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Research Article

Modeling two-way stop-controlled intersection crashes with zero-inflated models on Louisiana rural two-lane highways

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ABSTRACT

Intersection safety continues to be a crucial issue throughout the United States. In 2016, 27% of the 37,461 traffic fatalities on U.S. roadways occurred at or near intersections. Nearly 70% of intersection-related fatalities occurred at unsignalized intersections. 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. Research was performed to analyze safety performance for intersections on rural, two-lane roadways, with stop control on the minor roadway. Roadway, traffic, and crash data were collected from 4148 stop-controlled intersections of all 64 Parishes (counties) statewide in Louisiana, for the period of 2013 to 2017. Four count approaches, Poisson, Negative Binomial (NB), Zero-inflated Poisson (ZIP) and Zero-inflated Negative Binomial (ZINB) were used to model the number of intersection crashes for different severity levels. The results indicate that ZIP models provide a better fit than all other models. In addition to traffic volume, larger curve radii of major and minor roads and wider lane widths of major roads led to significantly smaller crash occurrences. However, higher speed limits of major roads led to significantly greater crash occurrences. Four-leg stop-controlled intersections have 35% greater total crashes, 49% greater fatal and injury crashes, and 25% greater property damage only (PDO) crashes, relative to three-leg intersections.

1. Introduction

Intersection safety continues to be a crucial issue throughout the United States. In 2016, 27% of the 37,461 traffic fatalities on U.S. roadways occurred at or near intersections. Nearly 70% of intersection-related fatalities occurred at unsignalized intersections [1]. Unsignalized intersections are of particular concern, because majority of intersections along low- to moderate-volume roads in rural and suburban areas are unsignalized. Unsignalized intersections represent potential hazards not present at signalized intersections. 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 [2]. Having an intersection on a horizontal curve could increase the crash risk, because of combined challenges. Although the 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 intersections on horizontal curves, if other solutions are prohibitively expensive [3]. 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 preliminary investigation. Fig. 1 shows a collision that occurred at a T-intersection (a common intersection type on rural, two-lane roadways with a stop sign on minor road) between a right-turning vehicle and a running off road vehicle, trying to negotiate the curve.

Intersection safety has been a long-standing problem in Louisiana. Unfortunately, in 2016, in Louisiana, intersection-related fatalities and severe injuries accounted for 19.1% of total fatalities and 39.9% of total severe injuries. More than 55% of intersection-related fatalities occurred at unsignalized intersections [4]. To get a better understanding of the influential factors on intersection crash frequency and injuries, count-data models are widely used to relate the number of crashes of different types or severities to site characteristics. These models always include traffic volume (Average Annual Daily Traffic, AADT), but also include site characteristics, such as lane width, radius/degree of horizontal curves, and presence of turn lanes at intersections. To fulfill the hefty goal established by Louisiana's Strategic Highway Safety Plan (SHSP) to reduce roadway departure, intersection, and non-motorized user

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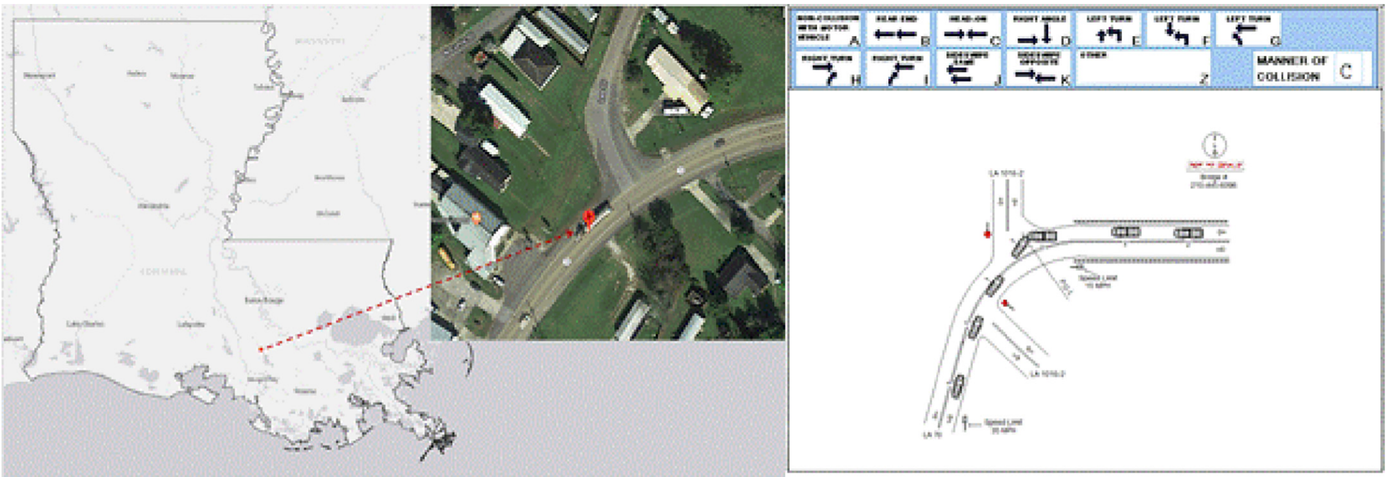

Fig. 1. A typical example of an intersection on a curve.

fatalities and severe injuries by 50% by 2030, there is a clear need to further investigate intersection safety performance on two-lane roads with geometric characteristics.

2. Literature review

Unsignalized intersection safety has been conducted by many studies in the past. Investigating characteristics of intersection crashes, identifying the risk factors related to the injury severity levels, and predicting crash frequency were the key focuses of these studies.

Various models were developed to study the relationship between crashes at unsignalized 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 Negative Binomial (NB) regression were used for the remaining intersection types. Since crash occurrences are more likely random events, Poisson and NB models have been used extensively in prior studies [6–10]. 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 [11].

The presence of horizontal curves adds complexity to intersections. Kuciemba and Cirillo's study has shown that safety is affected by the presence of horizontal curves in close vicinity of intersections [12]. Vogt and Bared Vogt (1999) described the development of a NB 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. 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 [7]. Savolainen and Tarko conducted a study for the Indiana Department of Transportation (INDOT) and found that curvature was a significant factor impacting the safety of intersections, where the intersection is two-lane two-way stop-controlled, and the major road is a rural four-lane divided highway. NB models were developed to determine the statistical relationship between the crash occurrence and intersection geometric characteristics. The same study stated that full curvature and superelevation increased crashes by 30%, in comparison to tangent intersections [3].

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 [11]. 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 [13]. Shankar et al. presented an empirical review into the applicability of zero-inflated count data modeling to roadway segment crash frequencies. The findings showed 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 [14]. A study by Lee et al. 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 [15]. Empirical models based on ZIP were presented and discussed in terms of their applicability to pedestrian crash in two studies [16,17]. The results showed that ZIP is effective enough to provide explanatory insights into the causality behind pedestrian-traffic crashes. Lord et al. used ZIP and ZINB to account for the dominance of excessive zeroes observed in crash count data of vehicle crashes [18]. Zero-inflated models have also been used to analyze crash severity on rural two-lane roadway segments [19].

There has been limited research using zero-inflated models to model the expected crashes with large localized intersection database. In Louisiana, proximately one-third of total two-way stop-controlled (stop sign on minor roadway) intersections have zero crashes during the most recent five years. Consider that factor and address the gap, research was performed to analyze safety performance for intersections on two-lane roadways, with stop control on the minor roadway. Roadway, traffic, and crash data were collected for 4148 stop-controlled intersections of all 64 Parishes (counties) statewide in Louisiana, covering the period of 2013 to 2017. A series of models were generated for different crash severities using conventional models (Poisson and NB) and zero-inflated models (ZIP and ZINB).

3. Data

Prior to the crash modeling, a huge effort was made to develop a comprehensive database based on the intersection crashes, traffic volume, and other relevant roadway characteristics for two-way stop-controlled intersections on Louisiana rural two-lane highways. The five-year crash data (2013 to 2017) were used to reflect the latest highway safety conditions. As shown in Fig. 2, there are several important

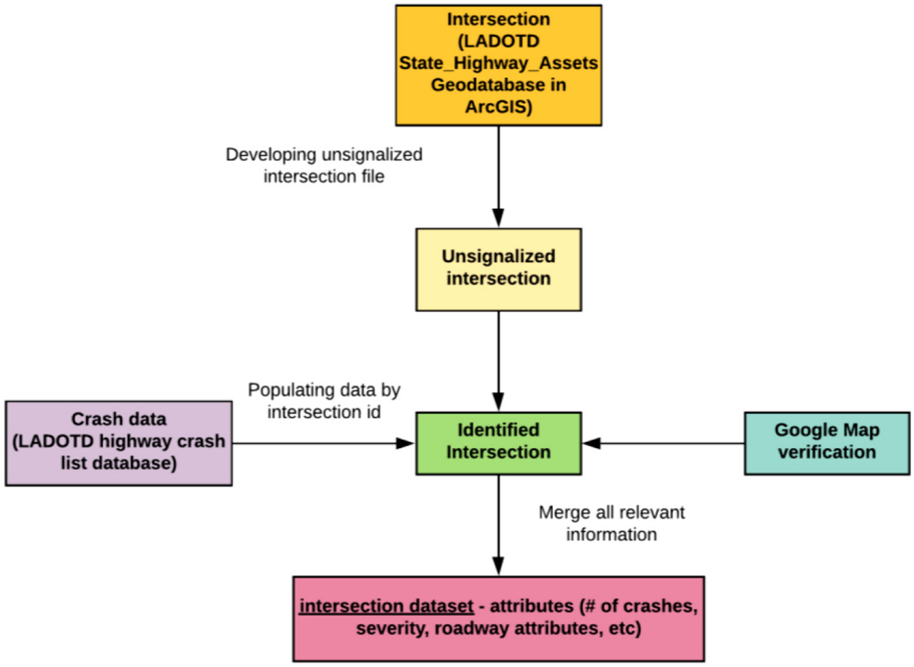

Fig. 2. Database development flow chart.

steps in retrieving and merging different data files from Louisiana Department of Transportation and Development (LaDOTD).

To assure the data accuracy, a significant effort was made to verify the information presented in the data files shown in Fig. 2. The shapefiles from the LaDOTD *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 AADT data was obtained system-wide, for each rural intersection, from the LaDOTD roadway inventory file. Satellite imagery and street-level imagery in Google Maps were utilized to exam the data accuracy intersection by intersection such as turning radiuses and type of traffic control. Further, additional information that was not included in the existing datasets, was manually collected, which includes the presence of left- and right-turn lane. The LaDOTD's crash database uses the ABCDE scale to describe the severity level of crashes. 'A' indicates fatal injury, 'B', 'C', and 'D' indicates incapacitating or severe injury, non-incapacitating or moderate injury, and possible or compliant injury, respectively. 'E' represents that no injuries occurred in the crash. In this study, A, B, C, and D levels of severity were combined as fatal and injury crashes. The end product from the process illustrated in Fig. 2 is a comprehensive database containing information on intersection, roadway, and crash characteristics. The data process was facilitated by the intersection identification number and intersection name, used in the LaDOTD system, which allowed data from different sources to be identified. Incomplete and, obviously, incorrect data (such as AADT entered as zero or blank) were removed. Table 1 gives an overview of descriptive statistics of the intersections used in the model development.

4. Methodology

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 (*7, 8, 17–19*). The probability of y_i crashes occurring at a given intersection i, $P(y_i|\lambda_i)$, is shown in Eq. 1:

Table 1
Overview of two-way stop-controlled intersections (4148 intersections).

Variable	Mean	SD	Min	Max
ADT (Average daily traffic)				
Major road	2322	2243	55	16,500
Minor road	387	776	10	12,000
Radius (Horizontal curve radius in ft.)				
Major road	1218.3	615.6	89.4	2498.0
Minor road	652.1	560.1	98.6	2301.7
Lane width (ft.)				
Major road	11.6	0.8	8	16
Minor road	9.5	1.9	6	14
Speed limit (mph)				
Major road	47.0	9.2	25	55
Minor road	30.9	13.5	15	55
Number of leg (0 if 3-leg, 1 if 4-leg)	0.142	0.350	0	1
Left-turn lane presence (0 if no, 1 if yes)	0.012	0.148	0	1
Right-turn lane presence (0 if no, 1 if yes)	0.009	0.122	0	1
Total crashes	1.014	2.232	0	36
Fatal and injury crashes	0.420	1.042	0	20
Property damage only crashes	0.594	1.440	0	21

$$P(y_i|\lambda_i) = \frac{e^{-\lambda_i}\lambda_i^{y_i}}{y_i!}; y_i = 0, 1, 2, 3\ldots \quad (1)$$

The relationship between the number of crashes at intersection i and the q parameter (X_{i1}, X_{i2}, X_{iq}) is shown in Eq. 2:

$$\lambda_i = \exp\left(\beta_0 + \sum_{j=1}^{q} X_{ij}\beta_j\right) \quad (2)$$

where, λ_i= expected number of crashes per year at intersection i, X_i is the independent variables at intersection i, and β_j is 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, considered to be a result of over-dispersion. In this study, 1382 intersections had zero crashes during 2013 to 2017. The Poisson model cannot be used for these cases, as it cannot handle the over-dispersion, due to these high number of zeros. To address this challenge the ZIP model can be alternatively used. The ZIP model serves as a dual-state method for modeling data, characterized by a significant amount 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: (i) the process generating excess zero count (zero-crash state) derived from a binary model and (ii) the process generating non-negative counts for intersection crashes including zero values, which estimated from the Poisson distribution [17]. Suppose π_i is the probability that intersection i 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 Eq. 3:

$$P(Y=y_i)=\begin{cases}\pi_i+(1-\pi_i)e^{-\lambda_i}; & y_i=0\\ (1-\pi_i)\dfrac{e^{-\lambda_i}\lambda_i^{y_i}}{y_i!}; & y_i>0\end{cases} \tag{3}$$

The probability of being in the zero-crash state, P_i, is often fitted using the logistic regression model, as follows in Eq. 4:

$$logit(P_i)=\ ln\left(\frac{P_i}{1-P_i}\right)=\beta_0+\sum\nolimits_{j=1}^{q}Z_{ij}\,\beta_j \tag{4}$$

where Z_{ij} is a function of at intersection i, and β_j is a vector of estimable regression coefficients. The mean and variance of ZIP are given as follows in Eq. 5 and 6:

$$E(Y)=\lambda_i(1-\pi_i) \tag{5}$$

$$Var(Y)=\lambda_i(1-\pi_i)(1+\lambda_i\pi_i) \tag{6}$$

Similar to ZIP model, the probability density function for the ZINB model is given by Eq. 7:

$$P(Y=y_i)=\begin{cases}\pi_i+(1-\pi_i)\dfrac{1}{(1+\alpha\lambda_i)^{1/\alpha}}; & y_i=0\\ (1-\pi_i)\dfrac{\Gamma\left(\dfrac{1}{\alpha}+y_i\right)}{\Gamma(1+y_i)\Gamma\left(\dfrac{1}{\alpha}\right)}\dfrac{(\alpha\lambda_i)^{y_i}}{(1+\alpha\lambda_i)^{\frac{1}{\alpha}+y_i}}; & y_i>0\end{cases} \tag{7}$$

where α is the dispersion parameter. As α increases, this indicates that the data are more dispersed, which leads to higher standard error values.

5. Results

5.1. Model selection

Four count approaches (Poisson, Negative Binomial, ZIP and ZINB) were used to model the number of intersection crashes occurring on the identified intersections. In statistically validating any zero-altered model, one has to distinguish between the count models. A statistical test to make this distinction has been proposed by Vuong (1989). The Vuong-test is based on the t-statistic and has reasonable power in count-data applications (see Greene, 1994). The Vuong-statistic (V-statistic) is computed as Eq. 8:

$$V=\frac{\overline{m}\sqrt{N}}{S_m} \tag{8}$$

where $\overline{m}$ is the mean of $m=\ ln\left[\frac{f_1(.)}{f_2(.)}\right]$, $f_1(.)$ is the density function of the ZIP/ZINB distribution, and $f_2(.)$ is the density function of the parent-Poisson/NB distribution, and S_m and N are the standard deviation and sample size, respectively. A value greater than 1.96 (the 95% confidence level for the t-test) for the V-statistic favors the ZIP/ZINB, while a value less than −1.96 favors the parent-Poisson/NB, with values in between 1.96 and − 1.96, meaning that the test is inconclusive.

Table 2 summarized the results of considered models. The Vuong statistic for the Poisson versus ZIP (p-value = 0.0000), NB versus ZIP (p-value <0.05) and ZINB versus ZIP (p-value <0.05) favors the ZIP model for total, injury and property damage only (PDO) crashes, which as shown in Table 3.

5.2. Model estimation results

The objective of this research is to quantify safety performance at two-way stop-controlled intersections in Louisiana, identifying relative effects of the roadway characteristics (e.g. curve radius, presence of turning lanes, traffic volume, speed, etc.) on crashes. The variable selection is based on extensive literature review and preliminary analysis of the dataset. Different coefficients specified for three different traffic severity levels (total, fatal and injury, and PDO crashes) are established for intersections on two-lane roadways, with stop control on the minor roadway, respectively. Open source statistical "R version 3.6.1" software was used for ZIP model estimation. The Vuong test results favor the ZIP model over all other models. The ZIP model estimation results for total, fatal and injury, and PDO crashes are shown in Table 4.

The predictors with positive coefficients indicate an increase in the likelihood of crash occurrences. Logarithm of ADT (Ln (ADT)) of major and minor roads, curve radii of major and minor road, lane widths of major roads, speed limits of major and minor roads, and number of legs were found to be statistically significant with p value less than 5%. Out of these variables, Ln (ADT) of major and minor roads, speed limits of major roads, number of legs are positively related to intersection crashes. On the contrary, curve radii of major and minor roads and lane widths of major roads have negative association.

Intersection crashes increase as traffic flow increases in all three different traffic severity levels, as expected. The results show that intersections with higher speed limits on major roads tend to have higher probability of crashes occurring. The probability of total crashes, fatal and injury crashes, and PDO crashes decreases as curve radii on major roads increases, as well as lane widths of major roads. Four-leg stop-controlled intersections were found to have 35% more total crashes, 49% more fatal and injury crashes, and 25% more PDO crashes, relative to the three-leg intersections. Left- and right-turn lanes were not found to significantly affect crash occurrence at rural three-leg stop-controlled and four-leg stop-controlled intersections, although this was likely due to a small sample of such intersections and crashes.

6. Discussion

This research aims to utilize ZIP models to investigate and estimate the safety performance for intersections on two-lane roadways, with

Table 2
Model goodness-of-fit results.

Model	Poisson	NB	ZIP	ZINB
Log-likelihood	−3743.99	−3351.96	−3080.72	−3090.35
α p-value	–	0.76	–	0.84
AIC	6277.15	6259.73	6221.67	6236.69

Table 3
Vuong test statistic.

Severity Types	ZIP vs Poisson	Vuong Test Statistic	p-value	ZIP vs NB	Vuong Test Statistic	p-value	ZIP vs ZINB	Vuong Test Statistic	*p*-value
Total Crashes	ZIP > Poisson	12.576	<0.001	ZIP > NB	2.576	0.005	ZIP > ZINB	2.264	0.012
Fatal and Injury Crashes	ZIP > Poisson	9.016	<0.001	ZIP > NB	2.016	0.022	ZIP > ZINB	1.770	0.040
PDO Crashes	ZIP > Poisson	11.053	<0.001	ZIP > NB	3.053	0.001	ZIP > ZINB	1.861	0.031

stop control on the minor roadway in Louisiana. To account for the excess zeros in crash data existence, separate models were developed for total crashes, fatal and injury crashes, and PDO crashes. Although many states have developed their state-specific safety performance functions for two-way stop-controlled intersections, intersections on horizontal curves were not specifically investigated because of the lack of comprehensive curve-related data. Massive data collection effort has been conducted for the scope in this study. Hence, a geographic representation of Louisiana was achieved.

Table 5 summarizes the state-level studies on the safety performance of two-way stop-control intersections on rural highways. The presence of intersections on horizontal curves could increase crash risk, which are in accordance with previous studies in two-way stop-control intersection safety analysis using other statistical methods, such as traditional Poisson and NB models [3,7] and Hierarchical Binomial Logistic models [21]. It can be observed that the R squared value varies considerably from state to state. There are several potential causes for the difference between the results from the Louisiana models and the results from other states. The data sources, sample size, modeling structure, and the direct variable selection could have contributed to the difference. These models did not consider excess zeros existence in the crash data.

Vuong test results indicate that ZIP models provide better statistical fit than Poisson and NB models. However, the inherent assumption of a

Table 4
Estimation results of zero-inflated Poisson regression model.

Variable	Total Crashes				Fatal and Injury Crashes				PDO Crashes			
	Coefficient	Std. Error	Z Value	*p*-value	Coefficient	Std. Error	Z Value	*p*-value	Coefficient	Std. Error	Z Value	*p*-value
Non-zero crash probability state as Poisson function												
(Intercept)	−6.023	0.202	−29.82	<0.001	−5.256	0.387	−13.57	<0.001	−6.327	0.265	−23.85	<0.001
Ln (ADT)												
Major road	0.500	0.016	32.25	<0.001	0.374	0.030	12.64	<0.001	0.509	0.021	24.65	<0.001
Minor road	0.266	0.010	26.73	<0.001	0.213	0.019	11.38	<0.001	0.262	0.013	19.90	<0.001
Radius												
Major road	−0.0002	0.0000	−6.38	<0.001	−0.0002	0.0001	−3.29	<0.001	−0.0002	0.0000	−4.21	<0.001
Minor road	−0.0003	0.0001	−2.92	0.004	−0.0002	0.0002	−1.17	0.242	−0.0004	0.0001	−2.76	0.006
Lane width												
Major road	−0.043	0.006	−7.42	<0.001	−0.026	0.011	−2.39	0.017	−0.049	0.007	−6.63	<0.001
Minor road	−0.022	0.013	−1.69	0.091	−0.004	0.025	−0.15	0.881	−0.029	0.017	−1.76	0.078
Speed limit												
Major road	0.016	0.001	14.39	<0.001	0.016	0.002	7.74	<0.001	0.015	0.001	10.46	<0.001
Minor road	0.002	0.001	1.38	0.168	0.002	0.003	0.81	0.420	0.007	0.002	3.91	<0.001
Number of legs												
3-leg	–	–	–	–	–	–	–	–	–	–	–	–
4-leg	0.300	0.023	13.01	<0.001	0.400	0.043	9.24	<0.001	0.226	0.030	7.51	<0.001
Left-turn lane presence												
No	–	–	–	–	–	–	–	–	–	–	–	–
Yes	−0.063	0.050	−1.26	0.208	−0.093	0.100	−0.93	0.355	−0.015	0.063	−0.23	0.814
Right-turn lane presence												
No	–	–	–	–	–	–	–	–	–	–	–	–
Yes	0.058	0.062	0.94	0.348	0.163	0.117	1.39	0.164	0.003	0.079	0.04	0.969
Zero crash probability state as logistic function												
(Intercept)	7.409	0.886	8.36	<0.001	9.144	1.040	8.79	<0.001	6.118	0.930	6.58	<0.001
Ln (ADT)												
Major road	−0.496	0.065	−7.66	<0.001	−0.616	0.077	−7.97	<0.001	−0.430	0.069	−6.20	<0.001
Minor road	−0.141	0.050	−2.80	0.005	−0.170	0.056	−3.02	0.003	−0.195	0.052	−3.75	<0.001
Radius												
Major road	0.0002	0.0001	1.18	0.236	0.000	0.000	0.93	0.353	0.000	0.000	1.53	0.125
Minor road	0.0005	0.0004	1.15	0.248	0.001	0.001	0.78	0.435	0.000	0.000	0.16	0.874
Lane width												
Major road	−0.140	0.068	−2.07	0.039	−0.149	0.078	−1.90	0.057	−0.022	0.069	−0.32	0.752
Minor road	−0.027	0.034	−0.80	0.421	−0.030	0.036	−0.82	0.413	−0.010	0.034	−0.31	0.757
Speed limit												
Major road	−0.021	0.006	−3.33	0.001	−0.026	0.008	−3.52	<0.001	−0.022	0.007	−3.26	0.001
Minor road	−0.016	0.005	−2.86	0.004	−0.009	0.006	−1.38	0.169	−0.014	0.006	−2.47	0.013
Number of legs												
3-leg	–	–	–	–	–	–	–	–	–	–	–	–
4-leg	−0.557	0.140	−3.97	<0.001	−0.355	0.143	−2.48	0.013	−0.572	0.143	−4.00	<0.001
Left-turn lane presence												
No	–	–	–	–	–	–	–	–	–	–	–	–
Yes	−0.285	0.506	−0.56	0.574	0.158	0.462	0.34	0.733	−0.080	0.421	−0.19	0.849
Right-turn lane presence												
No	–	–	–	–	–	–	–	–	–	–	–	–
Yes	−0.343	0.593	−0.58	0.563	−0.480	0.564	−0.85	0.394	0.000	0.477	0.00	1.000

Table 5
Summary of state-level studies on two-way stop-control intersections.

Author(s)	Year	State	Study Period	Roadway Type	Methodology	Intersection Type		Sample Size	Goodness of Fit	Dispersion Parameter	Horizontal Curve Indicator
Bonneson and McCoy [20]	1993	Minnesota	1985–1987	Rural two-lane	Generalized linear model	Two-way stop-control	Four-leg	125	–	1.110	Yes
Vogt and Bared [7]	1998	Minnesota	1985–1989	Rural two-lane	Poisson and NB	Two-way stop-control	Three-leg Four-leg	389 327	$R^2 = 0.4409$ $R^2 = 0.5944$	–	Yes
Bauer and Harwood [5]	2000	California	1990–1992	Rural two-lane	NB	Two-way stop-control	Three-leg Four-leg	2692 1434	$R^2 = 0.3400$ $R^2 = 0.3726$	–	No
Savolainen and Tarko [3]	2004	Indiana	1997–2000	Rural four-lane divided	NB	Two-way stop-control	Not specified	49	$R^2 = 0.23$	1.7276	Yes
Kim et al. [21]	2007	Georgia	1996–1997	Rural two-lane	Hierarchical Binomial Logistic Models	Unsignalized Signalized	Not specified	64 27	– –	 –	Yes
Tegge, Jo, and Ouyang [22]	2010	Illinois	2001–2005	Rural	NB	Two-way stop-control	Not specified	14,933	–	1.429	No
Monsere et al. [23]	2011	Oregon	2003–2007	Rural two-lane	NB	Two-way stop-control	Three-leg	115	–	2.400	No
Donnell, Gayah, and Li [24]	2016	Pennsylvania	2005–2012	Rural two-lane	NB	Two-way stop-control	Three-leg	414	Pseudo $R^2 = 0.0485$	1.117	No
							Four-leg	86	Pseudo $R^2 = 0.0322$	1.348	
Sun et al.	This research	Louisiana	2013–2017	Rural two-lane	ZIP	Two-way stop-control	Not specified	4148	$R^2 = 0.3542$	–	Yes

dual state process underlying the development of these models is inconsistent with crash data. If the only goal consists of finding the best statistical fit then the zero-inflated models may be appropriate, since they offer improved statistical fit compared to Poisson or NB models [18]. In this research, the comparison of the model outputs clearly distinguishes the impact of design related factors on different crash severity levels. The findings of this study are suggestive but limited as these models were based only on rural two-lane highways in Louisiana. Following the discoveries presented in this paper, the research team will continuously examine the validity of the model and non-parametric statistical methods to the extended dataset.

The intersection model developed herein with the data from all parishes can be used to predict and evaluate the level of safety for two-way stop-control intersections on rural two-lane roadways. The presence of intersections on horizontal curves is especially notable as these locations have characteristics that differ significantly from tangent intersections. Ultimately, the findings of this research offer a number of analytical resources to allow proactive safety planning practices, such as high-risk location identification. With the safety strategy plan emphasizing the Destination Zero Deaths objective, Louisiana must pay close attention to intersection safety. To reduce intersection crashes, particularly the fatal and injury crashes, it is critical to select countermeasures that target identified risk factors. Avoiding intersection on sharp curves, or design to compensate for reduced sight distance, enhancing sign and pavement markings, providing travel infrastructures, such as bypass lanes on shoulder at T-intersections, wide shoulder on two-lane highways, and roadway lightings, could work better for intersections safety.

7. Conclusion

Four count approaches (Poisson, NB, ZIP and ZINB) models were developed to estimate annual crash occurrences on two-way stop-controlled intersections on rural two-lane highways in Louisiana for the study period of 2013 to 2017. Based on the test statistic, ZIP models provided a better fit than all other models. The models were specified considering factors such as curve radius of major and minor roads, lane width of major and minor roads, speed limit of major and minor roads, number of legs, and left/right-turn lane presence, in addition to traffic volume. The ZIP estimation results show that, in addition to traffic volume, larger curve radii of major and minor roads and wider lane widths of major roads led to significantly smaller crash occurrences for stop-controlled intersections. Higher speed limits of major roads led to significantly greater crash occurrences. Comparison of the three-leg and the four-leg stop-controlled intersections showed that four-leg stop-controlled intersections have 35% greater total crashes, 49% greater fatal and injury crashes, and 25% greater PDO crashes, relative to the three-leg intersections.

Declaration of Competing Interest

None.

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