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Safety Performance Functions for Low-Volume Rural Stop-Controlled Intersections

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Abstract

This study involved the development of safety performance functions for rural, low-volume, minor road stop-controlled intersections in Michigan. Facility types included three-leg stop-controlled (3ST) and four-leg stop-controlled (4ST) intersections under state or county jurisdiction and were sampled from each of Michigan's 83 counties. To isolate lower-volume rural intersections, major roadway traffic volumes were limited to the range of 400–2,000 vehicles per day (vpd). Data were compiled from several sources for 2,023 intersections statewide. These data included traffic crashes, volumes, roadway classification, geometry, cross-sectional features, and other site characteristics covering the period of 2011–2015. Random effects negative binomial regression models were specified for each stop-controlled intersection type considering factors such as driveway density, lighting presence, turn lane presence, and intersection skew, in addition to volume. To account for the unobserved heterogeneity between counties, mixed effects negative binomial models with a county-specific random effect were utilized. Furthermore, unobserved temporal effects were controlled through the use of a year-specific random effect. Separate models were developed for fatal/injury crashes, property damage crashes, and select target crash types. The analysis found that skew angles of greater than five degrees led to significantly greater crash occurrence for both 3ST and 4ST intersections, while greater than two driveways near the intersection led to significantly greater angle crashes at 4ST intersections. Other factors were found to have little impact on crash occurrence. Comparison with the Highway Safety Manual (HSM) base models showed that the HSM models overpredict crashes on 4ST intersections and 3ST intersections with volumes between 1,200 and 2,000 vpd.

Safety on rural highways continues to be a serious concern throughout the United States. Nationwide, approximately one-half of motor vehicle fatalities occur in rural areas, although only approximately 20% of the U.S. population lives in rural areas. In 2016, the rural highway fatality rate (per vehicle miles traveled) in the U.S. was 2.5 times higher than for urban areas, providing further evidence of an overrepresentation of crashes in rural areas (*1*). Intersections in rural areas are particularly vulnerable to elevated crash risks because of factors that include higher speeds, extreme geometry, and lack of lighting, among others. Gaining a better understanding of the influence of such factors on crashes and injuries will assist traffic safety professionals towards development of targeted programs to reduce traffic crashes and resultant injuries and fatalities.

An important tool in this process is the Highway Safety Manual (HSM) (*2*). While the safety performance functions (SPFs) presented in HSM provide useful tools for road agencies, it is recommended that these functions are either calibrated or re-estimated using local data to improve their accuracy and precision (*2*). Several states, including Michigan, have subsequently developed SPFs based on local data, which has revealed considerable state-to-state variability in the accuracy of HSM's SPFs. This variability is likely reflective of differences in geography, design practices, driver behavior, weather, crash reporting, deer populations, and other factors. However, there remains a lack of research specific to safety performance on rural low-volume highways, particularly for roadways under county jurisdiction.

In Michigan and elsewhere, county highways typically possess characteristics that differ considerably from those maintained by the state department of transportation

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(DOT), which limits the usefulness of SPFs and crash modification factors (CMFs) generated based on rural state highways. These differences include traffic characteristics (e.g., lower traffic volumes, shorter trip distances, driver familiarity, etc.) and design characteristics (e.g., lower design speeds, gravel surfaces, extreme curvature, narrow lanes and shoulders, reduced sight distances, less frequent lighting, etc.) However, several factors make safety analysis on low-volume roads challenging and costly. Specifically, the sparsity of crashes on such roadways leads to small crash sample sizes, thereby increasing the number of study sites needed. Furthermore, there is a lack of available statewide datasets for county roadways, and such data must therefore typically be obtained directly from the individual counties, presenting data formatting and quality control issues. Finally, counties often have varying design standards and maintenance practices, which presents additional analytical challenges.

Although HSM provides details related to local calibration of the HSM's models, the fact remains that the HSM's SPFs were generated based on data obtained from select state highways, and may not accurately translate to county highways. While Michigan-specific intersection SPFs currently exist, they are limited to urban, state highways (*3*). Furthermore, while SPFs have recently been developed for rural roadways in Michigan, low-volume intersections were not specifically investigated (*4*, *5*). Thus, there is a clear need to further investigate intersection safety performance on rural county roads and other lower-volume rural highways.

To address these gaps in the available safety performance models, research was performed to develop safety performance functions for intersections on low-volume rural roadways with stop control on the minor roadway. Signalized intersections were not included in this evaluation because of the limited number of rural traffic signals in Michigan. To accomplish the aforementioned objective, roadway, traffic, and crash data were collected for a sample of county and lower-volume state-maintained rural three-leg stop-controlled (3ST) and four-leg stop-controlled (4ST) intersections in Michigan. A series of safety performance functions was generated using mixed effects negative binomial modeling techniques. The methods and results of this analysis are described in the sections that follow.

Literature on Rural Intersection Safety Performance

Prior research has explored the safety performance of rural intersections. The following paragraphs summarize the extant research literature regarding safety performance modeling for rural intersections, including the analytical methods specified in HSM. Among the various types of statistical models used for SPF development, generalized linear models and negative binomial models yield results that are easy to interpret and associate crash frequencies to sets of designated explanatory variables (*6*, *7*). Negative binomial models are standard for developing SPFs, including those found in HSM, and have been used extensively in prior studies (*8–11*).

Recent rural intersection SPF development in Oregon revealed the typical challenges associated with small crash sample sizes for rural intersections, as only 165 crashes occurred during a three-year period at 115 rural 3ST intersections, which represented a rate of 0.48 crashes per intersection per year. It was concluded that the lack of data and the significant costs of data collection were two major difficulties (*12*).

While it is widely understood that intersection crashes possess a non-linear relationship with the traffic volume entering a rural stop-controlled intersection, several studies have investigated site characteristics that affect crash occurrence at both rural 3ST and 4ST intersections. The effect of intersection lighting has been investigated extensively. For rural 4ST intersections with lighting, HSM provides a CMF of 0.91 relative to the base condition of no lighting present (*2*). Research completed in Minnesota and California found that illuminated intersections are associated with a reduction in night-time crash frequency of 3.6% and 6.5%, respectively (*13*). Intersection sight distance and intersection alignment have also shown to have a substantial influence on the safety of rural intersections (*8*). Perhaps the most extensive recent rural intersection safety analysis investigated the safety effects for both for rural signalized and unsignalized intersections (*14*). The primary safety performance findings from this evaluation are detailed in Table 1.

Data Collection

Prior to the development of safety performance functions, it was first necessary to assemble a comprehensive database of traffic crashes, traffic volume, and other relevant roadway data for rural intersections in Michigan for the five-year period of 2011 to 2015. The data were obtained from multiple sources and available geospatial datasets were utilized whenever possible.

Traffic Volume Data

Annual average daily traffic (AADT) volumes were obtained from three primary sources for use in this project. The particular volume data source was dependent on the roadway jurisdiction and federal aid classification, which are further described as follows. AADT data for Michigan Department of Transportation (MDOT) state

Table 1. Existing CMFs for the Texas Rural Intersection SPF Model (*14*)

CMF	Base conditions	Findings
Left-turn lane	Major-road legs: left-turn lane (or bay) not present	The introduction of left-turn lanes of adequate length in major approach decreases crashes. The proportion of average daily traffic volume on legs plays a major role in CMF calculation.
Right-turn lane	Major-road legs: right-turn lane (or bay) not present	Crashes decrease with the introduction of right-turn lanes of adequate length in the major approach. The proportion of average daily traffic volume on legs and presence of left-turn lane play a major role in CMF calculation.
Number of lanes	Major road: 2 lanes Minor road: 2 lanes	Crashes decrease when the number of major through lanes is 4 or more with increasing number of minor road through lanes because of redistribution of traffic patterns.
Driveway frequency	Major road: 1 driveway within 250 ft Minor road: 0 driveways within 250 ft	Number of crashes increases when there is more than 1 active driveway within 250 ft of the intersection when both major and minor roads are considered. Average daily traffic (ADT) of major and minor road influences the calculation of CMF.
Truck presence	15% trucks	The number of crashes decreases when the average percent of trucks during the peak hour is greater than 15%. CMF developed is appropriate for truck percentages ranging from 0 to 25%.
Shoulder width	Major road: 4-ft shoulder width Minor road: 4-ft shoulder width	CMF is applicable to shoulder widths ranging from 0 to 10 ft. A reduction in crashes occurs when the shoulder width is greater than 4 ft when average width of the outside shoulders on each leg is considered. ADT of major and minor road are also considered for CMF calculation.
Median presence	No median on major road	CMF is only derived for major roads. With a left-turn bay, CMF remains 1.0 for median width up to 16 ft, and decreases thereafter. For intersections without left-turn bay, crashes decrease by introduction of medians starting from width of 5 ft. The median should extend back from the stop line for a distance of 250 ft or more with a width of at least 4 ft.
Alignment skew angle	No skew	CMF is applicable to alignment skew angles in the range of 0 to 30 degrees where crashes increase with increasing skew angle. Different CMF curves are available for 4-leg and 3-leg intersections.

highways were obtained system-wide for each rural roadway segment directly from the MDOT roadway inventory file for each respective year in the study period (2011–2015). County federal aid roadway AADTs were obtained from the MDOT-maintained shapefile for all county federal aid roadways statewide. AADTs for county non-federal aid roadways, including rural collectors and local roadways, were obtained directly from the county road commission or the corresponding regional planning commission, where available. Because the AADTs for non-federal aid county roadways were obtained directly from the county or regional planning entity, the years for which traffic volumes were available varied from county-to-county, and preceded the analysis period in some cases.

Where necessary, to provide estimates for each of the five analysis years (2011–2015), growth factors were applied to the assembled county federal aid and non-federal aid annual traffic volumes. Appropriate roadway growth factors were obtained from MDOT each year from 2011 to 2015, and were applied directly to the applicable county federal aid and non-federal aid roadway volume data, respectively. Growth factors for years prior to 2010 were developed using traffic volume data from MDOT's Highway Performance Monitoring System (HPMS) database and were applied, where necessary, to the relevant county non-federal aid roadway volumes.

Manually Collected Data

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:

- Number of intersecting legs: Only traditional 3-leg and 4-leg intersections were included.
- Assignment of major and minor approaches: The major and minor approach legs were assigned to each intersection based on highest and lowest segment AADT, respectively.
- Number of stop-controlled approaches: The number of stop-controlled approaches for each 3ST and 4ST intersection was noted. Intersections for which street-level imagery was not available were removed from the dataset, as it was not possible to confirm the presence of stop control on the major and minor approaches. This issue typically only impacted non-federal aid intersections, as Street View imagery was available for all MDOT roadways and many county federal aid roadways.

- Number of through traffic lanes: The number of through lanes was determined for each individual approach of the intersection. Shared use lanes (i.e., combined through/turn) were counted as a through lane.
- Turn lane presence: Right- and left-turn lanes were identified based on presence of pavement markings, sign designations, or both. These data were aggregated by the number of approaches with turn lanes. Tapers or widened shoulders were not considered.
- Driveway counts: The number of driveways that were at least partially within a 211-ft radius of the center of the intersection was counted individually for each intersection leg.
- Skew angle: Intersection skew angles were obtained using the heading tool in Google Earth. 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 to a maximum of 89 degrees. For this study, skew was measured as the smallest angle between any two legs of the intersection. The heading of each leg was measured with respect to the centerline, and the absolute difference of those two headings was then calculated. The skew angle was calculated as the absolute difference of this angle from 90 degrees.
- Overhead flashing warning beacon presence.
- Lighting presence (mast-arm or single span wire with hanging light).
- Median presence: Medians were identified along the major legs only.
- Railroad crossing presence: At-grade railroad crossings that fell within a 211-ft radius of the center of the intersection were identified.

All relevant characteristics were collected and assembled into a single comprehensive database for use in SPF development for the rural stop-controlled intersections. Further details of each respective data source is provided in the following sections.

Rural Intersection Identification and Database Assembly

The Michigan Geographic Framework (MGF) All Roads shapefile provided the spatial basis for collection of the necessary roadway and traffic-related attributes for the intersections included within this study. The data collection process was facilitated by the roadway linear referencing system used in the MGF, which allowed data from different sources to be uniquely and independently matched to the network based on their relative roadway position.

To identify intersections within Michigan's roadway network, a spatially based algorithm was developed in ArcGIS to generate nodes based on the occurrence of intersecting lines from the All Roads shapefile. As shown in Figure 1, the algorithm consists of six main steps. First, the full road network was obtained from the All Roads shapefile, where each public road segment was represented by a unique line. The x,y coordinates were then generated at each vertex (i.e., whenever a segment changed direction or at the beginning or end of a segment) and the number of vertices occurring at any given location was counted. Accordingly, a potential intersection was identified whenever the number of vertices was equal to or greater than three, which also represented the number of legs at the intersection.

Geospatial datasets were also used in determining whether or not an intersection was rural. Rural areas are typically defined as an area with a population of 5,000 or less, as defined by boundaries determined by the U.S. Census Bureau. Only segments in rural areas were retained for analysis (*15*). In addition, to ensure all intersections included in the sample were truly rural in character, all incorporated areas (i.e., cities and villages) and unincorporated census designated places (CDPs) were excluded, regardless of population.

Geospatial software was also used to ensure that each intersection had volume data for the major leg and at least one minor leg on non-federal aid roads. All federal aid roads had volume data for all legs. Nodes were excluded from further analysis if any of the following situations applied:

- Not located at an intersection of public roadways
- Located at a roundabout
- Located at a freeway exit ramp
- Redundant or part of a larger intersection
- Within 0.08 mi (422 ft) of another node, such as at median divided intersections or offset "T" intersections
- Merge/diverge nodes at intersections within a horizontal curve

Crash Data Mapping

The annual statewide crash databases were provided by the Michigan State Police for the period of 2011 to 2015, which was the most recently available five-year period. These crash databases contain details of all reported public roadway crash records in the state of Michigan, sanitized of personal information. The crash data were aggregated annually and merged with the roadway inventory data for each segment. All relevant crash

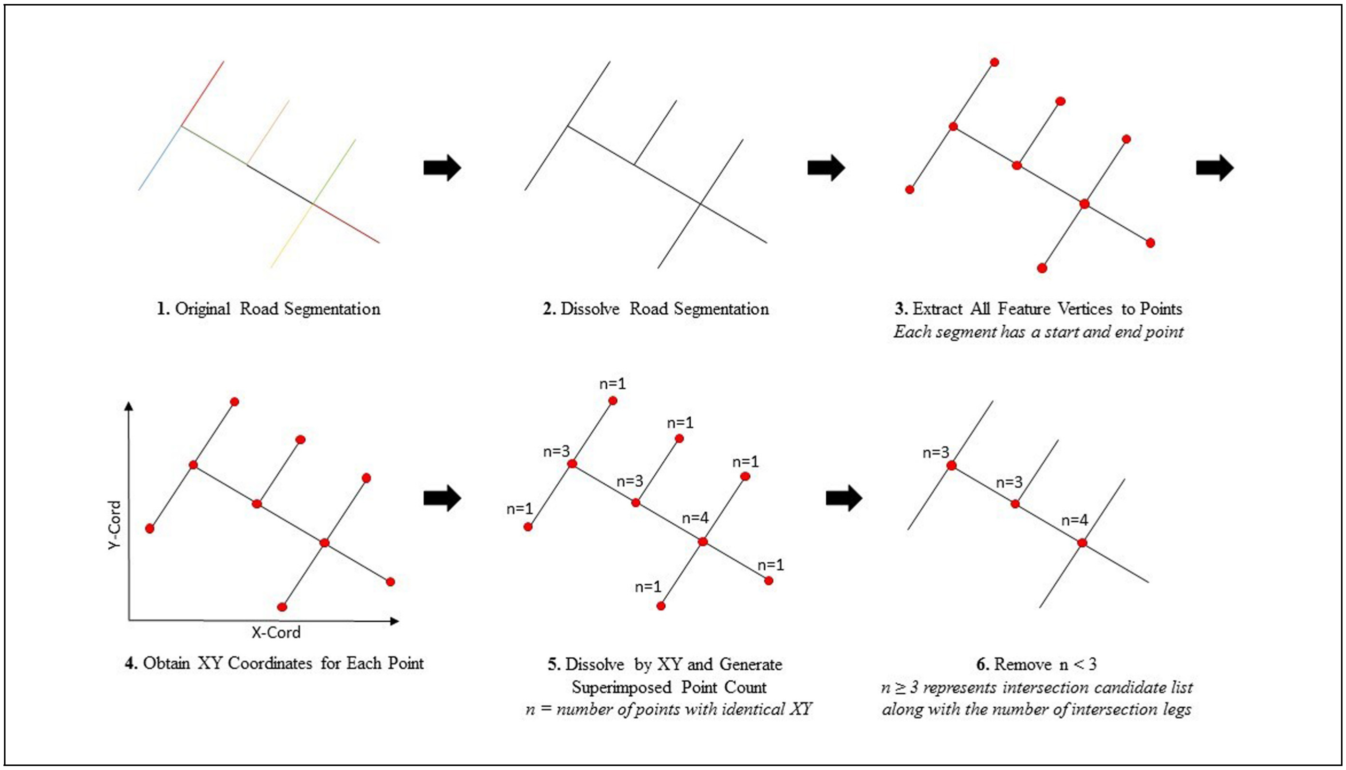

Figure 1. Node identification algorithm.

related fields (i.e., severity, crash type, etc.) were retained within the crash database.

Each crash was initially mapped based on longitude and latitude coordinates as presented in the crash records. Crashes were associated with each identified intersection node based on two primary constraints. First, the crashes were isolated to intersection-coded crashes, identified using the appropriate area-type code. Crashes were then matched to each intersection for further analysis by using a 0.04 mi (211.2 ft) radius around each intersection node. Note that this radius is smaller than the 250 ft radius (0.047 mi) used for the HSM intersection models. Because the GIS software utilized for crash query limited the intersection radius to 0.01 mi increments, the authors deemed it appropriate to utilize the smaller (0.04 mi vs. 0.05 mi) radius to isolate crashes truly associated with the rural intersections.

Descriptive Statistics

The subsections below summarize the descriptive statistics for 3ST and 4ST intersections. For purposes of this study, only those intersections with major road AADTs ranging from 400 to 2,000 were retained, which was consistent with the HSM volume categories. It should be noted that the free-flowing roadway was always designated as the major roadway, while the minor roadway was stop-controlled. For that reason, the minor AADT was greater than the major AADT in a small number of cases. The final dataset included a total of 2,023 rural stop-controlled intersections, which were approximately evenly split between 3ST and 4ST intersections. All 83 counties in Michigan were represented in the 3ST sample, while 81 of the 83 Michigan counties were represented in the 4ST sample.

Rural 4ST Intersections

Table 2 provides summary statistics for all relevant variables of interest considered during 4ST SPF development. More than 72% of intersections were county federal aid, with the remainder split between MDOT and county non-federal aid jurisdiction. Relative to 3ST intersections, a higher proportion of 4ST intersections were lit, with around 24% of intersections having street lighting present. Driveway counts were slightly higher for 4ST, with a mean of 1.8 per intersection. The majority of crashes (71%) were property damage only.

Rural 3ST Intersections

Table 3 provides summary statistics (i.e., mean, minimum, maximum, standard deviation) for all relevant variables of interest considered during 3ST SPF

Table 2. Descriptive Statistics for Rural 4ST Intersections (1,035 Intersections)

Factor	Mean	St. dev.	Min	Max
AADT-major roadway	1,136.93	445.579	400	2,000
AADT-minor roadway	481.082	352.087	10	1,999
MDOT major roadway	0.13	0.336	0	1
County Fed Aid major roadway	0.727	0.446	0	1
County Non-Fed Aid major roadway	0.143	0.35	0	1
Overhead caution beacon	0.039	0.194	0	1
Lighting present	0.243	0.429	0	1
Skew angle	4.02	10.613	0	63
Number of approaches with left-turn lane	0.02	0.24	0	4
Number of approaches with right-turn lane	0.049	0.324	0	4
Number of thru lanes on major roadway	1.006	0.076	1	2
Driveway count	1.841	1.951	0	12
Railroad presence	0.012	0.107	0	1
Superior Region	0.102	0.302	0	1
North Region	0.16	0.367	0	1
Grand Region	0.199	0.399	0	1
Southwest Region	0.099	0.298	0	1
University Region	0.252	0.434	0	1
Bay Region	0.177	0.382	0	1
Metro Region	0.012	0.108	0	1
Total	0.415	0.736	0	10
Fatal and injury (FI)	0.119	0.377	0	6
Property damage only (PDO)	0.296	0.586	0	5

Table 3. Descriptive Statistics for Rural 3ST Intersections (988 Intersections)

Factor	Mean	St. dev.	Min	Max
AADT-major roadway	1,086.82	447.495	400	2,000
AADT-minor roadway	452.793	382.361	5	2,875
MDOT major roadway	0.155	0.362	0	1
County Fed Aid major roadway	0.672	0.469	0	1
County non-Fed Aid major roadway	0.173	0.378	0	1
Lighting present	0.205	0.404	0	1
Skew angle	8.103	15.061	0	73
Number of approaches with left-turn lane	0.014	0.125	0	2
Number of approaches with right-turn lane	0.037	0.218	0	2
Number of thru lanes on major roadway	1.007	0.084	1	2
Driveway count	1.577	1.664	0	11
Railroad presence	0.01	0.099	0	1
Superior Region	0.155	0.362	0	1
North Region	0.174	0.379	0	1
Grand Region	0.161	0.367	0	1
Southwest Region	0.171	0.377	0	1
University Region	0.236	0.425	0	1
Bay Region	0.088	0.283	0	1
Metro Region	0.016	0.126	0	1
Total	0.27	0.567	0	4
Fatal and injury (FI)	0.048	0.225	0	2
Property damage only (PDO)	0.222	0.511	0	4

development. More than 67% of intersections were county federal aid, with the remainder split between MDOT and county non-federal aid jurisdictions, while around 20% of intersections had lighting present. Driveways within 211 ft of 3ST intersections were relatively sparse, with a mean value of 1.6 driveways per intersection. The majority of crashes (82%) were property damage only (PDO).

Analysis

As crash data are comprised of non-negative integers, traditional regression techniques (e.g., ordinary least-squares) are generally not appropriate. Given the nature of such data, the Poisson distribution has been shown to provide a better fit and has been used widely to model crash frequency data. The basic form of the Poisson distribution is shown in Equation 1:

$$\lambda_j = \exp(\beta_o + \beta_i X) \tag{1}$$

where, λ_j = the estimated mean annual crashes at intersection j, X is a vector of explanatory variables, and β is a vector of estimable parameters (*16*).

A limitation of this model is the underlying assumption of the Poisson distribution that the variance is equal to the mean. As such, the model cannot handle overdispersion wherein the variance is greater than the mean. With crash data, the variance often exceeds the mean, leading to overdispersion. For this reason, HSM recommends using negative binomial regression (*2*). Negative binomial regression is a form of the Poisson distribution, sometimes referred to as gamma-Poisson, and introduces a new term, ε, whereby $\exp(\varepsilon)$ has a mean value of 1 and variance α (*16*). In this way, the Poisson distribution is manipulated such that the variance is equal to the mean, and the variable ε is not considered in model interpretation, as its mean value is 1, and therefore drops out of the equation. However, the variance, α, represents the overdispersion parameter. As α increases, this indicates that the data are more dispersed, which leads to higher standard error values (*16*). The overdispersion parameter is also important for use in before-and-after studies (*2*, *17*).

Furthermore, this dataset contains data from the entire state of Michigan, which has region-dependent weather patterns, driver behaviors, and topography. In addition, many intersections contained in the dataset are under the jurisdiction of county road commissions, which

Table 4. Coefficients for Rural 4ST Intersections

Factor	Fatal and injury crashes				Property damage only crashes			
	Est.	Std. error	z value	Sig.	Est.	Std. error	z value	Sig.
Intercept	–8.509	0.815	–10.444	<0.001	–6.834	0.519	–13.172	<0.001
Volume (ln[AADT])								
Major road	0.242	0.121	2.000	0.045	0.438	0.075	5.846	<0.001
Minor road	0.700	0.068	10.226	<0.001	0.413	0.039	10.624	<0.001
Skew								
≤5 degrees	Baseline				Baseline			
>5 degrees	0.213	0.119	1.790	0.073	0.193	0.071	2.730	0.006
Major road jurisdiction								
State	Baseline				Baseline			
County FA	0.349	0.115	3.026	0.002	Baseline			
County non-FA	Baseline				–0.172	0.103	–1.673	0.094
Random effects								
County	-	0.348	-	-	-	0.284	-	-
Year	-	0.047	-	-	-	0.058	-	-
Dispersion parameter	1.601	-	-	-	5.741	-	-	-
AIC	3,738.8	-	-	-	6,894.9	-	-	-
Log-likelihood	–1,861.4	-	-	-	–3,439.5	-	-	-

utilize varying design standards and maintenance practices. To account for these unmeasurable differences, a county-specific random effect was included in the model. Furthermore, to account for temporal variation in the crash data, which spanned a five-year period, the crash year was also included as a random effect. The random effects incorporate into the model an error term, η, with a mean of 1 and variance of α (*16*).

Care needs to be taken when adding variables to avoid overfitting the SPF. More complex models are often poorer predictors, only accurately predicting crashes on the intersections that were used to estimate its parameters, as noise tends to be incorrectly included as systematic variations in crashes. To avoid this pitfall, researchers have suggested using a stepwise process for backward elimination of variables to determine the effects of removing each individual variable during model specification (*18*).

Results and Discussion

Rural 4ST Intersections

Table 4 summarizes the model results for fatal and injury (FI) and PDO crashes occurring at rural 4ST intersections. Rural 4ST intersections with skew angles greater than 5 degrees were found to have 24% greater FI crashes, and 21% greater PDO crashes relative to intersections with skew angles less than 5 degrees. Turning to the intersection jurisdiction factors, for FI crashes, county federal aid intersections experienced greater crash occurrence than intersections with MDOT or county non-federal aid jurisdictions. However, for PDO crashes, county non-federal aid intersections experienced lower crash occurrence than MDOT or county federal aid intersections. Jurisdiction of the major roadway was not found to be a significant factor in angle crashes. Although driveways were not found to significantly affect all FI and PDO crashes, a subsequent analysis of angle crashes revealed that intersections with greater than two driveways had 26% greater PDO angle crashes compared with intersections with two or fewer driveways. These results are displayed in Table 5.

All other factors were found to have an insignificant effect on crash occurrence, including lighting and left-turn lanes, which in many cases was because of small sample sizes. Notably, a subsequent analysis of night-time crashes found lighting to remain insignificant. Similarly, a follow-up analysis of left-turn head-on collisions found the presence of left-turn lanes to remain insignificant, although this is likely at least partially because of the very small sample of intersections possessing left-turn lanes.

Rural 3ST Intersections

Table 6 summarizes the model results for FI and PDO crashes occurring at rural 3ST intersections. Rural 3ST intersections with skew angles greater than 5 degrees were found to have 16% greater PDO crashes than intersections with skew below 5 degrees. However, intersection skew angle did not show a significant impact on FI crashes, although this was likely because of a small sample of such crashes. Similar to 4ST intersections, county non-federal aid intersections experienced lower crash occurrence than MDOT or county federal aid

Table 5. Coefficients for Angle Crashes at Rural 4ST Intersections

Factor	Property damage only crashes			
	Est.	Std. error	z value	Sig.
Intercept	–9.296	1.034	–8.987	<0.001
Volume (ln[AADT])				
Major road	0.307	0.154	2.000	0.046
Minor road	0.711	0.086	8.243	<0.001
Driveways at intersection				
≤2 driveways	Baseline			
>2 driveways	0.233	0.114	2.038	0.042
Random effects				
County	-	0.464	-	-
Year	-	0.000	-	-
Dispersion parameter	1.628	-	-	-
AIC	2,637.4	-	-	-
Log-likelihood	–1,311.7	-	-	-

Table 6. Coefficients for Rural 3ST Intersections

Factor	Fatal and injury crashes				Property damage only crashes			
	Est.	Std. error	z value	Sig.	Est.	Std. error	z value	Sig.
Intercept	–10.193	1.228	–8.298	<0.001	–5.787	0.594	–9.737	<0.001
Volume (ln[AADT])								
Major road	0.745	0.180	4.137	<0.001	0.391	0.086	4.526	<0.001
Minor road	0.317	0.081	3.935	<0.001	0.259	0.039	6.569	<0.001
Skew								
≤5 degrees	-	-	-	-	Baseline			
>5 degrees	-	-	-	-	0.150	0.070	2.146	0.032
Major road jurisdiction								
State or county FA	-	-	-	-	Baseline			
County non-FA	-	-	-	-	–0.278	0.126	–2.196	0.028
Random effects								
County	-	0.427	-	-	-	0.338	-	-
Year	-	0.092	-	-	-	<0.001	-	-
Dispersion parameter	4.267	-	-	-	2.185	-	-	-
AIC	1,879.3	-	-	-	5,552.0	-	-	-
Log-likelihood	–933.6	-	-	-	–2,768.0	-	-	-

intersections for PDO crashes. Jurisdiction was not found to have a significant effect on fatal and injury crashes. All other factors, including lighting, left-turn lanes, and driveway counts, were not found to significantly affect crash occurrence at rural 3ST intersections. Unlike the 4ST findings, these factors remained insignificant even during subsequent analyses of targeted crash types.

Comparison with HSM Models

A graphical representation of the Michigan-specific rural 4ST and 3ST model results for PDO and total crashes is shown in Figure 2 along with models for intersections with skew angles greater than 5 degrees in Figure 3. The respective HSM base models were also included in the figures for comparison purposes. For 3ST intersections, HSM's model under-predicts crashes at lower major roadway volumes, but begins to over-predict crashes when the major roadway AADT exceeds 1,200 vpd. HSM over-predicts crashes at all major roadway volumes for 4ST intersections. At the low end of major road volumes (i.e., 400 vpd), HSM over predicts 4ST crashes by approximately 15% compared with the Michigan-specific model. At higher volumes (i.e., 2,000 vpd), HSM's over-prediction of 4ST crashes increases to nearly 70%.

Skew cannot be directly compared between HSM and the models developed in this paper. Because of the small sample size, it was necessary to place intersection skew angle into categories. HSM's model for skew, on the

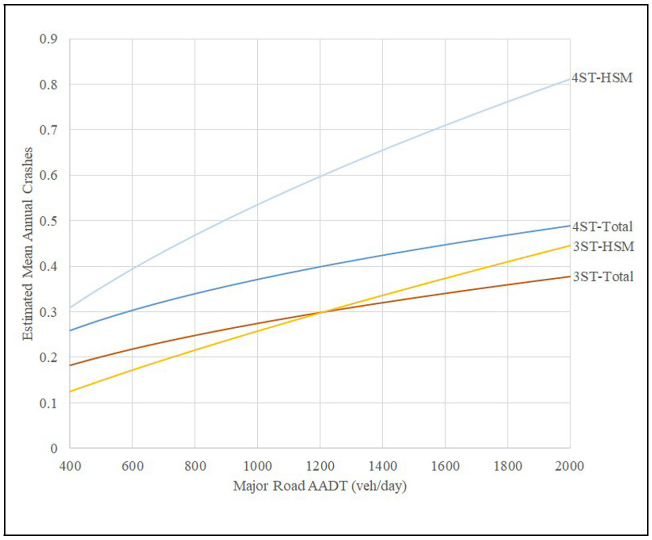

Figure 2. Model results for PDO crashes on 4ST and 3ST intersections for minor roadway AADT=500 vpd.

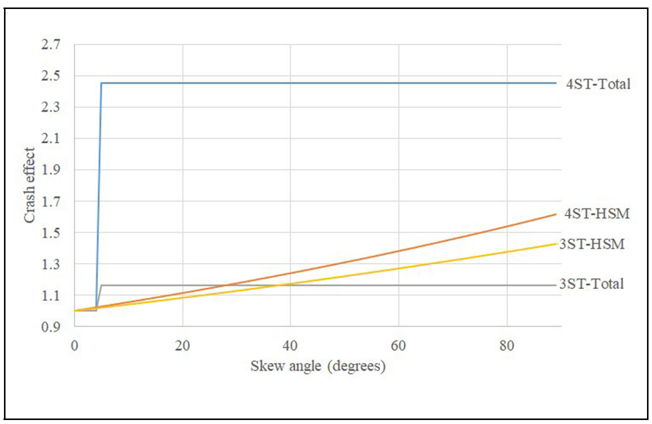

Figure 3. Skew crash effect based on skew angle.

other hand, is continuous, where the estimate of the effect of skew for total crashes on a 3ST intersection is equal to $\exp(0.004 * skew)$, where $skew$ = the absolute value of the difference between 90 degrees and the actual intersection angle. The total crash effect of skew at all skew angles above 5 degrees found in the model above is equal to $\exp(0.896)$, indicating HSM's models would overpredict the crashes caused by intersection skew at angles above around 35 degrees, and for 4ST intersections, at angles above about 50 degrees, as shown in Figure 3.

Summary and Conclusions

This study involved the estimation of safety performance functions for low-volume rural stop-controlled intersections in Michigan. To isolate lower-volume rural intersections, major roadway traffic volumes were limited to the range of 400–2,000 vpd. Furthermore, to create a robust sample of intersections within this volume range, both state and county roadways were included in the sample. Notably, each of Michigan's 83 counties were represented in the 2,023 intersection sample. A robust sample of roadway characteristic data, including traffic crashes, traffic volumes, roadway classification, geometry, cross-sectional features, and other site characteristics were collected for the period of 2011–2015.

After the data were assembled for the rural intersection sample, a series of SPFs were developed to estimate annual crash occurrence on 3ST and 4ST intersections. Separate random effects negative binomial models were developed for FI crashes, PDO crashes, and select target crash types. The models were specified considering factors such as driveway density, presence of lighting, turn lane presence, and intersection skew, in addition to volume. To account for the unobserved heterogeneity associated with differing design standards and other county-to-county differences, random effects negative binomial models with a county-specific random effect were utilized. Furthermore, unobserved temporal effects were controlled in the models through the use of a year-specific random effect.

The random effects negative binomial analysis found that of the aforementioned factors, skew angles of greater than five degrees led to significantly greater crash occurrence for both 3ST and 4ST intersections, while more than two driveways near the intersection led to significantly more angle crashes at 4ST intersections. Other factors were found to have little impact on crash occurrence, even when considering only targeted crash types, although this is likely a result of small crash sample sizes. Comparison of the Michigan-specific models with the uncalibrated HSM base models showed that the HSM 3ST model under-predicts crashes at lower major roadway volumes, but begins to over-predict crashes when the major roadway AADT exceeds 1,200 vpd. Compared with the Michigan-specific 4ST models, HSM over-predicts crashes across all major roadway volumes.

The rural intersection models developed herein will be of use to transportation professionals, as there is a limited amount of research on safety performance at low-volume, rural stop-controlled intersections. Particularly noteworthy is the inclusion of county-maintained intersections, including those on minor collectors and local roadways, as these facilities tend to have design and maintenance characteristics, travel patterns, and driver types that vary greatly from state-owned facilities. Ultimately, the results of this study provide a number of methodological tools that will allow for proactive safety planning activities, including network screening and identification of high-risk sites.

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Author Contributions

The authors confirm contribution to the paper as follows—study concept and design: TJG; data collection: SYS; analysis and interpretation of results: SYS, RA, SRG, RS; draft manuscript preparation: SYS, TJG. All authors reviewed the results and approved the final version of the manuscript.

References

1. National Highway Transportation Safety Administration. Rural/Urban Comparison of Traffic Fatalities. Report DOT HS 812 393. National Highway Transportation Safety Administration, Washington, D.C., 2017.
2. American Association of State Highway and Transportation Officials. *Highway Safety Manual*, 1st ed. AASHTO, Washington, D.C., 2010.
3. Savolainen, P., T. Gates, D. Lord, S. Geedipally, E. Rista, T. Barrette, B. Russo, and R. Hamzeie. *Michigan Urban Trunk Line Intersections Safety Performance Functions Development and Support*. RC-1628. Michigan Department of Transportation, Lansing, MI, 2015.
4. Stapleton, S. Y., A. Ingle, M. Chakraborty, T. J. Gates, and P. T. Savolainen. Safety Performance Functions for Rural Two-Lane County Road Segments. *Transportation Research Record: Journal of the Transportation Research Board*, 2018. 2672(52): 226–237.
5. Gates, T., P. Savolainen, R. Avelar, S. Geedipally, D. Lord, A. Ingle, and S. Stapleton. *Safety Performance Functions for Rural Road Segments and Rural Intersections in Michigan*. Report SPR-1645. Michigan Department of Transportation, Lansing, MI, 2018.
6. Young, J., and P. Y. Park. Benefits of Small Municipalities using Jurisdiction-Specific Safety Performance Functions Rather Than the Highway Safety Manual's Calibrated or Uncalibrated Safety Performance Functions. *Canadian Journal of Civil Engineering*, Vol. 40, No. 6, 2013, pp. 517–527.
7. Caliendo, C., and M. Guida. Microsimulation Approach for Predicting Crashes at Unsignalized Intersections using Traffic Conflicts. *Journal of Transportation Engineering*, Vol. 138, No. 12, 2012, pp. 1453–1467. https://doi.org/10.1061/(ASCE)TE.1943-5436.0000473.
8. Vogt, A., and J. Bared. Accident Models for Two-Lane Rural Segments and Intersections. *Transportation Research Record: Journal of the Transportation Research Board*, 1998. 1635: 18–29.
9. Vogt, A. *Crash Models for Rural Intersections: Four-Lane by Two-Lane Stop-Controlled and Two-Lane by Two-Lane Signalized*. FHWA-RD.99-I28. Federal Highway Administration, U.S. Department of Transportation, Washington, D.C., 1999.
10. Tegge, R. A., J. H. Jo, and Y. Ouyang. *Development of Safety Performance Functions for Illinois*. Research Report ICT-10-066. Illinois Center for Transportation, Rantoul, IL, 2006.
11. Garber, N. J., G. Rivera, and I. K. Lim. Safety Performance Functions for Intersections in Virginia. Presented at 90th Annual Meeting of the Transportation Research Board, Washington, D.C., 2011.
12. Monsere, C., T. Johnson, K. Dixon, J. Zheng, and I. Schalkwyk. *Assessment of Statewide Intersection Safety Performance*. SPR 667, FHWA-OR-RD-18. Oregon Department of Transportation, Salem, OR, 2011. https://doi.org/10.15760/trec.77.
13. Obeidat, M. S., and M. J. Rys. Intersection Lighting Impacts on Nighttime Crashes Reduction and Safety Improvement. Presented at 95th Annual Meeting of the Transportation Research Board, Washington, D.C., 2016.
14. Bonneson, J. A., and M. P. Pratt. *Roadway Safety Design Workbook*. Report No. FHWA/TX-09/0-4703-P2. College Station, TX., 2009.
15. State of Michigan. GIS Open Data. Metadata. [Online], 2017. http//gis-michigan.opendata.arcgis.com.
16. Washington, S. P., M. G. Karlaftis, and F. L. Mannering. *Statistical and Econometric Methods for Transportation Data Analysis*, 2nd ed. CRC Press, Boca Raton, FL, 2011.
17. Hauer, E. *Observational Before-After Studies in Road Safety*, 1st ed. Emerald Group, Bingley, UK, 1997.
18. Venables, W. N., and B. D. Ripley. *Modern Applied Statistics with S*, 4th ed. Springer, New York, NY, 2002.

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