Florida Department of Transportation

FDOT Contract BDV31-977-135

Characterizing Curve Crashes in Florida

FINAL REPORT

Prepared by:

University of Florida

August 2022

DISCLAIMER

METRIC CONVERSION CHART

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
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	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
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		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
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
NOTE: volumes greater than 1000 L shall be shown in m^3				

TECHNICAL REPORT DOCUMENTATION PAGE

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Characterizing Curve Crashes in Florida		5. Report Date August 2022 6. Performing Organization Code
7. Author(s) I. Bejleri, S. Srinivasan, X. Xu, K. Rodrigues-Silva		8. Performing Organization Report No.
9. Performing Organization Name and Address University of Florida 418 Architecture Building Gainesville, FL 32611		10. Work Unit No. (TRAIS) 11. Contract or Grant No. BDV31-977-135
12. Sponsoring Agency Name and Address Florida Department of Transportation 605 Suwannee Street, MS 30 Tallahassee, FL 32399		13. Type of Report and Period Covered Final Report May 2020 – August 2022 14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

Curve safety has been an essential issue since curves have a higher fatality crash rate than tangent roadways segments. Many existing studies have focused on finding the relationships between risk factors and curve safety and developing customized curve safety performance functions (SPFs). However, previous researchers studied the curve safety issues using their available dataset, which limits these curve safety studies either by the sample size or due to a complete understanding of the risk factors most associated with curve safety. This study presents a novel customized GIS curve dataset and safety performance analysis for curves. Using GIS, we generate curves and curve attributes statewide, and trace the network to obtain spatial characteristics of the adjacent curves and intersections. The GIS process enabled more customized data for safety performance analysis. With six years of crash data for the entire state of Florida, the research team developed 12 sets of curve SPFs with different characteristics. More than 30,000 curves were categorized by area type, travel direction, and spatial relationship with adjacent intersections. Machine learning methods were explored in the variable selections, and the negative binomial models were developed to determine the statistical relationship between the crash frequency and the risk factors. By interpreting the selected variables in SPFs, the study concluded that traffic volume, curve characteristics, roadway characteristics, and the spatial relationship with the intersections were the significant risk factors for the curve safety performance. The most important finding from the study is introducing into consideration the spatial relationship between curves and intersections. The results could help transportation engineers and planners better understand the safety impacts of curves and intersections. The curve SPFs allow identifying and prioritizing high-risk curve locations and implementing effective improvements more efficiently.

17. Key Word		18. Distribution Statement	
Horizontal curve, safety performance function, GIS, roadway safety		No restrictions	
19. Security Classify. (of this report)	20. Security Classify. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	101	

Form DOT F 1700.7 (8-72) Reproduction of completed page authorized

ACKNOWLEDGEMENTS

The research team would like to thank the FDOT project manager Rupert Giroux for his leadership, guidance, encouragement, and support throughout this research.

The authors are grateful to the FDOT research office for providing the funding support to make this research possible.

EXECUTIVE SUMMARY

Curve safety has been an essential issue since curves have a higher fatality crash rate than tangent roadways segments. Many existing studies have focused on finding the relationships between risk factors and curve safety and developing customized curve safety performance functions (SPFs). However, previous researchers studied the curve safety issues using their available dataset, which limits these curve safety studies either by the sample size or due to a complete understanding of the risk factors most associated with curve safety. This study presents a novel customized GIS curve dataset and safety performance analysis for curves. Using GIS, we generate curves and curve attributes statewide, and trace the network to obtain spatial characteristics of the adjacent curves and intersections. The GIS process enabled more customized data for safety performance analysis. With six years of crash data for the entire state of Florida, the research team developed 12 sets of curve SPFs with different characteristics. More than 30,000 curves were categorized by area type, travel direction, and spatial relationship with adjacent intersections. Machine learning methods were explored in the variable selections, and the negative binomial models were developed to determine the statistical relationship between the crash frequency and the risk factors. By interpreting the selected variables in SPFs, the study concluded that traffic volume, curve characteristics, roadway characteristics, and the spatial relationship with the intersections were the significant risk factors for the curve safety performance. The most important finding from the study is introducing into consideration the spatial relationship between curves and intersections. The results could help transportation engineers and planners better understand the safety impacts of curves and intersections. The curve SPFs allow identifying and prioritizing high-risk curve locations and implementing effective improvements more efficiently.

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LIST OF ACRONYMS

AADT	Average Annual Daily traffic
AASHTO	American Association of State Highway and Transportation Officials.
CAR	Crash Analysis and Reporting
CMF	Crash Modification Factor
CPM	Crash Prediction Model
FDOT	Florida Department of Transportation
FHWA	Federal Highway Administration
GIS	Geographic Information System
GPS	Global Positioning System
HFS	High Friction Surfacing
HSIS	Highway Safety Information System
HSM	Highway Safety Manual
IRI	International Roughness Index
MUTCD	Manual on Uniform and guidance for Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
PDO	Property Damage Only
RCI	Roadway Characteristics Inventory
RHR	Roadside Hazard Rating
SPF	Safety Performance Function

1 INTRODUCTION

1.1 Background Statement

Horizontal curves are a basic element of the roadway design. Unfortunately, they are also one of the hazardous locations on roads. In the US, horizontal curve alignments have a three times higher crash rate than other roadways configurations and a much higher crash rate than tangent sections on the same road. In 2019, close to 20% of highway crashes occurred on curves (NHTSA 2019). In addition, road departure crashes, mainly run-off-the-road and head-on traffic crashes, account for most fatal crashes on horizontal curves.

According to the curve dataset developed from a previous curve project funded by FDOT, Florida has over 200,000 curves on public roads with a total GIS centerline (single and dual) length of over 200,000 miles (Bejleri et al, 2021). Currently, there is limited information on curve safety statewide, which may hinder systematic safety improvement efforts on a statewide scale. Even though there are current efforts to include curves as variables in systemic safety analysis for county roads in small and rural counties, the risk factors for curve crashes on all roads for the entire state of Florida have not been thoroughly studied.

Nationally, significant research has been conducted in quantifying the risk factors that affect the safety performance of curves, but not broadly in the context of Florida. In addition, most dataset have major limitations due to curve identification methods. In 2019, an improved automated procedure to detect the curves on all roads and calculate curve characteristics method had been developed for FDOT by the University of Florida using a comprehensive GIS database. It provided an opportunity to study curve safety using a more complete dataset focused on public roads in a large geographic area such as the entire state of Florida.

1.2 Project Objective

The purpose of this research is to characterize the curve crashes in Florida. This research provides the State Safety Office with an overview of curve safety performance in Florida statewide. Based on the current curve safety performance in Florida, the research goal are: (1) a systemic safety analysis of characterizing curve crashes for all roads, (2) to identify contributing factors for curve crashes; (3) to develop safety performance functions (SPFs) for curves; and (4) to have a preliminary guidance on how to prioritize the most high-risk locations for curve improvements. The application of the research contributes to a better understanding of curve safety issues in Florida and inform transportation engineers and planners to select proper countermeasures and target resources more effectively.

1.3 Report Organization

The next chapter presents a review of existing literature on curve safety issues. Chapter 3 presents a review of the current curve dataset and the method to improve the curve dataset for safety analysis. Chapter 4 uses the improved curve data and review the current curve safety conditions in Florida statewide. Chapter 5 identifies the risk factors for curve-related crashes. Chapter 6 provides the discussions on the method for developing the SPFs. Chapter 7 presents the systemic safety analysis of curve-related crashes on all roads and the development of safety performance functions for curves at different injury severity levels. Chapter 8 provides the prioritization methods when adopting curve SPFs to obtain the predicted crash frequencies to screen the curves. Chapter 9 sums up conclusions and recommendations for implementing the curve SPFs.

2 REVIEW OF CURVE SAFETY LITERATURE

A significant body of research on the effects of highway curves on safety addresses both the factors that affect crash frequency and severity. In this document, the research team focused on how the literature determines the risk factors and improvements related to curve safety. This review helps broaden the understanding of the curve safety issues and learn from analyzing methods, including the systemic approaches, safety performance functions, and suggesting countermeasures to inform a suitable solution for Florida's situation.

2.1 Overview of Curve Safety Literature

Understanding characteristics of horizontal curves can help transportation agencies locate high-risk elements, apply countermeasures, and improve warning systems. To support these needs, several researchers attempted to quantify the factors that may affect safety performance related to curve elements, such as curve radius, curve length, degree of curvature, and tangent length. Previous literature (Khan et al. 2013; Schneider, Savolainen, and Zimmerman 2009; Zegeer et al. 1992) has examined crash prediction models for curves and has summarized the factors that influence horizontal curve crashes. A positive correlation between curve length and crashes, and a negative correlation between curve radius and crashes has been observed. Most researchers have employed curve samples based on available datasets, i.e., the curve geometry data from the Highway Safety Information System (HSIS) in the United States. However, the curve attributes have not always been available in these databases. HSIS does not have the curve attributes for all the participating states. For those states with curve attributes in HSIS, extracting curve information varied from delineating curves manually to developing curve data from construction drawings (Nujjetty, Mohamedshah, and Council 2014). The lack of details on the curve location and attributes makes it difficult to study curve safety, screen for high-risk locations, and apply further improvements. Therefore, this raises the question of efficiently identifying curves for large geographic areas in an automated fashion, with limited data available.

The literature shows a growing number of studies on automated curve identification using different data sources, such as satellite imagery, Global Positioning System (GPS) data, laser scanning, and GIS. Examples using satellite images (Easa et al. 2007) showed an applicable method to find curves and categorize the curve types. The identification accuracy depended on the image resolution and the technique used to distinguish roads from the environment. This method is limited to small geographic areas. As already identified, this research team has already developed and validated an automated approach for identifying and characterizing curves in Florida. The details of our algorithm and a discussion of past efforts in automating curve identification are presented in Bejleri et al. (2021).

2.2 Crash Prediction Model

The base model to predict crash frequency, as presented in HSM (AASHTO 2010), depends on the local infrastructure and operational characteristics. For each facility type, a Safety Performance Function (SPF) is presented along with the Crash Modification Factors (CMFs) related to this facility. An additional Calibration factor, C_r, can be used to adjust the model for a condition other than the one for which it was developed. The predictive method is addressed in HSM Part C, Appendix A, and the CMFs are presented in HSM Part D (AASHTO 2010).

A safety performance function (SPF) is an equation to predict the number of crashes at a location, with the explanatory variables (contributing factors or risk factors). For two-lane highway segments, the SPF is shown in Equation 1 (AASHTO 2010).

$$N_{SPF\ rs} = AADT \times L \times 365 \times 10^{-6} \times e^{0.312} \quad (1)$$

, where $N_{SPF\ rs}$ is the predicted crash number per year for the roadway segment.

AADT is the Average Annual Daily Traffic (veh/day);

L is the Length of the roadway segment (in miles).

Curves were mentioned in Chapter 10 of HSM first edition and its supplement for two-lane highways and freeways facility type. No specific SPFs were proposed for curved segments in HSM.

Instead, HSM suggests a crash modification factor (CMF) to adjust the prediction directly from the SPF of straight segments.

The HSM CMFs were based on the study of Zegeer et al. (1992) using the curves on two-lane rural roads in Washington State. From this study, CMF_{3r} and CMF_{4r} were taken was shown in Equations 2 and 3. The number of crashes on curves could be estimated by the multiplication of the Equations 1, 2 and 3.

$$CMF_{3r} = \frac{(1055 \times L_C) + \left(\frac{80.2}{R}\right) - (0.0012 \times S)}{1.55 \times L_C} \qquad (2)$$

, where CMF_{3r} is crash modification factor for the effect of the presence of horizontal curves;

L_c = length of the curved roadway segment (miles);

R = radius (feet);

S = 1 if present of the spiral transition on both ends; 0.5 if present on one end only; 0 if not present.

The CMF_{4r} was based on the curve superelevation deviation compared to the AASHTO criteria. When this difference is close to zero, the CMF is equal to 1.00.

$$\begin{aligned} CMF_{4r} &= 1.00 \; for \; SV < 0.01 \\ CMF_{4r} &= 1.00 + 6 \times (SV - 0{,}01) for \; 0.01 \leq SV < 0.02 \\ CMF_{4r} &= 1.06 + 3 \times (SV - 0.02) \; for \; SV \geq 0.02 \end{aligned} \qquad (3)$$

where CMF_{4r} is the crash modification factor for curve superelevation deviation.

SV = Difference of superelevation (m/m) than AASHTO criteria.

This estimation could have a bias since the equations were developed under some specific conditions, i.e., nearly 30 years ago. Other study concluded that the application of these CMFs could not reflect this element in crash prediction for some locations (Silva 2017).

Some initiatives have investigated further CMFs for various facility types (Banihashemi 2015, 2016; Harwood and Bauer 2015; Wu, Lord, and Geedipally 2017). However, previous studies have developed many customized curve SPFs to describe the relationships between the crash frequency on curves associated with various contributing factors, including the characteristics of the curve geometry, the characteristics of roadways, the traffic variables, and the spatial relationship with adjacent curves (Anarkooli et al. 2019; Aram 2010; Bauer and Harwood 2014; Findley et al. 2012; Gooch, Gayah, and Donnell 2016; Khan et al. 2013; Miaou and Lum 1993; Montella 2009; Saito et al. 2015; Saleem and Persaud 2017; Vogt and Bared 1998; Xin et al. 2019).

To develop customized curve SPFs using the obtained curve dataset, some steps are necessary to understand the contributing factors for curve safety issues. To fully understand the curve safety issues, we assembled all the previous curve SPF studies. We excluded the studies that analyzed curve safety issues but did not develop SPFs or a new CMF for the presence of a horizontal curve. All the studies in Table 2-1 made efforts to take into account curves in crash prediction models using the customized assembled data. Currently, these studies rely on limited data source availability of explanatory variables.

Table 2- 1 Studies that developed SPFs or a CMF for Curved Segments

Authors	Year	Crash sample	Curve sample	Target facilities	Location
Zegeer et al.	1992	Total crashes in 5 years (1982-1986)	7000 miles, 10900 curves in HSIS	Rural 2-lane roads	Washington
Miaou and Lum	1993	Total truck crashes	8668 lane-miles, 4983 segments in HSIS	Rural interstate highways	
Vogt and Bared	1998	Total Crashes 1985-1994 and 1993-1995	3,308 segments in HSIS for Minnesota and 6,144 segments for Washington	Rural 2-lane roads	Minnesota - Washington
Montella	2009	Total / injury / PDO crashes in 6 years (2001-2005)	15 curves for treatment, 312 untreated curves	One highway with divided 2 lanes	Italy
Aram	2010	Crashes 2007	200 km, 502 curved segments	Rural 2-lane roads	Iran
Findley et al.	2012	Total crashes in 5 years (2005-2009)	420 curves	Rural 2-lane roads	Florida
Khan et al.	2012, 2013	Total / fatal and injury crashes in 5 years (2006-2010)	114227 curves	Rural undivided roads	Wisconsin
Bauer and Harwood	2014, 2015	Total / fatal and injury / PDO crashes in 6 years (2003-2008)	3457 miles in HSIS	Rural 2-lane highways	Washington
Banihashemi	2015, 2016	Crashes in 3 years (2007–2009)	6,000 mi of highway, 212 mi of rural multilane and 560 miles of highways were urban arterial segments	Multilane and Arterial	Washington State
Saito et al.	2015	Crashes 2008-2012	1,495 randomly sampled curved	Rural 2-lane roads	Utah
Gooch et al.	2016, 2018	Total / fatal and injury crashes in 8 years (2005-2012)	29422 miles, 18831 curves	Rural 2-lane roads	Pennsylvania
Saleem and Persaud	2017	Total / fatal and injury crashes in 7 years (2005-2011)	3088 curves in HSIS	Rural 2-lane highways	Washington
Wu, Lord, and Geedipally	2017	Crashes in 3 yeas 2010-2012 calibration and 2013-2014 validation	26,234 curves	Rural 2-lane highways	Texas
Anarkooli et al.	2018	Total / fatal / injury / PDO crashes in 6 years (2009-2014)	4059 curves in HSIS	Rural 2-lane roads	Washington
Xin. et al.	2019	Single-motorcycle crashes 2005-2015	2444 curved segments	Rural 2-lane roads	Florida

2.3 Calculation of Crash Modification Factor

A Crash Modification Factor (CMF) is a multiplicative factor used to consider a characteristic's effect that differs from base conditions or after implementing a given countermeasure at a specific site. A CMF greater than 1.0 indicates an increase in predicted crashes because of the feature. In contrast, a value less than 1.0 means a reduction in predicted crashes related to the existence of a characteristic or a countermeasure implementation.

To obtain a Crash Modification Factor, two general analysis types are popular, experimental (cross-sectional with a control group) and observational (before and after). Experimental analyses are planned, meaning sites that are identified for some treatments are then randomly assigned to either a treatment or to a control group that is left untreated. The observational analysis is attained by observing the performance of an existing road system, comparing crash data from before and after the treatment was implemented at some sites.

CMFs are generally presented for the implementation of a countermeasure. Equation 4 shows the calculation of a CMF for the change in expected average crash frequency from site condition 'a' to site condition 'b', as described on HSM (AASHTO 2010).

$$CMF = \frac{Expected\ Average\ Crash\ Frequency\ with\ site\ condition\ b}{Expected\ Average\ Crash\ Frequency\ with\ site\ condition\ a} \quad (4)$$

The use of a CMF allows comparing a treatment option with a specified reference condition. A percentual change in crash frequency can be obtained by Equation 5.

$$Percentual\ change\ in\ Crash = 100 \times (1 - CMF) \quad (5)$$

2.4 Methods for developing Curve SPFs

Generally, Crash Prediction Models (CPMs) are developed using statistical methods applied to historical crash data from similar infrastructure but varying levels of AADT. An SPF is a CPM that uses only AADT and length as the independent variables (in the context of straight segments) to estimate crashes (Haas 2015; Lord and Mannering 2010). The Poisson, negative binomial, and generalized regression models are the most common statistical approaches used in SPF estimations. Additionally, Bayesian inference has been studied with these approaches (Silva 2017).

The Poisson distribution has been used in accident modeling since the work of L. von Bortkiewitcz, who, in 1989, undertook analyses of the number of deaths by horse-kicks for 20 years (Hauer 2015). Because of its practicality, research has commonly used this distribution to estimate the SPF (Bezerra et al. 2011; Caliendo, Guida, and Parisi 2007; Jovanis and Chang 1986; Miao 1993). The Poisson distribution assumes that the variance is equal to the mean; hence, the size of random variance in the count of accidents equals the expected number of accidents. Then, the number of accidents (K) in time the period (T) during which the mean number of accidents per unit of time (*l*) prevails (*k*), is given by the Poisson probability (P):

$$P(K = k|\mu) = \frac{e^{-\mu}\mu^k}{k!} \tag{6}$$

where μ is the number of accidents expected to be reported during T, given alternatively by the product of (*l*) and (T).

Although it represents a good starting point to fit safety models, the simple application of the Poisson distribution has had some inconveniencies on real transportation systems due to the nature of the crash generation process (Hauer 2015; Lord and Mannering 2010). The Negative Binomial regression is largely used (Ackaah & Salifu, 2011; Cafiso, Di Graziano, Di Silvestro, La Cava, & Persaud, 2010; Harwood et al., 2000; Lord & Persaud, 2000; McCullagh & Nelder, 1989; Srinivasan & Bauer, 2013) because of the possibility of accounting for the overdispersion of crash frequency. Negative Binomial regression is also preferred to a Poisson regression (AASHTO 2010).

These models can take different empirical forms, including just length and AADT, multiplicative coefficients to account for other roadway characteristics, as seen in Equation 7 (Haas 2016).

$$N = \exp\left(b_o + b_1 \ln AADT + b_2 \ln L + b_3 X_3 + \cdots + b_n X_n\right) \quad (7)$$

, where *N* is predicted crash frequency per year for a specified segment; *AADT* is annual average daily traffic volume (veh/hr) for the segment; *L* is length of the segment; $b_0,\ldots,b_n$ are regression coefficients and $X_1,\ldots,X_n$ are segment characteristics.

The generalized regression-based estimating equations have been applied to model crash data (Caliendo et al. 2007; Dinu and Veeraragavan 2011; Lord and Persaud 2000). This approach can assume several forms. The base model, called Generalized Linear Model (GLM), has a random and a systematic component and a link function. The popularity of this method comes from the simplification in the algorithm of estimation and interpretation of parameters.

In addition to the application of the SPFs, the Empirical Bayes methods can be used to correct the regression-to-mean bias (Elvik 2008; Hauer et al. 2002; Miaou and Lord 2003). The Empirical Bayes Method weighs the crash estimate from a statistical model with the historical crashes from that location. In the safety analysis, the best approach is obtained by combining two sources: accident history and a safety prediction modeling.

As discussed, the original method for developing SPFs was Poisson regression, since Poisson distribution models the discrete counting data, which suits traffic crash occurrence. Later, researchers discovered that the crash frequency data always has a larger variance than its mean, which violates the Poisson distribution properties. Therefore, consistent state-of-the-art methods used generalized linear modeling with the specification of a negative binomial (NB) to develop the crash prediction models in safety systemic analysis.

2.5 Datasets for Analyzing Curve Safety

Many studies used curve samples based on the existing curve dataset, i.e., the curve geometry data from the Highway Safety Information System (HSIS). The existing curve dataset allows the researchers to access a large quantity of curve-related data. However, the characteristics of curves were not always available in a roadway database. Even HSIS does not have the curve attributes for all the participating states. Some curve datasets only flag whether there is a curve on the roadway segment without further detailing critical safety-related attributes, such as the curve radius and the degree of curvature.

For different datasets, some researchers collected data by manually identifying curves, which resulted in using a small set of curves for developing SPFs. In addition, the curves may have a wide variety of characteristics. This reduces the sample size of segments with similar conditions necessary to study the influence of each variable on the model outcome.

It can be noticed that crashes are linked to traffic volumes, length, or risk exposure. The feasibility of the study is affected by the quality and availability of this information. Also, the investigation of the accuracy of the estimated curve parameter can be beneficial to the analysis. Finally, the safety performance analysis reflects certain conditions within a specific area and limit the sample size.

2.6 Risk Factors in Curve SPFs

Table 2-2 and Table 2-3, present the explanatory variables showing statistically significant effects in the curve SPFs literature. A "+" sign means the variable has a positive coefficient in the corresponded SPF (increased the number of crashes); a "-" sign indicates the variable has a negative coefficient in the SPF (decreases the number of crashes); and a "*" symbol means the variable is categorical in the SPF.

Many common explanatory variables in the tables showed the significance of curve SPFs, both in the studies using the HSIS dataset and another curve dataset. Those variables could be categorized as curve and roadway characteristics, traffic variables, and spatial distance. The curve characteristics are the variables related to horizontal curve design parameters. The roadway characteristics contain the variables associated with the design of a roadway facility. The traffic variable contains traffic-related variables. The spatial distance is about the spatial relationship of the curve with other roadway elements. Below is a detailed summary of how each variable influences the curve safety according to the curve SPFs from the synthesis study.

Table 2- 2 Summary of curve SPF literature using HSIS database

Author	Year	Sample Size	Model	Curve: Radius	Curve: Length	Curve: Presence of transition spiral	Curve: Average of shoulder widths	Roadway: Inside shoulder width	Roadway: Shoulder type	Roadway: Surface width	Roadway: Lane width	Roadway: Vertical grade	Roadway: Vertical curve length	Roadway: Sharpness of vertical curvature	Roadway: Difference between initial & final grades	Roadway: Functional classification	Roadway: Speed	Roadway: Roadside Hazard Rating	Traffic variables: Exposure	Traffic variables: AADT	Traffic variables: AADT per lane	Traffic variables: Truck percentage
Zegeer et al.	1992	10900 curves	Total crashes	-	+	+				+										+		
Miaou and Lum	1993	4983 segments	R1 (additive linear regression model)	-	+			- [1]				+	-								+	
			R2 (multiplicative linear regression model)	-	-			+				+	+								-	
			P1 (multiplicative Poisson regression model)	-	+			+				+	+								+	
			P2 (multiplicative Poisson regression model)	-	+			+				+	+								+	
			P3 (include truck mile)	-	+			+				+	+								+	+
Vogt and Bared	1998		Total crashes		+		+				-	+	+					*	+	+		
Bauer and Harwood	2014, 2015	3457 miles	Fatal and injury crashes on straight grades	-								+								+		
			PDO crashes on straight grads	-								+			+					+		
			Fatal and injury crashes on type 1 crest												+					+		
			PDO crashes on type 1 crest																	+		
			Fatal and injury crashes on type 2 crest	-																+		
			PDO crashes on type 2 crest	-																+		
			Fatal and injury crashes on type 1 sag											+	+					+		
			PDO crashes on type 1 sag											+	+					+		
			Fatal and injury crashes on type 2 sag	-																+		
			PDO crashes on type 2 sag												+					+		
Banihashemi[4]	2015-2016	212.5 miles of curved segments and 560 miles of intersections	Total crashes	-																		
Saito et al.	2015	1495 curves	Total crashes	-	+															+		-

Author	Year	Sample Size	Model	Curve				Roadway											Traffic variables			
				Radius	Length	Presence of transition spiral	Average of shoulder widths	Inside shoulder width	Shoulder type	Surface width	Lane width	Vertical grade	Vertical curve length	Sharpness of vertical curvature	Difference between initial & final grades	Functional classification	Speed	Roadside Hazard Rating	Exposure	AADT	AADT per lane	Truck percentage
Saleem and Persaud	2017	3088 curves	Total crashes on level grades	-	+		-													+		
			Fatal and injury crashes on level grades	-	+		-													+		
			PDO crashes on level grades	-	+		-													+		
			Total crashes on moderate grades	-	+		-													+		
			Fatal and injury crashes on moderate grades	-	+		-													+		
			PDO crashes on moderate grades	-	+		-													+		
			Total crashes on steep grades	-	+		-													+		
			Fatal and injury crashes on steep grades	-	+		-													+		
			PDO crashes on steep grades	-	+		-													+		
Anarkooli et al.	2018	4059 curves	PDO HNB	-	+							+	-			*				+		
			Possible injury with HTNB	-	+		-		*		-					*				+		
			Non-disabling injury with HPO	-	+								-			*	+			+		
			Fatal and serious injury with HPO	-	+											*	+			+		
			Total crashes with HTNB	-	+		-						-			*				+		

Table 2- 3 Summary of curve SPF literature using other curve databases

Author	Year	Sample Size	Model	Curve				Roadway										Traffic variable	Spatial distance		
				Radius	Length	Length of spiral	Deflection angle	Inside shoulder width	Shoulder type	Lane width [6]	Average IRI	Pavement	Speed	Vertical grade [9]	Presence of a bridge or tunnel	Presence of rumble strips	Roadside hazard rating	AADT	Sight distance	Distance to proximal adjacent curve	Distance to distal adjacent curve
Montella	2009	15 curves for treatment, 312 untreated curves	Total crashes	-			-						+	-				+			
			Nighttime crashes				-		*				+	-	-			+			
			Daytime crashes	-			-		*				+					+			
			Rainy crashes	-					*					-				+			
			Non-rainy crashes	-			-		*				+	-				+	-		
			ROR (run-off road) crashes	-					*				+	-				+			
			Non-ROR crashes	-					*				+					+			
			Injury crashes	-			-		*				+	-				+			
			PDO crashes	-					*									+	-		
Aram et. al.	2010	502 curves	Total crashes	-	+	-	+	+	-									+			
Findley et al.	2012	420 curves	Total crashes																	+	+
Khan et al.[4]	2012, 2013	11427 curves	HORC	-	+			-	*		-		+					+			-
			KABHORC	-	+				*		-		+					+			-
			HORC_N	-	+			-	*		-		+					+			-
			KABHORC_N	-	+			-	*		-							+			-
			ALL	-	+						-		-					+			-
			KABALL	-	+				*		-	*	+					+			-
			ALL_N	-	+			-			-	*	+					+			-
			KABALL_N	-	+			-	*		-							+			-
Gooch et al.	2016, 2018	18831 curves	Total crashes with adjacent curves	-	+					*			-			*	+	+		*	*
			Fatal and injury crashes with adjacent curves	-	+					*						*	+	+		*	*
Wu, Lord, and Geedipally	2017	26,234	Total crashes	-																	
Xin. et al.	2019	2444 curved segments	Single-motorcycle crash frequency	*	*				*	*		*	*	*				*			

- ***Curve characteristics***

The curve characteristic variables, such as radius, curve length, and deflection angle, were in almost all the curve SPF reviewed literature. These variables mostly differentiate a curve segment from a tangent segment on the roadway network. The curve characteristics variables' significant effects indicate the importance of developing curve specific SPFs, instead of using the general SPF as the tangent roads.

- ***Radius***

Radius has a negative coefficient in most of the curve SPFs in the literature. This indicates that a curve with a smaller radius would be more prone to crashes for all types and all severity levels. Some studies used the degree of curvature, which defines the sharpness or flatness of the curve, to obtain a positive coefficient with the degree of curvature. Also, the regressions may be tweaked to include the deflection of the curve.

- ***Curve length***

Curve length has a positive sign in most of the curve SPFs in the literature. This indicates that a longer curve would be more susceptible to have a higher number of crashes. In a few cases, the curve length showed an opposite impact on the SPFs (Miaou and Lum 1993). Not all SPFs could incorporate curve length as a variable because this information was not always available.

- ***Length of Spiral***

Generally, the spiral transition is used in shorter radius curves to gradually change curvature from a straight segment. Spiral curves may be perceived as a smoother alignment by drivers. Aram (2012) found a negative sign on the curve SPF, which implies that the number of crashes decreases as the length of the spiral transition increases. However, this variable is difficult to obtain, and most SPF models were not successful in considering it.

- ***Deflection angle***

Deflection angle was not considered in most of the curve SPF literature, more likely due to the non-availability of the HSIS database. Some research considering the deflection angle stated that it had a negative sign in the SPF. A curve with a larger deflection angle would have a lower possibility for crashes (Montella 2009). A possible explanation for this is that a large deflection angle is associated with smoother curves. Some explorations showed that the interaction between the deflection angle and the other parameters, such as curve length or radius, played a significant role in the SPF with a positive coefficient (Aram 2010; Bauer and Harwood 2013).

- **Roadway characteristics**

The roadway characteristic variables include shoulder, lane, pavement, grade, functional classification, speed, etc. Most of the curve SPF literature included at least two or three aspects of these variables depending on data availability. The studies that used a combination of dataset had more roadway characteristics variables than the studies using the HSIS data. The roadway characteristics variables would have similar safety effects on curves as on tangent roads. The previous studies examined which variables had more influence on specific types of curves and different crash severity levels on curves.

- ***Shoulder***

Shoulder widths and shoulder types were considered in most of the work discussed in this literature review. In general, the inside shoulder width (left shoulder width) has a negative sign in SPFs, meaning that a curve with a narrower left shoulder would have more predicted crashes. The outside shoulder width (right shoulder width) was considered in SPFs but did not significantly impact. Some researchers considered the average of the inside and outside shoulder width as the variable (Anarkooli et al. 2019; Saleem and Persaud 2017) and the deviation of the insider shoulder width from a base condition of 12 feet (Miaou and Lum 1993). The average of both shoulder widths still had a negative sign in SPF and the inside shoulder width. The deviation from the base condition width showed inconsistent among the models. Most of SPFs showed that the larger deviation implied in more crashes.

Inside shoulder type was explored in most of the presented literature that used a dataset other than HSISs. Montella (2009) stated that the shoulders with a cut were less likely to have crashes than those with an embankment. Khan et al. (2013) found that unpaved shoulders had a negative impact on safety (more crashes), while rumble strips had a positive impact (fewer crashes). Only one study using HSIS data considered a categorical variable shoulder type, finding that the shoulders with gravel were more prone to crashes with possible injuries (Anarkooli et al. 2019).

- ***Lane***

Many studies mentioned that they considered the lane width on the SPF development, but only the lane width showed statistically significant in a few SPFs. In those SPFs, the lane width was turned into a categorical variable aggregated into three categories: less than 16 feet, between 16 to 20 feet, and between 20 to 24 feet. The results from Gooch et al. (2016, 2018) suggested that the lane width had a non-linear relationship with the number of crashes. The lane width of less than 16 feet and with more than 20 feet showed more prone to have crashes than the lane width between 16 to 20 feet.

- ***Pavement***

Pavement conditions have a high impact on curve safety, as discussed in the previous studies. One paper (Buddhavarapu, Banerjee, and Prozzi 2013) specifically addressed the pavement issues on curve safety. In the curve SPF literature (Khan et al. 2013), some variables were explored, such as the average IRI (international roughness index), the pavement type, and the pavement surface age. The average IRI is measured for standardizing roadway roughness. It had a negative sign in all the considered SPFs, indicating that the number of crashes increases when the roadway pavement is more regular with a smaller IRI. The authors are uncertain about the explanation and pointed out that reducing pavement friction as pavement becomes too smooth could lead to an increase in crashes (Khan et al. 2013).

Several pavement types were considered in the SPFs. Compared to the asphalt pavement, the concrete pavement and the road mix pavement had fewer crashes on curves. The pavement surface age had a positive sign in SPFs, indicating that the older pavement surfaces presented more susceptible to crashes on curves.

- ***Grade***

HSIS collects and maintains a dataset of vertical grades. Therefore, the vertical grade has been included in the SPFs in many studies using HSIS data source. Bauer and Harwood (2013, 2014), and Saleem and Persaud (2017) developed the SPFs for curves based on different types of grades. Miaou and Lum (1993), Anarkooli et al. (2019), Montella (2009) used the vertical grade as an explanatory variable. Most of the studies found the vertical grade with a positive sign in the SPFs, with a few exceptions. The positive sign means that steeper grades had a higher number of crashes. These studies also found that the vertical grade length had a positive sign in the SPFs, indicating that more crashes were observed in a long grade.

- ***Functional classification***

Only a few researchers explored the variable of functional classification. Anarkooli et al. (2019) compared the rural collector, the rural minor arterial, and the principal rural arterial. They concluded that rural minor arterial and the principal rural arterial are more prone to crashes. Other studies focused on rural two-lane highways.

- ***Speed***

Speed is a critical variable in curve SPFs. Based on the SPFs developed by Montella (2009), Khan et al. (2013), and Gooch et al. (2016, 2018), the posted speed, the 85th percentile speed, and the operating speed consistency (absolute value of the 85th percentile speed reduction through successive elements of the road) are all found to have positive sign in the SPFs, indicating that a curve on a higher speed roadway would have more crashes. The difference between the posted speed and advisory speed would have a positive sign in most SPFs (Khan et al. 2013).

- ***Roadside Hazard Rating -RHR***

The Roadside Hazard Rating is a categorical variable that varies from 1 to 7 as described in Appendix 13 A.3 of HSM (AASHTO, 2010), rating the safety of the roadside considering the elements beyond the pavement edge line such as physical obstacles, vegetation, guardrails etc. Gooch et al. (2018) found that when the RHR is at 5 to 7, the curves are more prone to crashes.

- **Traffic variables**

Traffic volume is the primary explanatory variable in the SPF suggested by HSM (AASHTO 2010). AADT or AADT per lane was included in all the curve SPFs and found to have a positive sign, indicating that a larger AADT or AADT per lane results in a higher crash number on curves. A few studies considered the truck percentage of AADT and found it has a similar relationship (Miaou and Lum, 1993).

The exposure can be defined as the risk of a traffic crash, related to the distance traveled by each vehicle, given by vehicle-mile. The exposure expresses the amount of activity in which there is the possibility of an accident occurring (Elvik et al. 2009). Vogt and Bared (1993) exposure and traffic counts are the chief highway variables contributing to accidents

Other Spatial Factors

Only the studies using datasets other than HSIS made efforts to associate the spatial variables with the curve safety. Montella (2009) explored the sight distance and concluded that the greater the sight distance could lead to few crashes, especially for non-rainy crashes and PDO crashes. Findley et al. (2012), Khan et al. (2013), and Gooch et al. (2016, 2018) studied the spatial relationship of the adjacent curves in the curve SPFs. Khan et al. found that if there is an exceptionally long tangent roadway before the curve, it increased the possibility of crashes. Findley et al. used only the spatial variables, including the distance to the proximal adjacent curve, the distance to the distal adjacent curve, and the interacted term of the two distances for the SPFs. They concluded that each distance has a positive sign in the SPFs, meaning that the long distance to the adjacent curves, the higher the crash frequencies. It could be interpreted as the isolated curves being high-risk, and a series of curves are safer since drivers would notice the curves and react appropriately. Gooch et al. included the curve characteristics of the adjacent curves in the SPFs. The degree of curvature of the adjacent curves would have adverse effects on the SPFs.

2.7 Countermeasures for Curve Safety Issues

Among the types of crashes that can impact curve crash prediction, some are more likely to be affected by curvature, such as single vehicle run-off-road, multiple vehicles head-on, and sideswipe. The effectiveness of countermeasures is based on the forgiving road measures, such as enhancing lateral clearance, removing obstacles, and providing guardrails.

In that sense, the measures to avoid safety issues should focus on: 1. Making visible the roadway path; 2. Keeping vehicles on the roadway, 3. Treating the lateral roadway hazard 4. Minimizing the consequences of leaving the road, and 5. Reducing possible interaction with the opposite flow to avoid head-on and across-median crashes.

Some primary treatments for Horizontal Curve Safety were listed in NCHRP Report 500 and identified several strategies to address the specific safety problem at horizontal curves. These countermeasures were assessed as low-cost treatments (Albin et al. 2016):

- Longitudinal pavement markings, including centerline and Edge line.
- Delineators.
- Advance markings for curves, such as speed advisory markings in the lane, and speed reduction markings (also known as optical speed bars).
- Basic signing countermeasures: advance warning signs, advisory speed plaques; combination curve/intersection signs, supplemental devices in a curve, combination horizontal alignment/advisory speed signs, chevron alignment signs, and one-direction large arrow signs.
- Signing countermeasures with larger devices, doubling-up devices, retroreflective strips on signposts, high retroreflective and fluorescent sheeting, and flashing beacons.

- Dynamic curve warning systems.
- Skid-resistant pavement countermeasures, such high-friction surface treatments, pavement grooving, and enhanced superelevation.
- Shoulder treatments such as shoulder widening, paving, rumble strips, and rumble stripes.
- Roadside clearance, including clear zones, slope flattening, roadside barriers, and delineation on barriers.

For each of these countermeasures, the NCHRP report 500 provides information related to the design, safety effectiveness, and general application guidelines. Additionally, the effect of some of the listed countermeasures in curves was addressed in several studies and can be found on the CMF clearinghouse website (FHWA 2017).

The CMFs in the clearinghouse website ranking with a star quality rating criterion depending on the quality or confidence in the study results (1 – poor to 5 – excellent). Table 2-4 presents the maximum value of CMFs for curve countermeasures in the studies ranked with star quality from 3 (fair) to 5(excellent).

Nighttime driving roadway conditions are particularly important, especially when the alignment may not be readily visible. Some measures are used more ostensibly, such as retroreflective signs, pavement markings, and roadway lighting. The FHWA has a separate Nighttime Visibility section to ensure appropriate signs and markings are used (CQ Press 2020). The effect of some listed countermeasures on curves nighttime crashes was the object of some research found on the CMF clearinghouse website. These CMFs are shown in Table 2-5. It can be noticed that some of the measures can increase the total number of crashes. However, further investigation related to crash severity may show a positive impact on safety.

For nighttime, countermeasures that focus on making the highway path more visible, such as a combination of chevrons signs, curve warning signs, and/or sequential flashing beacons, pavement markings, have shown a positive effect.

Table 2- 4 CMF of the effect of a curve countermeasure for all crashes (FHWA, 2017)

Countermeasure	CMF
Flatten vertical crest curve	0.490
Flatten horizontal curve	0.315
Improve pavement friction (HFS-High Friction Surfacing)	0.759
Increase the degree of curve on freeways from 0 to 10 (curvature in degrees)	3.350
Increase the degree of curve on freeways from 0 to 15 (curvature in degrees)	6.120
Increase the degree of curve on freeways from 0 to 5 (curvature in degrees)	1.830
Install a combination of chevron signs, curve warning signs, and/or sequential flashing beacons	0.976
Install automated section speed enforcement system on curves	0.570
Install centerline rumble strips (horizontal curves)	1.010
Install centerline rumble strips on horizontal curves	1.160
Install chevron signs and curve warning signs	0.694
Install chevron signs on horizontal curves	0.721
Install chevron signs, curve warning signs, and sequential flashing beacons	0.627
Install dynamic speed feedback sign	0.950
Install edge line rumble strips at the horizontal curve	0.790
Install edge lines (curves)	0.741
Install edge lines (tangents and curves)	0.921
Install in-lane curve warning pavement markings	1.010
Install oversized chevron signs	0.946
Presence of a horizontal curve, intersection, or driveway in a sight restricted area	1.620
Provide below criteria Stopping Sight Distance	1.220
Raise posted speed	1.247
Safety effects of horizontal curves and tangents at type 1 crest vertical curves – tangents at type 1 crests	1.000
Safety effects of horizontal curves and tangents at type 2 crest vertical curves – tangents at type 2 crests	1.000
Safety effects of horizontal curves and tangents at type 2 sag vertical curves – tangents at type 2 sags	1.000

Table 2- 5 CMF of the effect of a curve countermeasure for nighttime crashes

Countermeasure	Total
Install a combination of chevron signs, curve warning signs, and/or sequential flashing beacons	0.592
Install chevron signs and curve warning signs	0.66
Install chevron signs on horizontal curves	0.78
Install chevron signs, curve warning signs, and sequential flashing beacons	0.231
Install in-lane curve warning pavement markings	0.649
Install new fluorescent curve signs or upgrade existing curve signs to fluorescent sheeting	0.66
Install oversized chevron signs	0.89

Local CMFs have been used in the Florida Department of Transportation – FDOT as summarized in Table 2-6.

Table 2- 6 CMF of the effect of a curve countermeasure - Florida Department of Transportation (FDOT, 2014)

Countermeasure	Number of Projects*	CMF
Curve warning Signing	2	0.65
Delineation of reflectorized raised pavement markers (centerline)	1	0.9
Guardrail at steep embankments	3	1.05
Guardrail at steep embankments with curve	1	3.56
Install double-sided guardrail on wider median	12	1.16
Install flashing warning signal (flashing beacon)	5	1.29
Install guardrail	9	1.38
Install rumble strips	9	0.78
Modify speed limit (increase or decrease)	1	0.48
New inverted AUDIBLE marking on CL or edge line	12	0.94
New roadway segment lighting	58	0.98
Paved shoulders & rumble strips	3	0.97
Pavement deslicking	4	1.03
Reconstruct curve	3	0.58
Signing and Pavement Markings	11	0.89
Skid Hazard overlay	95	1.06
Upgraded guardrail	1	1.22
Widen shoulder	1	1.09
Widen travel way	2	1.52

* Number of projects that the CMFs are based on.

Overall, most countermeasures are according to the Manual on Uniforms and guidance for Traffic Control Devices MUTCD recommendations. However, the evaluation of whether a treatment may be more intensive in a single location with a history of crashes than in others with similar characteristics is still pertinent.

2.8 Summary of Findings

From the presented review, it was possible to conclude that the variables used to build SPFs are not absolute, which means that the models differ depending on the quality and availability of the database. Data from only seven US states were included in the SPF studies for curves on the highway. This indicates there is still a gap in the knowledge to understand the effect of horizontal curvature on crashes in the US.

The objective of this literature review was to identify previous efforts on crash prediction models that have taken curves into account. Some methods were the baseline to address curves in the HSM method. To reach this objective, all variables were listed, and the impact on a SPF model was presented.

It can be noticed that the quality and the effectiveness of the CPMs are intrinsically dependent on appropriate data sources. Many common explanatory variables in the studies were obtained using the HSIS dataset combined with another curve dataset in the U.S. Curve dataset was attained from different resources in the various studies, such as satellite imagery, Global Positioning System (GPS) data, laser scanning and GIS. Roadway Characteristics Inventory (RCI) and Crash Analysis and Reporting (CAR) were also presented as the data source.

Most SPFs in the literature review show a consistent relationship between the crash frequency on curves and some explanatory variables. Note that only a few studies addressed the curve safety issues with the spatial aspect. It is challenging to explore the spatial relationship of curves with other roadway elements such as intersections.

The key parameters for horizontal curves included the following:

- The radius of curvature
- Length of the curve
- AADT

In addition, traffic variables combined or not with curve length had been present in most studies. Table 2-7 presents the frequency of each variable in the SPF literature review.

Table 2- 7 Frequency of each variable in the SPF literature review

Group	Variable	SPF %	SPF Frequency
Curve	Radius	87%	48
	Length	62%	34
	Length of spiral	2%	1
	Superelevation	2%	1
	Deflection angle	11%	6
	Presence of spiral transition	2%	1
Roadway	Inside shoulder width	20%	11
	Shoulder type	29%	16
	Average of shoulder widths	24%	13
	Lane width	7%	4
	Surface width	4%	2
	Average IRI	15%	8
	Pavement	4%	2
	Speed	31%	17
	Vertical grade	29%	16
	Vertical curve length	16%	9
	Sharpness of vertical curvature	5%	3
	Difference between initial & final grades	9%	5
	Presence of a bridge or tunnel	2%	1
	Presence of rumble strips	4%	2
	Roadside hazard rating	5%	3
	Functional classification	9%	5
Traffic	Exposure	4%	2
	AADT per lane	9%	5
	Truck percentage	4%	2
	AADT	84%	46
Spatial distance	Sight distance	4%	2
	Distance to proximal adjacent curve	5%	3
	Distance to distal adjacent curve	20%	11

In developing the SPFs for curves for Florida, we have considered including as many of the above variables as appropriate based on availability at a state-wide level. For example, variables such as curve length, radius, and number of lanes are available, while pavement conditions, roadside hazard rating, and presence of rumble strips/chevrons are not. In addition, we also considered the inclusion of other risk factors we found to be of critical interest in the context of previous efforts of the Transportation Safety Center. For example, we have noticed that the presence of an intersection on a curve or near a curve may have a significant impact on safety. Similarly, the presence of multiple curves near each other might be associated to risk factor for safety. Such attributes were determined by GIS processing, and these variables were considered for inclusion in our SPF development efforts. We developed the expanded or full SPFs (i.e., SPFs that include other risk factors beyond length and exposure measures) employing the cross-sectional approach (not before and after analyses). We explored machine learning methods for the variable selections and developed the SPFs using negative binomial regression models with the selected variables. The detailed SPF methods is explained in Chapter 6.

Finally, this review helped broaden the understanding of the curve safety issues and the variables that might be included in the systemic approaches, safety performance functions, and the impact of curve-related countermeasures to be considered for Florida's context.

3 IMPROVEMENT OF CURVE DATASET

3.1 Limitations of the previous curve dataset on the 2015 HERE network

The study is based on the curve dataset that has been developed using the 2015 HERE network (Bejleri et al, 2021). This dataset included the curve file, and the curve component file (see Figure 3-1). In the curve file, each curve consists of one or more curve components aggregated in a polyline; and in the component file, these components are divided into parts. Each curve, file includes the curve type, such as horizontal angle point, independent horizontal curve, compound curve, and reverse curve. A compound or a reverse curve (Figure 1c,1d) has multiple components with attributes, such as PC, PT, PO, and radii.

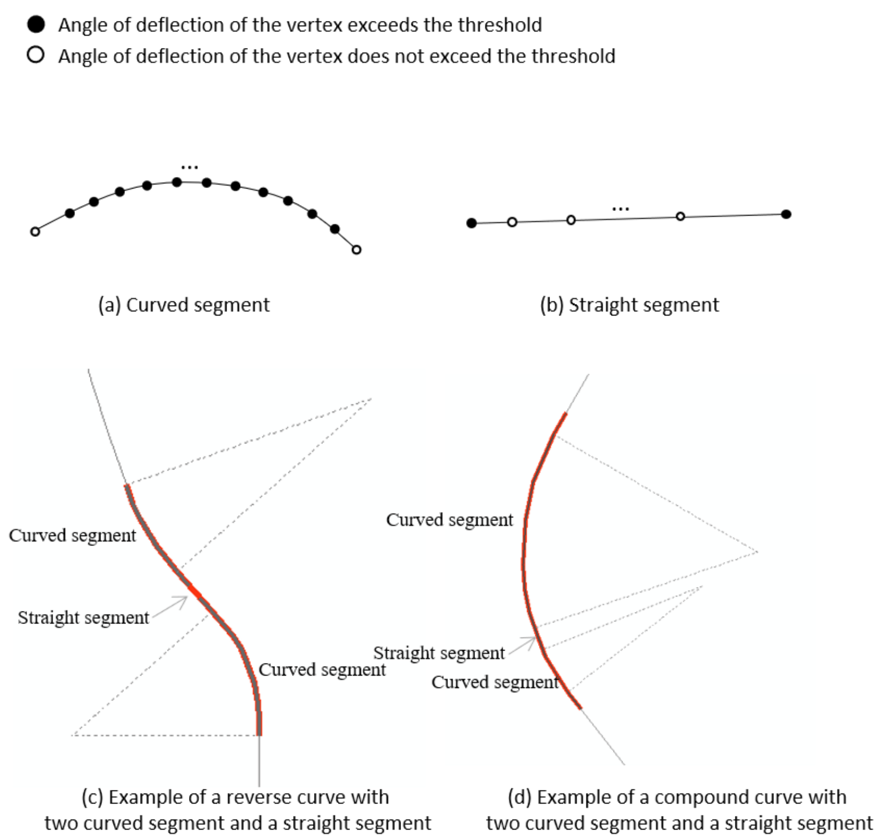

Figure 3- 1 Diagram of curve components: (a) Curved segment; (b) Straight segment; (c) Example of a reverse curve with curve components; (d) Example of a compound curve with curve components

- A *curved segment* (Figure 3-1a) – one to *n* consecutive vertices that exceed the deflection angle threshold in the same direction, along with the *n*+1 connected line segments. A straight segment that exceeds the straight segment threshold in length or a change in direction ends the curved segment. The threshold varies based on the roadway speed and vertex density.
- A *straight segment* (Figure 3-1b) – one to *n* consecutive vertices following a horizontal angle point or a curved segment that do not exceed the deflection angle threshold, along with the *n*+1 connected line segments. A straight segment cannot exceed the straight segment threshold in length, else the curve ends.

For all curved segments, we calculate the central angles and radii. For all horizontal angle points, we calculate the deflection angle. An independent horizontal curve has only one curved segment. A compound curve has multiple curved segments with the same direction. A reverse curve has two curved segments with opposite directions. A horizontal angle point is the curve with one special curved segment which contains only one vertex that exceed the deflection angle threshold.

Depending on the structure of curve and their components, it is difficult to match curve attributes since they are stored separately. One curve may have multiple curve components, thus multiple radii, central angles etc., especially for compound curves. When developing the SPFs using this curve dataset, it is important to build different SPF for simple curves and compound curves, since the curve attributes of simple curves and compound curves are different in structure. We acknowledged these based on our previous experience from the systemic safety analysis working with Florida DOT. However, when considering the compound curves as several adjacent simple curves, we may proceed with the investigation whether the difference in the SPF for simple curves and for compound curves persists. Therefore, in this task, the research team proposed to split the compound curves into several simple curves, and the curve SPFs would be developed based on the curve dataset including the simple and compound curves. More details are discussed in Chapter 3.2.

Another issue from the previous curve dataset is that there are many simple curves with one-side or both-side tangent tails. This problem is originated from the curve identification algorithm only looking for the network segments with a deflection angle larger than the threshold. Even though we used the dynamic threshold for curve identification, it could not guarantee the accuracy of the point of curvature (PC) and the point of tangency (PT). Therefore, we need to have an improved algorithm to further adjust the PC and PT.

3.2 Automated algorithm for curve improvement

- ***Compound curve split algorithm***

The compound curve split algorithm divides the existing long compound curves into several simple curves, as can be seen in Figure 3-2 as an example. The curve in Figure 2(left) is from the existing curve dataset. This curve was considered as one curve in the previous project, because the tangent segments between the curved segments would be shorter than the tangent thresholds. The tangent threshold is about 600 feet / 183 meters, but we adjusted the threshold based on the roadway speed.

The algorithm split the curve in Figure 2 (left) into three individual curves, with three records in the attribute table, as shown in Figure 2(right). The algorithm examines sequentially through the component segments in the curve component layer and aggregates the adjacent component segments with the same direction of curvature. The newly split curves have a new field named "compound ID" to maintain the curve ID from the previous curve dataset, so they can be traced back to the original compound curve if needed.

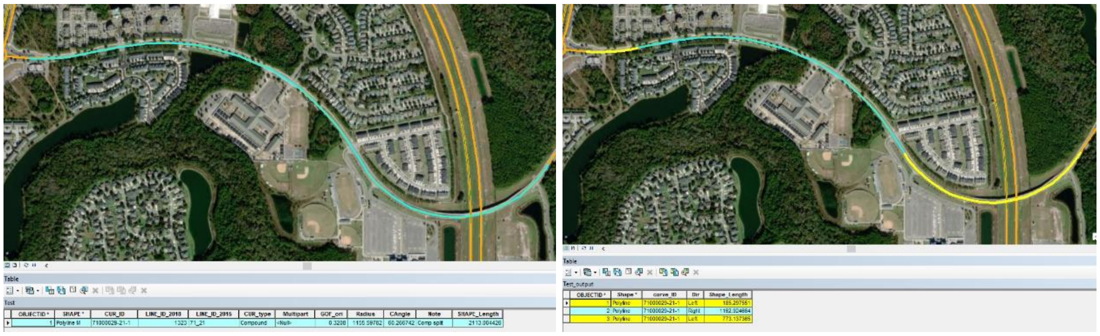

Figure 3- 2 An example of compound curve split algorithm

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- ***Tangent trim algorithm***

The tangent trim algorithm was aimed at simple curves with one-side or both-side tangent tails. When we developed the previous curve dataset, we found that the compound curves were three times longer than the simple curves, which should not be consistent with the roadway geometry design. Therefore, based on the metric of goodness of fit, the compound curves with high goodness of fit (about 0.9) were considered as simple curves. Most of these simple curves that have the one-side or both-side tangent tails problem originated from compound curves. The tangent tails significantly affect the accuracy of PC and PT, since it is going to show longer curve length, affecting the curve attributes such as radius.

Figure 3-3 shows an example of a simple curve with two-side tangent tails. First, we obtain the bearing angle for each vertex in the curve and plot the bearing angle versus the length. We observe that for the part of tangent tails, the dots on the plot should construct a horizontal line (Figure 3-3 light blue lines), while for the part of the actual curves, the dots should construct a non-horizontal line (Figure 3-3 yellow line). Therefore, the algorithm goes through all the combinations of the vertices, constructing two horizontal lines using the vertices from PC and PT, and a regression line using the rest middle vertices. The trimmed curve should combine with the least sum of squares of the difference from the vertices to the lines.

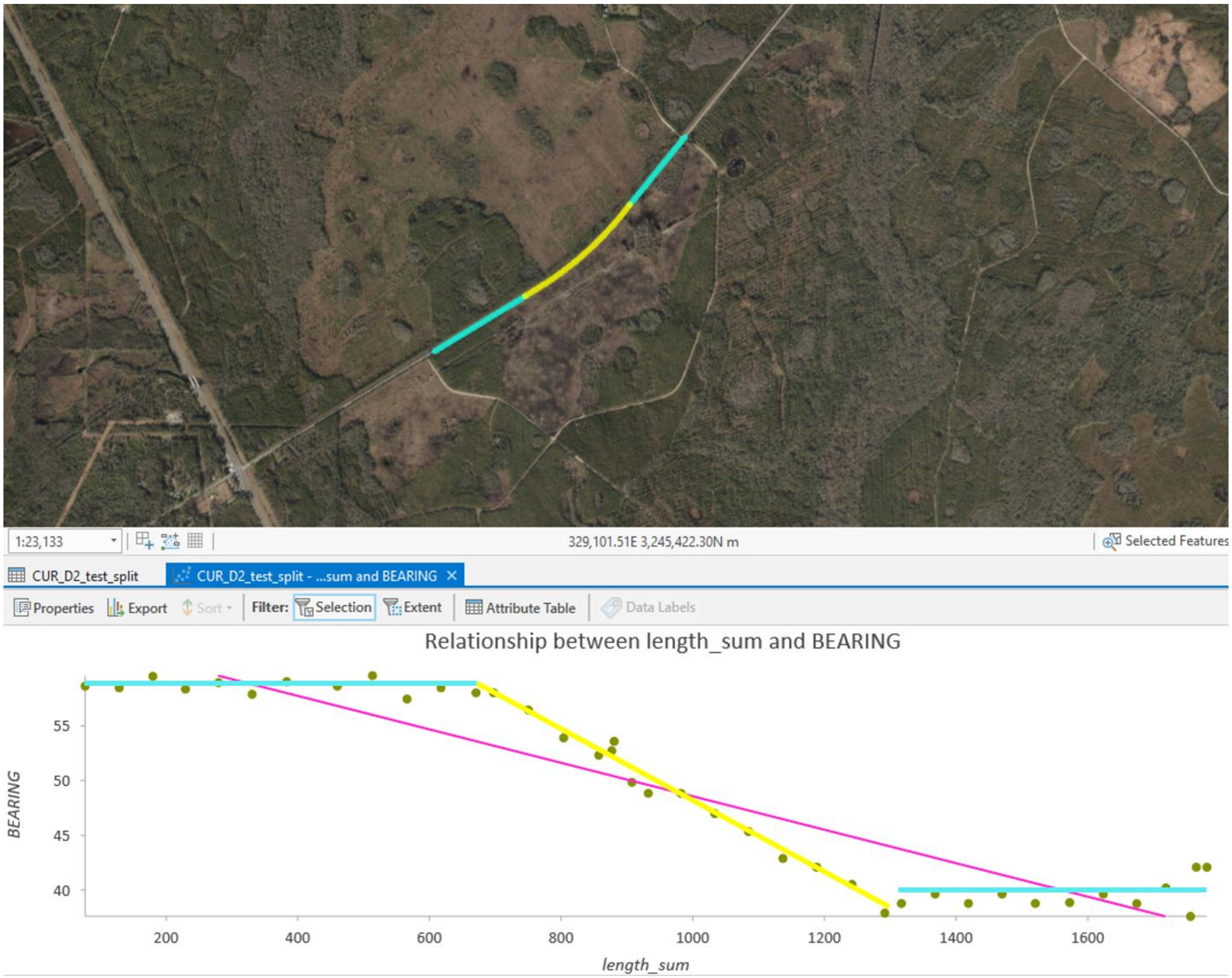


Figure 3- 3 An example of tangent trim algorithm

3.3 Summary

The curve improvement algorithm was applied to the previous curve dataset, and additional quality check was performed using the Levy County sample. The research team chose 37 curves and manually obtained the curve length and radii using the area photography. When comparing the accuracy of length and radii before and after running the improved algorithm, it can be noticed that the new algorithm provided values closer to those measured manually.

Curve segmentation was applied to all public roads in Florida, with a total GIS centerline (single and dual) length of over 320,000 km. More than 40,000 curves were identified. The length of the majority of the curves ranges from 35 to 800 meters, and the radius ranges from 15 to 605 meters. The descriptive statistics of curve radius, central angle, and curve length are summarized as the following table. The attributes in the updated curve dataset are explained and illustrated in Chapter 5. The definition of the attribute table is in Table 5-4.

Table 3- 1 Descriptive statistics of curve attributes by county

COUNTY ID	COUNTY Name	Total Number	Min Radius (meter)	Max Radius (meter)	Min Central Angle (degree)	Max Central Angle (degree)	Min Length (meter)	Max Length (meter)	Total Length (meter)
01	Charlotte	312	12.00	3372.61	5.10	89.83	19.94	1078.88	75106.45
02	Citrus	657	17.74	3760.67	6.88	89.84	20.27	1585.29	154197.62
03	Collier	317	29.28	4187.25	4.49	89.16	35.50	2804.99	89919.72
04	DeSoto	115	23.61	4246.90	5.56	89.01	34.15	603.45	21897.47
05	Glades	74	34.99	2475.61	7.59	89.34	46.00	1194.08	27151.79
06	Hardee	189	17.57	2291.57	3.87	88.91	28.83	726.57	31225.40
07	Hendry	100	19.96	2873.44	6.28	89.61	35.69	1145.13	28177.81
08	Hernando	439	18.55	3164.72	6.26	89.52	30.49	1504.81	115268.50
09	Highlands	363	23.40	3438.10	4.10	89.60	24.29	976.88	81926.81
10	Hillsborough	1453	10.32	4244.32	3.11	89.96	16.20	2398.68	372365.74
11	Lake	1119	18.76	4845.80	3.99	89.38	27.30	1567.58	260364.30
12	Lee	978	13.18	3461.97	5.42	89.97	13.67	1543.14	252781.56
13	Manatee	523	11.19	3356.59	4.41	89.80	21.02	1472.36	134231.11
14	Pasco	909	21.83	3811.81	5.13	89.87	23.65	1744.49	231237.67
15	Pinellas	876	7.42	4346.37	3.26	89.80	16.13	1087.87	182127.00
16	Polk	1391	11.18	4599.51	3.08	89.97	17.23	2200.68	350918.65
17	Sarasota	597	14.96	4825.60	3.58	89.59	22.73	2124.08	142768.25
18	Sumter	485	15.26	4937.68	5.95	89.99	24.70	1638.90	135050.98
26	Alachua	512	19.39	4424.07	3.71	89.73	20.99	1358.78	148170.99
27	Baker	206	20.42	4704.87	5.19	89.21	14.56	1308.69	51896.35
28	Bradford	239	18.97	3826.39	4.99	89.20	23.27	1545.10	58332.99
29	Columbia	323	19.57	3789.02	5.66	87.39	25.33	1500.71	84123.80
30	Dixie	183	16.70	4135.47	8.20	89.85	21.73	1177.22	48709.19
31	Gilchrist	54	20.24	2104.34	5.96	86.65	32.93	879.89	16941.72
32	Hamilton	302	9.15	3964.58	5.00	89.77	10.42	1040.85	74175.48
33	Lafayette	146	21.20	4277.35	6.39	88.54	29.47	1835.95	36031.07
34	Levy	198	15.17	3676.82	6.08	89.96	20.89	1402.57	68092.12
35	Madison	407	18.84	3466.81	4.73	89.98	19.80	2515.44	101352.91
36	Marion	944	19.22	4058.62	3.78	89.74	21.49	1859.82	251057.45
37	Suwannee	303	16.24	2700.30	6.25	89.20	21.80	1211.24	65391.14
38	Taylor	262	17.89	3633.84	5.33	88.92	22.34	1094.87	64709.75
39	Union	126	19.07	2131.05	6.95	89.85	37.32	1007.29	29441.38
46	Bay	393	16.04	4547.95	6.78	89.55	18.56	2298.23	106643.07
47	Calhoun	357	16.11	4480.43	6.64	89.53	14.42	1253.49	80211.64

48	Escambia	1017	12.23	4738.05	3.70	89.80	15.35	1256.80	210036.86
49	Franklin	288	21.76	3943.97	4.16	89.00	16.47	1128.92	61330.25
50	Gadsden	604	19.67	4927.40	4.22	89.35	26.24	1426.23	188336.31
51	Gulf	248	11.01	2926.53	3.54	89.53	18.00	1097.41	57773.03
52	Holmes	664	17.40	4854.41	3.13	88.59	34.14	1472.13	159521.14
53	Jackson	865	20.09	4301.34	3.23	89.92	21.62	1709.27	219556.14
54	Jefferson	443	14.65	3683.10	6.87	89.65	24.65	1844.19	104810.49
55	Leon	837	19.01	4957.82	3.46	89.76	8.52	1532.11	199549.94
56	Liberty	512	17.61	4190.10	4.80	89.75	20.92	957.03	117942.79
57	Okaloosa	887	12.64	4268.07	3.71	89.77	13.35	1713.01	197775.68
58	Santa Rosa	749	8.65	4412.45	4.95	89.95	17.68	2177.09	171647.95
59	Wakulla	334	28.05	4379.20	4.19	89.65	29.06	1645.81	76310.75
60	Walton	846	18.24	4505.51	3.32	89.70	23.58	2485.21	220380.99
61	Washington	571	14.62	4824.92	3.16	89.87	28.40	1536.11	131937.30
70	Brevard	959	16.13	4563.31	3.90	89.41	32.32	1635.09	230500.11
71	Clay	362	15.08	4197.05	5.39	89.63	23.22	1634.21	88283.75
72	Duval	1216	10.46	4074.61	3.11	89.89	12.79	2695.88	297437.77
73	Flagler	268	99.14	4402.39	5.23	88.88	70.73	1449.57	79216.01
74	Nassau	357	13.47	3553.20	5.34	87.68	17.55	1451.59	82868.43
75	Orange	2517	24.28	4764.71	3.39	89.61	24.38	2164.99	683498.44
76	Putnam	355	22.26	3670.32	5.28	87.89	15.71	1193.46	84505.58
77	Seminole	760	23.46	4983.95	3.05	90.00	30.69	1303.00	183517.15
78	St Johns	538	14.37	4936.99	5.79	88.99	18.44	1681.15	128070.47
79	Volusia	1284	14.36	4195.79	3.08	89.91	23.87	1588.79	269809.87
86	Broward	1647	8.11	4885.23	5.76	90.00	14.35	2538.32	466564.82
87	Miami Dade	1568	16.18	4704.75	3.19	89.87	18.43	3909.34	340209.37
88	Indian River	252	19.87	4901.17	4.71	89.33	26.11	1658.13	57352.72
89	Martin	392	14.66	4673.92	6.62	89.83	29.73	4138.50	101582.22
90	Monroe	219	10.37	3548.62	5.29	89.98	17.71	1391.88	42687.42
91	Okeechobee	90	20.98	4784.80	8.41	89.47	26.73	1768.97	27228.32
92	Osceola	766	10.67	3702.74	3.22	89.70	22.49	2059.91	225745.52
93	Palm Beach	1496	16.62	4085.81	4.03	89.92	25.09	1598.92	378290.58
94	St Lucie	530	29.73	4629.45	3.83	89.77	26.11	1933.24	157054.28
	Statewide	40293							10013330

4 CRASHES ON CURVES

To assign crashes on a curve, we performed the spatial join in GIS, the crashes that occurred within the curve length were considered as the crashes on the curve. For crashes on curves that are digitized on dual centerlines, we assigned the crashes based on the proximity to curves: each crash was assigned to the closest curve.

To better understand the distance from crashes to curves, we created the 100-feet buffer areas on curves' upstream and downstream. Each curve has the 100-feet buffer areas from the curve to the distance of 1900 feet from the PT / PC of the curve. Then the crashes that occurred on the roadways were also assigned to these buffer areas and considered the crashes on buffers.

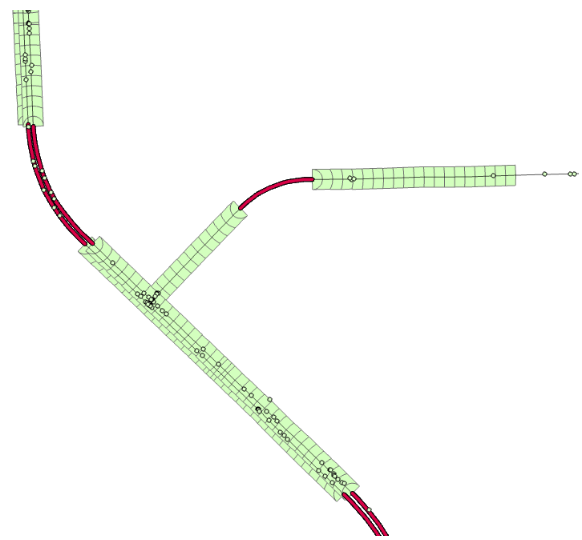


Figure 4- 1 Example of crashes on curves and crashes on buffers

Crashes on the curve could be assigned to both their physical and functional areas. The functional area is larger than the physical area and includes only the curve-related crashes such as run-off-road, head-on, sideswipe, and rollover. Crashes on curves were aggregated to physical curve area and different buffers to address functional curve area. The concept of functional curve area is not well understood, and no references were found in the literature. We consider that curve-related crashes could affect a longer length than curve boundaries for this study. Although this buffer length can vary depending on the traveling speed and distance between PC and PT, we tried to have a fixed buffer length where only the curve-related crashes were considered. Also, intersection-related crashes within the extended buffer area were excluded from the analysis since they could not be considered curve-related.

Historical crash data from 2015 to 2020 were addressed in the analysis. The distribution of the number of crashes inside the buffer is shown in Figure 6. It can be noticed that more than 200.000 crashes happened within curve boundaries.

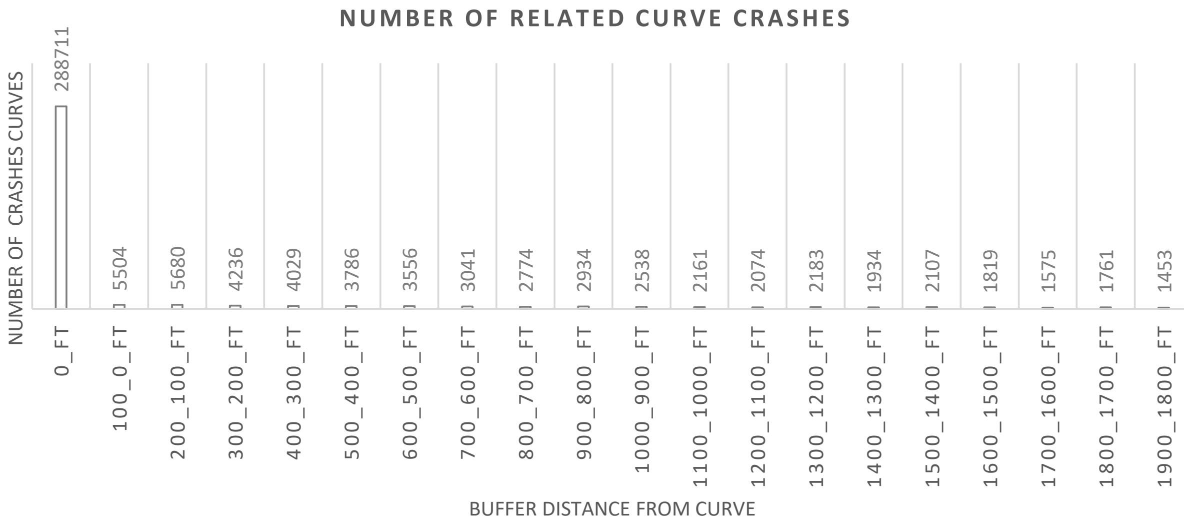


Figure 4- 2 Crashes on curve area and curve related crashes on buffers

The distribution of crashes that are distant from the physical curve area is shown in Figures 4-3. To identify functional curve area, we have employed the Kmeans clustering method. Using the mentioned clustering method, buffers until 600 ft could be grouped to curve.

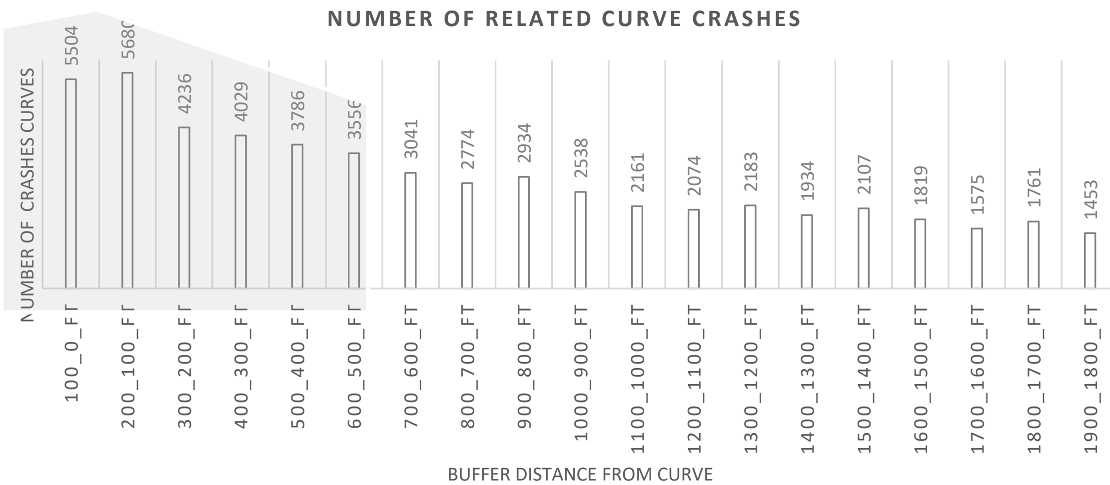


Figure 4- 3 Curve related crashes distribution by buffer areas

4.1 Number of total crashes on curves by county

The number of crashes on curves by count and the number of curves that presented crashes, revealed that some counties as Broward, Duval, Miami Dade, and Palm Beach have a high number of crashes on curves (Figure 4-4). Although Orange County has a significant number of crashes, it can be justified by the high number of curves, among other factors.

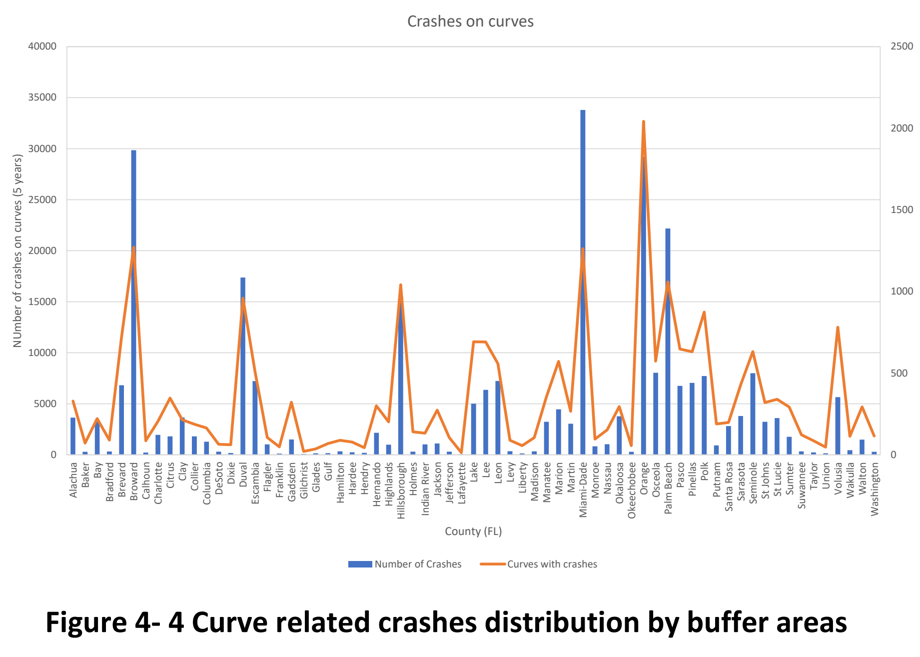


Figure 4- 4 Curve related crashes distribution by buffer areas

4.2 Severity level of crashes on curves

The investigation of crash severity on curves shows that around 28% are fatal-injury (FI) crashes. Figure 4-5 shows crashes on curves by severity level.

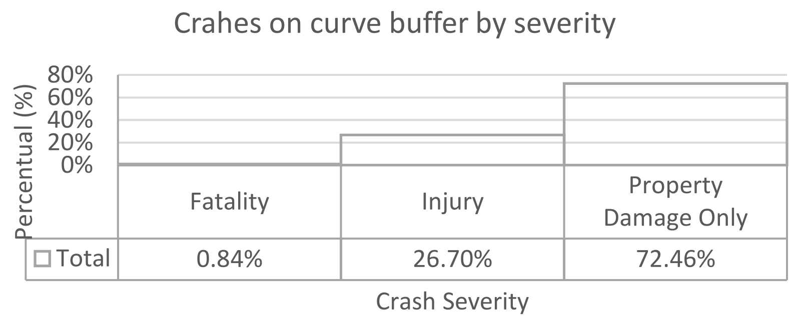


Figure 4- 5 Curve related crashes distribution, including buffer areas by severity

4.3 Crash types on curves

Crashes on curves were addressed under two perspectives: 1) Crashes physically on curves; 2) Crashes on the buffer area. We considered all crashes on the physical curve area for the first part. For the second one, only the related crashes Head-on, Sideswipe, Run-off-road, and Rollover were considered.

The combination of crashes on curves and related crashes in the buffer area produced the following profile (Figure 4-6). It can be noticed that rear-end crashes are relevant on curves. Further investigation about the number of curves within intersection should be done to understand this profile better.

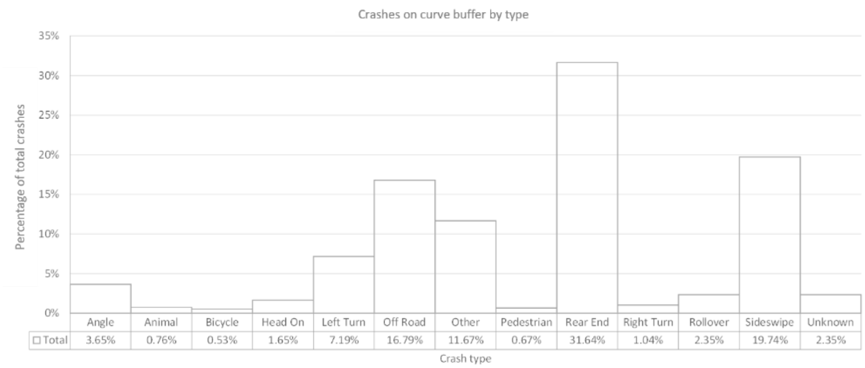


Figure 4- 6 Curve related crashes distribution, including buffer areas by type

4.4 Crashes on intersections

Since some intersections can be close enough or within curve limits, an examination whether we should include crashes in intersections was performed. All crashes outside the physical curve area that have an intersection were excluded from curve analysis. It can be noticed that one-third of the crashes within the boundary of curves happened in a curve with an intersection.

4.5 Crashes by functional road class

The distribution of crashes on curves by functional road classes can be found in Figure 4-7. A higher number of crashes occurred on roads where there is a combination of the high volume of traffic movement and moderate speeds between neighborhoods.

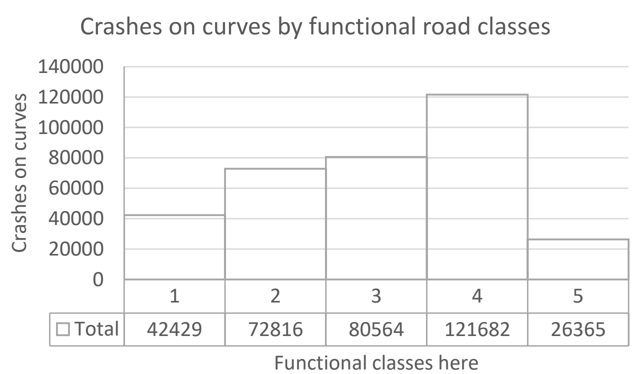


Figure 4- 7 Curve related crashes distribution including buffer areas by road classes

4.6 Crashes on curves by speed limits

The distribution of crashes on curves by speed category can be found in Figure 4-8. Despite the fact that there are more curves in the speed limit category 5, in category 4 there are more crashes.

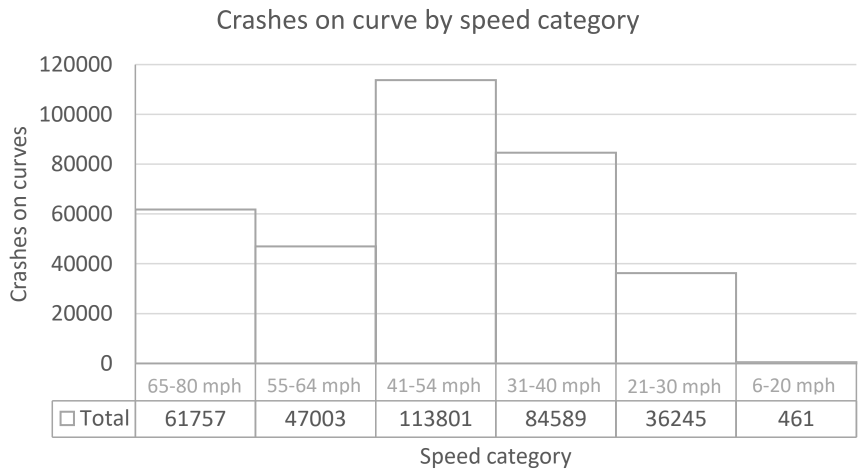


Figure 4- 8 Curve related crashes distribution, including buffer areas by speed category

4.7 Summary

Several aspects of curve variables were investigated in this task. Given that the curves are the fundamental data elements of this research, we worked to determine the curves data set limitations and accuracy for further safety analysis. Assessment of the accuracy of the existing curves using manual inspection and automated methods was provided.

After quality checks and curve inspection, some conservative exclusion criteria were selected. Curves with missing parameters, curves with a radius above 8,000 m, and curves with GOF less than 0.5 were excluded from the dataset in order to avoid bias or misprediction.

The research team conducted a review of the safety curves in Florida and developed descriptive statistics to address the profile by type and different severity levels of curve-related crashes. The curve safety performance was analyzed by County, by functional road class, speed limit, area type, relation to the intersection, and other variables.

A preliminary dataset for the development of SPFs was the result of this task, which served as the foundation for the SPF development in this research.

5 CURVE SAFETY RISK FACTORS

In this study, the research team has included more than 40 risk factors to be analyzed in the development of curve SPFs based on the previous curve safety studies. These risk factors can be categorized as curve characteristics, traffic volume, roadway characteristics, spatial relation to curves, and an intersection. If there are intersections on the curve, the intersection characteristics are also considered risk factors. The curve characteristics are the variables related to curves. The traffic volume is about the annual average daily traffic. The roadway characteristics are the variables associated with the roadway facilities. The spatial relation to curve and intersection is about the spatial relationship of the curve to its nearest other roadway elements. Below is a detailed list of risk factors included in the study.

5.1 Curve set for developing SPF

Based on the previous sections, we decided to exclude curves we found that cannot produce a good estimation from the set. The selected exclusion criteria were:

- Curves with missing parameters: for some curves, the algorithm could not calculate radius and length.
- Very large radius curves (radius above 8000 m): these curves behave actually as tangents. They have a slight variation in the alignment direction.
- Curves with GOF inferior to 0.5: the measurement of how well the curve polyline was fitted to a theoretical circular arc of 0.5 indicates that half curve is different from a circular arc.

After implementing these criteria, 920 over 40864 records were excluded from the curve set. In the new set of 39,944 curves, 13,649 have dual centerlines, of which 5613 are part of 9101 curves in the state highway system.

The exclusion criteria were chosen in order to be as conservative as possible and still have a large sample. We acknowledge that more restrictive measures may be considered in the next steps of this project.

5.2 Curve characteristics

The curve characteristic risk factors, such as radius, curve length, and central angle, are present in almost all the curve SPF literature. These variables mostly differentiate a curve segment from a tangent segment on the roadway network. The significant effects of curve characteristics variables indicate the importance of developing curve-specific SPFs, versus using the general SPFs based on tangent roads.

Radius

As we presented in the literature review, curves with a smaller radius tend to be more prone to crashes for all types and severity levels. To describe the Florida sample and understand possible limitations, a distribution of Radii was investigated (Figure 5-1).

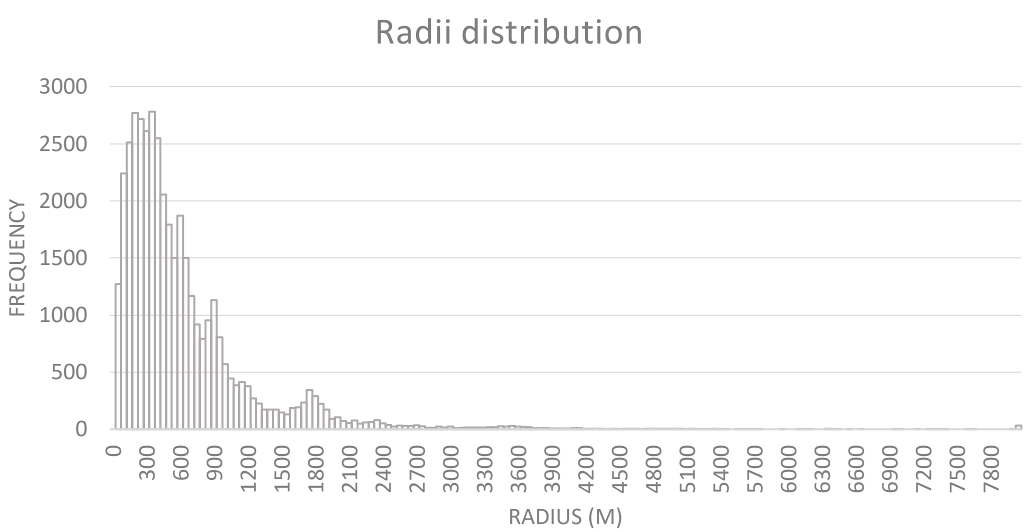


Figure 5- 1 Radii distribution of curves obtained by automated algorithm

It can be noticed that most curves have a radius smaller than 1000 meters. Few curves (8.6%) are very sharp, with a radius inferior to 100 meters. We investigated Radius calculation, and we found

313 missing values and 32 curves with a radius superior to 8000 meters over 40,864 curves. Most of these issues are due to poor digitalization of the GIS base map or a slight variation in a route direction. Since these curves could generate a bias-in-fit for SPF, they were excluded from the final set.

Curve length

In our previous literature review, we found that a longer curve would be more susceptible to having a higher number of crashes. In a few cases, the curve length showed an opposite impact on the SPFs. The data set distribution is shown in Figure 5-2.

All curves were treated as simple singular curves due to the complexity of using a single automated method to find spiral transitions. Generally, spiral transition is used in shorter radius curves to gradually change curvature from a straight segment.

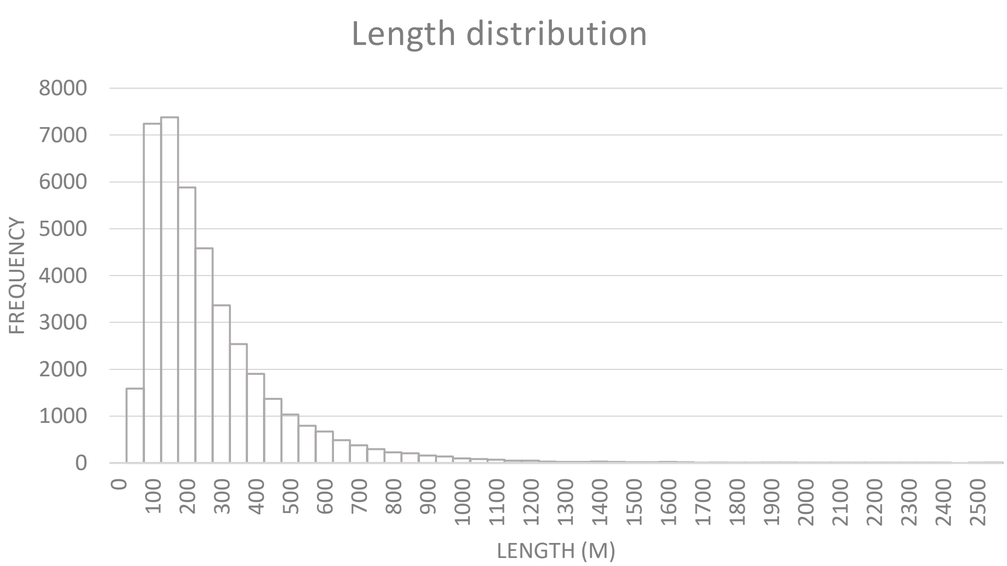


Figure 5- 2 Length distribution of curves obtained by the automated algorithm

Quality of GIS database digitalization

To assess the quality of the identified curves and curve components, we developed *goodness of fit* (GOF) metric to measure how well the curve polyline was fitted to a theoretical circular arc (see description in the previous report of task 2, chapter 2). The distribution of the GOF in the studied set can be seen in Figure 5-3. Since poor digitalization can impact the quality of SPF, values below 0.5 were excluded from the final curve set.

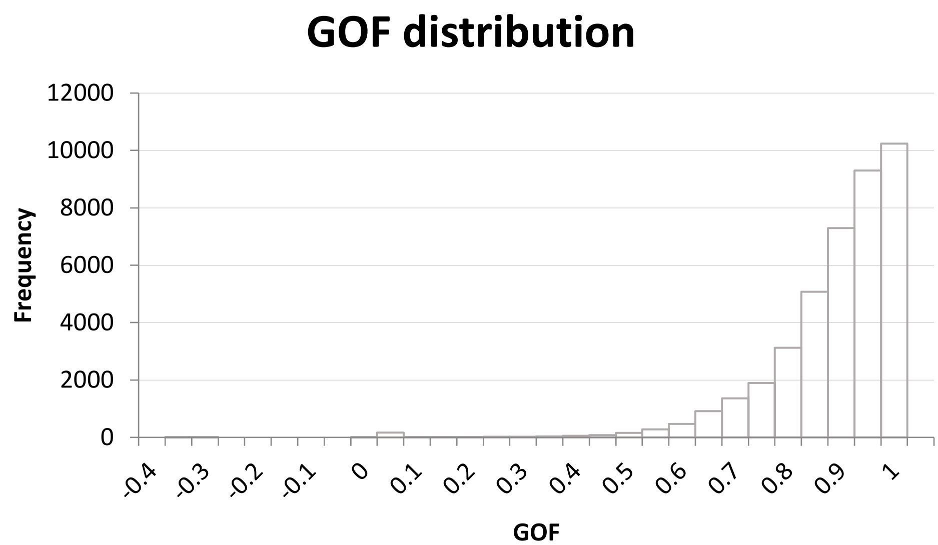


Figure 5- 3 GOF distribution of curves obtained by an automated algorithm

5.3 Traffic volumes

Traffic volume is the primary factor in the SPF calculation presented in the federal highway safety manual (HSM). AADT should be included in all SPFs, and it is found significantly positive, indicating that a larger AADT would have a higher crash frequency.

5.4 Roadway characteristics

The risk factors related to roadway characteristics include functional classification, speed, number of lanes, whether the curve is on the state highway system, and the FDOT District where the curve is located.

The roadway characteristic variables include functional classification, speed, number of lanes, traffic variable, and another spatial factor.

Lane

The distribution of the number of lanes of Florida studied curves revealed that most curves were found in two-way roads (Table 5-1). For a few curves, the information was not provided in the network.

Table 5- 1 Number of lanes in the Florida data set

Number of Lanes	% of curves
1	5.80%
2	83.99%
3	6.60%
4	3.19%
5	0.24%
6	0.17%
<Null>	0.02%
Grand Total	**100.00%**

Functional classification

Only a few researchers explored the variable of functional classification. They concluded that rural minor arterial and the principal rural arterial are more prone to crashes. To have this variable in our analysis, we investigate the functional classification distribution in the Florida data set (Table 5-2).

Table 5- 2 Functional classifications in the Florida data set

Functional Class	Description	% Number of curves
1	Roads allow for high volume, maximum speed traffic movement between and through major metropolitan areas	1.98%
2	Roads are used to channel traffic to Functional Class = 1 road for travel between and through cities in the shortest amount of time.	6.23%
3	Roads that interconnect Functional Class = 2 roads and provide a high volume of traffic movement at a lower level of mobility than Functional Class = 2 roads.	11.95%
4	Roads which provide for a high volume of traffic movement at moderate speeds between neighborhoods. These roads connect with higher functional class roads to collect and distribute traffic between neighborhoods.	46.11%
5	Roads whose volume and traffic movement are below the level of any functional class. In addition, walkways, the truck only roads, bus-only roads, and emergency vehicle-only roads receive Functional Class = 5.	33.73%
Grand Total		**100.00%**

Speed

Speed is a critical variable in curve SPFs. The speed distribution in the Florida curve data set is presented in Table 5-3. In most curves, a speed above 30 mph is allowed, which potentially have an impact on crashes.

Table 5- 3 Speed category in Florida data set

Speed category	Description	% Number of curves
2	65-80 MPH	4.44%
3	55-64 MPH	14.13%
4	41-54 MPH	22.33%
5	31-40 MPH	35.32%
6	21-30 MPH	23.11%
7	6-20 MPH	0.67%
Grand Total		**100.00%**

Dual Centerlines

As mentioned in Chapter 3, the GIS base map network is a combination of single and dual centerlines. To indicate whether the curve is on the dual centerlines or not, an attribute named "Dual" is created in the curve dataset. 13648 of the 39944 curves are dual center line curves.

5.5 Spatial relation to the curve

The previous curve safety studies have included the spatial relationship of a curve to the adjacent curves in the curve SPFs. In this study, the research team calculates the distance from any curve to its adjacent curves in both travel directions. See Figure 5-4 to 5-7. Figure 5-5 shows an example of a curve with neither side of the target curve has an adjacent curve within 600 ft; Figure 5-6 shows an example of a curve with only one side of the target curve has an adjacent curve within 600 ft; Figure 5-7 shows an example of a curve with both sides of the target curve have an adjacent curve within 600 ft. The curve characteristics of the adjacent curves, such as the radius, curve length, and central angle, are also considered as the risk factors in the curve SPFs.

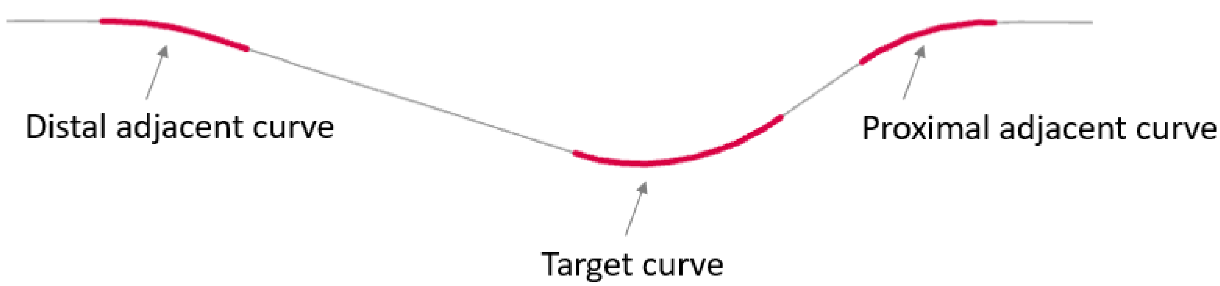


Figure 5- 4 Example of spatial relation to curves

- Example of curve relationship with its adjacent curves (the risk factor *cur_dist_600ft*)

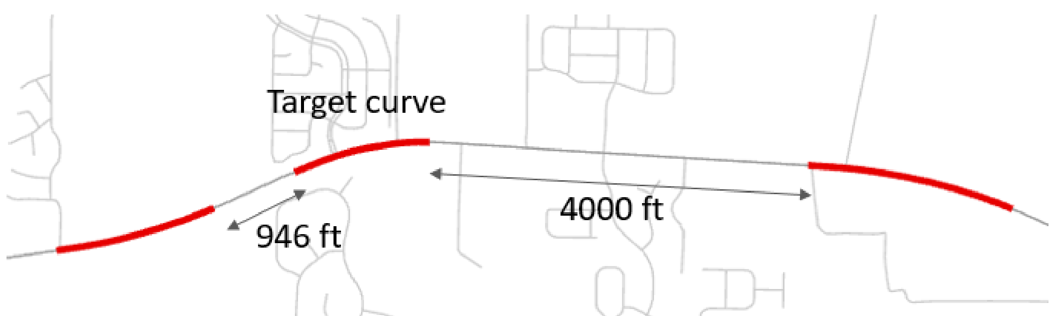


Figure 5- 5 Neither side of the target curve has an adjacent curve within 600 ft

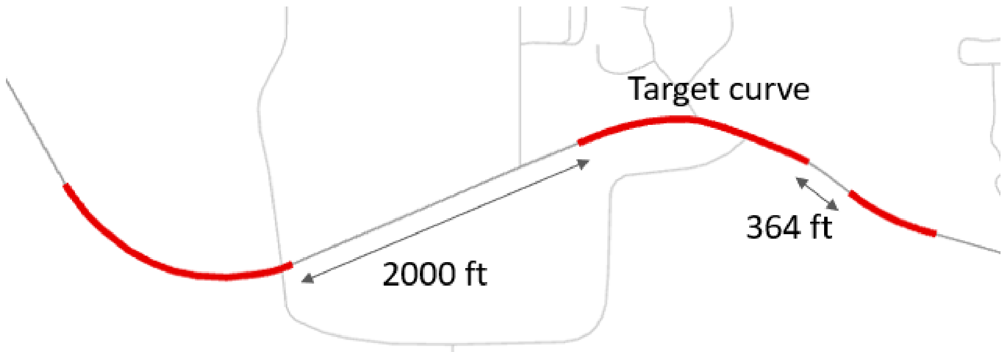


Figure 5- 6 Only one side of the target curve has an adjacent curve within 600 ft

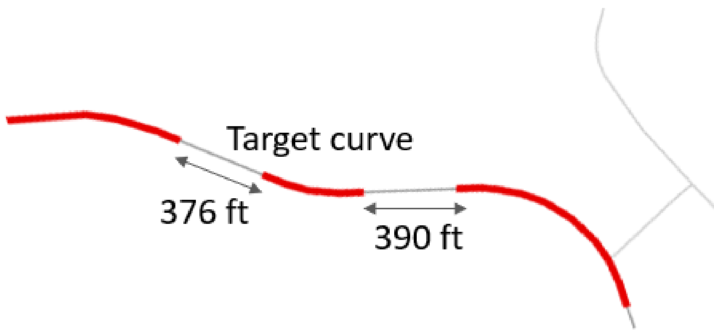


Figure 5- 7 Both sides of the target curve have an adjacent curve within 600 ft

5.6 Spatial relation to intersection

Similar to the spatial relation to the curve, we measure the distance from the curve to its adjacent intersections on both travel directions. See Figure 5-8 to 5-17. Figure 5-9 shows an example of a curve with neither side of the target curve has an adjacent intersection within 600 ft; Figure 5-10 shows an example of a curve with only one side of the target curve has an adjacent intersection within 600 ft; Figure 5-11 shows an example of a curve with both sides of the target curve have an adjacent intersection within 600 ft; Figure 5-12 shows an example of a curve with only one side of the target curve has an adjacent intersection within 600 ft, and the intersection does not have a signal; Figure 5-13 shows an example of a curve with only one side of the target curve have an adjacent intersection within 600 ft, and the intersection has a signal; Figure 5-14 shows an example of a curve with both sides of the target curve have an adjacent intersection within

600 ft, neither intersection has a signal; Figure 5-15 shows an example of a curve with both sides of the target curve have an adjacent intersection within 600 ft, and only of them has a signal; Figure 5-16 shows an example of a curve with both sides of the target curve have an adjacent intersection within 600 ft, and both of them have a signal. The intersection characteristics of the adjacent intersections, such as the number of approaches, the shape, whether it is the main intersection, whether it is on the state highway system, and whether it has a signal, stop sign, or yield sign, are also included in the consideration as the risk factors in the curve SPFs.

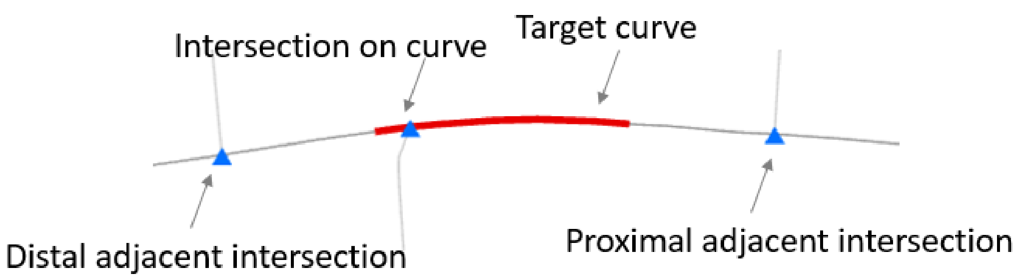


Figure 5- 8 Spatial relation to intersection example

- Example of curve relationship to its adjacent intersections (the risk factor *int_dist_600ft*)

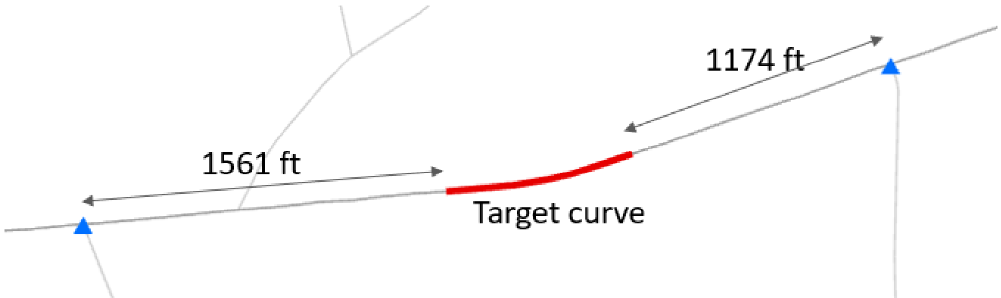


Figure 5- 9 Neither side of the target curve has an adjacent intersection within 600 ft

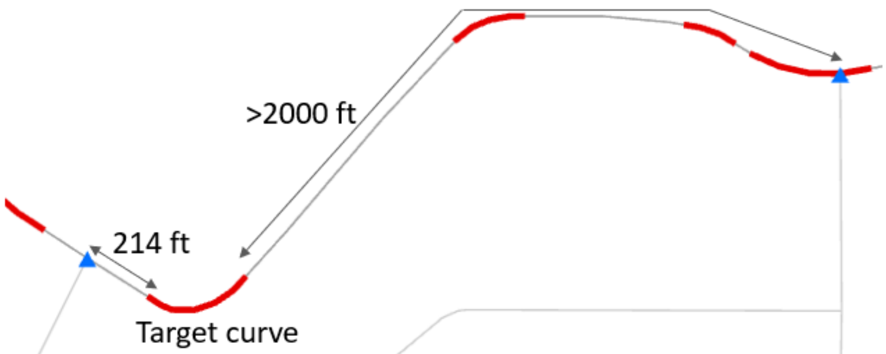


Figure 5- 10 One side of the target curve has an adjacent intersection within 600 ft

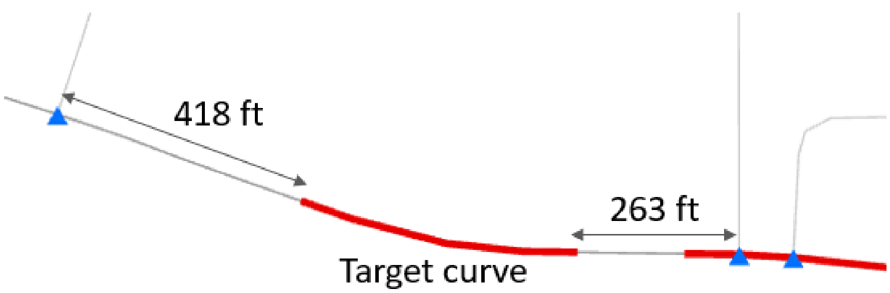


Figure 5- 11 Both sides of the target curve have an adjacent intersection within 600 ft

- Example of curve relationship with its adjacent signalized intersections (the risk factor *int_signal_dist_600ft*)

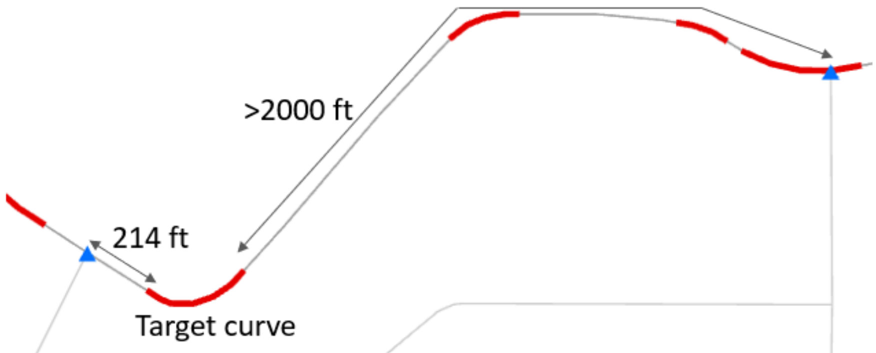


Figure 5- 12 One side of the target curve has an adjacent intersection within 600 ft, and the intersection does not have a signal

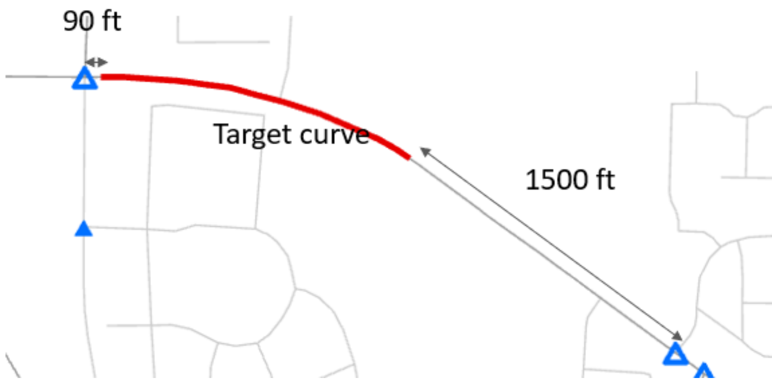


Figure 5- 13 One side of the target curve has an adjacent intersection within 600 ft, and the intersection has a signal

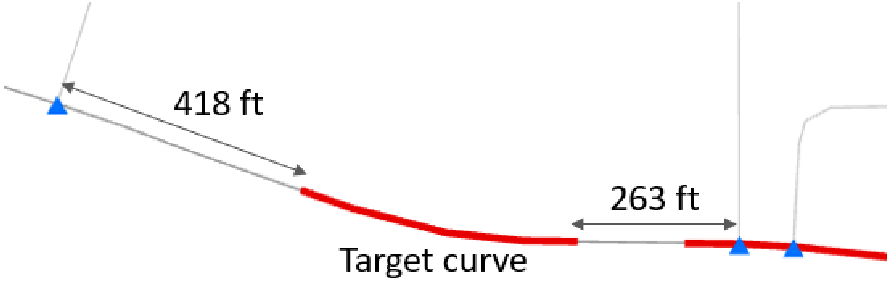


Figure 5- 14 Both sides of the target curve have an adjacent intersection within 600 ft, neither intersection has a signal

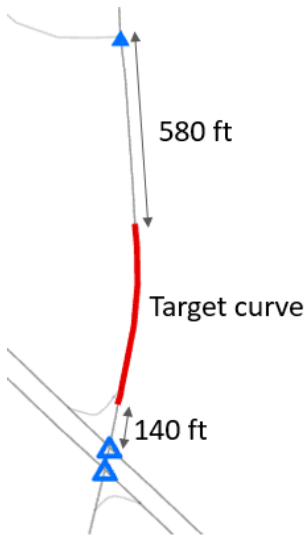


Figure 5- 15 Both sides of the target curve have an adjacent intersection within 600 ft, and only of them has a signal

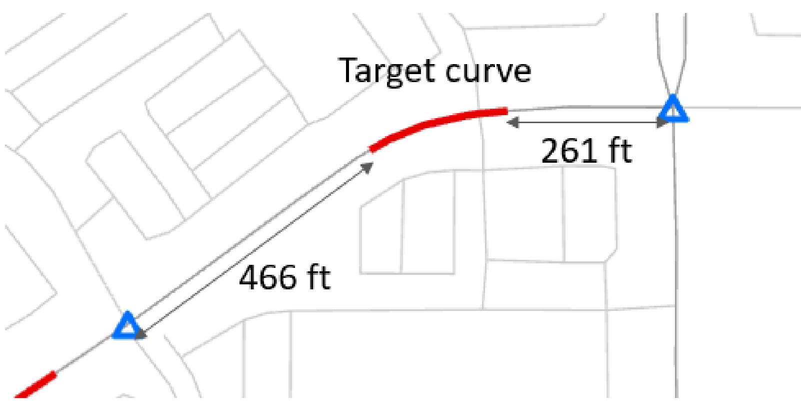


Figure 5- 16 Both sides of the target curve have an adjacent intersection within 600 ft, and both of them have a signal

5.7 Intersection on curve

If there are intersections on a curve, the intersection characteristics are also considered risk factors.

5.8 Summary of risk factors

Below is the table showing all the risk factors obtained in this study.

Table 5- 4 A summary of risk factors in developing the curve SPFs

Category		Risk factor	Symbol
Curve characteristics		Radius	cur_rad_log
		Central angle	cur_ang_log
		Curve length	cur_len_log
Traffic volume		AADT 6-year average	aadt_avg_log
Roadway characteristics		Functional classification	roa_func
		Speed category	roa_speed
		Number of lanes	roa_lane
		State highway system	roa_shs
		District	roa_dist
Spatial relation to adjacent curves	Proximal	Distance from the curve to the next curve	*cur_dist_short_log***
		Whether there is another curve within 600 feet from the curve	*cur_dist_short_600ft***
		Radius of the nearest curve	*cur_rad_short_log***
		Central angle of the nearest curve	*cur_ang_short_log***
		Curve length of the nearest curve	*cur_len_short_log***
	Distal	Distance from the curve to the next curve	*cur_dist_long_log***
		Whether there is another curve within 600 feet from the curve	*cur_dist_long_600ft***
		Radius of the nearest curve	*cur_rad_long_log***
		Central angle of the nearest curve	*cur_ang_long_log***
		Curve length of the nearest curve	*cur_len_long_log***
	Both	Average distance between curve to its next curves	*cur_dist_avg_log***
		0 – none side of the target curve has an adjacent curve within 600 ft	cur_dist_600ft*
		1 – one side of the target curve has an adjacent curve within 600 ft	
		2 – both sides of the target curve have an adjacent curve within 600 ft	
Spatial relation to adjacent intersections	Proximal	Distance from the curve to the next intersection	*int_dist_short_log***
		Whether there is an intersection within 600 feet from the curve	*int_dist_short_600ft***
		Intersection number of legs	*int_leg_short***
		Intersection shape	*int_shape_short***
		Intersection angle	*int_ang_short***
		Whether the nearest intersection is a main intersection	*int_main_short***
		Whether the nearest intersection is on SHS	*int_shs_short***
		Whether the nearest intersection has signal	*int_signal_short***
		Whether the nearest intersection has stop sign	*int_stop_short***
		Whether the nearest intersection has yield sign	*int_yield_short***
	Distal	Distance from the curve to the next intersection	*int_dist_long_log***
		Whether there is an intersection within 600 feet from the curve	*int_dist_long _600ft***
		Intersection number of legs	*int_leg_long***
		Intersection shape	*int_shape_long***
		Intersection angle	*int_ang_long***
		Whether the nearest intersection is a main intersection	*int_main_long***
		Whether the nearest intersection is on SHS	*int_shs_long***
		Whether the nearest intersection has signal	*int_signal_long***
		Whether the nearest intersection has stop sign	*int_stop_long***
		Whether the nearest intersection has yield sign	*int_yield_long***
	Both	Average distance from the curve to its next intersections	*int_dist_avg_log***
		0 – none side of the target curve has an adjacent intersection within 600 ft	int_dist_600ft*

		1 – one side of the target curve has an adjacent intersection within 600 ft	
		2 – both sides of the target curve have an adjacent intersection within 600 ft	
		0 – none side of the target curve has an adjacent intersection within 600 ft	int_sign_dist_600ft*
		10 – one side of the target curve has an adjacent intersection within 600 ft, and the intersection has no control (signal/stop sign/yield sign)	
		11 – one side of the target curve has an adjacent intersection within 600 ft, and the intersection has control (signal/stop sign/yield sign)	
		20 – both sides of the target curve have an adjacent intersection within 600 ft, and both intersections have no control (signal/stop sign/yield sign)	
		21 – both sides of the target curve have an adjacent intersection within 600 ft, and only one side intersection has control (signal/stop sign/yield sign)	
		22 – both sides of the target curve have an adjacent intersection within 600 ft, and both sides intersections have control (signal/stop sign/yield sign)	
		0 – none side of the target curve has an adjacent intersection within 600 ft	int_signal_dist_600ft*
		10 – one side of the target curve has an adjacent intersection within 600 ft, and the intersection doesn't have a signal	
		11 – one side of the target curve has an adjacent intersection within 600 ft, and the intersection has a signal	
		20 – both sides of the target curve have an adjacent intersection within 600 ft, and both intersections don't have a signal	
		21 – both sides of the target curve have an adjacent intersection within 600 ft, and only one side intersection has a signal	
		22 – both sides of the target curve have an adjacent intersection within 600 ft, and both sides intersections have a signal	
Interactive spatial relation to adjacent curves and intersections		Within 600 feet, there is no intersections nor curves	*int_cur_near_dist_short*** *int_cur_near_dist_long***
		Within 600 feet, there is only curve, no intersection	
		Within 600 feet, there is only intersection no curve	
		Within 600 feet, there are curve and intersection, curve is closer	
		Within 600 feet, there are curve and intersection, intersection is closer	
		Within 600 feet, there are curve and intersections, curve and intersection with the same distance	
One intersection on curve		Intersection number of legs	int_leg_on
		Intersection shape	int_shape_on
		Intersection angle	int_ang_on
		Whether the intersection on curve is a main intersection	int_main_on
		Whether the nearest intersection is on SHS	int_shs_on
		Whether the nearest intersection has signal	int_signal_on
		Whether the nearest intersection has stop sign	int_stop_on
		Whether the nearest intersection has yield sign	int_yield_on
Multiple intersections on curve		Number of intersections on curve	int_cnt_on
		Number of 3-leg intersections on curve	int_leg3_on
		Number of 4-leg intersections on curve	int_leg4_on
		Number of 5 or more leg intersections on curve	int_leg5_on
		Number of 90-degree intersections on curve	int_shape90_on
		Number of non-90-degree intersections on curve	int_shape91_on
		Number of main intersections on curve	int_main_on
		Number of SHS intersections on curve	int_shs_on
		Number of intersections with signal	int_signal_on
		Number of intersections with stop sign	int_stop_on
		Number of intersections with yield sign	int_yield_on

* We analyzed different distances between the curve and its adjacent curves or intersections, such as 600 feet, 1000 feet, 0.5 miles, and 1 mile. For example, the factor *cur_dist_600ft* means spatial relationship is within 600 feet. *cur_dist_1000ft* means the analyzing distance is 1000 feet; *cur_dist_05mi* means the analyzing distance is 0.5 miles; *cur_dist_1mi* means the analyzing distance is 1 mile.

** These are the factors that we initially explored when developing the SPFs but were not included in the final SPFs. While these factors could help increase the ability of model prediction, they also made the interpretation of the factor effects difficult. Therefore, these are currently excluded from the final models. An exploration of the tradeoff between predictive accuracy and interpretability is identified as an area of future research.

6 METHOD FOR DEVELOPING THE SAFETY PERFORMANCE FUNCTIONS

The curve SPF is a statistical model to predict the number of crashes on curves, which is used to describe the relationships between the crashes on curves associated with various contributing factors, including the characteristics of curve geometry, the attributes of roadways, traffic volume, spatial relationships with adjacent curves or intersections, and other factors. The risk factors listed in Table 1 are used to develop curve SPFs. The crash data used in this research was obtained from Signal Four Analytics. The research team adopted the negative binomial (NB) regression as outlined in the HSM as the method for the development of curve SPFs.

The HSM suggests the development of the SPF for a roadway segment using the following formula:

$$\mu_i = e^{\beta_0} * L * AADT^{\beta_1}$$

where $\mu_i =$ expected number of crashes on roadway segment i;

L = roadway segment length;

AADT = average annual daily traffic;

$\beta_0 =$ coefficient of the intercept;

$\beta_1 =$ coefficient for AADT.

The HSM manual also suggests that the SPF can take a different form by including more risk factors:

$$\mu_i = e^{\beta_0} * L * AADT^{\beta_1} * e^{(\beta_3 X_3 + \ldots + \beta_p X_p)}$$

where $X_2, \ldots, X_n =$ value of the jth explanatory variable for the roadway segment i ($j = 3, \ldots, p$);

$\beta_2, \ldots, \beta_n =$ coefficient of the jth explanatory variables ($j = 3, \ldots, p$).

Since we consider more than 40 risk factors for curve SPF development in this study, a more efficient method to screen the factors and select the most relevant factors included in the SPFs needs to be developed. To accomplish this, we start by adopting a conditional random forests regression model that continually searches for the links between response variables (crash counts) and the explanatory variables (risk factors). Also, we use the stepwise variable selection and shrinkage method to select the factors with the most impact on the response variables.

Conditional random forests

The random forest method is a vigorous tree-based method, simple and useful for interpretation. The R package *party* was used to perform the modeling. Initially, all the explanatory variables were included in the SPF modeling. Then, based on the variable importance measurements report, a subset of variables with a larger %IncMSE were selected.

Stepwise selection

The best subset selection went through every possible combination of all the explanatory variables and obtained the SPF with the cross-validated and other criteria, including AIC and adjusted R^2.

Shrinkage method

The shrinkage method with variable selection is a powerful method to stabilize the regressions and select variables. Some coefficients of the explanatory variables would be shrunken towards or exactly to zero. This is how the method performs the variable selection. The way the shrinkage method estimated the coefficients of variables is as the following, adding a penalty term:

$$\sum_{i=1}^{n}\left(\log(\mu_i) - \beta_0 - \sum_{j=1}^{p}\beta_j X_{ij}\right)^2 + \lambda\sum_{j=1}^{p}\hat{\omega}_j|\beta_j|.$$

, where λ= the tuning parameter chosen through the cross-validation;

$\hat{\omega}$ = the adaptive weights.

The R package *glmnet* was used to minimize the above quantity.

The variables selected by one of the three screening methods were considered potential explanatory variables and were tested using the negative binomial regression. If the variable shows the statistical significance at $p < 0.05$ level, then the variable was included in the curve SPF development. If the variable is not selected through the screening methods, then it is not considered a risk factor. Ultimately, we choose the final SPFs for each curve category based on the Akaike Information Criterion (AIC).

7 CURVE SAFETY PERFORMANCE FUNCTIONS

The curves on state-maintained roads are categorized into 12 groups based on the area type, the travel directions, and the relation with intersections. Table 2 presents the summary of the 12 curve categories. Note that not all the curves in the dataset include a valid AADT. Therefore, we only use the curves with a valid AADT for modeling the SPF. The AADT we used is the average value of the AADT from 2015 to 2020.

For each curve category, the research team analyzes the total crashes, the fatal and injury crashes (KABC), and fatal and severe injury crashes (KA). Crashes on the curve can be assigned to both their physical and functional areas, as mentioned in the Task 3 report. The functional area is larger than the physical area and includes only curve-related crashes such as run-off-road, head-on, sideswipe and rollover. We developed a Kmeans clustering method to identify the functional curve area, which is defined as the area with a buffer distance (such as 600 feet) of a curve. Crashes on curves (within curve boundaries) were aggregated to physical curve area. All crashes on the physical area are included.

The crashes that happened on a curve (physical area) and those that occurred within 600 feet of a curve (functional area) are compared during the development of the SPFs.

Table 7- 1 A summary of curve categories in each SPF model

SPF Model	Urban/Rural	Single/Dual centerline	Intersection	Query	Sample size	with AADT	%
1	urban	single	no int	Double IS NULL And Urban = 'Y' And Num_Int = 0	5972	5152	86%
2	urban	single	1 int	Double IS NULL And Urban = 'Y' And Num_Int = 1	4468	4137	92%
3	urban	single	multiple int	Double IS NULL And Urban = 'Y' And Num_Int > 1	2274	2132	94%
4	urban	dual	no int	Double = 'Y' And Urban = 'Y' And Num_Int = 0	5458	5366	98%
5	urban	dual	1 int	Double = 'Y' And Urban = 'Y' And Num_Int = 1	4562	4506	99%
6	urban	dual	multiple int	Double = 'Y' And Urban = 'Y' And Num_Int > 1	2139	2114	99%
7	rural	single	no int	Double IS NULL And Urban IS NULL And Num_Int = 0	9686	5399	56%
8	rural	single	1 int	Double IS NULL And Urban IS NULL And Num_Int = 1	3073	2261	74%
9	rural	single	multiple int	Double IS NULL And Urban IS NULL And Num_Int > 1	823	723	88%
10	rural	dual	no int	Double = 'Y' And Urban IS NULL And Num_Int = 0	951	946	99%
11	rural	dual	1 int	Double = 'Y' And Urban IS NULL And Num_Int = 1	389	386	99%
12	rural	dual	multiple int	Double = 'Y' And Urban IS NULL And Num_Int > 1	148	148	100%
Total					39943	33270	83%

7.1 SPF for the curves that are in an urban area, on single centerlines, no intersections

This category of curves makes up about 15% of total curves. Most curves are on low-speed roads (less than 40 mph). Curve characteristics make a significant contribution to crashes. The length of the curves, and the sharper curve radius, will significantly increase the crashes on curves. Roadway characteristics and traffic volume, such as the number of lanes, consistently increase the crash frequency. More lanes can result in more crashes on curves. The functional classification and speed on roadways also have a significant impact, such as major roads with higher speed limits have more crashes than minor and lower speed roads. The FDOT District of the curve location also makes significant contributions, such as District 5 mostly has more crashes and District 7 has fewer crashes. For the spatial relation to adjacent curves and intersections, the adjacent curves will decrease the crash counts. In contrast, the adjacent intersections will increase the total crash counts and reduce the possibility of fatal and severe injury crashes.

Table 7- 2 SPF models for the curves in the urban area, on single centerlines, no intersections

Risk factors	Levels	Data desc	Total crashes		Total crashes within 600ft buffer		Fatal and injury crashes		Fatal and injury crashes within 600ft buffer		Fatal and serious injury crashes		Fatal and serious injury crashes within 600ft buffer	
			Number of crashes											
			11393		15557		3372		477		634		875	
			Coef	Sig.[1]	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.
(Intercept)	--	--	-5.45	***	-4.13	***	-5.91	***	-4.04	***	-5.14	***	-3.31	***
AADT_avg_log	--	8.67	0.57	***	0.56	***	0.55	***	0.49	***	0.39	***	0.35	***
roa_lane	3	9.03%	0.54	***	0.67	***	0.52	***	0.48	***	0.40	**	0.49	***
roa_func	4	56.81%	-0.27	**	-0.34	***	-0.11		-0.14	.	-0.12		-0.13	
	5	35.50%	-0.48	***	-0.60	***	-0.38	**	-0.39	***	-0.55	**	-0.59	***
roa_dist	2	10.51%	0.04		0.12		0.19	.	0.18	.				
	3	6.89%	-0.08		-0.02		-0.13		-0.13					
	4	13.65%	-0.01		-0.01		-0.06		-0.12					
	5	32.08%	0.13	*	0.16	**	0.30	***	0.25	***				
	6	5.01%	0.08		0.19	*	-0.10		-0.08					
	7	15.90%	-0.22	**	-0.17	*	-0.04		-0.03					
roa_speed	4	18.69%					-0.01		-0.17	.	-0.15		-0.32	*
	5	31.35%					-0.16		-0.35	***	-0.41	*	-0.57	***
	6	44.08%					-0.40	**	-0.60	***	-0.73	***	-0.92	***
roa_shs	1	12.21%	0.18	*										
cur_len_log	--	4.81	0.58	***	0.41	***	0.57	***	0.38	***	0.61	***	0.34	***
cur_rad_log	--	5.51	-0.33	***	-0.30	***	-0.38	***	-0.33	***	-0.49	***	-0.38	***
cur_dist_600ft	1	46.10%	-0.20	***	-0.20	***	-0.26	***	-0.28	***	-0.35	***	-0.35	***
	2	19.62%	-0.25	***	-0.39	***	-0.32	***	-0.46	***	-0.33	*	-0.47	***
int_signal_dist_600ft	10	35.31%	0.26	***	0.04		0.12	.	-0.04				-0.07	
	11	5.94%	0.91	***	0.57	***	0.70	***	0.44	***			0.00	
	20	28.42%	0.20	***	-0.16	**	0.06		-0.24	***			-0.40	***
	21	5.07%	0.90	***	0.45	***	0.48	***	0.13				-0.57	**
	22	0.54%	1.03	***	0.60	**	0.70	*	0.33				-1.40	.

[1] Significant level: *** p<0.001; ** p<0.01; * p<0.05; * p<0.1

7.2 SPF for the curves that are in the urban area, on single centerlines, with one intersection

This category of curves makes up about 11% of total curves. The majority of curves are with a speed limit below 55 mph. Curve characteristics make a significant contribution to crashes. The length of the curves, and the sharper of the curve radius, will significantly increase the crash frequency on curves. Roadway characteristics and traffic volume, such as the number of lanes, consistently increase the number of crashes. More lanes can result in more crashes on curves. The speed on roadways only significantly impacts fatal and serious injury crashes. Lower speed roads (less than 30 mph) have a significantly smaller amount of fatal and serious injury crashes. The district of the curve location also makes significant contributions, such as Districts 2,3 and 6 have more total crashes, and Districts 5 and 7 have a larger number of fatal and serious injury crashes.

The characteristics of the intersection on the curve have some influence on crashes. Whether this intersection is the main intersection, is on state-highway-system, or has a signal, these characteristics will increase the crashes on a curve. Whether this intersection has a stop sign can increase the total crash counts and decrease the fatal and serious injury crashes. Whether this intersection has a yield sign can decrease the total crash counts.

For the spatial relation to adjacent curves and intersections, the adjacent curves will decrease the crash counts. The adjacent intersections on both sides of the curve will consistently decrease the crash counts. If there is any signalized control, it will decrease more crashes on the curve.

Table 7- 3 SPF models for the curves in the urban area, on single centerlines, with one intersection

Risk factors	Levels	Data desc	Total crashes		Total crashes within 600ft buffer		Fatal and injury crashes		Fatal and injury crashes within 600ft buffer		Fatal and serious injury crashes		Fatal and serious injury crashes within 600ft buffer	
			Number of crashes											
			37061		39499		10477		11082		1413		1524	
			Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.
(Intercept)	--	--	-3.74	***	-3.69	***	-5.21	***	-5.19	***	-5.70	***	-5.53	***
AADT_avg_log	--	8.78	0.57	***	0.57	***	0.56	***	0.57	***	0.45	***	0.46	***
roa_lane	3	13.08%	0.38	***	0.40	***	0.27	***	0.27	***	0.41	***	0.41	***
roa_dist	2	10.27%	0.16	*	0.21	**	0.15	.	0.19	*	-0.13		0.01	
	3	9.45%	0.23	**	0.23	***	0.15	.	0.14		-0.37	*	-0.29	.
	4	12.64%	0.14	*	0.12	.	-0.07		-0.08		-0.31	*	-0.26	.
	5	29.97%	0.11	.	0.11	*	0.28	***	0.27	***	0.23	*	0.25	*
	6	5.25%	0.53	***	0.54	***	0.17		0.18	.	0.06		0.17	
	7	17.04%	-0.06		-0.04		0.16	*	0.16	*	0.41	***	0.49	***
roa_speed	4	14.94%									-0.11		-0.21	
	5	34.98%									-0.25		-0.30	*
	6	46.05%									-0.57	***	-0.57	***
cur_len_log	--	4.94	0.42	***	0.41	***	0.48	***	0.46	***	0.42	***	0.39	***
cur_rad_log	--	5.62	-0.16	***	-0.15	***	-0.15	***	-0.14	***	-0.17	**	-0.17	**
int_main_on	1	17.21%	0.68	***	0.68	***	0.57	***	0.58	***	0.39	***	0.45	***
int_shs_on	1	24.34%	0.23	***	0.22	***	0.28	***	0.26	***	0.36	***	0.36	***
int_signal_on	1	6.94%	0.47	***	0.43	***	0.38	***	0.37	***	0.33	*		
int_stop_on	1	13.92%	0.17	**	0.14	**							-0.34	**
int_yield_on	1	0.92%	-0.55	**	-0.50	**								
int_leg_on	3	72.76%	-0.71	***	-0.66	***	-0.54	*	-0.48	*				
	4	24.39%	-0.22		-0.20		-0.07		-0.04					
	5	2.13%	-0.56	*	-0.52	*	-0.47	.	-0.44	.				
cur_dist_05mi	1	35.80%	-0.15	*	-0.15	*	-0.16	*	-0.16	*	-0.14		-0.14	
	2	56.18%	-0.37	***	-0.38	***	-0.44	***	-0.44	***	-0.37	**	-0.38	***
int_signal_dist_1000ft	10	20.72%	-0.23	**	-0.24	**	-0.18	*	-0.20	*	-0.12		-0.18	
	11	3.02%	-0.08		-0.10		-0.10		-0.12		-0.54	*	-0.52	**
	20	59.03%	-0.56	***	-0.59	***	-0.60	***	-0.64	***	-0.68	***	-0.75	***
	21	9.52%	-0.22	*	-0.25	**	-0.40	***	-0.44	***	-0.71	***	-0.70	***
	22	1.28%	-0.19		-0.21		-0.48	*	-0.53	**	-0.67	*	-0.71	*

7.3 SPF for the curves that are in the urban area, on single centerlines, with multiple intersections

This category of curves makes up about 6% of total curves. The majority of curves are between 20 mph and 55 mph. The length of the curves will significantly increase the crashes on curves. Radius barely significantly impacts total crashes and fatal and injury crashes. Roadway characteristics and traffic volume, such as the number of lanes, consistently increase crashes. More lanes can result in more crashes on curves. The functional classification and speed on roadways do not greatly impact crashes of all severity levels. Lower speed roads will have fewer fatal and severe injury crashes. The district of the curve location also makes significant contributions, such as District 6 has more crashes, District 7 has fewer crashes, and District 3 and 4 has fewer fatal and serious injury crashes.

The characteristics of the intersection on the curve have some influence on crashes. More intersections, more main intersections, and more signalized intersections on a curve will increase the crashes on a curve. The number of intersections with stop signs or yield signs will decrease the crash counts.

For the spatial relation to adjacent curves and intersections, the adjacent curves will decrease the crash counts. The adjacent intersections on both sides of the curve will consistently decrease the crash counts, and if there is any sign control, it will decrease more fatal and injury crashes on the curve.

Table 7- 4 SPF models for the curves in the urban area, on single centerlines, with multiple intersections

Risk factors	Levels	Data desc	Total crashes		Total crashes within 600ft buffer		Fatal and injury crashes		Fatal and injury crashes within 600ft buffer		Fatal and serious injury crashes		Fatal and serious injury crashes within 600ft buffer	
			Number of crashes											
			32459		33417		9376		9584		1224		1271	
			Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.
(Intercept)	--	--	-5.78	***	-5.51	***	-6.27	***	-6.15	***	-7.25	***	-6.09	***
AADT_avg_log	--	8.88	0.63	***	0.65	***	0.59	***	0.60	***	0.52	***	0.50	***
roa_lane	3	15.95%	0.39	***	0.43	***	0.35	***	0.34	***	0.30	**	0.29	**
roa_func	4	52.77%	-0.06											
	5	34.61%	-0.18	*										
roa_dist	2	10.23%	0.04		0.03						-0.27	.	-0.24	
	3	11.59%	0.09		0.10						-0.66	***	-0.55	***
	4	13.04%	0.02		0.00						-0.35	*	-0.22	
	5	27.72%	-0.04		-0.03						-0.14		-0.07	
	6	5.68%	0.69	***	0.65	***					-0.31		-0.21	
	7	15.95%	-0.25	**	-0.26	**					0.21		0.21	
roa_speed	4	16.84%	0.20										-0.24	
	5	36.73%	0.34	**									-0.54	**
	6	42.82%	0.29	*									-0.64	***
cur_len_log	--	5.48	0.44	***	0.39	***	0.45	***	0.44	***	0.51	***	0.44	***
cur_rad_log	--	6.03	-0.04		-0.04		-0.07	.	-0.07	.	-0.12	.	-0.14	*
int_main_on	--	0.26	0.34	***	0.35	***	0.21	***	0.22	***				
int_signal_on	--	0.09	0.49	***	0.48	***	0.49	***	0.47	***	0.36	***	0.42	***
int_stop_on	--	0.37									-0.19	***	-0.15	**
int_yield_on	--	0.01	-0.78	**	-0.66	*								
int_cnt_on	--	2.51	0.43	***	0.40	***	0.35	***	0.35	***	0.17	***		
int_leg3_on	--	1.88	-0.42	***	-0.39	***	-0.32	***	-0.32	***	-0.16	***		
int_leg4_on	--	0.47	-0.28	***	-0.24	***	-0.17	**	-0.18	**			0.14	**
int_leg5_on	--	0.02	-0.31	*										
cur_dist_1000ft	1	40.99%	-0.25	***	-0.25	***	-0.33	***	-0.34	***	-0.49	***	-0.43	***
	2	27.16%	-0.41	***	-0.42	***	-0.49	***	-0.51	***	-0.45	***	-0.35	**
int_sign_dist_600ft	10	21.53%	-0.10		-0.16	.	-0.13		-0.15					
	11	7.50%	-0.01		0.06		0.06		0.05					
	20	44.32%	-0.30	*	-0.31	***	-0.19	*	-0.24	**				
	21	8.96%	0.10		0.12		0.16		0.10					
	22	9.52%	-0.24		-0.24	*	-0.34	**	-0.39	**				

7.4 SPF for the curves that are in an urban area, on dual centerlines, no intersections

This category of curves makes up about 13% of total curves. About 20% of curves are on high-speed roads (greater than 55 mph). Curve characteristics make a significant contribution to crashes. The length of the curves, and the sharper curve radius, will significantly increase the crashes on curves. Traffic volume has a consistently positive impact on crashes. More lanes can result in more total crashes but not severe crashes. The functional classification also has significant impacts. Major roads have more crashes than minor roads. Speed impacts total crashes, such as lower-speed roads tend to have more crashes. The district of the curve location also makes significant contributions, such as Districts 4, 5, and 6 having more total crashes, while Districts 3 and 7 have fewer severe crashes. For the spatial relation to adjacent curves and intersections, the adjacent curves will decrease the crash counts. The adjacent intersections will increase the total crash counts and not significantly influence severe and fatal injury crashes.

Table 7- 5 SPF models for the curves in an urban area, on dual centerlines, with no intersections

Risk factors	Levels	Data desc	Total crashes		Total crashes within 600ft buffer		Fatal and injury crashes		Fatal and injury crashes within 600ft buffer		Fatal and serious injury crashes		Fatal and serious injury crashes within 600ft buffer	
			Number of crashes											
			33933		41162		8714		10487		1107		1415	
			Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.
(Intercept)	--	--	-10.31	***	-8.75	***	-11.57	***	-9.60	***	-9.32	***	-8.35	***
AADT_avg_log	--	9.20	1.02	***	0.98	***	1.07	***	1.01	***	0.78	***	0.78	***
roa_lane	2	62.80%	-0.05		-0.02									
	3	20.78%	0.24	*	0.32	***								
roa_func	3	16.62%	-0.67	***	-0.67	***	-0.51	***	-0.57	***	-0.39	**	-0.48	***
	4	50.84%	-0.89	***	-0.84	***	-0.68	***	-0.61	***	-0.55	***	-0.57	***
	5	15.93%	-0.98	***	-0.97	***	-0.76	***	-0.65	***	-0.88	***	-0.95	***
roa_dist	2	7.88%	0.54	***	0.55	***	0.26	**	0.28	**	-0.29	.	-0.20	
	3	4.68%	0.16		0.15	.	-0.06		-0.05		-0.48	*	-0.50	**
	4	17.61%	0.21	**	0.19	**	0.17	*	0.19	*	0.02		-0.02	
	5	34.33%	0.25	***	0.23	***	0.29	***	0.30	***	-0.13		-0.08	
	6	6.91%	0.45	***	0.38	***	-0.06		-0.11		-0.41	*	-0.52	**
	7	13.29%	-0.16	*	-0.14	*	-0.16	.	-0.09		-0.18		-0.11	
roa_speed	4	33.90%	0.31	***	0.25	***	0.12							
	5	29.87%	0.40	***	0.34	***	0.10							
	6	15.32%	0.71	***	0.60	***	0.44	**						
roa_shs	1	33.21%							0.12	*				
cur_len_log	--	5.34	0.66	***	0.50	***	0.60	***	0.46	***	0.74	***	0.54	***
cur_rad_log	--	6.27	-0.28	***	-0.28	***	-0.27	***	-0.31	***	-0.51	***	-0.44	***
cur_dist_600ft	1	37.89%	-0.12	*	-0.16	***	-0.11	*	-0.15	**	-0.21	*	-0.27	**
	2	15.67%	-0.17	*	-0.31	***	-0.34	***	-0.44	***	-0.66	***	-0.70	***
int_signal_dist_600ft	10	26.18%	0.34	***	0.21	***	0.28	***	0.18	***	0.19	*		
	11	16.60%	0.79	***	0.62	***	0.58	***	0.43	***	-0.01			
	20	17.42%	0.49	***	0.27	***	0.21	**	0.03		0.06			
	21	7.55%	0.98	***	0.74	***	0.56	***	0.38	***	-0.23			
	22	1.81%	1.07	***	0.80	***	0.74	***	0.56	***	0.20			

7.5 SPF for the curves that are in an urban area, on dual centerlines, with one intersection

This category of curves makes up about 11% of total curves. The majority of curves are within the speed limit between 30 mph and 55 mph. Curve characteristics make a significant contribution to crashes. The length of the curves, and the sharper curve radius, will significantly increase the crashes on curves. Roadway characteristics and traffic volume, such as the number of lanes, consistently increase crashes. More lanes can result in more crashes on curves. The speed on roadways has different significant impacts on total crashes and fatal and serious injury crashes. Lower speed roads (less than 40 mph) will have more total crashes, but significantly fewer fatal and serious injury crashes. The district of the curve location also makes significant contributions, such as Districts 2, 3, 4, 5, and 6 have more total crashes, and District 5 and 6 have more fatal, and injury crashes.

The characteristics of the intersection on the curve have some influence on crashes. Whether this intersection is the main intersection is on state-highway-system or has a signal, these characteristics will increase the crashes of all severity levels on the curve.

For the spatial relation to adjacent curves and intersections, the adjacent curves on both sides will significantly decrease the total crash counts and fatal and injury crashes. The adjacent intersections on both sides of the curve will consistently decrease the crash counts, and if both are signalized control, it will decrease more crashes of all severity levels on a curve.

Table 7- 6 SPF models for the curves in the urban area, on dual centerlines, with one intersection

Risk factors	Levels	Data desc	Total crashes		Total crashes within 600ft buffer		Fatal and injury crashes		Fatal and injury crashes within 600ft buffer		Fatal and serious injury crashes		Fatal and serious injury crashes within 600ft buffer	
			Number of crashes											
			81242		86614		21177		22374		2354		2526	
			Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.
(Intercept)	--	--	-6.71	***	-6.62	***	-7.27	***	-7.30	***	-8.26	***	-8.07	***
AADT_avg_log	--	9.21	0.80	***	0.81	***	0.73	***	0.75	***	0.61	***	0.62	***
roa_lane	2	62.38%	0.14	*	0.14	*	0.19	**	0.17	**	0.44	**	0.40	**
	3	20.46%	0.38	***	0.38	***	0.34	***	0.33	***	0.55	***	0.52	***
roa_dist	2	8.63%	0.40	***	0.41	***	0.41	***	0.42	***				
	3	4.77%	0.42	***	0.40	***	0.29	**	0.28	**				
	4	20.59%	0.21	***	0.20	***	0.12	.	0.12	.				
	5	28.70%	0.19	***	0.20	***	0.26	***	0.27	***				
	6	8.06%	0.71	***	0.71	***	0.28	**	0.27	***				
	7	14.80%	-0.10		-0.09		0.10		0.11					
roa_speed	4	39.99%	0.22	***	0.20	***					-0.07		-0.10	
	5	32.29%	0.22	**	0.20	**					-0.36	**	-0.41	***
	6	15.31%	0.36	***	0.34	***					-0.33	.	-0.37	*
cur_len_log	--	5.49	0.43	***	0.41	***	0.40	***	0.38	***	0.47	***	0.43	***
cur_rad_log	--	6.28	-0.15	***	-0.14	***	-0.10	**	-0.09	**	-0.17	**	-0.17	***
int_main_on	1	31.67%	0.40	***	0.40	***	0.28	***	0.28	***	0.14	*	0.14	*
int_shs_on	1	37.31%									0.25	***	0.22	***
int_signal_on	1	19.17%	0.66	***	0.63	***	0.64	***	0.61	***	0.27	***	0.23	**
int_leg_on	3	62.32%	-0.52	***	-0.52	***	-0.40	**	-0.40	***				
	4	33.73%	-0.22	.	-0.24	*	-0.10		-0.11					
	5	1.86%	-0.43	**	-0.45	**	-0.39	*	-0.39	*				
int_shape_on	0	17.31%									-0.18	*	-0.17	*
	1	47.16%									-0.23	***	-0.21	**
cur_dist_1mi	1	24.83%	-0.05		-0.04		-0.04		-0.04					
	2	68.91%	-0.18	*	-0.18	**	-0.19	*	-0.20	**				
int_sign_dist_600ft	10	22.10%	-0.10	*	-0.12	*	-0.12	*	-0.14	**	-0.06		-0.07	
	11	20.40%	0.03		0.01		-0.02		-0.04		-0.09		-0.12	
	20	18.64%	-0.21	***	-0.25	***	-0.27	***	-0.31	***	-0.18	.	-0.25	*
	21	9.72%	0.00		-0.03		-0.11		-0.13	.	-0.11		-0.16	
	22	6.57%	-0.31	***	-0.33	***	-0.39	***	-0.42	***	-0.41	**	-0.46	***

7.6 SPF for the curves that are in urban area, on dual centerlines, with multiple intersections

This category of curves makes up about 5% of total curves. The majority of curves are between 30 mph and 55 mph. The length of the curves will significantly increase the crashes on curves. Radius barely has an impact on crashes. Roadway characteristics and traffic volume, such as the number of lanes, consistently increase crashes. More lanes can result in more crashes on curves. The functional classification and speed of roadways have some influence on crashes. Lower speed roads will have more total crashes and fatal and injury crashes. The district of the curve location also makes significant contributions. Districts 2, 3, and 6 have more crashes, District 7 has fewer crashes, District 5 and 7 have more fatal and serious injury crashes, and District 3 has fewer fatal and serious injury crashes.

The characteristics of the intersection on the curve have some influence on crashes. More intersections, more main intersections, and more signalized intersections on a curve will increase crash frequency. The number of intersections with 4-leg intersections will increase the crash counts, and the number of intersections with non-90-degree will decrease the crash counts.

For the spatial relation to adjacent curves and intersections, the adjacent curves will decrease the crash counts. The adjacent intersections on both sides of the curve will consistently decrease the crash counts, and if there is any signal control, it will decrease more fatal and injury crashes on the curve.

Table 7- 7 SPF models for the curves in the urban area, on dual centerlines, with multiple intersections

Risk factors	Levels	Data desc	Total crashes		Total crashes within 600ft buffer		Fatal and injury crashes		Fatal and injury crashes within 600ft buffer		Fatal and serious injury crashes		Fatal and serious injury crashes within 600ft buffer	
			Number of crashes											
			67566		69925		18396		18888		2128		2224	
			Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.
(Intercept)	--	--	-8.81	***	-8.84	***	-9.47	***	-9.44	***	-9.15	***	-9.20	***
AADT_avg_log	--	9.26	0.89	***	0.89	***	0.78	***	0.78	***	0.48	***	0.49	***
roa_lane	2	61.83%	0.18	.	0.17	.	0.28	*	0.30	*	0.64	**	0.65	**
	3	22.99%	0.32	**	0.32	**	0.39	**	0.43	**	0.72	**	0.76	**
roa_func	3	29.19%	0.23	***	0.21	**	0.23	***	0.23	***	0.18	.	0.17	.
	4	43.52%	0.15	.	0.22	**	0.28	**	0.29	***	0.34	**	0.31	*
	5	12.44%	-0.11		-0.02		0.11		0.15		0.41		0.41	
roa_dist	2	7.95%	0.35	***	0.36	***	0.34	***	0.38	***	0.00		0.03	
	3	8.42%	0.19	*	0.18	*	0.08		0.08		-0.46	**	-0.48	**
	4	19.54%	0.07		0.10		0.10		0.11		-0.01		-0.02	
	5	27.86%	0.00		0.04		0.23	**	0.24	***	0.30	**	0.30	**
	6	7.66%	0.20	*	0.22	*	-0.11		-0.10		-0.31	.	-0.25	
	7	14.24%	-0.21	**	-0.19	*	0.08		0.08		0.47	***	0.45	***
roa_speed	4	43.47%	0.28	***	0.28	***	0.15	.	0.14	.				
	5	31.65%	0.38	***	0.37	***	0.19	.	0.16	.				
	6	14.43%	0.70	***	0.68	***	0.44	***	0.42	**				
roa_shs	1	47.68%			0.14	*	0.26	***	0.27	***	0.54	***	0.55	***
cur_len_log	--	5.94	0.51	***	0.51	***	0.52	***	0.51	***	0.60	***	0.61	***
cur_rad_log	--	6.49	-0.02		-0.02		-0.01		0.00		-0.05		-0.04	
int_main_on	--	0.37	0.28	***	0.28	***	0.25	***	0.25	***	0.13	*	0.14	**
int_signal_on	--	0.18	0.39	***	0.38	***	0.36	***	0.35	***	0.26	***	0.23	**
int_stop_on	--	0.19									-0.13	*	-0.11	.
int_cnt_on	--	2.53					0.06	*	0.06	*	0.06	.		
int_leg3_on	--	0.44	-0.13	***										
int_leg4_on	--	0.07	0.27	***	0.40	***	0.41	***	0.41	***	0.19	*	0.22	*
int_shape90_on	--	0.10	0.17	*										
int_shape91_on		0.44			-0.12	***	-0.16	***	-0.15	***				
cur_dist_05mi	1	35.81%	-0.15	*	-0.13	*	-0.09		-0.09		-0.12		-0.12	
	2	44.13%	-0.29	***	-0.27	***	-0.22	**	-0.21	**	-0.33	***	-0.32	***
int_signal_dist_600ft	10	24.74%	-0.14	*	-0.15	*	-0.14	.	-0.14	*	-0.14		-0.15	
	11	13.86%	0.09		0.09		0.06		0.06		-0.10		-0.07	
	20	33.07%	-0.19	**	-0.21	**	-0.23	**	-0.25	***	-0.21	.	-0.20	*
	21	11.92%	0.05		0.05		-0.07		-0.06		-0.26	*	-0.21	
	22	1.75%	0.01		0.01		-0.15		-0.17		-0.42		-0.46	.

7.7 SPF for the curves that are in a rural area, on single centerlines, with no intersections

This category of curves makes up about 24% of total curves. However, there are many curves in District 3 without valid AADT values. Half of the curves are on high-speed roads (greater than 55 mph). Very few curves would have a signalized intersection within their surroundings. Curve characteristics make a significant contribution to crashes. The length of the curves, and the sharper curve radius, will significantly increase the crashes on curves. Higher traffic volume increases the impact of the crashes. More lanes can result in more crashes. The functional classification also has significant impacts. Major roads have more crashes than minor roads. Speed do not show a significant impact. The district of the curve location also makes significant contributions, such as District 2 and 3 has fewer crashes. For the spatial relation to adjacent curves and intersections, the adjacent curves will decrease the crash counts. The adjacent intersections will increase the total crashes and fatal and injury crashes but may decrease the possibility of fatal and serious injury crashes.

Table 7- 8 SPF models for the curves in rural area, on single centerlines, no intersections

Risk factors	Levels	Data desc	Total crashes		Total crashes within 600ft buffer		Fatal and injury crashes		Fatal and injury crashes within 600ft buffer		Fatal and serious injury crashes		Fatal and serious injury crashes within 600ft buffer	
			Number of crashes											
			3061		4522		1377		2140		456		702	
			Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.
(Intercept)	--	--	-4.67	***	-4.02	***	-4.83	***	-5.00	***	-4.88	***	-3.64	***
AADT_avg_log	--	7.20	0.55	***	0.53	***	0.53	***	0.51	***	0.48	***	0.45	***
roa_lane	2	99.30%			0.80	.			1.56	*				
	3	0.46%			1.15	*			1.60	.				
roa_func	4	61.79%	-0.31	***	-0.26	***	-0.24	**	-0.23	**	-0.44	**	-0.43	***
	5	23.23%	-0.88	***	-0.85	***	-1.05	***	-0.99	***	-1.43	***	-1.29	***
roa_dist	2	28.71%	-0.50	***	-0.42	***	-0.46	***	-0.39	***	-0.58	***	-0.54	***
	3	34.65%	-0.45	***	-0.38	***	-0.45	***	-0.43	***	-0.84	***	-0.97	***
	4	1.87%	0.24		0.08		0.13		-0.05		-0.13		-0.42	
	5	15.56%	-0.30	***	-0.16	*	-0.03		-0.04		-0.18		-0.23	.
	6	0.91%	-0.49	.	-0.36	.	-0.53		-0.61	*	0.08		-0.36	
	7	7.00%	-0.13		-0.11		0.01		-0.02		0.03		0.01	
cur_len_log	--	5.27	0.74	***	0.43	***	0.75	***	0.43	***	0.70	***	0.36	***
cur_rad_log	--	6.15	-0.58	***	-0.46	***	-0.66	***	-0.50	***	-0.68	***	-0.44	***
cur_dist_1000ft	1	38.95%	-0.11	.	-0.16	***	-0.16	*	-0.22	***			-0.17	.
	2	13.48%	-0.23	**	-0.38	***	-0.30	**	-0.47	***			-0.44	**
int_dist_1000ft	1	37.88%	0.38	***	0.28	***	0.28	***	0.20	***			0.10	
	2	11.56%	0.37	***	0.17	**	0.23	*	0.02				-0.29	*

7.8 SPF for the curves that are in a rural area, on single centerlines, with one intersection

This category of curves makes up about 8% of total curves. Almost half of the curves are with a speed limit above 55 mph. Curve characteristics make a significant contribution to crashes. The length of the curves, and the sharper curve radius, will significantly increase the crashes on curves. Higher traffic volume increases crash. The functional classification on roadways also has a significant impact, such as major roads have more crashes than minor roads. The district of the curve location also makes some contributions, such as Districts 2 and 3 have less fatal and injury crashes, and District 7 has more fatal and injury crashes.

The characteristics of the intersection on the curve have some influence on crashes. Whether this intersection is the main intersection, is on state-highway-system, or has a stop sign, it will increase the crashes on a curve. For the spatial relation to adjacent curves and intersections, the adjacent curves, especially one side of the curve has an adjacent curve, will decrease the crash counts. The adjacent intersections will also consistently decrease the crash counts, and if both sides of the curve have an adjacent intersection, it will decrease crashes of all severity levels.

Table 7- 9 SPF models for the curves in a rural area, on single centerlines, with one intersection

Risk factors	Levels	Data desc	Total crashes		Total crashes within 600ft buffer		Fatal and injury crashes		Fatal and injury crashes within 600ft buffer		Fatal and serious injury crashes		Fatal and serious injury crashes within 600ft buffer	
			Number of crashes											
			5480		6045		2162		2439		570		649	
			Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.
(Intercept)	--	--	-4.74	***	-3.68	***	-4.44	***	-3.93	***	-5.66	***	-4.28	***
AADT_avg_log	--	7.35	0.69	***	0.59	***	0.57	***	0.56	***	0.52	***	0.47	***
roa_func	4	61.26%					-0.31	***	-0.31	***			-0.34	**
	5	19.20%					-0.67	***	-0.67	***			-0.89	***
roa_dist	2	31.84%			-0.12		-0.25	*	-0.21	*	-0.28	.	-0.32	*
	3	40.11%			-0.18	*	-0.41	***	-0.34	**	-0.67	***	-0.63	***
	4	0.44%			0.50		0.80	*	0.84	**	0.30		0.12	
	5	12.30%			0.20	*	0.16		0.21	.	0.22		0.18	
	6	0.31%			0.20		-0.25		0.16		-0.64		-0.19	
	7	6.02%			0.15		0.30	*	0.29	*	0.38	*	0.32	.
roa_shs	1	23.22%			0.28	***								
cur_len_log	--	5.49	0.51	***	0.45	***	0.59	***	0.50	***	0.61	***	0.52	***
cur_rad_log	--	6.21	-0.39	***	-0.37	***	-0.44	***	-0.41	***	-0.45	***	-0.44	***
int_main_on	1	17.69%	0.46	***	0.40	***	0.34	***	0.27	***				
int_shs_on	1	28.88%									0.29	*		
int_stop_on	1	2.21%	0.56	***	0.44	**								
cur_dist_600ft	1	23.84%	-0.14	*	-0.18	**	-0.19	*	-0.21	**	-0.36	**	-0.31	**
	2	4.60%	0.13		0.01		0.00		-0.08		-0.44	.	-0.39	
int_dist_600ft	1	38.52%	-0.26	***	-0.23	***	-0.25	***	-0.27	***	-0.10		-0.15	
	2	11.94%	-0.56	***	-0.57	***	-0.52	***	-0.60	***	-0.67	***	-0.68	***

7.9 SPF for the curves that are in a rural area, on single centerlines, with multiple intersections

This category of curves makes up about 2% of total curves. The majority of curves are between 30 mph and 55 mph. The length of the curves will significantly increase the crashes on curves. Radius has a significant impact on fatal and injury crashes. Traffic volume increasing will result in more crashes. The speed limit on roadways has some influence on crashes. Lower speed roads will have significantly fewer fatal and injury crashes.

The characteristics of the intersection on the curve have some influence on crashes. More main intersections on the curve will increase the total crashes and severe and fatal crashes.

For the spatial relation to adjacent curves and intersections, the adjacent curves will not influence the crash counts. The adjacent intersections on both sides of the curve will consistently decrease the crash counts of all severity levels.

Table 7- 10 SPF models for the curves in a rural area, on single centerlines, with multiple intersections

Risk factors	Levels	Data desc	Total crashes		Total crashes within 600ft buffer		Fatal and injury crashes		Fatal and injury crashes within 600ft buffer		Fatal and serious injury crashes		Fatal and serious injury crashes within 600ft buffer	
			Number of crashes											
			2851		2984		1067		1124		244		264	
			Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.
(Intercept)	--	--	-5.48	***	-5.27	***	-4.57	***	-4.33	***	-3.27	**	-3.33	***
AADT_avg_log	--	7.69	0.63	***	0.62	***	0.62	***	0.60	***	0.54	***	0.54	***
roa_speed	4	25.31%					-0.20	.	-0.21	.	-0.32	.	-0.28	
	5	32.50%					-0.51	***	-0.49	***	-0.98	***	-0.91	***
cur_len_log	--	5.91	0.40	***	0.38	***	0.33	***	0.32	***	0.27	.	0.29	*
cur_rad_log	--	6.49	-0.08		-0.08		-0.28	***	-0.26	***	-0.50	***	-0.48	***
int_main_on	--	0.32	0.37	***	0.35	***	0.25	***	0.23	**	0.24	*		
int_dist_1000ft	1	42.19%	-0.13		-0.13		-0.09		-0.11		-0.30	.	-0.28	
	2	35.68%	-0.25	*	-0.27	**	-0.26	*	-0.29	*	-0.55	**	-0.59	**

7.10 SPF for the curves that are in a rural area, on dual centerlines, no intersections

This category of curves makes up about 2% of total curves. More than 80% of curves are on roads with speed greater than 55 mph and about 67% are on roads with a speed limit greater than 65 mph. A few curves would have a curve or an intersection within their surrounding areas. Curve characteristics make a significant contribution to crashes. The length of the curves, and the sharper curve radius, will significantly increase the crashes on curves. Traffic volume has directly proportional to crash number. More lanes can result in more total crashes. The functional classification also has significant impacts. Major roads have more crashes than minor roads. Speed does not show a significant impact. The district of the curve location also makes significant contributions, such as District 5 has more total crashes, and Districts 2 and 3 have fewer severe crashes. For the spatial relation to adjacent curves and intersections, the buffer areas are extended from 600 feet to 0.5 mile and 1 mile since the curves are primarily on high-speed roads. Adjacent curves do not show any significance except for the fatal and injury crashes within 600 feet buffer areas. The presence of adjacent intersections within 1 mile buffer will decrease the possibility of crashes.

Table 7- 11 SPF models for the curves in a rural area, on dual centerlines, with no intersections

Risk factors	Levels	Data desc	Total crashes		Total crashes within 600ft buffer		Fatal and injury crashes		Fatal and injury crashes within 600ft buffer		Fatal and serious injury crashes		Fatal and serious injury crashes within 600ft buffer	
			Number of crashes											
			3995		5003		1272		1622		300		378	
			Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.
(Intercept)	--	--	-12.02	***	-9.66	***	-11.22	***	-8.60	***	-7.36	***	-5.88	***
AADT_avg_log	--	8.86	1.07	***	0.97	***	0.82	***	0.76	***	0.44	**	0.48	***
roa_lane	2	82.14%	0.59	.	0.59	.								
	3	13.64%	0.89	*	0.66	.								
roa_func	2	31.92%			-0.58	***	-0.78	***	-0.64	***	-1.20	***	-1.04	***
	3	35.62%			-0.34	*	-0.43	*	-0.34	*	-0.80	*	-0.81	**
roa_dist	2	21.78%	0.02		-0.13		-0.06		-0.10		-0.61	*	-0.63	**
	3	26.11%	0.34	*	0.08		-0.03		0.04		-0.64	*	-0.63	**
	4	8.46%	-0.15		0.00		-0.04		-0.02		-0.38		-0.33	
	5	22.20%	0.36	*	0.37	*	0.60	**	0.56	***	0.32		0.23	
	6	2.01%	0.15		0.14		-0.71		-1.23	*	-0.50		-0.95	
	7	6.13%	-0.66	**	-0.63	**	-0.42	.	-0.23		-0.47		-0.33	
roa_shs	1	78.33%			0.29	**	0.37	*	0.37	**	0.49	*	0.57	**
cur_len_log	--	6.05	1.05	***	0.77	***	1.17	***	0.84	***	1.00	***	0.67	***
cur_rad_log	--	7.15	-0.53	***	-0.43	***	-0.49	***	-0.44	***	-0.51	**	-0.45	**
cur_dist_05mi	1	33.40%							-0.31	**				
	2	15.75%							-0.05					
int_dist_1mi	1	34.36%	-0.14		-0.16	.			-0.02		0.01		-0.01	
	2	36.15%	-0.46	***	-0.46	***			-0.39	**	-0.60	*	-0.70	**

7.11 SPF for the curves that are in a rural area, on dual centerlines, with one intersection

This category of curves makes up about 1% of total curves. The majority of curves are with a speed limit above 55 mph. Curve characteristics make a significant contribution to crashes. The length of the curves, and the sharper curve radius, will significantly increase the crashes on curves. Traffic volume is also proportional to the number of crashes. The district of the curve location makes significant contributions to fatal and serious injury crashes, such as Districts 2 and 3 have fewer fatal and serious injury crashes.

The characteristics of the intersection on the curve do not have much influence on crashes. Whether this intersection is on a state-highway system will increase the curve's fatal and serious injury crashes.

For the spatial relation to adjacent curves and intersections, the adjacent curves will decrease the crash counts. The adjacent intersections on both sides of the curve will consistently decrease the crash counts of all severity levels.

Table 7- 12 SPF models for the curves in a rural area, on dual centerlines, with one intersection

Risk factors	Levels	Data desc	Total crashes		Total crashes within 600ft buffer		Fatal and injury crashes		Fatal and injury crashes within 600ft buffer		Fatal and serious injury crashes		Fatal and serious injury crashes within 600ft buffer	
			Number of crashes											
			3052		3307		987		1067		219		244	
			Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.
(Intercept)	--	--	-6.45	***	-6.16	***	-7.88	***	-7.46	***	-4.28	**	-5.61	***
AADT_avg_log	--	8.56	0.83	***	0.83	***	0.67	***	0.68	***	0.50	***	0.64	***
roa_dist	2	36.79%									-0.70	*	-0.69	**
	3	25.65%									-0.97	**	-0.93	**
	4	4.66%									-0.29		-0.27	
	5	15.03%									0.00		0.08	
	6	1.30%									1.12	.	0.82	
	7	2.85%									0.38		0.41	
roa_shs	1	81.35%					0.68	**	0.64	**				
cur_len_log	--	5.97	0.52	***	0.48	***	0.61	***	0.56	***	0.47	**	0.49	**
cur_rad_log	--	6.93	-0.26	.	-0.26	*	-0.18		-0.19		-0.40	*	-0.45	*
int_shs_on	1	73.83%											0.61	*
cur_dist_600ft	1	12.95%	-0.06		-0.12						-1.05	*	-0.81	*
	2	5.18%	-0.74	*	-0.80	*					-0.98		-0.63	
int_dist_1000ft	1	38.08%	-0.23		-0.25	.	-0.34	*	-0.36	*	-0.55	**	-0.57	**
	2	19.69%	-0.44	*	-0.45	*	-0.37	.	-0.41	.	-0.68	*	-0.71	*

7.12 SPF for the curves that are in a rural area, on dual centerlines, with multiple intersections

This category of curves makes up about 0.4% of total curves. The majority of curves are above the speed limit of 40 mph. Curve characteristics make a significant contribution to crashes. The length of the curves, and the sharper curve radius, will significantly increase the crashes on curves. Increasing traffic volumes results in more crashes. No other roadway characteristics make significant impact on crashes.

The characteristics of the intersection on the curve have some influence on crashes. More main intersections on a curve will increase the total crashes and fatal and serious crashes.

For the spatial relation to adjacent curves and intersections, the adjacent curves will influence the crash counts. When looking at adjacent curves within 0.5 miles of the curve, the existence of adjacent curves will decrease the fatal and serious injury crashes. When looking at adjacent curves within 1 mile of the curve, the existence of adjacent curves will increase the total crashes and the fatal and injury crashes. The adjacent intersections on both sides of the curve will consistently decrease the crash counts of all severity levels.

Table 7- 13 SPF models for the curves in a rural area, on dual centerlines, with multiple intersections

Risk factors	Levels	Data desc	Total crashes		Total crashes within 600ft buffer		Fatal and injury crashes		Fatal and injury crashes within 600ft buffer		Fatal and serious injury crashes		Fatal and serious injury crashes within 600ft buffer	
			Number of crashes											
			1485		1544		475		501		83		91	
			Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.	Coef	Sig.
(Intercept)	--	--	-6.56	***	-6.39	***	-6.21	***	-5.99	***	-1.57		-1.14	
AADT_avg_log	--	8.31	1.24	***	1.25	***	1.11	***	1.12	***	0.48	**	0.54	**
cur_len_log	--	6.28	0.31	*	0.29	*	0.40	*	0.40	**	1.03	***	0.83	**
cur_rad_log	--	6.94	-0.55	***	-0.55	***	-0.63	***	-0.66	***	-1.31	***	-1.18	***
int_main_on	--	0.50	0.48	***	0.48	***	0.41	***	0.39	***	0.27	.		
cur_dist_05mi	1	30.41%									0.00		-0.12	
	2	24.32%									-0.99	*	-1.18	**
cur_dist_1mi	1	32.43%	-0.20		-0.17		-0.21		-0.15					
	2	37.83%	0.44	*	0.44	*	0.45	*	0.47	*				
int_dist_05mi	1	18.92%	-0.31		-0.26		-0.48	.	-0.45		-0.67	.	-0.70	*
	2	74.32%	-0.60	*	-0.62	*	-0.92	***	-0.97	***	-0.81	*	-1.05	**

7.13 Summary

This task developed models to determine customized risk factors for curves statewide. Table 15 summarizes all the SPF models with selected risk factors. By interpreting the significant variables in SPFs, we conclude that traffic volume, curve characteristics, roadway characteristics, and the spatial relationship with adjacent curves and intersections are more relevant risk factors for the curve safety performance issues.

The most significant finding from this task is the consideration of the spatial relationship between curves and their adjacent curves and intersections. We analyzed different types of spatial relationship between curves and intersections: curve without intersection; curve with one intersection; and curve with multiple intersections. The distance from the curve to its adjacent curves is the significant risk factor that the adjacent curves will decrease the crashes on curves. For the curves without intersections, the distance from the curve to the adjacent intersections is the critical risk factor; for the curve with one or multiple intersections, the intersection characteristics are proved to be risk factors on the safety performance of curves.

When we compare the SPFs for crashes in the physical area (on curve) versus the SPFs for crashes in functional curve area (within 600 feet buffer area), there is not a significant difference in the selections of risk factors, and the signs and absolute values of the risk factor coefficients. When we compare the SPFs for the fatal and injury crashes versus the SPFs for the fatal and serious injury crashes, the SPF for fatal and injury crashes usually can include more risk factors in the SPFs. These findings will help narrow down the SPF models we choose to use in the prioritization.

Table 7- 14 Summary of SPF models with selected risk factors

Risk factor	Model 1	Model 2	Model 3	Model 4	Model 5	Model 6	Model 7	Model 8	Model 9	Model 10	Model 11	Model 12
	• Urban • Single - centerline • No intersection	• Urban • Single - centerline • With 1 intersection	• Urban • Single - centerline • With more than 1 intersections	• Urban • Dual- centerline • No intersection	• Urban • Dual - centerline • With 1 intersection	• Urban • Dual - centerline • With more than 1 intersections	• Rural • Single - centerline • No intersection	• Rural • Single - centerline • With 1 intersection	• Rural • Single - centerline • With more than 1 intersections	• Rural • Dual- centerline • No intersection	• Rural • Dual - centerline • With 1 intersection	• Rural • Dual - centerline • With more than 1 intersections
AADT_avg_log	+	+	+	+	+	+	+	+	+	+	+	+
roa_lane	+	+	+	+	+	+	+			+		
roa_func	+		+	+		+	+	+		+		
roa_dist	+	+	+	+	+	+	+	+		+	+	
roa_speed	+	+	+	+	+	+			+			
roa_shs	+			+		+		+		+	+	
cur_len_log	+	+	+	+		+	+	+	+	+	+	+
cur_rad_log	+	+	+	+		+	+	+	+	+	+	+
int_main_on		+	+		+	+		+	+			+
int_shs_on		+			+			+			+	
int_signal_on		+	+		+	+						
int_stop_on		+	+			+		+				
int_yield_on		+	+									
int_cnt_on			+			+						
int_leg_on		+			+							
int_leg3_on			+			+						
int_leg4_on			+			+						
int_leg5_on			+									
int_shape_on					+							
int_shape90_on						+						
int_shape91_on						+						
cur_dist_600ft	+			+				+			+	
cur_dist_1000ft			+				+					
cur_dist_05mi		+				+				+		+
cur_dist_1mi					+							+
int_dist_600ft								+				
int_dist_1000ft							+		+		+	
int_dist_05mi												+
int_dist_1mi										+		
int_sign_dist_600ft			+		+							
int_signal_dist_600ft	+			+		+						
int_signal_dist_1000ft		+										

+: The factor shows a significant impact on the SPF.
Blank: The factor does not show a significant impact on the SPF.
Shaded: The factor is not applicable in the SPF.

8 PRIORITIZATIONS

The research team adopted the customized curve SPFs and obtained the statewide predicted crash frequencies based on different normalization methods. We used the fatal and injury SPFs as an example. Here are the steps to select the top 10% high-risk curve locations statewide.

1. Apply the curve SPFs for the 12 categories to obtain each curve's absolute predicted crash frequencies.
2. Combine and rank the curves based on the absolute predicted crash frequencies.
3. Normalize the predicted crash frequencies based on only the AADT, only on the curve length, and both on the AADT and the curve length.
4. Select the top 10% of the curves based on the following criteria: the absolute predictions, predictions normalized by the AADT, predictions normalized by the curve length, and predictions normalized by both AADT and the curve length.

Table 8-1 presents the descriptive statistics of the statewide top 10% high-risk curves.

Table 8- 1 Summary statistics of statewide top 10% high-risk curves

Characteristics	Absolute prediction		Normalized by AADT		Normalized by curve length		Normalized by AADT and curve length		All curves	
	# of curves	%	# of curves	%	# of curves	%	# of curves	%	# of curves	%
Urban	3207	97.24	2118	64.22	3254	98.67	2215	67.16	23238	70.44
Dual centerline	2494	75.62	1379	41.81	1920	58.22	636	19.28	13409	40.64
District										
1	323	9.79	396	12.01	276	8.37	545	16.53	4599	13.94
2	398	12.07	652	19.77	437	13.25	649	19.68	4865	14.75
3	298	9.04	631	19.13	271	8.22	405	12.28	5155	15.63
4	522	15.83	326	9.88	471	14.28	237	7.19	3984	12.08
5	975	29.56	825	25.02	914	27.71	801	24.29	8656	26.24
6	311	9.43	114	3.46	422	12.80	201	6.09	1568	4.75
7	471	14.28	354	10.73	507	15.37	460	13.95	4164	12.62
AADT										
<400			252	7.64			364	11.04	1097	3.33
400-2K			841	25.50	8	0.24	1100	33.35	5707	17.30
2K-5K	9	0.27	593	17.98	85	2.58	716	21.71	7528	22.82
5K-10K	256	7.76	541	16.40	361	10.95	474	14.37	7867	23.85
10K-20K	1317	39.93	718	21.77	1303	39.51	457	13.86	7145	21.66
20K-30K	838	25.41	255	7.73	856	25.96	148	4.49	2166	6.57
>30K	878	26.62	98	2.97	685	20.77	39	1.18	1481	4.49
Radius										
<100m (<328ft)	20	0.61	154	4.67	276	8.37	861	26.11	2056	6.23
100-250m (328-820ft)	150	4.55	411	12.46	505	15.31	1011	30.65	5822	17.65
250-500m (820-1640ft)	646	19.59	877	26.59	840	25.47	870	26.38	9691	29.37
500-800m (1640-2625ft)	814	24.68	730	22.13	710	21.53	327	9.92	6727	20.39
800-1km (2625-3281ft)	492	14.92	430	13.04	335	10.16	97	2.94	3185	9.65
1-2km (0.62-1.24mi)	892	27.05	566	17.16	509	15.43	113	3.43	4336	13.14
>2km (>1.24mi)	284	8.61	130	3.94	123	3.73	19	0.58	1174	3.56

Characteristics	Absolute prediction		Normalized by AADT		Normalized by curve length		Normalized by AADT and curve length		All curves	
	# of curves	%	# of curves	%	# of curves	%	# of curves	%	# of curves	%
Curve length										
<100m	87	2.64	201	6.09	709	21.50	1525	46.24	5716	17.33
100-250m	659	19.98	697	21.13	1337	40.54	1364	41.36	14155	42.91
250-500m	1316	39.90	1240	37.60	893	27.08	362	10.98	9280	28.13
500-800m	744	22.56	733	22.23	252	7.64	34	1.03	2750	8.34
800-1km	237	7.19	206	6.25	66	2.00	7	0.21	578	1.75
>1km	255	7.73	221	6.70	41	1.24	6	0.18	512	1.55
Speed										
2: 65-80mph	535	16.22	95	2.88	188	5.70	1	0.03	1759	5.33
3: 55-64mph	435	13.19	743	22.53	255	7.73	349	10.58	5532	16.77
4: 41-54mph	1386	42.03	1171	35.51	1247	37.81	668	20.25	8502	25.77
5: 31-40mph	756	22.92	851	25.80	1098	33.29	1128	34.20	9845	29.84
6: 21-30mph	186	5.64	426	12.92	504	15.28	1122	34.02	7185	21.78
7: 6-20mph			12	0.36	6	0.18	30	0.91	168	0.51
Functional Class										
1	334	10.13	22	0.67	179	5.43	2	0.06	791	2.40
2	737	22.35	265	8.04	449	13.61	63	1.91	2478	7.51
3	1021	30.96	751	22.77	977	29.62	319	9.67	4721	14.31
4	1134	34.38	1794	54.40	1497	45.39	1965	59.58	17380	52.68
5	72	2.18	466	14.13	196	5.94	949	28.78	7621	23.10
Lane count										
1	23	0.70	62	1.88	38	1.15	101	3.06	2173	6.59
2	1511	45.82	2661	80.69	1519	46.06	2775	84.14	26784	81.19
3	1143	34.66	392	11.89	981	29.75	224	6.79	2615	7.93
4	497	15.07	166	5.03	635	19.25	188	5.70	1259	3.82
>5	124	3.76	17	0.52	125	3.79	10	0.30	160	0.48
Intersection on curve										
No Int	368	11.16	98	2.97	250	7.58	504	15.28	16694	50.60
1 Int	1449	43.94	1593	48.30	1944	58.94	2114	64.10	11204	33.96
Multi Int	1481	44.91	1607	48.73	1104	33.47	680	20.62	5093	15.44
Spatial relation to curves: whether there is a curve located within 600 ft of the curve										
Neither side	2386	72.35	2321	70.38	1843	55.88	1548	46.94	16917	51.28
One side	777	23.56	786	23.83	1165	35.32	1326	40.21	11731	35.56
Both sides	135	4.09	191	5.79	290	8.79	424	12.86	4343	13.16
Spatial relation to intersections: whether there is an intersection located within 600 ft of the curve										
Neither side	1006	30.50	1247	37.81	651	19.74	923	27.99	10769	32.64
One side	1364	41.36	1300	39.42	1314	39.84	1263	38.30	12275	37.21
Both sides	928	28.14	751	22.77	1333	40.42	1112	33.72	9947	30.15
Total	3298		3298		3298		3298		32991	

At the statewide level, there are two key inferences reflecting the risk factors we have created:

- Curves with one or more intersections.
- Isolated curves, which are the curves with no surrounding curves.

About 50% of curves statewide are curves with one or more intersections. However, for the subset of the top 10 % high-risk curves, more than 80% appear in each of the 4 criteria. In some criteria more than 95% of high-risk curves are curves with one or more intersections.

About 50% of curves statewide are curves with no surrounding curves on both sides (within 600 feet). More than 70% of high-risk curves are isolated curves in some criteria.

For the top 10% selected by the prioritization criteria, we also noticed that the impacts of the method on the selection of these high-risk curves are:

- If we look at absolute values, 97.24% of the prioritized curves are in urban areas.

- If normalized by AADT, most of the prioritized curves are on single centerlines, and most of the prioritized curves are in functional classification categories 3 and 4, which differs from the total sample where the majority of the curves are in categories 4 and 5.
- All criteria have prioritized curves with one or more intersections.
- If normalized by both AADT and curve length, more than 90% of prioritized curves have a radius of less than 800 meters.
- Speed categories did not show any apparent concentration in the prioritized curves.
- All the criteria show that curves with two lanes make most of the prioritized list as expected since curves with two lanes represent more than 80% of the total sample.
- Most criteria prioritize the curves with no surrounding curves.
- Spatial relationship to intersection does not significantly differ from the statewide reference.

Table 8-2 presents a cross-tabulation showing the curve distribution by the above two risk factors – the presence of intersections on curves and spatial relationship to other curves. We can see that about 25% of statewide curves contain one or more intersections and no surrounding curves. These curves are considered to be high risk based on the customized SPFs.

Table 8- 2 Summary statistics of statewide curves by risk factors of curves with intersections and adjacent to neighboring curves

		Spatial relation to curves: whether there is another curve located within 600 ft of the curve					
		On neither side		On one side		On both sides	
Intersections on curves	No Intersection	8419	25.52%	6045	18.32%	2230	6.76%
	One Intersection	5636	17.08%	4047	12.27%	1521	4.61%
	Multiple intersections	2862	8.68%	1639	4.97%	592	1.79%

Therefore, we recommend that the FDOT investigate curves with intersections and isolated curves statewide as these are high risk.

Tables 8-3, 8-4, and 8-5 correspondingly display the crash type distributions on curves with one or more intersections, on curves with no intersections and isolated curves. Rear-end, sideswipe, and 'other' are the top 3 crash types in all crash severity levels. Rear end, left turn, and off-road crashes are the top 3 fatal and injury crash types. We noticed that the number of crashes rises whenever the mentioned risk factors are present. Regarding the distribution of crashes by type, curves with intersections present higher numbers of rear-end, left turn, right turn, and collision with pedestrian crashes. In contrast, off-road crashes, sideswipe, rollover, and head-on crashes are more prominent in curves with no intersections.

While developing countermeasures will require a more detailed study, the potential countermeasures for these situations may include adding warning flashing lights, signs, or alerts for the isolated curves and suggesting speed reductions. For intersections within curve boundaries, adding transversal strips, lighting, and eliminating lateral hazards to increase visibility may help mitigate the risk of crashes. Additional geometric corrections to improve sight distances might be considered case by case.

Table 8- 3 Crash type distribution on curves with one or more intersections

Crash type	# of crashes on curves with one or more intersections	% of crashes on curves with one or more intersections	# of fatal and injury crashes on curves with one or more intersections	% of fatal and injury crashes on curves with one or more intersections	# of crashes on curves	% of crashes on curves
Rear End	90109	38.35%	22755	34.94%	108791	31.64%
Sideswipe	32868	13.99%	3789	5.82%	67883	19.74%
Other	31138	13.25%	6640	10.20%	40122	11.67%
Off Road	23544	10.02%	8210	12.61%	57717	16.79%
Left Turn	23464	9.99%	10230	15.71%	24712	7.19%
Angle	11844	5.04%	4815	7.39%	12554	3.65%
Unknown	6693	2.85%	1258	1.93%	8064	2.35%
Right Turn	3371	1.43%	723	1.11%	3581	1.04%
Rollover	3301	1.40%	1922	2.95%	8068	2.35%
Head On	3136	1.33%	1438	2.21%	5658	1.65%
Pedestrian	1991	0.85%	1745	2.68%	2301	0.67%
Animal	1876	0.80%	226	0.35%	2598	0.76%
Bicycle	1656	0.70%	1369	2.10%	1807	0.53%
Total	234991	100.00%	65120	100.00%	343856	100.00%

Table 8- 4 Crash type distribution on curves without intersections

Crash type	# of crashes on curves without intersections	% of crashes on curves without intersections	# of fatal and injury crashes on curves without intersections	% of fatal and injury crashes on curves without intersections
Rear End	18682	34.8%	5081	33.68%
Off Road	10649	19.8%	3862	25.60%
Other	8984	16.7%	1978	13.11%
Sideswipe	8503	15.8%	1244	8.25%
Rollover	1494	2.8%	980	6.50%
Unknown	1371	2.6%	351	2.33%
Left Turn	1248	2.3%	417	2.76%
Angle	710	1.3%	222	1.47%
Animal	722	1.3%	91	0.60%
Head On	686	1.3%	419	2.78%
Pedestrian	310	0.6%	261	1.73%
Right Turn	210	0.4%	45	0.30%
Bicycle	151	0.3%	134	0.89%
Total	53720	100.0%	15085	100.00%

Table 8- 5 Crash type distribution on isolated curves

Crash type	# of crashes on isolated curves	% of crashes on isolated curves	# of fatal and injury crashes on isolated curves	% of fatal and injury crashes on isolated curves
Rear End	75645	39.75	19941	37.15
Sideswipe	27764	14.59	3638	6.78
Other	25009	13.14	5391	10.04
Off Road	23138	12.16	8075	15.04
Left Turn	14554	7.65	6560	12.22
Angle	7028	3.69	2918	5.44
Unknown	5004	2.63	1112	2.07
Rollover	3415	1.79	2115	3.94
Head On	2249	1.18	1138	2.12
Right Turn	2110	1.11	503	0.94
Animal	2000	1.05	226	0.42
Pedestrian	1354	0.71	1179	2.20
Bicycle	1041	0.55	882	1.64
Sum	190311	100.00	53678	100.00

8.1 Prioritizations by predictions from SPF models

In this section, the research team proposes a generalized method to prioritize curves based on predictions from curve SPFs. This method can be applied to different geographic scales or any specific roadways.

In this chapter, we demonstrate how these predictions could be prioritized for a given county. We selected Marion County as an example because it has a balanced number of curves in the urban and rural areas. We used predicted fatal, and injury crash counts and normalized predictions.

Table 8-6 presents the top 10% of high-risk curves out of 887 curves in the urban areas of the County. We selected the top 10% by considering (1) absolute prediction, (2) prediction normalized by AADT, (3) prediction normalized by curve length, (4) prediction normalized by both AADT and curve length. The distribution of all curves in the county is included as a reference.

Table 8- 6 Summary statistics of top 10% high-risk curves in Marion County

Characteristics	**Absolute prediction**		**Normalized by AADT**		**Normalized by curve length**		**Normalized by AADT and curve length**		**Selected by all 4 criteria**		**All curves**	
	# of curves	%	# of curves	%	# of curves	%	# of curves	%	# of curves	%	# of curves	%
Urban	71	81.61	40	45.98	78	89.66	36	41.38	11	100.00	421	47.52
Dual centerline	48	55.17	13	14.94	37	42.53	3	3.45	2	18.18	246	27.77
AADT												
<400			4	4.60			5	5.75			11	1.24
400-2K			32	36.78	1	1.15	35	40.23			172	19.41
2K-5K	7	8.05	32	36.78	11	12.64	33	37.93	2	18.18	377	42.55
5K-10K	30	34.48	9	10.34	26	29.89	6	6.90	2	18.18	208	23.48
10K-20K	28	32.18	6	6.90	33	37.93	4	4.60	3	27.27	90	10.16
20K-30K	11	12.64	4	4.60	9	10.34	4	4.60	4	36.36	17	1.92
>30K	11	12.64			7	8.05					11	1.24
Radius												
<100m (<328ft)			2	2.30			9	10.34			26	2.93
100-250m (328-820ft)	7	8.05	23	26.44	22	25.29	32	36.78	2	18.18	148	16.70
250-500m (820-1640ft)	21	24.14	27	31.03	27	31.03	30	34.48	5	45.45	262	29.57
500-800m (1640-2625ft)	12	13.79	14	16.09	12	13.79	10	11.49	1	9.09	175	19.75
800-1km (2625-3281ft)	15	17.24	9	10.34	7	8.05	2	2.30	2	18.18	113	12.75
1-2km (0.62-1.24mi)	25	28.74	11	12.64	16	18.39	4	4.60	1	9.09	144	16.25
>2km (>1.24mi)	7	8.05	1	1.15	3	3.45					18	2.03
Curve length												
<100m			3	3.45	8	9.20	17	19.54			82	9.26
100-250m	17	19.54	21	24.14	45	51.72	50	57.47	5	45.45	407	45.94
250-500m	35	40.23	41	47.13	26	29.89	20	22.99	6	54.55	305	34.42
500-800m	30	34.48	15	17.24	7	8.05					77	8.69
800-1km	5	5.75	4	4.60	1	1.15					11	1.24
>1km			3	3.45							4	0.45

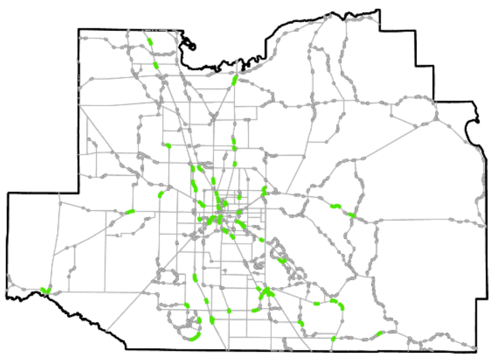
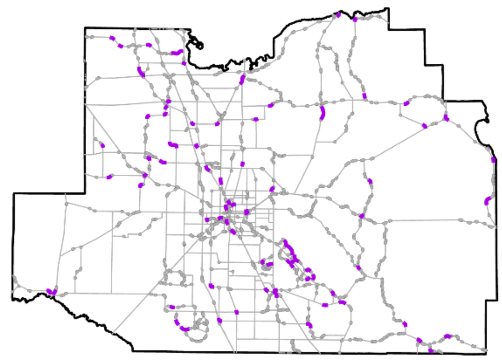
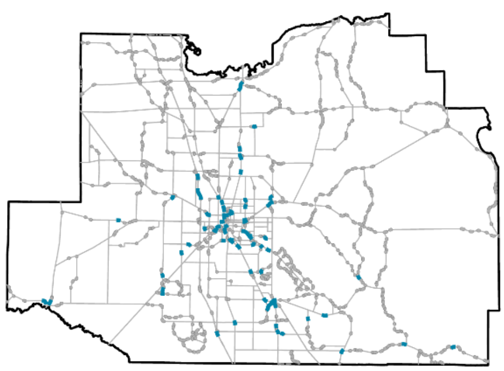
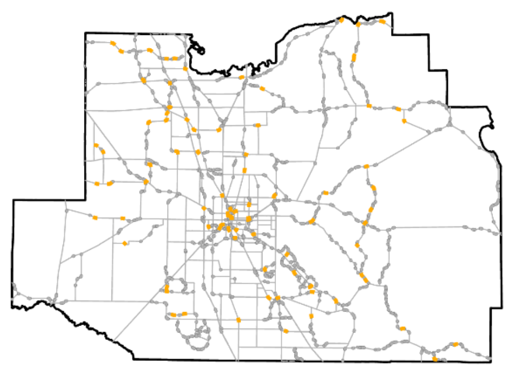
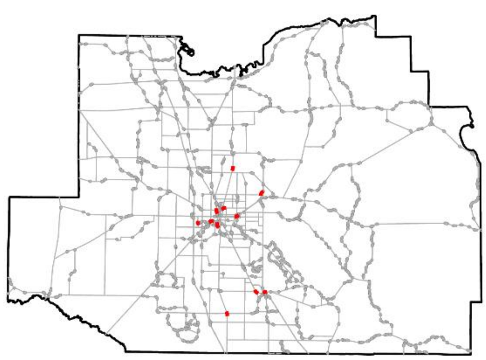
Characteristics	Absolute prediction		Normalized by AADT		Normalized by curve length		Normalized by AADT and curve length		Selected by all 4 criteria		All curves	
	# of curves	%	# of curves	%	# of curves	%	# of curves	%	# of curves	%	# of curves	%
Speed												
2: 65-80mph	14	16.09			6	6.90					34	3.84
3: 55-64mph	11	12.64	27	31.03	14	16.09	25	28.74	2	18.18	296	33.41
4: 41-54mph	39	44.83	30	34.48	28	32.18	26	29.89	4	36.36	234	26.41
5: 31-40mph	20	22.99	14	16.09	31	35.63	17	19.54	4	36.36	176	19.86
6: 21-30mph	3	3.45	16	18.39	8	9.20	19	21.84	1	9.09	136	15.35
7: 6-20mph											10	1.13
Functional Class												
1	14	16.09			6	6.90					16	1.81
2	27	31.03	9	10.34	20	22.99	4	4.60	4	36.36	86	9.71
3	8	9.20	8	9.20	11	12.64	4	4.60	1	9.09	115	12.98
4	34	39.08	55	63.22	44	50.57	62	71.26	5	45.45	514	58.01
5	4	4.60	15	17.24	6	6.90	17	19.54	1	9.09	155	17.49
Number of Lanes												
1							1	1.15			36	4.06
2	61	70.11	83	95.40	69	79.31	80	91.95	7	63.64	812	91.65
3	16	18.39	2	2.30	7	8.05	1	1.15	2	18.18	20	2.26
4	8	9.20	2	2.30	9	10.34	3	3.45	2	18.18	16	1.81
>5	2	2.30			2	2.30	2	2.30			2	0.23
Intersection on curve												
No Int	14	16.09	4	4.60	8	9.20	9	10.34			488	55.08
1 Int	28	32.18	44	50.57	51	58.62	62	71.26	6	54.55	263	29.68
Multi Int	45	51.72	39	44.83	28	32.18	16	18.39	5	45.45	135	15.24
Spatial relation to curves: whether there is a curve located within 600 ft of the curve												
Neither side	61	70.11	66	75.86	48	55.17	51	58.62			508	57.34
One side	21	24.14	18	20.69	33	37.93	31	35.63	8	72.73	304	34.31
Both sides	5	5.75	3	3.45	6	6.90	5	5.75	3	27.27	74	8.35
Spatial relation to intersections: whether there is an intersection located within 600 ft of the curve												
Neither side	30	34.48	38	43.68	25	28.74	41	47.13	2	18.18	379	42.78
One side	33	37.93	33	37.93	39	44.83	31	35.63	6	54.55	341	38.49
Both sides	24	27.59	16	18.39	23	26.44	15	17.24	3	27.27	166	18.74
Total	87		87		87		87		11		886	

The characteristics of these high-risk curves in Marion County are as follows:

- Most of the prioritized curves are in urban areas when not normalized by AADT; if normalized by AADT, about half are in urban areas, and half are in rural areas.
- Most of the prioritized curves are on single centerlines when normalized by AADT.
- All criteria have prioritized curves with one or more intersections.
- When normalized by AADT, about 75% of the prioritized curves are on roads with AADT between 400-5000.
- When normalized by both AADT and curve length, about 95% of prioritized curves have a radius of less than 800 meters.
- The majority of the prioritized curves are on roadways with a speed range between 31-54 mph.

  If normalized by AADT, most of the prioritized curves are located in roadways classified in Navteq categories 4 and 5. Category 4 is applied to roads that provide for a high volume of traffic movements at a moderate speed between neighborhoods. Category 5 includes roadways below any other functional class.

Table 8- 7 Maps of top 10% high-risk curves in Marion County

Prioritization based on absolute predictions	Prioritization based on predictions normalized by AADT
	
Prioritization is based on predictions normalized by curve length	Prioritization is based on predictions normalized by AADT and curve length
	
Prioritization based on all four criteria	
	

- All criteria show curves with two lanes make up most of the prioritized list, but curves with two lanes make up more than 90% of the county. All criteria also show curves with more than two lanes having a higher share in the prioritized list than when all the curves in the entire county are used as a base reference.

- The absolute prediction and the prediction normalized only by AADT prioritize the curves with no surrounding curves.
- The spatial relationship to the intersection does not show a significant difference compared to the county-wide reference.

8.2 Prioritizations by observations and predictions

In addition, the research team suggests site selection by sorting crash frequency observations and predictions. Using this method, the curves are categorized based on historical observations into three groups: high, medium, and low. The top 1/3 of curves with most crashes are labeled as high, medium 1/3 are labeled as median, and the bottom 1/3 of the angles with the least crashes are labeled as low. Similarly, the curves are categorized into three groups based on predictions (absolute or normalized predictions) from curve SPFs. This method can allow for sorting by high crash – high risk, high-crash – low-risk, low crash – high risk, and low-crash – low-risk categories. These different combinations of observation and prediction labels can provide additional insights to prioritize site visit locations. The curves with a high-crash – high-risk label (shown in **bold**) are the highest priority, and those with a low-crash – low-risk label are the lowest. The label high-crash – low-risk (colored in gray) suggests looking for local problems since the crash risk from the statewide SPFs is low. The label high-crash – low-risk means it may need some time before a crash happens, or there may already be local corrections. Table 8-8 presents the statewide curves with crash observations, and predictions labels. Table 8-9 and maps in Tables 8-10 and 8-11 demonstrate examples of Marion County with different prioritized locations.

Table 8- 8 Summary of statewide curves by observations and predictions

		Prediction											
		Absolute			Normalized by AADT			Normalized by curve length			Normalized by AADT and curve length		
		High	Median	Low	High	Median	Low	High	Median	Low	High	Median	Low
Observation	High	**5748**	1103	96	**4248**	2070	629	**5107**	1588	252	**2944**	2557	1446
	Median	3239	3950	1782	3027	3281	2663	3174	3658	2139	2987	3116	2868
	Low	2010	5944	9119	3722	5646	7705	2716	5751	8606	5066	5324	6683

Table 8- 9 Summary of curves in Marion County by observations and predictions

		Prediction											
		Absolute			Normalized by AADT			Normalized by curve length			Normalized by AADT and curve length		
		High	Median	Low	High	Median	Low	High	Median	Low	High	Median	Low
Observation	High	**122**	26	4	**99**	42	11	**106**	40	6	**68**	57	27
	Median	107	118	48	102	97	74	99	112	62	91	98	84
	Low	66	151	244	94	156	211	90	143	228	136	140	185

Table 8- 10 Maps of prioritizations based on observation and prediction labels in Marion County (Absolute and Normalized by AADT)

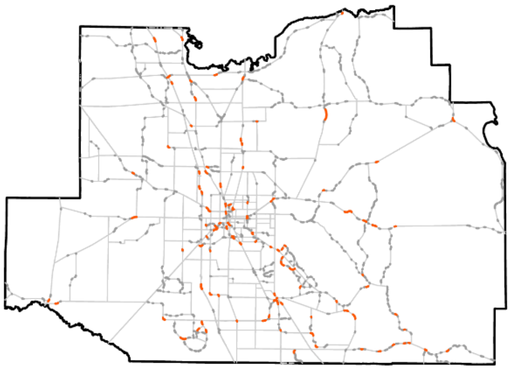
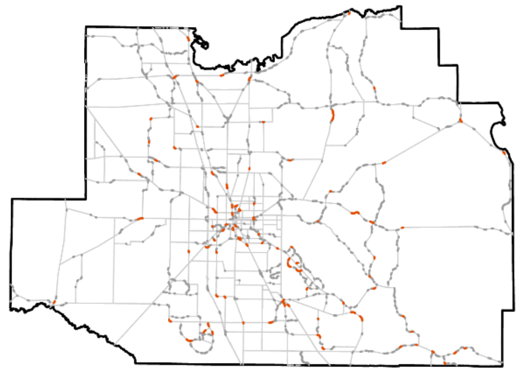
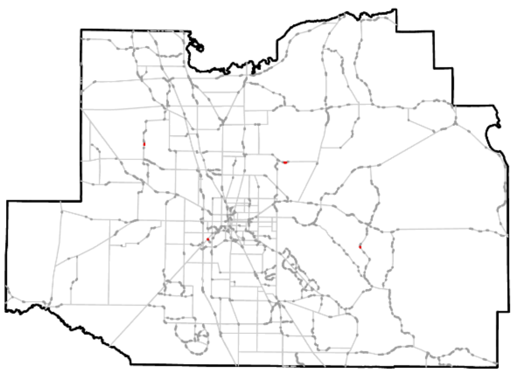
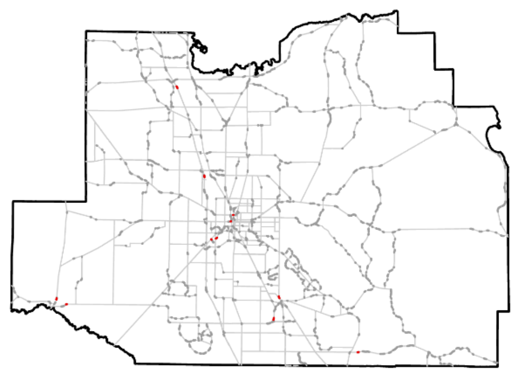
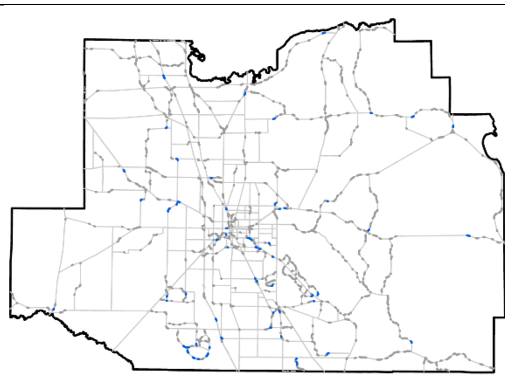
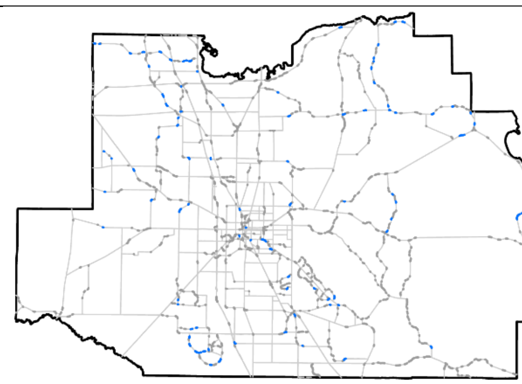
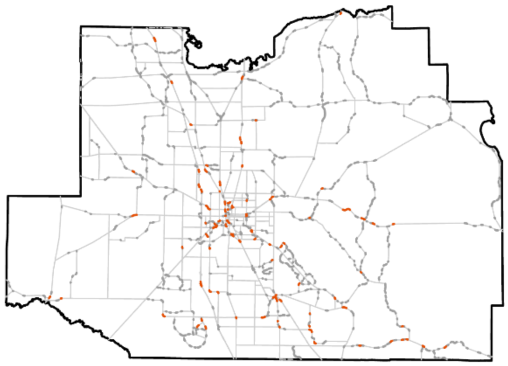
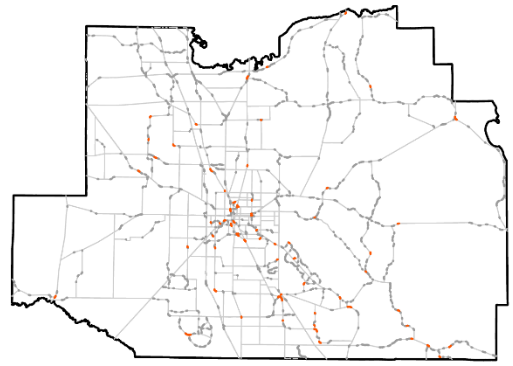
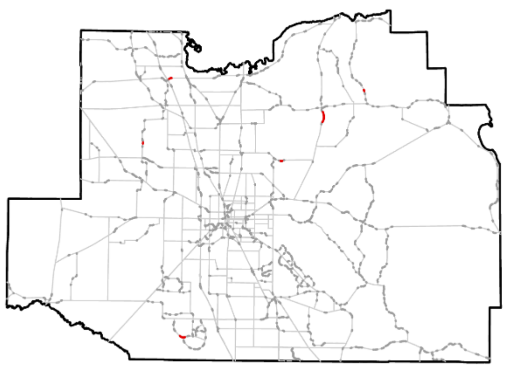
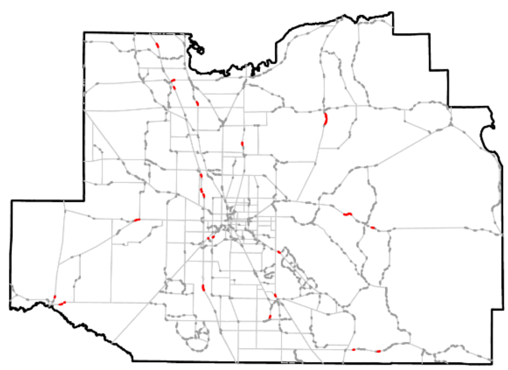
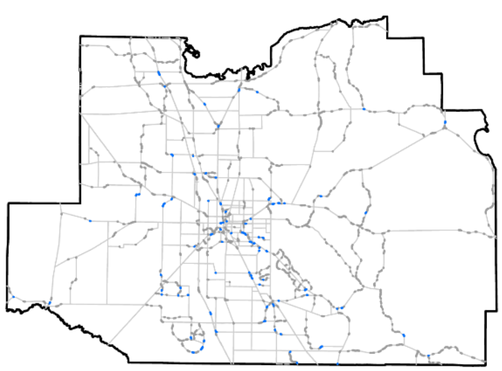
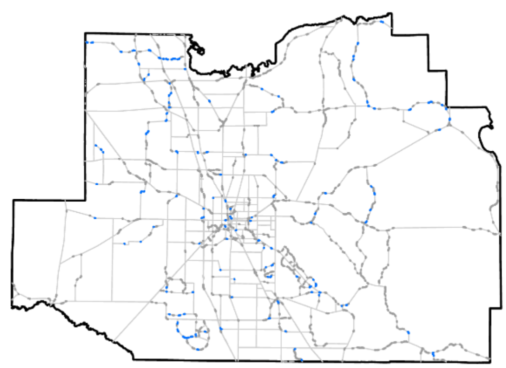
Risk type	Absolute	Normalized by AADT
High crash – High risk		
High crash – Low risk		
Low crash – High risk		

Table 8- 11 Maps of prioritizations based on observation and prediction labels in Marion County (Normalized by Length and Normalized by AADT and Length)

Risk type	Normalized by curve length	Normalized by AADT and curve length
High crash – High risk		
High crash – Low risk		
Low crash – High risk		

8.3 Summary

This study used multiple risk metrics to prioritize curves. Metrics include total predicted crashes, crashes per AADT, and ratio of observed to predicted crashes for all curves in Florida's roads. In addition, the research team summarized how the risk factors impact the curve safety and developed methods to prioritize high-risk curve locations based on the customized curve SPFs. By adopting curve SPFs and analyzing the statewide predicted crash frequencies with the risk factors, the study concludes that curves with intersections and isolated curves (the curves with no surrounding curves) are at high risk in general. After introducing the spatial relationship between curves and their neighboring curves and intersections into the curve SPFs, the study found that this spatial relationship affects the curve safety risks. More considerations are needed when addressing countermeasures and improvements. The study also suggested several methods to prioritize high-risk locations based on predictions from the curve SPFs.

9 CONCLUSION AND RECOMMENDATIONS

This research presents the efforts to develop a novel customized GIS curve dataset and safety performance analysis for curves. We applied the GIS automation process statewide to generate curves and curve attributes and trace the network to obtain spatial characteristics of the adjacent curves and intersections. The GIS process enabled more customized data for safety performance analysis. With six years of crash data from Florida, the research team developed 12 sets of SPFs for curves with different characteristics. By interpreting the significant variables in SPFs, we conclude that traffic volume, curve characteristics, roadway characteristics, and the spatial relationship with adjacent curves and intersections are more relevant risk factors for the curve safety performance issues.

One contribution from this research is the curve dataset updated with improved automated algorithms. Given that the curves are the fundamental data elements for this research, it is essential to ensure that the curves are accurately determined on the network. The research team validated the existing curves using manual inspection and automated methods and improved them for the safety analysis. The updated curve dataset is also submitted as a deliverable.

The most significant finding from this research is the consideration of the spatial relationship between curves and their adjacent curves and intersections. We analyzed different types of spatial relationship between curves and intersections: curve without intersection; curve with one intersection; curve with multiple intersections. The distance from the curve to its adjacent curves is the significant risk factor that the adjacent curves will decrease the crashes on curves. For the curves without intersections, the distance from the curve to the adjacent intersections is the critical risk factor; for the curve with one or multiple intersections, the intersection characteristics are proved to be risk factors on the safety performance of curves.

When we compare the SPFs for crashes in the physical area (on curve) versus the SPFs for crashes in functional curve area (within 600 feet buffer area), there is not a major difference in the selections of risk factors, and the signs and absolute values of the risk factor coefficients. When we compare the SPFs for the fatal and injury crashes versus the SPFs for the fatal and serious injury crashes, the SPF for fatal and injury crashes usually can include more risk factors in the SPFs. These findings help narrow down the SPF models we choose to use in the next research steps.

This study used multiple risk metrics to prioritize curves. Metrics include total predicted crashes, crashes per AADT, and ratio of observed to predicted crashes for all curves in Florida's roads. In addition, the research team summarized how the risk factors impact the curve safety and developed methods to prioritize high-risk curve locations based on the customized curve SPFs. By adopting curve SPFs and analyzing the statewide predicted crash frequencies with the risk factors, the study concludes that curves with intersections and isolated curves (the curves with no surrounding curves) are at high risk in general. After introducing the spatial relationship between curves and their neighboring curves and intersections into the curve SPFs, the study found that this spatial relationship affects the curve safety risks. More considerations are needed when addressing countermeasures and improvements. The study also suggested several methods to prioritize high-risk locations based on predictions from the curve SPFs.

The prioritization procedures could allow traffic safety analysts and transportation engineers to screen curves based on their needs and have flexible choices in selecting high-risk locations. Districts can potentially start from this database and prioritize sites for further evaluations. In the future, these locations can then be incorporated into the GIS dashboard to help screen, monitor, and assess the impact of interventions for the various sites.

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