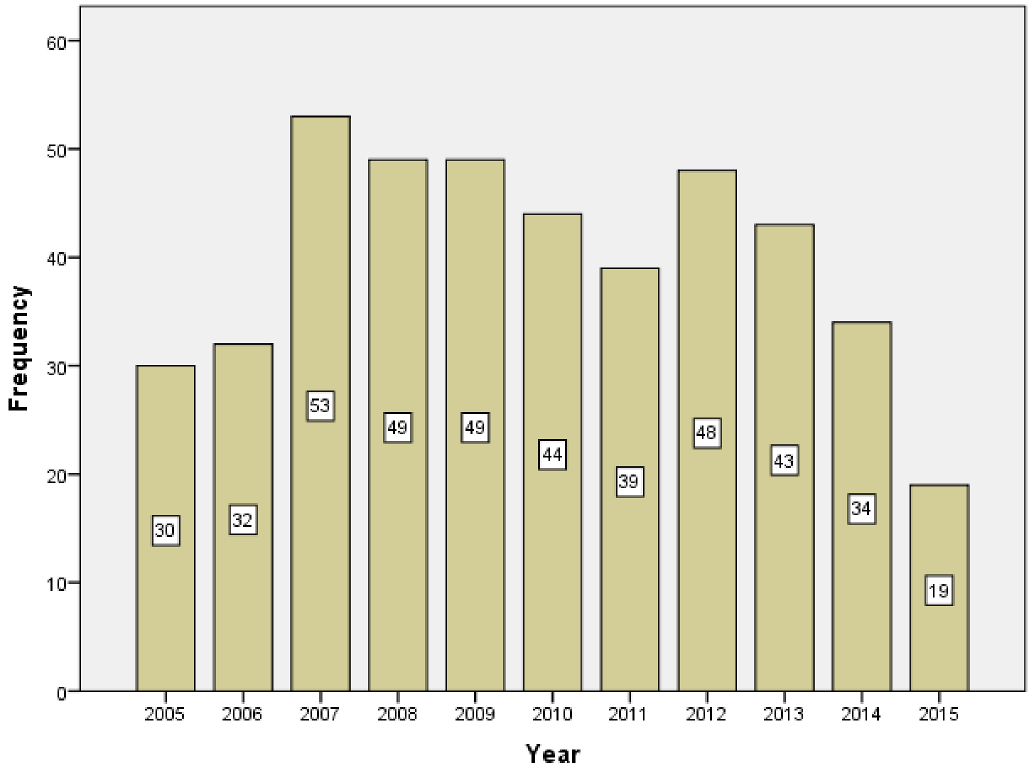

Figure 64. Distribution of RTN Motorcycle Crash Frequency by Year

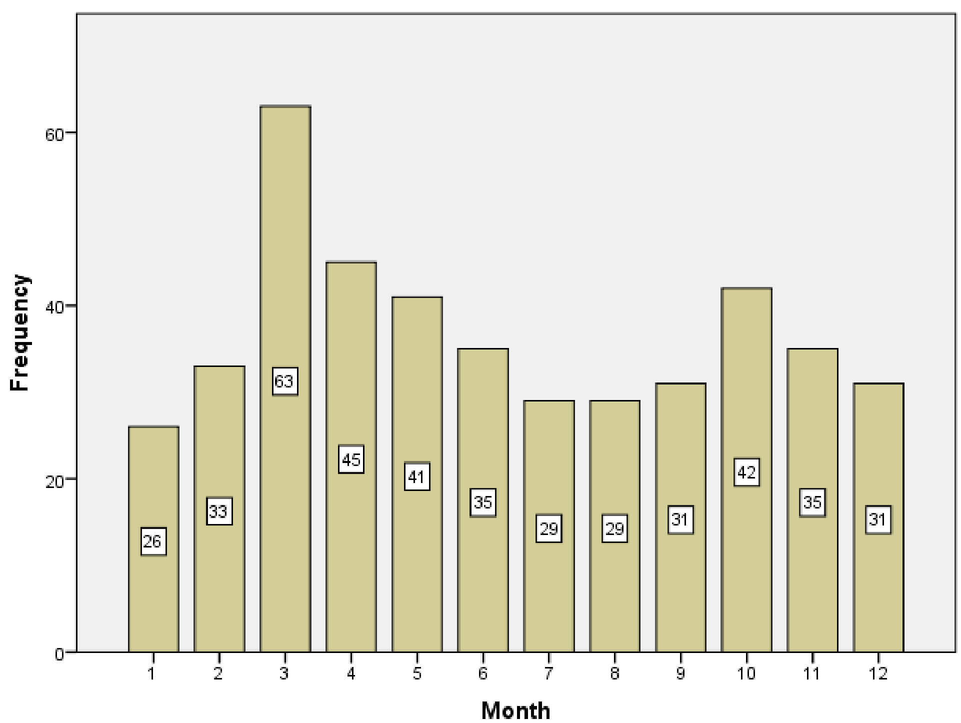

Figure 65. Distribution of RTN Motorcycle Crash Frequency by Month

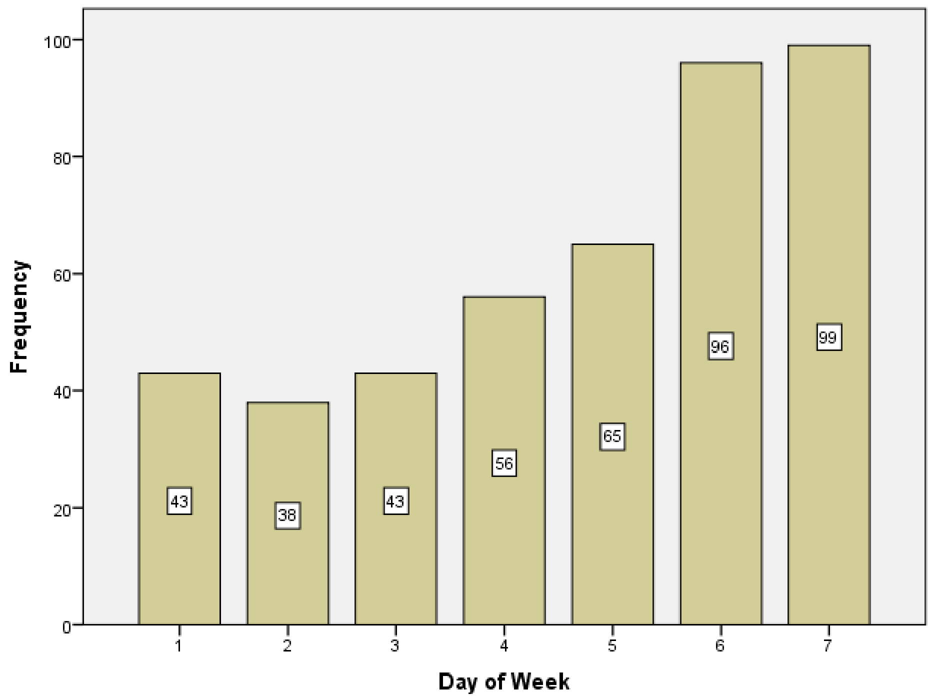

Figure 66. Distribution of RTN Motorcycle Crash Frequency by Day of Week

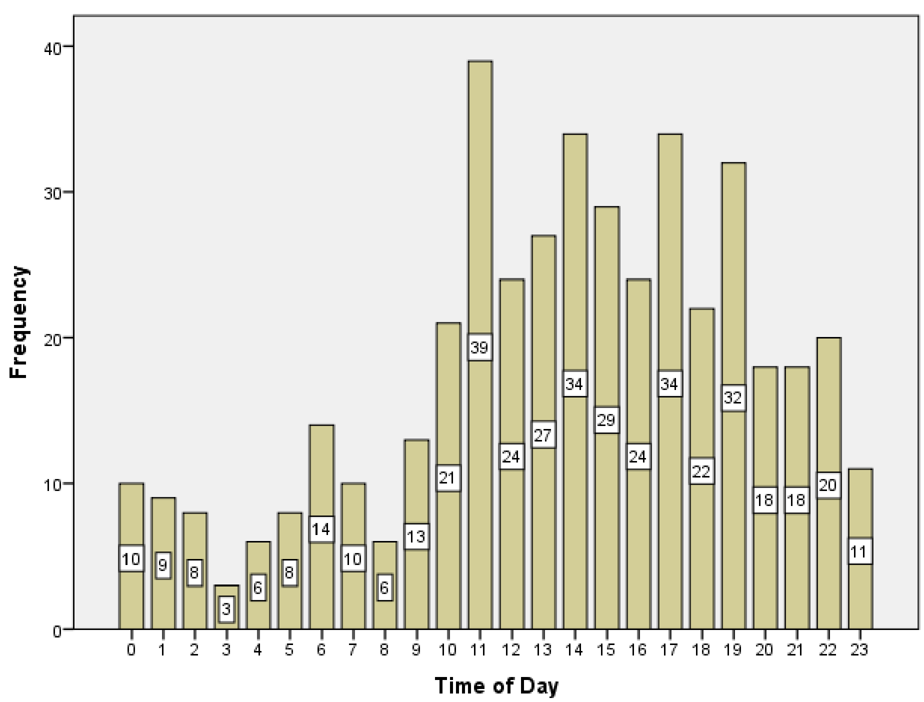

Figure 67. Distribution of RTN Motorcycle Crash Frequency by Time of Day

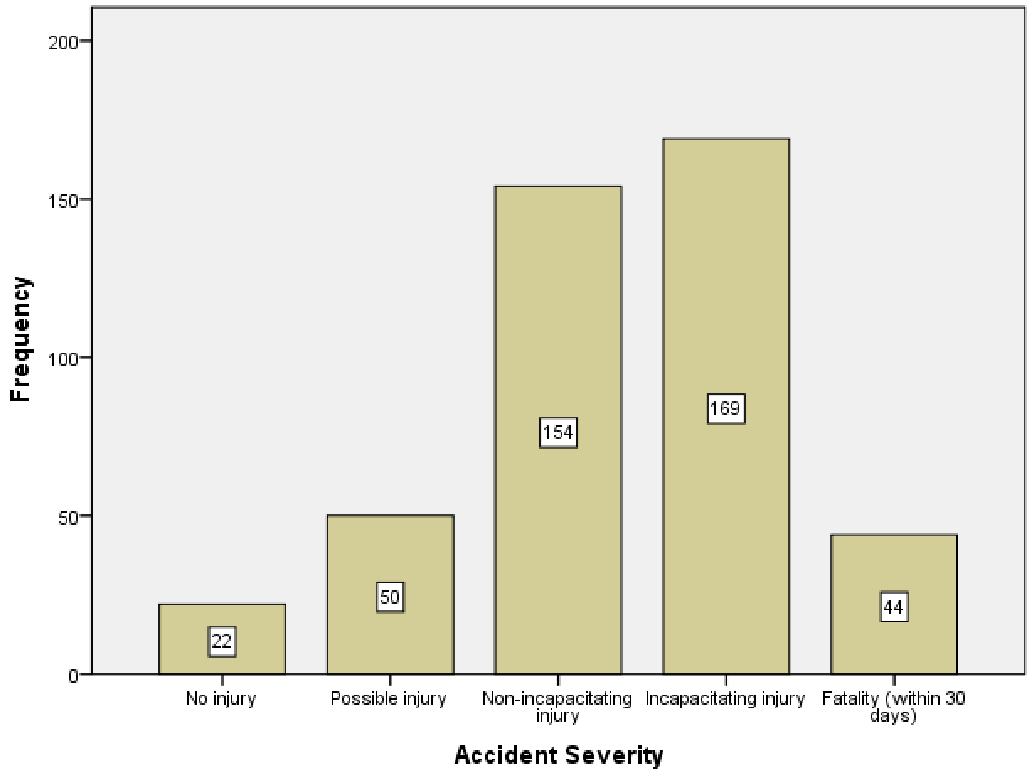

Figure 68. Distribution of RTN Motorcycle Crash Frequency by Severity

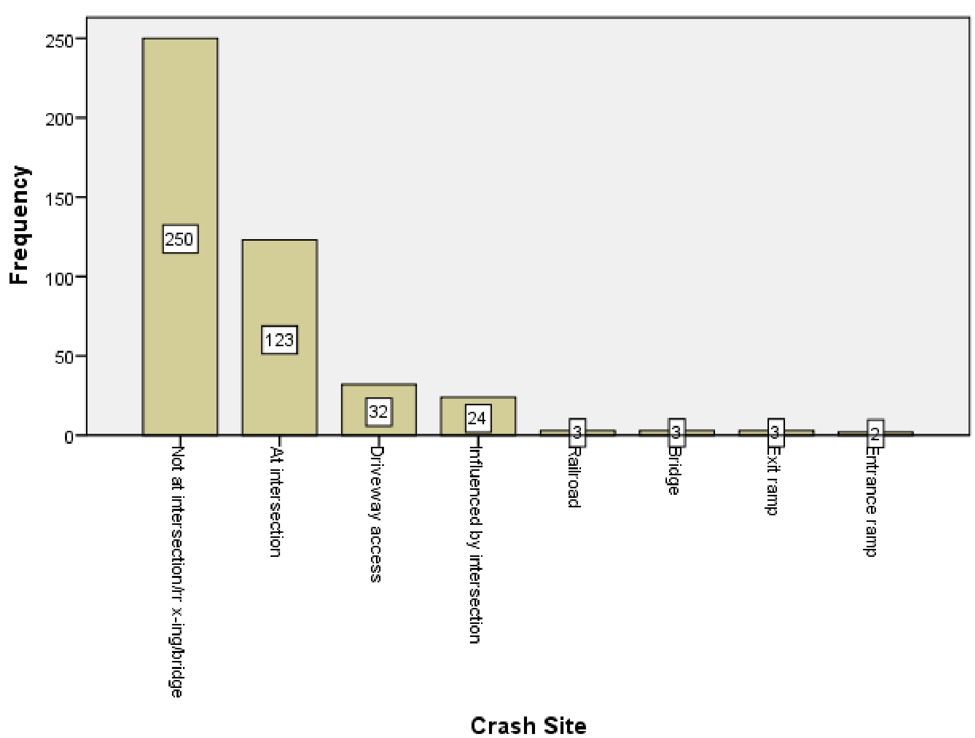

Figure 69. Distribution of RTN Motorcycle Crash Frequency by Site Location

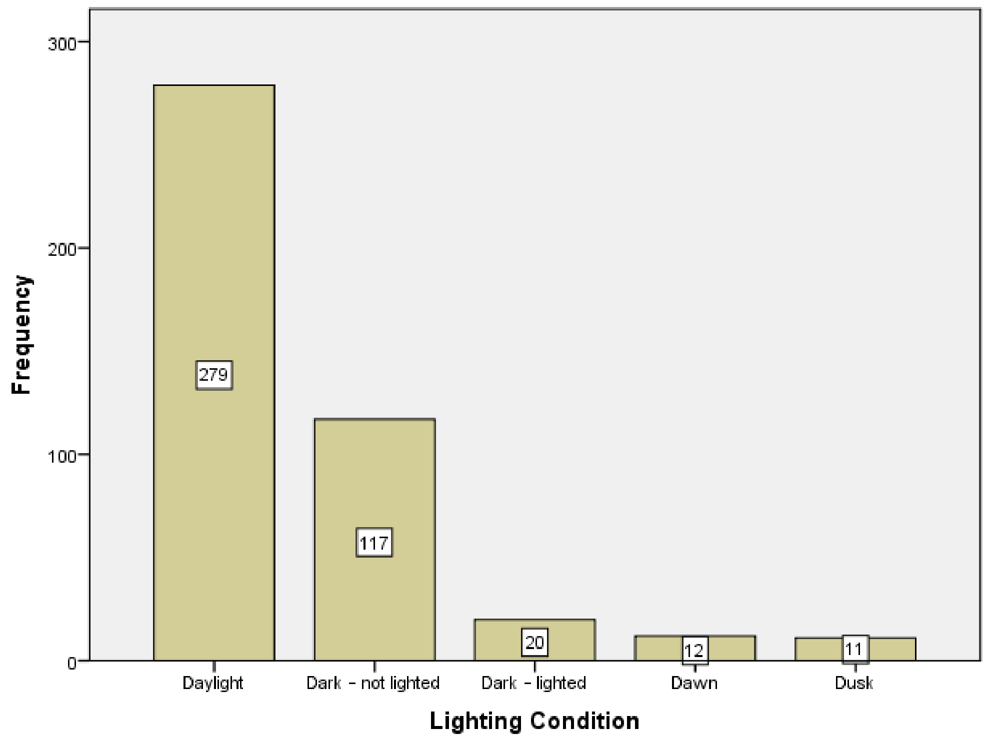

Figure 70. Distribution of RTN Motorcycle Crash Frequency by Lighting Condition

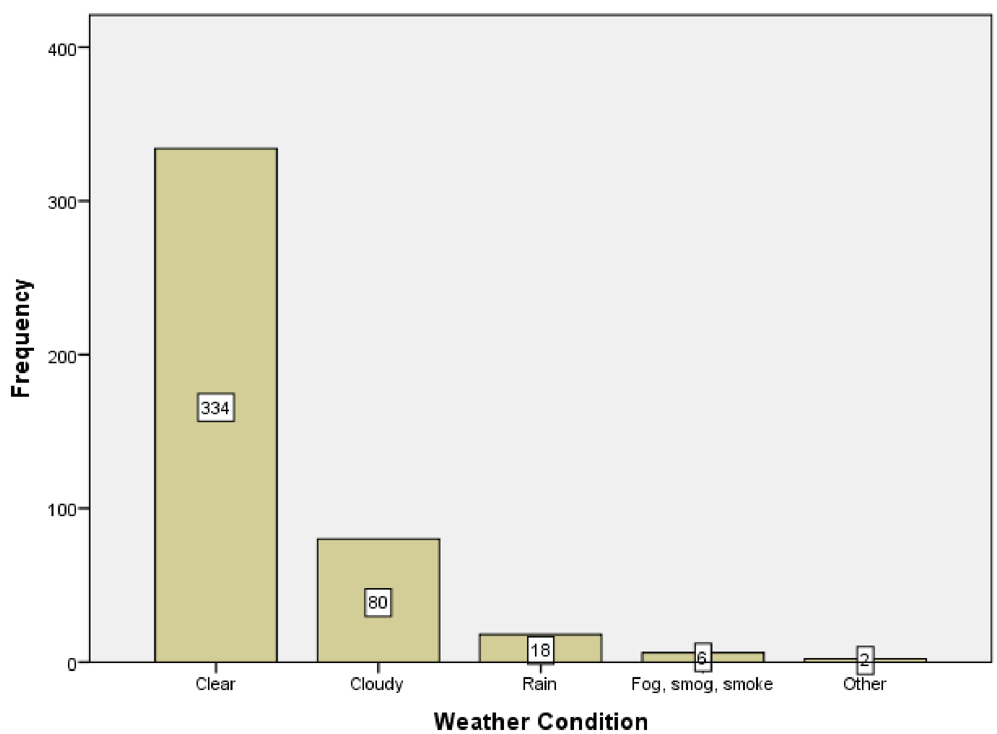

Figure 71. Distribution of Motorcycle Crash Frequency by Weather Condition

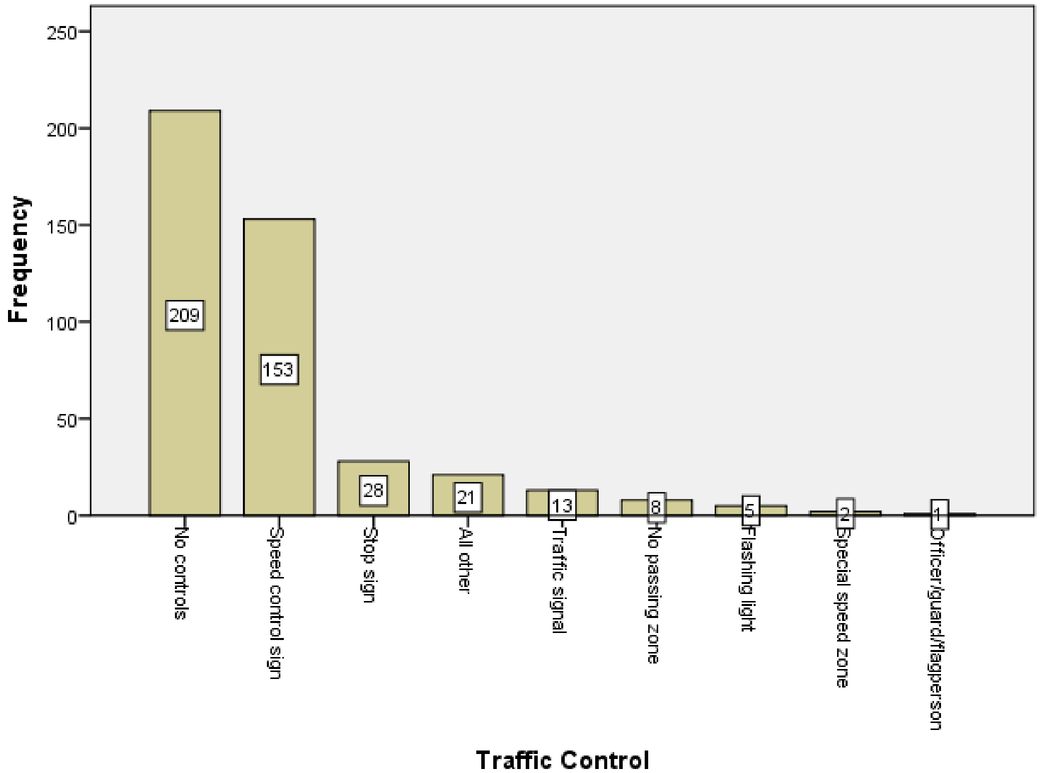

Figure 72. Distribution of Motorcycle Crash Frequency by Traffic Control

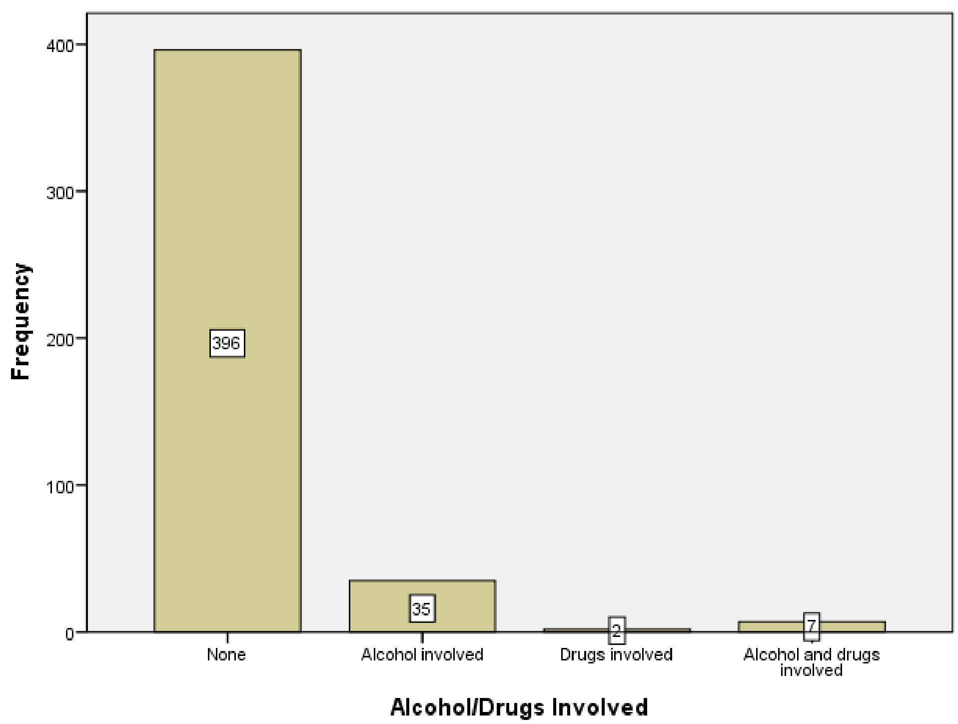

Figure 73. Distribution of RTN Motorcycle Crash Frequency by Alcohol/Drugs Involved

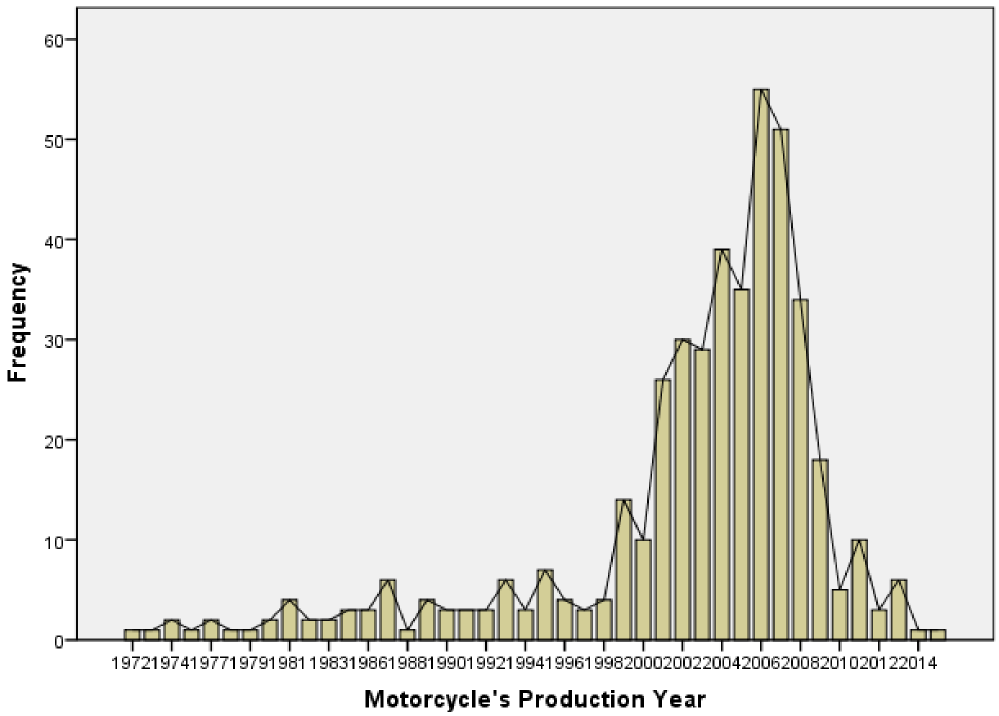

Figure 74. Distribution of RTN Motorcycle Crash Frequency by Motorcycle Production Year

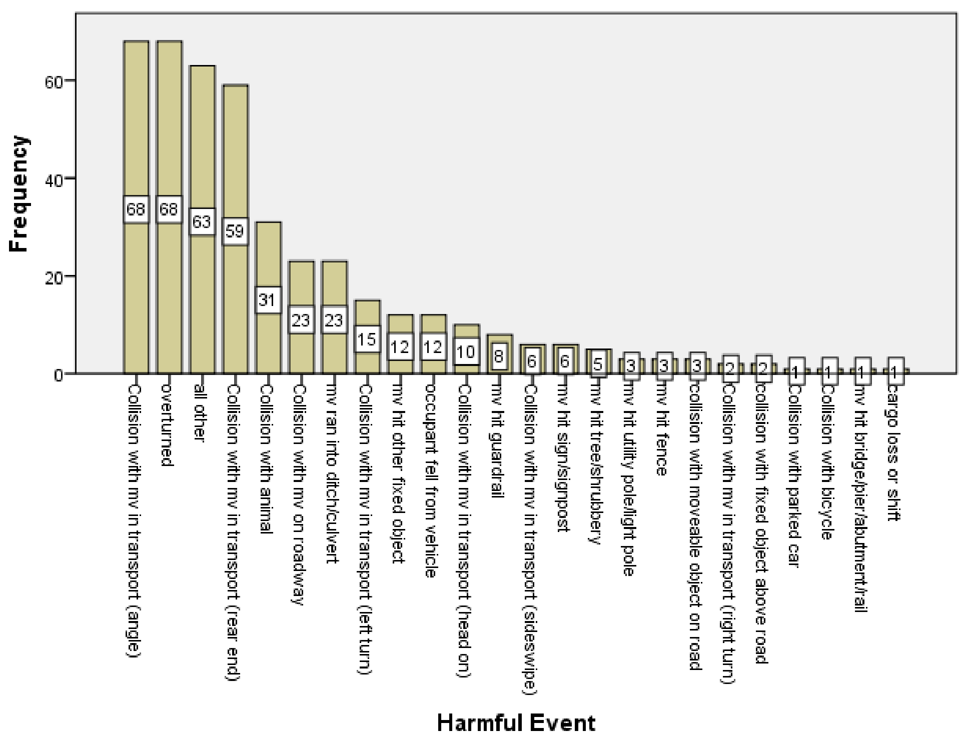

Figure 75. Distribution of RTN Motorcycle Crash Frequency by Harmful Event

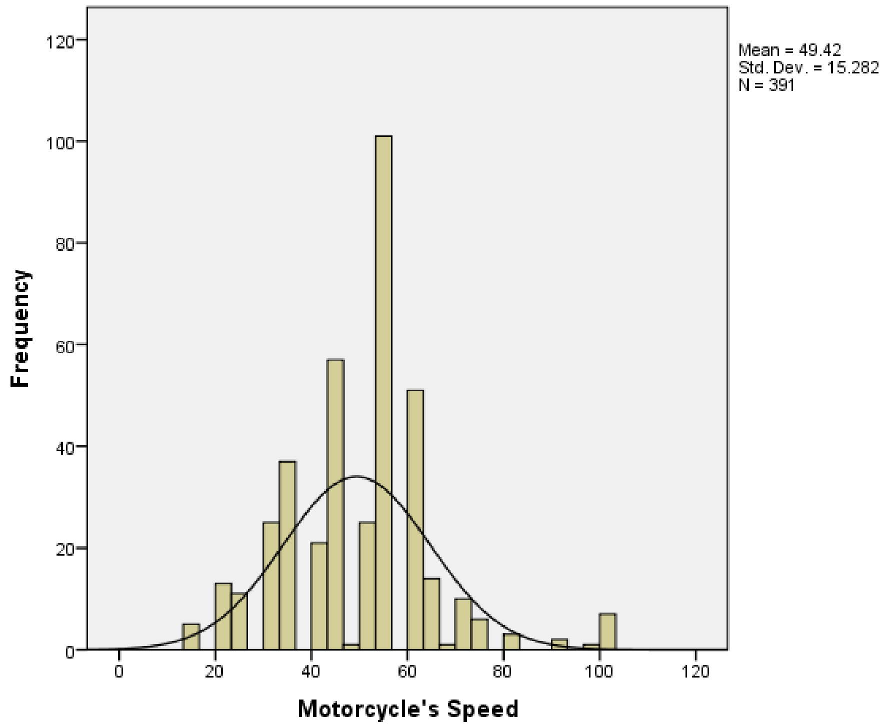

Figure 76. Distribution of RTN Motorcycle Crash Frequency by Motorcycle Speed

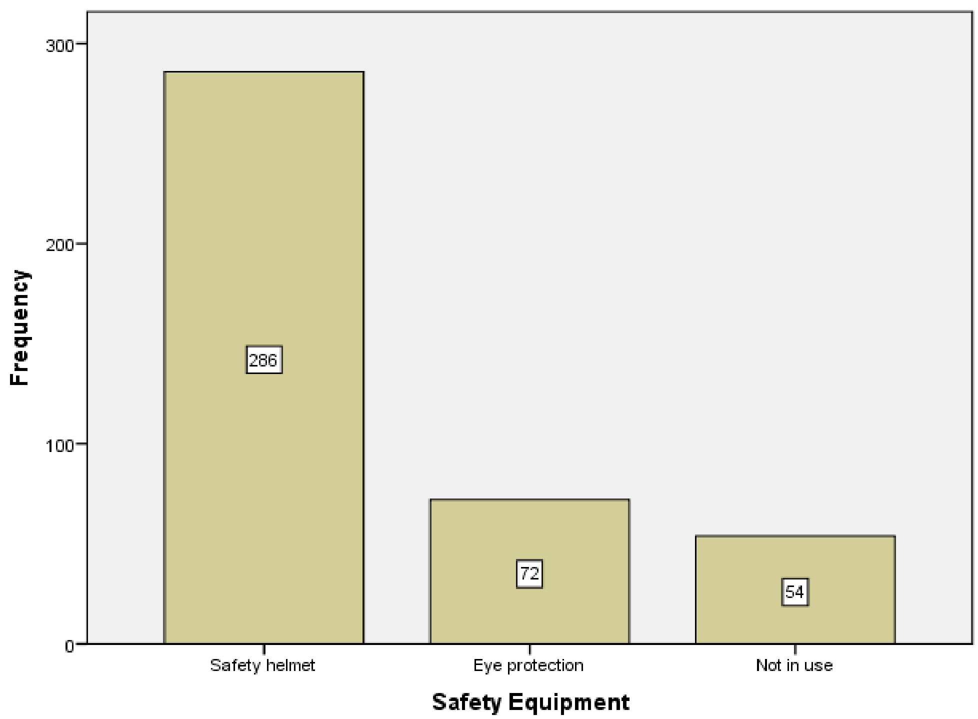

Figure 77. Distribution of RTN Motorcycle Crash Frequency by Safety Equipment

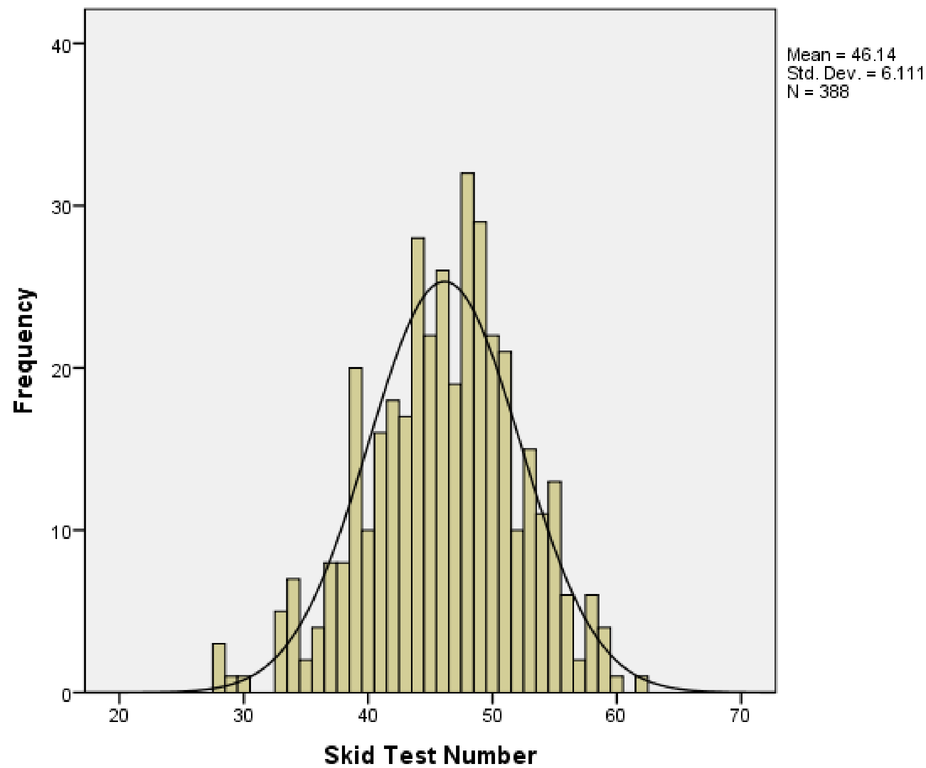

Figure 78. Distribution of RTN Motorcycle Crash Frequency by Skid Test Number

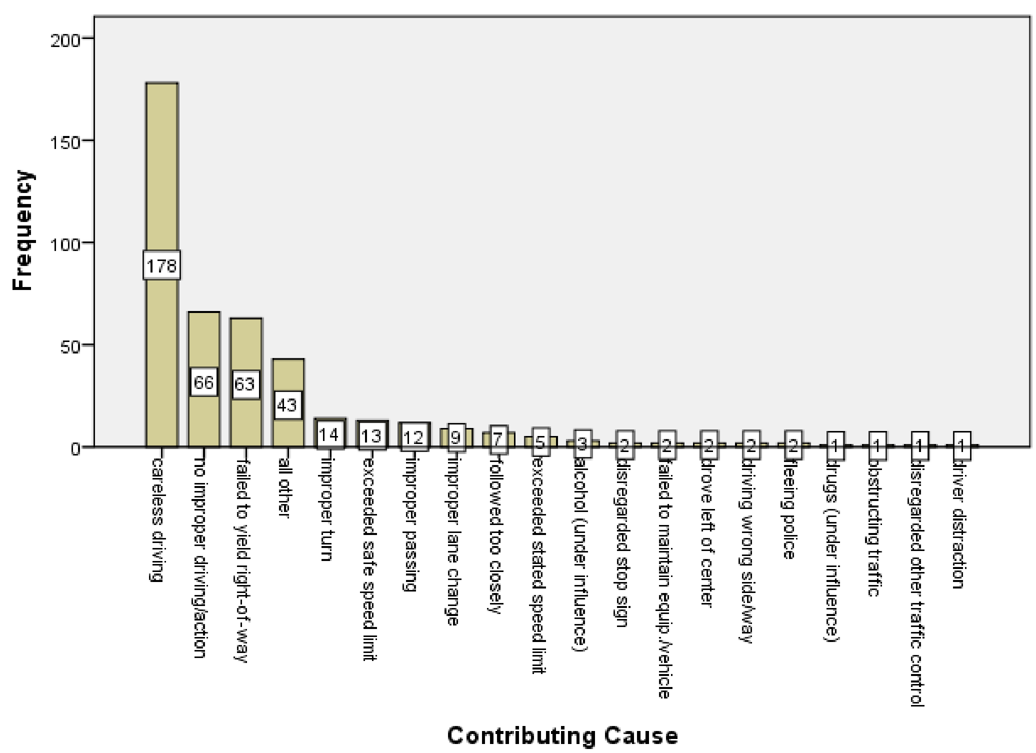

Figure 79. Distribution of RTN Motorcycle Crash Frequency by Contributing Cause

Figure 80. Distribution of RTN Motorcycle Crash Frequency by Motorcycle Rider's Age

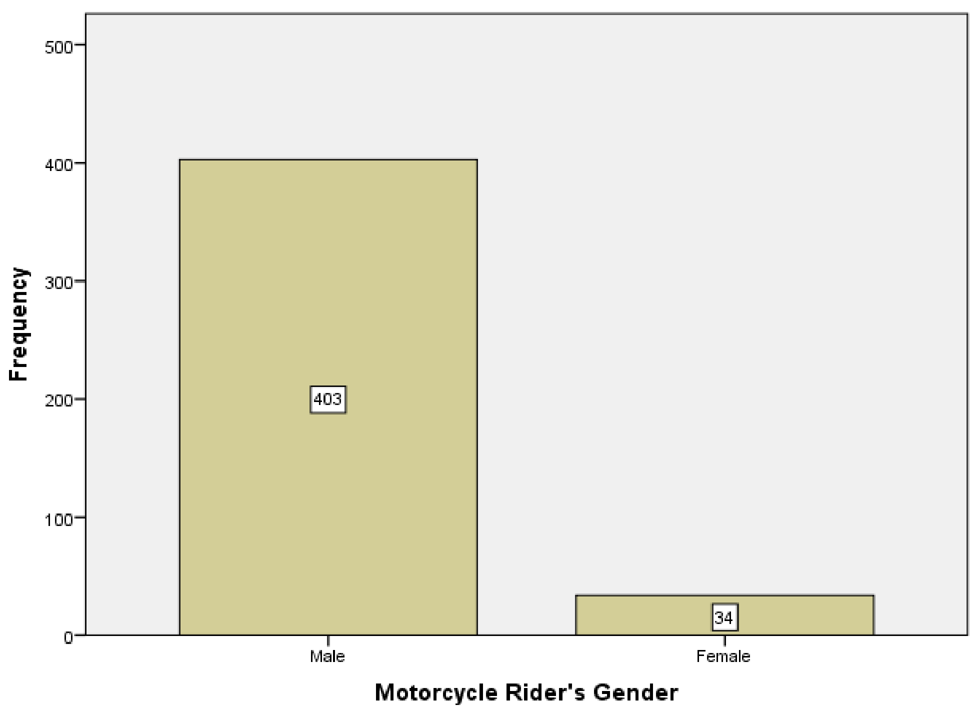

Figure 81. Distribution of Motorcycle Crash Frequency by Motorcycle Rider Gender

A.3 Descriptive Analysis of Control Sites (RTN Straight Segments)

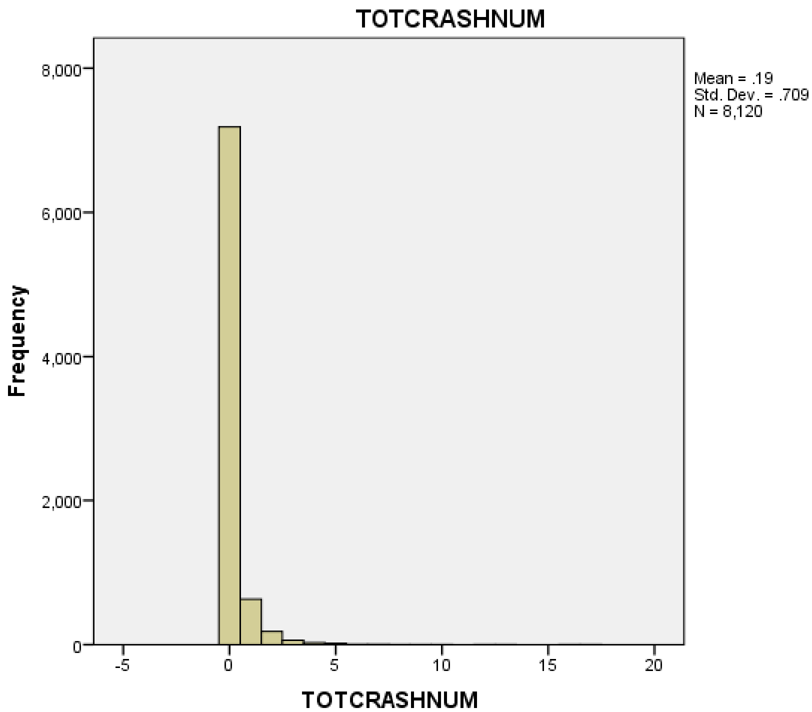

Figure 82. Distribution of Control Sites by Total Number of Motorcycle Crashes

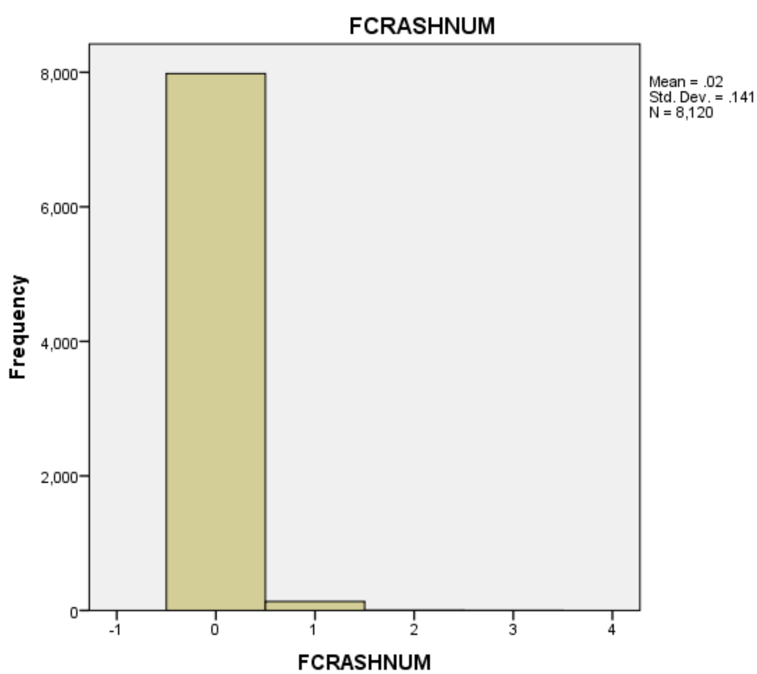

Figure 83. Distribution of Control Sites by Number of Fatal Motorcycle Crashes

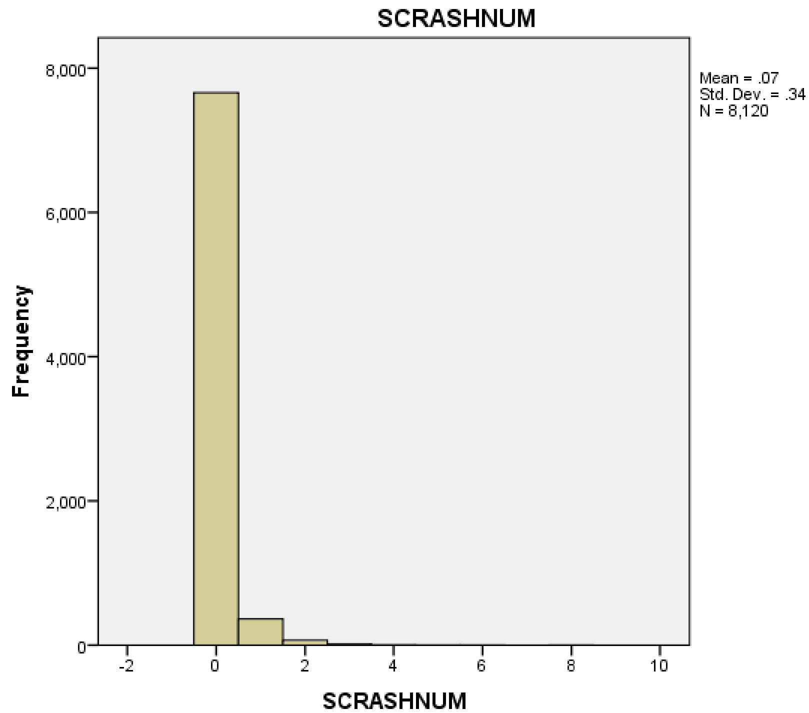

Figure 84. Distribution of Control Sites by Number of Serious Injury Motorcycle Crashes

Appendix B
Dynamic Speed Feedback Signs
on W. Ozello Trail, Crystal River, Florida

Figure 85. Sign 1 (Westbound)

Figure 86. Sign 2 (Westbound)

Figure 87. Sign 3 (Westbound)

Figure 88. Sign 4 (Westbound)

Figure 89. Sign 5 (Westbound)

Figure 90. Sign 6 (Westbound)

Figure 91. Sign 7 (Westbound)

Figure 92. Sign 8 (Westbound)

Figure 93. Sign 9 (Westbound)

Figure 94. Sign 10 (Westbound)

Figure 95. Sign 11 (Eastbound)

Figure 96. Sign 12 (Eastbound)

Figure 97. Sign 13 (Eastbound)

Figure 98. Sign 14 (Eastbound)

Figure 99. Sign 15 (Eastbound)

Figure 100. Sign 16 (Eastbound)

Figure 101. Sign 17 (Eastbound)

Figure 102. Sign 18 (Eastbound)

Appendix C
IRB Review and Participant Recruitment

C.1 IRB Approval Letter

USF
UNIVERSITY OF SOUTH FLORIDA

RESEARCH INTEGRITY AND COMPLIANCE
Institutional Review Boards, FWA No. 00001669
12901 Bruce B. Downs Blvd., MDC035 • Tampa, FL 33612-4799
(813) 974-5638 • FAX (813) 974-7091

1/25/2018

Zhenyu Wang, Ph.D.
CUTR - Center for Urban Transportation Research
4202 E. Fowler CUT100
Tampa, FL 33647

RE: **Full Board Approval for Initial Review**
IRB#: Pro00032091
Title: Study on Motorcycle Safety in Negotiation with Horizontal Curves in Florida and Development of Crash Modification Factors

Study Approval Period: 12/15/2017 to 12/15/2018

Dear Dr. Wang:

On 12/15/2017, the Institutional Review Board (IRB) reviewed and **APPROVED** the above application and all documents contained within, including those outlined below.

Approved Item(s):
Protocol Document(s):
Study on Motorcycle Safety in Negotiation with Horizontal Curves in Florida and Development of Crash Modification Factors V1 01.02.2018

Consent/Assent Document(s)*:
Adult, Version Ver. 1 01.02.2018.pdf

*Please use only the official IRB stamped informed consent/assent document(s) found under the "Attachments" tab. Please note, these consent/assent documents are valid until the consent document is amended and approved.

As the principal investigator of this study, it is your responsibility to conduct this study in accordance with IRB policies and procedures and as approved by the IRB. Any changes to the approved research must be submitted to the IRB for review and approval via an amendment. Additionally, all unanticipated problems must be reported to the USF IRB within five (5) calendar days.

We appreciate your dedication to the ethical conduct of human subject research at the University of South Florida and your continued commitment to human research protections. If you have any questions regarding this matter, please call 813-974-5638.

Sincerely,

John Schinka, Ph.D., Chairperson
USF Institutional Review Board

C.2 IRB Protocol

Title: Study on Motorcycle Safety in Negotiation with Horizontal Curves in Florida and Development of Crash Modification Factors

PI: Zhenyu Wang

Co-PI: Pei-sung Lin, Chanyoung Lee

IRB Protocol

1. Rationale and Background

Horizontal curves are likely to reduce motorcyclist's sight distance and adversely impact motorcycle-handling capabilities, increasing the potential for motorcycle crashes and fatalities. In Florida, curved segments experienced 57% of fatal single-motorcycle crashes, 36% of incapacitating single-motorcycle crashes, 26% of non-incapacitating single-motorcycle crashes, and 32% of total single-motorcycle crashes while the curved segments accounts for only 5.75% of total mileage. Furthermore, according to an FDOT District 7 data analysis on motorcycle crashes, 33% of all motorcycle crashes involve only the motorcyclist and nearly one third of motorcycle fatalities relate to problems negotiating a curve prior to the motorcycle crash.

Motorcycle speed is the critical factor contributing to the risk of motorcycle on curves since high speed tends to increase the difficulty in negotiation with horizontal curves and potential motorcycle crashes. Speed control is an effective countermeasure to reduce motorcycle crash on curves. To achieve this purpose, Florida Department of Transportation (FDOT) District 7 has implemented Speed Feedback Signs in selected curved roadway segments. The Speed Feedback Sign is a traffic calming device powered by radar and designed to slow speeders down by alerting them of their speeding. However, most existing tests on speed feedback signs focused on vehicles rather than motorcycles. This lack of knowledge on safety performance of speed feedback signs restricts the assessment and promotion of this countermeasure in Florida. Thus, it is necessary to conduct a research project to investigate the impacts of speed advisory signs in reducing motorcycle speeding on curves and improve motorcycle safety.

2. Existing Research

According our literature review, many previous studies focused on the impacts of speed feedback signs on vehicles. No documents were found to specially address the impacts of speed feedback signs on motorcycle to negotiate curves in Florida roadway environment.

3. Research Objectives, Questions and Purpose

This project aims to identify the effectiveness of speed feedback signs in speeding reduction of motorcycles at horizontal curve segments considering various roadway conditions. More specifically, the research objectives are:

- The research team will cooperate project managers to decide testing sites equipped with speed feedback signs.

- The research will collect riding behaviors with different configurations of the sign at multiple sites. The riding behaviors include speed, acceleration, and attention-of-point.
- The research team will statistically compare riding behaviors with different configurations to address the safety improvements after implementation of the sign. Various roadway conditions will be considered in this analysis.
- The purpose of the study is to quantify the effectiveness of the speed feedback signs in reduction of risky riding behaviors in curve negotiation and provide recommendations on implementation of speed feedback signs to FDOT.

These research questions are to be answered with the data collected from the study. The analysis will identify contributing factors and help understand riding behaviors interacting with speed feedback signs on curves:

- Do speed feedback signs effectively reduce motorcycle speed when entering curves?
- How motorcyclists interact with speed feedback signs?
- What settings of speed feedback signs most effectively to improve motorcycle safety on curves?

4. Study Design

W. Ozello Trail at Crystal River, FL was selected as the test bed because, it is an attraction to motorcycle enthusiasts with significant motorcycle exposure and has 18 speed feedback signs since 2015. Up to 50 motorcyclists will be summoned on-site or through social median. Two devices will be used in this study:

- Tobii Pro eye tracker, to capture human viewing behaviors when speed feedback signs present. Eye trackers, which monitors drivers' attention on traffic hazard conditions (such as presence of curves) or traffic controls (roadside signs), has been widely used in safety-related driving behavior studies 4-7.

Tobii Pro Eye Tracker

- VBox Sport, to measure location, speed, trajectory, and timestamps when a rider approaches a speed feedback sign at a high sampling rate (20Hz). Speed profile and trajectory were used in many previous studies (*88–91*) to indicate traffic safety performance.

VBox Sport Sensor

Three configurations of speed feedback signs will be tested:

- C1: OFF (No display on SFS) — baseline
- C2: Flashing with "SLOW DOWN"
- C3: "SLOW DOWN" without flashing

The test procedure is:

Step 1: Summon motorcyclists with their own motorcycles through social media. The expected number of participants are up to 50. Motorcyclists will be requested to ride their own motorcycles to the test site (W Ozello Trail) at scheduled date.

Step 2: When motorcyclists arrive at the test site, they will be required complete the following activities before test:

- Read and sign the consent form.
- Show his/her driver license with a motorcycle endorsement, insurance, and registration. Researchers will verify all these documents are valid.
- Sign the consent form to confirm they are in a good health condition to take the test (e.g., NOT intoxicated or fatigued).
- The participants have two options: wearing the Tobii eye tracker or not. The participants who feel discomfort on the Tobii eye tracker or must wear the sunglasses or prescription glasses will take the test with the VBox Sport only.
- During this period, researchers will answer any question from participants to make sure they fully understand the test content.

Step 2: Randomly set the 18 signs in different configurations.

Step 3: Test

Step 3.1: Install the VBox Sport on the motorcycle and calibrate the Tobii eye tracker with the participant's eyes (if participants agree to wear the eye tracker).

Step 3.2: The participant will take a short test with the Tobii eye (if participants agree to wear the eye tracker) and the VBox Sport to make sure the devices work well.

Step 3.2: The rider rides from the east end (Shell gas station) to the west end (restaurant) and return to the east end.

Step 3.3: A short survey to be questioned to the rider to obtain rider's characteristics and evaluation on SFS.

Step 3.4: Repeat the test (Step 3.1 to 3.3) for another rider until we finish all tests.

Step 4: Retrieve and match data from eye trackers and VBox Sports in Lab.

Step 5: Conduct statistical analysis on rider's behavior reacting to different SFS configurations and get the most effective SFS configuration to improve motorcycle safety on curves considering different roadway conditions.

5. Sample Size

The study is funded to collect data for up to 50 participants.

6. Study Population

Since the study is a motorcycle behavior study, the participants need to be motorcyclists. For the purposes of the study, a motorcyclist is defined as a person who either commutes to work via motorcycle or a person who rides a motorcycle recreationally. The participants will be required to bring their own motorcycles for the experiment and have a valid driver license and car insurance. Participants should speak and read English and without any physical or mental health issue influencing normal riding (such as drunk, drug, and fatigue). Participants who must wear sunglasses or prescription glasses will be excluded from the Tobii eye tracker component of the study.

7. Expected Results

The statistical analysis will be applied to compare motorcyclist behaviors with different configurations of speed feedback signs. The effectiveness of speed feedback signs on riding behaviors will be evaluated. For data that include interactions between motorcyclists and curves, further analysis will be performed to understand how the speed feedback signs affect riding behaviors in negotiating with curves. The recommendations on implementation and configuration of speed feedback signs will be developed based on the analyses.

8. Name of the Principal Investigator

The PI is Zhenyu Wang, Ph.D., Research Associate at the Center for Urban Transportation Research (CUTR) at USF.

9. Potential Risks to the Subjects

The eye tracker and VBox sports will be used to collect data for the study. The VBox Sport is designed to add minimal weight on a motorcycle and will be mounted in a way not to interfere with regular riding. A rider will wear an eye tracker and ride the motorcycle normally. Minimal risks, such as discomfort, light sensitivity, etc., may apply to some riders. Thus, the risks to subjects are expected to be none or minimal.

Participants who must wear sunglasses or prescription glasses will be excluded from the Tobii eye tracker component of the study.

10. Potential benefits to the Subjects

No identified benefits to the subjects are available.

11. Human subjects considerations

Informed consent process

Each participant will be informed about the study, risks, benefits, will be trained to use the application, and be allowed ample time to read and sign the consent form. Questions will be asked about the study procedures to ensure understanding.

Privacy and confidentiality

During intake, the subjects will be assigned a unique random number. This number will be their identifier during the rest of the study. It will be used to link the data collected with their questionnaire replies. The study staff will not discuss or share the subjects' identities with anyone. All the data will be saved on a secure and encrypted flash drive in the VBox Sport and Eye Tracker until being retrieved by study staff. Even if the device or bicycle is stolen, no one can access the data with the encryption key.

The data will be then transferred and housed to a secure server at the CUTR building. The data will be housed securely at the University of South Florida's Center for Urban Transportation research for 5 years after the Final Report is submitted to the IRB.

Compensation

Option 1: You will receive an Amazon gift card of $60 for taking part in this study if you agree to install an on-motorcycle device (VBox) and wear eye tracker (Tobii Pro).

Option 2: You will receive an Amazon gift card of $20 if you agree to mount on-motorcycle devices only (but not wear eye tracker).

If you stop participating before the study is over, you will not receive any compensation for taking part in this study.

C.3 Motorcyclist Recruitment Flyer

USF RESEARCHERS WANT YOUR HELP IN A RESEARCH STUDY TO IMPROVE MOTORCYCLE SAFETY

USF
UNIVERSITY OF SOUTH FLORIDA

We want you (and your friends)…
To Participate in the Motorcycle safety study of understanding how riders interact with pavement surface on W.Ozello Trail.

Why should I participate?
You get to know that you have helped improve motorcycle safety. In 2015, Florida experienced 550 motorcycle traffic fatalities and a significant increase of 2.23 times from 2001.

We realize you will have to take time out of your life to participate so there is compensation of $60 (Amazon gift card) if you complete two tests (VBox Sport + Eye Tracker). If you take the VBox test only, you will have an Amazon gift card of $20.

What should I know about the study?
After completing the intake process, each participant is scheduled to take part in the study. Whole study process is about 60 minutes, which include completing the survey questionnaire, riding the motorcycle (with VBox sport + Eye Tracker mounted) for 18 to 20 miles which will take approximately 30 minutes.

What will you do to my motorcycle?
We will install instruments that will collect speed, acceleration, eye movement, and other data for each ride. There will be no permanent damage to your bicycle.

Am I eligible?
You are eligible if you:

- Must be 18 years or older
- Have a motorcycle, a valid motorcycle license and motorcycle insurance
- Are able to read and speak English
- Are able to ride your own motorcycle to W. Ozello Trail, Crystal River at scheduled time

What do I have to do?
Please contact Mr. Rama Kolla at kolla@cutr.usf.edu for more detailed information. We will schedule an appointment for you to take the test on W. Ozello Trail at Crystal River.

Data kept confidential. IRB# Pro00032091

www.cutr.usf.edu 813.974.8998

C.4 Informed Consent Form

UNIVERSITY OF SOUTH FLORIDA

Informed Consent to Participate in Research Information to Consider Before Taking Part in the Research Study

Pro # 32019

You are being asked to take part in a research study. Research studies include only people who choose to take part. This document is called an informed consent form. Please read this information carefully and take your time making your decision. Ask the researcher or study staff to discuss this consent form with you, please ask him/her to explain any words or information you do not clearly understand. We encourage you to talk with your family and friends before you decide to take part in this research study. The nature of the study, risks, inconveniences, discomforts, and other important information about the study are listed below.

We are asking you to take part in a research study called:

Study on Motorcycle Safety in Negotiation with Horizontal Curves in Florida and Development of Crash Modification Factors

The person who is in charge of this research study is Dr. Zhenyu Wang**.** This person is called the Principal Investigator. However, other research staff may be involved and can act on behalf of the person in charge.

The research will be conducted at **W. Ozello Trail, Crystal River, FL**.

This research is being sponsored by **Florida Department of Transportation**.

Purpose of the study

By doing this study, we hope to find out motorcycle riders' assessment on roadway and environmental conditions of W. Ozello Trail. The results will help FDOT to improve motorcycle safety and operations at W. Ozello Trail and other roadway segments for motorcycle enthusiasts.

Why are you being asked to take part?

We are asking you to take part in this research study because you are a motorcycle rider and have your own motorcycle.

Study Procedures:

If you take part in this study, you will be asked to:

- You will be asked to bring your own motorcycle and have a valid drive license.
- You will be asked to mount a VBox Sport on your motorcycle (no damage) to record your speed and trajectory (VBox).
- You will be asked to wear Tobii Pro Glass to track your attention on road. (If you must wear sunglasses or prescription eye glasses during the test, please dismiss this request).
- If you agree to wear Tobii Pro Glass, a researcher will give you a guidance and help you calibrate and practice with the eye tracker before test.
- You will be asked to naturalistically ride your motorcycle from the east end (Shell gas station) to the west end (Seafood Restaurant – Peck's Old Port Cove) and back to the east end (Shell gas station). The total travel distance is 18 around miles.
- You will be asked to answer a short questionnaire survey after riding.
- We will detach the devices from your motorcycle.
- The whole duration is 50 – 60 minutes.

Total Number of Participants

About 50 individuals will take part in this study.

Alternatives / Voluntary Participation / Withdrawal

You do not have to participate in this research study. You should only take part in this study if you want to volunteer. You should not feel that there is any pressure to take part in the study. You are free to participate in this research or withdraw at any time. There will be no penalty or loss of benefits you are entitled to receive if you stop taking part in this study.

Benefits

You will receive no benefit(s) by participating in this research study.

Risks or Discomfort

This research is considered to be minimal risk. That means that the risks associated with this study are the same as what you face every day. There are no known additional risks to those who take part in this study.

However, riding with Tobii eye trackers may cause discomfort, light sensitivity, and other potential risks for some participants. If you wear sunglasses or prescription glasses, please select Option 2 in Compensation.

The research team will NOT take the responsibility to any accident involving in this experiment, either covered by your insurance or not.

Compensation

Option 1: You will receive an Amazon gift card of $60 for taking part in this study if you agree to install an on-motorcycle device (Vbox) and wear eye tracker (Tobii Pro).

Option 2: You will receive an Amazon card of $20 if you agree to mount on-motorcycle devices only (but not wear eye tracker).

If you stop participating before the study is over, you will not receive any compensation for taking part in this study.

Costs

It will not cost you anything to take part in the study.

Privacy and Confidentiality

We will keep your study records private and confidential. Certain people may need to see your study records. Anyone who looks at your records must keep them confidential. These individuals include:

- The research team, including the Principal Investigator, study coordinator, and all other research staff.
- Certain government and university people who need to know more about the study, and individuals who provide oversight to ensure that we are doing the study in the right way.
- Any agency of the federal, state, or local government that regulates this research. This includes the Department of Health and Human Services (DHHS) and the Office for Human Research Protection (OHRP).
- The USF Institutional Review Board (IRB) and related staff who have oversight responsibilities for this study, including staff in USF Research Integrity and Compliance.
- The sponsors of this study and contract research organization: Florida Department of Transportation.

We may publish what we learn from this study. If we do, we will not include your name. We will not publish anything that would let people know who you are.

You can get the answers to your questions, concerns, or complaints

If you have any questions, concerns or complaints about this study, or experience an unanticipated problem, call Dr. Zhenyu Wang at 813-974-8998.

If you have questions about your rights as a participant in this study, or have complaints, concerns or issues you want to discuss with someone outside the research, call the USF IRB at (813) 974-5638 or contact by email at RSCH-IRB@usf.edu.

Consent to Take Part in this Research Study

Option I (wearing Tobii Eye Tracker)

I freely give my consent to take part in this study and wear a Tobii eye tracker with a VBox Sport mounted to my motorcycle. I understand that by signing this form I am agreeing to take part in research and confirm my health condition is good to take the test (NOT intoxicated or fatigued). I have received a copy of this form to take with me.

____ ____________
Signature of Person Taking Part in Study Date

____
Printed Name of Person Taking Part in Study

Option II (Not wearing Tobii Eye Tracker)

I freely give my consent to take part in this study with a VBox Sport mounted to my motorcycle. But I will not wear an eye tracker. I understand that by signing this form I am agreeing to take part in research and confirm my health condition is good to take the test (NOT intoxicated or fatigued). I have received a copy of this form to take with me.

____ ____________
Signature of Person Taking Part in Study Date

____
Printed Name of Person Taking Part in Study

Statement of Person Obtaining Informed Consent

I have carefully explained to the person taking part in the study what he or she can expect from their participation. I confirm that this research subject speaks the language that was used to explain this research and is receiving an informed consent form in their primary language. This research subject has provided legally effective informed consent.

____ ____________
Signature of Person obtaining Informed Consent Date

____
Printed Name of Person Obtaining Informed Consent