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Intersection on Horizontal Curves: Problems and Potential Solutions

by

Xiaoduan Sun, Ph.D., P.E.
Ming Sun, Ph.D. Candidate

University of Louisiana at Lafayette

4101 Gourrier Avenue | Baton Rouge, Louisiana 70808
(225) 767-9131 | (225) 767-9108 fax | www.ltrc.lsu.edu

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2. Author(s)
   Xiaoduan Sun, Ph.D., P.E.
   Ming Sun
3. Performing Organization Name and Address
   Department of Civil Engineering
   University of Louisiana at Lafayette
   Lafayette, LA 70504
4. Sponsoring Agency Name and Address
   Louisiana Department of Transportation and Development
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13. Abstract
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urban two-lane highways are developed, which includes AADT, curve radius, and intersection skewness as independent variables. Based on the analysis and final site investigation, the research strongly recommends using the following low-cost speed reduction strategies to reduce roadway departure crashes at TWSC curved intersections with small curve radius even though these intersections have not manifested high yearly single vehicle crashes due to their light traffic volume: adding exclusive left-turn lane on major roadways with high AADT and left-turning traffic volume; making stop bar visible, moving stop bar forward, and trimming bushes regularly in summertime for better sight-distance on minor roads; and installing intersection on curve signs that are currently not widely used in the state.

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LTRC appreciates the dedication of the following Project Review Committee Members in guiding this research study to fruition.

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Safety Research Manager

Members

Trey Jesclard
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Steve Strength
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Bert Moore
Ben Boudreaux

Directorate Implementation Sponsor

Christopher P. Knotts, P.E.
DOTD Chief Engineer

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By
Xiaoduan Sun, Ph.D., P.E.
Ming Sun, Ph.D. Candidate

Department of Civil Engineering
University of Louisiana at Lafayette
Lafayette, LA 70504

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Abstract

Horizontal curves and intersections pose challenges to drivers and other roadway users because of their unique design and function, which is why both features have been recognized as the target areas for safety improvement in many states' highway safety strategies. There is little research on assessing safety of intersections on horizontal curves. Thus, this project's goal was to quantitatively investigate safety of intersections on curves, specifically the Two-Way Stop-Controlled (TWSC) intersections. The analysis results show that clearly there is a safety problem associated with intersections placed on horizontal curves and the magnitude of the problem depends on the AADT, curve radius, intersection skewness angle, number of intersection legs, and speed limit on major road. The single vehicle crashes are the most common type of crashes on curve intersections, particularly on rural two-lane highway. Using the risk analysis process developed to facilitate the systemic safety approach, the project develops the ranking models for TWSC intersection on curves. With the rich data created by this project, the safety performance models for TWSC intersections on rural and urban two-lane highways are developed, which includes AADT, curve radius, and intersection skewness as independent variables. Based on the analysis and final site investigation, the research strongly recommends using the following low-cost speed reduction strategies to reduce roadway departure crashes at TWSC curved intersections with small curve radius even though these intersections have not manifested high yearly single vehicle crashes due to their light traffic volume: adding exclusive left-turn lane on major roadways with high AADT and left-turning traffic volume; making stop bar visible, moving stop bar forward, and trimming bushes regularly in summertime for better sight-distance on minor roads; and installing intersection on curve signs that are currently not widely used in the state.

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Implementation Statement

The results of this project offer implementation potentials in two aspects:

1. Since the research has revealed that TWSC intersection on curve (with radius less than 1,500 ft.) has higher crash risk, the state DOTD may consider to program these locations for improvement based on the ranking methodologies with the flexible weighting factors developed by the study to count the individual jurisdiction safety improvement priorities.
2. The developed safety performance model for TWSC intersection may consider to replace or serve as a complement to the HSM models to predict and evaluate the TWSC intersection safety performance.

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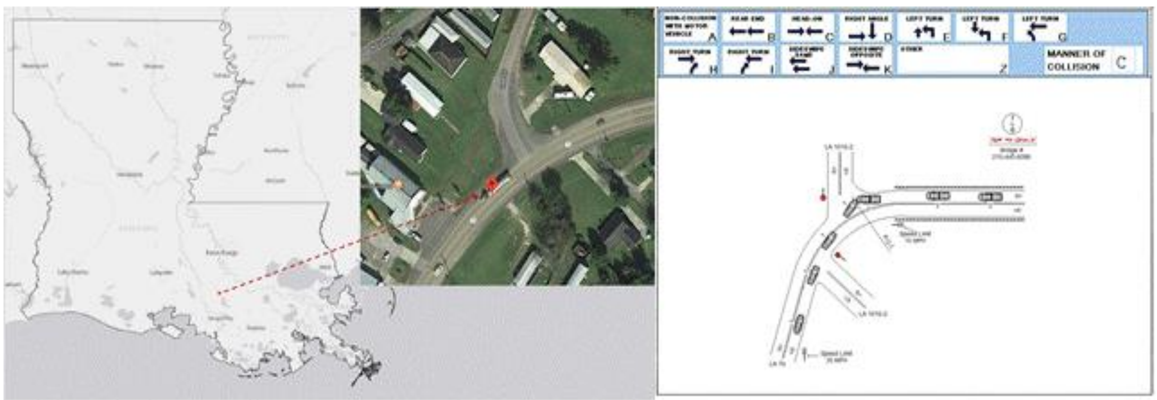
Introduction

Horizontal curves and intersections pose challenges to drivers and other roadway users because of their unique design and function, which is why both have been separately recognized as the target areas for safety improvement in many states' highway safety strategies. On horizontal curves, vehicles are more likely to leave the travel lane of a roadway when the roadway alignment changes direction, particularly on curves with small radius. In 2016, approximately 25% of roadway fatalities occurred along horizontal curves in the United States according to the Fatality Analysis Reporting System (FARS). The average crash rate for horizontal curves is about three times higher than that of tangent segments [1]. Furthermore, about 76% of the horizontal curve-related fatal crashes involve single vehicles leaving the roadway and striking trees, utility poles, rocks, or other fixed objects or overturning [2].

Intersections are locations where two or more roads join or cross one another. The crossing and turning maneuvers that occur at intersections create conflicts between vehicles, vehicle and pedestrian/bicycle, which may result in traffic crashes. Thus, intersections are likely points for concentrations of traffic crashes [3]. According to FHWA about one-quarter of traffic fatalities and roughly half of all traffic injuries over the last several years are attributed to intersections in the United States. In 2017, 10,301 fatalities (27.7% of total traffic fatalities) involved an intersection in the U.S. Nearly 70% of the intersection related fatalities occurred at unsignalized intersections. The common types of intersection crashes are rear-end and angle-collisions, which are the most severe types of crashes, often leading to death or severe injury. The safety of unsignalized intersections is of particular concern because the majority of intersections along low- to moderate-volume roads in rural and suburban areas are unsignalized. Stop-controlled intersections represent the potential hazards not present at signalized intersections. The probability of a fatality per 100 crashes is more than 12 times greater at rural stop-controlled intersections compared to urban signalized intersections [4]. At such intersections, vehicles stopping or slowing to turn create speed differentials between vehicles traveling in the same direction. This is particularly problematic on two-lane highways.

Undoubtedly, having an intersection on a horizontal curve could increase the crash risk because of these combined challenges. Although AASHTO states that "an intersection on a sharp curve should be avoided or designed to compensate for reduced sight distance," in design practice, it is often allowed to have an intersection on a super elevated curve if other solutions are prohibitively expensive. Many such intersections were constructed after or long after the major roadway was built in order to provide accessibility to a minor street. There are many intersections on horizontal curves located on state-owned and locally-owned roads in Louisiana based on our investigation. Figure 1 shows a collision that occurred at a T-intersection (a common intersection type on rural two-lane roadway with stop sign on minor road) between a right-turning vehicle and a running off roadway vehicle trying to negotiate the curve.

Figure 1. A typical example of an intersection on a horizontal curve



To improve the roadway safety, Louisiana’s Strategic Highway Safety Plan (SHSP) aims to reduce roadway departure, intersection, and non-motorized user fatalities and severe injuries by 50% by 2030. Unfortunately, in 2016 Louisiana intersection-related fatalities and severe injuries accounted for 19.1% of total fatalities and 39.9% of total severe injuries, respectively. Furthermore, roadway departure-related fatalities and severe injuries accounted for 57.7% of total fatalities and 40.5% of total severe injuries. In order to decrease these numbers, achieve the target, and prevent further intersection crashes, we need to better understand the magnitude of the problem and identify the risk factors or roadway characteristics that contribute to fatalities and severe injuries at intersections on horizontal curves on all public roads in Louisiana.

Literature Review

The goal of this literature review is to see what crash contributing factors on stop-controlled intersections have been identified and how to quantify crash risk and develop safety performance functions (SPFs) of stop-controlled intersections.

Risk Factors

Traffic Volume

Various predictive models have been developed over time relating stop-controlled intersection safety to traffic volume. Most of the studies [5, 6, 7, 8, 9, 10, 11, 12, 13, 14] [15, 16, 17] have found traffic volume to be by far the most important variable.

Bonneson and McCoy conducted a study of 125 Two-Way Stop-Control (TWSC) rural four-leg intersections in Minnesota [13]. They found ADT values to be the only significant variable contributing to accident frequency. In their case, separate variables were created for the ADT on each road as shown here:

$$N = K * (ADT_1)^{0.258}(ADT_2)^{0.831} \qquad [1]$$

Where,
N = mean number of crashes per unit time
K = constant
ADT1 = ADT on major road
ADT2 = ADT on minor road

In addition to traffic volume, past researchers have shown a variety of geometric design elements to have a wide range of effects on the number of crashes at an intersection. Vogt and Bared [6] developed a set of negative binomial modes for three-leg intersections and four-leg intersections on rural two-lane highways. Their model predicted the mean number of crashes per unit time and was of the form:

$$\hat{y} = exp[-11.48 + 0.82LOG(ADT1) + 0.51LOG(ADT2) + 0.26VI + 0.36HI + 0.027SPDI + 0.18HRI + 0.24RT] \qquad [2]$$

Where,
$\hat{y}$ = mean number of crashes per unit time

ADT1 = ADT on major road
ADT2 = ADT on minor road
VI = crest curve grate rate
HI = degree of curve for horizontal curves
SPDI = posted speed on the major road
HRI = roadside hazard rating
RT = exactly one right-turn lane

As expected, traffic volume plays an important role in crash occurrence. Crash frequency increases significantly as the volume increases on each road. Intersection crashes depend primarily on traffic, as well as most of the roadway variables collected. These design elements are of concern because they may help transportation professionals correct and avoid potential safety problems.

Number of Intersection Legs

Harwood et al. [18] showed that four-leg intersections on a divided highway (major road) experienced almost twice as many crashes as three-leg intersections for narrow medians (16 ft.). Bauer and Harwood [5] showed that rural and urban stop-controlled four-leg intersections had twice as many crashes as the three-leg intersections. Kulmala [9] has found that a four-leg intersection is safer than two three-leg intersections for low minor approach traffic volume, but less safe for high minor approach volume.

Curvature

Past research has conclusively shown that the presence of horizontal curves adds complexity to intersections and negatively affects safety. Kuciemba and Cirillo's studies found that safety is affected by the presence of horizontal curves in close vicinity of intersections [19]. Zegeer et al. found the degree of curve increase the crash rate by 1.5 to 4 times than that of a similar tangent section [20]. Shankar et al. found increasing curvature has a negative impact on safety in their study of rural freeway accidents [21]. Hauer found that for any given deflection angle, the design with the larger curve radius is always safer than a similar intersection with a smaller radius, and the change in accidents is proportional to the change in radius length [22]. Further explanations of the relationship between curvature and safety were provided by McGee et al. [23] and Vogt and Bared [6]. Vogt and Bared [6] described the development of a negative binomial regression model for three types of intersections on rural roads in California and

Michigan, for the period of 1993 to 1995. The study involved 84 three-leg intersections, 72 four-leg intersections, and 49 signalized intersections. The degree of curve was found to increase the total number of crashes on three-leg intersections between four-lane major roads and two-lane stop-controlled minor roads. Savolainen and Tarko conducted a study for the Indiana Department of Transportation (INDOT) and found that curvature was a significant factor in the relative safety of intersections, where the intersection is two-lane TWSC, and the major road is a rural four-lane divided highway. Negative Binomial (NB) models were developed to determine the statistical relationship between crash occurrence and intersection geometric characteristics. The same study stated that full curvature and super elevation increased crashes by 30%, in comparison to tangent intersections [24].

Lane Width

Narrow travel lanes (9-11 ft.) on rural two-lane highways have been associated with increases in single vehicle run-off-the-road, head-on, and sideswipe crashes [25, 26], and the effect is most pronounced at lane widths of 9 ft. or less. However, a recent study in rural Pennsylvania found a lower occurrence of total crashes and fatal and injury (FI) crashes with narrower lanes [27]. Yet another study found that narrower lane widths were associated with reductions in same-direction crashes, fatal, and incapacitating injury crashes, but an increase in single-vehicle crashes as well as total crashes, non-incapacitating injury (B and C), and property damage only (PDO) crashes [28].

Left and Right-Turn Lanes

Auxiliary turn lanes—either for left turns or right turns—provide physical separation between turning traffic that is slowing or stopped and adjacent through traffic at approaches to intersections. Turn lanes can be designed to provide for deceleration prior to a turn, as well as for storage of vehicles that are stopped and waiting for the opportunity to complete a turn. While turn lanes provide measurable safety and operational benefits at many types of intersections, they are particularly helpful at TWSC intersections [29]. Crashes occurring at these intersections are often related to turning maneuvers. Since the major route traffic is free flowing and typically travels at higher speeds, crashes that do occur are often severe. The main crash types include collisions of vehicles turning left across opposing through traffic and rear-end collisions of vehicles turning left or right with other vehicles following closely behind. Turn lanes reduce the potential for these types of crashes. According to “Proven Safety Countermeasures” published by FHWA in 2017, left turn lanes at TWSC intersections can reduce total crashes by 28-48%, while right turn lanes can lead to 14-26% reduction in total crashes.

Kulmala [9] found that the inclusion of a left-turn lane on the major approach reduced the number of rear-end crashes at stop-controlled intersections. Similarly, Vogt [30] found that the presence of one or more left-turn lanes for four-leg stop-controlled intersections resulted in a reduction in total crashes.

Hauer [31] found that providing left-turn lanes at stop-controlled intersections, and at the same time combined with the installation of curbs or raised medians, reduced crashes by 70%, 65%, and 60% at urban, suburban, and rural areas, respectively.

Bauer and Hardwood [5] indicated that right-turn channelization resulted in a decrease in both total multiple-vehicle crashes and fatal and injury multiple-vehicle crashes. A comprehensive study was conducted by Hardwood et al. [32] to evaluate the safety effectiveness of left- and right-turn lane improvements, and also developed quantitative safety effectiveness measures for installation design improvements. The study found a 5% reduction in the number of crashes when providing a right-turn lane on one major approach to a rural stop-controlled intersection, and a 10% reduction when the provision is done along both major approaches. Savolainen and Tarko also found that right-turn lanes tend to significantly decrease the number of crashes occurring at an intersection [12]. However, according to Vogt and Bared's research, peculiarities of the models include the positive coefficient for right-turn lanes. Right-turn lanes on the major roads increased the likelihood of crashes at three-leg intersections by 27%, while it is not significant at four-leg intersections [6]. An interesting finding was that having no right-turn lanes or one right-turn lane on the major road decrease fatal injury probability [17].

Intersection Skewness

Optimally, an intersection should be designed to have roadways cross at a 90-degree angle. In situations where the intersecting angles are 60 degrees or less, the intersections are considered skewed. According to "Intersection Safety: A Manual for Local Rural Road Owners," which was published by FHWA in 2011, potential problems associated with skewed intersections include [33]:

- Vehicles may have a longer distance to traverse while crossing or turning onto the intersecting roadway, resulting in an increased period of exposure to the cross-street traffic;

- Older drivers may find it more difficult to turn their heads, necks, or upper bodies for an adequate line of sight down an acute-angle approach;
- The driver's sight angle for convenient observation of opposing traffic and pedestrian crossings is decreased;
- Drivers may have more difficulty aligning their vehicles as they enter the cross street to make a right or left turn;
- Drivers making right turns around an acute-angle radius may encroach on lanes intended for oncoming traffic from the right;
- The larger intersection area may confuse drivers and cause them to deviate from the intended path;
- Motorists on the major road making left turns across an obtuse angle may attempt to maintain a higher than normal turning speed and cut across the oncoming traffic lane on the intersecting street; and
- The vehicle body may obstruct the line of sight for drivers with an acute angle approach to their right.

McCoy et al. [34] found that as the skew angle increased, crashes at rural TWSC three- and four-leg intersections increased as well. Vogt and Bared [6] used adjusted intersection angle $DELT = (\alpha - 15)^2/100$ in degrees squared to indicate the relationship between intersection crash frequency and intersection angles. The results showed the negative coefficient for four-leg intersections. Burchett and Maze conducted a study for 200 TWSC expressway intersections in Iowa. They concluded that skewed intersections tend to have more severe crashes than intersections with other features. Haleem and Abdel-Aty [17] found that intersection's skewness angle less than or equal to 75 degrees significantly increases fatal injury probability by 0.4%, when compared to the skewness angle greater than 75 degrees.

Speed

Summersgill et al. [35] and Pickering and Hall [36] found that there was no sufficient evidence that vehicles' speed on both major and minor roads have an influence on crashes. It is to be noted that this result was based on a narrow band of speed data, since Pickering and Hall analyzed only rural stop-controlled intersections with speed limits over 50 mph, and Summersgill and Kennedy analyzed only three-leg stop-controlled intersections on 30 and 40 mph roadways. Hence, a significant trend between speed and crash occurrence was difficult to result with such limited speed data.

By contrary, the study conducted by Brude [37] showed that lower speeds were found to improve intersection safety. Similarly, Haleem and Abdel-Aty [17] found that lower speed limits (less than 45 mph) significantly reduce fatal and severe injury probability for both three-leg and four-leg intersections. This confirmed the studies by Malyshkina and Mannering [38] and Renski, Khattak, and Council [39], who examined the safety effect of speed limits on severe crashes and found that high speed limits are associated with high crash severities.

Lighting

The presence of lighting at stop-controlled intersections appears to be associated with lower crash rates. For example, Bauer and Harwood [5] found that lighted rural four-leg stop-controlled intersections experienced fewer crashes than non-lighted intersections. In the same trend, Brude [37] found that, in dark hours, there were 30 percent fewer crashes at lighted intersections than unlighted intersections. Preston and Schoenecker [40] and Donnell, Porter, and Shankar [41] performed statistical analysis of crash frequencies and other crash characteristics at isolated rural intersections to see the effects of installing street lighting.

Risk Factor Analysis Methods

A procedure for ranking rural stop-controlled intersections was proposed by Montella and Mauriello [42]. This procedure used quantitative safety evaluations performing as part of the safety inspection process. The procedure evaluated a safety index that can be used to rank intersections for further investigation. The safety index was formulated by combining two components of risk: exposure of road users to road hazards and the probability of their becoming involved in a crash. The safety index can be assessed whether crash data are available or not. If crash data are available and their quality is good, the safety index can be effectively used in conjunction with the Empirical Bayes (EB) estimate of frequency as ranking criteria. If crash data are not available or poor, the safety index can be used as a proxy for crash data and becomes the only ranking criterion. The safety index was assessed in 22 three-leg intersections in Italy. In the same intersections, a safety performance function was calibrated and the EB refinement technique was used to obtain a better estimate of existing safety performance. Correlation between safety index values and EB safety estimates was highly significant, with 84% of the variation in the estimated number of crashes explained by the safety index value. The results showed that rankings from the safety index and the EB estimate agree at the 99.9% significance level.

Several studies utilized classification models of data mining techniques to identify the risk factor and its importance [43, 44, 45, 46]. A classifier is a function that classifies the class variable given a set of input variables, which are called feature or attribute variables. Typically, crash occurrence or severity level is set as a class variable and risk factors are set as feature variables. Among the classification models, the decision tree classifier is commonly used in data mining. The decision tree does not require any specific functional form to build a model, and the model can be easily interpreted for obtaining insights on risk factors. Furthermore, the decision tree does not require any assumption on dependency among the risk factors, and it is known to work well regardless of the dependency among the data fields.

Delen et al. presented the dependent/response variable (injury severity) as a binary variable with two possible outcomes (low- versus high-level of injury severity) for automobile crashes [43]. The study applied three prevalent data mining techniques: multi-layered perception type neural networks, support vector machines, and decision trees, along with the logistic regression models to identify the relative importance of the crash related risk factors.

Geurts et al. performed a sensitivity analysis to investigate how big the impact would be on the current ranking of crash locations in Flanders (Belgium) when only taking into account the most serious injury per crash instead of all the injured occupants [44]. Each site, where in the three years (1997-1999) that three or more crashes have occurred, was selected. Then, a location was considered to be dangerous when its score for priority (S) equals 15 or more, as shown here:

$$S = 1 \times X + 3 \times Y + 5 \times Z \quad [3]$$

Where,
X = total number of light injuries
Y = total number of serious injuries (each casualty that is admitted more than 24 hours in hospital)
Z = total number of deadly injuries (each casualty that died within 30 days after the crash)

This method corresponded with the “method of the crash severity ratio,” where road sections are classified according to their gravity rate, which is calculated using weighted coefficients for different types of casualties. They proposed a Bayesian ranking plot in order to visualize the probability that a location will be ranked as dangerous, based on estimates from a hierarchical Bayes model.

Papadimitriou et al. conducted the review and comparative assessment of infrastructure related crash risk factors, with the explicit purpose of ranking them based on how detrimental they are towards road safety (i.e., crash risk, frequency, and severity) [45]. Kwon et al. investigated 25 fields in the crash reports between 2004 and 2010 that are most relevant to vehicle crashes in California [46]. Using two classification methods, the Naive Bayes classifier and the decision tree classifier, the relative importance of the data fields (i.e., risk factors) is revealed with respect to the resulting severity level. The analysis showed that only a handful of the risk factors in the data dominated the severity level and that dependency among the top risk factors was an imperative trait to consider for an accurate analysis.

Modeling

Various models were developed to study the relationship between crashes at intersections and contributing factors. Bauer and Harwood [5] applied multiple linear regression analysis in developing crash prediction models for at-grade intersections in California, using three years of crash data (1990 to 1992), as well as geometric design, traffic control, and traffic volume data. The multiple linear regression was used for urban four-leg stop-controlled and signalized intersections, while Poisson and NB regression were used for the remaining intersection types. Poisson and NB models have been used extensively in prior studies [6, 7, 10, 47, 48]. The results indicated that roadway geometric, vehicular, and operational features had an effect on crash frequency. Therefore, those factors that significantly affect crashes should be given more attention in crash analyses at intersections [49].

Data collected from the states of Minnesota (1985-1989) and Washington (1993-1995) on rural two-lane highways were used to build crash models for road segments, one-way stop-controlled intersections with three legs, and TWSC intersections with four legs. Poisson, NB, and extended NB models concluded that intersection crashes depend primarily on traffic volume [6]. A. Vogt presented a model that described the collection, analysis, and modeling of crash and roadway data for three-leg intersections on rural roads in California and Michigan for the years 1993-1995. NB models were developed in this study [30]. A simultaneous-equations model of crash frequency by collision type was developed and presented using crash data for rural intersections in Georgia [50]. Poisson and NB regression models were fit to intersection crash data from Georgia, California, and Michigan in a study, which proposed a macro level crash prediction model that can be used to understand and identify effective countermeasures for improving stop-controlled intersections on multiple-lane highways in rural areas [51].

Several states have developed their own intersection SPFs, including Illinois, Oregon, Virginia, Pennsylvania, and Michigan. Tegge, Jo, and Ouyang [52] developed SPFs for the following rural intersection subcategories in Illinois: (1) rural minor leg stop-control, (2) rural all-way stop-control, (3) rural signalized intersections, and (4) rural undetermined. Each SPF was developed for different severity subcategories, which included fatal (K), injury (A, B), and fatal injury (FI). Monsere et al. [53] documented two SPFs for Oregon intersections, one for rural three-leg minor stop-control intersections and the other for urban four-leg signalized intersections and used data collected at 115 rural three-leg stop-controlled intersections between 2005 and 2007.

Garber and Rivera [54] developed SPFs for both total crashes and fatal and injury crashes of urban and rural, three-leg and four-leg, and signalized and stop-controlled intersections in Virginia using generalized linear modeling. Major and minor road AADTs as well as left-turn lanes and presence of lighting were the independent variables considered in their model. All of these studies show that calibrated SPFs based on the Highway Safety Manual (HSM) predictive method have considerably different precisions for different states.

Donnell, Gayah, and Li [55] have documented SPFs for different facilities in Pennsylvania. As such, SPF models were developed for three-leg and four-leg rural intersections with minor street stop-controlled, all-way stop-controlled, and signalized intersections. NB regression was used to develop these models. It is worth noting that this research did not use crash modification factors to account for site geometric variables but included these variables in the regression model. The SPFs included variables such as major and minor AADTs, left and right shoulder width on the major and minor roads, paved width on major roads, and posted speed limits.

Gates et al. [56] developed SPFs for rural road segments and intersections in the state of Michigan. The facility types included two-lane and four-lane state trunklines (divided and undivided), rural county roadways, signalized intersections, and stop-controlled intersections with data from 2011 to 2015. NB regression was used in this study. In addition to AADT, detailed models were developed, which also considered factors such as shoulder widths, driveway density, horizontal curvature, median presence, road surface types, and intersection skew.

When there is a zero-crash record over a period of time, it may indicate either that the intersection is nearly safe, or that the zero record is a chance occurrence or crashes are not reported. Since the standard Poisson and NB models do not help to identify crash contributory factors in this case, it becomes necessary to model the two states [49]. To handle count data with excess zeros, the zero-inflated models (ZIP and ZINB) have been used in many traffic safety studies. Miaou et al. first used ZIP structure for traffic crash analysis [57]. Shankar et al. presented an empirical review into the applicability of zero-inflated count data modeling to roadway segment crash frequencies. The findings show that the ZIP structure models have great flexibility in uncovering processes affecting crash frequencies on roadway sections observed with zero crash and those with observed crash occurrence [58]. A study by Lee and Mannering used zero-inflated count models and nested logit models for developing crash frequency models and severity models. The findings also showed significant potential in applying these two techniques to single vehicle crash analysis [59]. Empirical models based on ZIP were presented and discussed in terms of their applicability to pedestrian crashes in two studies [60, 61]. The results showed that ZIP is effective enough to provide explanatory insights into the causality behind pedestrian crashes. Lord et al. used ZIP and ZINB to account for the dominance of excessive zeroes observed in crash data of vehicle crashes [62]. Zero-inflated models have also been used to analyze crash severity on rural two-lane roadway segments [63]. Recently, more crash modeling techniques have been studied, such as the Negative Binomial–Lindley (NB–L) model [64, 65] and the NB-L generalized linear model [66]. Lord and Mannering [67] provided discussions about the advantages and limitations of these distributions and models.

While recognizing the safety challenges at intersections and horizontal curves, there is little work on how the combination of these two features affect roadway safety. The safety models in the first edition of HSM assume relationship between safety performance and traffic volumes is the same on curve and tangent intersections even though previous research shows this might not be the case. To sustain the long-term crash reduction trend, the state safety program needs to work on all highway facilities that have high safety risk but not been identified because of relatively low disposure to traffic. TWSC intersections on horizontal could be one of such roadway facilities.

Objective

The goal of this project was to quantify safety performance of two-way stop-control intersections on horizontal curves of Louisiana state and non-state roads. Specifically, the objectives were to:

1. Determine significance, magnitude, and relevance of the problem
2. Identify risk factors or roadway characteristics associated with intersections on horizontal curves
3. Develop a list of possible countermeasures that target the identified risk factors

Scope

In the original proposal, the project scope covers all stop-controlled intersections on state and non-state roadways. However, after the time-consuming data processing that includes verification and validating each intersection's location, number of approaches, and type of traffic control, researchers found out:

- Many important data are unavailable, missing, or inaccurate for intersections on non-state roadway.
- The majority of stop-controlled intersections are TWSC (only 18 intersections identified as all-way stop-control).

Thus, this research is on Louisiana TWSC intersections that consist of either a state roadway intersecting another state roadway or a state roadway with a non-state roadway. In all cases, a state roadway is the major roadway.

Methodology

Database Development

Location Identification Methodology

To better understand the relationship between roadway characteristics and safety performance on TWSC intersections in Louisiana, we need to develop a comprehensive intersection database that contains both intersection feature and safety (crashes by severity and collision type) in Louisiana. The information was obtained from a variety of sources.

Data Sources

The types of data used in this research include location, roadway information, traffic data, and crash data. These data were obtained from different sources and were integrated together. The most recent five-year crash data (2013 to 2017) were used to reflect the latest highway safety. The raw data obtained are shown in the following table.

Table 1. Data source

Source	Data Platform	File Name	Main Data Elements
Base map	On GIS platform (polyline)	LA_Roadways.gdb	Highway design, control section, functional class/highway class
Geodatabase – Curve.gdb	On GIS platform (polyline)	Curve (State roads)	Highway type (arc or tangent), radius, deflection degree, elevation, control section
		HORIZONTAL_CURVE_LOCAL (non-state roads)	
Geodatabase – State_ Highway_Assets.gdb	On GIS platform (point)	INTERSECTION_2012	District, Parish number, control section, logmile, highway class, latitude & longitude
		LANE_WIDTH_2012	Lane width
		SPEED_LIMIT_SIGN_2012	Speed limit

Source	Data Platform	File Name	Main Data Elements
Excel worksheet (DOTD intersection)		dbo_intersection_legs_ 2016 _combined_rev	Intersection name (XX@XX), number of legs, AADT on major (2% missing) and minor roadways (21% missing)
Crash data (DOTD Highway Crash List)		CSV file	Crash characteristics, severity, longitude/latitude, environmental conditions

Intersection Identification and Database Assembly

The shapefiles from the DOTD State Highway Assets Geodatabase in ArcGIS format provide the spatial basis for gathering the necessary roadway attributes for the intersections, such as horizontal curve radius for major and minor roads, lane widths, number of intersection legs, speed limits, etc. The data process was facilitated by the intersection identification number and intersection name, used in the DOTD system, which allowed data from different sources to be identified.

As shown in Figure 2, there are several important steps in retrieving and merging different data files from DOTD, which are summarized as follows:

- Step 1. Set up a curve file with radius less than 1,500 ft. based on the file curve.
- Step 2. Set up a new intersection file by retrieving intersections not controlled by signals from INTERSECTION_2012.
- Step 3. Merge above two files together as the intersection on curve and the intersection on tangent.
- Step 4. Verify and correct files developed in step 3 with Google Map (intersection by intersection on each parish) to delete the followings:
  - I. Curve or intersection turning (as shown in Figure 3)
  - II. Roundabout and service road (as shown in Figure 4)
  - III. Signalized (as shown in Figure 5)
- Step 5. Populate crash data into the file developed in step 4
- Step 6. Merge all relevant information into one data file

Figure 2. Database development flow chart

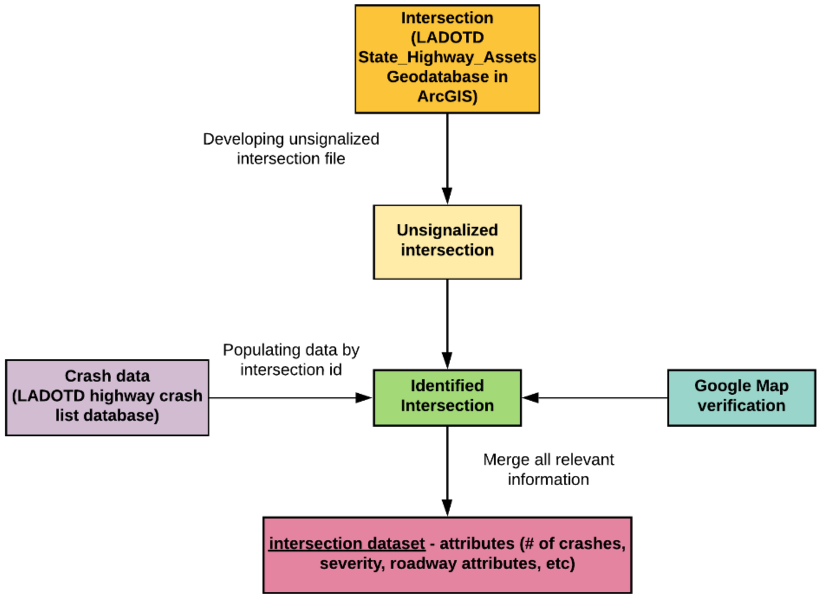


Figure 3. An example of intersection turning coded as curve

Figure 4. An example of a roundabout turning coded as curve

Figure 5. An example of a signalized intersection coded as a TWSC intersection

Intersections with incomplete and, obviously, incorrect data (such as AADT entered as zero or blank) were removed from the analysis. Two unique databases of intersections were developed: the first included only tangent intersections, while the second included only curve intersections.

Traffic Volume

AADT data for DOTD state highways (major roadways) and non-state roadways (minor roadways) were obtained system-wide for each intersection directly from DOTD highway crash list and the 2016 DOTD intersection inventory file, where available.

AADT data for non-state roadways is not 100% available in the current DOTD highway crash list database and the 2016 DOTD intersection inventory file (21% missing), and the years for which traffic volumes were available varied, the research team used intersection identification number and intersection name to merge AADT data from the above two sources, where available.

Manually Collected Data and Verification

Satellite imagery and street-level imagery was utilized to manually collect additional roadway data that was not otherwise included in the existing data sets, including:

- Turn lanes presence: Right and left turn lanes were identified based on presence of pavement markings and/or sign designations. Tapers or widened shoulders were not considered.
- Skewness: Intersection skew angles were obtained using the ruler tool in Google Earth. The HSM defines intersection skew angle as the absolute value of the deviation from an intersection angle of 90 degrees. In this definition, skew can range from zero for a perpendicular intersection and to a maximum of 89 degrees. For this study, skew was measured as the smallest angle between any two legs of the intersection.

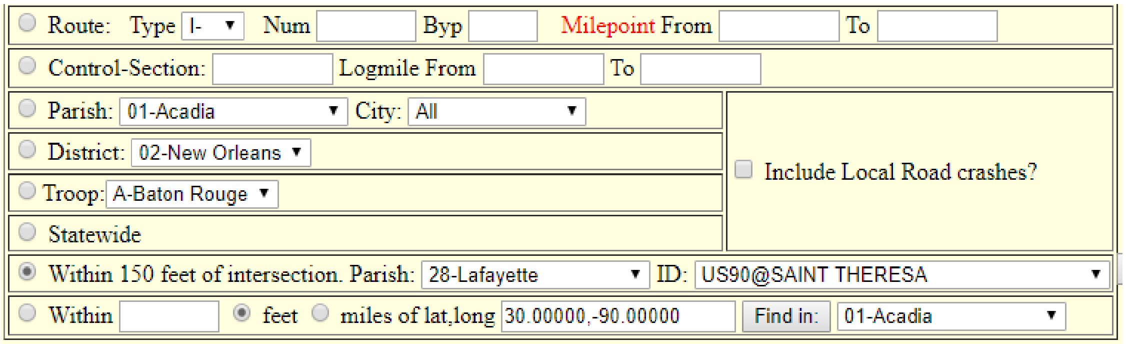
To assure the data accuracy, a significant effort was made to verify and correct the information presented in the data files shown in Figure 2. Google Maps and Google Earth were also utilized to examine the data accuracy intersection by intersection such as turning radii and type of traffic control (15% of the data) to improve data accuracy.

Crash Data

According to DOTD, an intersection crash refers to a crash occurred within a 150-ft. radius of an intersection. Once all the curve and tangent intersections were geographically referenced in the map, all crashes occurring within 150 ft. of those intersections were obtained for years 2013 through 2017. The DOTD highway crash list database was queried to select crashes along those intersections by parish and intersection

ID. An example is shown in Figure 6. All relevant crash related fields (i.e., severity, crash type, etc.) were collected from the crash database. Each intersection has a unique identification number that links the crash records and the intersection datasets together.

Figure 6. An example of crash data collection for an intersection



A comprehensive dataset was created by joining all the five years of crash data on the curve intersections to the previously created intersection dataset with all the road, traffic, lane, etc. information. A similar dataset was obtained for the tangent intersections as well.

Using the DOTD highway crash list database, the following parameters were recorded for each crash:

- Total number of injuries
- Total number of fatalities
- Date of crash
- Time of crash
- Manner of collision
- Type of vehicles involved in the accident
- Contributing factor(s)
- Severity
- Latitude/longitude
- Lighting conditions
- Road surface conditions

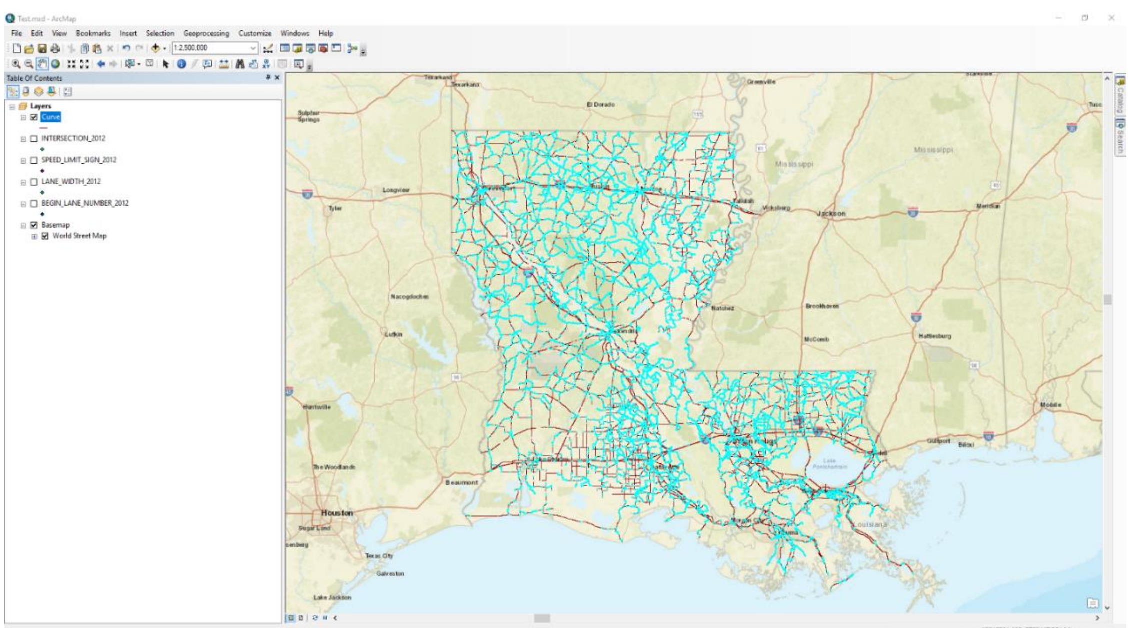
- Roadway departure
- Lane departure

The DOTD's crash database uses the ABCDE scale to describe severity level of crashes. 'A' indicates fatal injury and 'B,' 'C,' and 'D' indicate incapacitating or severe injury, non-incapacitating or moderate injury, and possible or compliant injury, respectively. 'E' represents PDO crash.

ArcGIS Software

Curve intersections and tangent intersections were identified using ArcGIS 10.4.5 software. Location details and extents obtained as discussed earlier were used to select the intersections with "Select by Attributes" and "Select by Locations" functions in ArcGIS 10.4.5 Software. After all the intersections were selected, the selected intersections were exported as a new layer in the map which represented exclusively the curve intersections or tangent intersections. Radius, deflection, degree and other information were included in the attribute table. Figure 7 shows an example of location identification using the ArcGIS 10.4.5 software.

Figure 7. An example of location identification



Summary

The number of TWSC intersections on curve after the data processing is listed in Table 2.

Table 2. Summary of curve intersections

Type	Major Curve		Minor Curve		Curve on Both Roadways	
	Number of intersections	%	Number of intersections	%	Number of intersections	%
Rural two-lane	1,554	93%	53	3%	64	4%
Rural multiple-lane	17	55%	13	42%	1	3%
Urban two-lane	468	98%	5	1%	3	1%
Urban-multiple-lane	140	91%	7	5%	6	4%

The two-lane highways, rural and urban, have the most of TWSC intersections. There are relative few intersections with curve on both roadways (64 on rural two-lane highway and only 10 on other three types combined. Thus, three cases are combined as intersection on curve. Table 3 lists the number of crashes in five years by each type of roadway.

Table 3. Summary of crashes by type of roadway and intersection alignment

Type	Curve*				Tangent**			
	Number of intersections	%	Number of crashes	%	Number of intersections	%	Number of crashes	%
Rural two-lane	1,671	32.60%	1,510	30.30%	3,455	67.40%	3,474	69.70%
Rural multiple-lane	31	12.25%	103	10.82%	222	87.75%	849	89.18%
Urban two-lane	476	21.70%	2,364	25.43%	1,718	78.30%	6,932	74.57%
Urban multiple-lane	153	14.78%	1,756	14.43%	882	85.22%	10,410	85.57%
Total	2,331	27.08%	5,733	20.92%	6,277	72.92%	21,665	79.08%
Overall total number of intersections	8,608							

* Radius less than or equal to 1,500 ft.

** Tangent and curve with radius bigger than 1,500 ft.

Crash Analysis

The major analysis results are presented next by four different types of roadways. The analysis includes intersection on tangent for comparison. Intersection crash rate is calculated as shown in Equation 4:

$$Intersection\ crash\ rate = \frac{Number\ of\ crashes\ in\ the\ 5\ year\ period \times 1{,}000{,}000}{(AADT_{major} + AADT_{minor}) \times 365 \times 5\ years} \quad [4]$$

Rural Two-lane TWSC Intersections

Table 4 lists the average crash rate for rural two-lane TWSC intersections by radius, AADT, and other design related factors. Table 5 provides the summary for crash characteristics of rural two-lane TWSC intersections.

Table 4. Average crash rate by design related factors for rural two-lane TWSC intersections

		On Curve Alignment			On Tangent Alignment		
		Number of intersections	Number of crashes	Average crash rate	Number of intersections	Number of crashes	Average crash rate
Radius (feet)	R≤500	391	457	0.344	3,455	3,474	0.186
	500 <R≤1,000	632	503	0.253			
	1,000<R≤1,500	648	550	0.218			
AADT on Major Road	<1,000	773	301	0.280	1,032	297	0.196
	1,000-1,999	413	363	0.273	871	577	0.184
	2,000-2,999	215	300	0.243	504	624	0.210
	3,000-3,999	110	191	0.222	354	464	0.171
	4,000-5,000	69	120	0.198	263	400	0.154
	>5,000	91	235	0.176	431	1,112	0.172
Curve Length (feet)	L_c≤500	738	691	0.300	N/A	N/A	N/A
	500< L_c ≤1,000	729	611	0.230	N/A	N/A	N/A
	L_c >1,000	204	208	0.229	N/A	N/A	N/A
Speed Limit on Major Road (mph)	<26	97	73	0.194	56	27	0.228
	26-35	166	228	0.248	364	408	0.178
	36-45	217	184	0.238	731	693	0.148
	46-55	958	926	0.288	2,201	2,305	0.203
	No speed limit within 0.5 mile	233	99	0.205	103	41	0.097
Intersecting Angle Skewness	less than 30º	1,602	1,432	0.256	N/A	N/A	N/A
	greater than 30º	69	78	0.358	N/A	N/A	N/A
Left Turn Lane on Major Road	Absent	1,662	1,466	0.259	3,416	3,338	0.185
	Present	9	44	0.508	39	136	0.278
Right Turn Lane on Major Road	Absent	1,668	1,499	0.261	3,435	3,410	0.185
	Present	3	11	0.365	20	64	0.363
Number of Intersection Legs	3-leg	1,531	1,286	0.253	2,894	2,364	0.155
	4-leg	140	224	0.346	561	1,110	0.346

The aggregated crash rates listed above yields the following discussion:

- There is clearly a safety concern for TWSC intersection on curve. In general, the average crash rates on the curve intersections are bigger than that on the tangent TWSC intersections.
- The average crash rate for curve intersection decreases as curve radius increases. When the curve radius is less than or equal to 500 ft., the crash rate on rural two-lane curve TWSC intersections is 85% higher than that on the tangent (0.344 vs. 0.186).
- As expected, the crash rate increases as speed limits increase for both intersection alignments, except for tangent intersection at the lowest speed limit where the crash rate is the highest. Speeding is probably the factor.
- Clearly the intersecting angle makes a difference in intersection safety, having a skewness angle bigger than 30 degrees (not recommended by the design guideline) results in a higher crash rate (0.358 vs. 0.256).
- Because of very few intersections having turning lanes, the crash rates do not lead to any reliable discussion.
- Due to a reduced number of conflicting points, T-intersections are safer than four-leg intersections (0.253 vs. 0.346 on curve intersections and 0.155 vs. 0.346 on tangent intersections).

Table 5. Crash characteristics for rural two-lane TWSC intersections

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
Time of Day	12AM-3AM	114	7.56%	41%	163	4.71%	59%
	3AM-6AM	118	7.83%	37%	202	5.83%	63%
	6AM-9AM	202	13.40%	28%	522	15.07%	72%
	9AM-12PM	173	11.48%	28%	451	13.02%	72%
	12PM-3PM	231	15.33%	29%	554	16.00%	71%
	3PM-6PM	298	19.77%	28%	783	22.61%	72%
	6PM-9PM	213	14.13%	30%	499	14.41%	70%
	9PM-12AM	158	10.48%	35%	289	8.35%	65%
	Total	1,507	100%		3,463	100%	
	Missing information	3	0.20% (out of 1,510)		11	0.32% (out of 3,474)	
Manner of Collision	Single vehicle	777	51.46%	41%	1,100	31.66%	59%
	Rear end	224	14.83%	20%	889	25.59%	80%
	Head-on	35	2.32%	38%	57	1.64%	62%
	Right angle	167	11.06%	22%	581	16.72%	78%
	Left turn - angle	27	1.79%	17%	136	3.91%	83%
	Left turn - opposite direction	37	2.45%	20%	144	4.15%	80%
	Left turn - same direction	26	1.72%	25%	80	2.30%	75%
	Right turn - same direction	11	0.73%	17%	55	1.58%	83%
	Right turn - opposite direction	6	0.40%	18%	27	0.78%	82%
	Sideswipe - same direction	24	1.59%	18%	106	3.05%	82%
	Sideswipe - opposite direction	60	3.97%	44%	77	2.22%	56%
	Other	116	7.68%	34%	222	6.39%	66%

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
	Total	1,510	100%		3,474	100%	
Crash Severity	Fatal	21	1.39%	35%	39	1.12%	65%
	Severe	12	0.79%	32%	26	0.75%	68%
	Moderate	186	12.32%	38%	309	8.89%	62%
	Complaint	434	28.74%	29%	1,045	30.08%	71%
	PDO	857	56.75%	29%	2,055	59.15%	71%
	Total	1,510	100%		3,474	100%	
Driver Age	< 20	199	13.88%	29%	496	14.81%	71%
	20-39	679	47.35%	31%	1,515	45.25%	69%
	40-59	349	24.34%	30%	814	24.31%	70%
	60-80	188	13.11%	29%	465	13.89%	71%
	>80	19	1.32%	25%	58	1.73%	75%
	Total	1,434	100%		3,348	100%	
	Missing information	76	5.03% (out of 1,510)		126	3.63% (out of 3,474)	
Driver Gender	Male	938	65.05%	31%	2,119	63.05%	69%
	Female	504	34.95%	29%	1,242	36.95%	71%
	Total	1,442	100%		3,361	100%	
	Missing information	68	4.50% (out of 1,510)		113	3.25% (out of 3,474)	
Driver Condition	Normal	394	26.09%	31%	877	25.24%	69%
	Inattentive	681	45.10%	28%	1,728	49.74%	72%
	Distracted	72	4.77%	24%	232	6.68%	76%
	Illness	4	0.26%	40%	6	0.17%	60%
	Fatigued	15	0.99%	29%	37	1.07%	71%
	Apparently asleep/blackout	34	2.25%	34%	67	1.93%	66%
	Drinking alcohol - impaired	133	8.81%	42%	183	5.27%	58%
	Drinking alcohol - not impaired	10	0.66%	31%	22	0.63%	69%

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
	Drug use - impaired	11	0.73%	18%	51	1.47%	82%
	Drug use - not impaired	0	0.00%	N/A	0	0.00%	N/A
	Physical impairment (eyes, ear, limb)	0	0.00%	0%	4	0.12%	100%
	Unknown	148	9.80%	37%	255	7.34%	63%
	Other	8	0.53%	40%	12	0.35%	60%
	Total	1,510	100%		3,474	100%	
Alcohol	Yes	182	12.05%	40%	272	7.83%	60%
	No	1,328	87.95%	29%	3,202	92.17%	71%
	Total	1,510	100%		3,474	100%	
Vehicle Type	Passenger car	544	36.39%	28%	1,400	40.67%	72%
	Truck	505	33.78%	30%	1,196	34.75%	70%
	SUV	227	15.18%	31%	497	14.44%	69%
	Other	219	14.65%	39%	349	10.14%	61%
	Total	1,495	100%		3,442	100%	
	Missing information	15	0.99% (out of 1,510)		32	0.92% (out of 3,474)	
Lighting Condition	Daylight	896	59.34%	28%	2,259	65.10%	72%
	Dark - no streetlight	444	29.40%	36%	803	23.14%	64%
	Dark - continuous streetlight	45	2.98%	26%	125	3.60%	74%
	Dark - streetlight at intersection only	60	3.97%	30%	142	4.09%	70%
	Dusk	27	1.79%	32%	58	1.67%	68%
	Dawn	28	1.85%	29%	68	1.96%	71%
	Unknown	7	0.46%	35%	13	0.37%	65%
	Other	3	0.20%	60%	2	0.06%	40%
	Total	1,510	100%		3,470	100%	
	Missing information	0	0.0% (out of 1,510)		4	0.12% (out of 3,474)	

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
Surface Condition	Dry	1,236	81.85%	30%	2,898	83.49%	70%
	Wet	265	17.55%	33%	545	15.70%	67%
	Snow/slush	1	0.07%	11%	8	0.23%	89%
	Ice	4	0.26%	36%	7	0.20%	64%
	Contaminant (sand, mud, dirt, oil, etc.)	2	0.13%	22%	7	0.20%	78%
	Unknown	1	0.07%	14%	6	0.17%	86%
	Other	1	0.07%	100%	0	0.00%	0%
	Total	1,510	100%		3,471	100%	
	Missing information	0	0.00% (out of 1,510)		3	0.09% (out of 3,474)	

The most striking fact from the previous table is that the top-ranking crash type is single vehicle on both intersection alignments. For curve intersections, more than half of total crashes are single vehicle running off roadway. At tangent intersections, 32% of total crashes are single vehicle crashes. Another noticeable point is about 26% of curve intersection crashes occurred at night, between 9 pm and 6 am when traffic volume is the lowest on rural two-lane highways, which is further confirmed by the crash distribution with lighting conditions. It is interesting to know that 42% of crashes caused by drinking alcohol and impaired drivers is on the curve intersections.

Urban Two-lane TWSC Intersections

Table 6 provides the average crash rate for urban two-lane TWSC intersections by radius, AADT, and other design related factors. Table 7 provides the summary for crash characteristics of urban two-lane TWSC intersections.

Table 6. Average crash rate by design related factors for urban two-lane TWSC intersections

<table>
<tr><th colspan="2" rowspan="2"></th><th colspan="3">On Curve Alignment</th><th colspan="3">On Tangent Alignment</th></tr>
<tr><th>Number of intersections</th><th>Number of crashes</th><th>Average crash rate</th><th>Number of intersections</th><th>Number of crashes</th><th>Average crash rate</th></tr>
<tr><td rowspan="3">Radius (feet)</td><td>R≤500</td><td>104</td><td>576</td><td>0.424</td><td rowspan="3">1,718</td><td rowspan="3">6,932</td><td rowspan="3">0.273</td></tr>
<tr><td>500 <R≤1,000</td><td>194</td><td>841</td><td>0.361</td></tr>
<tr><td>1,000<R≤1,500</td><td>178</td><td>947</td><td>0.344</td></tr>
<tr><td rowspan="12">AADT on Major Road</td><td><1,000</td><td>33</td><td>35</td><td>0.498</td><td>58</td><td>65</td><td>0.517</td></tr>
<tr><td>1,000-1,999</td><td>42</td><td>57</td><td>0.397</td><td>108</td><td>112</td><td>0.256</td></tr>
<tr><td>2,000-2,999</td><td>43</td><td>162</td><td>0.536</td><td>113</td><td>190</td><td>0.270</td></tr>
<tr><td>3,000-3,999</td><td>40</td><td>99</td><td>0.261</td><td>180</td><td>288</td><td>0.206</td></tr>
<tr><td>4,000-4,999</td><td>64</td><td>206</td><td>0.323</td><td>263</td><td>791</td><td>0.291</td></tr>
<tr><td>5,000-5,999</td><td>23</td><td>70</td><td>0.222</td><td>114</td><td>387</td><td>0.261</td></tr>
<tr><td>6,000-6,999</td><td>46</td><td>377</td><td>0.560</td><td>203</td><td>855</td><td>0.287</td></tr>
<tr><td>7,000-7,999</td><td>25</td><td>112</td><td>0.276</td><td>104</td><td>568</td><td>0.356</td></tr>
<tr><td>8,000-8,999</td><td>37</td><td>337</td><td>0.424</td><td>90</td><td>379</td><td>0.237</td></tr>
<tr><td>9,000-9,999</td><td>27</td><td>167</td><td>0.306</td><td>71</td><td>310</td><td>0.224</td></tr>
<tr><td>1,0000-1,1000</td><td>18</td><td>114</td><td>0.287</td><td>83</td><td>425</td><td>0.241</td></tr>
<tr><td>>1,1000</td><td>78</td><td>628</td><td>0.257</td><td>331</td><td>2,562</td><td>0.275</td></tr>
<tr><td rowspan="3">Curve Length (feet)</td><td>L_c≤500</td><td>260</td><td>1,351</td><td>0.386</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td>500< L_c ≤1,000</td><td>162</td><td>766</td><td>0.368</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td>L_c >1,000</td><td>54</td><td>247</td><td>0.287</td><td>N/A</td><td>N/A</td><td>N/A</td></tr>
<tr><td rowspan="4">Speed Limit on Major Road (mph)</td><td><26</td><td>44</td><td>290</td><td>0.336</td><td>45</td><td>160</td><td>0.183</td></tr>
<tr><td>26 - 35</td><td>153</td><td>688</td><td>0.353</td><td>515</td><td>1,897</td><td>0.259</td></tr>
<tr><td>36 - 45</td><td>166</td><td>842</td><td>0.367</td><td>647</td><td>2,768</td><td>0.285</td></tr>
<tr><td>46 - 55</td><td>113</td><td>544</td><td>0.405</td><td>511</td><td>2,107</td><td>0.278</td></tr>
<tr><td rowspan="2">Left Turn Lane on Major Road</td><td>Absent</td><td>451</td><td>2,188</td><td>0.371</td><td>1,614</td><td>6,047</td><td>0.270</td></tr>
<tr><td>Present</td><td>25</td><td>176</td><td>0.316</td><td>104</td><td>885</td><td>0.318</td></tr>
<tr><td rowspan="2">Right Turn Lane on Major Road</td><td>Absent</td><td>469</td><td>2,288</td><td>0.366</td><td>1,681</td><td>6,624</td><td>0.271</td></tr>
<tr><td>Present</td><td>7</td><td>76</td><td>0.503</td><td>37</td><td>308</td><td>0.322</td></tr>
<tr><td rowspan="2">Number of Intersection Legs</td><td>3-leg</td><td>415</td><td>1,927</td><td>0.348</td><td>1,483</td><td>5,457</td><td>0.248</td></tr>
<tr><td>4-leg</td><td>61</td><td>437</td><td>0.506</td><td>235</td><td>1,475</td><td>0.427</td></tr>
</table>

The aggregated crash rates previously listed reveal somewhat expected trends and a few interesting points:

- Similar to the TWSC intersection on rural two-lane highway, there is a safety concern for the intersection on curve. The average crash rate for TWSC intersections on curve is higher than that on tangent (0.368 vs. 0.273).
- The average crash rate decreases as the radius increases. When the curve radius is less than or equal to 500 ft., the crash rate on urban two-lane curve TWSC intersections is 55% higher than that on the tangent (0.424 vs. 0.273).
- As the speed limit increases, the average crash rate increases on curve intersections.
- Again, due to reduced conflicting points, the average crash rate of T-intersections is smaller than that of four-leg TWSC intersections (0.348 vs. 0.506 on curve intersections and 0.248 vs. 0.427 on tangent intersections).

Table 7. Crash characteristics for urban two-lane TWSC intersections

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
Time of Day	12AM-3AM	108	4.57%	34%	212	3.06%	66%
	3AM-6AM	87	3.68%	29%	210	3.03%	71%
	6AM-9AM	301	12.75%	24%	957	13.83%	76%
	9AM-12PM	324	13.72%	27%	897	12.96%	73%
	12PM-3PM	390	16.52%	24%	1,237	17.87%	76%
	3PM-6PM	660	27.95%	24%	2,041	29.49%	76%
	6PM-9PM	336	14.23%	27%	929	13.42%	73%
	9PM-12AM	155	6.57%	26%	438	6.33%	74%
	Total	2,361	100%		6,921	100%	
	Missing information	3	0.13% (out of 2,364)		11	0.16% (out of 6,932)	
Manner of Collision	Single vehicle	519	21.95%	33%	1,046	15.09%	67%
	Rear end	817	34.56%	23%	2,733	39.43%	77%
	Head-on	54	2.28%	30%	125	1.80%	70%
	Right angle	349	14.76%	21%	1,304	18.81%	79%
	Left turn - angle	67	2.83%	27%	178	2.57%	73%
	Left turn - opposite direction	111	4.70%	27%	293	4.23%	73%
	Left turn - same direction	63	2.66%	23%	212	3.06%	77%
	Right turn - same direction	26	1.10%	18%	119	1.72%	82%
	Right turn - opposite direction	25	1.06%	30%	59	0.85%	70%
	Sideswipe - same direction	69	2.92%	23%	230	3.32%	77%
	Sideswipe - opposite direction	93	3.93%	37%	161	2.32%	63%
	Other	171	7.23%	27%	472	6.81%	73%
	Total	2,364	100%		6,932	100%	

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
Crash Severity	Fatal	11	0.47%	21%	41	0.59%	79%
	Severe	14	0.59%	24%	45	0.65%	76%
	Moderate	147	6.22%	26%	421	6.07%	74%
	Complaint	580	24.53%	24%	1,872	27.01%	76%
	PDO	1,612	68.19%	26%	4,553	65.68%	74%
	Total	2,364	100%		6,932	100%	
Driver Age	< 20	332	14.83%	24%	1,038	15.82%	76%
	20-39	1,031	46.05%	25%	3,090	47.08%	75%
	40-59	554	24.74%	27%	1,529	23.30%	73%
	60-80	289	12.91%	27%	801	12.20%	73%
	>80	33	1.47%	24%	105	1.60%	76%
	Total	2,239	100%		6,563	100%	
	Missing information	125	5.29% (out of 2,364)		369	5.32% (out of 6,932)	
Driver Gender	Male	1,347	59.87%	26%	3,862	58.37%	74%
	Female	903	40.13%	25%	2,754	41.63%	75%
	Total	2,250	100%		6,616	100%	
	Missing information	114	4.82% (out of 2,364)		316	4.56% (out of 6,932)	
Driver Condition	Normal	348	14.72%	21%	1,314	18.96%	79%
	Inattentive	1,491	63.07%	27%	4,097	59.10%	73%
	Distracted	133	5.63%	21%	510	7.36%	79%
	Illness	15	0.63%	42%	21	0.30%	58%
	Fatigued	14	0.59%	32%	30	0.43%	68%
	Apparently asleep/blackout	26	1.10%	29%	63	0.91%	71%
	Drinking alcohol - impaired	98	4.15%	32%	212	3.06%	68%
	Drinking alcohol - not impaired	5	0.21%	16%	26	0.38%	84%
	Drug use - impaired	28	1.18%	33%	57	0.82%	67%

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
	Drug use - not impaired	2	0.08%	40%	3	0.04%	60%
	Physical impairment (eyes, ear, limb)	1	0.04%	13%	7	0.10%	87%
	Unknown	185	7.82%	25%	563	8.12%	75%
	Other	18	0.76%	38%	29	0.42%	62%
	Total	2,364	100%		6,932	100%	
Alcohol	Yes	147	6.22%	31%	332	4.79%	69%
	No	2,217	93.78%	25%	6,600	95.21%	75%
	Total	2,364	100%		6,932	100%	
Vehicle Type	Passenger car	1,054	44.81%	25%	3,230	46.97%	75%
	Truck	659	28.02%	26%	1,911	27.79%	74%
	SUV	440	18.71%	27%	1,179	17.14%	73%
	Other	199	8.46%	26%	557	8.10%	74%
	Total	2,352	100%		6,877	100%	
	Missing information	12	0.51% (out of 2,364)		55	0.79% (out of 6,932)	
Lighting Condition	Daylight	1,676	70.99%	25%	5,092	73.51%	75%
	Dark - no streetlight	307	13.00%	30%	707	10.21%	70%
	Dark - continuous streetlight	193	8.17%	24%	597	8.62%	76%
	Dark - streetlight at intersection only	110	4.66%	25%	325	4.69%	75%
	Dusk	41	1.74%	26%	115	1.66%	74%
	Dawn	28	1.19%	26%	78	1.13%	74%
	Unknown	5	0.21%	33%	10	0.14%	67%
	Other	1	0.04%	25%	3	0.04%	75%
	Total	2,361	100%		6,927	100%	
	Missing information	3	0.13% (out of 2,364)		5	0.07% (out of 6,932)	
	Dry	1,823	77.18%	24%	5,707	82.36%	76%

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
Surface Condition	Wet	529	22.40%	31%	1,195	17.25%	69%
	Snow/slush	2	0.08%	25%	6	0.09%	75%
	Ice	4	0.17%	24%	13	0.19%	76%
	Contaminant (sand, mud, dirt, oil, etc.)	0	0.00%	0%	3	0.04%	100%
	Unknown	4	0.17%	44%	5	0.07%	56%
	Other	0	0.00%	N/A	0	0.00%	N/A
	Total	2,362	100%		6,929	100%	
	Missing information	2	0.08% (out of 2,364)		3	0.04% (out of 6,932)	

The crash characteristics analysis previously listed reveal interesting points:

- Compared to the tangent TWSC intersections, curve TWSC intersections have higher percentage of crashes at night.
- Single-vehicle crash at curve TWSC intersections is 22% compared to 15% for tangent TWSC intersections.
- While 22% of total TWSC intersections are curve intersections, 21% of fatalities and 31% alcohol involvement crashes occurred on such intersections.
- Unlike the rural intersections, the most common type of crashes at urban TWSC intersections is rear-end collisions.

TWSC Intersections on Multiple-Lane Highways

Table 8 lists crash rate by road design factors and AADT for TWSC intersections on rural multiple-lane highways, and Table 9 lists average crash rate by crash characteristics. Table 10 lists crash rate by road design factors and AADT for TWSC intersections on urban multiple-lane highway and Table 11 lists crash rate by crash characteristics. Due to the much smaller sample size, it is hard to drawn reliable discussion.

Table 8. Average crash rate by design related factors for rural multiple-lane TWSC intersections

		On Curve Alignment			On Tangent Alignment		
		Number of intersections	Number of crashes	Average crash rate	Number of intersections	Number of crashes	Average crash rate
Radius (feet)	R≤500	15	69	0.249	222	849	0.205
	500 <R≤1,000	3	1	0.461			
	1,000<R≤1,500	13	33	0.306			
AADT on Major Road	<500	2	2	1.415	N/A	N/A	N/A
	500-999	N/A	N/A	N/A	N/A	N/A	N/A
	1,000-1,499	N/A	N/A	N/A	4	6	0.449
	1,500-1,999	2	2	0.280	1	2	0.493
	2,000-2,499	N/A	N/A	N/A	4	0	0.000
	2,500-2,999	2	5	0.453	8	28	0.438
	3,000-3,499	1	0	0.000	4	0	0.000
	3,500-3,999	N/A	N/A	N/A	4	8	0.245
	4,000-4,499	2	0	0.000	8	3	0.042
	4,500-5,000	1	0	0.000	11	4	0.041
	>5,000	21	94	0.229	178	798	0.213
Curve Length (feet)	L_c≤500	15	65	0.280	N/A	N/A	N/A
	500< L_c ≤1,000	12	33	0.389	N/A	N/A	N/A
	L_c >1,000	4	5	0.056	N/A	N/A	N/A
Speed Limit on Major Road (mph)	<26	2	2	0.280	2	3	0.122
	26 - 35	N/A	N/A	N/A	25	107	0.315
	36 - 45	15	64	0.240	60	221	0.199
	46 - 55	9	22	0.472	57	231	0.184
	>56	5	15	0.136	78	287	0.191
Left Turn Lane on Major Road	Absent	19	54	0.324	93	306	0.203
	Present	12	49	0.245	129	543	0.206
Right Turn Lane on Major Road	Absent	27	100	0.326	186	588	0.187
	Present	4	3	0.075	36	261	0.299
Number of Intersection Legs	3-leg	22	29	0.260	144	514	0.165
	4-leg	9	74	0.376	78	335	0.277

The previous aggregated crash rates listed yield a few discussion points:

- There is safety concern on curve intersections. The average crash rates on curve TWSC intersections are bigger than that on the tangent TWSC intersections (0.293 vs. 0.205).
- Because of the limited number of TWSC intersections on rural multiple-lane highways, the differences in crash rates by AADT, or curve radius, speed limits, and turning lanes do not reveal any meaningful patterns.
- Due to the reduced number of conflicting points, the average crash rate of three-leg TWSC intersections is smaller than that of four-leg TWSC intersections (0.260 vs. 0.376 on curve intersections and 0.165 vs. 0.277 on tangent intersections).

Table 9. Crash characteristics for rural multiple-lane TWSC intersections

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
Time of Day	12AM-3AM	2	1.94%	10%	19	2.24%	90%
	3AM-6AM	2	1.94%	5%	39	4.60%	95%
	6AM-9AM	14	13.59%	9%	141	16.63%	91%
	9AM-12PM	18	17.48%	14%	111	13.09%	86%
	12PM-3PM	22	21.36%	11%	172	20.28%	89%
	3PM-6PM	26	25.24%	11%	202	23.82%	89%
	6PM-9PM	15	14.56%	12%	113	13.33%	88%
	9PM-12AM	4	3.88%	7%	51	6.01%	93%
	Total	103	100%		848	100%	
	Missing information	0	0.00% (out of 103)		1	0.12% (out of 849)	
Manner of Collision	Single vehicle	7	6.80%	5%	134	15.78%	95%
	Rear end	19	18.45%	9%	188	22.14%	91%
	Head-on	0	0.00%	0%	3	0.35%	100%
	Right angle	32	31.07%	11%	257	30.27%	89%
	Left turn - angle	3	2.91%	10%	27	3.18%	90%
	Left turn - opposite direction	7	6.80%	12%	52	6.12%	88%
	Left turn - same direction	1	0.97%	3%	33	3.89%	97%
	Right turn - same direction	0	0.00%	0%	15	1.77%	100%
	Right turn - opposite direction	3	2.91%	27%	8	0.94%	73%
	Sideswipe - same direction	9	8.74%	13%	61	7.18%	87%
	Sideswipe - opposite direction	7	6.80%	64%	4	0.47%	36%
	Other	15	14.56%	18%	67	7.89%	82%
	Total	103	100%		849	100%	
Crash Severity	Fatal	0	0.00%	0%	12	1.41%	100%
	Severe	2	1.94%	8%	22	2.59%	92%

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
	Moderate	9	8.74%	8%	98	11.54%	92%
	Complaint	28	27.18%	10%	266	31.33%	90%
	PDO	64	62.14%	12%	451	53.12%	88%
	Total	103	100%		849	100%	
Driver age	< 20	12	11.76%	13%	84	10.22%	87%
	20-39	44	43.14%	11%	343	41.73%	89%
	40-59	25	24.51%	10%	215	26.16%	90%
	60-80	17	16.67%	10%	152	18.49%	90%
	>80	4	3.92%	13%	28	3.41%	87%
	Total	102	100%		822	100%	
	Missing information	1	0.97% (out of 103)		27	3.18% (out of 849)	
Driver Gender	Male	52	50.98%	9%	508	61.43%	91%
	Female	50	49.02%	14%	319	38.57%	86%
	Total	102	100%		827	100%	
	Missing information	1	0.97% (out of 103)		22	2.59% (out of 849)	
Driver Condition	Normal	48	46.60%	14%	290	34.16%	86%
	Inattentive	45	43.69%	10%	427	50.29%	90%
	Distracted	1	0.97%	3%	28	3.30%	97%
	Illness	0	0.00%	0%	1	0.12%	100%
	Fatigued	0	0.00%	0%	4	0.47%	100%
	Apparently asleep/blackout	1	0.97%	10%	9	1.06%	90%
	Drinking alcohol - impaired	2	1.94%	10%	18	2.12%	90%
	Drinking alcohol - not impaired	0	0.00%	0%	3	0.35%	100%
	Drug use - impaired	0	0.00%	0%	3	0.35%	100%
	Drug use - not impaired	0	0.00%	N/A	0	0.00%	N/A
	Physical impairment (eyes, ear, limb)	0	0.00%	0%	1	0.12%	100%
	Unknown	6	5.83%	9%	59	6.95%	91%

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
	Other	0	0.00%	0%	6	0.71%	100%
	Total	103	100%		849	100%	
Alcohol	Yes	2	1.94%	6%	34	4.00%	94%
	No	101	98.06%	11%	815	96.00%	89%
	Total	103	100%		849	100%	
Vehicle Type	Passenger car	39	37.86%	10%	333	40.27%	90%
	Truck	30	29.13%	10%	279	33.74%	90%
	SUV	16	15.53%	13%	110	13.30%	87%
	Other	18	17.48%	15%	105	12.70%	85%
	Total	103	100%		827	100%	
	Missing information	0	0.00% (out of 103)		22	2.59% (out of 849)	
Lighting Condition	Daylight	81	78.64%	12%	602	71.07%	88%
	Dark - no streetlight	11	10.68%	7%	143	16.88%	93%
	Dark - continuous streetlight	3	2.91%	8%	36	4.25%	92%
	Dark - streetlight at intersection only	6	5.83%	18%	28	3.31%	82%
	Dusk	1	0.97%	6%	17	2.01%	94%
	Dawn	1	0.97%	5%	20	2.36%	95%
	Unknown	0	0.00%	N/A	0	0.00%	N/A
	Other	0	0.00%	0%	1	0.12%	100%
	Total	103	100%		847	100%	
	Missing information	0	0.00% (out of 103)		2	0.24% (out of 849)	
Surface Condition	Dry	89	86.41%	11%	712	83.86%	89%
	Wet	14	13.59%	10%	130	15.31%	90%
	Snow/slush	0	0.00%	0%	1	0.12%	100%
	Ice	0	0.00%	0%	5	0.59%	100%
	Contaminant (sand, mud, dirt, oil, etc.)	0	0.00%	0%	1	0.12%	100%
	Unknown	0	0.00%	N/A	0	0.00%	N/A

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
	Other	0	0.00%	N/A	0	0.00%	N/A
	Total	103	100%		849	100%	

The crash characteristics analysis previously listed reveal that the most common type of crashes at rural multiple-lane TWSC intersections is right-angle collisions for both alignments. Compared to the tangent TWSC intersections, curve TWSC intersections have higher percentage of crashes between 6 pm and 9 pm (14.56% vs. 13.33%).

Table 10. Average crash rate by design related factors for urban multiple-lane TWSC intersections

		On Curve Alignment			On Tangent Alignment		
		Number of intersections	Number of crashes	Average crash rate	Number of intersections	Number of crashes	Average crash rate
Radius (feet)	R≤500	21	136	0.223	882	10,410	0.341
	500<R≤1,000	47	610	0.391			
	1,000<R≤1,500	85	1,010	0.353			
AADT on Major Road	1,000-1,999	3	6	0.864	5	28	2.227
	2,000-2,999	4	2	0.078	17	52	0.402
	3,000-3,999	3	6	0.244	16	100	0.537
	4,000-5,000	3	26	0.907	10	76	0.671
	>5,000	140	1,716	0.334	834	10,154	0.320
Curve Length (feet)	L_c≤500	58	766	0.411	N/A	N/A	N/A
	500< L_c ≤1,000	79	796	0.296	N/A	N/A	N/A
	L_c >1,000	16	194	0.363	N/A	N/A	N/A
Speed Limit on Major Road (mph)	<26	18	154	0.256	14	205	0.443
	26 - 35	65	1,041	0.432	284	3,597	0.402
	36 - 45	54	497	0.326	473	5,517	0.308
	46 - 55	15	55	0.162	102	1,036	0.316
	>56	1	9	0.307	9	55	0.238
Left Turn Lane on Major Road	Absent	122	1465	0.334	518	5,728	0.324
	Present	31	291	0.398	364	4,682	0.364
Right Turn Lane on Major Road	Absent	138	1606	0.345	711	8,110	0.330
	Present	15	150	0.360	171	2,300	0.385
Number of Intersection Legs	3-leg	101	923	0.329	595	5,834	0.299
	4-leg	52	833	0.380	287	4,576	0.427

The aggregated crash rates previously listed reveal:

- Again, there is a safety concern on in TWSC intersections on curves. The average crash rates on curve TWSC intersections are bigger than that on the tangent TWSC intersections (0.347 vs. 0.341).
- Because of the small number of TWSC intersections on the rural multiple-lane highway, the average crash rates by AADT, curve radius, speed limits, and turning lanes do not offer reliable discussion.
- Again, due to the reduced number of conflicting points, the average crash rate of three-leg TWSC intersections is smaller than that of four-leg TWSC intersections (0.329 vs. 0.380 on curve intersections and 0.299 vs. 0.427 on tangent intersections).

Table 11. Crash characteristics for urban multiple-lane TWSC intersections

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
Time of Day	12AM-3AM	42	2.39%	14%	264	2.54%	86%
	3AM-6AM	32	1.82%	13%	212	2.04%	87%
	6AM-9AM	202	11.52%	15%	1,164	11.19%	85%
	9AM-12PM	281	16.02%	16%	1,467	14.11%	84%
	12PM-3PM	406	23.15%	15%	2,242	21.56%	85%
	3PM-6PM	492	28.05%	14%	3,114	29.95%	86%
	6PM-9PM	215	12.26%	14%	1,371	13.18%	86%
	9PM-12AM	84	4.79%	13%	565	5.43%	87%
	Total	1,754	100%		10,399	100%	
	Missing information	2	0.11% (out of 1,756)		11	0.11% (out of 10,410)	
Manner of Collision	Single vehicle	135	7.69%	21%	520	5.00%	79%
	Rear end	531	30.24%	13%	3,479	33.42%	87%
	Head-on	17	0.97%	12%	129	1.24%	88%
	Right angle	417	23.75%	15%	2,357	22.64%	85%
	Left turn - angle	59	3.36%	17%	293	2.81%	83%
	Left turn - opposite direction	71	4.04%	11%	560	5.38%	89%
	Left turn - same direction	79	4.50%	20%	325	3.12%	80%
	Right turn - same direction	47	2.68%	18%	217	2.08%	82%
	Right turn - opposite direction	8	0.46%	13%	54	0.52%	87%
	Sideswipe - same direction	251	14.29%	15%	1,461	14.03%	85%
	Sideswipe - opposite direction	17	0.97%	12%	126	1.21%	88%
	Other	124	7.06%	12%	889	8.54%	88%
	Total	1,756	100%		10,410	100%	
Crash Severity	Fatal	2	0.11%	6%	34	0.33%	94%
	Severe	14	0.80%	13%	90	0.86%	87%

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
	Moderate	117	6.66%	14%	729	7.00%	86%
	Complaint	406	23.12%	14%	2,541	24.41%	86%
	PDO	1,217	69.31%	15%	7,016	67.40%	85%
	Total	1,756	100%		10,410	100%	
Driver Age	< 20	145	8.95%	12%	1,044	11.09%	88%
	20-39	761	46.98%	14%	4,545	48.27%	86%
	40-59	388	23.95%	14%	2,302	24.45%	86%
	60-80	267	16.48%	17%	1,318	14.00%	83%
	>80	59	3.64%	22%	207	2.20%	78%
	Total	1,620	100%		9,416	100%	
	Missing information	136	7.74% (out of 1,756)		994	9.55% (out of 10,410)	
Driver Gender	Male	929	56.34%	15%	5,351	55.94%	85%
	Female	720	43.66%	15%	4,214	44.06%	85%
	Total	1,649	100%		9,565	100%	
	Missing information	107	6.09% (out of 1,756)		845	8.12% (out of 10,410)	
Driver Condition	Normal	430	24.63%	14%	2,697	25.98%	86%
	Inattentive	946	54.18%	15%	5,532	53.28%	85%
	Distracted	90	5.15%	16%	461	4.44%	84%
	Illness	2	0.11%	7%	26	0.25%	93%
	Fatigued	5	0.29%	16%	26	0.25%	84%
	Apparently asleep/blackout	10	0.57%	20%	39	0.38%	80%
	Drinking alcohol - impaired	35	2.00%	17%	171	1.65%	83%
	Drinking alcohol - not impaired	3	0.17%	14%	18	0.17%	86%
	Drug use - impaired	14	0.80%	29%	35	0.34%	71%
	Drug use - not impaired	1	0.06%	50%	1	0.01%	50%
	Physical impairment (eyes, ear, limb)	4	0.23%	33%	8	0.08%	67%
	Unknown	199	11.40%	13%	1,315	12.67%	87%

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
	Other	7	0.40%	12%	53	0.51%	88%
	Total	1,746	100%		10,382	100%	
	Missing information	10	0.57% (out of 1,756)		28	0.27% (out of 10,410)	
Alcohol	Yes	53	3.02%	16%	273	2.62%	84%
	No	1,703	96.98%	14%	10,137	97.38%	86%
	Total	1,756	100%		10,410	100%	
Vehicle Type	Passenger car	845	48.59%	14%	5,142	50.54%	86%
	Truck	404	23.23%	16%	2,141	21.04%	84%
	SUV	368	21.16%	16%	1,974	19.40%	84%
	Other	122	7.02%	12%	918	9.02%	88%
	Total	1,739	100%		10,175	100%	
	Missing information	17	0.97% (out of 1,756)		235	2.26% (out of 10,410)	
Lighting Condition	Daylight	1,399	79.85%	15%	8,114	78.09%	85%
	Dark - no streetlight	44	2.51%	17%	220	2.12%	83%
	Dark - continuous streetlight	224	12.79%	12%	1,591	15.31%	88%
	Dark - streetlight at intersection only	40	2.28%	17%	202	1.94%	83%
	Dusk	24	1.37%	14%	144	1.39%	86%
	Dawn	14	0.80%	18%	63	0.61%	82%
	Unknown	7	0.40%	18%	32	0.31%	82%
	Other	0	0.00%	0%	24	0.23%	100%
	Total	1,752	100%		10,390	100%	
	Missing information	4	0.23% (out of 1,756)		20	0.19% (out of 10,410)	
Surface Condition	Dry	1,492	85.16%	14%	8,967	86.13%	86%
	Wet	253	14.44%	15%	1,399	13.46%	85%
	Snow/slush	0	0.00%	0%	2	0.02%	100%
	Ice	1	0.06%	13%	7	0.07%	87%
	Contaminant (sand, mud, dirt, oil, etc.)	1	0.06%	17%	5	0.05%	83%

		On Curve Alignment			On Tangent Alignment		
		Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes	Number of crashes	Percentage of crashes by analysis category	Percentage of Intersection crashes
	Unknown	5	0.29%	18%	23	0.22%	82%
	Other	0	0.00%	0%	2	0.02%	100%
	Total	1,752	100%		10,405	100%	
	Missing information	4	0.23% (out of 1,756)		5	0.05% (out of 10,410)	

The most common type of crashes at urban multiple-lane TWSC intersections is rear-end collisions for both intersection alignments. Compared to the tangent TWSC intersections, curve TWSC intersections have a higher percentage of alcohol impaired driving (3.02% vs. 2.62%).

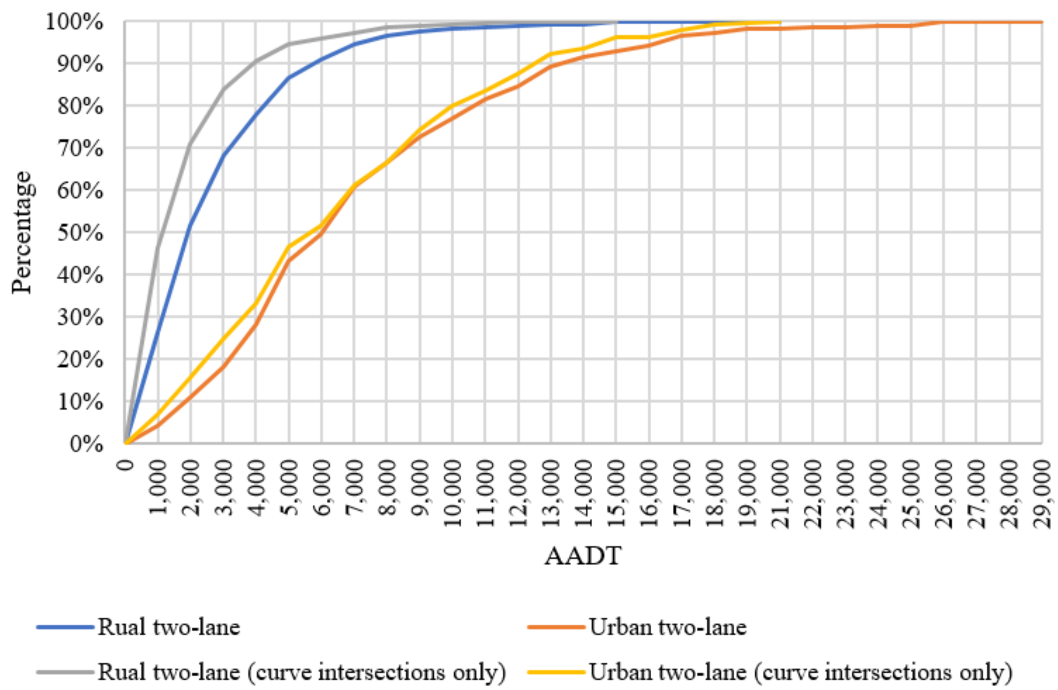
Risk Analysis

The above analysis shows the importance of risk analysis because 72% of TWSC curved intersections on rural two-lane highways have AADT less than 2,000 as shown in Figure 8 including the 28% less than 500. The conventional systematical safety program based on crash analysis would hardly pick up these locations for improvement because of annual low crashes or even zero crashes at such low AADT intersections. To proactively improve the safety at the system level, the systemic safe approach works better because crashes on the TWSC curved intersections are typically spread over to many intersections year by year and are not as clustered as crashes on intersections with high AADT. Systemic improvements can address these crashes because they focus on high-risk intersection features not specific locations. A systemic approach to safety involves widely implemented improvements based on high-risk roadway features correlated with specific crash types. As it is stated by the FHWA Office of Safety's program of *A Systemic Approach to Safety – Using Risk to Drive Action*, "The approach helps agencies broaden their traffic safety efforts at little extra cost."

Crash risk level can be assessed by either crashes or just roadway and/or "environment" conditions. Using roadway exposure and design characteristics to assess the safety risk is the systemic safety approach.

Two risk estimation methods are developed by this project. Each has its own ranking mechanism as well as limitations.

Figure 8. AADT distribution for rural and urban two-lane TWSC intersections



Risk Estimation Based on Classifier

After reviewing all risk analysis or predicting methods from previous studies, the research team used the decision tree classifier and random forest because the two methods provide the quantitative basis for risk ranking. The other methods have little practical application potentials in roadway safety because they are mainly used in assessing product or system reliability. Decision tree is represented as a tree structure that contains branches splitting the dataset from one root node (the topmost node in a tree) to leaf nodes. Each leaf node generally represents a class value that is classified through the splitting path from the root node to the leaf node. Random forest is a set of multiple decision trees. Decision tree yields deterministic results while random forest accounts for stochastic nature.

With both methods, the intersections are classified by crash occurrence, zero or non-zero. Figures 9 and 10 illustrate the data used for the analysis.

Figure 9. Distribution of datasets for analysis

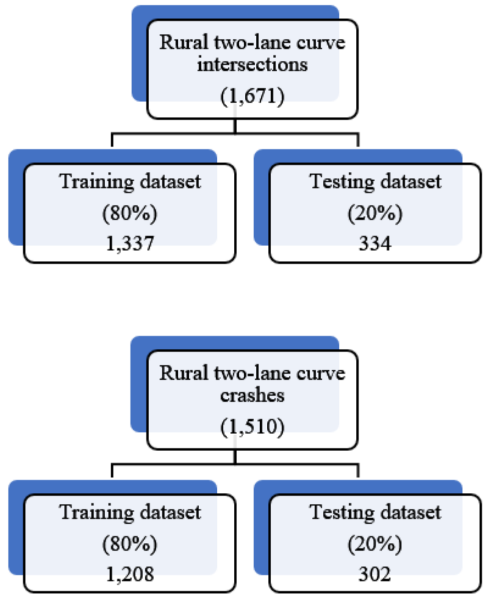
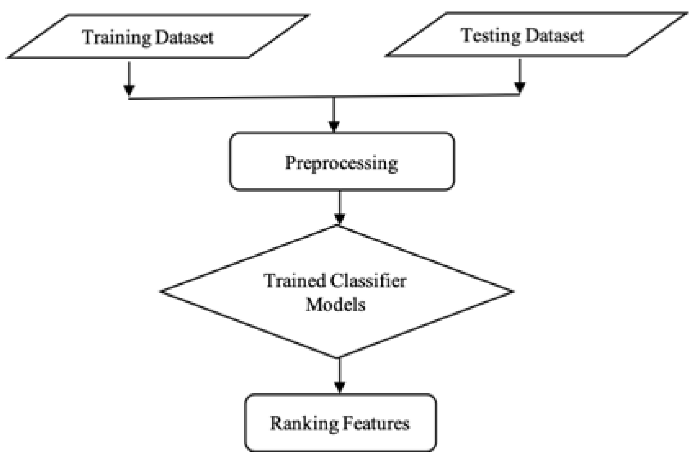


Figure 10. Processing of datasets and ranking risk factors



Feature importance is calculated as the decrease in node impurity weighted by the probability of reaching that node. The node probability can be calculated by the number of samples that reach the node, divided by the total number of samples. The higher the value the more important the feature.

For each decision tree, Scikit-learn (a library in Python programming) calculates a node's importance using Gini Importance, assuming only two child nodes (binary tree):

$$ni_j = w_j C_j - w_{left(j)} C_{left(j)} - w_{right(j)} C_{right(j)} \quad [5]$$

Where,
ni_j = the importance of node j
w_j = weighted number of samples reaching node j
C_j = the impurity value of node j
left(j) = child node from left split on node j
right(j) = child node from right split on node j

The importance for each feature on a decision tree is then calculated as:

$$fi_i = \frac{\sum_{j:node\ j\ splits\ on\ feature\ i} ni_j}{\sum_{k \in all\ nodes} ni_k} \quad [6]$$

Where,
fi_i = the importance of feature i
ni_j = the importance of node j

These can then be normalized to a value between 0 and 1 by dividing by the sum of all feature importance values:

$$normfi_i = \frac{fi_i}{\sum_{j \in all\ features} fi_j} \quad [7]$$

As shown in Table 12, the results show that major road AADT is the most significant factor for crash occurrence. Major road radius also has a strong impact. Major road speed limit, major road lane width, minor road AADT, and number of intersection legs carry gradual significance, respectively. Random forest classifier provides a similar result.

Table 12. Decision tree and random forest classifier's feature importance results for rural two-lane TWSC intersections

Rank	Variable	Importance Feature	
		Decision tree	Random forest
1	AADT-Major Road	0.235	0.260
2	Radius-Major Road (feet)	0.198	0.209

Rank	Variable	Importance Feature	
		Decision tree	Random forest
3	Speed Limit-Major Road (mph)	0.193	0.186
4	Lane Width- Major Road (feet)	0.154	0.153
5	AADT-Minor Road	0.066	0.093
6	Number of Legs	0.044	0.033

Then the research team rank the intersections by the following method as shown in Equation 8:

$$Rank = Feature_i \times Importance_i \quad [8]$$

Where,

$Feature_i$ = numerical value of variable i, i = AADT-major, curve radius, speed limit, lane width, AADT-minor, and number of legs

$Importance_i$ = importance value calculated by decision tree classifier or random forest of variable i

Table 13 provides a summary of the ranking results for the top 30 TWSC intersections on rural two-lane highways, based on the decision tree classifier.

Table 13. Decision tree ranking summary for rural two-lane TWSC intersections

Rank	Intersection ID	Radius on major road (ft)	AADT on major road	AADT on minor road	Lane width on major road (ft)	Speed limit on major road (mph)	Number of legs	Total crashes
1	33929	1,302	14,400	61	12	45	3	3
2	59747	692	14,600	101	11	30	3	0
3	10679	792	13,700	156	11	25	3	1
4	2785	879	13,200	449	12	55	3	3
5	1673	642	11,500	5,600	11	30	3	10
6	11302	1,035	12,100	34	12	55	3	4
7	1665	685	11,500	214	13	30	4	1
8	51641	>1,500	10,600	650	12	55	3	1
9	33910	1,275	10,500	219	12	55	3	2
10	45757	1,074	10,300	119	12	55	3	2
11	45745	979	10,300	134	12	45	3	0
12	45754	802	10,300	119	12	55	3	3
13	45741	516	10,300	266	12	45	3	10

Rank	Intersection ID	Radius on major road (ft)	AADT on major road	AADT on minor road	Lane width on major road (ft)	Speed limit on major road (mph)	Number of legs	Total crashes
14	3034	1,164	9,600	128	12	30	3	0
15	34443	568	10,000	260	13	25	3	2
16	2399	661	9,600	128	12	35	3	3
17	45768	1,052	8,500	119	12	55	3	0
18	59754	1,108	8,400	146	12	45	3	5
19	2624	92	8,900	1210	12	45	3	0
20	44336	1,444	7,600	1450	13	55	3	7
21	33765	447	8,600	837	12	55	3	3
22	45477	975	6,600	6397	12	35	4	8
23	2626	125	8,900	164	11	45	3	1
24	48473	975	8,100	219	12	55	3	2
25	2464	1,235	7,700	399	12	35	4	1
26	59721	1,276	7,600	363	12	50	3	2
27	2463	1,210	7,700	142	13	35	3	1
28	9600	1,084	7,700	419	12	55	3	2
29	34759	1,321	7,500	400	12	55	3	3
30	34756	1,230	7,500	306	12	55	3	2

The ranking results from random forest are listed on Table 14.

Table 14. Random forest ranking summary for rural two-lane TWSC intersections

Rank	Intersection ID	Radius on major road (ft)	AADT on major road	AADT on minor road	Lane width on major road (ft)	Speed limit on major road (mph)	Number of legs	Total crashes
1	33929	1,302	14,400	61	12	45	3	3
2	59747	692	14,600	101	11	30	3	0
3	10679	792	13,700	156	11	25	3	1
4	2785	879	13,200	449	12	55	3	3
5	1673	642	11,500	5,600	11	30	3	10
6	11302	1,035	12,100	34	12	55	3	4
7	1665	685	11,500	214	13	30	4	1
8	51641	>1,500	10,600	650	12	55	3	1
9	33910	1,275	10,500	219	12	55	3	2
10	45757	1,074	10,300	119	12	55	3	2
11	45745	979	10,300	134	12	45	3	0
12	45754	802	10,300	119	12	55	3	3

Rank	Intersection ID	Radius on major road (ft)	AADT on major road	AADT on minor road	Lane width on major road (ft)	Speed limit on major road (mph)	Number of legs	Total crashes
13	45741	516	10,300	266	12	45	3	10
14	3034	1,164	9,600	128	12	30	3	0
15	34443	568	10,000	260	13	25	3	2
16	2399	661	9,600	128	12	35	3	3
17	45477	975	6,600	6397	12	35	4	8
18	2624	92	8,900	1210	12	45	3	0
19	45768	1,052	8,500	119	12	55	3	0
20	59754	1,108	8,400	146	12	45	3	5
21	44336	1,444	7,600	1450	13	55	3	7
22	33765	447	8,600	837	12	55	3	3
23	2626	125	8,900	164	11	45	3	1
24	48473	975	8,100	219	12	55	3	2
25	2464	1,235	7,700	399	12	35	4	1
26	59721	1,276	7,600	363	12	50	3	2
27	9600	1,084	7,700	419	12	55	3	2
28	2463	1,210	7,700	142	13	35	3	1
29	34759	1,321	7,500	400	12	55	3	3
30	34756	1,230	7,500	306	12	55	3	2

In summary, curve intersections with major road radius between 500 to 1000 ft. and major road AADT greater than10,000 have a higher potential crash risk. Horizontal curve radius has a strong impact on the crash occurrence. The biggest drawback of these two methods are the underlining assumption: the intersection with zero crashes are risk free, which is not entirely correct. Thus, a new weighting and ranking method is developed, which is based on the crash occurrences as well as the design element.

Risk Estimation Based on Crash Analysis and Design

The biggest limitation from the above two methods is that the analysis is entirely based on intersections with and without crashes. In theory, an intersection without observed crashes during the observation time period (5 years in this study) does not mean crash risk free. Zero crash locations usually have relatively small traffic volume, and traffic volume has been recognized as the biggest influential factor for level of safety. Zero crash locations could also have great potentials for safety improvement if the exposure increases.

Risk level should be assessed by both crashes and roadway characteristics (design elements and operation: geometry, volume, or location). Systemic safety approach, widely recognized in recent years, focus on the risk analysis that is not entirely based on crashes. Acknowledging crashes alone may not be sufficient to identify all high-risk locations, the research team developed a risk estimation method based on the crash analysis as well as the weighting factor as shown in the following equation:

$$R = \sum S_{ij} \times W_i \qquad [9]$$

Where,
R = overall risk,
S_{ij} = significance factor for crash contributing variable i, i= AADT, curve radius, speed limit, number of legs, and skewness; j = subgroup of variable i
W_i = weighting factor of variable i

Significance factors indicate the relative importance of each variable to crash occurrences that is determined by the average crash rates and the risk factors from the decision tree analysis, namely, AADT, curve radius, speed limit, number of legs, and skewness. Equation 10 is used for the factor estimation.

$$S_{ij} = \frac{r_j}{\sum \overline{r_j}} \qquad [10]$$

Where,
S_{ij} = significance factor for crash contributing variable i, i= AADT, curve radius, speed limit, number of legs, and skewness; j = subgroup of variable i,
r_j = average crash rate of subgroup j of variable i, and
$\sum \overline{r_j}$ = sum of average crash rate of variable i.

Table 15 provides a summary of the significance factors for TWSC intersections on rural two-lane highways.

Table 15. Significance factor summary for rural two-lane TWSC intersections

Variable	Subgroup	Significance Factor
Radius on Major Road (feet)	R≤500	0.423
	500 <R≤1,000	0.311

Variable	Subgroup	Significance Factor
	1,000<R≤1,500	0.267
AADT on Major Road	<500	0.113
	500-999	0.109
	1,000-1,499	0.104
	1,500-1,999	0.100
	2,000-2,499	0.095
	2,500-2,999	0.091
	3,000-3,499	0.086
	3,500-3,999	0.082
	4,000-4,499	0.078
	4,500-5,000	0.073
	>5,000	0.069
Speed Limit on Major Road (mph)	<26	0.200
	26-35	0.256
	36-45	0.245
	46-55	0.298
Skewness	less than 30º	0.417
	greater than 30º	0.583
Number of Legs	3-leg	0.423
	4-leg	0.577

The weighting factors provide the flexibility to the safety program, which can reflect the decision makers' priorities or experts' preference towards concerned factor(s) at different jurisdiction. In this study, three weighting factor schemes are proposed as shown in Table 16. Weighting factor is calculated as shown in the following equation:

$$W_i = \frac{w_i}{\sum w_i} \quad [11]$$

Where,
W_i = weighting factor of variable i, and
w_i = weight value of variable i.

Table 16. Three weighting factor schemes

Variable	Scheme 1	Scheme 2	Scheme 3
AADT on Major Road	5 (33%)	10 (50%)	1 (20%)

Variable	Scheme 1	Scheme 2	Scheme 3
Radius on Major Road (feet)	4 (27%)	4 (20%)	1 (20%)
Speed Limit on Major Road (mph)	3 (20%)	3 (15%)	1 (20%)
Number of Legs	2 (13%)	2 (10%)	1 (20%)
Skewness	1 (7%)	1 (5%)	1 (20%)

Compared to the traditional highway safety risk analysis method (such as crash frequency, crash rate, and safety performance functions), weighting factor method can identify the high safety risk intersection with zero crashes during the selected time period.

There are several important steps in ranking the intersections:

- Step 1. Calculate intersection average crash rate by variables (major road AADT, major road radius, major road speed limit, number of intersection legs, and skewness) and their subgroups (Equation 4).
- Step 2. Calculate significance factor for crash contributing variables for each intersection (Equation 10).
- Step 3. Set up weighting factor scheme for each variable.
- Step 4. Calculate ranking by Equation 9.
- Step 5. Sort above results by descending order.

Table 17 provides a summary of ranking results for the top 30 TWSC intersections on rural two-lane highways, based on crash frequency, crash rate, and risk estimation (including significance factor and three weighting factor schemes).

Table 17. Top 30 TWSC intersections on rural two-lane highways by ranking methods

Rank	Crash rate	Crash frequency	Fatal + severe	Ranking 1 (33%)	Ranking 2 (50%)	Ranking 3 (20%)
1	53258	53060	46046	9907	9907	53258
2	29692	4871	4900	36447	36447	29692
3	53521	45761	15215	35027	35027	53521
4	42763	53258	54888	8546	8546	42763
5	46458	64515	38691	46046	46046	46458
6	64515	46458	1679	37096	37096	64515
7	5803	11909	54477	37099	37099	5803
8	11967	34370	42859	37198	37198	11967
9	35027	46499	60062	35707	35707	35027
10	30957	29692	9546	5233	5233	30957
11	35221	38704	53999	37800	36579	35221
12	39971	35061	9997	36579	35289	39971
13	7014	39414	31730	35289	30671	7014
14	7041	45476	34756	53000	37800	7041
15	58221	45741	10239	35502	15489	58221
16	47838	1673	35336	30671	36284	47838
17	53060	4900	12685	15489	53000	53060
18	49985	9891	6966	36284	35502	49985
19	28182	15215	63261	63261	63261	28182
20	35227	34997	4866	39414	39414	35227
21	40905	45477	53060	52356	27940	40905
22	37198	39971	45761	3880	35502	37198
23	4436	47838	11909	7008	28315	4436
24	43631	9912	52356	1679	62427	43631
25	40915	52356	5403	51954	52356	40915
26	34370	35087	2399	51259	3880	34370
27	30217	53259	5246	53825	7008	30217
28	41794	46987	53960	28277	54743	41794
29	7034	5116	45364	39409	39410	7034
30	45761	53233	34936	29751	28461	45761

Because AADT on rural two-lane highways are generally smaller than that of any other type of roadways, there are lots of intersections with zero crash during the selected five years of the study period. In theory, every single intersection bears the crash risk that varies greatly from intersection to intersection because of the differences in AADT, design configuration, and roadway users' characteristics. Out of curiosity, the research team even investigated the crash statistics in the 10-year time periods (2008-2017). As shown in Table 18, there are 2,469 TWSC intersections without crashes. There are 495 TWSC intersections with a radius less than or equal to 500 ft., 7% of the total TWSC intersections on two-lane highway in Louisiana (391 on rural and 104 on urban roadways).

Table 18. TWSC intersections without crashes on rural two-lane highways

Crash Status	Number of curve intersections	Number of tangent intersections	Total
Zero-crash during the 10 years	780	1,689	2,469

The results of risk estimation (including significance factor and three weighting factor schemes) in Table 19 show that curve intersections with radius less than 500 ft. account for 90%-100% of the cases in the top 30 risky intersections. According to the ranking results from crash frequency and crash rate, around 33-43% intersections have radius less than 500 ft. Intersection with sharp curves are more likely to involve in crashes. For AADT greater than 1,000, 83% of the top 30 risky intersections are in this category based on the ranking results of number of fatal and severe crashes, while it is 90% based on crash frequency. For other ranking methods 33-63% of the top 30 risky locations are in the AADT greater than 1,000 range. Although traffic volume may be the most important factor contributing to intersection crashes, locations with low AADT even zero crash may have high risk due to the roadway design.

Table 19. Summary of different ranking methods

Ranking method	R < 500	AADT > 1000
Crash rate	43%	27%
Crash frequency	43%	90%
Fatal + severe	33%	83%
Ranking 1 (33%)	100%	60%
Ranking 2 (50%)	100%	33%
Ranking 3 (20%)	90%	63%

Stop-Controlled Intersection Safety Performance Modeling

The development of safety performance function of two-lane TWSC intersection is described in this section.

Count Data Modeling

Given the nature of random, discrete, and non-negative crash data, the Poisson distribution has been shown to provide a better fit and has been used widely to model crash frequency data [6] [7] [62] [61] [63]. The probability of y_i crashes occurring at a given intersection i, $P(y_i|\lambda_i)$, is shown in Equation 12:

$$P(y_i|\lambda_i) = \frac{e^{-\lambda_i}\lambda_i^{y_i}}{y_i!};\ y_i = 0,1,2,3\ ... \qquad [12]$$

The relationship between the number of crashes at intersection i and the q parameter (X_{i1}, X_{i2}, X_{iq}) is shown in Equation 13:

$$\lambda_i = \exp\left(\beta_0 + \sum_{j=1}^{q} X_{ij}\beta_j\right) \qquad [13]$$

Where,

λ_i = expected number of crashes per year at intersection i,

X_i = the independent variables at intersection i, and
β_j = a vector of estimable regression coefficients.

The Poisson regression model assumes that the mean of crash counts is equal to its variance (equal-dispersion). However, in much of the crash data, the variance is greater than the mean, well known as over-dispersion. For these cases, applying a Poisson regression model for intersection crash data would result in underestimation of the standard error of the regression parameters, which can ultimately lead to a biased selection of covariates. In some cases, excess zeros in crash data exist and are considered to be a result of over-dispersion. The Poisson model cannot be used for these cases, as it cannot handle the over-dispersion, due to these zeros.

To address this challenge, the NB model can be alternatively used. A gamma distributed error term was included in the Poisson model to serve as a NB model, which is shown in Equation 14:

$$\lambda_i = \exp(\beta X_i + \varepsilon_i) \qquad [14]$$

Where,
$\exp(\varepsilon_i)$ = gamma distributed variable with mean 1 and variance α (the overdispersion parameter).

Zero-inflated models have also been used in traffic safety studies to modeling crashes. The ZIP model serves as a dual-state method for modeling data, characterized by a significant number of zeros, or more zeros than one would expect in a traditional Poisson distribution. The ZIP model assumes that all zero counts come from two different processes: (1) the process generating excess zero count (zero-crash state) derived from a binary model and (2) the process generating non-negative counts for intersection crashes including zero values, estimated from the Poisson distribution [61]. Suppose π_i is the probability that an intersection will exist in the zero-crash state, and $1 - \pi_i$ is the probability that crash counts are generated according to a Poisson model. Therefore, the probability distribution of the ZIP random variable is shown in Equation 15:

$$P(Y = y_i) = \begin{cases} \pi_i + (1 - \pi_i)e^{-\lambda_i}; & y_i = 0 \\ (1 - \pi_i)\dfrac{e^{-\lambda_i}\lambda_i^{y_i}}{y_i!}; & y_i > 0 \end{cases} \qquad [15]$$

The probability of being in the zero-crash state, P_i, is often fitted using the logistic regression model, as follows in Equation 16:

$$logit(P_i) = ln\left(\frac{P_i}{1-P_i}\right) = \beta_0 + \sum_{j=1}^{q} Z_{ij}\beta_j \text{ where,} \quad [16]$$

Z_{ij} = a function of intersection i, and

β_j = a vector of estimable regression coefficients.

The mean and variance of ZIP are given as follows in Equation 17 and 18:

$$E(Y) = \lambda_i(1-\pi_i) \quad [17]$$

$$Var(Y) = \lambda_i(1-\pi_i)(1+\lambda_i\pi_i) \quad [18]$$

However, the zero-inflated models were criticized in the past. The inherent assumption of a dual state process underlying the development of these models is inconsistent with crash data. Every road has some risk of a crash. When the proportion of zeros is below 80%, the traditional NB distribution offers a performance that is equal to that of the zero-inflated models. In this study, NB was used to develop safety performance models.

The variable selection is based on an extensive literature review and preliminary analysis of the data. Models for total crashes are established for three-leg and four-leg intersections, respectively. R programming data analysis statistical software was used for the NB model estimation.

Three-Leg TWSC Rural Intersections

The NB model estimation results for total crashes occurring at three-leg TWSC intersections on rural two-lane highways are shown in Table 20. The logarithm of AADT of major and minor roads, curve radius of major roads, and intersection skewness were found to be statistically significant with p-value less than 5 percent. Out of these variables, logarithm of AADT of major and minor roads and intersection skewness are positively related to intersection crashes. On the contrary, curve radius of major has a negative association with the expected intersection crashes.

Table 20. Coefficients for rural two-lane three-leg TWSC intersections

Variable	Total Crashes			
	Coefficient	Std. Error	Z Value	p-value
(Intercept)	-5.9720	0.3591	-16.63	0.0000
Major road AADT (in natural log) (vehicles/day)	0.6391	0.0470	13.6	0.0000
Minor road AADT (in natural log) (vehicles/day)	0.2508	0.0382	6.57	0.0000
Curve radius on major road (ft.)	-0.0003	0.0001	-3.03	0.0025
Skewness (0 - skew angle less than 30 degree, 1 - skewness angle greater than 30 degree)	0.3282	0.1870	2.18	0.0291
Over-dispersion parameter	1.09			
Log-likelihood	-1701.97			
AIC	3413.95			

Equation 19 gives the Louisiana-specific SPF for three-leg TWSC intersections on rural two-lane highways.

$$\text{Number of total crashes} = \exp\left(-5.9720 + 0.6391 \times \ln(AADT_{major}) + 0.2508 \times \ln(AADT_{minor}) - 0.0003 \times Curve\ radius + 0.3282 \times Skewness\right) \quad [19]$$

Four-Leg TWSC Rural Intersections

Table 21 summarizes the NB model results for total crashes at four-leg TWSC intersections on rural two-lane highways. Similar to three-leg intersections, intersection crashes increase as traffic flow increases. The probability of total crashes decreases as curve radius on major roads increases. Intersection skewness was not found to significantly affect crash frequency for total crashes with p-value less than 5 percent.

Table 21. Coefficients for rural two-lane four-leg TWSC intersections

Variable	Total Crashes			
	Coefficient	Std. Error	Z Value	p-value
(Intercept)	-6.2928	1.1408	-5.52	0.0000
Major road AADT (in natural log) (vehicles/day)	0.5862	0.1622	3.61	0.0003

Variable	Total Crashes			
Minor road AADT (in natural log) (vehicles/day)	0.4341	0.1094	3.97	0.0001
Curve radius on major road (ft.)	-0.0002	0.0003	3.59	0.0003
Over-dispersion parameter	0.95			
Log-likelihood	-207.20			
AIC	381.68			

Equation 20 gives the Louisiana-specific SPF for four-leg TWSC intersections on rural two-lane highways.

$$\text{Number of total crashes} = \exp\left(-6.2928 + 0.5862 \times \ln(AADT_{major}) + 0.4341 \times \ln(AADT_{minor}) - 0.0002 \times Curve\ radius\right) \quad [20]$$

Three-Leg TWSC Urban Intersections

The NB model estimation results for total crashes occurring at three-leg TWSC intersections on urban two-lane highways are shown in Table 22. The logarithm of AADT of major and minor roads and curve radius of major roads were found to be statistically significant with p-value less than 5 percent. Out of these variables, logarithm of AADT of major and minor roads are positively related to intersection crashes. On the contrary, curve radius of major roads has a negative association with the expected intersection crashes.

Table 22. Coefficients for urban two-lane three-leg TWSC intersections

Variable	Total Crashes			
	Coefficient	Std. Error	Z Value	p-value
(Intercept)	-6.5250	0.6180	-10.56	0.0000
Major road AADT (in natural log) (vehicles/day)	0.6827	0.0700	9.76	0.0000
Minor road AADT (in natural log) (vehicles/day)	0.3480	0.0401	8.67	0.0000
Curve radius on major road (ft.)	-0.0002	0.0001	2.50	0.0122
Over-dispersion parameter	0.88			
Log-likelihood	-990.49			
AIC	1988.97			

Equation 21 gives the Louisiana-specific SPF for three-leg TWSC intersections on urban two-lane highways.

$$\text{Number of total crashes} = \exp\big(-6.5250 + 0.6827 \times \ln(AADT_{major}) + 0.3480 \times \ln(AADT_{minor}) - 0.0002 \times Curve\ radius \qquad [21]$$

Four-Leg TWSC Urban Intersections

Table 23 summarizes the NB model results for total crashes at four-leg TWSC intersections on urban two-lane highways. Similar to three-leg intersections, intersection crashes increase as traffic flow increases. The probability of crashes decreases as curve radius on major roads increases.

Table 23. Coefficients for urban two-lane four-leg TWSC intersections

Variable	Total Crashes			
	Coefficient	Std. Error	Z Value	p-value
(Intercept)	-4.0915	1.4009	-2.92	0.0035
Major road AADT (in natural log) (vehicles/day)	0.3121	0.1490	2.1	0.0361
Minor road AADT (in natural log) (vehicles/day)	0.4519	0.0928	4.87	0.0000
Curve radius on major road (ft.)	-0.0002	0.0003	2.78	0.0054
Over-dispersion parameter	0.58			
Log-likelihood	-170.83			
AIC	349.67			

Equation 22 gives the Louisiana-specific SPF for four-leg TWSC intersections on urban two-lane highways.

$$\text{Number of total crashes} = \exp\big(-4.0915 + 0.3121 \times \ln(AADT_{major}) + 0.4519 \times \ln(AADT_{minor}) - 0.0002 \times Curve\ radius \qquad [22]$$

After a variable is included in the model and the parameters are estimated, Hauer recommends the use of cumulative residual (CURE) plots to obtain further insight into whether the selected appropriate functional form was reasonable and assess the quality of model [68]. In the CURE method, the cumulative residuals (the difference between the observed and predicted values for each site from the model) are plotted in increasing order for each covariate separately. The data in the CURE plot are expected to oscillate about 0. If the cumulative residuals are consistently drifting upward within a particular range of AADT, then it would imply that there were more observed than predicted crashes by the SPF. On the other hand, if the cumulative residuals are drifting downward within a particular range of AADT, then it would imply that there were fewer observed than predicted crashes by the model. Also plotted are graphs of the 95 percent confidence limits. If there is no bias in the model, the plot of cumulative residuals should stay inside of these limits. Hauer and Bamfo derived confidence limits for the plot (±2σ) beyond which the plot should rarely go [69].

CURE plots for the SPFs for major road AADT, minor road AADT, and major road curve radius versus total crashes on 3ST and 4ST intersections are provided in the following figures (Figure 11-22). The results show that the overall fit is good for the covariate in that the cumulative residuals oscillate around the value of zero and lie between the two standard deviation boundaries.

Figure 11. CURE plot major road AADT vs. total crashes on rural two-lane three-leg intersections

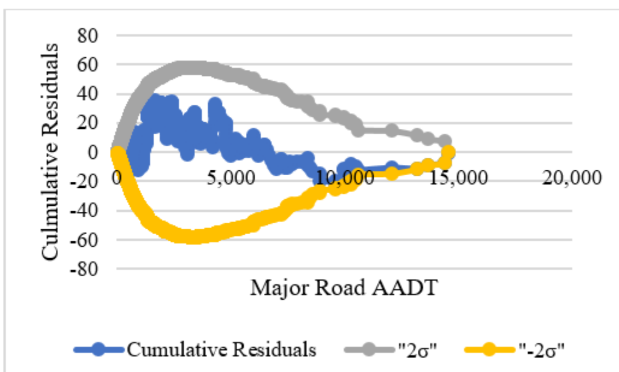


Figure 12. CURE plot minor road AADT vs. total crashes on rural two-lane three-leg intersections

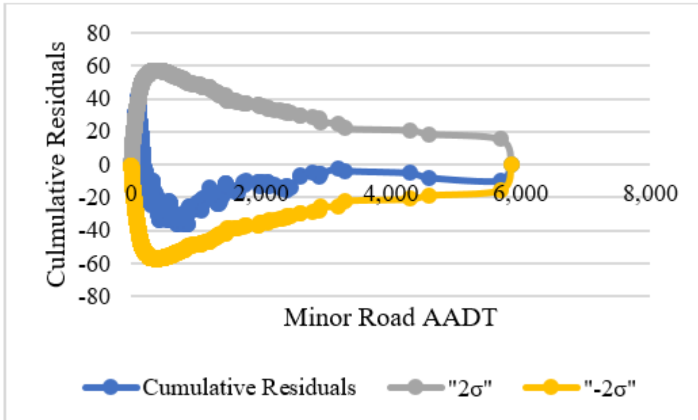


Figure 13. CURE plot major road curve radius vs. total crashes on rural two-lane three-leg intersections

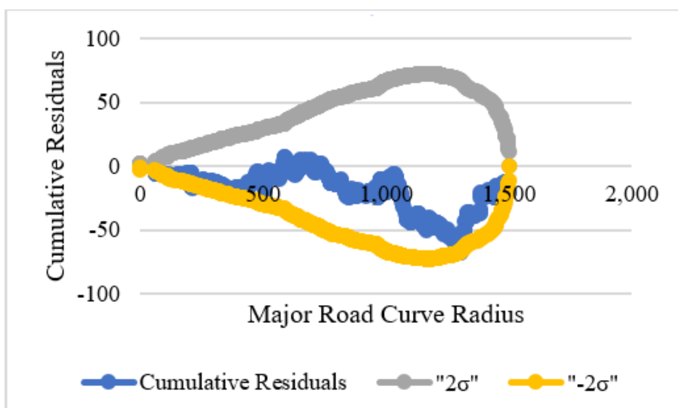


Figure 14. CURE plot major road AADT vs. total crashes on rural two-lane four-leg intersections

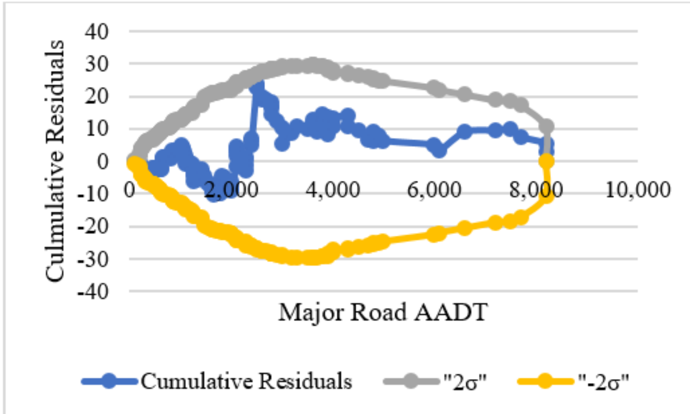


Figure 15. CURE plot minor road AADT vs. total crashes on rural two-lane four-leg intersections

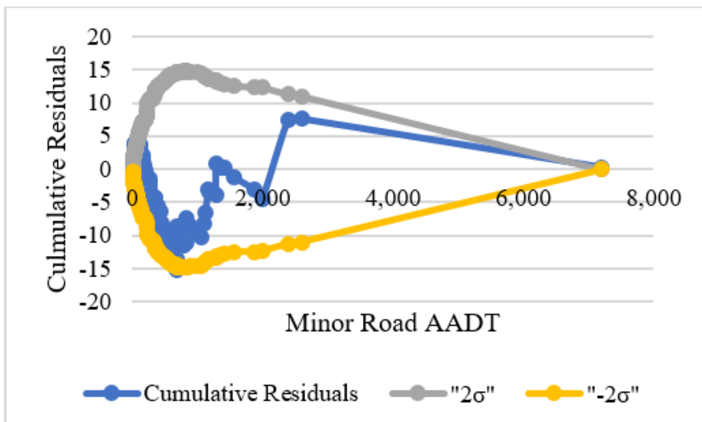


Figure 16. CURE plot major road curve radius vs. total crashes on rural two-lane four-leg intersections

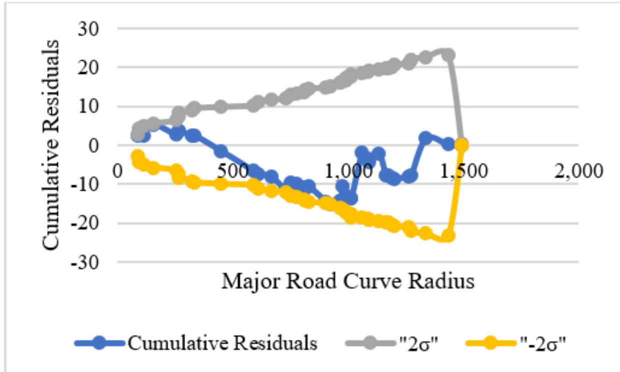


Figure 17. CURE plot major road AADT vs. total crashes on urban two-lane three-leg intersections

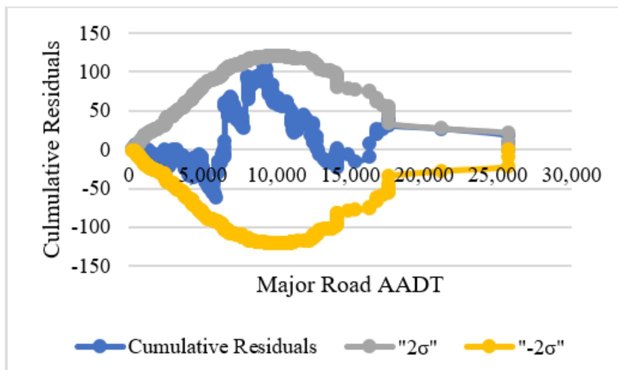


Figure 18. CURE plot minor road AADT vs. total crashes on urban two-lane three-leg intersections

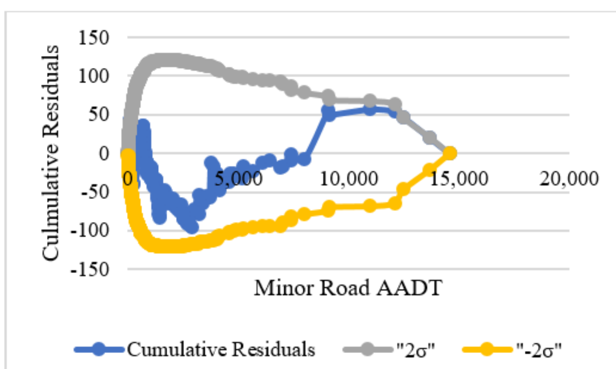


Figure 19. CURE plot major road curve radius vs. total crashes on urban two-lane three-leg intersections

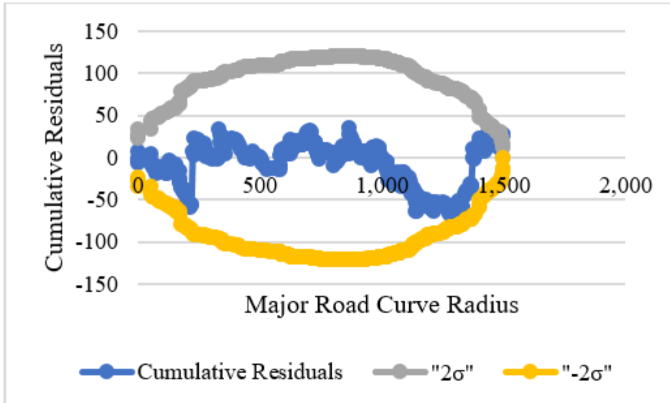


Figure 20. CURE plot major road AADT vs. total crashes on urban two-lane four-leg intersections

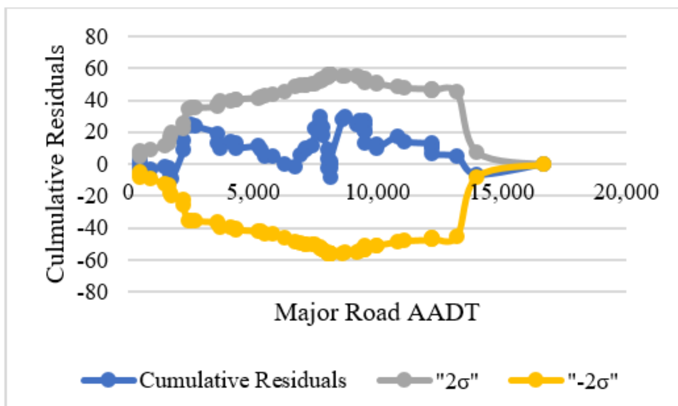


Figure 21. CURE plot minor road AADT vs. total crashes on urban two-lane four-leg intersections

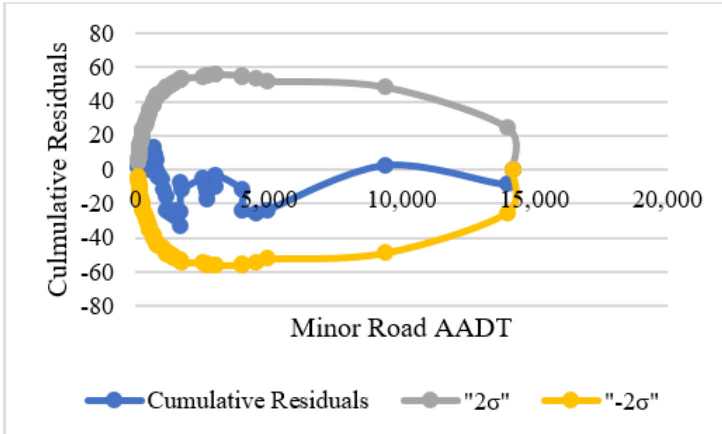
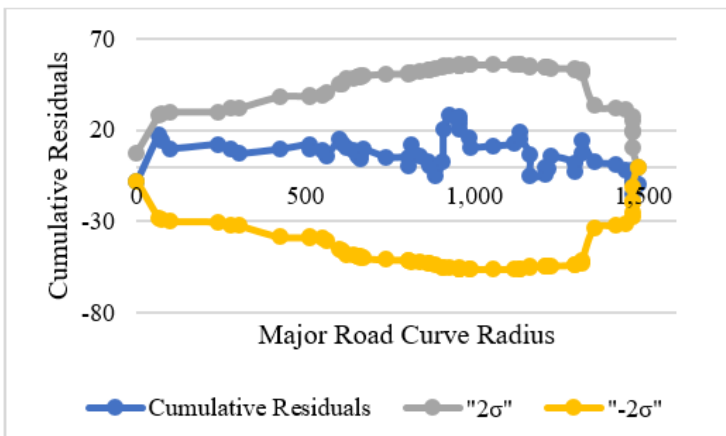


Figure 22. CURE plot major road curve radius vs. total crashes on urban two-lane four-leg intersections



Countermeasures Selection

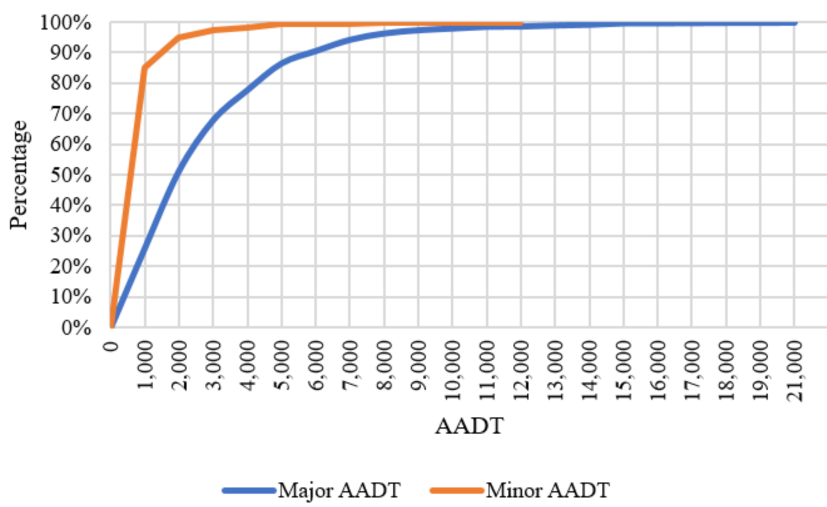
After quantitatively identifying the safety problems of curved intersections, the final step of this project was to look for solutions that can reduce crash risk of the curved TWSC intersection. This section contains the brief discussion on the site investigation and the corresponding countermeasure selection for the targeted problems.

Site Investigation

Because of the COVID-19 outbreak, the last step of research must be modified from the already scheduled field inspection to the "site investigation" on Google Earth Pro. The purpose of the "site visit" was to identify specific potential risk factors and propose the countermeasures accordingly.

All sites investigated on rural two-lane highways are from the top 30 lists by at least two ranking methods; two urban intersections were also investigated. For putting the intersection crashes in perspective, the AADT percentile on both major and minor roads are provided based on the AADT accumulative distribution curve illustrated in Figure 23 that shows the AADT is 500 and 2,000 at the 50th percentile and 1,000 and 4,600 at the 85th percentile for minor and major roads, respectively.

Figure 23. AADT distribution for rural two-lane TWSC intersections



While different TWSC intersection may have different problems, there are lots of commonalities, which is summarized below:

- Intersections with a sharp curve (radius less than or close to 500 ft.) on major roadway, the crash rate of single vehicle running off roadway crashes is high, which indicates a high lane departure risk at such locations. Higher operating speed is the main cause of such crashes.

- Insufficient sight distance on minor streets can cause collisions between vehicles on minor and major roadways. The insufficient sight distance is caused by the location of a stop bar, lack of stop line, overgrown bushes and trees, and a sharp curve on major roadway.
- The high number of rear-end collisions on major roadways occurs at the intersections with high major road AADT.
- High number of crashes at the intersection with high and roughly equal AADT on major and minor roads. Some locations (site #12) even have higher AADT on minor roadways, which indicate TWSC may not be an appropriate type of traffic control.

The problems unique to locations are:

- Because of the legacy issues, few intersections have irregular geometrics and traffic control (site #6 and site #12)
- Curved intersection at the end of a bridge (site #4)

Through the site investigation and driving experience in the state, it is clear some curved TWSC intersections were not designed by following the design guidelines. Some minor or farming roads apparently were connected to an existing roadway for convenience. These TWSC intersections would bear great crash risk if they are no longer just serving local drivers.

Selecting Countermeasure

Although there are very little countermeasures available on the safety performance of the curved TWSC intersections, there are many crash countermeasures published for intersections and horizontal curves separately. The most reliable ones are from FHWA studies and NCHRP reports. Many of these reliable countermeasures were developed by the well-accepted scientific methodology during the last decade. The most relevant documents are listed as follows:

- Federal Highway Administration, “Low-Cost Treatments for Horizontal Curves Safety 2016” [2]
- Federal Highway Administration, “Intersection Safety: A Manual for Local Rural Road Owners” [33]

- Federal Highway Administration, “Objectives and Strategies for Improving Safety at Unsignalized and Signalized Intersections” [70]
- Federal Highway Administration, “Intersection Safety Strategies Brochure” [71]
- FHWA CMF Clearinghouse [72]
- Federal Highway Administration, “Low-Cost Safety Enhancements for Stop-Controlled and Signalized Intersections” [73]
- Federal Highway Administration, “Manual for Selecting Safety Improvements on High Risk Rural Roads” [74]
- NCHRP Report 500, Volume 7, “A Guide for Reducing Collisions on Horizontal Curves” [75]
- NCHRP Report 500, Volume 5, “A Guide for Addressing Unsignalized Intersection Collisions” [3]
- Crash reduction factors (CRFs) for supplemental stop-controlled intersection countermeasures have been taken from the “FHWA Toolbox of Countermeasures and Their Potential Effectiveness for Intersection Crashes” [76].

While the above does not represent an all-inclusive list of countermeasures for TWSC intersections and horizontal curves, the project develops a table listing countermeasures targeted to the problem identified by the crash analysis and site investigation in Table 24 and by type of countermeasures (geometric alternation and traffic control devices) in Table 25.

Under the financial constraints, it is important for roadway safety improvement programs to know not only the effectiveness of a countermeasure but also its cost. Apparently, the low-cost countermeasures are most cost-effective for improving the safety of curved TWSC intersections with low AADT. Low AADT can be defined as 400 (FHWA low-volume road definition) or as 2,000 for rural two-lane highway since 2,000 is at the 50th percentile of major roadway’s AADT distribution. To our knowledge, however, there is no official definition on the low cost, which is somewhat understandable because an expensive countermeasure can be justified economically if it can reduce a large number of severe crashes at locations. Traffic control devices (positive guidance) such as signs and pavement markings, rumble strips, and intersection corner shrub/tree cleaning are relatively cheap compared to roadway geometric alternations such as flattening a curve, widening lane and shoulder width. It is generally hard to find the cost information because it varies by jurisdiction, cost estimation practice, and time. Table 26 lists the cost associated with some specific countermeasures from a document published 11 years ago, which can only serve as a reference.

Table 24. Countermeasures targeted to the problem identified by the crash analysis and site investigation

Identified Problem	Countermeasures	CMF	Source
Single vehicle ROR due to speeding on curve	Use of optical speed bars		https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Install targeted longitudinal rumble strips on the outside of horizontal curves	0.85	https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Install advisory speed limit	0.71-0.87	http://www.cmfclearinghouse.org
	Install retroreflective strips on sign posts		https://safety.fhwa.dot.gov/local_rural/training/fhwasa1108/fhwasa1108.pdf
	Install speed display panel		Proposed by this project
Rear-end and angle crashes	Install left-turn lane	0.42-0.73	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install left-turn lane painted separation	0.61-0.67	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install left-turn lane (physical channelization)	0.75-0.87	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install turn and bypass lanes	0.81-0.95	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install right-turn lane	0.74-0.86	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
Crashes caused by insufficient sight distance on minor road	Improve sight distance	0.44-0.89	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	move STOP bar to extended curb lines		https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
Crashes caused by poor visibility	Install double stop signs	0.45	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install larger stop signs		https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install raised pavement markers		https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Provide a stop bar on minor road approaches		https://safety.fhwa.dot.gov/local_rural/training/fhwasa1108/fhwasa1108.pdf

Identified Problem	Countermeasures	CMF	Source
	Install stop-ahead pavement markings	0.4-0.92	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install transverse rumble strips on approaches		https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Improve visibility of intersections by providing enhanced signing and delineation		https://safety.fhwa.dot.gov/local_rural/training/fhwasa1108/fhwasa1108.pdf
	Provide improved maintenance of stop signs		https://safety.fhwa.dot.gov/local_rural/training/fhwasa1108/fhwasa1108.pdf
	Provide supplementary stop signs mounted over the roadway		https://safety.fhwa.dot.gov/local_rural/training/fhwasa1108/fhwasa1108.pdf
Crashes caused by ignoring upcoming intersection	Install flashing beacons as advance warning		https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install flashing beacons at stop-controlled intersections	0.85	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
Crashes caused by unawareness of upcoming horizontal curve	Install curve warning signs	0.70	https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Install/upgrade curve warning signs with fluorescent yellow sheeting	0.66	https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Install chevron signs	0.36-0.75	https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Install arrow signs at horizontal curve locations		https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Install post-mounted delineators at horizontal curves		https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
Crashes caused by unawareness of upcoming	Combination curve/intersection signs		https://safety.fhwa.dot.gov/roadway_dept/horicurves/fhwasa15084/fhwasa15084rev011720_508_FINAL.pdf
	Double use of advanced warning signs for curves or intersections		https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Install intersection on curve sign		Proposed by this project

Identified Problem	Countermeasures	CMF	Source
curved intersection			

Table 25. Countermeasures targeted to the problem identified by types (geometric alternation and traffic control devices)

Countermeasures		CMF	Source
Geometric alternation	Install left-turn lane	0.42-0.73	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install left-turn lane painted separation	0.61-0.67	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install left-turn lane (physical channelization)	0.75-0.87	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Improve sight distance	0.44-0.89	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install turn and bypass lanes	0.81-0.95	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install right-turn lane	0.74-0.86	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
Traffic control (positive guidance) and roadway maintenance	Install double stop signs	0.45	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install flashing beacons as advance warning		https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install flashing beacons at stop controlled intersections	0.85	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install larger stop signs		https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Add centerline and move STOP bar to extended curb lines		https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install raised pavement markers		https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Provide a stop bar on minor road approaches		https://safety.fhwa.dot.gov/local_rural/training/fhwasa1108/fhwasa1108.pdf
	Install stop-ahead pavement markings	0.4-0.92	https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install transverse rumble strips on approaches		https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa10005/docs/brief_8.pdf
	Install speed display panel		Proposed by this project
	Improve visibility of intersections by providing enhanced signing and delineation		https://safety.fhwa.dot.gov/local_rural/training/fhwasa1108/fhwasa1108.pdf
	Provide improved maintenance of stop signs		https://safety.fhwa.dot.gov/local_rural/training/fhwasa1108/fhwasa1108.pdf

Countermeasures		CMF	Source
	Provide supplementary stop signs mounted over the roadway		https://safety.fhwa.dot.gov/local_rural/training/fhwasa1108/fhwasa1108.pdf
	Install retroreflective strips on sign posts		https://safety.fhwa.dot.gov/local_rural/training/fhwasa1108/fhwasa1108.pdf
	Install curve warning signs	0.70	https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Install/upgrade curve warning signs with fluorescent yellow sheeting	0.66	https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Double use of advanced warning signs for curves or intersections		https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Use of optical speed bars		https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Install advisory speed limit	0.71-0.87	http://www.cmfclearinghouse.org
	Install intersection on curve sign		Proposed by this project
	Install chevron signs	0.36-0.75	https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Install arrow signs at horizontal curve locations		https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Install post-mounted delineators at horizontal curves		https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Install targeted longitudinal rumble strips on the outside of horizontal curves	0.85	https://safety.fhwa.dot.gov/hsip/hrrr/manual/hrrr_2014.pdf
	Combination curve/intersection signs		https://safety.fhwa.dot.gov/roadway_dept/horicurves/fhwasa15084/fhwasa15084rev011720_508_FINAL.pdf

Table 26. Crash reduction factors, typical crash thresholds, additional application factors, and estimated implementation cost ranges for countermeasures at stop-controlled intersections

Countermeasure	Crash Reduction Factor	Typical Urban Crash Threshold	Typical Rural Crash Threshold	Additional Implementation Factors	Typical Implementation Cost Range per Intersection
Basic set of sign and marking improvements	40%	10 crashes in 5 years	4-5 crashes in 5 years	None	$5,000 to $8,000
Installation of a 6 ft. or greater raised divider on stop approach (installed separately as a supplemental counter measure)	15%	20 crashes in 5 years	10 crashes in 5 years	Widening required to install island	$25,000 to $75,000 (pavement widening but no ROW required)
Either a) flashing solar powered LED beacons on advance intersection warning signs and STOP signs or b) flashing overhead intersection beacons	10% (13% for right angle crashes)	15-20 crashes in 5 years	8-10 crashes in 5 years	None	$5,000 to $15,000
Dynamic warning sign which advises through traffic that a stopped vehicle is at the intersection and may enter the intersection	Unknown	20-30 crashes in 5 years	10-20 crashes in 5 years	5 angle crashes in 5 years and inadequate sight distance from the stop approach	$10,000 to $25,000
Transverse rumble strips across the stop approach lanes in rural areas where noise is not a concern and running STOP signs is a problem ("Stop Ahead" pavement marking legend if noise is a concern)	28% (transverse rumble strips) 15% ("Stop Ahead" pavement markings)	5 running STOP sign crashes in 5 years	3 running STOP sign crashes in 5 years	Inadequate stopping sight distance on the stop approach	$3,000 to $10,000
Dynamic warning sign on the stop approach to advise high-speed approach traffic that a stopped condition is ahead	Unknown	8 running STOP sign crashes in 5 years	5 running STOP sign crashes in 5 years	Inadequate stopping sight distance on the stop approach	$10,000 to $25,000
Extension of the through edge line using short skip pattern may assist drivers to stop at the optimum point	Unknown	10 crashes in 5 years	5 crashes in 5 years	Wide throat and observed vehicles stopping too far back from the intersection	Less than $1,000
Reflective stripes on sign posts may increase attention to the sign, particularly at night	Unknown	10 crashes in 5 years	5 crashes in 5 years	Sign visibility or conspicuity significantly degraded particularly at night	Less than $1,000

Discussions of Results

This project *quantitatively* reveals the safety problem of TWSC intersections on horizontal curves in Louisiana, proposes using a risk analysis method to prioritize the intersections for improvement as part of systemic safety approach, develops safety performance models for TWSC intersections with the data from all parishes in Louisiana and recommends countermeasures for site-specific problems. The overall results are discussed in this section.

Crash Analysis

TWSC intersection on curve is clearly a high crash risk location comparing with TWSC intersection on tangent, particularly on the rural two-lane highways where the majority of TWSC intersections reside in Louisiana. Table 27 lists the average crash rate on curved TWSC intersections by highway type and alignment.

Table 27. Average crash rate on curved TWSC intersections by highway type and alignment

Type	Rural two-lane	Urban two-lane	Rural multiple-lane	Urban multiple-lane
Curve	0.261	0.368	0.293	0.347
Tangent	0.186	0.273	0.205	0.341
% difference	40%	35%	43%	2%

As shown in the above table, all TWSC intersections on curves have a higher average crash rate than that on the tangent alignment. The smallest difference is from urban multiple-lane TWSC intersections. The crash analysis shows how the level of safety varies by curve radius, AADT, intersection skewness, number of intersection legs, and speed limit on major roads. The highest crash rate is associated the smallest curve radius. The common type of crash is single vehicle-running-off-road on major roadway, which has little to do with the TWSC intersection and everything to do with the challenging horizontal alignment. With higher AADT on major road, the most common type of crash is rear-end collision, a typical type of collision at intersection. Table 28 lists the most notable crash characteristics by highway type.

Table 28. Crash characteristics at selected categories on the curve intersections

Comparison Attribute	Rural two-lane	Urban two-lane	Rural multiple-lane	Urban multiple-lane
Crash rate change				
The difference in crash rate between intersections with radius 500 ft. and 1,500 ft.	-36.6%	-18.9%	+22.9%	+58.3%
Intersection skewness bigger than 30º vs. less than 30º	+40%	N/A	N/A	N/A
Percentage of crashes				
Single vehicle crash	51.5%	22.0%	6.8%	7.7%
Rear-end collision	14.8%	34.6%	18.5%	30.2%
Right-angle collision	11.1%	14.8%	31.1%	23.8%

The analysis clearly reveals that there is a safety concern for all TWSC intersections on horizontal curves in Louisiana, especially on the rural highways where the difference in the average intersection crash rate between the curve and tangent alignment is 40% and 43% for two-lane and multiple-lane highways, respectively. The curve sharpness impacts the level of safety particularly on the rural two-lane highways where the crash rate is 1.6 times higher at the intersection with curve radius less than or equal to 500 ft. than that at the intersections with curve radius between 1,000 and 1,500 ft. Table 29 further reveals how the curve radius affects single vehicle ROR crashes on rural two-lane highways.

Table 29. Crash rate comparison by curve radius

Radius (feet)	Average Crash Rate	
	Total crash rate	Single vehicle crash rate
R≤500	0.344	0.236
500 <R≤1,000	0.253	0.179

1,000<R≤1,500	0.218	0.109

The high percentage (51.5% for combined three-leg and four-leg intersections) of single vehicle crashes at curved TWSC intersections is alarming because it is much bigger than the numbers listed in the first edition of HSM (29.4% on three-leg TWSC intersections and 14.7% on four-leg TWSC intersections). The first edition of HSM does not include the TWSC intersection on curve. As revealed in this project, Louisiana has more than 2,331 TWSC intersections on horizontal curves including 1,671 on rural two-lane highways—about 72% of all TWSC intersection on rural two-lane highways. The sheer number of curved TWSC intersections in the state indicates the importance to include this type of intersection to the grand scheme of safety improvement program. The crash characteristics revealed using the data driven techniques can help to establish the targeted safety improvement strategies and procedures.

Additional analysis on the lighting condition of curved TWSC intersection further quantitatively confirms what has been known for a long time, lighting improves intersection safety. The lighting analysis is conducted on urban two-lane highways because of the available number of intersections with lighting. Majority of rural intersections have no lighting. As shown in Figure 24, the intersection lighting investigated in this project probably does not meet the state intersection light standard.

Figure 24. Intersection lighting

After reviewing 476 curved TWSC intersection on urban two-lane highway through Google map, the project identified 176 intersections without any lighting and 284 with lighting. The average crash rates for the group with different lighting conditions are listed in Table 30, which shows that even the sub-standard lighting helps roadway safety. Flash light in this report refers intersection control beacons placed overhead to mark the intersection.

Table 30. Intersection characteristics by type of intersection lighting

Intersection lighting	Number of intersections	Number of crashes	Average crash rate
No	176	922	0.382
Yes	284	1,277	0.337
Yes + flash light	13	162	0.862
Can’t verify by Google Map (no street view)	3	3	0.481
Grand Total	476	2,364	0.368

Risk Analysis and Ranking

In addition to confirming the influential crash contributing factors identified in the crash analysis, the developed risk analysis and ranking methods can serve as a tool for the systemic safety approach since 72% of TWSC intersections on curve are on rural two-lane highways with relatively low AADT. The classifier ranking method is entirely based on the crash analysis, and the second is based on both the crash analysis and the weighting factor that can be decided by the safety program priority. The flexible weighting factors give the jurisdiction safety program opportunity to emphasize their targeted safety areas in programming their specific safety investment.

While the different methods yield different risk ranking results, there are some commonalities. Table 31 shows the characteristics of repeated intersections in different ranking methods.

Table 31. Characteristics of repeated intersections in different ranking methods

Intersection ID	Radius on major road (ft)	AADT on major road	AADT on minor road	Lane width on major road (ft)	Speed limit on major road (mph)	Number of legs	Total crashes
53258	223	1,660	65	12	35	3	14
64515	1,304	1,340	889	12	35	3	14
46458	1,174	670	1,380	12	55	3	13
34370	1,321	2,400	680	11	55	4	12
29692	406	960	570	11	55	3	11
39971	280	1,290	114	12	No speed limit within 0.5 mile	3	7
47838	250	1,200	313	12	55	3	7
4900	1,056	2,100	1,172	12	55	4	8
15215	1,329	5,200	1,080	12	55	3	8
45761	151	4,300	60	12	55	3	16
11909	184	6,000	1,720	12	45	3	13
9907	476	1,100	360	11	55	4	0
36447	151	590	347	11	55	4	2
35027	155	660	30	11	55	4	4
8546	286	630	820	13	55	4	2
46046	840	3,900	520	12	35	3	5
37096	111	460	24	11	55	4	0
37099	136	400	400	11	55	4	1
37198	266	460	24	11	55	4	2
35707	335	110	15	11	55	4	0
5233	>1,500	2,300	560	12	55	4	2
37800	>1,500	1,570	490	12	55	4	1
53000	404	2,600	2,600	12	55	4	2
35502	>1,500	2,800	1,280	12	55	4	3
30671	321	810	60	11	40	4	1
15489	296	55	22	11	55	3	0
36284	301	440	47	11	55	3	0
63261	88	2,300	400	12	55	3	0
39414	155	2,100	4,500	11	55	3	10
52356	62	1,810	350	12	30	4	7
3880	228	1,640	436	11	35	4	0
7008	252	1,530	673	12	30	4	0
51259	278	1,780	87	13	55	3	4

Intersection ID	Radius on major road (ft)	AADT on major road	AADT on minor road	Lane width on major road (ft)	Speed limit on major road (mph)	Number of legs	Total crashes
53825	371	1,940	152	12	55	3	0
39409	>1,500	3,200	1,360	13	50	3	5
45476	977	6,600	834	14	35	4	10
36579	206	1,430	439	11	35	4	4
35289	294	1,270	1,870	11	30	4	0
62427	285	850	1,056	11	45	3	0
1679	>1,500	6,000	1,550	12	55	4	5
5403	671	1,650	1,380	10	45	3	4

TWSC Intersection Safety Models

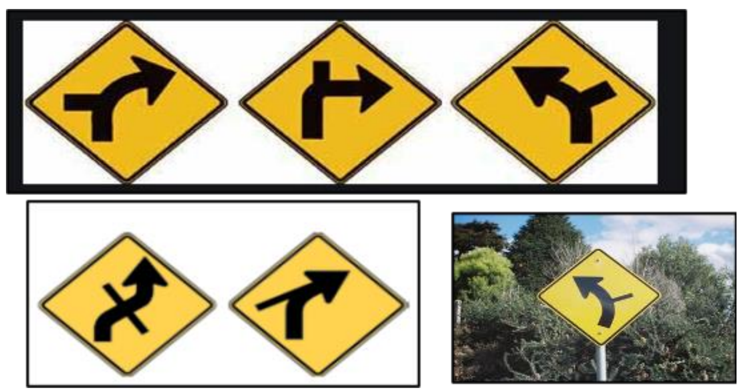
The Louisiana-specific safety model developed in this project with the data from all parishes can be used to predict and evaluate the level of safety for TWSC intersections on two-lane highways. To our knowledge, it is the first time that a TWSC intersection safety model was developed for a state with the data collected from entire state.

Countermeasure Selection

There are many documented crash countermeasures for horizontal curve and stop controlled intersections from reliable sources such as FHWA and NCHRP reports. Other than reinventing the wheel, this project develops a list to show the countermeasure from these reliable documents that targeted the commonly identified problems that also include the source and available CMFs. There are little countermeasures targeting the combination of horizontal curve and intersection. However, this research shows those published countermeasures would work for TWSC intersections on curves. Common low-cost countermeasures for intersections on small curves and low AADT are speed reduction devices to combat the high risk of single vehicle-running-off-road problem. Adding left-turning lane would be effective at the intersections with frequent left-turning vehicles on major roadway to minimize the number of rear-end collision. Trimming intersection corner would help to reduce crashes caused by insufficient sight distance. It is important to be aware of that each location could be different and crash analysis for the group of similar intersection should serve as the basis for countermeasure selection. While there is no official definition of low-cost, the traffic control devices (positive guidance) and rumble strips are generally considered as the low-cost while alternating intersection layout and fattening curves fall in the high-cost category. The engineering economic analysis method, such as ratio of benefit to cost, can justify the high-cost solutions at intersections with consistent higher annual crash frequency.

It is worth to note that lack of "Intersection on Curve" sign shown in Figure 25 on Louisiana curved TWSC intersections might be responsible for some crash occurrences.

Figure 25. Examples of intersection on curve signs



Conclusions

By developing a database containing more than 8,600 TWSC intersections from all 64 parishes in Louisiana, this project quantitatively reveals the scope, magnitude, and characteristics of the intersection safety problems; proposes the risk ranking methods that can be used as the systemic safety approach; develops the TWSC intersection safety performance models, and demonstrates crash countermeasure selection based on the site investigation, which leads to the following conclusions:

- TWSC intersection on curve is a risky location compared to TWSC on tangent. The magnitude of crash risk depends on AADT, curve radius, intersection skewness, speed limit on major roadways, and time of the day. When the curve radius on a major roadway is less than or equal to 500 ft., the crash rate can be 85% and 58% higher than that on tangent intersection and curved intersection with radius between 1,000 and 1,500 ft., respectively.
- The single vehicle crash consists of 51.5% of total crashes at rural two-lane curved TWSC intersections. The curve radius is a critical contributing factor to single vehicle crashes, the difference in crash rate between radius less than or equal to 500 ft. and less than 1,500 ft. but bigger than 1,000 ft. is 117% higher. The countermeasures targeting on single vehicle crash should be considered as top priority.
- Speeding, or improper operating speed, is a major contributing factor to single vehicle-running-off-roadway crashes. Some drivers may not be aware of the proper speed because the speed limit sign is not near the intersection, there is no advisory speed limit, and there is no warning sign on upcoming sharp curve or curved intersection ahead.
- Rear-end collision is the highest type of collision on urban roadways (two-lane or multiple-lane). Lack of turning lanes on major roadways at intersections is the cause of problem, which is not clear in our aggregated crash rate analysis because of very small number of intersections with the turning lane, but it is clear in our site analysis. This type of collision is also a concern on rural two-lane when AADT on major roadway is higher than 5,000.

- It is clear some drivers are challenged at curved TWSC intersections particularly at night, which is evidenced by higher percentage of crashes at night and higher fatal alcohol involvement crashes.
- Under the financial constraints, prioritizing locations by the risk instead of historical crash frequency would work better for TWSC intersections on rural two-lane highways because of their relatively lower AADT.
- There is clearly a need to improve TWSC intersections on curves at a system level. The low-cost countermeasures are more economical for the intersections with low-traffic volume, but high risk and the more costly measures are suitable for the locations with high traffic volume and high crash risk.

To maintain a sustainable crash reduction trend, the safety problem at TWSC intersections calls for the targeted solutions at the system level with systemic safety approach. Considering 72% or 1,671 curved TWSC intersections and 73.6% of intersections with radius less than or equal to 500 ft. on rural two-lane highways, it is necessary to tackle these problems now, starting with rural two-lane highways.

Recommendations

Based on the results, the following recommendations are made to the state DOTD Safety Improvement Program to consider:

- Ranking all state TWSC intersections with the weighting factor reflecting DOTD's safety goals and objectives on the emphasized areas for improvement.
- Setting up plans to annually program the low-cost countermeasures implementation for the TWSC curve intersections with low AADT at the state or district level.
- Setting up plans to target the top-ranking locations with high AADT and consistent high crash occurrences in three years for more expensive countermeasures.
- Adopting the developed safety model for rural two-lane TWSC intersection performance prediction and evaluation.
- Re-examining TWSC intersections where AADT on both major and minor roadways are high and similar for alternative traffic control method (roundabout, signalized, or all-way stop sign)

Acronyms, Abbreviations, and Symbols

Term	**Description**
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
CRF	Crash Reduction Factor
CURE	Cumulative Residual
EB	Empirical Bayes
FHWA	Federal Highway Administration
ft.	foot (feet)
HSM	Highway Safety Manual
DOTD	Louisiana Department of Transportation and Development
LTRC	Louisiana Transportation Research Center
NB	Negative Binomial
PDO	Property Damage Only
SPF	Safety Performance Function
TWSC	Two-Way Stop-Control
ZIP	Zero-inflated Poisson
ZINB	Zero-inflated Negative Binomial
SG	Signalized Intersections

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Appendix

Ranking Intersection

Method 1 - Classifier

Step 1. Group curve intersections for training (80%) and testing (20%). The intersections are classified by crash occurrence, zero or non-zero. Training dataset consists of around 60% of zero crash and 40% of non-zero crash in this study. For test dataset, data distribution follows the similar ratio.

Step 2. LabelEncoder is a utility class to help encode target labels in Python version 3.7.0. LabelEncoder is used to transform non-numerical labels. For example, the intersection number of legs three-leg and four-leg can be replaced by 0 and 1. If feature variables have more subgroups, LabelEncoder encode these labels with value between 0 and n.

Step 3. Apply scikit-learn library in Python for decision classifier and random forest classifier. Then "feature importance" library was used to find important features in ascending order.

Step 4. Calculate ranking by multiplying classifier importance values and feature values (major road AADT, major road radius, major road speed limit, major road lane width, minor road AADT, and number of intersection legs) for each intersection (Equation 8).

Step 4. Sort above results from largest to smallest by descending order.

Method 2 - Crash Analysis and Design

Step 1. Calculate intersection average crash rate by variables (major road AADT, major road radius, major road speed limit, number of intersection legs, and skewness) and their subgroups.

Step 2. Calculate significance factor for crash contributing variables for each intersection (Equation 10).

Step 3. Set up weighting factor scheme for each variable.

Step 4. Calculate ranking by Equation 9.

Step 5. Sort above results by descending order.

Calculation Example

The intersection information is given in the following table.

Table B1.1. Overview of intersection of LA1 and LA15

Intersection name	Intersection of LA1 and LA15
Highway type	Rural two-lane
Number of legs	Four-leg
Alignment	Curve
AADT-major road	630
AADT-minor road	820
Radius on major road	286 ft.
Skewness	less than 30^{o}
Speed limit on major road	55 mph

The predicted number of crashes is calculated as:

$$\begin{aligned} N_{4ST} &= \exp\big(-6.2928 + 0.5862 \times \ln(AADT_{major}\big) + 0.4341 \times \ln(AADT_{minor}) \\ &\quad - 0.0002 \times Curve\ radius \\ &= \exp(-6.2928 + 0.5862 \times \ln(630) + 0.4341 \times \ln(820) \\ &\quad - 0.0002 \times 286 = 1.406 \end{aligned}$$

$$w_1 = \frac{1}{1+k\times P}$$

where,

w_1= weight

k = overdispersion parameter of the SPF

P = total number of crashes

$$w_1 = \frac{1}{1+k\times P} = \frac{1}{1+0.95\times 1.406} = 0.428$$

The EB estimated number of crashes is then calculated as:

$$E = P \times w_1 + A \times (1 - w_1)$$

where,

A = observed number of crashes for the intersection

$$E = P \times w_1 + A \times (1 - w_1) = 1.406 \times 0.428 + 2 \times (1 - 0.428) = 1.746$$

Significance factors are calculated as:

$$S_{ij} = \frac{r_j}{\sum \overline{r_j}}$$

Where,

S_{ij} = significance factor for crash contributing variable i, i= AADT, curve radius, speed limit, number of legs, and skewness; j = subgroup of variable i,
r_j = average crash rate of subgroup j of variable i, and
$\sum \overline{r_j}$ = sum of average crash rate of variable i.

For example, the significance factor when number of legs (variable i) is 4 (subgroup j) equals to:

$$S_{ij} = \frac{r_j}{\sum \overline{r_j}} = \frac{0.346}{0.253+0.346} = 0.577$$

Similarly, the significance factors for AADT on major road, curve radius on major road, speed limit on major road, and skewness equal to 0.109, 0.423, 0.298 and 0.417, respectively.

Assume using weighting factor scheme 1,

Table B1.2. Weighting factor scheme 1

Variable	Scheme 1
AADT on Major Road	5
Radius on Major Road (feet)	4
Speed Limit on Major Road (mph)	3
Number of Legs	2
Skewness	1

$$W_i = \frac{w_i}{\sum w_i}$$

where,

W_i = weighting factor of variable i, and
w_i = weight value of variable i.

For example, the weighting factor for AADT equals to:

$$W_{AADT} = \frac{w_i}{\sum w_i} = \frac{5}{5+4+3+2+1} = 0.333$$

Similarly, the weighting factors for curve radius on major road, speed limit on major road, number of legs, and skewness equal to 0.267, 0.2, 0.133 and 0.067, respectively.

Overall risk is calculated as:

$$R = \sum S_{ij} \times W_i$$

where,

R = overall risk,
S_{ij} = significance factor for crash contributing variable i, i= AADT, curve radius, speed limit, number of legs, and skewness; j = subgroup of variable i
W_i = weighting factor of variable i

$$R = \sum S_{ij} \times W_i = 0.109 \times 0.333 + 0.423 \times 0.267 + 0.298 \times 0.2 + 0.577 \times 0.133 + 0.417 \times 0.067 = 0.314$$

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