EVALUATING SAFETY PERFORMANCE OF RURAL COUNTY HIGHWAYS USING MIXED-EFFECTS NEGATIVE BINOMIAL MODELS

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ABSTRACT

EVALUATING SAFETY PERFORMANCE OF RURAL COUNTY HIGHWAYS USING MIXED-EFFECTS NEGATIVE BINOMIAL MODELS

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Safety on rural highways continues to be a serious concern in the United States. While only 20 percent of the population live in rural areas, approximately one-half of motor vehicle fatalities occur on rural roadways, resulting in a rural fatal crash rate that is approximately double that of urban areas. In many states, most rural arterial highways are owned by the state department of transportation. However, several states, including Michigan, possess a large rural county highway network. For example, nearly 75 percent of the approximately 120,000 miles of public roadways in Michigan are owned by one of the 83 county road agencies across the state.

County-owned highways typically possess characteristics that differ considerably from those owned by the state department of transportation, which limits the usefulness of safety performance functions (SPFs) and crash modification factors (CMFs) generated based on state highways, including those found in *the Highway Safety Manual (HSM)*. Thus, assumptions made from models generated using data from state highways may not apply county highways due to differences in traffic, design, and maintenance. As a substantial proportion of rural crashes occur on county roads, identification of factors affecting safety performance on rural county roads is critical to support highway safety improvement programs and development of design standards.

A cross-sectional safety performance analysis was performed for county highway segments and stop-controlled intersections throughout rural Michigan, including both federal aid and non-federal aid highways, as well as paved and unpaved road surfaces. SPFs were developed using mixed effects negative binomial regression to determine the safety effect of various design

elements and site characteristics, including cross-sectional and geometric characteristics, which were included in the models as fixed effects. Random intercepts were incorporated into the models to account for unobserved heterogeneity between counties and between individual sites.

One particularly noteworthy contribution of this research was to investigate the impacts of horizontal curvature on safety performance. Curve radii data extracted from the Michigan roadway shapefile allowed for the safety performance effects of decreasing curve design speed to be assessed in an incremental manner. Horizontal curves on paved county roads with design speeds below 40 mph experienced crash occurrence that was more than four times greater than segments without substandard curvature. On unpaved roadways, such curves experienced three times greater crash occurrence compared to segments without substandard curvature. Deer-related crashes, however, were shown to be fewer in frequency along horizontal curves.

For stop-controlled intersections, skew angle was a variable of interest. At rural four-leg stop-controlled intersections, skew angles between 10 and 39 degrees were associated with increased crash frequency at intersections across all intersection classes. Skew had the greatest effect when the major road was county non-federal aid, where skew angles between 10 and 39 degrees experienced 60 percent more crashes than intersections without skew. Considering federal-aid intersections, the skew effect was diminished by approximately one-half.

As expected, county-specific SPFs differed from models previously developed for state highways, including the SPFs included in the *HSM*. Generally speaking, at intersections, county highways were found to experience fewer crashes per unit of traffic volume than state highways, with county non-federal aid highways showing the lowest crash occurrence. County highway segments tend to have higher crash frequency than state roads. However, this is not the case at all traffic volumes, which further shows the need for county-specific safety performance models.

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1. INTRODUCTION

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 percent of the U.S. population lives in rural areas. In 2018, the rural highway fatal crash rate (per vehicle-miles traveled) in the U.S. was approximately double that of urban areas, providing further evidence of an overrepresentation of crashes in rural areas [1]. Several factors contribute to the elevated rural crash risk, including speeds, geometry, lack of lighting, and other factors, each of which contribute to an elevated risk for lane departure crashes, including head-on, sideswipe, or run-off-road, which are among the most severe types.

Beginning with the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU) and continuing through the current transportation funding bill, states have been required to have in place a Highway Safety Improvement Program (HSIP) that "emphasizes a data-driven, strategic approach to improving highway safety on all public roads that focuses on performance" [2]. Given the prevailing focus on implementing roadway safety practices that are data-driven, recent research has focused on gaining a more thorough understanding of how several factors affect the frequency, type, and severity of traffic crashes at specific roadway sites, such as horizontal curves and intersections.

A valuable tool in this process is the *Highway Safety Manual* (*HSM*), published by the American Association of State Highway and Transportation Officials (AASHTO) [3]. Part C of the *HSM* provides a series of predictive models that can be utilized to estimate the frequency of traffic crashes on specific road facilities as a function of traffic volumes, roadway geometry, type of traffic control, and other factors. These models, referred to as safety performance functions

(SPFs), are useful for estimating the safety impacts of site-specific design alternatives or for prioritizing candidate locations for safety improvements on a network basis. As a part of this process, these SPFs can also be integrated with common decision support tools, such as *Safety Analyst* and the *Interactive Highway Safety Design Model* (*IHSDM*).

The *HSM* includes separate families of SPFs to estimate annual crash occurrence for three specific roadway facility types: rural two-lane/two-way roads, rural multilane highways, and urban and suburban arterials [3]. More recently, a supplement introduced SPFs for limited-access freeways [4]. Separate SPFs exist for intersections and road segments for the base conditions within each facility type, while crash modification factors (CMFs) are provided to account for deviations from the base condition of the facility type. Because the SPFs contained in the *HSM* were developed based on a limited sample of data collected from select states, specifically, California, Minnesota, Texas, and Washington for the rural highway models, these functions must be calibrated or re-estimated using local data to improve their accuracy and precision [5-6]. A variety of states have conducted research to this end, including Colorado, Florida [7], Georgia, Illinois [8], Kansas [9], Michigan, North Carolina [10], Oregon [11], Utah, and Virginia [12]. Collectively, these studies have shown that the accuracy of the SPFs from the *HSM* vary considerably from state to state, a result that may be reflective of differences in geography, design practices, driver behavior, weather, crash reporting requirements, or other factors.

1.1 Problem and Knowledge Gap

In many states, the majority of arterial highways in rural areas are under the jurisdiction of the state department of transportation (DOT). However, several states, including many in the Midwest and Great Lakes regions, possess a substantial rural county highway network. This includes Michigan, where nearly 75 percent of the 120,000 miles of public roadways are owned by one of the 83 county road agencies across the state, with the remainder owned by the state (8 percent) or city/village (17 percent). Given the size of Michigan's county roadway network, it is not surprising that 60 percent of the 71,402 traffic crashes in rural areas in 2015 occurred on county-owned facilities [13]. Thus, the determination of factors affecting crashes on rural county highways, including both road segments and intersections, is important to support highway safety programs in Michigan and other states with substantial county road networks.

Because the SPFs contained in the *HSM* were developed based on a limited sample of data collected from select states, direct application of the SPFs from the *HSM* does not tend to provide accurate results unless the models are calibrated using local data [5-12, 14]. Although the *HSM* provides details related to local calibration of the models, prior research estimating SPFs has shown that not only does the magnitude of the local curve differ from that published in the *HSM*, but the shape of the curves differs as well [15-16]. This further emphasizes the importance of developing SPFs utilizing local data, rather than simply calibrating the SPFs found within the *HSM*. Furthermore, the fact remains that the *HSM*'s original SPFs were generated based on data obtained from select state highways. Therefore, assumptions made on the general effect of characteristics, such as traffic volume or lane width, may not apply to low-volume, county-owned highways.

In Michigan and elsewhere, county-owned highways typically have characteristics that differ considerably from those owned by the state DOT, which limits the usefulness of SPFs and CMFs generated based on data from rural state highways. Compared to state highways, the differences inherent to county roadways often include traffic characteristics (e.g., lower traffic volumes, shorter trip lengths, greater driver familiarity, etc.), design characteristics (e.g., lower design speeds, prevalence of unpaved/gravel surfaces, smaller curve radii, narrower lanes and shoulders, reduced sight distances, reduced clear zones, etc.), and maintenance characteristics (e.g., less aggressive snow removal, less frequent resurfacing, less frequent maintenance of traffic control devices, etc.).

Furthermore, it is also important to consider differences between the various classes of county roadways, in particular, the distinction between those roadways that are eligible for federal funding (i.e., federal aid roadways) and those that are supported only by state and/or local funds (i.e., non-federal aid roadways). Federal aid roadways are subject to design standards approved by the Federal Highway Administration (FHWA), which are typically more stringent than those for non-federal aid roadways. Specifically, minimum design standards must be maintained in compliance with the posted speed limit for select controlling geometric elements on federal aid roadways with design speeds greater than or equal to 50 mph. These controlling geometric elements include design speed, lane width, shoulder width, horizontal curve radius, superelevation rate, and stopping sight distance [17]. It is also important to note that the majority of unpaved roadways are non-federal aid. Thus, it is imperative that county roadway safety performance models account for the differences between federal aid and non-federal aid roadway designs, while also investigating differences in safety performance between these roadway types.

Due to its importance as a primary controlling geometric criterion, horizontal curvature has been researched extensively in prior highway safety research. Previous research has found that the presence of a horizontal curve with a design speed at or below 55 mph on a rural highway segment contributed to 43 to 56 percent greater crash occurrence than on segments without such curves [18-19]. However, these effects merely related to the *presence* of a horizontal curve on a segment, and do not describe the *amount* of curvature along the segment.

Furthermore, scant research exists related to the incremental effects of curve design speed on safety performance. Collectively, it is clear that further investigation is needed to provide a more comprehensive indication of the safety performance characteristics associated with horizontal curvature, in addition to the safety performance of other important geometric characteristics.

While Michigan-specific SPFs have been previously developed, they are limited to urban and rural state-owned road segments and intersections [15-16]. Also, although *HSM* calibration factors are available for Michigan county road segments and intersections, fully-specified SPFs utilizing local data have not been developed for county roadways. Furthermore, the Michigan-specific SPFs, along with those contained in the *HSM,* are only applicable to paved roads [3], and additional research related to the safety performance of unpaved highways is also limited. Thus, there is a clear need for development of fully-specified safety performance models that are applicable across all classes of rural county highways, including federal aid and non-federal aid roadways, while considering a broad range of geometric factors, paved and unpaved road segments, and three-leg and four-leg minor road stop-controlled intersections.

1.2 Research Objectives and Contributions

The primary goal of this research was to develop a uniform, consistent approach that can be applied to estimate the safety performance of rural county road segments and intersections at the aggregate (i.e., total crash) level. To attain this goal, a series of safety performance functions and crash modification factors were developed using data collected from across all classes of rural county roadways throughout Michigan. This included both paved and unpaved roadways, federal aid and non-federal aid classifications, and covered both road segments and minor road stop-controlled intersections. These distinctions are important because, as previously stated, design standards are known to differ based on whether the roadway is subject to federal aid standards.

It was also important to consider the effects of geometric conditions on safety performance, including substandard horizontal curvature, lane width, and shoulder width, as these are controlling geometric design elements for which minimum standards must be achieved. Specifically, this research moved beyond simply considering curve presence on a segment, instead quantifying the proportion of each segment with horizontal curvature falling within a specific design speed range. Parameterizing the horizontal curve data in this manner also allowed for assessment of the incremental effects of curve design speed on safety performance. Intersection skew was also an important factor to consider given the general association with crash occurrence and the relative frequency at which intersection skew occurs within the county roadway network.

The study results will provide an important reference to guide states and local agencies toward making informed decisions as to planning and programming decisions for safety projects, and to provide researchers with guidance regarding future work within the realm of rural highway safety. To achieve these aforementioned goals, the specific objectives were as follows:

1. Review and summarize the extant literature related to SPF and CMF development and associated data collection for rural roadway segments and intersections.
2. Identify sites and collect data for the following rural segment and intersection types:
    a. Rural county two-lane two-way paved federal aid segments
    b. Rural county two-lane two-way paved non-federal aid segments
    c. Rural county unpaved non-federal aid segments
    d. Rural three-leg minor-road stop-controlled intersections
    e. Rural four-leg minor-road stop-controlled intersections
3. Develop SPFs for each of the rural segment and intersection types listed above.

4. Develop CMFs for various design factors for each of the rural segment and intersection types listed above, including horizontal curves and intersection skew. Specifically, consider the incremental effects of curve design speed and the curved proportion of segment on segment crash occurrence.
5. Investigate the relationship between deer crash occurrence and roadway characteristics.
6. Make comparisons and draw contrasts with existing highway safety research.

To accomplish these objectives, county highway data, including traffic volumes, roadway characteristics, geometric characteristics, and traffic crashes were collected from across Michigan using both available datasets and manual data collection techniques. The data were subsequently analyzed utilizing mixed-effects negative binomial modeling techniques, with details provided in subsequent chapters.

1.3 Dissertation Structure

This dissertation document details the activities involved in the development of SPFs and CMFs for rural county road segments and minor road stop-controlled intersections in Michigan. The report is divided into seven chapters. Chapter 2 provides a summary of the state-of-the-art research literature. Chapter 3 describes the methods related to site selection and data collection, including details of the data sources and activities involved in database development for both rural county road segments and intersections, in addition to analytical methods for development of safety performance models. Chapter 4 provides the resulting SPFs and CMFs for rural, two-lane, two-way county roadway segments. Chapter 5 presents SPFs and CMFs for three- and four-leg minor road rural stop-controlled intersections along two-way two-lane county roadways. Chapter 6 presents SPFs for deer crashes along rural two-way two-lane highway segments. Conclusions and directions for future research are discussed in Chapter 7.

2. LITERATURE REVIEW

Prior research has explored the development of safety performance models for roadway segments and intersections and has estimated the effects of various traffic, roadway cross-sectional, geometric, and other characteristics on crashes and injuries on rural highways. The following subsections summarize the existing research literature on these subjects.

2.1 The Highway Safety Manual

SPFs are part of the core methods documented in the *HSM*, and the *HSM*'s methodology incorporates many advanced analytical tools, such as the empirical Bayes (EB) method. SPFs constitute the basis for analysis in highway safety studies and key components of other types of safety analyses or evaluations. The main purpose of an SPF is to estimate the expected frequency of crashes given various traffic and site characteristics, such as traffic volume, segment length, and lane width. Transportation agencies and practitioners typically apply SPFs in their processes to select safety projects for funding. There are two general approaches described in the *HSM* to ensure that SPFs are appropriate to use for a particular jurisdiction: the agency or the safety analyst can either: (1) use a jurisdiction-specific SPF for the facility and crash types of interest, or (2) calibrate and use the corresponding SPF available from the *HSM* [3].

As defined in the *HSM*, an SPF has three components: (1) a base SPF, (2) CMFs and (3) a calibration factor, C. as shown in Equation 1.

$$N = N_0 \times C \times \prod CMF \tag{1}$$

Where, N= predicted annual average crash frequency; N_0 = predicted average crash frequency under base conditions; C = calibration factor to adjust SPF for local conditions; and $\prod CMF$ = the product of the set of applicable CMFs.

2.1.1 Base SPF

A base SPF is a crash prediction model for a facility type that accounts for exposure to traffic flow as the only independent variable. All other variables of relevance (e.g., speed limit, number of lanes, shoulder information, etc.) are not explicitly accounted for in the base SPF because it implies a fixed value for each of these variables (i.e., they are fixed at the base conditions of the SPF). It has been argued that placing an excessive number of independent variables in the base SPF would potentially tangle the effects of certain variables with others [20].

The set of fixed values is referred to as the base conditions of the base SPF. These conditions may include such variables as 12-foot lanes and 6-foot shoulders for rural segments or no left-turn lanes for intersections. Of particular interest to this research, the generic base models for intersection SPFs (for rural or urban facilities) found in the *HSM* have the functional form shown in Equation 2.

$$N_0 = \exp[\beta_0 + \beta_1 \times \ln\left(AADT_{major}\right) + \beta_2 \times \ln(AADT_{minor})] \quad (2)$$

Where, N_0 = predicted average crash frequency at base conditions, $AADT_{major}$ = annual average daily traffic (AADT) for the major road, $AADT_{minor}$ = AADT for the minor road, and $\beta_0, \beta_1, \beta_2$ = estimated parameters.

The base models for segment SPFs (for rural or urban facilities) found in the *HSM* usually have the functional form shown in Equation 3:

$$N_0 = \exp[\beta_0 + \beta_1 \times \ln(AADT) + \ln(L)] \quad (3)$$

Where, N_0 = predicted average crash frequency at base conditions, $AADT$ = AADT on the segment, L = segment length in miles, and β_0, β_1= estimated parameters.

Care needs to be taken when adding variables to avoid overfitting the SPF. The more complex models are often poorer predictors, only accurately predicting crashes on the segments that were used to estimate its parameters, as statistical noise tends to be incorrectly included as systematic variation in crashes. To avoid this pitfall, researchers [21] suggested using backward elimination in the well-documented stepwise model selection process in statistical analysis [22]. This method identifies significant variables by a stepwise regression approach, including all variables, then eliminating each separately, to determine if each variable significantly degrades the information given by the model.

2.1.2 Crash Modification Factors

The purpose of CMFs is to account for deviations from base conditions for variables known to have an impact on crash frequency, such as geometric or traffic control features. For example, if the base condition for an intersection SPF is adjacent approaches with no skew, applying this SPF to a location with one approach with a significantly skewed angle will require the application of the corresponding CMF. A CMF value above one indicates that the number of crashes is expected to increase, while a value below one means that the number of crashes is expected to go down.

It is important that the application of CMFs for countermeasures be separated from the application of CMFs to adjust for base conditions. The CMFs applied to these models allow for crash estimates that distinguish between sites with various geometric or traffic control features. The *HSM* warns that only the CMFs presented in Chapters 10 and 11 apply to the respective Part C predictive method as adjustments to base conditions for that facility type. Other CMFs are found in Part D, Chapter 13 for roadway segments and Chapter 14 for intersections, and are applicable in estimating the impact of various safety countermeasures. In such cases, the expected average crash frequency of a proposed project or a project design alternative can be evaluated.

Chapters 10 and 11, Part C of the *HSM* present a set of CMFs for rural segments (two-lane and multilane) and rural intersections. Additional CMFs can also be found in FHWA's *CMF Clearinghouse* [23]. The *CMF Clearinghouse* is a web-based database of CMFs that provides supporting documentation to assist users in estimating the impacts of various safety countermeasures. All CMFs are developed with an assumption that all other conditions and site characteristics remain constant, aside from the condition being represented in the CMF. For this reason, the validity of CMFs is reliant on consistent and agreeable base conditions. The *HSM* documents base conditions for each of the rural segment and intersection facility types for which SPFs are developed in Chapters 10 and 11.

CMFs are mainly developed from before-after and cross-sectional studies [24]. Although it is common practice to estimate the combined effect of multiple CMFs by multiplying the individual CMFs together, this practice relies on the assumption of independence between CMFs. However, that assumption is not necessarily true in every case, and the result could be a significant overestimation or underestimation of the combined effect [25].

2.1.3 Calibration Factors

To take advantage of the value of the multiple SPFs presented in the *HSM*, such SPFs can be calibrated to local conditions. Calibration intends to account for the variation of crash data between different jurisdictions and for factors that were not involved in the model. On a project level, the development of a typical SPF can take 450-1,050 staff-hours, whereas calibration requires only 24-40 staff-hours for data collection and preparation [21]. When using an already-existing SPF taken from part C of the *HSM* or *Safety Analyst*, calibration is essential because crash frequencies fluctuate for a variety of reasons that cannot be accounted for when developing the SPF, such as climate, criteria for reporting crashes, topography, animal population, law enforcement practices, vehicle characteristics, and other factors that differ between jurisdictions [21, 26-30].

The calibration factor is estimated using Equation 4 and is applied to the base SPF as a multiplicative scaling factor.

$$C = \frac{\sum_{i=1}^{n} N_{obs,i}}{\sum_{i=1}^{n} N_{pre,i}} \quad (4)$$

Where, $N_{obs,i}$ = the observed annual average crash frequency, $N_{pre,i}$ = predicted annual average crash frequency, and *n* = sample size, equal to the number of sites in the calibration process.

Similarly, calibration is recommended when applying an SPF to a new jurisdiction, but a calibration between different time periods is also recommended [27, 31]. When translating SPFs across states, calibration factors are a given, but major physiographic division within a state should also be considered [32].

The *HSM* recommends calibrating the models using data from 30-50 locations, which collectively possess at least 100 crashes per year. However, recent research has shown that this number of sites is insufficient for most cases [33-34]. Several research studies have provided further or improved guidelines to calibrate the models for local conditions [27, 35]. Considering the caveats of the calibration procedure, it is preferable to develop new predictive models if enough data are available.

The use of calibration factors provides a standardized model to be calibrated for different jurisdictions and road conditions [36]. Calibration factors for the *HSM* models have been developed for rural intersections and segments in several states. The first two sections below describe studies that attempted to calibrate *HSM* models for rural intersections and segments. The last section covers general issues related to the calibration procedure.

2.1.3.1 Rural Intersections

Table 1 shows the value of the calibration factor for different rural intersection models (or facilities) in Oregon [31, 37], Florida [38], North Carolina [39], Maryland [40] and Missouri [41]. As shown in Table 1, the value of the calibration factor tends to be smaller than one, which indicates that the pre-fitted *HSM* models tend to overestimate the number of crashes for different types of rural intersections for most cases documented in this table.

The calibration effort in Oregon [31, 37] showed that obtaining the minor AADT flows for rural intersections is a difficult task, as these values are rarely available. To overcome this difficulty, in a more recent effort, researchers developed an AADT estimation model for minor approaches [42]. The model included land-use and demographic variables as well as the characteristics of the main highway to which the minor approach intersects.

Table 1: Rural Intersection Calibration Factors

Facility	Calibration factor				
	Oregon	**Maryland**	**Florida[a]**	**North Carolina[b]**	**Missouri**
Rural two-lane					
3-leg, minor stop	0.31	0.16	0.8	0.57	0.77
4-leg, minor stop	0.31	0.2	0.8	0.68	0.49
4-leg, signalized	0.45	0.26	1.21	1.04	-
Rural multi-lane					
3-leg, minor stop	0.15	0.18	na	na	0.28
4-leg, minor stop	0.39	0.37	na	na	0.39
4-leg, signalized	0.15	0.11	0.37	0.49	na

[a] For this state, several yearly calibration factors were derived from 2005 to 2009. Values derived in 2009 are reported.
[b] Both one- and three-year period calibration factors were derived for this state. Table shows three-year factor only.
Note: na = not available

Calibration factors have been derived for several other types of facilities (e.g., urban intersections and segment models) in Oregon, Florida, North Carolina, Maryland, and Missouri, as well. However, this document focuses on calibration efforts documented for rural segments and intersections only. Several other states such as Utah [43], Illinois [44], and Alabama [45] have also performed local calibration of the *HSM* SPFs, although rural intersections were not included in the local calibration.

2.1.3.2 Rural Segments

Researchers in Kansas calibrated base models developed using both the *HSM* procedure and new procedures that address specific qualities of the state's highway system [46]. Later, other researchers presented a revised method to develop calibration factors for five types of urban and suburban roadways with consideration of recent changes to the crash recording threshold (CRT) for property damage crashes, which occurred in Illinois in 2009 [47]. The study established a revised method to supplement and adopt a standard approach to develop calibration factors in the *HSM*, considering impact of the new CRT. The higher the CRT, the fewer recorded PDO crashes. Before and after the threshold change, calibration factors for four lane divided facilities were 0.68 and 0.55 respectively. Table 2 shows the value of the calibration factor for different rural segment models (or facilities) in North Carolina [39], Oregon [37], Florida [38], and Illinois [44]. All the calibration factors are for all (i.e., KABCO) crashes. Table 2 shows the value of the calibration factor varies greatly for different states, from a low of 0.36 to more than 4.0.

Table 2: Rural Segment Calibration Factors

Facility	Calibration factor			
	North Carolina	**Oregon**	**Florida**	**Illinois**
Two-lane undivided (2U)	4.04	0.74	1.05	1.58
Four-lane undivided (4U)	na	0.36[a]	na	na
Four-lane divided (4D)	na	0.78[a]	0.70[a]	na

[a] Referred as multilane rural highways (includes a limited number of 6-lane segments).
Note: na = not available

2.1.3.3 General Calibration Issues

Although states usually develop one single calibration factor for the whole state, recent research on urban intersections in Michigan [48] showed that the value of the calibration factor could be significantly different in different regions of Michigan. To overcome this issue, the authors estimated several region-specific calibration factors.

In the safety literature in general, and the *HSM* in particular, calibration is presented as a tool to incorporate local conditions of the current jurisdiction into a model that was fitted (or developed) for another jurisdiction. However, although calibrating the models through a scalar factor seems adequate for the overall fit of the model, there is no guarantee that same results will be achieved, even when each variable is analyzed independently (such as AADT), or by group of variables [49]. Furthermore, the application of a single scalar factor was found to be biased compared to the recently introduced Bayesian model averaging (BMA) method. This limitation was investigated using the BMA method by carefully evaluating a series of locally developed and calibrated models [50]. Cumulative residuals (CURE) plots are often used to verify goodness of fit for the AADT variable [51]. Results from this study show that the bias from calibrated models is substantially larger than the BMA models.

2.1.3.4 Calibration Factors for County Roads

In 2018, safety performance functions were developed for rural highways in Michigan as a part of the Michigan Department of Transportation's (MDOT) research program. Additionally, the *HSM*'s models were also calibrated using the methodology contained in the *HSM*. The resulting calibration factors, specific to each MDOT geographic region, are shown in Table 3 for rural state-owned two-lane two-way segments, Table 4 for county two-lane two-way segments, and Table 5 for rural two-lane two-way stop-controlled intersections.

For rural segments, calibration factors were developed for MDOT-owned (i.e., trunkline) highways, as well as county federal aid (FA) and county non-federal aid (non-FA) roadways. For intersections, calibration factors were developed for three-leg (3ST) and four-leg (4ST) rural stop-controlled intersections, and the factors presented were developed from a sample that included intersections were the major road was trunkline, county FA, and county non-FA.

Calibration factors were not developed in some cases. For example, there are no rural state-owned segments in the Metro region, and so calibration was impossible. In other cases, calibration factors could not be developed because there were not at least 100 crashes per year on that particular class of roadway in a given region; for instance, in the Superior region, there were only 14 crashes in the county non-federal aid sample.

Table 3. Calibration Factors for *HSM* Models on MDOT Rural Trunkline Segments [16]

Region	Count of segments	Segment mileage	$N_{observed}$ (Midblock crashes 2011-2015)	$N_{observed}$ (Midblock non-deer crashes 2011-2015)	$N_{predicted}$ (*HSM* 2011-2015)	Calibration factor for midblock crashes on tangent sections	Calibration factor for midblock non-deer crashes on tangent sections
Statewide	946	3,003	39,925	11,861	18,491	2.16	0.64
Superior	185	658	5,161	1,304	2,192	2.35	0.59
North	210	705	8,771	2,381	3,768	2.33	0.63
Grand	161	458	7,757	2,522	3,641	2.13	0.69
Bay	204	677	11,122	3,105	4,948	2.25	0.63
Southwest	99	236	3,267	1,254	1,864	1.75	0.67
University	87	269	3,847	1,295	2,078	1.85	0.62
Metro	0	0	0	0	0	Not applicable	

Table 4. Calibration Factors for *HSM* Models on Michigan Rural County Road Segments [16]

Region	Count of segments	Segment mileage	$N_{observed}$ (Midblock crashes 2011-2015)	$N_{observed}$ (Midblock non-deer crashes 2011-2015)	$N_{predicted}$ (*HSM* 2011-2015)	Calibration factor for midblock crashes on tangent sections	Calibration factor for midblock non-deer crashes on tangent sections
County FA							
Statewide	8,318	3,558	27,661	9,858	13,078	2.12	0.75
Superior	634	303	991	304	342	2.9	0.89
North	1,496	636	4,007	1,343	1,676	2.39	0.8
Grand	2,032	845	7,103	2,586	2,704	2.63	0.96
Bay	1,085	465	3,942	1,087	1,736	2.27	0.63
Southwest	332	159	1,335	561	810	1.65	0.69
University	2,403	1,033	8,701	3,241	4,649	1.87	0.7
Metro	336	118	1,582	736	1,162	1.36	0.63
County non-FA							
Statewide	2545	1293.7	3658	1330	1707	2.14	0.78
Superior	15	6.2	14	13	4	Not applicable	
North	203	76.1	198	64	120	1.65	0.53
Grand	418	212	522	239	283	1.85	0.85
Bay	321	139.4	529	190	343	1.54	0.55
Southwest	513	270.6	565	254	273	2.07	0.93
University	1061	582.7	1816	564	678	2.68	0.83
Metro	14	6.8	14	6	6	Not applicable	
Unpaved							
Statewide	3,054	1,436	1,474	902	541	2.73	1.67
Superior	2	3	3	2	0	Not applicable	
North	120	46	23	14	14	1.64	1
Grand	268	132	110	76	32	3.41	2.36
Bay	156	72	92	33	28	3.32	1.19
Southwest	135	67	30	17	13	2.34	1.33
University	2,056	939	965	569	349	2.76	1.63
Metro	317	177	251	191	104	2.4	1.83

Table 5. Calibration Factors for *HSM* Models at Michigan Rural Intersections [16]

Region	Count of intersections	$N_{observed}$ (Intersection crashes 2011-2015)	$N_{predicted}$ (*HSM* 2011-2015)	Calibration factor for intersection crashes
4ST				
Statewide	2,513	9,853	14,010	0.7
Superior	198	562	671	0.84
North	360	1,301	1,878	0.69
Grand	521	2,197	3,235	0.68
Bay	516	2,390	3,521	0.68
Southwest	278	1,212	1,682	0.72
University	583	1,988	2,783	0.71
Metro	57	203	239	0.85
3ST				
Statewide	2,297	5,395	6,376	0.85
Superior	287	583	498	1.17
North	381	1,107	1,248	0.89
Grand	388	1,030	1,182	0.87
Bay	229	691	913	0.76
Southwest	381	780	1,005	0.78
University	564	1,056	1,357	0.78
Metro	67	148	173	0.85

Upon review of the calibration factors for the various *HSM* models, it is evident that the accuracy of the base SPFs from the *HSM* for prediction of crashes in Michigan vary widely by roadway classification. These differences are reflective of several factors, including state-specific differences (e.g., driver characteristics, road design standards, weather, etc.). The most prominent state-specific characteristic is the overabundance of animal crashes attributed to the high deer population in Michigan. Generally, the *HSM* models tend to under-predict total mid-block segment crashes, but over-predict deer-excluded mid-block crashes, although consideration must be given to the fact that a certain (albeit much lower) percentage of the *HSM* crash data involved animals.

The *HSM* models generally tend to over-predict crashes at stop-controlled intersections. As with segments, these differences are reflective of several factors, including state-specific differences (e.g., driver characteristics, road design standards, weather, etc.) and unobserved heterogeneity between sites (e.g., vertical curvature, roadside hazard rating, etc.). Some of these differences between the segment and intersection calibration factors may be the consequence of the method used in this study for distinguishing between segment and intersection crashes. These differences suggest that the accuracy of crash estimation will be improved through the development of Michigan specific SPFs.

2.2 Rural Highway Segment Safety Performance Characteristics

A review of the existing research of the safety performance of rural two-lane, two-way highway segments are presented in the following subsections.

2.2.1 Lane Width

Wider travel lanes on two-lane highways have been associated with reductions in single-vehicle run-off-the-road, head-on, and sideswipe type crashes [3, 52], and the effect is most pronounced for two-lane roadways when comparing wider lines with lane widths of 9 feet or less. A case-control study revealed several interesting relationships between lane and paved surface width and crashes. The study found that increasing total pavement width was associated with a reduction in crashes; however, when evaluating the effect of different lane and shoulder widths on segments of equivalent total paved surface width, the results were less clear. The general trend, however, favored increased lane widths relative to shoulder widths [53]. Looking more specifically at minor arterials and major collectors, roadway functional classifications that are common on county highways, a study found that lane width is much more significant a factor in crash reduction than shoulder width; this is in contrast with principal arterials, where the study found shoulder width to be a stronger factor in crash reduction [54]. Another study found that the effect of increased lane width and reduced crash frequency is more pronounced on higher-volume roads [55].

Not all research has found that wider lanes are less crash-prone. A recent study in rural Pennsylvania found a lower occurrence of total crashes and fatal and injury crashes at locations with narrower lane widths relative to wider lanes [19]. Another study found that narrower lane widths were associated with reductions in same-direction crashes, and fatal and incapacitating injury crashes, but an increase in single-vehicle crashes as well as total crashes and non-incapacitating injury and property damage only (BCO) crashes [56]. Another study found that 12-foot lanes, in particular, are the most crash prone, with lane widths both greater than and less than 12 feet showing lower crash frequency; the author noted that there were confounding factors involved, however, such as a relationship between lane width and speed limit [57].

Prior research in Michigan has also found a relationship between lane width and crash reduction. On rural, county-owned federal aid highways, highway segments with lane widths greater than 12 feet were found to experience 26.3 percent fewer non-deer fatal and injury crashes relative to baseline conditions of less than 11-foot lane widths, although lane width was not found to be significant for total non-deer crashes [18]. Other research on Michigan county-owned federal aid highways found that wider lanes are associated with a lower probability of high-severity crashes; the same study found that traveled-way width on county non-federal aid highways is associated with reductions in both fatal and injury and property damage only crashes [58].

2.2.2 Shoulder Width

While the effect of lane width on crashes on this type of road segment is mixed, research has consistently found that wider shoulders on rural highways are associated with fewer crashes [3, 16, 52, 56], due to the increased recovery and vehicle storage space and increased separation from roadside hazards. While the size of the effect depends on traffic volumes, the frequency of traffic crashes tends to increase as paved shoulder widths are reduced below 6 feet. Further, safety performance tends to degrade substantially as the paved shoulder width decreases below 2 feet on roadways with greater than 2,000 vehicles per day [3].

A study using data from Pennsylvania, using both case-control and cohort approaches, found that shoulder widths below 6 feet are associated with increases in crashes, while shoulder widths greater than 7 feet are associated with decreases in crashes [59]. Another study found that crashes decrease with shoulder widths of 9 feet or greater when using a case-control approach and 8 feet or greater when using a cross-sectional approach [60]. Another study found that increases in shoulder width were associated with crash decreases for interstate highways only; for state highways, there was a negative relationship, but it was not statistically significant [55].

Prior research in Michigan has found that increases in shoulder width on county paved federal aid highways are associated with a reduction in fatal and injury non-deer crashes and that wider shoulders are associated with less severe crashes [58].

2.2.3 Access Points

Several prior studies have showed that increasing access point density leads to an increase in crash occurrence, particularly for multi-vehicle crashes [3, 61-62]. This is at least partially due to driving errors caused by intersections and/or driveways, which may result in rear-end and/or sideswipe type crashes [3]. Specifically, the NCHRP (National Cooperative Highway Research Program) Report 420 concluded that increasing the access point density from 10 to 20 per mile led to a 40 percent increase in crashes, while increasing access points to 40 per mile was associated with a doubling of crash occurrence [62]. Research from arterial roads in Oregon has found that driveway clusters are associated with higher crash frequency than isolated driveways [63].

Research in Michigan has found that increasing driveway density is associated with increases in crashes; the highest increase was found to be for commercial driveways, while the increase in crashes was lower for industrial and residential driveways. Notably, while total crashes were similar for residential and industrial driveways, industrial driveways had higher rates of fatal and injury crashes than residential driveways [64]. Another study, looking at total driveway density on county federal-aid highways, found increases in crashes when driveway density was higher than 5 driveways per mile, with the greatest increases when driveway density was 15 driveways per mile or greater, although this was only significant for total non-deer crashes; it was not significant for fatal and injury crashes. Driveway density was not significant with respect to crashes on non-federal aid highways [18].

2.2.4 Alignment

Horizontal curvature is among the most critical geometric design elements related to the influence of driver behavior and crash risk [65]. In fact, early research showed that the most significant factors in predicting crashes are degree of curve and average daily traffic (ADT) [66]. Early research found that, in addition to curve flattening, widening lanes and shoulders at horizontal curves results in crash reduction; it was less clear to what extent crashes are reduced by correcting superelevation [67]. Similar to wider shoulders and lanes being associated with reduced crashes along horizontal curves, increased sight distance, in general, is associated with crash reduction along horizontal curves [68]. Increased shoulder width is also associated with fewer crashes along horizontal curves involving motorcyclists, in particular [69].

One study evaluating motorcycle crashes along horizontal curves found that better pavement conditions may cause increases in crashes, suggesting users adjust behavior to perceived risk [70]. In other behavioral factors, a naturalistic study found that driver distraction plays a large role in horizontal curve crashes, with distracted drivers being three times more likely to crash than those who are not distracted [71]. When there is a platoon of vehicles at a horizontal curve, the lead vehicle's behavior influences following vehicles' behavior [72].

Looking at curve radius, specifically, horizontal curves with radii less than 2,600 feet tend to cause a reduction in highway running speeds below that of adjacent tangent sections, with substantial speed declines seen for curves with radii less than 800 feet [73]. It is generally understood that crash occurrence tends to increase as the degree of curvature and/or length of curvature increases along a rural highway segment [8, 14-15]. On two-lane rural highways, horizontal curves increase crash risk, particularly if operating speeds through the curve are reduced by more than 3 mph from the adjacent tangent section [6]. Any reduction in speed is associated with crash increases, and this effect is higher with increased speed reduction (relative to speeds along tangent section) [74]. A recent analysis of state-owned rural two-lane roads in Pennsylvania found 43 percent more total crashes and 48 percent more fatal and injury crashes at locations with curve radii less than 1,008 feet, which is the approximate radius of a curve designed for 55 mph with a superelevation of 6 percent [19].

Prior research has also showed that steeper vertical grades are associated with higher crash rates [8, 10], especially when combined with a horizontal curve [75-76]. Total crash rates generally increase with the degree of vertical curvature [8], particularly where hidden horizontal curves, intersections, or driveways are present [65].

2.2.5 Pavement Surface

Rural unpaved roads include a wide variety of design standards, design speeds, and surface characteristics, which can be greatly affected by the effects of weather and heavy traffic loads. The safety of these roads may also be affected by a lack of pavement markings and insufficient signage, narrow road widths, and the absence of shoulders. A limited amount of research has investigated the safety effects of paved versus unpaved surfaces for low volume roadways. Differing design standards between primary and local roadways make it difficult to compare safety performance between paved and unpaved roadways without constraining such analyses to roadways with lower traffic volumes and lower functional classes. Nevertheless, research has found that at the lowest of volumes (e.g., less than 250 vehicles per day), little to no difference in crash occurrence between paved and unpaved roads is seen. However, at higher volumes, paved roads were found to have lower crash occurrence than unpaved roads [77].

2.2.6 Deer-Vehicle Crashes

There is currently limited conclusive evidence regarding roadway factors or countermeasures that influence deer-vehicle crashes (DVCs), which is largely due to difficulties in obtaining accurate data on deer populations and roadway crossing frequency. Many strategies to mitigate or prevent DVCs have not proven to be effective, including reflective lighting to frighten deer [78] and increased mowing frequency to reduce the roadside cover for deer [79-80]. The size of the deer harvest was also not found to have an impact on deer-vehicle crash rates, suggesting that hunting may not be an effective crash reduction strategy. Animal crossing warning signs have shown some evidence of reducing animal-vehicle collisions, although these findings were only supported by crash counts without accounting for differences in mileage or traffic volume between locations with signs versus locations without signs. However, the number of signs per segment was considered [81].

A study conducted in Iowa, using deer-vehicle crash data as well as deer carcass salvage data, found that DVCs in urban areas increased when the speed limit was 50 mph or higher, when the adjacent land cover was grassland, and when the right shoulder was a gravel shoulder (as opposed to a paved shoulder). Furthermore, deer crashes were found to be less common on two-lane roads than on multilane [82].

There has also been research evaluating the use of odor repellant to deter deer from roadways. In Czechia, researchers, using animal carcass and crash data with a Bayesian analysis approach, found that the use of odor repellants could reduce these types of crashes by 26 to 46 percent in locations where these crashes are most common. Odor repellant was applied to wooden poles 80 cm (2.6 feet) tall, placed 10 m (32.8 feet) apart, and replenished every 3 months [83]. However, a study conducted in Ontario found that using various odor-based repellants did not have an impact on which trails wildlife chose to travel along [84]. Other studies have shown that that, while odor repellants may be effective in reducing DVCs in the short term, wildlife become habituated and therefore the treatments lose effectiveness over time [85-86].

A primary issue with deer crash mitigation strategies is identification of primary deer crossing areas for installation of the treatments. Research has showed that animal crossing events can be detected with over 90 percent accuracy using a buried sensing cable along the roadside [87]. A detection system such as this could provide researchers with data about animal crossing locations to determine the proper locations for mitigation strategies and could also serve as an activation trigger for certain countermeasures, such as active warning devices. Other research has found that roadkill data can be used to find potential hot spots [88].

2.3 Rural Intersection Safety Performance Characteristics

Prior research has explored the safety performance of rural intersections. The following paragraphs summarize the existing research literature on safety performance modeling for rural intersections, including the analytical methods specified in the *HSM*. Among the several types of statistical models used for SPF development, generalized linear models and negative binomial models yield easy-to-interpret results and associate crash frequencies to sets of designated explanatory variables [89-90]. Negative binomial models are commonly used for SPFs development and have been used extensively in prior studies, including the *HSM* [8, 91-93].

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 three-leg stop-controlled 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 [94].

While it is widely understood that intersection crashes have 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 three- and four-leg intersections. The effect of intersection lighting has been investigated extensively. For rural four-leg stop-controlled intersections with lighting, the *HSM* provides a CMF of 0.91 relative to the base condition of no lighting present [3]. Research in Minnesota and California found that illuminated intersections are associated with a reduction in nighttime crash frequency of 3.6 percent and 6.5 percent, respectively [95]. Intersection sight distance and intersection alignment have also shown to have a substantial influence on the safety of rural intersections [93].

2.3.1 Turn Lane Presence

Turn lanes generally are associated with reductions in crashes, relative to intersections without turn lanes, with higher crash reductions on intersections with large proportions of vehicles making turning movements. Furthermore, when additional through lanes are introduced, crash frequency tends to decrease [96]. However, right-turn lanes at three-leg intersections may increase crash likelihood, while a decrease in crashes was found when there are right-turn lanes on four-legged intersections. It was acknowledged that the presence of turn lanes is correlated with higher proportions of turning movements [93]. Another study found that right-turn lanes are associated with increased crash frequency and that left-turn lanes did not significantly reduce crashes, although this is confounded by the fact that intersections with left turn lanes are correlated with higher proportions of left-turning vehicles [97]. Left-turn movements are associated with angle crashes [98], which can be quite severe. One difficulty in attributing a crash effect associated with turn lane presence is that, while certain crash types (e.g., angle) may increase, others (e.g., rear-end) may decrease [56].

2.3.2 Access Point Frequency

Access point frequency also has an effect in crash frequency, with higher numbers of access points leading to increasing numbers of crashes. This is due to the increase in conflict points and the potential for vehicles turning into or out of these driveways to interfere with the intersection's operation [96]. Driveway density at rural intersections is particularly associated with property damage only crashes; authors noted that, in addition to the increase in conflict points, drivers may focus attention on vehicles at driveways rather than the traffic ahead of them [99]. High driveway frequency at intersections also leads to unexpected braking, which can cause following vehicles to rear-end the turning vehicle [97]. Commercial driveways, in particular, are prone to crashes [100]; this is not surprising due to the high intensity of turning movements in these locations.

2.3.3 Other Geometric Factors

Other geometric factors that influence crash frequency in rural intersections include shoulder width, where increases in shoulder width are associated with crash reduction. Medians are also associated with fewer crashes when they are wider than 16 feet; when turning lanes are present, medians of 5 feet or greater are associated with crash reduction. Increases in intersection skew angle are associated with increases in crash frequency [96].

Looking at skew angle, in particular, research has found that when skew angle exceeds 10 percent, susceptibility to crashes increases; this is particularly so when there is also horizontal curvature involved [101]. A study using a continuous variable for skew angle found it to be significantly positively correlated with crash frequency, with 60-degree skew angles showing crashes increase by a factor of 1.2 [102]. A study from Ohio found that, on rural four-leg two-lane intersections, intersection angles between 60 and 55 degrees (i.e., skew angles between 30 and 35 degrees) had the highest increase in crash frequency, while the most extreme intersection angles (i.e., 20 degrees and below, corresponding with a skew angle of 70 degrees or greater) actually showed decreases in crash frequency [103]. In one study, increases in skew angle were associated with increases in fatal and injury crash frequency for rural two-lane two-way four-leg intersections, but was not a significant factor on the corresponding three-leg intersections [104].

2.3.4 Traffic-Related Factors

In terms of non-geometric factors, proportions of heavy vehicles or trucks during the peak hour can influence crash frequency; when trucks make up greater than 15 percent of peak hour traffic, crashes are reduced [96].

3. METHODOLOGY

The sections below describe the process whereby safety performance functions for rural segments and intersections in Michigan were developed, including the data collection process, as well as the analytical method.

3.1 Data Collection

To provide a better understanding of the relationship between various roadway characteristics and safety performance on rural roadways and intersections in Michigan, it was first necessary to assemble a comprehensive database of traffic crash and roadway data obtained for a sample of rural roadway segments and intersections across all regions of Michigan. These data were obtained from a variety of sources for the five-year period of 2011 through 2015. Details on the identification of county highway segments and collection of the relevant data are provided in the sections that follow.

The correct calibration of SPFs largely depends on the quality of the data from which they are developed. SPF development requires a crash database that is comprehensive and includes information on specific crash location, collision type, severity, and whether the crash occurred on a segment or at an intersection, among other factors. In addition to crash data, roadway data are also collected and serve as predictor variables in the SPF models. Such factors typically relate to traffic volumes, geometry, or physical features within the right-of-way of the roadway.

As a part of this study, the data were sought out and assembled for rural roadway segments and rural intersections from a diverse array of sources, including state and local agencies. Available geospatial datasets were used whenever possible, although some characteristics required manual collection using satellite or street-level imagery. The aim of the data collection task was to quantify relevant roadway characteristics and assemble comprehensive databases for use in SPF development for the following types of rural roadway segments and rural intersections (examples of each are displayed in Figure 1):

a) Rural county two-lane two-way paved federal aid segments

b) Rural county two-lane two-way paved non-federal aid segments

c) Rural county unpaved non-federal aid segments

d) Rural three-leg minor-road stop-controlled intersections

e) Rural four-leg minor-road stop-controlled intersections

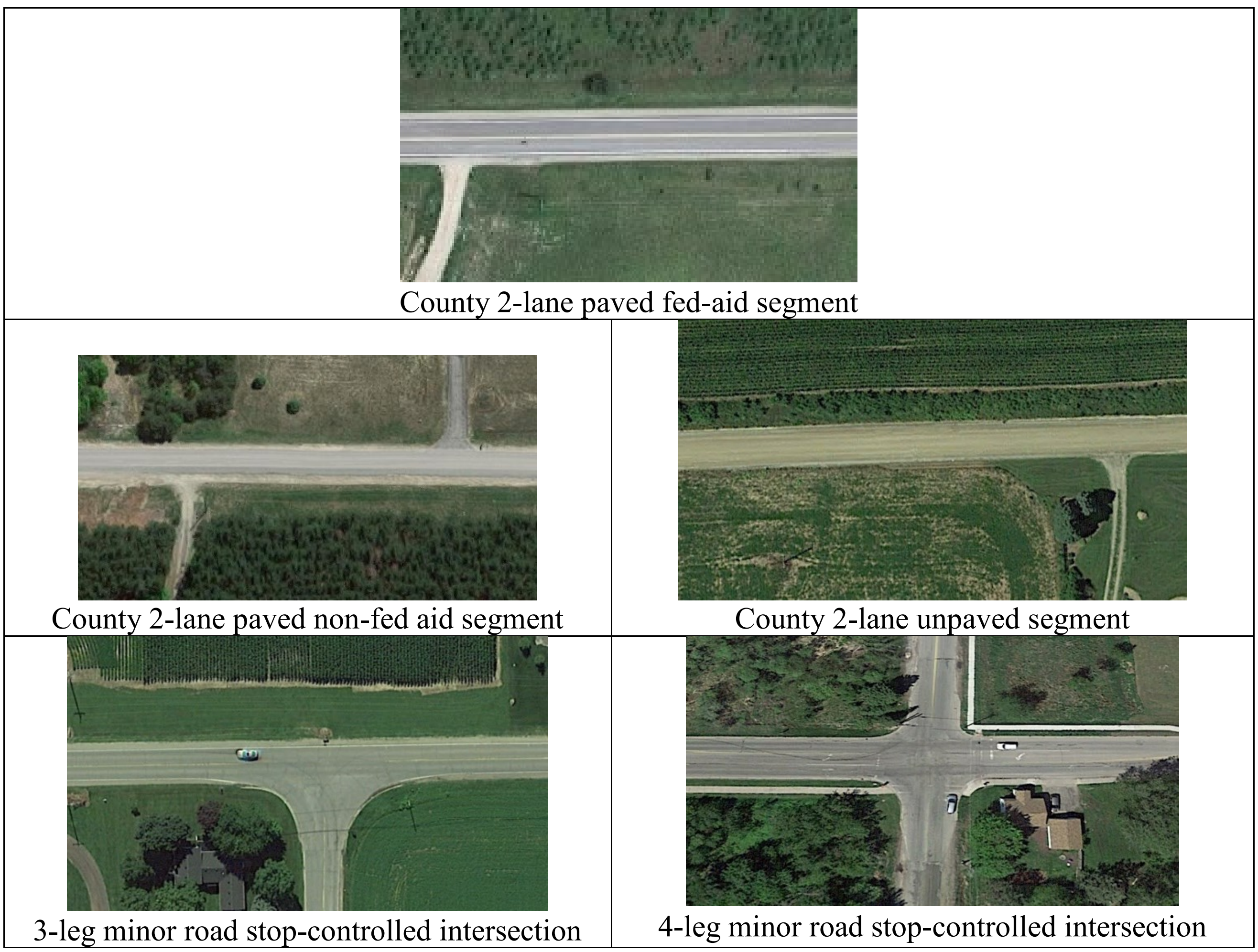


Figure 1: Rural facility types for Michigan SPF development

Data were initially collected for each of the five rural facility types from existing data sources that were available either publicly or through direct contact with MDOT. These data sources included the following databases and files

- Annual statewide crash database obtained from the MDOT Crash Reporting Information System (CRIS);
- All Roads shapefile and other relevant shapefiles based on the Michigan Geographic Framework obtained from the Michigan Geographic Data Library;
- Census boundary shapefiles; and
- MSU's statewide horizontal curve database.

Google Earth satellite imagery was used to manually collect other data for SPF development that was not otherwise included in the existing data sets. Further details of each respective data source are provided in the following sections of this document. Upon completion of the data collection, the volume, crash, and roadway inventory data were then merged into a comprehensive dataset for each of the various roadway and intersection classes included in this analysis.

3.1.1 Roadway Segmentation using the Michigan Geographic Framework

The Michigan Geographic Framework All Roads (MGF-AR) shapefile provided the spatial basis for collection of the necessary roadway and traffic related attributes for segments and intersections. The MGF represents a digital base map for the state, consisting of all public road segments, in addition to urban boundaries, census boundaries, jurisdictional ownership, and other geographic characteristics. All roadway data collected for this study was spatially referenced based on the roadway linear referencing system (LRS) used in the Michigan Geographic

Framework. Updates to the framework occur annually, and version 16a, which uses 2015 data, was used in this study.

The MGF-LRS subdivides the public roadway network into a series of segments based on physical road (PR) number and begin/end mile points. The LRS allows for data from different sources (e.g., crashes, traffic volume, other roadway characteristics) to be uniquely and independently matched to the network based on their relative roadway position. Segment begin/end mile points within the MGF-AR are based on a change in one or more primary characteristics, including pavement surface, annual average daily traffic (AADT), major junction, jurisdictional boundary, and numerous other features. Thus, the PR and mile points from the MGF-AR file effectively partition each roadway into unique homogeneous segments, which provided the roadway segmentation basis for data collection performed during this study. The roadway jurisdictional class (e.g., MDOT, county federal aid, county non-federal aid) was identified using the MGF framework classification code (FCC).

U.S. Census boundaries were used to isolate rural segments and intersections for use in this study. Rural areas are typically defined as locations that fall outside of urban boundaries with populations greater than 5,000. However, this research sought to isolate high-speed sections of county highways where the statutory rural speed limit of 55 mph would apply. Thus, road segments falling inside any incorporated census area boundary were excluded from this sample, including small cities and villages with populations of less than 5,000 and unincorporated census designated places. This step was important, as speed limit signs are not required on roadways utilizing the statutory speed limit, making speed limit verification difficult.

The segments and intersections were initially screened using the U.S. Census designations found in the MGF All Roads shapefile. Only those road segments and intersections falling outside of each of the following boundaries were considered rural and carried forward for further analysis

- Adjusted census urban boundary (ACUB) minimum population of 5,000;
- Urbanized area, as designated by the U.S. Census; or
- Corporate limits of any incorporated city or village designated as partially urban by the Census.

To further distinguish between rural areas and unincorporated rural communities, a shapefile of census-designated places (CDPs) was obtained and integrated with the All Roads shapefile in ArcGIS. CDPs are defined as a concentration of population named by the Census Bureau for statistical purposes, exclusive of incorporated cities, towns, and villages. For a list of CDPs and incorporated areas in Michigan, please refer to the Michigan census block maps kept by the U.S. Census Bureau.

3.1.2 Traffic Volume Data

AADT volumes were obtained from two primary sources for use in this analysis. The volume data source was dependent on the roadway federal aid classification, which are further described below.

County federal aid roadway AADTs were obtained from the MDOT-maintained GIS (geographic information systems) shapefile for statewide non-trunkline federal aid (NTFA) roadways, entitled NTFA_Segment.shp. AADTs were obtained for either the year 2014 or 2015 for nearly the entire population of rural federal aid county roadways across all 83 counties statewide.

County non-federal aid (non-FA) roadways AADTs, including rural collectors and local roadways, were obtained directly from the county road commission (typically from the Roadsoft asset management system used by transportation agencies in Michigan) or the corresponding regional planning commission, where available. Volume data for rural non-federal aid county roadways were ultimately obtained for 27 counties across all portions of the state, including: Arenac, Baraga, Barry, Charlevoix, Clinton, Dickinson, Eaton, Genesee, Grand Traverse, Gratiot, Ingham, Iosco, Kalamazoo, Kent, Livingston, Luce, Macomb, Marquette, Mason, Mecosta, Muskegon, Oakland, Ogemaw, Roscommon, Schoolcraft, Washtenaw, and Wayne counties. 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.

Each of the traffic volume data sets were also exported as KMZ files for access through Google Earth so that roadway inventory information could be assessed and added to a single comprehensive dataset for each facility type. Where necessary, growth factors were applied to the assembled county FA and county non-FA annual traffic volumes to provide estimates for each of the five analysis years (2011-2015). Statewide "urban/rural" and "rural" roadway growth factors were obtained from MDOT each year for 2011 to 2015 and were applied directly to the applicable county FA data and county non-FA county roadway data, respectively. Growth factors for years prior to 2010 were developed using traffic volume data from MDOT's Highway Performance Monitoring System (HPMS) database for the statewide county roadway network and were applied, where necessary, to the relevant non-FA roadway volumes.

3.1.3 Traffic Crash Data

The annual statewide crash databases were provided by MDOT for 2011-2015, which was the most recently available five-year period. The crash data were provided as extracts from MDOT's Crash Reporting Information System (CRIS), which is derived from the official statewide crash database kept by the Criminal Justice Information Center (CJIC) of the Michigan State Police (MSP). The crash database has details of all reported public roadway crash records in the state of Michigan, sanitized of any personal information. Records in this database are kept at the crash-, vehicle-, and person-levels with a total of eight separate spreadsheets included in the database.

For the purposes of this analysis, only crash level data was needed from the “1 crash” and “2 crash location” files. These sheets were linked in Microsoft Access using the “crsh_id” field. After joining the two sheets together, the information relevant to the report was exported. The relevant fields are defined below.

- crsh_id- unique identifier for each crash, used as the basis for linking spreadsheets
- date_val- contains the date the crash occurred
- fatl_crsh_ind- shows the crash as having at least one fatality
- num_injy_a- total number of people sustaining “A-level” injuries in the crash
- num_injy_b- total number of people sustaining “B-level” injuries in the crash
- num_injy_c- total number of people sustaining “C-level” injuries in the crash
- prop_damg_crsh_ind- shows the crash as being property damage only (PDO)
- crsh_typ_cd- defines the crash as single-vehicle or one of nine multiple-vehicle types
- mdot_area_type_cd- code provided by MDOT to differential between intersection-related and non-intersection-related crashes.
- spcl_crcm_deer- indicator for deer involvement in the crash
- ped_invl_ind- shows that a pedestrian was involved in the crash
- bcyl_invl_ind- shows that a bicycle was involved in the crash
- PR- shows the physical road on which the crash occurred, per MDOT’s LRS
- MP- shows the mile point along a physical road where a crash occurred

The data extracts were assembled into a single annual database on a “crash” level of detail, meaning each row in the database represented one crash. Injury severity was defined for each crash based on the most significant injury sustained by anyone involved in the incident. Crashes involving bicycles or pedestrians were separated from vehicle-only crashes for the data analysis. From there, various aggregations of the data were performed to compute crash frequencies by injury status (i.e., fatal/injury vs. PDO) and type (i.e., single vehicle vs. multiple vehicle) on an annual basis. Deer crashes were excluded from the primary segment and intersection analyses; deer crashes on rural highway segments were analyzed and reported separately. Since SPFs were developed separately for segment and intersection facilities, it was first necessary to filter crashes that corresponded to the proper facility type.

Segment crashes were identified by using the “mdot_area_type_cd” equal to 3, which indicated that the crash occurred on the “mid-block” part of the segment (i.e., between intersections), and were matched to the proper roadway segment based on PR (physical road) and mile point for each segment. Intersection crashes were identified by using “mdot_area_type_cd” equal to 2, which indicates “intersection”, and were matched with each intersection by using a 0.04-mile (211.2 feet) radius around the intersection node. Intersection node identification will be described later in this chapter.

3.1.3.1 Horizontal Curves

Horizontal curve information for each segment was obtained through an extraction process initially developed by researchers at Wayne State University and applied to all rural roadways in Michigan, including MDOT trunkline and county roadways. The extraction process estimates the radius and length of horizontal curves based on the All Roads shapefile using tools and code written for GIS. The information includes number of curves with radii of up to 0.5 miles, length of the curved part of the segment, fraction of segment length that is curved, and average radii of curves up to 0.5 miles for a segment. The information was organized in cumulative categories, decreasing in order of radii, from 0.5-mile radii to 0.088-mile radii. The curve data were then merged with the roadway inventory data for the respective segment. To account for segment breaks across curves, the curve data were compiled for each radius threshold in the following manner: length of the curved part of the segment, curved proportion of the segment, and the average radii of curves on the segment. After preliminary investigation, it was decided that the curved proportion of the segment was most suitable for this analysis.

Curve data were then binned based on design speed increments of 5 mph (e.g., 50 to 55 mph) for further analysis. Horizontal curve design speed corresponds with MDOT's Standard Plan R-107-H, where a design speed of 55 mph corresponds to a curve radius of 1,008 feet, a design speed of 50 mph with a curve radius of 794 feet, a design speed of 45 mph with a curve radius of 614 feet, and a design speed of 40 mph with a curve radius of 464 feet, and so on [74]. For purposes of this research, 55 mph was utilized as the threshold for defining horizontal curvature. This was because any curve with a design speed of less than the speed limit, which was the statutory rural limit of 55 mph for the sample of county roads evaluated herein, is required to have a curve warning sign per the Manual on Uniform Traffic Control Devices (MUTCD) [75]. While it was not possible to verify the presence of a curve warning sign at each location, 55 mph was a reasonable upper threshold as curves with design speeds falling below the statutory speed limit were deemed substandard per the MUTCD requirement. Furthermore, for federal aid county roadways with the statutory 55 mph speed limit, curves with design speeds below 40 mph would require re-alignment during a 3R or 4R (i.e., major rehabilitation or reconstruction) project unless a design exception is granted. Thus, it was deemed important to assess the incremental impacts of decreasing horizontal curve design speed beginning with 55 mph and decreasing in 5 mph increments to design speeds below 40 mph.

3.1.3.2 Rural Intersection Identification and Database Assembly

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.shp file. This algorithm consisted of six primary steps, which are demonstrated in Figure 2 and described in further detail in the subsequent paragraphs.

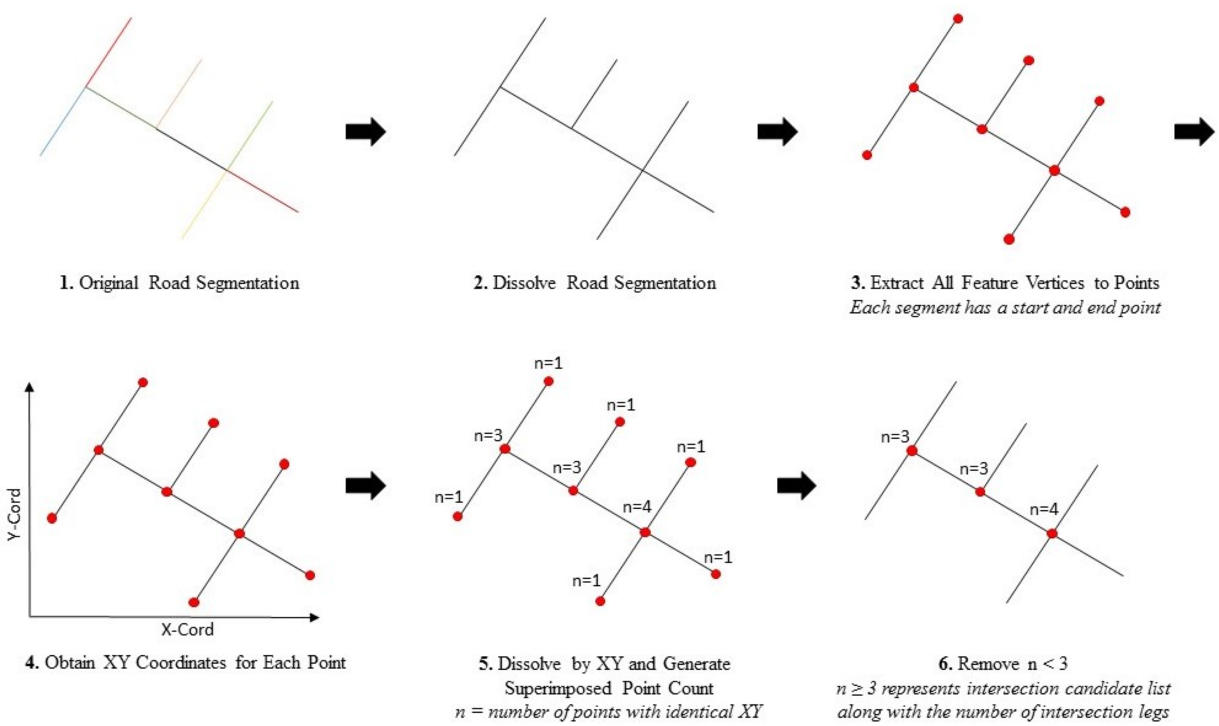


Figure 2: Node identification algorithm

First the full road network was obtained via the All_Roads.shp file, where each public road segment was represented by a unique line in 2-dimensional GIS space. Points were generated at each vertex of the aggregated roadway network, where vertices have the following general properties:

- Vertices exist wherever a segment changes direction.
- Each segment contains a beginning and ending vertex.
- If two segments meet together, the ending vertex of Segment 1 and beginning vertex of Segment 2 will occupy the same location in two-dimensional space. The same condition applies to three or more segments meeting together.

From there, segment vertices were converted to points, and the X (longitude) and Y (latitude) coordinates were obtained for each individual point, which is repeated whenever two or more segments meet. Based on this condition, the point database then dissolved via the concatenated XY coordinates to obtain a count of each time that the concatenated XY coordinates were repeated. This count is the number of segments meeting together at a specific spatial location. Accordingly, a potential intersection exists whenever the count is equal to or larger than three, with the count number also being the number of legs at the intersection. To limit the node database solely to potential intersections, any point with a count of less than three was removed from the database. The final list is all intersections of public roadways in the state of Michigan.

Following the node generation process for potential intersections, any intersection node found within an ACUB, town or village limit, or CDP were also excluded. Segment information from the All_Roads.shp file was then attached to each node for all corresponding node legs via a one-to-one spatial join with a sensitivity search radius of 5 feet. The spatial join was performed to build a relationship between the node dataset and segment dataset for purposes of joining available traffic volume data to each leg of the node. To determine the availability of traffic volume data, nodes were categorized (MDOT, county federal aid, or county non-federal aid) based on the framework classification code (FCC) of each leg. For a node to be included in the analysis, it was necessary for both of the following conditions to be met:

- At least one of the interesting roadways was county-owned; and
- Each major and minor roadway must each major and minor roadway must have at least one leg with traffic volume data.

This was only an issue for non-federal aid county roadways, as traffic volume data were available within existing statewide databases for all MDOT trunklines and county federal-aid roadways.

After populating the nodes with traffic volumes for the major and minor roadways, a KMZ file was assembled for purposes of reviewing all identified nodes using Google Earth satellite imagery. Each node for which traffic volume was available for both the major and minor intersecting roadways were reviewed to verify whether nodes were properly found as a complete intersection. Nodes were excluded from further analysis if any of the following situations applied:

- Signalized;
- Four-way stop controlled;
- Not found 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 miles (422 ft) of another node, such as at median divided intersections or offset "T" intersections; or
- Merge/diverge nodes at intersections within a horizontal curve.

Each crash was initially mapped in GIS (geographic information systems) space based on longitude and latitude coordinates as presented in the crash records. Crashes were associated with each node based on two primary constraints. First, eligible intersection crashes were isolated to "mdot_area_type_cd" equal to 2 (i.e., intersection). Crashes were then matched to each intersection for further analysis by using a 0.04-mile (211.2 ft) radius around the intersection node, as shown in Figure 3.

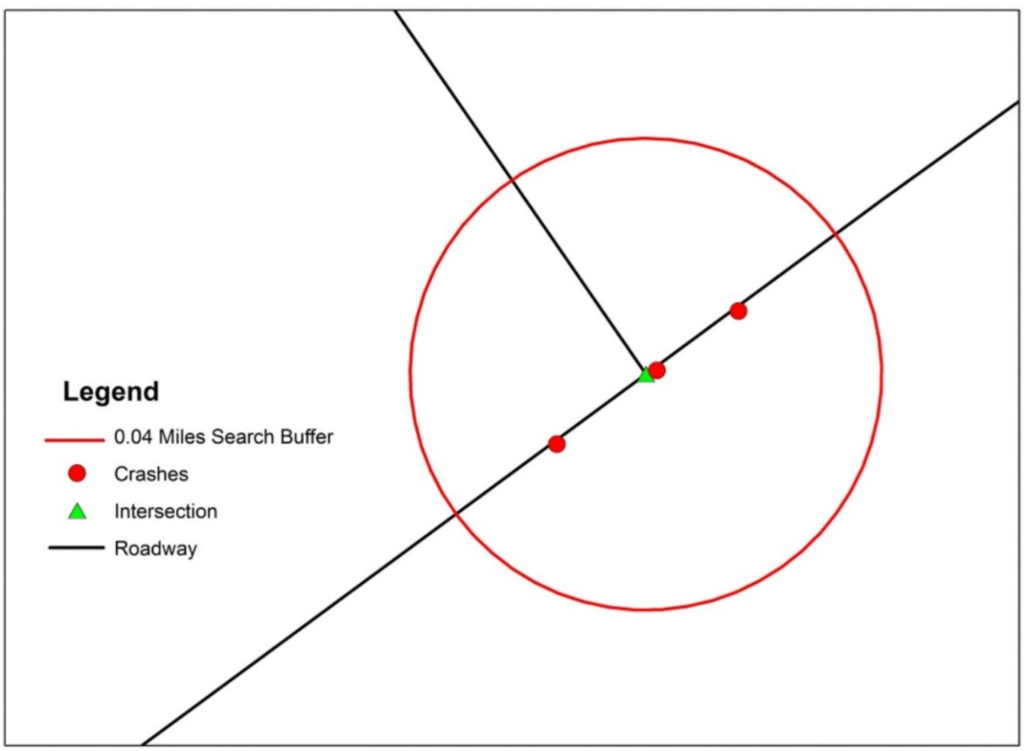


Figure 3: 3-leg Intersection with crash search threshold

Table 6 provides details of the resulting data set, including a count of the number of intersections by type, as well as averages of the major AADT, minor AADT, and total annual crashes. It should be noted that each of Michigan's 83 counties were represented in the 3ST and 4ST datasets.

Table 6: Rural County Road Intersection Summary Statistics

Statistic	3ST				4ST			
	MDOT	County FA	County non-FA	Total	MDOT	County FA	County non-FA	Total
Number of intersections	664	1,212	421	2,297	818	1,389	306	2,513
Average major road AADT	4,715	2,033	544	2,536	4,803	2,200	619	2,855
Average minor road AADT	1,042	730	186	721	1,033	743	254	778
Average annual crashes per intersection	0.78	0.43	0.1	0.47	1.12	0.72	0.2	0.78

3.1.3.3 Rural Segment Database Assembly

The county segment dataset assembly process consisted of three main parts. First, all non-trunkline rural segments were identified in the All Roads shapefile. The selection criteria for this pool excluded all state trunklines and any un-coded roadways (i.e., national functional classification (NFC) is equal to 0), and included only those segments which were located outside of the ACUB and CDP boundaries, had a left-right rural designation, and were categorized as principal arterial, minor arterial, and general non-certified segments. AADT values were spatially matched via the developed linear referencing system (LRS) to the pool of the rural county road segments using the PR, beginning mile point, and ending mile point values of each segment. Volumes for federal aid county roadways were matched first, due to the systemwide availability of these volumes, followed by non-federal aid county roadway volumes, where available. The latest available year of traffic volume data was used in any case where multiple years of volume data were available. In addition, because the roadway segmentation of the AADT volumes differed from the segmentation of the used framework, only those volumes which were a 100 percent match with the roadway segment were applied. Segments without any AADT volumes were removed from the sample and subsequently excluded from further analysis.

Following the assignment of AADT volumes to segments, crashes occurring between 2011 and 2015 were matched to the applicable segment in an equivalent manner using the PR and MP values as presented in each crash record. A secondary criterion was implemented to include only those crashes whose “mdot_area_type_cd” is equal to 3, which represents crashes that are not associated with an interchange or intersection (i.e., midblock). Lastly, all assigned crashes were tabulated by year, type, and severity for each segment. Deer crashes were extracted and analyzed separately from the primary analyses.

Finally, the county segment database was screened to include only segments that were 0.1 miles or more in length, which is the smallest segment length recommended by the *HSM* to represent physical and safety conditions for the facility [3]. Table 7 provides details of the resulting data set, including a count of the number segments and segment mileage by facility type, as well as averages of the AADT, total annual segment crashes (per mile), non-deer annual segment crashes (per mile), and deer crashes as a proportion of total segment crashes. It can be observed from Table 7 that the proportion of deer crashes ranges from 0.38 to 0.69, depending on facility type, which far exceeds the proportion of deer crashes (0.121) reported for the crash data from Washington state that was used to develop the two-lane two-way SPF found in the *HSM*. This has significant implications on the transferability of the *HSM* segment models for use in Michigan, and further emphasizes the need for development Michigan-specific SPFs.

Table 7: Rural County Road Segment Summary Statistics

Statistic	County paved FA	County paved non-FA	Unpaved
Number of segments	9,912	2,873	3,983
Segment mileage	4,423.7	1,463.4	2,007.2
Average AADT	1,717	585	241
Average annual segment crashes per mile	1.49	0.56	0.24
Average annual non-deer segment crashes per mile	0.58	0.22	0.15
Deer crashes as proportion of total segment crashes	0.61	0.61	0.38

3.1.4 Additional Manual Data Collection

Although existing spatial datasets were used to the extent possible, it was also necessary to collect certain important intersection or segment attributes using manual methods. These manual data were typically using Google Earth, including aerial view and Street View, where available.

3.1.4.1 Intersection Data

Relevant count data (e.g., number of driveways and railroad crossing presence) were collected manually using Google Earth aerial imagery based on a 211-foot radius of the intersection node. The following characteristics were assessed during the manual data collection at intersections:

- Number of intersecting legs: Only traditional three-leg and four-leg intersections were included.
- Assignment of major and minor approaches: The major and minor approach legs were assigned to each intersection where the uncontrolled approach was defined as the major leg and the stop-controlled approach was defined as the minor leg.
- Number of stop-controlled approaches: The number of stop-controlled approaches for each 3-leg and 4-leg 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 affected intersections where the major roadway was county non-federal

aid, as Street View imagery was available for all MDOT roadways and many county federal aid roadways. These data were used to identify intersections that included stop-control on the minor approach only.

- Number of through traffic lanes: The number of through lanes were 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 found based on presence of pavement markings and/or sign designations. These data were aggregated by the number of approaches with turn lanes. Tapers or widened shoulders were not considered to be turn lanes.
- Driveway counts: The number of driveways that were at least partially within a 211-foot 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. 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 calculated by first measuring 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.
- Flashing beacon presence.
- Lighting presence (mast-arm or single span wire with hanging light).

- Median presence: Median divided intersections were excluded from this analysis.
- Curb presence: Curbs were considered present if they were found on any of the intersection legs within a 211-foot radius of the center of the intersection.
- Sidewalk presence: Sidewalks were considered present if they were found on any of the intersection legs within a 211-foot radius of the center of the intersection.
- Railroad crossing presence: At-grade railroad crossings that fell within a 211-foot radius of the center of the intersection were identified.

In addition to serving as important analytical factors for SPF and CMF development, these manually collected data were, in some cases, also used for additional screening for identification of proper study sites. For example, to provide consistency with the *HSM*, only cases with minor roadway stop control (i.e., one-stop leg for three-leg intersections and two-stop legs for four-leg intersections) were kept for further analysis. Intersections where all-way stop control existed were excluded from further analyses, as few such intersections occur on rural roadways in Michigan and, thus, were outside the scope of this research. Furthermore, intersections with high skew angles that were a part of a perpendicular intersection with a bypass curve between adjacent legs were removed from the analysis because the nature of the turning traffic movements is not properly shown by the major and minor AADT values. This case is common in rural settings where the through movement follows a 90-degree turn, but the tangent legs are kept as minor road approaches.

<u>3.1.4.2 Segment Data</u>

For the county roadway segment dataset, each segment in the KMZ file was located in Google Earth aerial imagery based on the PR and begin/end mile points from the MGF All Roads shapefile. For geometric characteristics, the Google Earth ruler tool was used to make measurements from the aerial imagery. It was only necessary to collect these data for the county roadways, as the data were already available within the sufficiency file or other existing spatial dataset for MDOT roadways. The following list provides details on the data that were collected manually for county roadway segments:

- Driveway count by type: Driveways falling within the segment boundaries were counted and classified as residential or commercial/industrial to replicate the procedure utilized by MDOT to assemble the trunkline driveway file. Field driveways that did not lead to a structure were not included.
- Surface type: Surface type was classified as paved or unpaved (i.e., gravel).
- Surface width: For paved roadways, the surface width (in feet) was measured from paved edge to paved edge. For unpaved roadways, the surface width was taken as the predominant extent of width.
- Traveled way width: Width in feet between edge lines (if present) on paved surfaces only. If edge lines were not present, traveled way width was equal to surface width.
- Lane width: Calculated as the traveled way width divided by the number of lanes. Lane width was an important safety performance characteristic to evaluate, as it is one of the controlling geometric elements that must be brought to standard during resurfacing, restoration, rehabilitation, or reconstruction projects on federal aid roadways [17].
- Shoulder width: Calculated as the difference between the surface width and the traveled way width, divided by two. Similar to lane width, shoulder width is also a controlling geometric element that must be brought to standard during resurfacing, restoration, rehabilitation, or reconstruction projects on federal aid roadways [17].

- Number of lanes: Predominant number of lanes (both directions) within segment boundary.
- Presence of edge lines, centerlines, curbs, two-way left turn lanes, rumble strips, passing lanes, and on-street parking were each individually assessed using aerial imagery, supplemented by Street View, where present. Unobservable cases were noted.

3.1.5 Quality Control/Quality Assurance Verification

In order to ensure accuracy within the data, quality assurance/quality control (QA/QC) checks were performed. The same resources used to create the initial dataset, Google Earth primarily, were used to perform the QA/QC review. This entailed a separate observer assessing all characteristics for 5 percent of segments. Evidence of systematic errors (e.g., improper coding, inaccurate width measurements, etc.) caused all data collection for the particular observer to be repeated by a more experienced observer.

3.2 Model Calibration

The *HSM* presents a methodology for calibrating the models contained in the manual, and in order to evaluate the benefits of developing new safety performance functions, it was necessary to calibrate *HSM* models to provide a basis for comparison.

Calibration was performed by estimating the number of crashes at each segment or intersection using the *HSM* models and comparing this estimated number to the actual number of crashes. The equation for calculating the calibration factor, C, was previously introduced as Equation 4 in the literature, and is restated below for the sake of convenience.

$$C = \frac{\sum_{i=1}^{n} N_{obs,i}}{\sum_{i=1}^{n} N_{pre,i}} \qquad (4)$$

Where, $N_{obs,i}$ = the observed annual average crash frequency, $N_{pre,i}$ = predicted annual average crash frequency, and n = sample size, equal to the number of sites in the calibration process.

Calculating the predicted annual average crash frequency was accomplished using the *HSM Spreadsheet Tools*, developed at the Texas A&M Transportation Institute and maintained by AASHTO [105]. It was not possible to apply the horizontal curve CMF from the *HSM* due to the way that the Michigan horizontal curve data were specified. Thus, only tangent segments without horizontal curvature were utilized for calibration, and the CMF related to horizontal curvature was not applied. Tangent was defined as not having any horizontal curves with radii less than 2,640 feet. Similarly, due to a lack of information, CMFs for vertical grade, roadside hazard rating, and side slopes were not applied.

3.3 Analytical Methods

In analyzing the safety performance of a given segment, there are several approaches, including: crash frequency, crash rate, and regression analysis. Crash frequency tends to be biased in favor of prioritizing the highest volume segments for treatment, as traffic volume is positively correlated with crashes. On the other hand, using crash rate tends to be biased in favor of low-volume segments, due to the nonlinear relationship between crashes and AADT, or short segments, due to the overrepresentation of crash causal factors on such segments. For this reason, regression analysis was chosen.

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. In the Poisson model, the probability of segment i experiencing y_i crashes during a one-year period is given by Equation 5:

$$P(y_i) = \frac{\exp(-\lambda_i)\lambda_i^{y_i}}{y_i!} \tag{5}$$

where $P(y_i)$ is probability of segment i experiencing y_i crashes and λ_i is the Poisson parameter for segment i, which is equal to the segment's expected number of crashes per year, $E[y_i]$. Poisson models are estimated by specifying the Poisson parameter λ_i (the expected number of crashes per period) as a function of explanatory variables. The most common functional form is shown in Equation 6:

$$\lambda_i = \exp(\beta X_i) \tag{6}$$

where X_i is a vector of explanatory variables and β is a vector of estimable parameters.

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. Overdispersion is common in crash data and may be caused by data clustering, unaccounted temporal correlation, model misspecification, or ultimately by the nature of the crash data, which are the product of Bernoulli trials with unequal probability of events [106]. Overdispersion is generally accommodated through the use of negative binomial models (also referred to as Poisson-gamma models).

The negative binomial model is derived by rewriting the Poisson parameter for each segment as shown in Equation 7:

$$\lambda_i = \exp(\beta X_i + \varepsilon_i) \tag{7}$$

where $\exp(\varepsilon_i)$ is a gamma-distributed error term with mean 1 and variance α. The addition of this term allows the variance to differ from the mean as $VAR[y_i] = E[y_i] + \alpha E[y_i]^2$. The negative binomial model is preferred over the Poisson model since the latter cannot handle overdispersion and, as such, may lead to biased parameter estimates [107]. Consequently, the *HSM* recommends using the negative binomial model for the development of SPFs.

If the overdispersion parameter (α) is equal to zero, the negative binomial reduces to the Poisson model. Estimation of λ_i can be conducted through standard maximum likelihood procedures. While alternatives, such as the Conway-Maxwell model, have the advantage of accommodating both overdispersion and underdispersion (where the variance is less than the mean) [107], the negative binomial model remains the standard in SPF development.

One concern that arises when evaluating the safety of the county road system in Michigan is the occurrence of unobserved heterogeneity, defined as unknown variability in the effect of variables across the sample population. In this context, unobserved heterogeneity may be introduced when collecting data from across various counties and regions of the state, due to the inability to measure or otherwise quantify all data necessary to account for this variability. For example, design standards and maintenance practices are known to vary from county to county, particularly for non-federal aid roads [108]. Other factors, such as weather, topography, land use, and driver behavior also vary widely across the various regions of the state. If these variances are not considered, and the effects of observable variables are held the same across all observations, the estimated parameters will be biased [109].

To account for these differences, a county-specific random effect was incorporated into the analysis, whereby the intercept term is allowed to vary across counties. Furthermore, an additional site-specific random intercept term was utilized in order to account for the non-independence associated with the annual replication of the data for each location within the data file. Prior research has compared this approach with a methodology that incorporates only one line of data per site; it was found that the traditional method underestimates variance, and thus may find factors to be statistically significant that would not be significant if site location had been controlled [110]. Recent papers have addressed this bias by incorporating a site-specific random effect [111]. In order to capture annual variations in crashes, the random effect approach was used; a model of county federal aid segments using fixed effects, whereby each line of data incorporates all five years of crashes per site can be found in Table 57 (Appendix B). It is important to note that the model contained in Appendix B is estimating five years of crash data rather than the one-year period that all other models in this document utilize.

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 statistical noise tends to be incorrectly included as systematic variations in crashes. A stepwise process was used whereby factors would be removed from models to evaluate the changes in other parameter estimates and P-values.

After examining the general distributions of traffic volumes and proportion of federal aid classification, it was decided that three separate series of SPFs were developed for segments (i.e., paved federal aid, paved non-federal aid, and unpaved) and six separate series of SPFs for intersections. A full list of models are as follows:

- Rural county segments (non-deer)
    - Paved federal aid
    - Paved non-federal aid
    - Unpaved
- Rural stop-controlled intersections (non-deer)
    - Three-leg
        - Combined set (major road state, county FA, and county non-FA all included)
        - County FA

        - County non-FA
    - Four-leg
        - Combined set (major road state, county FA, and county non-FA all included)
        - County FA
        - County non-FA
- Rural segments (only deer crashes)
    - State
    - County paved federal aid
    - County paved non-federal aid
    - Unpaved

With the exception of the deer-only models, only non-deer crashes were included in the models due to the relative frequency and unpredictability of such crashes, particularly when considering roadway design factors.

It is also noted that the natural log of segment length was included as an offset in each model, with a parameter estimate fixed at one, thereby forcing the model to treat crashes as a direct one-to-one relationship with segment length. Segment length, when not constrained by an offset, tends to be very close to one [112]; for this reason, segment is generally considered to be an offset when developing safety performance functions [113-115]. A set of models where segment length was not treated as an offset were developed and are included in Tables 58-60 (Appendix C). The models in Appendix C have parameter estimates for the natural log of length that are very close to one.

The functional form for the mixed effects negative binomial model for prediction of annual crash frequency results is presented in Equation 8 below.

$$N = L * AADT^{\beta_1} * \exp(\beta_0 + x_2\beta_2 + \cdots + x_n\beta_n) \tag{8}$$

Where, N = estimated number of annual crashes; n = number of model parameters; L = segment length in miles; β_0 = model intercept; β_1 = model parameter estimate for AADT; $x_2 \ldots x_n$ = additional model parameter values (for binary factors, this would equal one if present or applicable, zero if not present or applicable); and $\beta_2 \ldots \beta_n$ = additional model parameter estimates.

The functional form for interpreting intersections model results is presented in Equation 9 below.

$$N = Major\ AADT^{\beta_1} * Minor\ AADT^{\beta_2} * \exp(\beta_0 + x_3\beta_3 + \cdots + x_n\beta_n) \tag{9}$$

Where, N = estimated number of annual crashes; n = number of model parameters; β_0 = model intercept; β_1 = model parameter estimate for major road AADT; β_2 = model parameter estimate for minor road AADT; $x_3 \ldots x_n$ = additional model parameter values (for binary factors, this would equal one if present or applicable, zero if not present or applicable); and $\beta_3 \ldots \beta_n$ = additional model parameter estimates.

4. SAFETY PERFORMANCE FUNCTIONS FOR COUNTY-OWNED RURAL HIGHWAY SEGMENTS

The safety performance of rural two-way two-lane county highway segments were analyzed using the data collected from 30 counties within Michigan, as described in Chapter 3. Due to the differences in design characteristics, traffic volumes, trip distances, driver characteristics, and other factors, separate datasets were created for federal aid and non-federal aid county highways. Non-federal aid county highways were further partitioned into paved and unpaved roadway datasets for analysis. Safety performance functions were developed for the following three categories of rural county road segments:

a) Rural county two-lane two-way paved federal aid segments;
b) Rural county two-lane two-way paved non-federal aid segments; and
c) Rural county unpaved non-federal aid segments.

A series of CMFs were also developed to describe the effects of horizontal curve radius on segment safety performance. It is important to note that while rural unpaved county federal aid roadways do exist, the number of such roadway within Michigan is very small and, consequently, not included in this analysis. The sections that follow will include a data summary and data diagnostics section, an explanation of the analytical methods, and results and discussion.

4.1 Data Summary, Data Screening, and Data Diagnostics

Figure 4 and Table 8 display the distribution of county two-lane two-way segment study locations throughout the state of Michigan. The following counties were represented in the county road segment database: Arenac, Baraga, Barry, Charlevoix, Clinton, Dickinson, Eaton, Emmet, Genesee, Grand Traverse, Gratiot, Ingham, Iosco, Kalamazoo, Kent, Keweenaw, Livingston, Luce, Macomb, Marquette, Mason, Mecosta, Monroe, Muskegon, Oakland, Ogemaw, Roscommon, Schoolcraft, Washtenaw, and Wayne. These 30 counties were utilized due to the availability of traffic volume data, particularly for non-federal aid county roadways. It is worth noting that each of the seven MDOT geographic regions were represented in the sample.

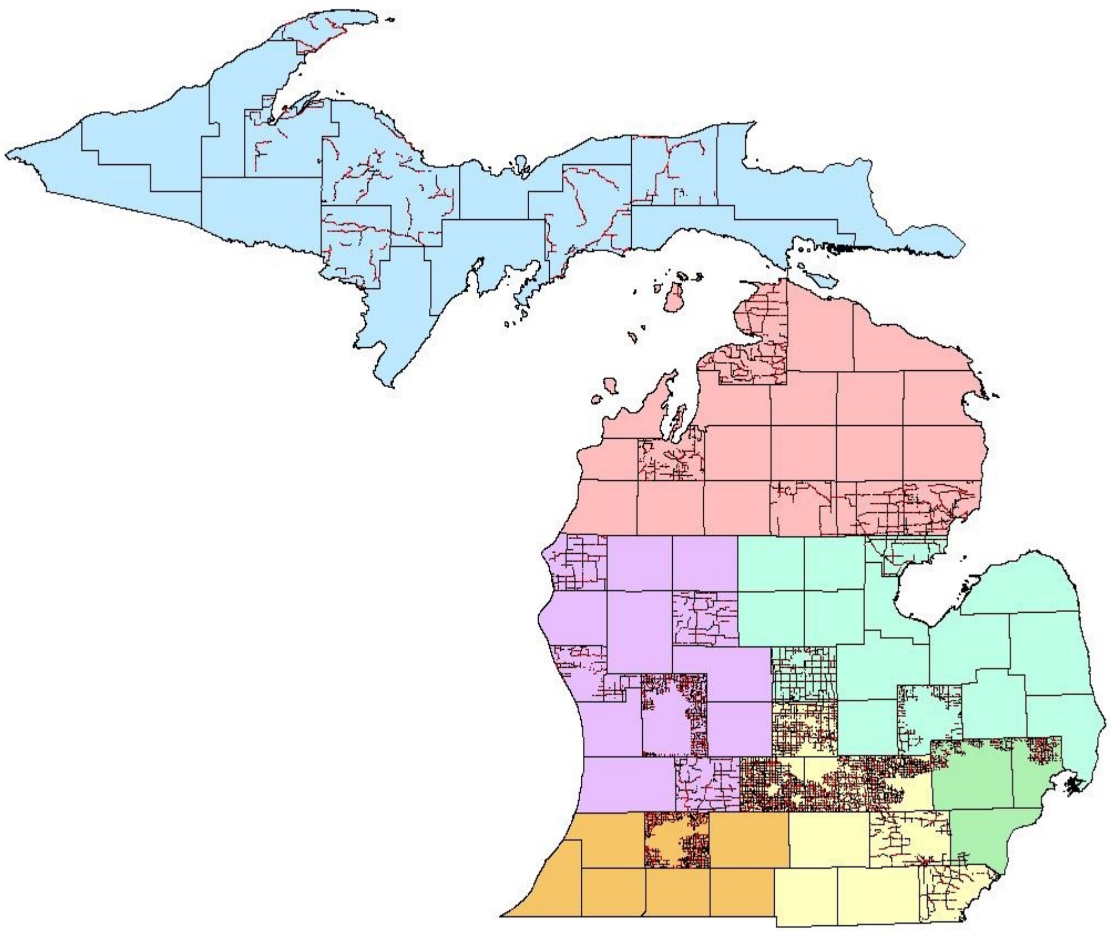


Figure 4: Map of rural county highway segments

Table 8: Represented Counties and Corresponding Segment Mileage (Segments)

County	Miles			
	County FA	County non-FA	Unpaved	Total
Arenac	126	0	2	128
Baraga	101	0	8	108
Barry	225	4	13	243
Charlevoix	117	0	30	147
Clinton	215	99	178	493
Dickinson	101	1	12	113
Eaton	228	171	446	845
Emmet	157	0	0	157
Genesee	113	74	3	189
Grand Traverse	136	56	20	213
Gratiot	236	61	89	387
Ingham	208	309	38	554
Iosco	166	25	31	223
Kalamazoo	171	307	71	548
Kent	196	210	129	536
Keweenaw	60	0	0	60
Livingston	113	40	386	539
Luce	68	0	44	113
Macomb	29	5	117	152
Marquette	154	13	20	187
Mason	181	0	11	193
Mecosta	195	0	3	197
Monroe	161	0	0	161
Muskegon	170	10	1	180
Oakland	29	3	128	161
Ogemaw	151	6	8	165
Roscommon	99	0	2	101
Schoolcraft	83	2	63	149
Washtenaw	150	2	31	184
Wayne	23	0	6	28
Total	4,162	1,399	1,892	7,453

4.1.1 Segment Descriptive Statistics

In total, 7,453 miles of county highways were included in the analysis, of which 55.8 percent were paved federal aid segments (from 30 counties), 18.8 percent were paved non-federal aid segments (from 19 counties), and 25.4 percent were unpaved roadways (from 27 counties). The full descriptive statistics for the modeled variables associated with each of the three county roadway categories can be found in Table 9 (paved federal aid), Table 10 (paved non-federal aid), and Table 11 (unpaved non-federal aid).

Table 9: County Road Segment Summary Statistics (Federal Aid)

Variable	N (segments)	Min	25th%	50th%	75th%	Max	Mean	Std dev
AADT	9,264	10	616	1,058	1,779	5,143	1,449.0	1,122.3
Segment length (mi)	9,264	0.100	0.219	0.372	0.505	8.19	0.449	0.330
Surface width (feet)	9,264	19.0	22.0	23.0	24.0	40.0	24.2	3.367
Lane width (feet)	9,264	9.5	10.5	11.0	11.0	13.0	11.0	0.685
Paved shoulder width (feet)	9,264	0.0	0.0	0.5	1.0	8.0	1.0	1.444
Driveway count	9,264	0	2	4	7	69	6.0	6.481
Driveway density (mi^{-1})	9,264	0.0	5.0	11.3	17.8	138.7	14.5	13.612
0-to-4.9 driveways per mi	2,321	n/a	n/a	n/a	n/a	n/a	0.251	0.433
5-to-14.9 driveways per mi	3,448	n/a	n/a	n/a	n/a	n/a	0.372	0.483
15-to-24.9 driveways per mi	1,903	n/a	n/a	n/a	n/a	n/a	0.205	0.404
≥25 driveways per mi	1,592	n/a	n/a	n/a	n/a	n/a	0.172	0.377
Curved portion of segment								
≥55 mph design speed	9,264	0.000	1.000	1.000	1.000	1.000	0.969	0.144
50-54.9 mph design speed	9,264	0.000	0.000	0.000	0.000	1.000	0.014	0.096
45-49.9 mph design speed	9,264	0.000	0.000	0.000	0.000	1.000	0.010	0.077
40-44.9 mph design speed	9,264	0.000	0.000	0.000	0.000	1.000	0.005	0.057
<40 mph design speed	9,264	0.000	0.000	0.000	0.000	1.000	0.002	0.035
Minor arterial	803	n/a	n/a	n/a	n/a	n/a	0.087	0.281
Major collector	8,435	n/a	n/a	n/a	n/a	n/a	0.911	0.285
Minor collector	23	n/a	n/a	n/a	n/a	n/a	0.002	0.050
Local	2	n/a	n/a	n/a	n/a	n/a	0.000	0.015
Variable	**Five-year crash count**	**Annual crashes per segment**						
		Min	**25th%**	**50th%**	**75th%**	**Max**	**Mean**	**Std dev**
Midblock total crashes	29,377	0	0	0	1	15	0.634	1.058
Midblock total non-deer crashes	10,862	0	0	0	0	8	0.235	0.576
Midblock fatal and injury non-deer crashes	2,956	0	0	0	0	5	0.064	0.267
Midblock property damage only non-deer crashes	7,906	0	0	0	0	7	0.171	0.472

Note: mi = miles; mph = miles per hour; n/a = not applicable; std dev = standard deviation; min = minimum; max = maximum; N = number of

Table 10: County Road Segment Summary Statistics (Paved Non-Federal Aid)

Variable	N (segments)	Min	25th%	50th%	75th%	Max	Mean	Std dev
AADT	2,713	5	203	378	595	1,681	483.0	359.6
Segment length (mi)	2,713	0.100	0.257	0.490	0.636	2.012	0.515	0.301
Surface width (feet)	2,713	18.0	20.0	22.0	22.0	36.0	21.6	1.965
Lane width (feet)	2,713	9.0	10.0	10.5	11.0	13.0	10.6	0.693
Paved shoulder width (feet)	2,713	0.0	0.0	0.0	0.0	7.0	0.2	0.645
Driveway count	2,713	0	3	6	11	62	8.6	7.764
Driveway density (mi^{-1})	2,713	0.0	8.0	14.4	21.1	108.1	17.4	13.549
0-to-4.9 driveways per mi	395	n/a	n/a	n/a	n/a	n/a	0.145	0.353
5-to-14.9 driveways per mi	1,013	n/a	n/a	n/a	n/a	n/a	0.373	0.484
15-to-24.9 driveways per mi	704	n/a	n/a	n/a	n/a	n/a	0.259	0.438
≥25 driveways per mi	602	n/a	n/a	n/a	n/a	n/a	0.222	0.416
Curved proportion of segment								
≥55 mph design speed	2,713	0.000	1.000	1.000	1.000	1.000	0.967	0.144
50-54.9 mph design speed	2,713	0.000	0.000	0.000	0.000	1.000	0.011	0.077
45-49.9 mph design speed	2,713	0.000	0.000	0.000	0.000	0.889	0.008	0.067
40-44.9 mph design speed	2,713	0.000	0.000	0.000	0.000	1.000	0.009	0.073
<40 mph design speed	2,713	0.000	0.000	0.000	0.000	0.785	0.005	0.044
Minor arterial	0	n/a	n/a	n/a	n/a	n/a	0.000	0.000
Major collector	14	n/a	n/a	n/a	n/a	n/a	0.005	0.073
Minor collector	508	n/a	n/a	n/a	n/a	n/a	0.187	0.390
Local	2,191	n/a	n/a	n/a	n/a	n/a	0.807	0.394

Variable	Five-year crash count	Annual crashes per segment						
		Min	25th%	50th%	75th%	Max	Mean	Std dev
Midblock total crashes	3,663	0	0	0	0	7	0.270	0.621
Midblock total non-deer crashes	1,389	0	0	0	0	4	0.102	0.347
Midblock fatal and injury non-deer crashes	399	0	0	0	0	3	0.029	0.176
Midblock property damage only non-deer crashes	990	0	0	0	0	3	0.073	0.286

Note: mi = miles; mph = miles per hour; n/a = not applicable; std dev = standard deviation; min = minimum; max = maximum; N = number of

Table 11: County Road Segment Summary Statistics (Unpaved Non-Federal Aid)

Variable	N (segments)	Min	25th%	50th%	75th%	Max	Mean	Std dev
AADT	3,747	4	78	130	203	658	172.7	132.6
Segment length (mi)	3,747	0.100	0.253	0.458	0.567	4.575	0.505	0.365
Surface width (feet)	3,747	14.0	18.0	20.0	22.0	33.0	21.0	3.526
Driveway count	3,747	0	2	4	7	50	5.9	5.944
Driveway density (mi^{-1})	3,747	0.0	4.4	10.0	15.9	93.0	12.3	10.626
0-to-4.9 driveways per mi	1,013	n/a	n/a	n/a	n/a	n/a	0.270	0.444
5-to-14.9 driveways per mi	1,521	n/a	n/a	n/a	n/a	n/a	0.406	0.491
15-to-24.9 driveways per mi	773	n/a	n/a	n/a	n/a	n/a	0.206	0.405
>25 driveways per mi	440	n/a	n/a	n/a	n/a	n/a	0.118	0.322
Curved proportion of segment								
>55 mph design speed	3,747	0.000	1.000	1.000	1.000	1.000	0.966	0.135
50-54.9 mph design speed	3,747	0.000	0.000	0.000	0.000	1.000	0.008	0.057
45-49.9 mph design speed	3,747	0.000	0.000	0.000	0.000	1.000	0.009	0.065
40-44.9 mph design speed	3,747	0.000	0.000	0.000	0.000	1.000	0.007	0.057
<40 mph design speed	3,747	0.000	0.000	0.000	0.000	0.825	0.010	0.062
Minor arterial	0	n/a	n/a	n/a	n/a	n/a	0.000	0.000
Major collector	437	n/a	n/a	n/a	n/a	n/a	0.117	0.321
Minor collector	227	n/a	n/a	n/a	n/a	n/a	0.061	0.239
Local	3,083	n/a	n/a	n/a	n/a	n/a	0.823	0.382
Variable	**Five-year crash count**	**Annual crashes per segment**						
		Min	**25th%**	**50th%**	**75th%**	**Max**	**Mean**	**Std dev**
Midblock total crashes	2,080	0	0	0	0	5	0.111	0.358
Midblock total non-deer crashes	1,335	0	0	0	0	5	0.071	0.285
Midblock fatal and injury non-deer crashes	376	0	0	0	0	2	0.020	0.143
Midblock property damage only non-deer crashes	959	0	0	0	0	5	0.051	0.239

Note: mi = miles; mph = miles per hour; n/a = not applicable; std dev = standard deviation; min = minimum; max = maximum; N = number of

4.1.2 Data Screening

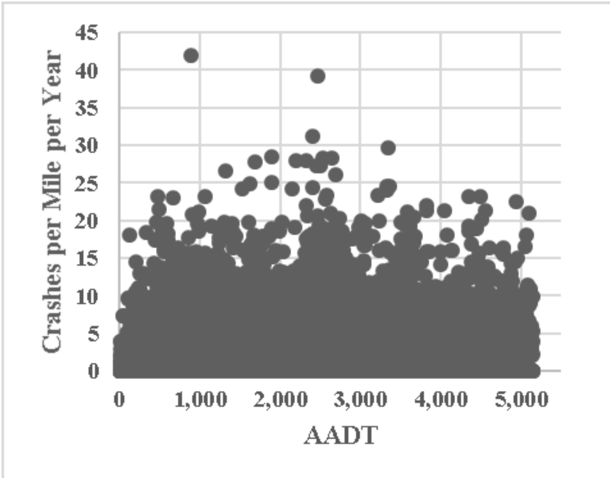
In order to address sites with atypical characteristics, segments were constrained to those with lane widths from 10 to 13 feet on paved federal aid segments, nine to 13 feet on paved non-federal aid segments, and surface widths from 14 to 33 feet on unpaved non-federal aid segments. Furthermore, on paved federal aid segments, those segments with paved shoulder widths greater than eight feet were excluded. A thorough investigation of a representative sample of such locations found that they typically possessed atypical features, typically involving widening at driveways, intersections, or bridges. These exceptions represented less than one percent of all segments. In addition, segments comprising of the top 5 percent of volumes were removed from this analysis in order to focus on the lower-AADT sites where the vast majority of the data reside. These exclusions explain the difference between some of the descriptive statistics in this chapter with those in Chapter 3.

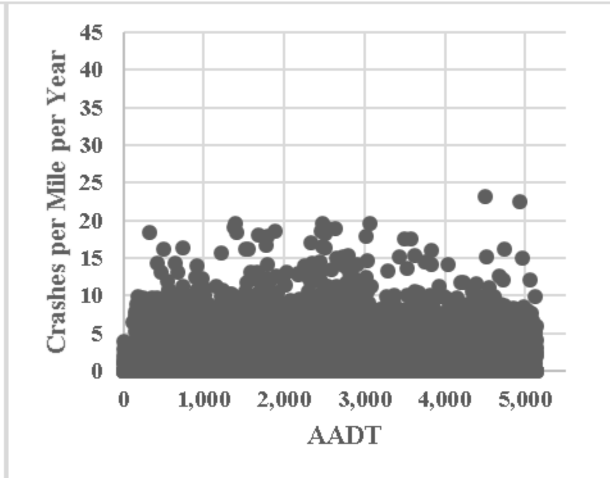
In addition to the differences in data collection between federal aid and non-federal aid highways, previously described in Chapter 3, the differences in funding source between federal aid and non-federal aid highways show key differences between these roadways. The most critical is the functional classification; while 91 percent of paved federal aid segments are major collectors, 81 percent of paved non-federal aid segments are local roads. Not surprisingly, these functional classifications differences are also reflected in the AADT volumes, with a 75th percentile AADT of 1,779 vehicles per day on paved federal aid segments, but only 595 vehicles per day on paved non-federal aid segments.

It is also worth noting the descriptive statistics for the crashes themselves across the roadway segment categories. For example, on paved federal aid highways, 63 percent of crashes involved deer, and on paved non-federal aid highways, 62 percent of crashes involved deer. In the *HSM*, only 12 percent of the crashes used to develop their two-way two-lane rural segment SPF involved animals [3]. Due to their large proportion, as well as the lack of known deer-mitigation strategies in use in Michigan, deer crashes were excluded from the primary segment models that were developed, and were reserved for a separate analysis that is detailed in Chapter 6. On paved federal aid segments, 39 percent of segments experienced a crash of any kind during the five-year analysis period, while only 19 percent of segments experienced a non-deer related crash. On paved non-federal aid segments, 21 percent of segments experienced a crash of any kind, while only 9.6 percent of segments experienced a non-deer related crash during the analysis period.

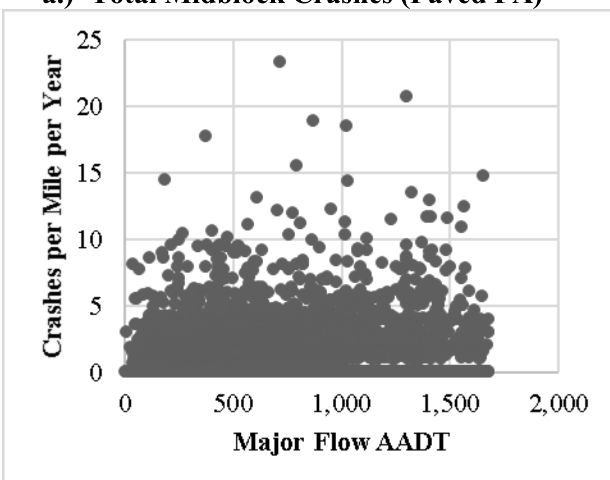
4.1.3 Data Diagnostics

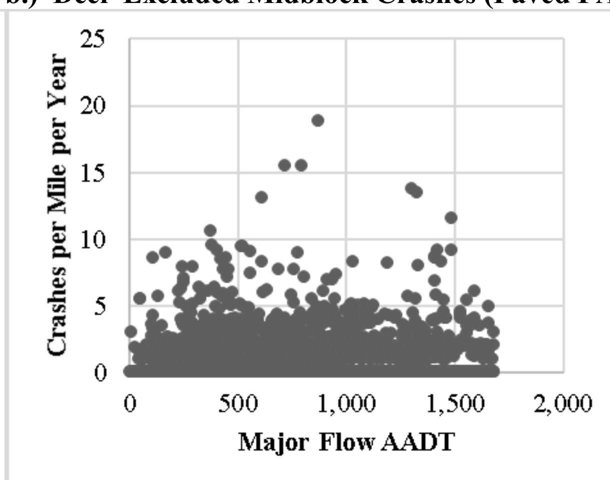
Prior to SPF development, various data diagnostics were initially conducted to examine general trends across all locations for each facility type. This included assessment of the relationships between AADT and annual crash frequency (normalized on a per-mile basis) with scatterplots of these relationships generated for total and deer-excluded crashes for each of the three segments types, which are shown in Figure 5.



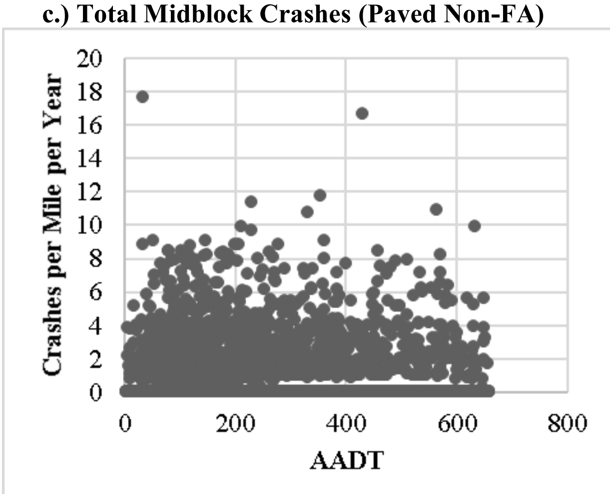


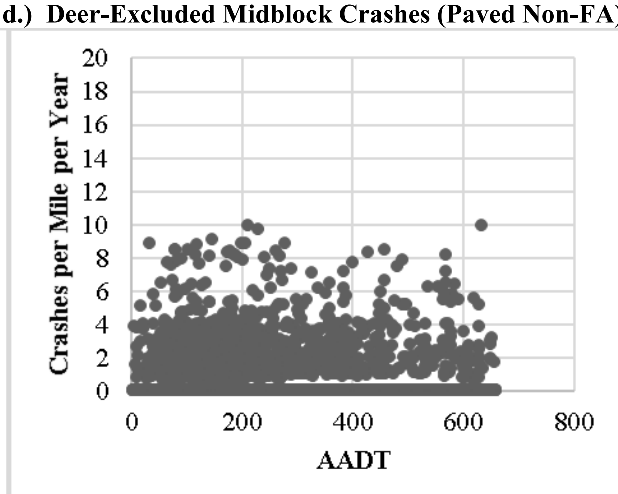
a.) Total Midblock Crashes (Paved FA) **b.) Deer-Excluded Midblock Crashes (Paved FA)**





c.) Total Midblock Crashes (Paved Non-FA) **d.) Deer-Excluded Midblock Crashes (Paved Non-FA)**





e.) Total Midblock Crashes (Unpaved Non-FA) **f.) Deer-Excluded Midblock Crashes (Unpaved Non-FA)**

Figure 5: Annual midblock crashes per mile vs AADT, county segments (2011-2015)

Various additional factors were plotted against AADT, including lane width, paved shoulder width, driveway density, and curved segments proportions for each design speed range. These two-way scatter plots are displayed in Figures 6-8. Each of these factors showed correlation with AADT, which is expected, as many of these factors are design standards established based on traffic volumes. For example, design standards for lane and shoulder width typically increase with increasing traffic volume. Not surprisingly, lane width and shoulder width (or total surface width for unpaved roads) on county road segments are found to be positively correlated with AADT. The association with AADT is stronger for shoulder width and is strongest for total surface width on unpaved roadways. It is also worth noting that that wider lanes (i.e., 11- and 12-foot lanes) are found in a wider range of traffic volumes than narrower lanes (i.e., 9- and 10-foot lanes). Driveway density was also found to be correlated with AADT; also, not a surprising result. Curves with the lowest design speeds are found mostly on lower-volume highways, while curves with design speeds between 45-49 mph and 50-54 mph are found along a much wider range of traffic volumes, including higher-volume segments. In general, these associations between the various roadway factors and AADT were strongest for the paved federal aid roadways and diminished at the lower roadway classes.

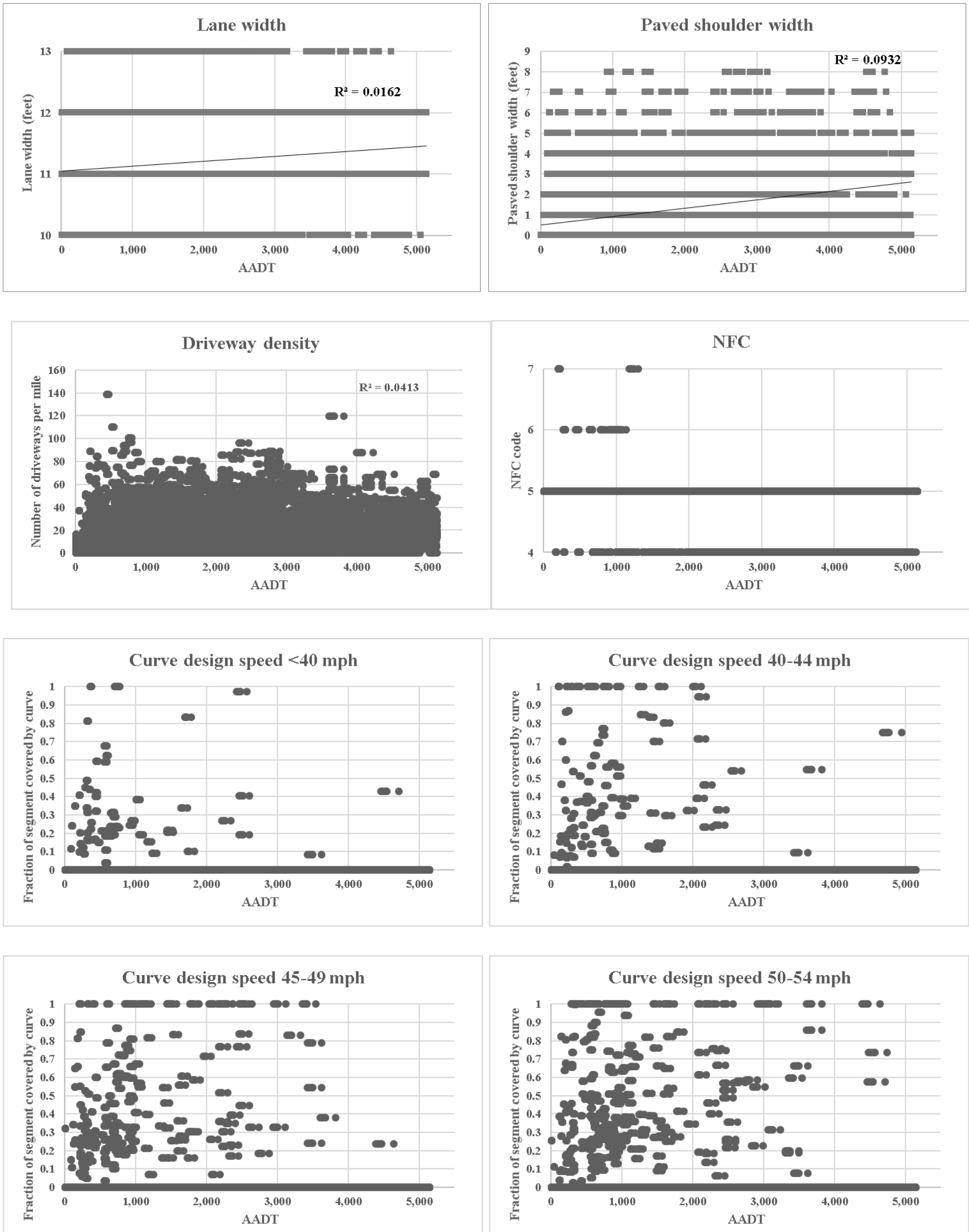


Figure 6: Lane width, shoulder width, driveway density, NFC, and curve proportions vs. AADT on paved federal aid county segments

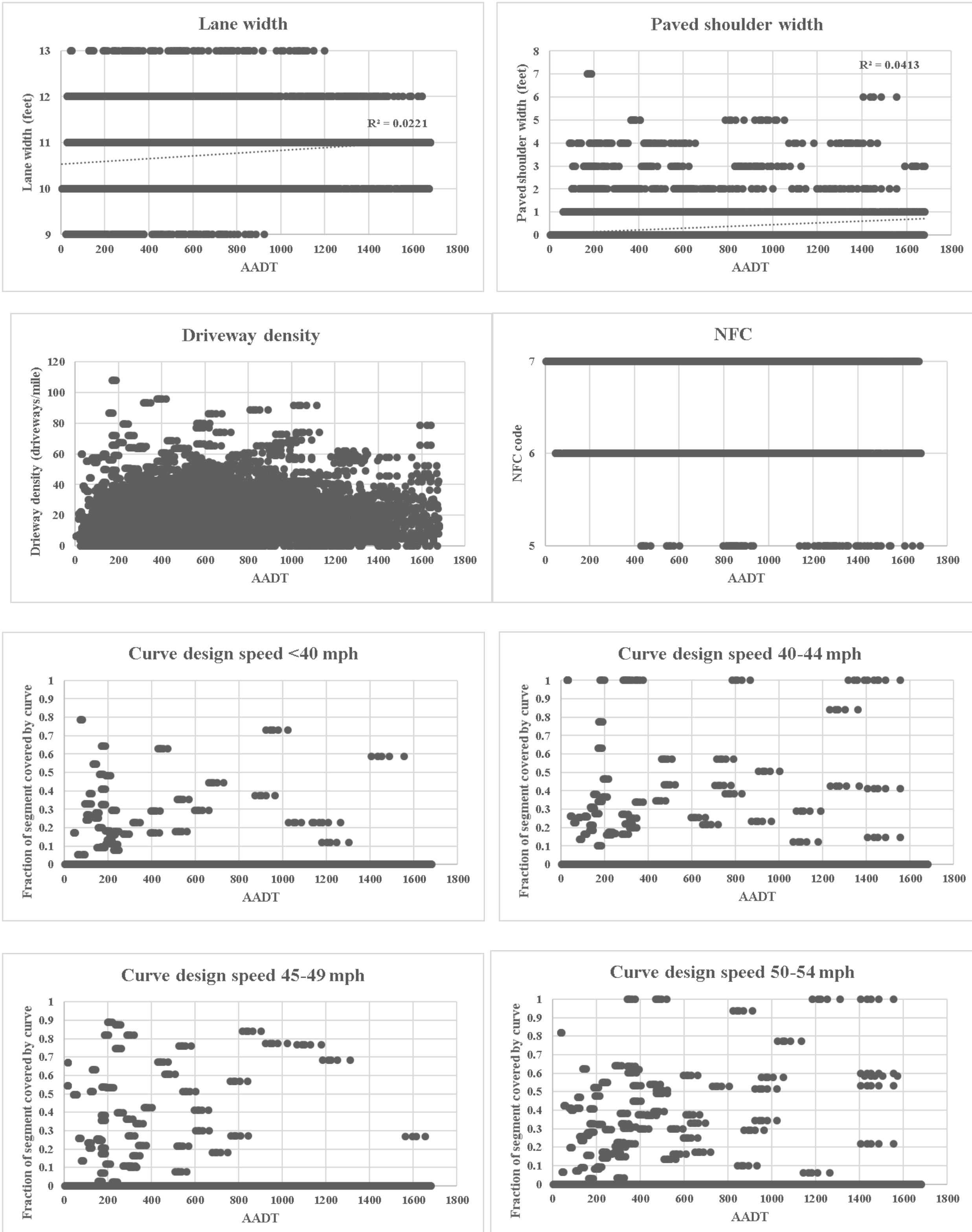


Figure 7: Lane width, shoulder width, driveway density, and curve proportions vs. AADT on paved non-federal aid county segments

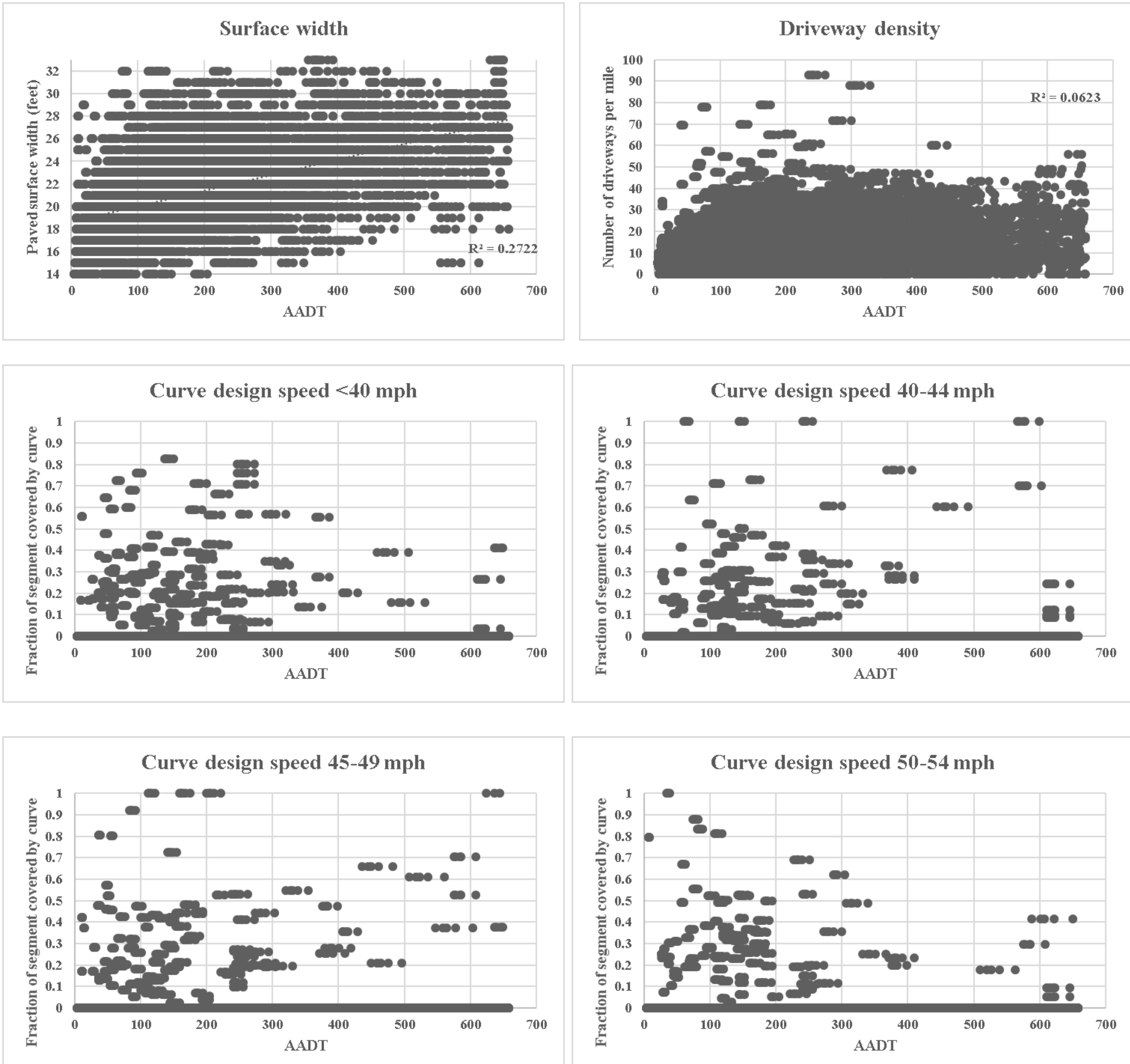


Figure 8: Surface width, driveway density, and curve proportions vs. AADT on unpaved non-federal aid county segments

Tables 12-14 show the crash distributions for each of the three segment types. In comparison to the default distributions presented in Chapter 10 of the *HSM*, Michigan's two-lane two-way county segments have much lower proportions of severe crashes and much greater proportions of animal (deer) crashes. In direct comparison to MDOT state trunkline rural two-way two-lane segments, the two-lane county segments have a higher proportion of other single-vehicle crashes, which includes fixed object collisions, across all crash severities [16]. This type of crash might likely be related to the available clear zone, road hazard rating, or sideslopes, none of which were feasible for collection in this study, but would typically be reflected in the design standards for county roadways compared to MDOT trunkline highways. The over-representation of deer crashes on county segments explains why the proportion of multiple-vehicle collisions on Michigan's two-lane county segments is so much lower than the default distributions in the *HSM*.

Table 12: Crash Severity and Crash Type Distributions for Rural Paved Federal Aid County Segments

Crash severity level	Count of midblock crashes (2011-2015)	Percentage of total midblock crashes
Fatal (Type K)	124	0.4%
Incapacitating injury (Type A)	432	1.5%
Non-incapacitating injury (Type B)	1,075	3.7%
Possible injury (Type C)	1,691	5.8%
Fatal + injury (Type K+ABC)	3,322	11.3%
Property damage only (Type PDO)	26,055	88.7%
Single motor vehicle	26,827	91.3%
Single motor vehicle (deer excluded)	8,387	28.5%
Deer crashes	18,515	63.0%
Multiple vehicle crashes	2,460	8.4%
Day crashes	10,131	34.5%
Dark crashes	19,246	65.5%
Total crashes (5 years)	**29,377**	**100.0%**

Collision type	Percentage of fatal and injury	Percentage of property damage only	Percentage of total segment crashes
Single-vehicle crashes			
Collision with animal	11.0%	69.7%	63.0%
Collision with bicycle	1.4%	0.0%	0.2%
Collision with pedestrian	1.1%	0.0%	0.1%
Overturned	19.9%	3.8%	5.6%
Other single-vehicle crash	45.2%	19.8%	22.7%
Total single-vehicle crash	78.7%	93.3%	91.6%
Multiple-vehicle crashes			
Angle collision	3.0%	0.9%	1.1%
Head-on collision	5.8%	0.4%	1.0%
Read-end collision	7.6%	2.2%	2.8%
Sideswipe collision	3.4%	2.1%	2.2%
Other multiple-vehicle collision	1.6%	1.1%	1.1%
Total multiple-vehicle collision	21.3%	6.7%	8.4%
Total Crashes	**100.0%**	**100.0%**	**100.0%**

Table 13: Crash Severity and Crash Type Distributions for Rural Paved Non-Federal Aid County Segments

Crash severity level	Count of midblock crashes (2011-2015)	Percentage of total midblock crashes
Fatal (Type K)	23	0.6%
Incapacitating injury (Type A)	51	1.4%
Non-incapacitating injury (Type B)	153	4.2%
Possible injury (Type C)	229	6.3%
Fatal + injury (Type K+ABC)	456	12.4%
Property damage only (Type PDO)	3,207	87.6%
Single motor vehicle	3,312	90.4%
Single motor vehicle (deer excluded)	1,051	28.7%
Deer crashes	2,274	62.1%
Multiple vehicle crashes	331	9.0%
Day crashes	1,184	32.3%
Dark crashes	2,479	67.7%
Total crashes (5 years)	**3,663**	**100.0%**

Collision type	Percentage of fatal and injury	Percentage of property damage only	Percentage of total segment crashes
Single-vehicle crashes			
Collision with animal	12.5%	69.1%	62.1%
Collision with bicycle	0.9%	0.0%	0.1%
Collision with pedestrian	3.3%	0.0%	0.4%
Overturned	14.0%	2.5%	3.9%
Other single-vehicle crash	54.2%	20.2%	24.4%
Total single-vehicle crash	84.9%	91.8%	91.0%
Multiple-vehicle crashes			
Angle collision	3.7%	1.3%	1.6%
Head-on collision	3.9%	0.4%	0.8%
Read-end collision	3.7%	2.2%	2.4%
Sideswipe collision	2.2%	2.5%	2.5%
Other multiple-vehicle collision	1.5%	1.7%	1.7%
Total multiple-vehicle collision	15.1%	8.2%	9.0%
Total Crashes	**100.0%**	**100.0%**	**100.0%**

Table 14: Crash Severity and Crash Type Distributions for Rural Unpaved Non-Federal Aid County Segments

Crash severity level	Count of midblock crashes (2011-2015)	Percentage of total midblock crashes
Fatal (Type K)	7	0.3%
Incapacitating injury (Type A)	58	2.8%
Non-incapacitating injury (Type B)	146	7.0%
Possible injury (Type C)	183	8.8%
Fatal + injury (Type K+ABC)	394	18.9%
Property damage only (Type PDO)	1,686	81.1%
Single motor vehicle	1,804	86.7%
Single motor vehicle (deer excluded)	1,063	51.1%
Deer crashes	745	35.8%
Multiple vehicle crashes	267	12.8%
Day crashes	927	44.6%
Dark crashes	1,153	55.4%
Total crashes (5 years)	**2,080**	**100.0%**

Collision type	Percentage of fatal and injury	Percentage of property damage only	Percentage of total segment crashes
Single-vehicle crashes			
Collision with animal	4.6%	43.1%	35.8%
Collision with bicycle	1.0%	0.1%	0.2%
Collision with pedestrian	1.0%	0.0%	0.2%
Overturned	24.4%	6.8%	10.1%
Other single-vehicle crash	59.4%	36.5%	40.8%
Total single-vehicle crash	90.4%	86.4%	87.2%
Multiple-vehicle crashes			
Angle collision	1.8%	3.2%	2.9%
Head-on collision	2.0%	1.4%	1.5%
Read-end collision	1.8%	2.1%	2.0%
Sideswipe collision	3.0%	5.1%	4.7%
Other multiple-vehicle collision	1.0%	1.8%	1.7%
Total multiple-vehicle collision	9.6%	13.6%	12.8%
Total Crashes	**100.0%**	**100.0%**	**100.0%**

4.2 Results and Discussion

The final model results for estimating non-deer crashes on county-owned rural two-lane, two-way roads on paved federal aid segments, paved non-federal aid segments, and unpaved non-federal aid segments are displayed in Table 15, Table 16, and Table 17, respectively. Coefficient estimates, standard errors, and p-values are provided in each table. Due to the small number of crashes at each location, models estimating crashes of all severity levels were developed rather than isolating specific crash types and severities. Unless otherwise noted, further discussion of crashes in this chapter should assume exclusion of deer crashes, which are modeled separately in Chapter 6.

4.2.1 Paved Federal Aid County Road Segments

The results of the mixed effects negative binomial models for federal aid county road segments, which are presented in Table 15, yielded several interesting results. Horizontal curvature was found to be a significant factor, and the parameter estimates were found to increase as the curve radius decreased, suggesting greater crash occurrence with decreasing curve design speeds. The effect was found to increase relatively consistently and monotonically with decreasing design speed. Note that the curve parameters were formulated to represent the "curved proportion of the segment." In order to isolate the effects of the curves, all subsequent discussion of the horizontal curve effects will consider the value of this variable to equal 1.0, indicating a fully curved segment. Horizontal curves with design speeds from 50-54.9 mph experienced approximately twice as many crashes than the baseline condition of no substandard horizontal curves along the segment. For curves with a design speed below 40 mph, the increase in crashes more than doubles again, with a 4.2 times increase in crashes relative to base condition. This is shown visually in Figure 9, which shows the expected annual frequency of crashes per mile for curves across the varying design speed categories, compared to the base condition. Note that base conditions were assumed for all other factors when generating these plots.

Table 15: Mixed Effects Negative Binomial Model Results for Paved Federal Aid Segments

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-5.932	0.003	0.152	<0.001
Segment length	Offset, natural log of, miles				
AADT	Natural log of, vehicles per day	0.681	1.976	0.020	<0.001
Horizontal curve design speed					
>55 mph	Baseline				
50-54.9 mph	Curved proportion of segment	0.724	2.063	0.137	<0.001
45-49.9 mph	Curved proportion of segment	1.097	2.995	0.149	<0.001
40-44.9 mph	Curved proportion of segment	0.999	2.715	0.225	<0.001
<40 mph	Curved proportion of segment	1.432	4.186	0.327	<0.001
10-ft lane	Baseline				
11-ft lane	Width in feet	0.016	1.016	0.041	0.701
12-ft lane	Width in feet	0.053	1.054	0.048	0.274
13-ft lane	Width in feet	0.131	1.140	0.088	0.139
0 to 1 ft shoulder	Baseline				
2-ft shoulder	Width in feet	-0.044	0.957	0.049	0.362
3 to 8 ft shoulder	Width in feet	0.045	1.046	0.037	0.215
0-to-4.9 driveways per mile	Baseline				
5-to-14.9 driveways per mile	Binary indicator variable	0.108	1.114	0.036	0.003
15-to-24.9 driveways per mile	Binary indicator variable	0.173	1.189	0.040	<0.001
≥25 driveways per mile	Binary indicator variable	0.267	1.306	0.043	<0.001
Site random effect				0.559	
County random effect				0.263	
Overdispersion parameter		0.044			
AIC		49,264.3			
Log likelihood		-24,615.2			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion; mph = miles per hour; ft = foot

As previously mentioned, when considering segments containing substandard horizontal curvature, 46 percent of the length of these segments, on average, does not consist of substandard curvature. Therefore, a separate analysis was conducted to determine if the extrapolations drawn from these results are valid. Only to types of segments were retained in this analysis: 1) segments which were entirely substandard within one particular design speed category; or 2) segments that entirely met standards. This was done in order to have a truly binary dataset with respect to horizontal curve design speed. Results are presented in Table 61 (Appendix D), and are comparable to the results presented in this chapter for curves with design speeds between 40-54.9 mph. However, there were not enough segments whose entire segment length had a design speed of <40 mph for significant results to be found within this category. Therefore, a second additional analysis was performed that included segments where the proportion of the segment containing a curve with a design speed of less than 40 mph ranged from 0.8 to 1.0. For these segments, zero to 20 percent of segment length consisted of roadway that was tangent or whose curvature met design standards; these segments did not contain horizontal curves with design speeds between 40-54.9 mph, as this would interfere with the binary status of those design speed categories. These results are presented in Table 62 (Appendix D) and are similar to those presented in this chapter.

Previous research on federal aid highways in Michigan showed that segments with presence of a curve with a design speed below 55 mph, as a binary factor, experienced 56 percent more total crashes and 54 percent more fatal and injury crashes than segments without such curves [18]. This corresponds well to the model results presented in this paper; when looking only at segments the contain substandard horizontal curvature, the average segment comprises, in terms of length, of 46 percent of the segment having no substandard curvature, 24 percent of the segment having a design speed between 50-54.9 mph, 17 percent between 45-49.9 mph, 9 percent between 40-44.9 mph, and 4 percent of the segment having a design speed below 40 mph. When calculating the crash effect of such curvature (using the model results presented in Table 15, the formula would be $\exp(0.24 * 0.724 + 0.17 * 1.097 + 0.09 * 0.999 + 0.04 * 1.432))$, it corresponds to a 66 percent increase in crashes. In Pennsylvania, a 43 percent increase in total crashes and a 48 percent increase in injury crashes was observed on 55 mph state highway segments that included a 55-mph curve on state-owned highways [19]. The research presented here builds upon prior research in that it includes a continuous variable for the curved proportion of the segment. This is important as the curve effects are parameterized based on the amount of curvature on the segment, rather than simply a binary indicator for curve presence.

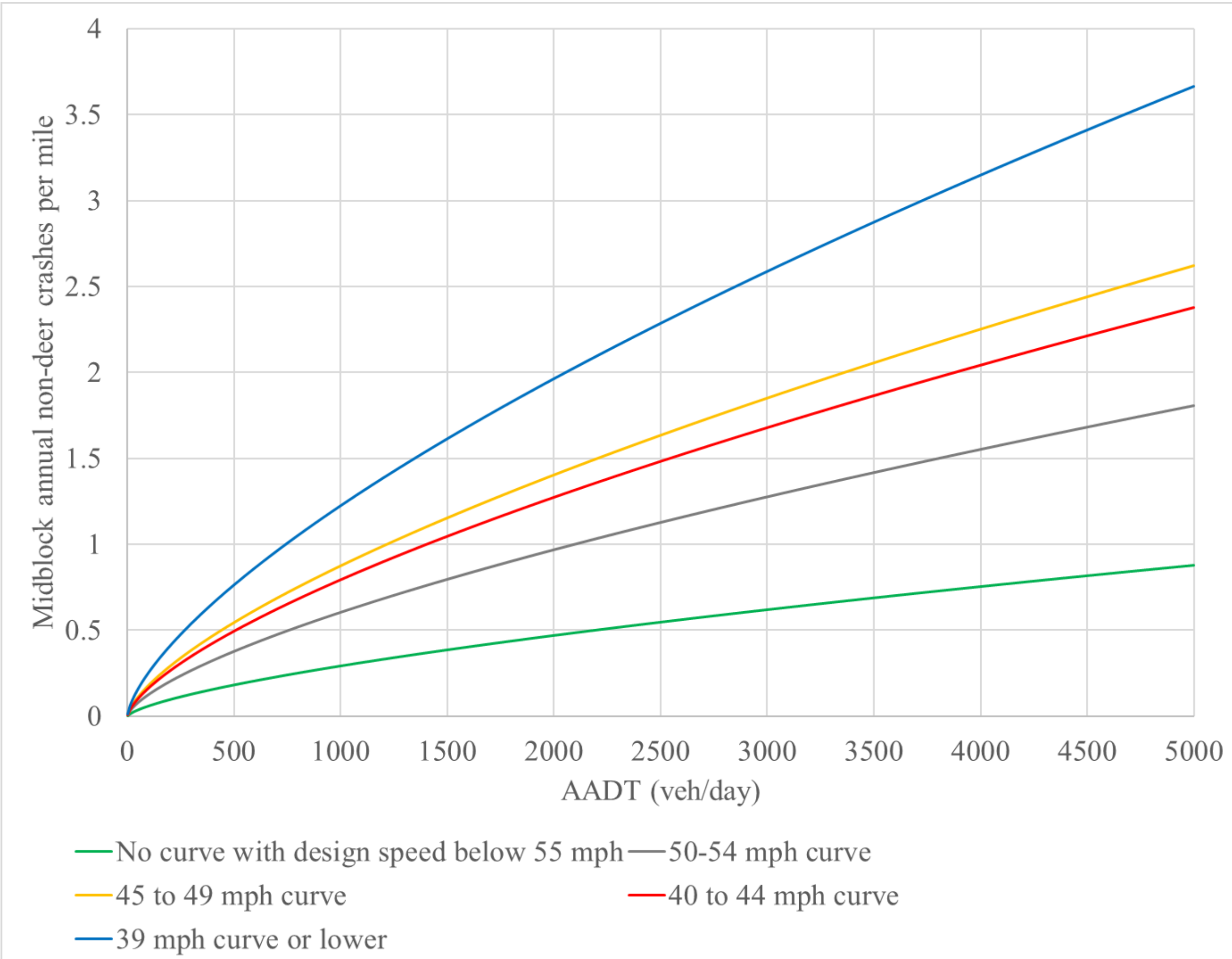


Figure 9: Comparison of SPF crash results on county federal-aid segments by curve design speed

Increasing driveway density was also associated with increasing crashes, which is not a surprising result, as increasing the number of driveways increases the number of conflict points. However, driveway density did not appear to increase crashes to the same extent as substandard horizontal curvature. Segments with 5 to 14.9 driveways per mile had approximately 11 percent more crashes than segments with fewer than five driveways per mile, while segments with 25 or more driveways per mile saw nearly 31 percent more crashes. Prior research has also found total crashes to increase with increasing driveway density on rural two-lane two-way roads [116].

Lane width did not have a significant effect on total crashes, although preliminary fixed effects models showed reduced crashes associated with wider lanes. Fixed effects models can be found in Appendix A. Those findings correspond somewhat with previous research associating wider lanes with fewer non-incapacitating injury and PDO crashes (BCO crashes) [56] and fewer total crashes [3, 52]. As previously shown in the data diagnostics section, lane width and AADT were found to be correlated with each other, which likely confounds the results of these models.

Similar to lane width, shoulder width was not found to be a significant factor. Although the body of research has consistently found that wider shoulders result in fewer crashes [3, 19, 52, 56], the findings of this analysis are likely confounded by the correlation between shoulder width and AADT, particularly, the fact that design standards are determined by a road's AADT. Furthermore, as a roadside assessment was not conducted, the impacts of roadside characteristics could not be determined. The effect of roadside characteristics presents another potential confounding variable with shoulder width, with regards to the effect of fixed object crashes, whereby both shoulder width and roadside conditions will affect the ability of drivers to correct course to avoid collision, as well as visibility at driveways.

Model fit can be evaluated in many ways, two of which are log likelihood and Akaike information criterion (AIC). Log likelihood is the natural logarithm of the maximum likelihood function, and is a measure of how closely data fit to the developed model. A model's log likelihood is a summation of the log likelihood of individual observations. The equation for calculating log likelihood (LL) can be found below in Equation 10 [117]:

$$LL = -\frac{n}{2}\ln(2\pi) - \frac{n}{2}\ln(\sigma^2) - \frac{1}{2\sigma^2}(Y - X\beta)^T(Y - X\beta) \tag{10}$$

Where, n is the number of observations, σ^2 represents the variance of a disturbance term, Y is the dependent variable (i.e., crash occurrence), and $X\beta$ represents a matrix of the dependent variables. Log likelihood is a useful measure for comparing the goodness-of-fit for models using the same dataset, rather than comparing models with different datasets. Log likelihood values are negative and better-fitting models are closer to zero.

AIC is directly related to log likelihood. The equation for calculating AIC is shown as Equation 11:

$$AIC = 2Q - 2LL(\theta) \qquad (11)$$

where Q is the number of parameters and $LL(\theta)$ is the log-likelihood at convergence [117]. Similar to log likelihood, values of AIC closer to zero indicate a better fit, although, unlike log likelihood, the values of AIC are positive. As indicated in the equation, AIC penalizes the use of a large number of parameters. When comparing the mixed effects model in Table 15 with the fixed effects model in Table 52 (Appendix A), it can be seen that both AIC and log likelihood are improved in the mixed effects model, with values being closer to zero. Compared to the fixed effects model, the mixed effects model provides more conservative estimates regarding the crash effect of parameters. The standard deviations of the site- and county-specific random effects indicate that there is more variation between sites in general than there is variation in sites between counties.

In addition, the overdispersion parameter for the mixed effects model is lower than on the fixed effects model; this means that when applying these models using the predictive method outlined in the *HSM*, the expected number of crashes at any given location will be influenced more by the model parameters than with the fixed effects model. It is worth noting that, due to the rare and random nature of crashes, there are variations from year-to-year in crash occurrence at any given site. A manual review of the highest crash sites found that, while on average, they experience high crash frequency from year-to-year, but often experience a year or two with few-to-no crashes. Care should be taken when applying models to particularly high-crash sites, as models may under-predict crashes in these locations.

4.2.2 Paved Non-Federal Aid County Road Segments

Paved non-federal aid segments, displayed in Table 16, showed somewhat similar model results to those of federal aid segments. While horizontal curves with design speeds from 45 to 54 mph did not perform significantly different from base conditions, curves with design speeds from 40-44 mph experienced 2.6 times more crashes than base conditions when the curve occupied the entire segment, and curves with design speeds below 40 mph occupying an entire segment. experienced 4.2 times more crashes than base conditions, which is comparable to federal aid segment performance. This is shown in Figure 10, where curves of varying design speeds are compared, with the assumption that the curve occupies the entire segment, and all other base conditions prevail. Curves with design speeds between 45 and 49 mph and between 50 and 54 mph were not found to be statistically significant, but are shown on the figure. While not statistically significant from base conditions, curves with design speeds of 45-49 mph and curves with design speeds of 50-54 mph show slightly higher crash frequency from base conditions; due to the similar relative risk that these two categories have (1.308 for 50-54.9 mph and 1.310 for 45-49.9 mph) they appear as a single line on the chart.

Also similar to federal aid roadways, the effects of lane width and paved shoulder width was not significant. This is somewhat surprising, as increases in surface width are typically associated with reductions in crashes for reasons previously discussed. However, given that approximately 81 percent of the included paved non-federal aid segments were classified as local roads, driver familiarity and travel behavior will likely be much different than for arterials, which have provided the basis for the majority of prior research on the safety effects of shoulders, including the *HSM* SPFs. Furthermore, as was the case on federal aid segments, shoulder width and AADT are positively correlated.

The body of research is unclear on the effect of lane width on safety [19, 56]. It is difficult to untangle the effect of lane width and roadside characteristics on driver speed, particularly on rural, low-volume roads. There are other potential confounds; it is possible that the safety benefit associated with wider lanes (i.e., more space to correct course) could be counteracted by the safety detriment caused by faster operating speeds associated with wider lanes.

Driveway densities of 25 driveways per mile or greater were associated with a 37 percent increase in crashes – larger than the 31 percent increase found on federal aid roads. It is unclear why the effect is greater on non-federal aid highways; one potential reason could be reduced visibility.

Similar to on federal aid segments, the diagnostic parameters (i.e., AIC and log likelihood) in the mixed effects model (Table 16) show a better fit than the corresponding fixed effects model, located in Appendix A (Table 53), as well as a lower overdispersion parameter.

Table 16: Mixed Effects Negative Binomial Model Results for Paved Non-Federal Aid Segments

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-6.848	0.001	0.310	<0.001
Segment length	Offset, natural log of, miles				
AADT	Natural log of, vehicles per day	0.800	2.225	0.047	<0.001
Horizontal curve design speed					
>55 mph	Baseline				
50-54.9 mph	Curved proportion of segment	0.269	1.308	0.431	0.533
45-49.9 mph	Curved proportion of segment	0.270	1.310	0.568	0.635
40-44.9 mph	Curved proportion of segment	0.944	2.570	0.446	0.034
<40 mph	Curved proportion of segment	1.440	4.220	0.664	0.030
11-ft lane	Baseline				
12- or 13-ft lane	Width in feet	-0.067	0.935	0.110	0.544
9- or 10-ft lane	Width in feet	0.043	1.044	0.069	0.539
0-ft shoulder	Baseline				
1-ft shoulder	Width in feet	0.059	1.061	0.088	0.500
2-ft shoulder or wider	Width in feet	0.093	1.098	0.165	0.572
0-to-4.9 driveways per mile	Baseline				
5-to-14.9 driveways per mile	Binary indicator variable	0.096	1.101	0.111	0.384
15-to-24.9 driveways per mile	Binary indicator variable	0.072	1.075	0.115	0.532
≥25 driveways per mile	Binary indicator variable	0.313	1.367	0.116	0.007
Site random effect				0.638	
County random effect				<0.001	
Overdispersion parameter		0.022			
AIC		8,418.4			
Log likelihood		-4,193.2			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion; mph = miles per hour; ft = foot

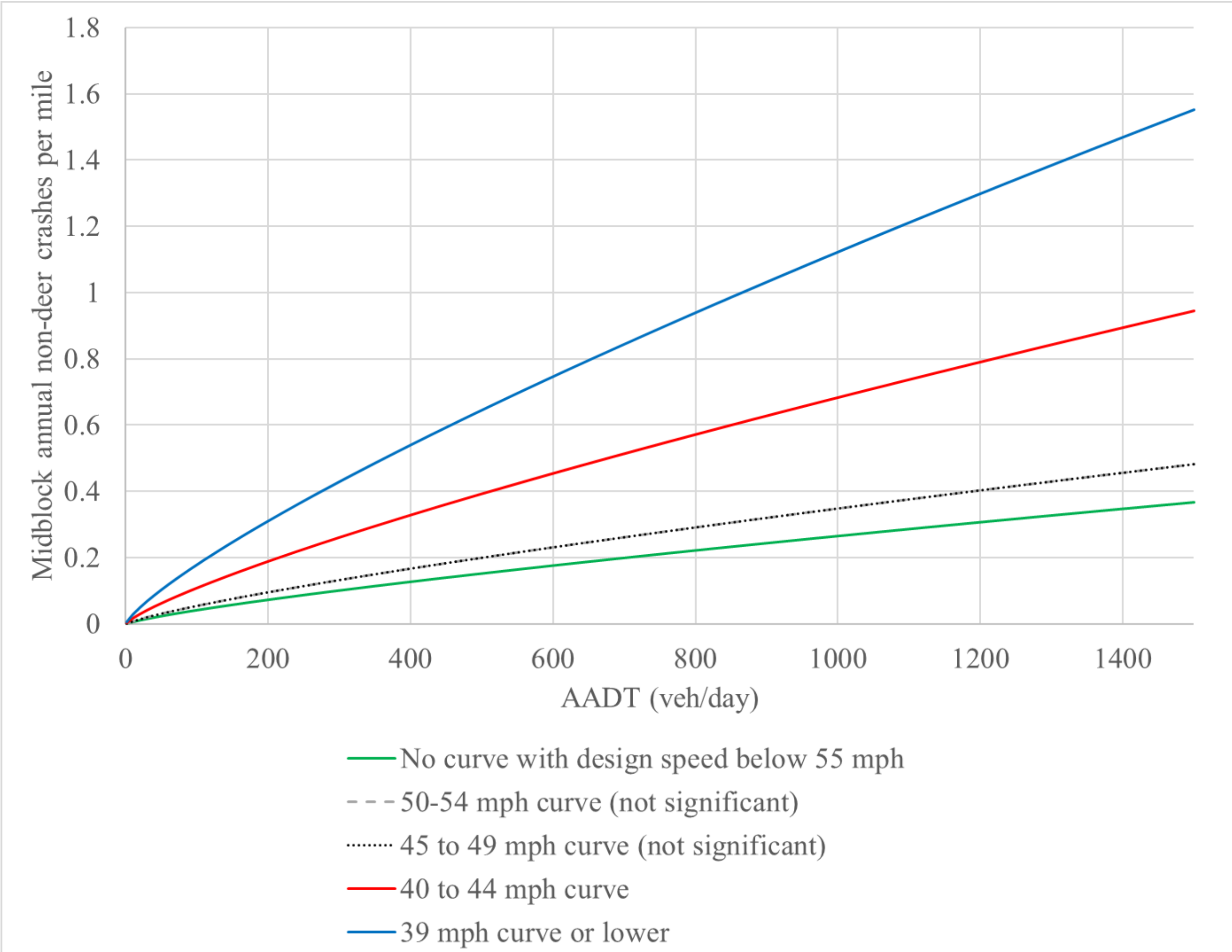


Figure 10: Comparison of SPF crash results on paved county non-federal aid segments by curve design speed

4.2.3 Unpaved Non-Federal Aid Segments

Unpaved non-federal aid segments, displayed in Table 17, showed somewhat different model results compared to those for the other segment types. While horizontal curves with design speeds below 55 mph did show increases in crashes, the relationship was not in the same manner as on paved roads (i.e., a clear pattern of ascending crash frequency with descending curve design speed). This is not unexpected, as the "free-flow" speed, i.e., the speed at which drivers feel comfortable traveling in the absence of traffic or weather conditions, is often below 55 mph on unpaved roads for a variety of reasons, including surface quality and visibility. Curves with design speeds below 55 mph showed a clear increase in crashes relative to base conditions, but in terms of the four categories of substandard horizontal curvature, they did not experience significantly different results from each other. The effects of the various design speed categories of horizontal curvature are shown in Figure 11, where it was assumed the curve occupied the whole length of the segment and all other base conditions prevailed.

Similar to other models, surface width was not found to be a significant factor. The model diagnostics (i.e., AIC and log likelihood) show that the mixed effects model below in Table 17 has a better fit than the fixed effects model located in Appendix A (Table 54).

Table 17: Mixed Effects Negative Binomial Model Results for Unpaved Non-Federal Aid Segments

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-5.781	0.003	0.668	<0.001
Segment length	Offset, natural log of, miles				
AADT	Natural log of, vehicles per day	0.608	1.836	0.051	<0.001
Horizontal curve design speed					
>55 mph	Baseline				
50-54.9 mph	Curved proportion of segment	1.715	5.556	0.367	<0.001
45-49.9 mph	Curved proportion of segment	1.384	3.992	0.311	<0.001
40-44.9 mph	Curved proportion of segment	1.270	3.561	0.382	0.001
<40 mph	Curved proportion of segment	1.283	3.606	0.335	<0.001
Surface width	Width in feet, natural log of	0.080	1.083	0.235	0.733
0-to-4.9 driveways per mile	Baseline				
5-to-14.9 driveways per mile	Binary indicator variable	0.156	1.169	0.086	0.070
15-to-24.9 driveways per mile	Binary indicator variable	0.009	1.009	0.098	0.929
≥25 driveways per mile	Binary indicator variable	0.163	1.177	0.108	0.130
County random effect				0.753	
Overdispersion parameter		0.025			
AIC		8,944.5			
Log likelihood		-4,460.2			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion; mph = miles per hour; ft = foot

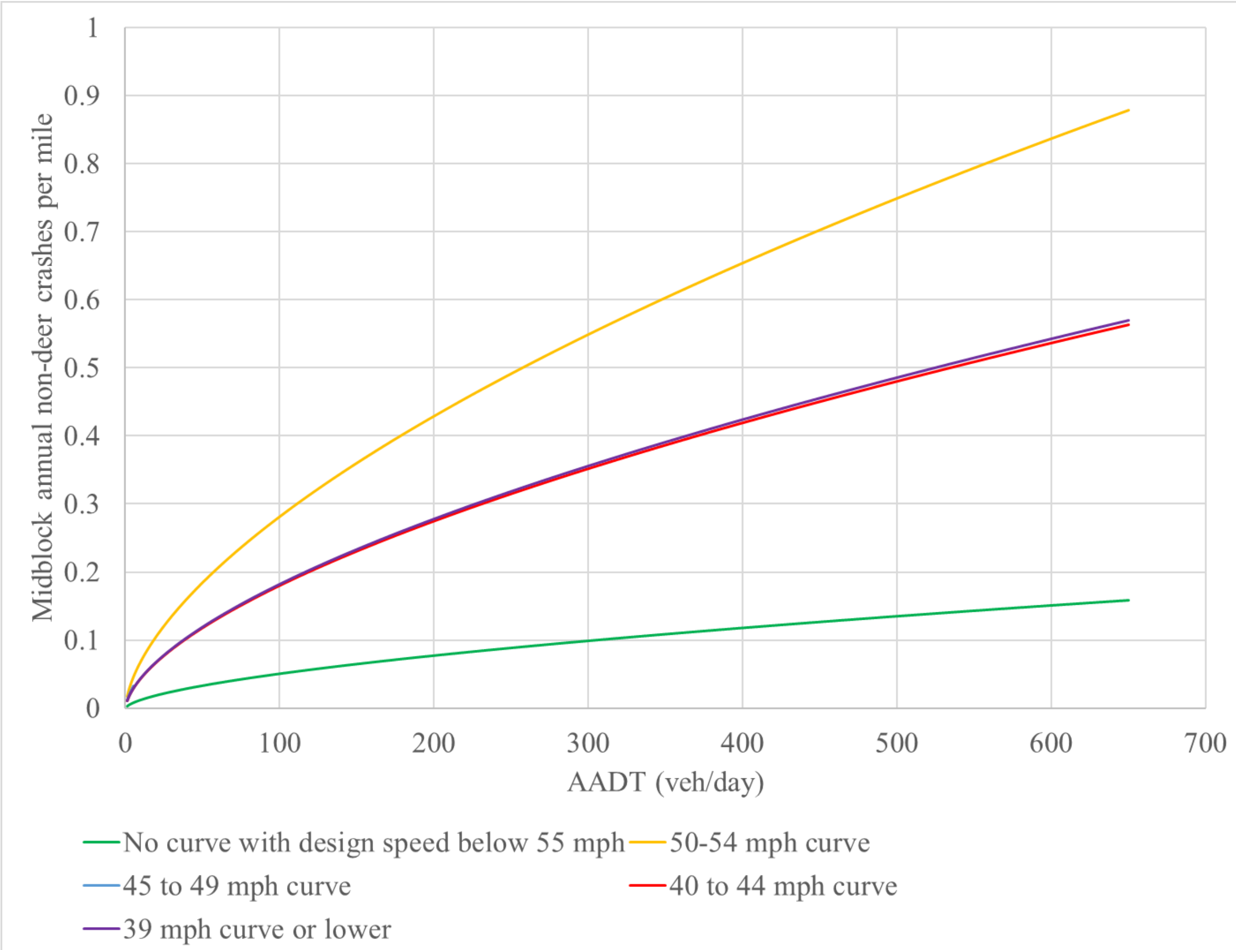


Figure 11: Comparison of SPF crash results on unpaved county non-federal aid segments by curve design speed

4.2.4 Crash Modification Factors for Rural County Segments

From these results, a set of CMFs were developed for horizontal curvature and driveway density within each funding and pavement surface condition, and these are shown in Table 18. These CMFs are the reciprocal of the Exp(B) values, or relative risk, in the results tables. The values in the results tables describe the effect of these site characteristics when deviating from base conditions, but the reciprocal is taken to determine the opposite effect (i.e., returning to base conditions).

Table 18: CMFs Developed for Rural County Segments

Original condition	CMFs			
	County FA	County non-FA	Unpaved	Remarks
Design speed 50-54.9 mph	0.48	ns	0.18	Final condition: design speed ≥55 mph
Design speed 45-49.9 mph	0.33	ns	0.25	
Design speed 40-44.9 mph	0.37	0.39	0.28	
Design speed <40 mph	0.24	0.24	0.28	
5-to-14.9 driveways per mile	0.92	ns	ns	Final condition: <5 driveways per mile
15-to-24.9 driveways per mile	0.86	ns	ns	
25 driveways per mile or greater	0.80	0.76	ns	

Note: ns = Not significant

4.2.5 Comparison to MDOT and Calibrated HSM SPFs

Comparisons were also made between the three county road SPFs presented in this document and those previously developed for state-owned rural two-lane highways in Michigan [16]. In addition, a comparison with the *HSM* is included. The *HSM* model presented is calibrated for each class of roadway; a discussion of the method for calibrating *HSM* models for county-owned roadways can be found in Chapters 2 and 3. Deer crashes were not included in the state-owned models, nor were they included in the *HSM* calibration; this is because, as previously noted, deer crashes were not included in the models developed for county roadways presented in this chapter. The calibration factor calculated for county federal aid roadways was 0.79, for county non-federal aid the calibration factor was 0.87, and for unpaved the value was calculated to be 1.81.

Calibrated models were evaluated for goodness-of-fit using mean absolute deviation (MAD), which is a measure of how calculated values relate with the mean value of the original dataset. The equation for calculating MAD is shown in Equation 12 below, as presented in [117]:

$$MAD = \frac{1}{n}\sum_{i=1}^{n} |N_{observed} - N_{predicted}|$$

Where, n = the number of observations, i represents an individual observation, $N_{observed}$ = the number of crashes observed, and $N_{predicted}$ = the number of crashes observed in a given model.

On paved segments, calibrated models performed well compared to Michigan-specific models when evaluating using MAD. On paved federal aid roads, the model presented in this chapter had an MAD value of 0.34 while the calibrated model had a value of 0.31. On paved non-federal aid roads, both the model presented in this chapter, as well as the calibrated model, had a MAD value of 0.17. For unpaved roads, the model in this chapter had an MAD value of 0.096, while the calibrated model had a value of 0.12.

MAD is useful to understanding how models compare with the dataset used to develop the models in the aggregate. However, in comparing models, it is also useful to compare plots of model results to determine how model shape differs. Figure 12 makes the need for county-specific, rather than calibrated, models clear; the *HSM* model, calibrated for county federal aid highways in Michigan, is a linear model, and underpredicts crashes below AADTs of approximately 3,800 and overpredicts when volumes are higher. Because the calibrated models are based on the summation of all crashes within the dataset, they are susceptible to bias from outlier sites.

All models were set at the same base conditions, which included 12-foot lanes (or equivalent total surface width), 6-foot shoulders, no driveways, and no substandard horizontal curves. Each SPF was then plotted as a function of AADT within the general range of traffic volumes. It can be seen that the shape of each curve is different, and that the elasticity of the AADT parameter affects the shape. For instance, below AADTs of approximately 80, gravel roads have the highest crash occurrence, but over 80 vehicles per day, paved federal aid has the highest crash frequency. The *HSM* calibrated models are linear, and do not take into account the differences in elasticity with respect to AADT that can be found in the Michigan-specific models.

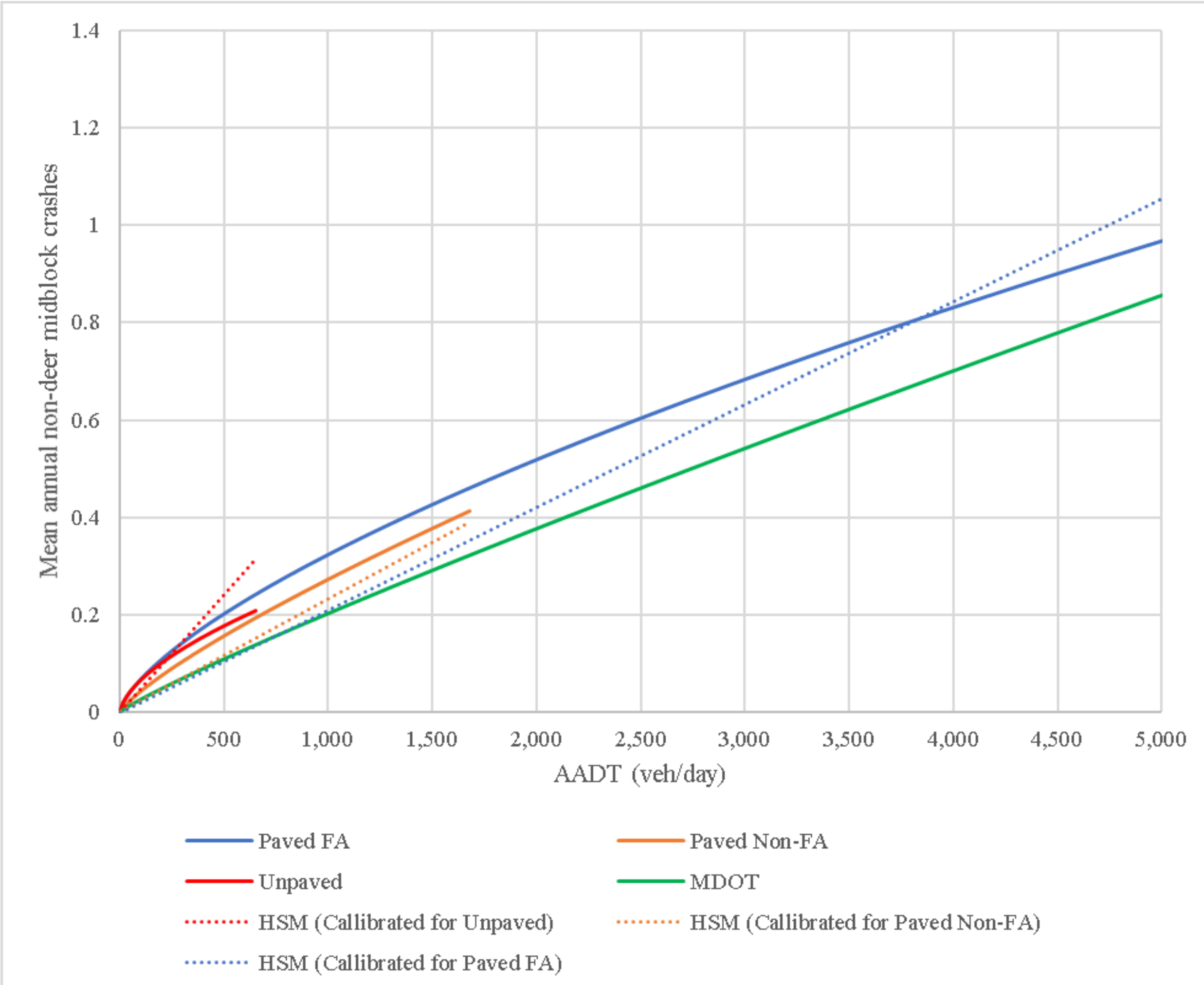


Figure 12: Comparison of SPF total crash results at base conditions

4.3 Summary and Conclusions

The safety performance of county or local roadways is rarely investigated to the same level of detail as state highways. However, several states, including Michigan, possess a substantial network of rural county highways. While SPFs exist within the *HSM* and other resources, in Michigan and elsewhere, county-owned highways typically possess characteristics that differ considerably from those under the jurisdiction of the state DOT. This limits the usefulness of SPFs generated based on state-owned rural highways, including those developed by MDOT or found within the *HSM*. Furthermore, the SPFs contained in the *HSM* are only applicable to paved roads, which limits application for county and local road agencies for whom unpaved roads may be a substantial portion of their network. Another concern that arises is the differences in design and maintenance standards between counties; however, in all models, the standard deviation of the random effect for site was greater than the random effect for county, indicating that there is greater variation between sites in general than there is between counties.

Since greater than one-half of rural crashes in Michigan occur off of the state highway system, there is a clear need for additional guidance on how to better design county roadways for safety, given the different design and user characteristics compared to rural state highways. To that end, research was undertaken to SPFs unique to county highways. To accomplish this objective, county highway inventory data from 30 counties across Michigan were obtained and paired with traffic crashes from 2011-2015. Separate SPFs were then generated for paved county federal aid roadways, paved county non-federal aid roadways, and unpaved non-federal aid highways.

Not surprisingly, the county SPF results were generally different than would be expected on state-owned facilities. County paved federal aid roadways showed a higher crash occurrence rate than county paved non-federal aid, the calibrated *HSM* model for county federal roadways (at volumes below 3,800 vehicles per day), and MDOT highways. However, lane width, roadway surface width, and paved shoulder width had little to no impact on crashes across each of the three county roadway models. Increasing driveway density was found to be associated with increased crash occurrence, although these results were only significant for crashes on paved county roadways.

The most consistent roadway geometry related results were associated with the presence of curves with a design speed at or below 55 mph. This relationship was most clear on county federal aid segments, with lower curve radii associated with higher crash frequencies. On paved federal aid and unpaved non-federal aid highways, curves with substandard design speeds (i.e., less than 55 mph) resulted in higher crash frequency than base conditions, while on paved non-federal aid highways, only curves with design speeds below 45 mph performed significantly different from base conditions.

The results of this research can be utilized towards various safety programs within Michigan and beyond. This includes performing network screening and crash prediction estimates to support local agency safety programs, in addition to providing similar support for the High Risk Rural Roads program.

5. SAFETY PERFORMANCE FUNCTIONS FOR RURAL MINOR ROAD STOP CONTROLLED INTERSECTIONS

Rural two-way two-lane intersections were analyzed on county-owned roads in Michigan. Both three-leg (3ST) and four-leg (4ST) minor road stop-controlled intersections were analyzed, and intersections where the major road was state-owned, county federal aid, and county non-federal aid were included. Intersections with state-owned highways were included only if the minor cross-road was a county road. This was deemed important in order to fully capture the safety performance impacts of stop-controlled intersections that included county roadways. However, it is important to note that when the major road was under state jurisdiction, the entire intersection was under the jurisdiction of MDOT rather than the county road commission, and subject to different design standards. In order to account for this, separate models were developed for each jurisdictional class. The sections that follow will include a data summary, an explanation of the analytical method, and results and discussion.

5.1 Data Summary, Data Screening, and Data Diagnostics

The subsections below summarize the descriptive statistics for 3ST and 4ST intersections with stop control on the minor roadway. 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 5,659 rural stop-controlled intersections, of which there were slightly more 4ST intersections than 3ST. All 83 counties in Michigan were represented. The focus of this analysis was the evaluation of intersections with county-owned highways; sites where the uncontrolled road is under MDOT's jurisdiction were included because they intersect with county highways, which are stop-controlled.

5.1.1 Rural Four Leg Stop-Controlled Intersections (4ST)

Table 19 displays the number intersections from each county, by each of the three funding and jurisdictional classes. Considering intersections where the major road is under MDOT jurisdiction, 81 of Michigan's 83 counties were represented, for intersections where the major road was county federal aid, 82 counties were included, and 16 counties had at least one major road non-federal aid intersection included in the sample. The small sample of counties for non-federal aid roadways was due to the limited availability of traffic volume data for these roadways and gave further impetus to development of models based on major road jurisdictional classification A map of the location of the 4ST intersections included is displayed in Figure 13.

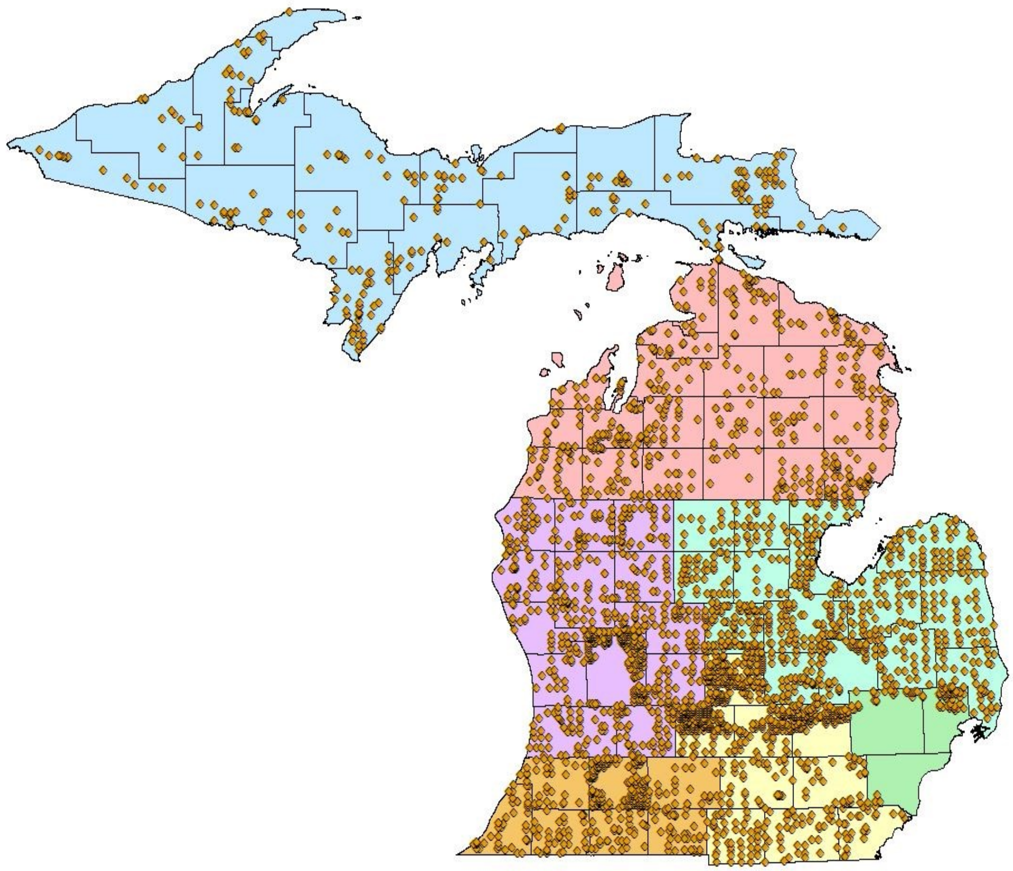


Figure 13: Map of rural four leg stop-controlled (4ST) intersections

Table 20 provides summary statistics (i.e., mean, minimum, maximum, standard deviation) for all relevant variables of interest considered during 4ST SPF development. Table 21 shows the same information for intersections whose major road is under MDOT jurisdiction, Table 22 for county federal aid, and Table 23 for county non-federal aid. Approximately 57 percent of intersections were county federal aid, 33 percent were under MDOT jurisdiction, and county non-federal aid jurisdiction made up the remainder. Approximately 42 percent of intersections had street lighting present. Driveway within 211 feet (0.04 miles) of 4ST intersections were relatively sparse, with a mean of 2.7 per intersection, which is indicative of the fact that only rural areas were included in the sample. The majority of crashes (73 percent) were property damage only. Forty-five percent of intersections experienced at least one crash of any kind, while 38 percent of intersections experienced at least one non-deer related crash during the 5-year analysis period.

The mean skew angle for the entire sample was 5.7 degrees. The skew data was also categorized into a series of binary variables for analytical purposes, as follows: 0 degrees, 1 to 9 degrees, 10 to 39 degrees, greater than or equal to 40 degrees. These categorization ranges were formulated based on the similarity of parameter estimates obtained from preliminary modeling efforts. Categorization of the skew variable in this manner allowed for improved model fit. A histogram showing the frequency of various skew angle categories can be seen in Figure 14, which shows that the vast majority of intersections have a skew angle less than five degrees, and very few intersections have skew angles of 40 degrees or more.

Table 19: Represented Counties and Intersection Count by Major Roadway Class (Four-Leg Intersections)

County	Number of sites (major road)				County	Number of sites (major road)			
	State	County FA	County non-FA	Total		State	County FA	County non-FA	Total
Alcona	7	13	0	20	Lake	15	21	0	36
Alger	15	2	0	17	Lapeer	13	27	0	40
Allegan	18	39	0	57	Leelanau	11	4	0	15
Alpena	8	13	0	21	Lenawee	20	19	1	40
Antrim	8	10	0	18	Livingston	1	54	49	104
Arenac	10	16	0	26	Luce	9	2	0	11
Baraga	8	3	0	11	Mackinac	13	5	0	18
Barry	24	23	0	47	Macomb	1	31	8	40
Bay	7	36	0	43	Manistee	15	13	0	28
Benzie	8	7	0	15	Marquette	11	3	0	14
Berrien	18	25	0	43	Mason	8	22	0	30
Branch	5	32	0	37	Mecosta	16	14	0	30
Calhoun	15	14	1	30	Menominee	20	23	0	43
Cass	22	16	0	38	Midland	3	14	0	17
Charlevoix	10	6	0	16	Missaukee	9	11	0	20
Cheboygan	12	21	0	33	Monroe	6	22	0	28
Chippewa	20	23	0	43	Montcalm	23	33	0	56
Clare	8	8	0	16	Montmorency	7	6	0	13
Clinton	19	97	37	153	Muskegon	6	25	0	31
Crawford	6	11	0	17	Newaygo	25	30	0	55
Delta	10	5	0	15	Oakland	0	18	8	26
Dickinson	6	1	0	7	Oceana	13	19	0	32
Eaton	32	68	58	158	Ogemaw	11	11	0	22
Emmet	7	10	0	17	Ontonagon	8	1	0	9
Genesee	13	34	6	53	Osceola	17	24	0	41
Gladwin	12	15	0	27	Oscoda	9	8	0	17
Gogebic	10	2	0	12	Otsego	3	7	0	10
Grand Traverse	19	22	9	50	Ottawa	2	20	0	22
Gratiot	32	44	15	91	Presque Isle	17	9	0	26
Hillsdale	25	26	0	51	Roscommon	2	5	0	7
Houghton	6	9	0	15	Saginaw	22	47	0	69
Huron	25	29	1	55	St. Clair	6	31	0	37
Ingham	12	49	12	73	St. Joseph	17	16	0	33
Ionia	10	27	0	37	Sanilac	27	27	0	54
Iosco	14	23	12	49	Schoolcraft	9	3	0	12
Iron	15	2	0	17	Shiawassee	11	38	0	49
Isabella	3	38	0	41	Tuscola	24	27	0	51
Jackson	10	23	1	34	Van Buren	17	16	0	33
Kalamazoo	4	84	51	139	Washtenaw	6	29	0	35
Kalkaska	15	13	0	28	Wayne	0	3	0	3
Kent	27	88	51	166	Wexford	17	10	0	27
Keweenaw	3	0	0	3	TOTAL	1,028	1,775	3,20	3,123

Table 20: Descriptive Statistics for Rural 4ST Intersections (All)

Variable	N (sites)	Min	25th%	50th%	75th%	Max	Mean	Std dev
AADT-major roadway	3,123	57	1,064	2,251	3,824	21,414	3,049.3	2,691.4
AADT-minor roadway	3,123	2	288	638	1,090	10,009	981.2	1,056.5
Lighting provided	1,305	n/a	n/a	n/a	n/a	n/a	0.418	0.493
Overhead beacon provided	468	n/a	n/a	n/a	n/a	n/a	0.150	0.357
Skew angle	3,123	0.0	0.0	0.0	0.0	79.3	5.663	12.500
Skew 0 degrees	2,408	n/a	n/a	n/a	n/a	n/a	0.771	0.420
Skew 1 to 9 degrees	121	n/a	n/a	n/a	n/a	n/a	0.039	0.193
Skew 10 to 39 degrees	475	n/a	n/a	n/a	n/a	n/a	0.152	0.359
Skew $\geq$40 degrees	119	n/a	n/a	n/a	n/a	n/a	0.038	0.191
Number of through lanes (major)	3,123	1	1	1	1	2	1.031	0.174
Number of through lanes (minor)	3,123	0	1	1	1	2	1.002	0.047
Number of right turn lanes	3,123	0	0	0	0	4	0.192	0.609
Number of left turn lanes	3,123	0	0	0	0	4	0.214	0.744
Railroad crossing within 211 feet of intersection	49	n/a	n/a	n/a	n/a	n/a	0.016	0.124
Driveway count	3,123	0	1	2	3	18	2.683	2.950
MDOT major roadway	1,028	n/a	n/a	n/a	n/a	n/a	0.329	0.470
County FA major roadway	1,775	n/a	n/a	n/a	n/a	n/a	0.568	0.495
County non-FA major roadway	320	n/a	n/a	n/a	n/a	n/a	0.102	0.303
Variable	**Five-year crash count**	**Annual crashes per intersection**						
		Min	**25th%**	**50th%**	**75th%**	**Max**	**Mean**	**Std dev**
Midblock total crashes	12,898	0	0	0	1	13	0.826	1.267
Midblock total non-deer crashes	10,671	0	0	0	1	13	0.683	1.184
Midblock fatal and injury non-deer crashes	3,585	0	0	0	0	6	0.230	0.565
Midblock property damage only non-deer crashes	9,313	0	0	0	1	11	0.596	0.993

Note: n/a = not applicable; std dev = standard deviation; min = minimum; max = maximum; N = number of

Table 21: Descriptive Statistics for Rural 4ST Intersections (Major Road MDOT)

Variable	N (sites)	Min	25th%	50th%	75th%	Max	Mean	Std dev
AADT-major roadway	1,028	431	2,844	4,400	5,872	21,414	4,990.7	3,107.9
AADT-minor roadway	1,028	2	441	898	1,445	9,914	1,258.9	1,212.0
Lighting provided	622	n/a	n/a	n/a	n/a	n/a	0.605	0.489
Overhead beacon provided	221	n/a	n/a	n/a	n/a	n/a	0.215	0.411
Skew angle	1,028	0.0	0.0	0.0	8.7	75.4	8.902	15.128
Skew 0 degrees	678	n/a	n/a	n/a	n/a	n/a	0.660	0.474
Skew 1 to 9 degrees	52	n/a	n/a	n/a	n/a	n/a	0.051	0.219
Skew 10 to 39 degrees	224	n/a	n/a	n/a	n/a	n/a	0.218	0.413
Skew ≥40 degrees	74	n/a	n/a	n/a	n/a	n/a	0.072	0.258
Number of through lanes (major)	1,028	1	1	1	1	2	1.077	0.266
Number of through lanes (minor)	1,028	1	1	1	1	2	1.001	0.031
Number of right turn lanes	1,028	0	0	0	0	4	0.483	0.895
Number of left turn lanes	1,028	0	0	0	0	4	0.470	1.006
Railroad crossing within 211 feet of intersection	26	n/a	n/a	n/a	n/a	n/a	0.025	0.157
Driveway count	1,028	0	1	2	4	17	3.207	3.446
Variable	**Five-year crash count**	**Annual crashes per intersection**						
		Min	**25th%**	**50th%**	**75th%**	**Max**	**Mean**	**Std dev**
Midblock total crashes	6,228	0	0	1	2	13	1.212	1.543
Midblock total non-deer crashes	5,139	0	0	0	1	13	1.000	1.461
Midblock fatal and injury non-deer crashes	1,614	0	0	0	0	6	0.314	0.669
Midblock property damage only non-deer crashes	4,614	0	0	1	1	11	0.898	1.222

Note: n/a = not applicable; std dev = standard deviation; min = minimum; max = maximum; N = number of

Table 22: Descriptive Statistics for Rural 4ST Intersections (Major Road County FA)

Variable	N (sites)	Min	25th%	50th%	75th%	Max	Mean	Std dev
AADT-major roadway	1,775	68	1,013	1,815	2,756	12,191	2,360.5	1,837.3
AADT-minor roadway	1,775	10	336	632	1,054	10,009	949.4	981.3
Lighting provided	662	n/a	n/a	n/a	n/a	n/a	0.373	0.484
Overhead beacon provided	244	n/a	n/a	n/a	n/a	n/a	0.137	0.344
Skew angle	1,775	0.0	0.0	0.0	0.0	79.3	4.358	10.965
Skew 0 degrees	1,444	n/a	n/a	n/a	n/a	n/a	0.814	0.390
Skew 1 to 9 degrees	62	n/a	n/a	n/a	n/a	n/a	0.035	0.184
Skew 10 to 39 degrees	226	n/a	n/a	n/a	n/a	n/a	0.127	0.333
Skew ≥40 degrees	43	n/a	n/a	n/a	n/a	n/a	0.024	0.154
Number of through lanes (major)	1,775	1	1	1	1	2	1.011	0.103
Number of through lanes (minor)	1,775	0	1	1	1	2	1.002	0.058
Number of right turn lanes	1,775	0	0	0	0	4	0.059	0.339
Number of left turn lanes	1,775	0	0	0	0	4	0.103	0.572
Railroad crossing within 211 feet of intersection	22	n/a	n/a	n/a	n/a	n/a	0.012	0.111
Driveway count	1,775	0	1	2	3	18	2.596	2.760
Variable	**Five-year crash count**	**Annual crashes per intersection**						
		Min	**25th%**	**50th%**	**75th%**	**Max**	**Mean**	**Std dev**
Midblock total crashes	6,357	0	0	0	1	10	0.716	1.112
Midblock total non-deer crashes	5,287	0	0	0	1	10	0.596	1.040
Midblock fatal and injury non-deer crashes	1,883	0	0	0	0	6	0.212	0.532
Midblock property damage only non-deer crashes	4,474	0	0	0	1	8	0.504	0.861

Note: n/a = not applicable; std dev = standard deviation; min = minimum; max = maximum; N = number of

Table 23: Descriptive Statistics for Rural 4ST Intersections (Major Road County Non-FA)

Variable	N (sites)	Min	25th%	50th%	75th%	Max	Mean	Std dev
AADT-major roadway	320	57	230	438	756	5,255	633.2	604.3
AADT-minor roadway	320	18	98	180	271	2,030	265.2	262.7
Lighting provided	21	n/a	n/a	n/a	n/a	n/a	0.066	0.248
Overhead beacon provided	3	n/a	n/a	n/a	n/a	n/a	0.009	0.096
Skew angle	320	0.0	0.0	0.0	0.0	55.0	2.491	8.351
Skew 0 degrees	286	n/a	n/a	n/a	n/a	n/a	0.894	0.308
Skew 1 to 9 degrees	7	n/a	n/a	n/a	n/a	n/a	0.022	0.146
Skew 10 to 39 degrees	25	n/a	n/a	n/a	n/a	n/a	0.078	0.268
Skew ≥40 degrees	2	n/a	n/a	n/a	n/a	n/a	0.006	0.079
Number of through lanes (major)	320	1	1	1	1	1	1.000	0.000
Number of through lanes (minor)	320	1	1	1	1	1	1.000	0.000
Number of right turn lanes	0	0	0	0	0	0	0.000	0.000
Number of left turn lanes	1	0	0	0	0	2	0.006	0.112
Railroad crossing within 211 feet of intersection	1	n/a	n/a	n/a	n/a	n/a	0.003	0.056
Driveway count	320	0	0	1	2	8	1.484	1.465
Variable	**Five-year crash count**	**Annual crashes per intersection**						
		Min	**25th%**	**50th%**	**75th%**	**Max**	**Mean**	**Std dev**
Midblock total crashes	313	0	0	0	0	4	0.196	0.483
Midblock total non-deer crashes	245	0	0	0	0	4	0.153	0.428
Midblock fatal and injury non-deer crashes	88	0	0	0	0	2	0.055	0.239
Midblock property damage only non-deer crashes	225	0	0	0	0	3	0.141	0.398

Note: n/a = not applicable; std dev = standard deviation; min = minimum; max = maximum; N = number of

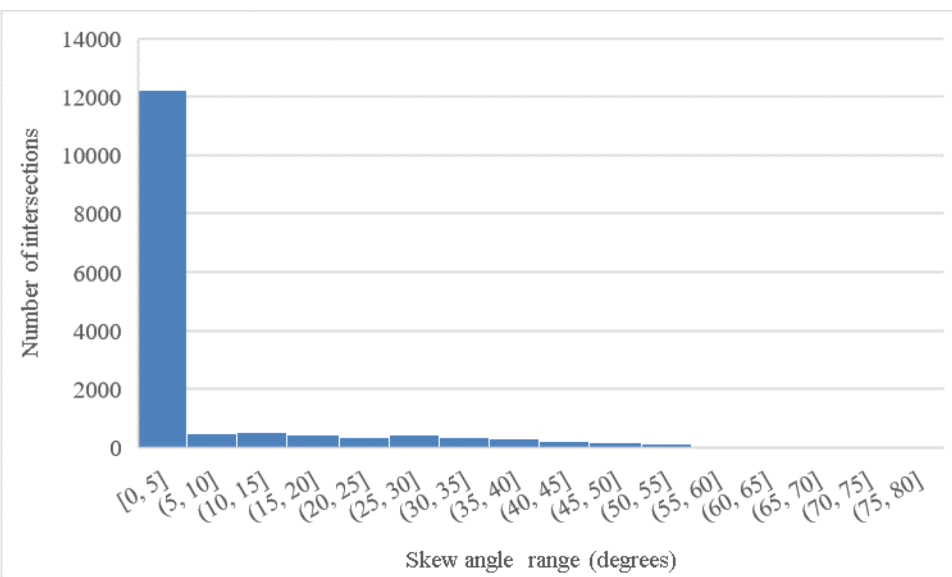
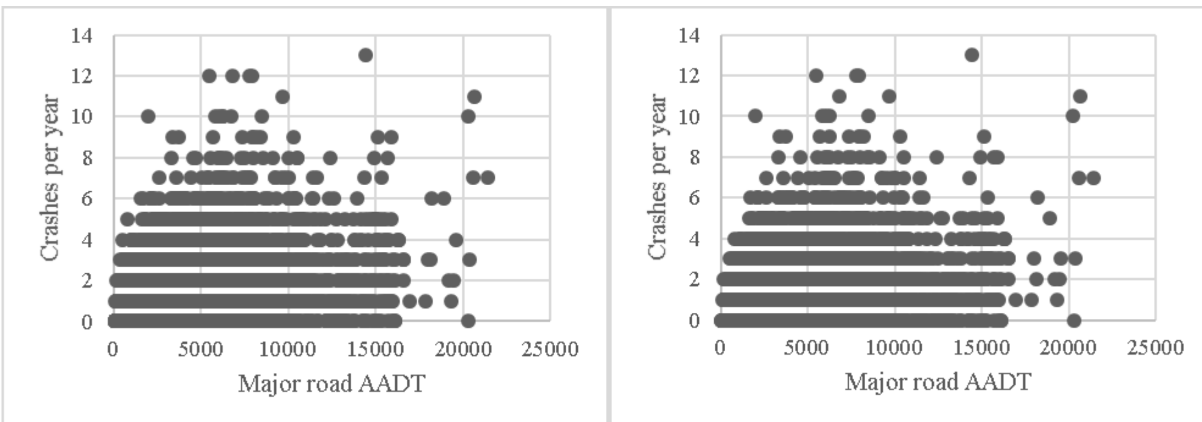


Figure 14: Distribution of skew angle across 4ST intersections

5.1.1.1 Data Diagnostics

Prior to SPF development, various data diagnostics were initially conducted to examine general trends across all locations for each facility type. This included assessment of the relationships between AADT and annual crash frequency, with scatterplots of these relationships generated for total and deer-excluded crashes for 4ST intersections, which are shown in Figure 15. Crash severity and crash type distributions were also reported and analyzed.



a.) Total intersection crashes (4ST) **b.) Deer-excluded intersection crashes (4ST)**

Figure 15: Annual intersection crashes vs AADT, 4ST (2011-2015)

Tables 24-27 show the crash severity and crash type distributions for rural four-leg intersections. It can be observed that MDOT intersections (Table 25) have a lower proportion of crashes involving fatalities and/or injuries compared to the other jurisdictions (Tables 26-27). In addition, 4ST rural Michigan intersections (Table 24) experience a lower proportion of fatal/injury crashes than the default distributions presented in Chapter 10 of the *HSM* [3]. Within the crash type distribution, angle collisions comprised a far greater proportion of intersection crashes for intersections under county jurisdictions compared to MDOT intersections. A potential explanation for this situation is the available intersection sight distance at MDOT intersections as compared to the county road system. This could manifest either in horizontal sight triangles clear of obstructions or vertical sight distance along the approaches.

Table 24: Crash Severity and Crash Type Distributions for Rural 4ST Intersections (All)

Crash severity level, collision type, or light condition	Count of intersection crashes (2011-2015)	Percent of total intersection crashes
Fatal (Type K)	133	1.03%
Incapacitating injury (Type A)	486	3.77%
Other injury (Type B+C)	2,966	23.00%
Fatal + injury (Type K+ABC)	3,585	27.80%
Property damage only (Type PDO)	9,313	72.20%
Single motor vehicle	4,066	31.52%
Single motor vehicle (deer excluded)	1,862	14.44%
Deer crashes	2,227	17.27%
Multiple vehicle crashes	8,778	68.06%
Day crashes	8,545	66.25%
Dark crashes	4,353	33.75%
Total non-deer crashes (5 years)	10,671	82.73%
Total crashes (5 years)	**12,898**	100.00%

Collision type	Percent of FI intersection crashes	Percent of PDO intersection crashes	Percent of total intersection crashes
Single-vehicle crashes			
Collision with deer	0.98%	23.29%	17.27%
Collision with bicycle	0.45%	0.02%	0.14%
Collision with pedestrian	0.81%	0.08%	0.28%
Other single-vehicle crash	12.05%	15.93%	14.68%
Total single-vehicle crash	13.03%	39.22%	31.94%
Multiple-vehicle crashes			
Angle collision	60.42%	27.67%	36.77%
Head-on collision	1.67%	0.59%	0.89%
Read-end collision	10.49%	14.76%	13.58%
Sideswipe collision	1.95%	14.76%	4.02%
Other multiple-vehicle collision	12.44%	2.99%	12.79%
Total multiple-vehicle collision	86.97%	60.78%	68.06%
Total crashes	**100.00%**	**100.00%**	**100.00%**

Table 25: Crash Severity and Crash Type Distributions for Rural 4ST Intersections (MDOT)

Crash severity level, collision type, or light condition	Count of intersection crashes (2011-2015)	Percent of total intersection crashes
Fatal (Type K)	53	0.85%
Incapacitating injury (Type A)	220	3.53%
Other injury (Type B+C)	1,341	21.53%
Fatal + injury (Type K+ABC)	1,614	25.92%
Property damage only (Type PDO)	4,614	74.08%
Single motor vehicle	1,865	29.95%
Single motor vehicle (deer excluded)	783	12.57%
Deer crashes	1,089	17.49%
Multiple vehicle crashes	4,331	69.54%
Day crashes	4,160	66.80%
Dark crashes	2,068	33.20%
Total non-deer crashes (5 years)	5,139	82.51%
Total crashes (5 years)	**6,228**	100.00%

Collision type	Percent of FI intersection crashes	Percent of PDO intersection crashes	Percent of total intersection crashes
Single-vehicle crashes			
Collision with deer	0.93%	23.13%	17.49%
Collision with bicycle	0.56%	0.04%	0.18%
Collision with pedestrian	1.05%	0.09%	0.34%
Other single-vehicle crash	10.59%	13.96%	12.97%
Total single-vehicle crash	11.52%	37.08%	30.46%
Multiple-vehicle crashes			
Angle collision	53.04%	24.82%	32.13%
Head-on collision	1.86%	0.59%	0.92%
Read-end collision	14.31%	17.23%	16.47%
Sideswipe collision	2.48%	17.23%	4.91%
Other multiple-vehicle collision	16.79%	3.06%	15.11%
Total multiple-vehicle collision	88.48%	62.92%	69.54%
Total crashes	**100.00%**	**100.00%**	**100.00%**

Table 26: Crash Severity and Crash Type Distributions for Rural 4ST Intersections (County FA)

Crash severity level, collision type, or light condition	**Count of intersection crashes (2011-2015)**	**Percent of total intersection crashes**
Fatal (Type K)	76	1.20%
Incapacitating injury (Type A)	259	4.07%
Other injury (Type B+C)	1,548	24.35%
Fatal + injury (Type K+ABC)	1,883	29.62%
Property damage only (Type PDO)	4,474	70.38%
Single motor vehicle	2,064	32.47%
Single motor vehicle (deer excluded)	1,009	15.87%
Deer crashes	1,070	16.83%
Multiple vehicle crashes	4,272	67.20%
Day crashes	4,191	65.93%
Dark crashes	2,166	34.07%
Total non-deer crashes (5 years)	5,287	83.17%
Total crashes (5 years)	**6,357**	100.00%

Collision type	**Percent of FI intersection crashes**	**Percent of PDO intersection crashes**	**Percent of total intersection crashes**
Single-vehicle crashes			
Collision with deer	1.06%	23.13%	16.83%
Collision with bicycle	0.37%	0.00%	0.11%
Collision with pedestrian	0.58%	0.07%	0.22%
Other single-vehicle crash	13.17%	17.48%	15.97%
Total single-vehicle crash	14.23%	40.61%	32.80%
Multiple-vehicle crashes			
Angle collision	65.91%	30.38%	40.90%
Head-on collision	1.59%	0.56%	0.87%
Read-end collision	7.54%	12.72%	11.18%
Sideswipe collision	1.54%	12.72%	3.30%
Other multiple-vehicle collision	9.19%	3.02%	10.95%
Total multiple-vehicle collision	85.77%	59.39%	67.20%
Total crashes	**100.00%**	**100.00%**	**100.00%**

Table 27: Crash Severity and Crash Type Distributions for Rural 4ST Intersections (County Non-FA)

Crash severity level, collision type, or light condition	Count of intersection crashes (2011-2015)	Percent of total intersection crashes
Fatal (Type K)	4	1.28%
Incapacitating injury (Type A)	7	2.24%
Other injury (Type B+C)	77	24.60%
Fatal + injury (Type K+ABC)	88	28.12%
Property damage only (Type PDO)	225	71.88%
Single motor vehicle	137	43.77%
Single motor vehicle (deer excluded)	70	22.36%
Deer crashes	68	21.73%
Multiple vehicle crashes	175	55.91%
Day crashes	194	61.98%
Dark crashes	119	38.02%
Total non-deer crashes (5 years)	245	78.27%
Total crashes (5 years)	**313**	100.00%

Collision type	Percent of FI intersection crashes	Percent of PDO intersection crashes	Percent of total intersection crashes
Single-vehicle crashes			
Collision with deer	0.00%	29.78%	21.73%
Collision with bicycle	0.00%	0.00%	0.00%
Collision with pedestrian	1.14%	0.00%	0.32%
Other single-vehicle crash	14.77%	25.78%	22.36%
Total single-vehicle crash	14.77%	55.56%	44.09%
Multiple-vehicle crashes			
Angle collision	78.41%	32.44%	45.37%
Head-on collision	0.00%	1.33%	0.96%
Read-end collision	3.41%	4.89%	4.47%
Sideswipe collision	1.14%	4.89%	0.96%
Other multiple-vehicle collision	2.27%	0.89%	4.15%
Total multiple-vehicle collision	85.23%	44.44%	55.91%
Total crashes	**100.00%**	**100.00%**	**100.00%**

5.1.2 Rural Three-Leg Stop-Controlled Intersections (3ST)

Table 28 displays the number of intersections included from each county, by each of the three funding and jurisdictional classes. Of Michigan's 83 counties, 80 were represented among intersections where the major road was under MDOT's jurisdiction, all 83 counties were represented for county federal aid major road intersections, while 15 counties had at least one major road non-federal aid intersection included in the sample. The small sample of counties for non-federal aid roadways was due to the limited availability of traffic volume data for these roadways. The lack of statewide coverage for non-federal aid intersections further emphasized the importance of developing separate models across the three jurisdictional classes of roadways. A map of the location of the 3ST intersections included is displayed in Figure 16.

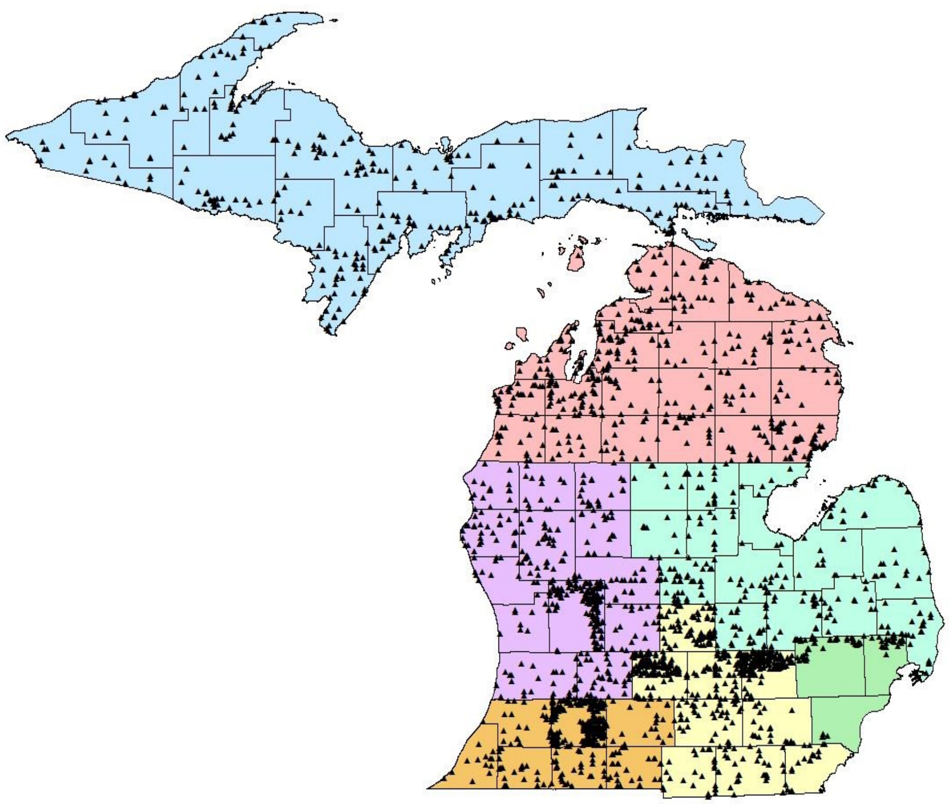


Figure 16: Map of rural three-leg stop-controlled (3ST) intersection locations

Table 28: Represented Counties and Intersection Count by Major Roadway Class (Three-Leg Intersections)

County	Number of sites (major road)				County	Number of sites (major road)			
	State	County FA	County non-FA	Total		State	County FA	County non-FA	Total
Alcona	8	8	0	16	Lake	4	11	0	15
Alger	9	8	0	17	Lapeer	2	12	1	15
Allegan	6	26	0	32	Leelanau	12	9	0	21
Alpena	7	5	0	12	Lenawee	14	18	0	32
Antrim	19	18	0	37	Livingston	5	64	104	173
Arenac	3	3	0	6	Luce	6	6	0	12
Baraga	13	9	0	22	Mackinac	17	14	0	31
Barry	22	20	0	42	Macomb	4	12	8	24
Bay	1	4	0	5	Manistee	9	10	0	19
Benzie	22	7	0	29	Marquette	23	12	1	36
Berrien	7	6	0	13	Mason	5	11	0	16
Branch	12	19	0	31	Mecosta	6	10	0	16
Calhoun	6	17	3	26	Menominee	15	20	0	35
Cass	13	10	0	23	Midland	3	11	0	14
Charlevoix	13	12	0	25	Missaukee	7	10	0	17
Cheboygan	12	13	0	25	Monroe	4	16	0	20
Chippewa	17	8	0	25	Montcalm	5	19	0	24
Clare	4	5	0	9	Montmorency	11	6	0	17
Clinton	2	55	25	82	Muskegon	1	12	0	13
Crawford	5	9	0	14	Newaygo	13	24	0	37
Delta	17	13	0	30	Oakland	0	39	4	43
Dickinson	7	4	0	11	Oceana	5	24	0	29
Eaton	21	44	68	133	Ogemaw	2	13	0	15
Emmet	6	13	0	19	Ontonagon	14	3	0	17
Genesee	14	12	3	29	Osceola	7	12	0	19
Gladwin	15	3	0	18	Oscoda	6	6	0	12
Gogebic	10	7	0	17	Otsego	4	6	0	10
Grand Traverse	20	27	8	55	Ottawa	1	8	0	9
Gratiot	1	41	7	49	Presque Isle	12	8	0	20
Hillsdale	14	10	0	24	Roscommon	3	12	0	15
Houghton	8	7	0	15	Saginaw	5	11	0	16
Huron	17	3	0	20	St. Clair	4	22	0	26
Ingham	4	52	11	67	St. Joseph	13	18	0	31
Ionia	11	10	0	21	Sanilac	7	8	0	15
Iosco	19	28	5	52	Schoolcraft	23	8	0	31
Iron	14	10	0	24	Shiawassee	6	18	0	24
Isabella	0	7	0	7	Tuscola	7	2	0	9
Jackson	16	25	0	41	Van Buren	5	15	0	20
Kalamazoo	20	97	135	252	Washtenaw	5	17	0	22
Kalkaska	6	11	0	17	Wayne	0	4	0	4
Kent	23	78	47	148	Wexford	8	6	0	14
Keweenaw	6	2	0	8	Total	773	1,333	430	2,536

Table 29 provides summary statistics for all relevant variables of interest considered during 3ST SPF development. Table 30 shows the same information for intersections whose major road is under MDOT jurisdiction, Table 31 for county federal aid, and Table 32 for county non-federal aid. More than 52 percent of intersections were county federal aid, 31 percent were under the jurisdiction of MDOT, and the remainder were county non-federal aid jurisdictions. Relative to 4ST intersections, a lower proportion of 3ST intersections were lit, with around 34 percent of intersections having lighting present. Driveway counts were also slightly lower for 3ST, with a mean of 1.9 per intersection. The majority of crashes (75 percent) were property damage only. Thirty-one percent of intersections experienced any kind of crash, while 25 percent of intersections experienced a non-deer related crash.

Interestingly, compared to 4ST intersections, skew was more common at 3ST intersections, with 67 percent of intersections possessing no skew compared to 77 percent of 4ST intersections. The skew was also more extreme at 3ST intersections, as 7.2 percent of intersections possessed skew greater than 40 degrees, compared to only 3.8 percent of 4ST intersections. The average skew as also higher at 3ST when compared to 4ST intersections (9.00 degrees vs. 5.66 degrees). A histogram showing the frequency of various skew angle categories can be seen in Figure 17, which shows that the vast majority of intersections have a skew angle less than five degrees, and very few intersections have skew angles of 40 degrees or more.

Table 29: Descriptive Statistics for Rural 3ST Intersections (All)

Variable	N (sites)	Min	25th%	50th%	75th%	Max	Mean	Std dev
AADT-major roadway	2,536	26	771	1,740	3,140	32,006	2,651.3	2,822.0
AADT-minor roadway	2,536	4	167	456	871	8,480	803.7	991.6
Lighting provided	863	n/a	n/a	n/a	n/a	n/a	0.340	0.474
Overhead beacon provided	90	n/a	n/a	n/a	n/a	n/a	0.035	0.185
Skew angle	2,536	0.0	0.0	0.0	8.0	80.0	9.003	16.238
Skew 0 degrees	1,669	n/a	n/a	n/a	n/a	n/a	0.658	0.474
Skew 1 to 9 degrees	151	n/a	n/a	n/a	n/a	n/a	0.060	0.237
Skew 10 to 39 degrees	534	n/a	n/a	n/a	n/a	n/a	0.211	0.408
Skew ≥40 degrees	182	n/a	n/a	n/a	n/a	n/a	0.072	0.258
Number of through lanes (major)	2,536	1	1	1	1	2	1.030	0.169
Number of through lanes (minor)	2,536	0	1	1	1	1	0.948	0.223
Number of right turn lanes	2,536	0	0	0	0	2	0.123	0.396
Number of left turn lanes	2,536	0	0	0	0	3	0.104	0.380
Railroad crossing within 211 feet of intersection	47	n/a	n/a	n/a	n/a	n/a	0.019	0.135
Driveway count	2,536	0	0	1	2	13	1.936	2.079
MDOT major roadway	773	n/a	n/a	n/a	n/a	n/a	0.305	0.460
County FA major roadway	1,333	n/a	n/a	n/a	n/a	n/a	0.526	0.499
County non-FA major roadway	430	n/a	n/a	n/a	n/a	n/a	0.170	0.375

Variable	Five-year crash count	Annual crashes per intersection						
		Min	25th%	50th%	75th%	Max	Mean	Std dev
Midblock total crashes	6,178	0	0	0	1	14	0.487	0.924
Midblock total non-deer crashes	4,663	0	0	0	0	13	0.368	0.811
Midblock fatal and injury non-deer crashes	1,188	0	0	0	0	5	0.094	0.334
Midblock property damage only non-deer crashes	3,475	0	0	0	0	12	0.274	0.682

Table 30: Descriptive Statistics for Rural 3ST Intersections (MDOT)

Variable	N (sites)	Min	25th%	50th%	75th%	Max	Mean	Std dev
AADT-major roadway	773	177	2,229	4,100	5,787	32,006	4,815.4	3,592.1
AADT-minor roadway	773	10	314	752	1,327	8,200	1,187.4	1,267.0
Lighting provided	431	n/a	n/a	n/a	n/a	n/a	0.558	0.497
Overhead beacon provided	64	n/a	n/a	n/a	n/a	n/a	0.083	0.276
Skew angle	773	0.0	0.0	0.0	18.0	80.0	13.026	18.217
Skew 0 degrees	466	n/a	n/a	n/a	n/a	n/a	0.603	0.489
Skew 1 to 9 degrees	50	n/a	n/a	n/a	n/a	n/a	0.065	0.246
Skew 10 to 39 degrees	189	n/a	n/a	n/a	n/a	n/a	0.245	0.430
Skew ≥40 degrees	68	n/a	n/a	n/a	n/a	n/a	0.088	0.283
Number of through lanes (major)	773	1	1	1	1	2	1.089	0.285
Number of through lanes (minor)	773	0	1	1	1	1	0.868	0.338
Number of right turn lanes	773	0	0	0	0	2	0.320	0.606
Number of left turn lanes	773	0	0	0	0	3	0.263	0.573
Railroad crossing within 211 feet of intersection	19	n/a	n/a	n/a	n/a	n/a	0.025	0.155
Driveway count	773	0	0	1	3	12	2.025	2.271

Variable	Five-year crash count	Annual crashes per intersection						
		Min	25th%	50th%	75th%	Max	Mean	Std dev
Midblock total crashes	3,098	0	0	0	1	14	0.802	1.223
Midblock total non-deer crashes	2,364	0	0	0	1	13	0.612	1.109
Midblock fatal and injury non-deer crashes	609	0	0	0	0	5	0.158	0.439
Midblock property damage only non-deer crashes	1,755	0	0	0	0	12	0.454	0.931

Table 31: Descriptive Statistics for Rural 3ST Intersections (Major Road County FA)

Variable	N (sites)	Min	25th%	50th%	75th%	Max	Mean	Std dev
AADT-major roadway	1,333	87	867	1,583	2,510	15,947	2,073.9	1,729.3
AADT-minor roadway	1,333	5	207	508	877	8,480	778.7	845.9
Lighting provided	416	n/a	n/a	n/a	n/a	n/a	0.312	0.463
Overhead beacon provided	26	n/a	n/a	n/a	n/a	n/a	0.020	0.138
Skew angle	1,333	0.0	0.0	0.0	5.5	75.0	8.298	15.701
Skew 0 degrees	900	n/a	n/a	n/a	n/a	n/a	0.675	0.468
Skew 1 to 9 degrees	88	n/a	n/a	n/a	n/a	n/a	0.066	0.248
Skew 10 to 39 degrees	257	n/a	n/a	n/a	n/a	n/a	0.193	0.395
Skew ≥40 degrees	88	n/a	n/a	n/a	n/a	n/a	0.066	0.248
Number of through lanes (major)	1,333	1	1	1	1	2	1.004	0.061
Number of through lanes (minor)	1,333	0	1	1	1	1	0.977	0.148
Number of right turn lanes	1,333	0	0	0	0	2	0.049	0.229
Number of left turn lanes	1,333	0	0	0	0	3	0.046	0.248
Railroad crossing within 211 feet of intersection	25	n/a	n/a	n/a	n/a	n/a	0.019	0.136
Driveway count	1,333	0	1	2	2	13	2.017	2.103
Variable	**Five-year crash count**	**Annual crashes per intersection**						
		Min	**25th%**	**50th%**	**75th%**	**Max**	**Mean**	**Std dev**
Midblock total crashes	2,862	0	0	0	1	7	0.429	0.782
Midblock total non-deer crashes	2,138	0	0	0	0	7	0.321	0.670
Midblock fatal and injury non-deer crashes	541	0	0	0	0	3	0.081	0.300
Midblock property damage only non-deer crashes	1,597	0	0	0	0	7	0.240	0.571

Table 32: Descriptive Statistics for Rural 3ST Intersections (Major Road County Non-FA)

Variable	N (sites)	Min	25th%	50th%	75th%	Max	Mean	Std dev
AADT-major roadway	430	26	177	346	560	9,871	550.8	801.9
AADT-minor roadway	430	4	67	113	193	2,436	191.4	234.2
Lighting provided	16	n/a	n/a	n/a	n/a	n/a	0.037	0.189
Overhead beacon provided	0	n/a	n/a	n/a	n/a	n/a	0.000	0.000
Skew angle	430	0.0	0.0	0.0	0.0	65.0	3.956	11.761
Skew 0 degrees	369	n/a	n/a	n/a	n/a	n/a	0.858	0.349
Skew 1 to 9 degrees	9	n/a	n/a	n/a	n/a	n/a	0.021	0.143
Skew 10 to 39 degrees	35	n/a	n/a	n/a	n/a	n/a	0.081	0.274
Skew $\geq$40 degrees	17	n/a	n/a	n/a	n/a	n/a	0.040	0.195
Number of through lanes (major)	430	1	1	1	1	2	1.002	0.048
Number of through lanes (minor)	430	0	1	1	1	1	0.998	0.048
Number of right turn lanes	430	0	0	0	0	1	0.002	0.048
Number of left turn lanes	430	0	0	0	0	1	0.002	0.048
Railroad crossing within 211 feet of intersection	3	n/a	n/a	n/a	n/a	n/a	0.007	0.083
Driveway count	430	0	0	1	2	8	1.523	1.519
Variable	**Five-year crash count**	**Annual crashes per intersection**						
		Min	**25th%**	**50th%**	**75th%**	**Max**	**Mean**	**Std dev**
Midblock total crashes	218	0	0	0	0	3	0.101	0.340
Midblock total non-deer crashes	161	0	0	0	0	3	0.075	0.290
Midblock fatal and injury non-deer crashes	38	0	0	0	0	1	0.018	0.132
Midblock property damage only non-deer crashes	123	0	0	0	0	2	0.057	0.259

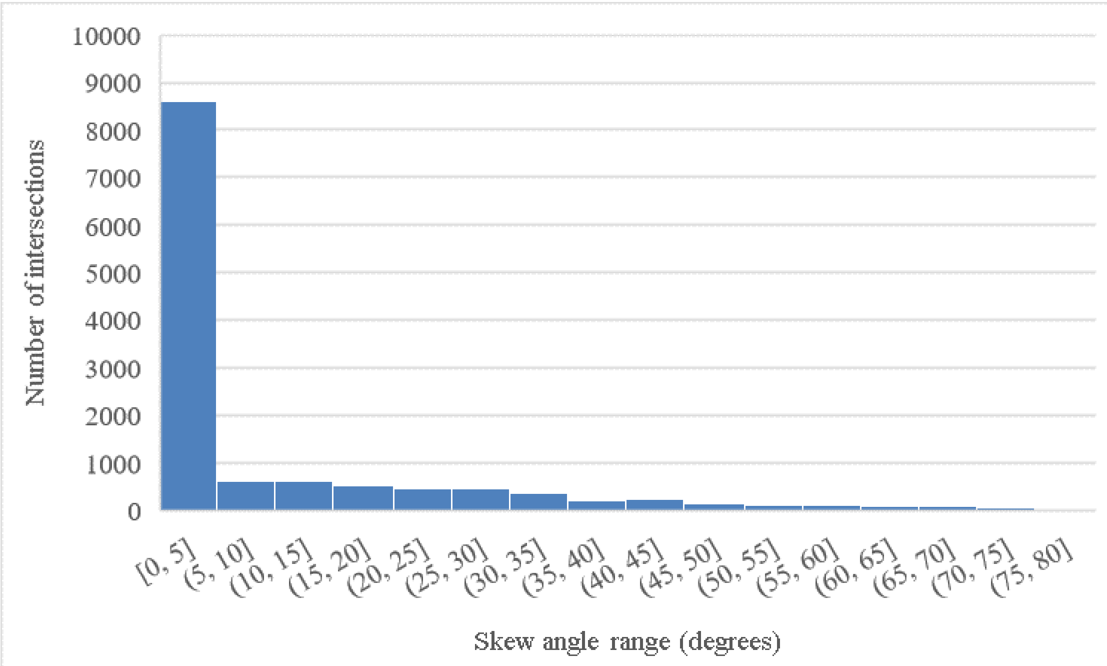
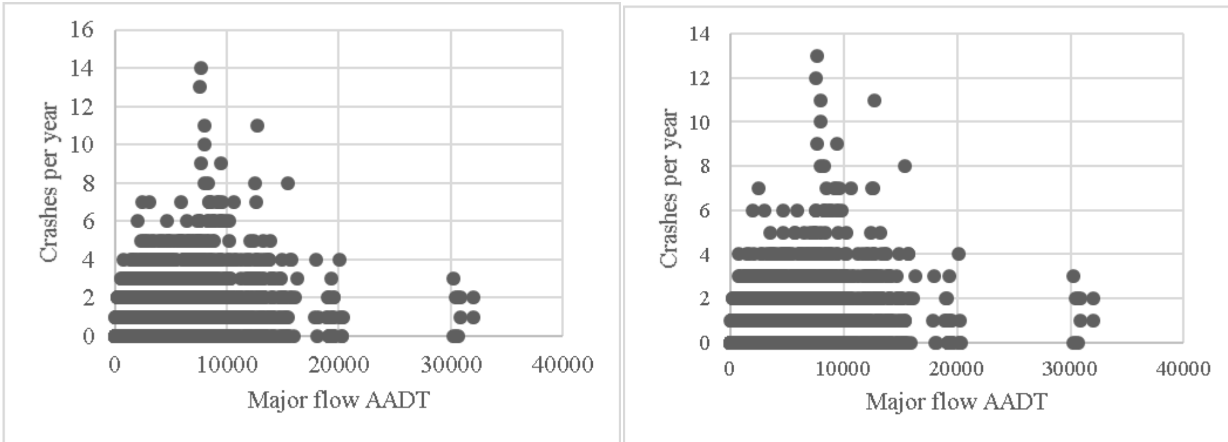


Figure 17: Distribution of skew angle across 3ST intersections

<u>5.1.2.1 Data Diagnostics</u>

Prior to SPF development, various data diagnostics were initially conducted to examine general trends across all locations for each facility type. This included assessment of the relationships between AADT and annual crash frequency with scatterplots of these relationships generated for total and deer-excluded crashes for 3ST intersections, which are shown in Figure 18. Crash severity and crash type distributions were also reported and analyzed.



a.) Total intersection crashes (3ST) **b.) Deer-excluded intersection crashes (3ST)**

Figure 18: Annual intersection crashes vs AADT, 3ST (2011-2015)

Tables 33-36 show the crash severity and crash type distributions for rural three leg intersections. In comparison to the default distributions presented in Chapter 10 of the *HSM* [3], Michigan's rural 3ST intersection crashes tend to be less severe (Table 33). In consideration of crash types, a relatively high proportion of single vehicle crashes involved deer (approximately 25 percent), likely contributing to the lower severity compared to the *HSM*. Angle and rear-end collisions are the most prevalent specific categories of multiple-vehicle crashes at 3ST intersections in Michigan, which is consistent with the default distributions in the *HSM*. Angle crashes make up 11 percent of crashes at 3ST intersections compared with 37 percent of crashes at 4ST intersections.

The proportion of crashes occurring in dark conditions is notably higher than the default distribution in the *HSM* [3], again, likely due to the high proportion of deer crashes. Compared with 4ST intersections, crashes at 3ST intersections tend to be less severe, with 80.4 percent of crashes being PDO at 3ST intersections, compared with 72.2 percent at 4ST. In addition, the proportion of multiple-vehicle crashes is much lower at 3ST intersections, with only 43.4 percent being multiple-vehicle, compared with 68.06 percent at 4ST intersections, likely reflecting the reduced number of conflict points at 3ST.

Table 33: Crash Severity and Crash Type Distributions for Rural 3ST Intersections (All)

Crash severity level, collision type, or light condition	Count of intersection crashes (2011-2015)	Percent of total intersection crashes
Fatal (Type K)	26	0.42%
Incapacitating injury (Type A)	163	2.64%
Other injury (Type B+C)	1,022	16.54%
Fatal + injury (Type K+ABC)	1,211	19.60%
Property damage only (Type PDO)	4,967	80.40%
Single motor vehicle	3,472	56.20%
Single motor vehicle (deer excluded)	1,972	31.92%
Deer crashes	1,515	24.52%
Multiple vehicle crashes	2,681	43.40%
Day crashes	3,350	54.22%
Dark crashes	2,828	45.78%
Total non-deer crashes (5 years)	4,663	75.48%
Total crashes (5 years)	**6,178**	100.00%

Collision type	Percent of FI intersection crashes	Percent of PDO intersection crashes	Percent of total intersection crashes
Single-vehicle crashes			
Collision with deer	1.90%	29.74%	24.52%
Collision with bicycle	0.66%	0.10%	0.21%
Collision with pedestrian	0.74%	0.06%	0.19%
Other single-vehicle crash	41.29%	30.14%	32.08%
Total single-vehicle crash	43.19%	59.88%	56.60%
Multiple-vehicle crashes			
Angle collision	18.83%	9.32%	11.18%
Head-on collision	3.39%	0.79%	1.29%
Read-end collision	14.04%	14.46%	14.37%
Sideswipe collision	2.56%	14.46%	3.32%
Other multiple-vehicle collision	18.00%	1.11%	13.22%
Total multiple-vehicle collision	56.81%	40.12%	43.40%
Total crashes	**100.00%**	**100.00%**	**100.00%**

Table 34: Crash Severity and Crash Type Distributions for Rural 3ST Intersections (Major Road MDOT)

Crash severity level, collision type, or light condition	Count of intersection crashes (2011-2015)	Percent of total intersection crashes
Fatal (Type K)	12	0.39%
Incapacitating injury (Type A)	82	2.65%
Other injury (Type B+C)	531	17.14%
Fatal + injury (Type K+ABC)	625	20.17%
Property damage only (Type PDO)	2,473	79.83%
Single motor vehicle	1,477	47.68%
Single motor vehicle (deer excluded)	746	24.08%
Deer crashes	734	23.69%
Multiple vehicle crashes	1,607	51.87%
Day crashes	1,819	58.72%
Dark crashes	1,279	41.28%
Total non-deer crashes (5 years)	2,364	76.31%
Total crashes (5 years)	**3,098**	100.00%

Collision type	Percent of FI intersection crashes	Percent of PDO intersection crashes	Percent of total intersection crashes
Single-vehicle crashes			
Collision with deer	2.56%	28.91%	23.69%
Collision with bicycle	0.80%	0.12%	0.26%
Collision with pedestrian	0.64%	0.08%	0.19%
Other single-vehicle crash	30.72%	22.97%	24.44%
Total single-vehicle crash	33.28%	51.88%	48.13%
Multiple-vehicle crashes			
Angle collision	18.72%	9.46%	11.33%
Head-on collision	3.52%	0.73%	1.29%
Read-end collision	19.68%	20.06%	19.98%
Sideswipe collision	3.36%	20.06%	3.91%
Other multiple-vehicle collision	21.44%	-2.18%	15.36%
Total multiple-vehicle collision	66.72%	48.12%	51.87%
Total crashes	**100.00%**	**100.00%**	**100.00%**

Table 35: Crash Severity and Crash Type Distributions for Rural 3ST Intersections (Major Road County FA)

Crash severity level, collision type, or light condition	Count of intersection crashes (2011-2015)	Percent of total intersection crashes
Fatal (Type K)	12	0.42%
Incapacitating injury (Type A)	77	2.69%
Other injury (Type B+C)	459	16.04%
Fatal + injury (Type K+ABC)	548	19.15%
Property damage only (Type PDO)	2,314	80.85%
Single motor vehicle	1,836	64.15%
Single motor vehicle (deer excluded)	1,124	39.27%
Deer crashes	724	25.30%
Multiple vehicle crashes	1,016	35.50%
Day crashes	1,425	49.79%
Dark crashes	1,437	50.21%
Total non-deer crashes (5 years)	2,138	74.70%
Total crashes (5 years)	**2,862**	100.00%

Collision type	Percent of FI intersection crashes	Percent of PDO intersection crashes	Percent of total intersection crashes
Single-vehicle crashes			
Collision with deer	1.28%	30.47%	25.30%
Collision with bicycle	0.36%	0.09%	0.14%
Collision with pedestrian	0.91%	0.04%	0.21%
Other single-vehicle crash	51.82%	36.73%	39.20%
Total single-vehicle crash	53.10%	67.20%	64.50%
Multiple-vehicle crashes			
Angle collision	19.16%	9.08%	11.01%
Head-on collision	3.28%	0.86%	1.33%
Read-end collision	8.21%	9.12%	8.94%
Sideswipe collision	1.46%	9.12%	2.73%
Other multiple-vehicle collision	14.78%	4.62%	11.50%
Total multiple-vehicle collision	46.90%	32.80%	35.50%
Total crashes	**100.00%**	**100.00%**	**100.00%**

Table 36: Crash Severity and Crash Type Distributions for Rural 3ST Intersections (Major Road County Non-FA)

Crash severity level, collision type, or light condition	Count of intersection crashes (2011-2015)	Percent of total intersection crashes
Fatal (Type K)	2	0.92%
Incapacitating injury (Type A)	4	1.83%
Other injury (Type B+C)	32	14.68%
Fatal + injury (Type K+ABC)	38	17.43%
Property damage only (Type PDO)	180	82.57%
Single motor vehicle	159	72.94%
Single motor vehicle (deer excluded)	102	46.79%
Deer crashes	57	26.15%
Multiple vehicle crashes	58	26.61%
Day crashes	106	48.62%
Dark crashes	112	51.38%
Total non-deer crashes (5 years)	161	73.85%
Total crashes (5 years)	**218**	100.00%

Collision type	Percent of FI intersection crashes	Percent of PDO intersection crashes	Percent of total intersection crashes
Single-vehicle crashes			
Collision with deer	0.00%	31.67%	26.15%
Collision with bicycle	2.63%	0.00%	0.46%
Collision with pedestrian	0.00%	0.00%	0.00%
Other single-vehicle crash	63.16%	43.89%	47.25%
Total single-vehicle crash	63.16%	75.56%	73.39%
Multiple-vehicle crashes			
Angle collision	15.79%	10.56%	11.47%
Head-on collision	2.63%	0.56%	0.92%
Read-end collision	5.26%	6.11%	5.96%
Sideswipe collision	5.26%	6.11%	2.75%
Other multiple-vehicle collision	7.89%	1.11%	5.50%
Total multiple-vehicle collision	36.84%	24.44%	26.61%
Total crashes	**100.00%**	**100.00%**	**100.00%**

5.2 Results and Discussion

The sections below will present and explain the model results for both 4ST and 3ST type intersections. Coefficient estimates, standard errors, and p-values are provided in each table. Due to the small number of crashes at each location, models estimating crashes of all severity levels were developed rather than isolating specific crash types and severities. Unless otherwise noted, further discussion of crashes in this chapter should assume exclusion of deer crashes.

5.2.1 Four-Leg Stop-Controlled Rural Intersections (4ST)

The model results for annual crash occurrence at four-leg stop-controlled rural intersections of all jurisdictional classifications are summarized in Table 37. Four-leg stop-controlled rural intersections with skew angles between 10 degrees and 39 degrees were found to have 28 percent greater crash frequency relative to intersections with no intersection skew. On the other hand, skew angles greater than or equal to 40 degrees or less than 10 degrees were not found to be significantly different from those with no intersection skew. Intersection skew is associated with reduced visibility for drivers, particularly due to the blind spots the vehicle's frame creates. Minor skew (<10 degrees) does not appear to impact impacted safety performance. Safety performance is also not impacted by extreme skew, although this is likely at least somewhat due to small sample size. However, it may also be due to drivers proceeding with increased caution at intersections with such extreme skew. Further exploration into these effects is warranted in future work.

Turning to the intersection jurisdiction factors, intersections where a state highway was the major jurisdiction were found to have the highest crash frequency, while county non-federal aid were found to have the lowest crash frequency. The presence of a railroad crossing within the intersection's influence zone (i.e., 211 feet) increased crash frequency by 26 percent. The presence of a railroad crossing creates an opportunity for rear-end crashes, as does the presence of any traffic control device that compels drivers to stop or yield.

All other factors were not found to have a significant effect on crash occurrence, including lighting, driveway county, and the presence of left turn lanes, which in many cases, was due to small sample sizes. Notably, a subsequent analysis of nighttime 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 due to the very small sample of intersections possessing left-turn lanes.

To account for differences in roadway, driver, and trip characteristics between the three jurisdictional and funding classes, and to focus on county-owned roadways, separate models were generated for cases where the major intersecting roadway was county federal aid, in addition to a separate model for county non-federal aid. Due to the small number of intersections with crashes, fixed effects analysis was used rather than mixed effects.

Results for county federal aid intersections, shown in Table 38, were very similar to the mixed effects model for all jurisdictions, with the same factors being significant, and with estimates within each other's margin of error. While the mixed effects model estimates a 28 percent increase in crashes at intersections when the skew angle is between 10 and 39 degrees, the county federal aid-specific fixed effects model estimates a 30 percent increase. The county non-federal aid model (Table 39) shows an even stronger effect, with a 60 percent greater crash occurrence when skew angle is between 10 and 39 degrees compared to intersections with no skew. Intersections with skew angles of 40 degrees or more did not demonstrate a significant difference from intersections with no skew in any analysis, nor did intersections with skew angles between 1 and 9 degrees. Again, the lack of measurable effects of extreme skew are likely at least somewhat due to small sample size, although drivers may also be proceeding with increased caution at such locations. Further exploration into these effects is warranted in future work.

Model diagnostics (i.e., AIC and log likelihood) show that the mixed effects model in Table 37 is more accurate in predicting crashes that the fixed effects model located in Appendix A (Table 56). Mixed effects models, i.e., models that incorporate random effects in addition to fixed effects, tend to be more accurate than fixed effects models. As previously discussed, fixed effects models generally include one line of data per year which introduces a bias; each line of data is assumed to be independent, but multiple observations at the same site are not truly independent from each other. The random effects incorporated in this model address this bias through the site-specific random effect, in addition to a county-specific random effect to address both the differences in maintenance and design practices between county road commissions as well as weather and population differences, among others.

Table 37: Mixed Effects Negative Binomial Model Results for 4ST Rural Intersections

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-7.499	0.001	0.215	<0.001
Major road AADT	Natural log of, vehicles per day	0.411	1.508	0.026	<0.001
Minor road AADT	Natural log of, vehicles per day	0.551	1.735	0.021	<0.001
Railroad crossing	Present within 211 feet	0.228	1.256	0.124	0.067
Skew 0 degrees	Deviation from 90 degrees	baseline			
Skew 1 to 9 degrees	Deviation from 90 degrees	0.115	1.121	0.087	0.186
Skew 10 to 39 degrees	Deviation from 90 degrees	0.244	1.276	0.046	<0.001
Skew ≥40 degrees	Deviation from 90 degrees	-0.015	0.985	0.086	0.862
State highway	Major road jurisdiction	baseline			
County FA	Major road jurisdiction	-0.139	0.870	0.041	0.001
County non-FA	Major road jurisdiction	-0.343	0.710	0.101	0.001
County random effect				0.129	
Site random effect				0.631	
Overdispersion parameter		0.0393			
AIC		30,151.20			
Log-likelihood		-15,063.6			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion

Table 38: Fixed Effects Negative Binomial Model Results for 4ST Rural Intersections (Major Road County FA)

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-7.548	0.001	0.188	<0.001
Major road AADT	Natural log of, vehicles per day	0.432	1.540	0.027	<0.001
Minor road AADT	Natural log of, vehicles per day	0.548	1.730	0.021	<0.001
Railroad crossing	Present within 211 feet	0.139	1.149	0.136	0.308
Skew 0 degrees	Deviation from 90 degrees	baseline			
Skew 1 to 9 degrees	Deviation from 90 degrees	0.018	1.018	0.089	0.839
Skew 10 to 39 degrees	Deviation from 90 degrees	0.265	1.304	0.046	<0.001
Skew ≥40 degrees	Deviation from 90 degrees	0.096	1.100	0.102	0.350
Overdispersion parameter		0.845			
AIC		16,963.00			
Log-likelihood		-16,947.3			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion

Table 39: Fixed Effects Negative Binomial Model Results for 4ST Rural Intersections (Major Road County Non-FA)

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-7.641	0.000	0.574	<0.001
Major road AADT	Natural log of, vehicles per day	0.534	1.706	0.108	<0.001
Minor road AADT	Natural log of, vehicles per day	0.409	1.505	0.100	<0.001
Railroad crossing	Present within 211 feet	1.450	4.263	0.445	0.001
Skew 0 degrees	Deviation from 90 degrees	baseline			
Skew 1 to 9 degrees	Deviation from 90 degrees	0.534	1.706	0.350	0.127
Skew 10 to 39 degrees	Deviation from 90 degrees	0.468	1.597	0.200	0.019
Skew ≥40 degrees	Deviation from 90 degrees	-20.490	0.000	21370.00	0.999
Overdispersion parameter		0.186			
AIC		1,317.5			
Log-likelihood		-650.7			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion

5.2.2 Three-Leg Stop-Controlled Rural Intersections (3ST)

Thee model results for deer-excluded crashes occurring at three-leg stop-controlled rural intersections are summarized in Table 40. Intersection skew angle did not show a significant difference between intersections with no skew and those with skew angles between one and 39 degrees. On the other hand, there was a negative correlation between crash reduction and skew angles of 40 degrees or greater; a prior study found that skew angles of 70 degrees or higher were associated with crash reduction [103]. It is important to note that the vast majority of sites had skew angles of zero, and very few sites had skew angles of 40 degrees or greater. The cause of this decrease is unclear; however, there are some potential explanations that may be rooted in driver behavior, such as drivers being more cautious at intersections with extreme skew.

Similar to four-leg intersections, county non-federal aid intersections experienced lower crash occurrence than MDOT or county federal aid intersections. All other factors, including lighting, left turn lanes, and driveway counts, were not found to significantly affect crash occurrence at rural 3ST intersections.

Similar to 4ST intersections, to account for differences in roadway, driver, and trip characteristics between the three jurisdictional and funding classes, separate models were generated for cases where the major intersecting roadway was county federal aid or county non-federal aid. Due to the small number of crashes at each location and the small number of sites, fixed effects analysis was used rather than mixed effects. Results for county federal aid intersections, shown in Table 41, were quite similar to those in the mixed effects model, with the same factors being significant, and with estimates within each other's margin of error. The mixed effects model estimates a 28 percent decrease in crashes and the county federal aid-specific model estimates a 24 percent decrease in crashes at intersections when the skew angle is 40 degrees or greater, while the county non-federal aid-specific fixed effects model (Table 42) does not find this factor to be significant. No models found a significant difference in crash frequency when skew angle was between 1 and 39 degrees.

Model diagnostics (i.e., AIC and log likelihood) show that the mixed effects model below in Table 40 is more accurate in predicting crashes that the fixed effects model located in

Appendix A (Table 55). Mixed effects models, i.e., models that incorporate random effects in addition to fixed effects, tend to be more accurate than fixed effects models. As previously discussed, fixed effects models generally include one line of data per year which introduces a bias; each line of data is assumed to be independent, but multiple observations at the same site are not truly independent from each other. The random effects incorporated in this model address this bias through the site-specific random effect, in addition to a county-specific random effect to address both the differences in maintenance and design practices between county road commissions as well as weather and population differences.

Table 40: Mixed Effects Negative Binomial Model Results for 3ST Rural Intersections

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-7.117	0.001	0.263	<0.001
Major road AADT	Natural log of, vehicles per day	0.345	1.413	0.032	<0.001
Minor road AADT	Natural log of, vehicles per day	0.530	1.698	0.024	<0.001
Skew 0 degrees	Deviation from 90 degrees	baseline			
Skew 1 to 9 degrees	Deviation from 90 degrees	-0.034	0.967	0.093	0.714
Skew 10 to 39 degrees	Deviation from 90 degrees	-0.042	0.959	0.055	0.449
Skew ≥40 degrees	Deviation from 90 degrees	-0.327	0.721	0.090	<0.001
State highway	Major road jurisdiction	baseline			
County FA	Major road jurisdiction	-0.245	0.783	0.052	<0.001
County non-FA	Major road jurisdiction	-0.635	0.530	0.117	<0.001
County random effect				0.133	
Site random effect				0.658	
Overdispersion parameter		0.00657			
AIC		17,089.10			
Log-likelihood		-8,533.6			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion

Table 41: Fixed Effects Negative Binomial Model Results for 3ST Rural Intersections (Major Road County FA)

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-7.243	0.001	0.261	<0.001
Major road AADT	Natural log of, vehicles per day	0.376	1.456	0.037	<0.001
Minor road AADT	Natural log of, vehicles per day	0.508	1.662	0.027	<0.001
Skew 0 degrees	Deviation from 90 degrees	baseline			
Skew 1 to 9 degrees	Deviation from 90 degrees	0.059	1.061	0.094	0.527
Skew 10 to 39 degrees	Deviation from 90 degrees	0.070	1.072	0.059	0.236
Skew ≥40 degrees	Deviation from 90 degrees	-0.274	0.760	0.105	0.009
Overdispersion parameter		0.393			
AIC		8,962.60			
Log-likelihood		-4,474.3			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion

Table 42: Fixed Effects Negative Binomial Model Results for 3ST Rural Intersections (Major Road County Non-FA)

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-7.537	0.001	0.607	<0.001
Major road AADT	Natural log of, vehicles per day	0.310	1.363	0.116	0.007
Minor road AADT	Natural log of, vehicles per day	0.576	1.778	0.112	<0.001
Skew 0 degrees	Deviation from 90 degrees	baseline			
Skew 1 to 9 degrees	Deviation from 90 degrees	0.744	2.105	0.435	0.087
Skew 10 to 39 degrees	Deviation from 90 degrees	0.193	1.213	0.237	0.415
Skew ≥40 degrees	Deviation from 90 degrees	-0.938	0.391	0.590	0.112
Overdispersion parameter		0.497			
AIC		1,086.6			
Log-likelihood		-536.3			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion

5.2.3 Crash Modification Factors Developed for Rural Intersections

From these results, a set of CMFs were developed for correcting intersection skew angle within each funding and jurisdictional category, and these are shown in Table 43. These CMFs are the reciprocal of the Exp(B) values in the results tables. The values in the results tables describe the effect of these site characteristics when deviating from base conditions, but the reciprocal is taken to determine the opposite effect (i.e., returning to base conditions).

Table 43: CMFs Developed for Rural Intersections

Original condition	CMFs for the following major road classification			
	MDOT	County FA	County non-FA	Remarks
4ST intersections				
Skew 1 to 9 degrees	ns	ns	ns	Final condition:
Skew 10 to 39 degrees	0.78	0.77	0.63	skew 0 degrees
Skew $\geq$40 degrees	ns	ns	ns	
3ST intersections				
Skew 1 to 9 degrees	ns	ns	ns	Final condition:
Skew 10 to 39 degrees	ns	ns	ns	skew 0 degrees
Skew $\geq$40 degrees	1.39	1.32	ns	

Note: ns = not significant

5.2.4 Comparison to HSM Models

A graphical representation of the Michigan-specific rural 4ST and 3ST model results, as presented in this chapter, are shown in Figure 19. The respective *HSM* base models were also included in the figures for comparison purposes. The *HSM* models have been calibrated to major road county federal aid data using the methodology presented in Chapters 2 and 3. The calibration factor for three-leg intersections was found to be 0.66 and the for four-leg intersections it was found to be 0.59. Only lower volumes are shown in Figure 19 order to emphasize the role that model shape plays in prediction, and how shape can vary based on jurisdiction. A minor road volume of 500 vehicles per day was selected as the median value for minor road AADT was 456 and 638 vehicles per day at 3ST and 4ST intersections, respectively.

Calibrated models were evaluated for goodness-of-fit using mean absolute deviation. On paved segments, calibrated models performed well compared to Michigan-specific models when evaluating using MAD. At three-leg intersections where the major road was county federal aid, the model presented in this chapter had an MAD value of 0.21 while the calibrated model had a value of 0.38, indicating a better fit for the Michigan-specific model. At four-leg intersections where the major road was county federal aid, the model presented in this chapter had an MAD value of 0.24 while the calibrated model had a value of 0.77, indicating an even greater improvement in accuracy.

For 3ST intersections, the calibrated *HSM*'s model under-predicts crashes at lower major roadway volumes, but begins to over-predict crashes when the major roadway AADT exceeds approximately 3,000 vehicles per day. The calibrated *HSM* model over-predicts crashes at major roadway volumes that exceed approximately for 1,000 vehicles per day at 4ST intersections. At higher volumes (i.e., 2,000 vehicles per day), the calibrated *HSM*'s over-prediction of 4ST crashes increases to 27 percent at county federal aid intersections. This is not surprising, as calibration of the *HSM*'s models in various states has found that the *HSM*'s 4ST models generally overpredicts crash occurrence. For example, in North Carolina, a calibration factor of 0.68 was assigned, while in Oregon, the *HSM* was found to overpredict by an even greater degree, with a calibration factor of 0.31 assigned [118]. Another analysis found that stop-controlled intersections in North America (both 3ST and 4ST) should be assigned a calibration factor of 0.56 [119].

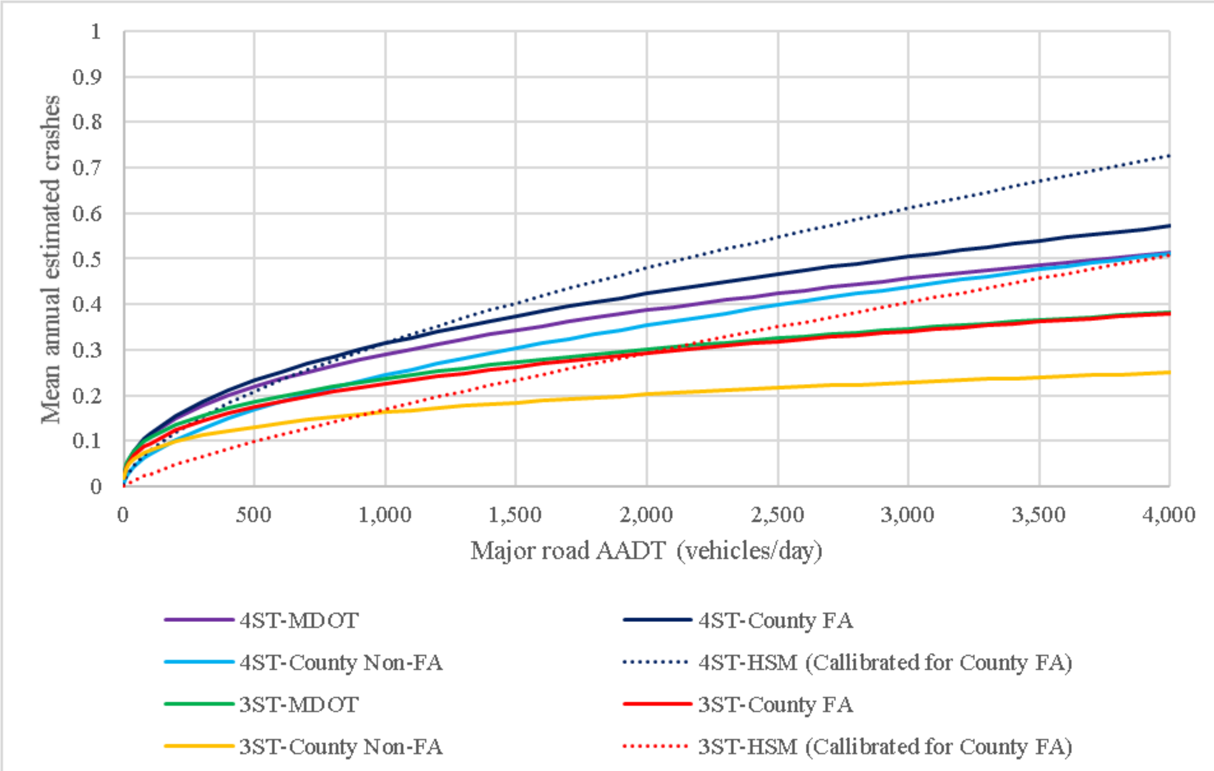


Figure 19: Model results for non-deer crashes on 4ST and 3ST intersections for minor roadway AADT=500 veh/day

5.3 Summary and Conclusions

This study involved the estimation of SPFs for low-volume rural stop-controlled intersections in Michigan. In order 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 5,659-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 three-leg (3ST) and four-leg (4ST) intersections that included intersections of all funding and jurisdictional classes (i.e., MDOT, county federal aid, and county non-federal aid). 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, a site-specific random effect was used to account for the lack of independence among the five data points each intersection provided.

In addition, due to the fact that models developed for different funding or jurisdictional classes are expected to have a different "shape," as was the case for highway segments, separate analyses were performed for intersections where the major road was county federal aid and county non-federal aid. Due to a small sample size, fixed effects analyses were used for these subsets. While results of the "combined" mixed effects models were quite similar to the subset fixed effects models in terms of which factors were significant and in which direction the results trended in, the shape of each model was different.

The mixed effects negative binomial analysis found that of the aforementioned factors, skew angles of between 10 and 39 degrees led to significantly greater crash occurrence for 4ST intersections. Intersections with skew angles in this category comprised of only approximately 15 percent of 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 to 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 3,000 vehicles per day. Compared to the Michigan-specific 4ST models, the *HSM* over-predicts crashes when AADT exceeds 1,000 vehicles per day.

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-owned 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.

6. EVALUATION OF DEER CRASHES ON RURAL SEGMENTS

Deer-vehicle crashes continue to be a problem in the United States, with 1.2 million such crashes occurring annually. Such crashes are a particular issue on two-lane rural highways in Michigan, accounting for more than 60 percent of all crashes. Such a high proportion of deer vehicle crashes limits the transferability of existing safety models, including those found in the *HSM*, that are often based on data from states with considerably lower proportions of deer crashes. Furthermore, deer crashes also introduce unwanted bias when modeling the relationships between crash occurrence and geometry or other roadway related factors. As a result, the primary safety performance functions developed in this study for county road segments and intersections, presented in Chapters 4 and 5, categorically excluded deer crashes from these models in order to improve the prediction capabilities of the roadway related factors

However, there remains a clear need for further research on the impacts that roadway characteristics have on deer crash occurrence across the primary classes of rural roadways, including both state and county two-lane highway segments. A cross-sectional analysis of deer crashes was performed using the 2011-2015 crash data sample described in Chapter 3. This analysis also included state-owned rural two-lane highways, for which roadway data were obtained from the MDOT sufficiency file, which serves as the primary roadway inventory file for the MDOT rural highway network. The data were analyzed across four categories of rural two-lane roadways, including: state highways, federal aid county roadways, non-federal aid county roadways, and unpaved county roadways. Mixed effects negative binomial regression models utilizing spatial (i.e., county) and temporal (i.e., crash year) random effects were generated separately for each of the rural two-lane roadway types. The following sections detail the descriptive statistics, analytical method, results and discussion of deer-related crashes on county-owned highway segments.

6.1 Descriptive Statistics

A total of 17,285 segments comprising of 12,746 miles of rural two-lane roadway were analyzed. 42 percent of miles analyzed were state highways, 35 percent were paved county federal aid, 11 percent were paved county non-federal aid, and 12 percent were unpaved. The location of state highway segments is shown in Figure 20 and county segments in Figure 21. Tables 44-47 show summary statistics for state, county federal aid, county non-federal aid, and unpaved rural roadway segments. Particularly noteworthy is the proportion of deer crashes to total crashes, which is above 0.6 in all categories, with the exception of unpaved roads. AADT values range from an average of more than 4,000 vehicles per day, with a standard deviation of more than 3,000 vehicles, on state highway segments, to an average of 217 vehicles per day on unpaved segments. All sites across all jurisdictional categories were two-lane roads.

In order to have a clear understanding of the effect of lane width, segments were constrained to those with lane widths between 9 ft and 13 ft for all analyses, which accounts for 100 percent of state-owned segments, 99.3 percent of county federal-aid segments, 99.4 percent of county non-federal-aid segments, and 84.4 percent of unpaved segments. Lane widths were rounded to the nearest foot (i.e., 10.5 ft was rounded to 11 ft), as suggested by the *HSM*. Maps of the state and county highway segments utilized in the deer crash analysis are provided in the figures that follow.

Table 44: Descriptive Statistics for State Highway Segments included in Deer Crash Analysis

Statistic	Mean	St dev	Min	Max
Segment length (mi)	3.439	2.798	0.105	21.743
AADT	4,382.15	3,016.97	23	23,481.00
Number of lanes	2	0	2	2
Lane width (ft)	11.633	0.5	10	12
Paved shoulder width (ft)	4.771	2.521	0	12
Driveway density (driveways/mi)	14.773	9.956	0	85.053
Substandard curves/mi	0.076	0.443	0	9.524
Public deer licenses per square mile	1.575	1.57	0	5.717
Private deer licenses per square mile	7.656	5.901	0	22.133
Superior Region	0.225			
North Region	0.262			
Grand Region	0.108			
Bay Region	0.161			
Southwest Region	0.124			
University Region	0.106			
Metro Region	0.013			
Total annual midblock crashes/mi	2.705	2.277	0.000	28.571
Midblock annual deer crashes/mi	1.781	1.760	0.000	20.161
Midblock annual FI deer crashes/mi	0.034	0.141	0.000	4.032
Percent deer crashes	65.8%			
Number of segments	1,556			

Note: ft = feet, mi = miles, std dev = standard deviation; min = minimum; max = maximum

Table 45: Descriptive Statistics for County Federal-Aid Segments (Deer Crashes)

Statistic	Mean	St dev	Min	Max
Segment length (mi)	0.447	0.329	0.100	8.188
AADT	1,721	1,678	10	12,781
Number of lanes	2	0	2	2
Lane width (ft)	11.0	0.697	9.0	13.0
Paved shoulder width (ft)	1.1	1.551	0.0	10.0
Driveway density (driveways/mi)	14.922	13.895	0.000	138.686
Substandard curves/mi	0.210	1.043	0.000	15.625
Public deer licenses/sq mi (5-year average)	1.020	0.902	0.000	3.419
Private deer licenses/sq mi (5-year average)	12.626	8.053	0.000	25.640
Total annual midblock crashes/mi	1.590	2.803	0.000	42.017
Midblock deer crashes/mi	0.960	2.085	0.000	33.613
Percent deer crashes	60.4%			
Number of segments	9,847			

Note: ft = feet, mi = miles, std dev = standard deviation; min = minimum; max = maximum

Table 46: Descriptive Statistics for County Non-Federal Aid Segments (Deer Crashes)

Statistic	Mean	St dev	Min	Max
Segment length (mi)	0.51	0.299	0.1	2.012
AADT	586.358	636.213	5	12,628
Number of lanes	2	0	2	2
Lane width (ft)	10.585	0.689	9	13
Paved shoulder width (ft)	0.249	0.683	0	8
Driveway density (driveways/mi)	17.626	13.694	0	108.108
Substandard curves/mi	0.242	1.138	0	13
Public deer licenses/sq mi (5-year average)	1.089	0.768	0	3
Private deer licenses/sq mi (5-year average)	15.794	6.258	0	25.64
Total annual midblock crashes/mi	0.588	1.494	0	23
Midblock deer crashes/mi	0.355	1.121	0	19
Percent deer crashes	60.4%			
Number of segments	2,856			

Note: ft = feet, mi = miles, std dev = standard deviation; min = minimum; max = maximum

Table 47: Descriptive Statistics for Unpaved Segments (Deer Crashes)

Statistic	Mean	St dev	Min	Max
Segment length (mi)	0.508	0.365	0.1	4.575
AADT	216.639	332.945	7	6,298
Number of lanes	2	0	2	2
Lane width (ft)	10.604	1.201	9	13
Paved shoulder width (ft)	0	0	0	0
Driveway density (driveways/mi)	12.766	10.894	0	93
Substandard curves/mi	0.258	1.148	0	15
Public deer licenses/sq mi (5-year average)	1.618	1.121	0	3
Private deer licenses/sq mi (5-year average)	17.52	6.409	0	25.64
Total annual midblock crashes/mi	0.254	0.945	0	18
Midblock deer crashes/mi	0.091	0.542	0	9
Percent deer crashes	35.8%			
Number of segments	3,026			

Note: ft = feet, mi = miles, std dev = standard deviation; min = minimum; max = maximum

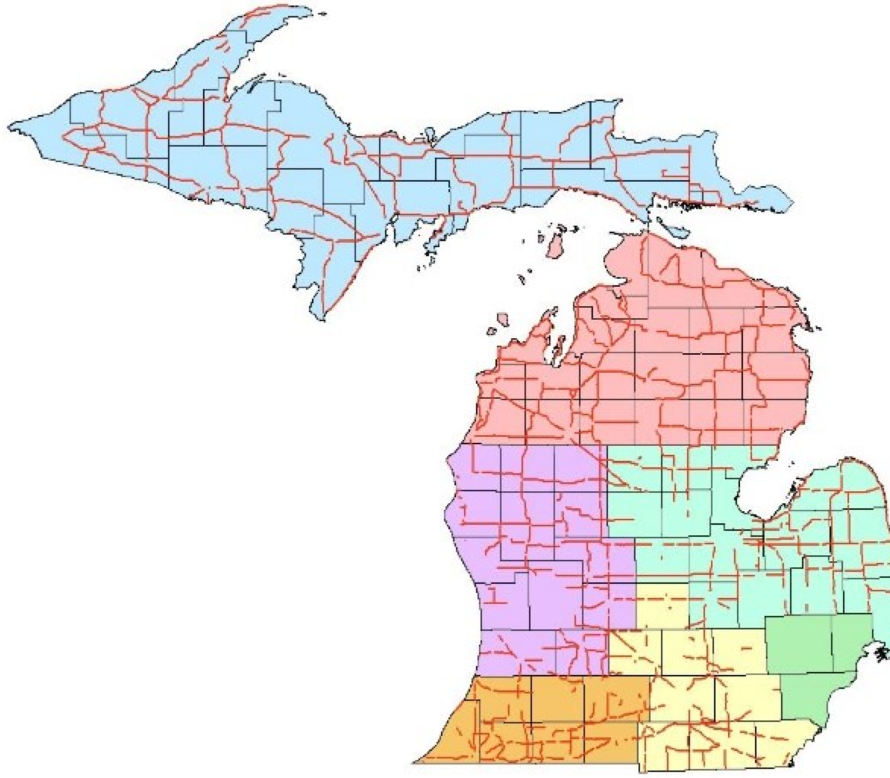


Figure 20: Map of rural state highway study segments (deer crashes)

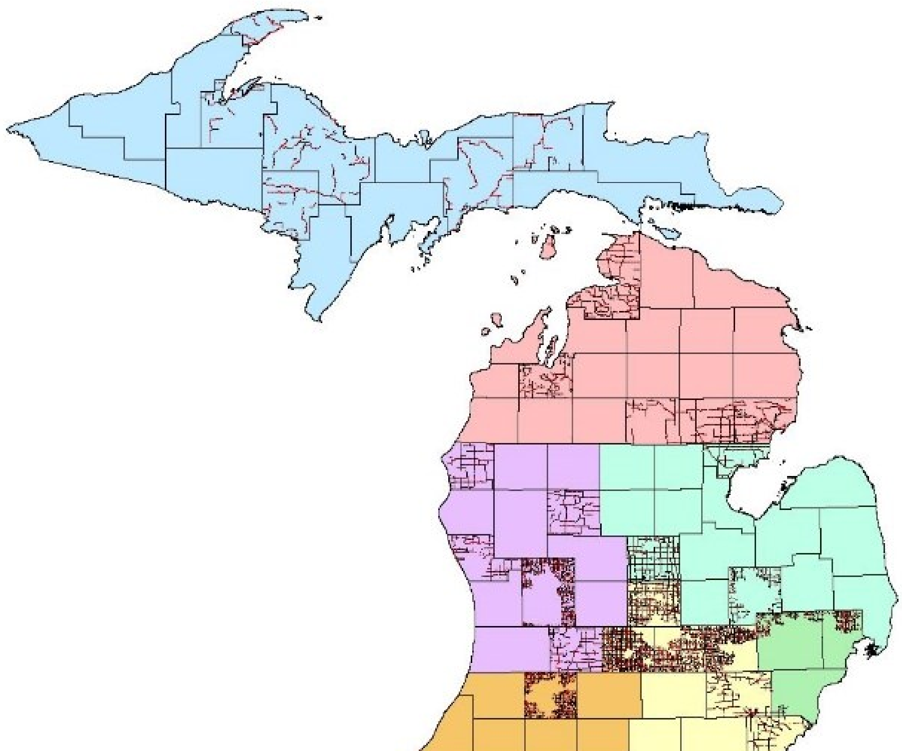


Figure 21: Map of rural county highway study segments (deer crashes)

6.2 Results and Discussion

The mixed effects negative binomial regression models yielded several interesting results. The full model results for state highways, county federal aid, county non-federal aid, and unpaved segments are presented in Table 48, Table 49, Table 50, and Table 51 respectively. In all cases, factors potentially related to speed were found to be a significant predictor variable for deer crashes. This is an intuitive finding, as faster speeds give drivers less time to react to deer, increasing the likelihood of collision.

For example, wider lanes were associated with increased crashes in the case of county federal aid, county non-federal aid, and unpaved segments, although this relationship was not significant on county-non-federal aid segments. In particular, on county federal aid segments, a 12-foot lane is associated with 24 percent more deer crashes than a 10-foot lane, while on unpaved segments, it is associated with an 8 percent increase. Readers should be aware that the average lane width for county segments (both federal aid and non-federal aid) was approximately 11 feet, and are referred to Tables 44-47 for full descriptive statistics. These results were consistent on state highways as well, where 12-foot lanes were associated with 14 percent greater fatal and injury crashes relative to 11-foot lanes. The effect of lane width was not significant for 10-foot lanes, or property damage only (PDO) crashes on state highway segments. While lane width was not significant for county non-federal-aid segments, the results still suggested increased crashes with wider lanes, consistent with all other segment categories. These findings are consistent with the notion that wider lanes are associated with faster speeds [120], perhaps contributing to greater crash occurrence, particularly those involving injury.

On the other hand, wider shoulders were associated with fewer PDO crashes, perhaps due to the increased separation between the roadside and traveled way along with the additional recovery area when evasive maneuvers are necessary for collision avoidance. Some research supports the notion that wider cross-sections, which wider shoulders imply, are associated with decreased deer activity [82].

Analysis of segment design-hour level of service (LOS) provided perhaps another indication of the association between faster speeds and increased deer crashes. MDOT's roadway inventory file includes design hour level of service ratings for all state highway segments, which was subsequently included in the state highway model. Relative to LOS A, all other levels of service showed a significant decrease in deer crashes, including decreases in fatal and injury crashes. With PDO crashes, where all categories of level-of-service were statistically significant, each decline in level-of-service was associated with a further decline in deer crashes.

The last factor likely related to speed was the number of curves designed below 55 mph (the statutory speed limit on all study segments was 55 mph), which was also associated with a decrease in deer crashes on paved roads across all jurisdictional categories. However, number of curves was not a significant factor on unpaved roads. This is shown graphically in Figure 22, which shows the estimated number of annual crashes for each jurisdictional category (under the following conditions: no paved shoulder, 12-ft lanes, no driveways, no substandard curves) compared with the same road classification with one substandard curve. This could be due to drivers generally traveling more slowly on unpaved roads, providing additional reaction time. This hypothesis is supported by the lack of deer crashes in relation to total crashes on unpaved roads (36 percent) compared to state highways, county federal aid, and county non-federal aid roadways (66 percent, 60 percent, and 60 percent, respectively).

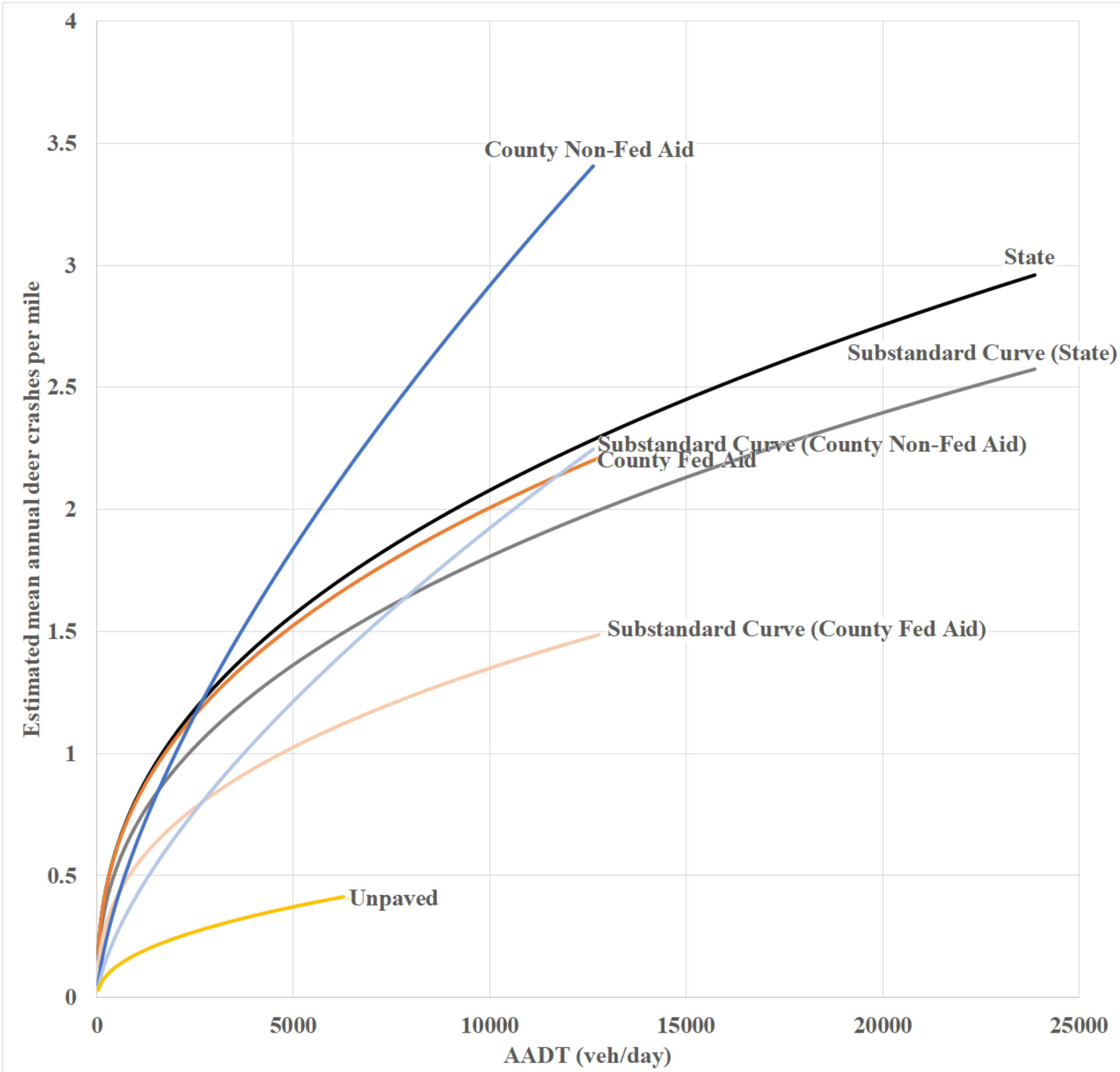


Figure 22: Deer crash model results under base conditions and with substandard curves

Driveway density was also a significant factor in deer crashes across all categories, although this result differed between state highway and county segments. On state highway segments, driveway density was associated with an increase in deer crashes. Anecdotally, hunters will modify and manipulate trails and access roads to direct deer to them [121-122], as wildlife will often use human-made paths. However, this trend did not hold for county segments, where driveway density was associated with a small decline in deer crashes, perhaps due to the increased human presence associated with greater driveway density. Further research is needed to more completely investigate the relationship between driveway density and deer crashes.

Lastly, the number of antlerless deer licenses offered by the Michigan Department of Natural Resources was included as a variable. The purpose was to serve as a surrogate for deer management practices, as antlerless deer licenses are the only type of deer hunting license offered in Michigan with geographic restrictions in order to incentivize hunting in specific areas. The results were inconsistent in terms of significance and sign, and very small in magnitude. This could indicate several things, one of which is that incentivizing deer hunting in specific locations may not have an influence on crashes. However, there are several limitations certainly leading to the statistical uncertainty that readers should be aware of. This variable measures the density of antlerless deer licenses available in the county or DMU of a given road segment. This is geographically imprecise, and some DMUs span several counties, making this even less precise. There is also a lack of a licensing system that considers geography with respect to bucks with antlers, and a lack of estimates of the total deer population by county or region.

Table 48: Mixed Effects Negative Binomial Model for Deer Crashes on State Highway Segments

Factor	Fatal and injury crashes			Property damage only crashes		
	Est	Std error	Sig	Est	Std error	Sig
Intercept	-7.14	0.644	<0.001	-3.022	0.177	<0.001
Segment length (ln[mi])	1			1		
Volume (ln[AADT])	0.456	0.081	<0.001	0.405	0.021	<0.001
Antlerless deer license quota (per square mile within county)						
Public land	-0.032	0.017	0.071	-0.005	0.005	0.306
Private land	-0.001	0.097	0.989	-0.004	0.025	0.885
Lane width						
12 ft	baseline					
10 ft	-0.194	0.488	0.692	-0.156	0.115	0.175
11 ft	-0.133	0.08	0.098	-0.016	0.021	0.448
Paved shoulder width						
<4 ft	baseline					
>4 ft	0.043	0.076	0.568	-0.048	0.02	0.014
Level of service						
A	baseline					
B	-0.241	0.102	0.018	-0.108	0.026	<0.001
C	-0.193	0.112	0.086	-0.131	0.03	<0.001
D	-0.215	0.171	0.209	-0.318	0.046	<0.001
E	-0.544	0.444	0.22	-0.299	0.102	0.003
Driveway density ($mile^{-1}$)						
<5 driveways	baseline					
>5 driveways	0.309	0.132	0.019	0.426	0.032	<0.001
Number of substandard curves	-0.059	0.055	0.285	-0.081	0.013	<0.001
Random effects						
MDOT region		0.114			0.134	
Year		0.085			0.061	
Overdispersion parameter	0.115			0.34		
AIC	5,275.00			37,731.40		
Log-likelihood	-2,621.50			-18,849.70		

Note: ft = feet, mi = miles, std = standard; sig = statistical significance

Table 49: Mixed Effects Negative Binomial Model for Deer Crashes on County Federal Aid Segments

Factor	Est.	Std error	Sig
Intercept	-4.054	0.253	<0.001
Segment length (ln[mi])	1.000		
Volume (ln[AADT])	0.395	0.011	<0.001
Public	-0.018	0.013	0.158
Private	0.017	0.002	<0.001
Driveway density (per mi)	-0.007	0.001	<0.001
Lane width			
9 ft	Baseline		
10 ft	0.894	0.237	<0.001
11 ft	1.044	0.237	<0.001
12 ft	1.112	0.237	<0.001
13 ft	1.349	0.246	<0.001
Number of substandard curves	-0.396	0.032	<0.001
Random effects			
MDOT region		0.157	
Year		0.039	
Overdispersion parameter	0.572		
AIC	75,921		
Log likelihood	-37,947		

Note: ft = feet, mi = miles, std = standard; sig = statistical significance

Table 50: Mixed Effects Negative Binomial Model for Deer Crashes on County Non-Federal Aid Segments

Factor	Est.	Std error	Sig
Intercept	-5.381	0.289	<0.001
Segment length (ln[mi])	1.000		
Volume (ln[AADT])	0.663	0.028	<0.001
Public land	0.073	0.037	0.047
Private land	0.003	0.008	0.688
Driveway density (per mile)	-0.015	0.002	<0.001
Lane width			
9 ft	Baseline		
10 ft	0.124	0.212	0.558
11 ft	0.313	0.213	0.142
12 ft	0.346	0.220	0.116
13 ft	0.152	0.407	0.709
Number of substandard curves	-0.416	0.085	<0.001
Random effects			
MDOT region		0.257	
Year		0.048	
Overdispersion parameter	0.665		
AIC	12,650		
Log-likelihood	-6,312		

Note: ft = feet, mi = miles, std = standard; sig = statistical significance

Table 51: Mixed Effects Negative Binomial Model for Deer Crashes on Unpaved Segments

Factor	Est	Std error	Sig
Intercept	-5.259	0.391	<0.001
Segment length (ln[mi])	1.000		
Volume (ln[AADT])	0.456	0.054	<0.001
Public land	-0.091	0.059	0.122
Private land	0.015	0.014	0.310
Driveway density (per mile)	-0.016	0.005	0.001
Lane width			
9 ft	Baseline		
10 ft	0.312	0.138	0.024
11 ft	0.402	0.160	0.012
12 ft	0.392	0.159	0.014
13 ft	0.794	0.198	<0.001
Number of substandard curves	-0.054	0.069	0.433
Random effects			
MDOT region		0.579	
Year		0.116	
Overdispersion parameter	0.636		
AIC	5,076		
Log-likelihood	-2,525		

Note: ft = feet, mi = miles, std = standard; sig = statistical significance

6.3 Summary and Conclusions

The primary objective of this research was to determine relationships between deer crashes and roadway characteristics across all classes of two-lane rural roadways in Michigan, including both paved and unpaved roadway surfaces. To accomplish this objective, highway data, including traffic volumes, roadway characteristics, and traffic crashes, were collected on state-owned rural roads statewide and on county-owned rural roads within a 30-county sample, and subsequently analyzed using mixed effect negative binomial modeling techniques.

The results showed that factors likely to be speed-related, including lane width and horizontal curvature, had a significant effect on vehicle deer crashes occurring on most categories of rural two-lane two-way roadway segments in the state of Michigan, although these factors did not have as much of an effect on unpaved roads, which see fewer DVCs and lower travel speeds Wider lanes were associated with a greater occurrence of deer crashes, perhaps due to higher prevailing travel speeds. Conversely, more curves with design speeds lower than the statutory speed limit were associated with fewer deer crashes, perhaps due to lower travel speeds on curved segments. Wider shoulders, which afford greater separation between the travel lanes and the roadside, were found to significantly reduce deer crash occurrence, furthering the hypothesis that wider clear zones are associated with a decrease in deer activity. Unfortunately, the concentration of hunting licenses, a potentially useful predictor for deer crashes, did not appear to have a consistent influence on vehicle-deer crashes.

Policymakers and practitioners can use this information in several ways. Primarily, decision-makers should be aware of the impact speed-related geometric features have on deer crashes, particularly as the state continues its trend of raising speed limits on highways and freeways in rural areas. For instance, the conventional wisdom is that wider lanes are safer, but this may not be the case in locations with high deer populations due to higher travel speeds and subsequent reduced reaction times. Adding paved shoulders and widening the clear-zone may also help mitigate deer-vehicle crashes in problem areas. Further research needs to be conducted to determine a more precise relationship between vehicle speeds and/or speed limit policy and vehicle-deer crashes, as well as the relationship between the roadside conditions and these crashes

7. CONCLUSIONS, AND RECOMMENDATIONS

Since 2005, federal highway funding bills in the U.S. have required states to have data-driven strategic highway safety plans [123]. In most states, considerable attention is given within these plans towards addressing rural highway safety issues, which remain a considerable problem in many parts of the country. The *Highway Safety Manual* assists towards that end, by providing models for estimating crash occurrence, as well as crash modification factors when parameters differ from base conditions. But while safety performance models for rural highway segments and intersections exist within the *HSM* and other literature sources, these models were typically developed using data from state-owned highways, which limits the transferability to secondary classes of rural highways, including those owned and maintained by county road agencies.

While Michigan-specific SPFs have been previously been developed, they were limited to urban and rural state-owned road segments and intersections [15-16]. Also, although *HSM* calibration factors are available for Michigan's rural highway network, including specific factors for county road segments and intersections, fully-specified SPFs utilizing local data have not been developed for county roadways. Prior research has shown that, when evaluating highways of the same functional class, improvements in the predictive capabilities will generally be achieved if SPFs are developed using local data rather than calibrating *HSM* SPFs, due to the variability in the parameter estimates between the *HSM* and state-specific models.

Rural county highways typically possess traffic, driver, and geometric characteristics that differ considerably from rural state highways. However, the safety performance of rural county roadways is rarely investigated to the same level of detail as that for state highways. This is an important gap, as many states, particularly those in the Midwest and Great Lakes regions, possess a substantial network of rural county-owned highways. Thus, determination of how various roadway and traffic related factors affect crashes on rural county highways, including both road segments and intersections, was the primary aim of this research. The findings would serve to support development of guidance for roadway designs and highway safety programs unique to rural county roadways and other rural secondary road networks.

As a part of this research, it was also important to consider differences *between* the various classes of county roadways, in particular, the distinction between federal aid and non-federal aid roadways. Federal aid roadways are subject to design standards approved by the FHWA, which are typically more stringent than those for non-federal aid roadways. Specifically, minimum design standards must be maintained in compliance with the posted speed limit for select controlling geometric elements, most notably horizontal and vertical curvature, on high speed federal aid roadways. Furthermore, nearly all available safety performance models are only applicable to paved roads, which further limits the applicability of these models for use by county or other local road agencies, which often maintain a substantial network of unpaved (gravel) roads. Thus, it was imperative that the county roadway safety performance models account for the differences between federal aid and non-federal aid roadway designs, while also investigating differences in safety performance between these roadway types.

It was also important to provide a more detailed investigation into the safety performance impacts of various roadway geometric characteristics, most notably horizontal curvature. While prior research has investigated the safety performance effects related to the *presence* of a horizontal curve on a segment, these models did not account for the *amount* curvature along the segment. Furthermore, there was little prior research available related to the incremental effects of curve design speed on safety performance. The safety performance effects of other design attributes, including intersection skew, were also taken into consideration.

To address these gaps, research was undertaken to investigate the safety performance characteristics of rural county highways. This included development of a series of safety performance functions for rural county highway segments and stop-controlled intersections. A series of fully-specified safety performance models were developed across all classes of rural county highways, including federal aid and non-federal aid roadways, while considering a broad range of geometric factors, paved and unpaved road segments, and 3-leg and 4-leg stop-controlled intersections. Specifically, safety performance functions were developed for the following roadway facility types using data collected from across Michigan:

a. Rural county two-lane two-way paved federal aid segments
b. Rural county two-lane two-way paved non-federal aid segments
c. Rural county unpaved non-federal aid segments
d. Rural three-leg minor-road stop-controlled intersections
e. Rural four-leg minor-road stop-controlled intersections

CMFs were also developed for various design factors for each of the rural segment and intersection types listed above, most notably, horizontal curves and intersection skew. Specific consideration was given to the incremental effects of curve design speed and the curved proportion of segment on segment crash occurrence, as these two aspects had not been fully researched in prior safety performance models. The results of this research serve to provide an important reference to guide states and local agencies toward making informed decisions as to planning and programming decisions for safety projects and roadway design standards, and to provide researchers with guidance regarding future work within the realm of safety performance on rural secondary roadways.

In general, the resulting county SPF results were generally different than prior models developed for similar state-owned highways, although some similarities were observed. It was determined that the jurisdiction and surface type of a roadway also affected model shape, which further demonstrated the need for county-specific SPFs. The SPFs and CMFs developed in this dissertation will provide additional tools for highway engineers to make safety-related design decisions on county roadways, as opposed to the common method of calibrating or otherwise applying SPFs and CMFs developed for state highways to county roadways.

Each of the models were developed utilized negative binomial regression, and, where appropriately, also included one or more random intercept terms, thereby resulting in mixed-effects models. Negative binomial regression is generally used in developing SPFs, and is the technique that was used to develop most of the models contained in the *HSM* [3]. However, one problem that arises when using a fixed effects model is that each observation is assumed to be independent from other observations. However, this is not the case, as each site or segment has five observations (from five years of annual crash counts), which are not truly independent from each other. For this reason, site-specific random effects were incorporated. In addition, this research addressed county highways, with multiple sites or segments analyzed within a given county. Because each county road commission maintains its own practices regarding construction, maintenance, and/or design for non-federal aid roadways, in addition to climatic, geographic, and driver related differences, there exists unobserved county-to-county heterogeneity that cannot be easily quantified by fixed factors, prompting the inclusion of a county-level random effect. Very little existing research has involved the use of county-specific random effects, which reflects the general lack of research on the safety performance of county highways.

7.1 Rural County-Owned Highway Segments

Some key findings concerning county-owned segments include the effect horizontal curvature has on crash frequency, particularly on federal aid segments. In general, lower curve design speed is associated with greater crash occurrence. The relationship between crash frequency and substandard curvature (i.e., horizontal curves that have design speeds below the statutory speed limit of 55 mph) was present across all curve design speed categories on paved federal-aid highways, which tend to be major collectors, and the magnitude of this increase monotonically increases with decreasing design speed.

For paved non-federal aid county highways, for which construction and maintenance is funded solely by state and/or local dollars, the increase in crashes was only significant for curves with design speeds of less than 45 mph. This finding is important, as such extreme horizontal curvature is more likely to be encountered on non-federal aid roadways compared to higher classes of rural highways. The CMFs presented in this dissertation provide an opportunity for designers to make educated decisions concerning horizontal curve correction during reconstruction and rehabilitation projects, and also opens the opportunity for local agencies to receive safety funding that require appropriate CMFs to justify spending. In particular, on paved highways, correcting horizontal curves with design speeds of less than 40 mph could reduce crashes by more than fourfold.

On all three classes of roadway, there was a significant increase in crashes, relative to base conditions, when curve radius was lower than 40 miles per hour. This is significant, because during roadway reconstruction or rehabilitation of a federal-aid roadway, horizontal curves with design speeds 15 miles per hour or lower than the posted speed limit or overall roadway design speed (e.g., 40 mph for a 55-mph posted speed limit), must either be re-aligned or granted a design exception from FHWA [124]. Interestingly, the deer-specific analysis from Chapter 6 showed the opposite results, where the presence of horizontal curvature is associated with reduced crash frequency, likely due to the reduced travel speeds of motorists at horizontal curve locations.

This research also confirms prior research demonstrating a higher crash rate associated with higher access point frequency. This was especially notable for paved segments with 25 driveways per mile or more; on county federal aid highways, where drivers may be less familiar with their surroundings due to trip characteristics (non-federal aid highways tend to be local roads while federal aid tend to be collectors), crash occurrence also increased when there were between 5 and 25 driveways per mile. This provides additional evidence pointing to the need to consolidate driveways on federal aid highways, in particular.

This research demonstrates the importance of using SPFs developed specifically for county-owned roadways, and between funding categories. For rural highway segments, it was shown that the shape of each function is quite different; although there are overarching trends concerning which category of roadway (i.e., state, county federal aid, county non-federal aid, and unpaved) experience the most or fewest crashes, these patterns do not hold at all traffic volumes. For instance, unpaved roads experience the highest crash frequency at low AADTs but the lowest crash frequency at more moderate AADTs. Similarly, MDOT roadways experience fewer crashes than paved non-federal aid segments at lower volumes, but more crashes at higher volumes. If calibration were used, rather than developing new SPFs, this could lead to under- and over-prediction of crashes.

7.2 Rural Minor Road Stop-Controlled Intersections

At rural stop-controlled intersections, the most significant geometric factor that influenced crash frequency was intersection skew. Intersections with skew angles between 1 and 9 degrees did not experience significant differences in crashes compared to intersections with no skew. However, at four leg stop-controlled intersections, sites with skew angles between 10 and 39 degrees experienced significantly more crashes than those with no skew, with model results estimating an increase in crashes of 28 percent. On four-leg intersections where the major road is county non-federal aid, the increase in crashes was even greater, with a 60 percent increase in crashes. In contrast, the models developed for three-leg stop controlled intersections did not show a significant increase in crashes when skew angle was between 10 and 39 degrees.

Similar to rural segments, the safety performance of rural intersections varied depending on site type. Intersections with the major roadway under state jurisdiction experienced the highest crash occurrence, while county federal aid experienced the least. There were also significant differences between the models developed here and the models presented in the *HSM*, with the *HSM* generally overpredicting. As with county segments, model shape varied depending on the site type.

7.3 Recommendations for Future Work

The research described in this dissertation has implications for future research. For rural county highway segments, horizontal curvature was one of the factors evaluated, and CMFs for various design speeds were developed. However, the methods for collecting and subsequently structuring the data was focused on describing the attributes of the segments themselves, rather than curves, specifically. This is best demonstrated by the fact that segmentation was provided by the Michigan Geographic Framework's All Roads file, and curve data was subsequently integrated into the dataset. A relevant future analysis would begin by identifying all horizontal curves within a state, or a subset of the state, in order to investigate the safety effects of whether the curve was isolated or as a part of a series of successive curves. Thus, such an analysis must include characteristics such as the length of the tangent leading into the curve (or between successive curves), as it is expected that a compound curve (S-curve) or any series of horizontal curves would have different safety performance than an isolated curve. Furthermore, although the curved proportion of the segment was included as a safety performance factor, the length of the curve itself was not considered in this research, again, owing to the nature of how the data were collected.

Another key question related to horizontal curvature that arises from this research is to investigate the radius at which a horizontal curve begins to possess safety performance that is equivalent to a tangent segment. In other words, determining the minimum radius at which curvature no longer impacts safety performance. While this research compared curves with design speeds below 55 mph with segments without such *substandard* curves, future research should also include horizontal curves of with design speeds *above* 55 mph. This dissertation did demonstrate that on non-federal highways, horizontal curves with design speeds between 45 mph and 55 mph did not perform significantly different from base conditions, but it is important to remember that curves with design speeds of 55 mph or greater were included in the base condition. It was not possible to separate curves with higher design speeds from pure tangent sections based on the way that the data were collected for this study.

Another area that was beyond the scope of this research is the effect of speed transition zones, i.e., reduced speed limits as vehicles lead into build-up areas. This research focused on highway segments with speed limits of 55 miles per hour, the statutory speed limit in Michigan for rural county roads. However, in order to develop guidance with respect to when speed transitions are warranted, the manner in which they are implemented (e.g., how many 10 mph "steps" the speed limit is reduced by, how far in advance of the built-up area they should be used, and length between "steps") should be further explored.

With respect to rural intersections, this research presents a comprehensive analysis of three- and four-leg rural intersections of all jurisdictional classes, with a focus on intersection skew angle. This research confirmed a previous piece of research that found that, while moderate skew angles are associated with crash increases, extreme skew angles can be associated with crash reductions relative to intersections with little-to-no skew. However, a causal explanation for this counter-intuitive result has not been determined. While there are several potential explanations, such as drivers taking more care at intersections they perceive to be dangerous, the model results themselves do not indicate the cause of this effect. Future research to evaluate skew could involve the use of the SHRP-2 naturalistic driving experiment to determine how drivers behave at intersections of varying skew angles.

There are other approaches that do not involve direct observation of human subjects. For instance, researchers could evaluate skew along with other factors, such as the percentage of left-turning versus right-turning traffic, and correlate this to the angle at which most vehicles are turning (i.e., are most vehicles making a turn greater than or less than 90 degrees). Turning movement data were not available when this research was being completed.

Other aspects of the intersection zone, which was defined in this research as being within a 211-foot radius of the center of the intersection, can be explored further. For instance, skew was explored in this paper; however, correcting intersection skew requires the introduction of horizontal curvature in advance of the intersection on the leg that is stop-controlled. The effect of curvature within the intersection influence zone is an important area that needs to be researched further, as it can be used to develop guidelines on when, and how, to correct intersections with nonzero skew angles.

Lastly, while this research focused on traditional three- and four-leg intersections, there are other types of intersections whose safety performance should be quantified. For instance, intersections with five or more legs without a traffic signal are uncommon, but do exist, and it is useful to know how their safety can be improved. More common atypical intersection configuration which can be researched further include so-called “curved corner” intersections, where the free-flowing leg is on a curve, as well as “offset T” intersections (i.e., a four-leg intersection where stop-controlled legs are separated from each other by some lateral distance.

APPENDICES

Appendix A: Fixed Effects Models

Table 52: Fixed Effects Negative Binomial Model Results for Paved Federal Aid Segments

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-6.006	0.002	0.108	<0.001
Segment length	Offset, natural log of, miles				
AADT	Natural log of, vehicles per day	0.730	2.076	0.015	<0.001
Horizontal curve design speed					
>55 mph	Baseline				
50-54.9 mph	Curved proportion of segment	0.776	2.174	0.114	<0.001
45-49.9 mph	Curved proportion of segment	1.029	2.798	0.126	<0.001
40-44.9 mph	Curved proportion of segment	1.033	2.810	0.191	<0.001
<40 mph	Curved proportion of segment	1.613	5.015	0.260	<0.001
10-ft lane	Baseline				
11-ft lane	Width in feet	-0.063	0.939	0.032	0.046
12-ft lane	Width in feet	-0.056	0.945	0.036	0.113
13-ft lane	Width in feet	-0.143	0.866	0.068	0.036
0 to 1 ft shoulder	Baseline				
2-ft shoulder	Width in feet	-0.088	0.916	0.038	0.020
3 to 8 ft shoulder	Width in feet	-0.014	0.986	0.026	0.590
0-to-4.9 driveways per mile	Baseline				
5-to-14.9 driveways per mile	Binary indicator variable	0.150	1.162	0.030	<0.001
15-to-24.9 driveways per mile	Binary indicator variable	0.224	1.251	0.033	<0.001
≥25 driveways per mile	Binary indicator variable	0.308	1.360	0.035	<0.001
Overdispersion parameter		0.172			
AIC		50,205.7			
Log likelihood		-25,087.9			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion; mph = miles per hour; ft = foot

Table 53: Fixed Effects Negative Binomial Model Results for Paved Non-Federal Aid Segments

Factor	Description	Estimate	Exp(B)	Std error	P-value
Intercept		-6.683	0.001	0.278	<0.001
Segment length	Offset, natural log of, miles				
AADT	Natural log of, vehicles per day	0.804	2.234	0.042	<0.001
Horizontal curve design speed					
>55 mph	Baseline				
50-54.9 mph	Curved proportion of segment	0.287	1.332	0.377	0.447
45-49.9 mph	Curved proportion of segment	0.288	1.334	0.517	0.577
40-44.9 mph	Curved proportion of segment	0.916	2.498	0.393	0.020
<40 mph	Curved proportion of segment	1.534	4.638	0.563	0.006
11-ft lane	Baseline				
12- or 13-ft lane	Width in feet	-0.077	0.926	0.097	0.428
9- or 10-ft lane	Width in feet	0.068	1.070	0.061	0.268
0-ft shoulder	Baseline				
1-ft shoulder	Width in feet	0.058	1.059	0.075	0.442
2-ft shoulder or wider	Width in feet	0.062	1.064	0.144	0.667
0-to-4.9 driveways per mile	Baseline				
5-to-14.9 driveways per mile	Binary indicator variable	0.094	1.099	0.100	0.344
15-to-24.9 driveways per mile	Binary indicator variable	0.076	1.079	0.104	0.462
≥25 driveways per mile	Binary indicator variable	0.316	1.371	0.103	0.002
Overdispersion parameter		0.082			
AIC		8,465.6			
Log likelihood		-4,218.8			

Table 54: Fixed Effects Negative Binomial Model Results for Unpaved Non-Federal Aid Segments

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-7.322	0.001	0.539	<0.001
Segment length	Offset, natural log of, miles				
AADT	Natural log of, vehicles per day	0.634	1.885	0.047	<0.001
Horizontal curve design speed					
>55 mph	Baseline				
50-54.9 mph	Curved proportion of segment	1.596	4.935	0.377	<0.001
45-49.9 mph	Curved proportion of segment	1.593	4.920	0.313	<0.001
40-44.9 mph	Curved proportion of segment	1.051	2.860	0.407	0.010
<40 mph	Curved proportion of segment	1.563	4.772	0.343	<0.001
Surface width	Width in feet, natural log of	0.528	1.695	0.199	0.008
0-to-4.9 driveways per mile	Baseline				
5-to-14.9 driveways per mile	Binary indicator variable	0.566	1.762	0.082	<0.001
15-to-24.9 driveways per mile	Binary indicator variable	0.557	1.745	0.091	<0.001
≥25 driveways per mile	Binary indicator variable	0.752	2.122	0.099	<0.001
Overdispersion parameter		0.048			
AIC		9,110.8			
Log likelihood		-4,544.4			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion; mph = miles per hour; ft = foot

Table 55: Fixed Effects Negative Binomial Model Results for 3ST Rural Intersections

Factor	Description	Est	Exp(B)	Std error	Sig
Intercept		-6.831	0.001	0.191	<0.001
Major road AADT	Natural log of, vehicles per day	0.336	1.399	0.023	<0.001
Minor road AADT	Natural log of, vehicles per day	0.535	1.707	0.018	<0.001
Skew 0 degrees	Deviation from 90 degrees	baseline			
Skew 1 to 9 degrees	Deviation from 90 degrees	-0.056	0.945	0.068	0.411
Skew 10 to 39 degrees	Deviation from 90 degrees	-0.063	0.939	0.041	0.126
Skew ≥40 degrees	Deviation from 90 degrees	-0.339	0.712	0.068	<0.001
State highway	Major road jurisdiction	baseline			
County FA	Major road jurisdiction	-0.254	0.776	0.037	<0.001
County non-FA	Major road jurisdiction	-0.616	0.540	0.09353	<0.001
Overdispersion parameter		0.515			
AIC		17,581.00			
Log-likelihood		-8,781.7			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion

Table 56: Fixed Effects Negative Binomial Model Results for 4ST Rural Intersections

Factor	Description	Est	Exp(B)	Std error	Sig
Intercept		-7.060	0.001	0.143	<0.001
Major road AADT	Natural log of, vehicles per day	0.375	1.455	0.018	<0.001
Minor road AADT	Natural log of, vehicles per day	0.557	1.746	0.015	<0.001
Railroad crossing	Present within 211 feet	0.238	1.268	0.081	0.003
Skew 0 degrees	Deviation from 90 degrees	baseline			
Skew 1 to 9 degrees	Deviation from 90 degrees	0.075	1.078	0.061	0.221
Skew 10 to 39 degrees	Deviation from 90 degrees	0.263	1.301	0.031	<0.001
Skew ≥40 degrees	Deviation from 90 degrees	-0.029	0.972	0.060	0.632
State highway	Major road jurisdiction	baseline			
County FA	Major road jurisdiction	-0.112	0.894	0.027	<0.001
County non-FA	Major road jurisdiction	-0.319	0.727	0.0759	<0.001
Overdispersion parameter		0.505			
AIC		31,295.00			
Log-likelihood		-15,637.4			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion

Appendix B: Temporally Aggregated Model

Table 57: Temporally Aggregated Fixed Effects Negative Binomial Model Results for Paved Federal Aid Segments

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-4.858	0.008	0.135	<0.001
Segment length	Offset, natural log of, miles				
AADT	Natural log of, vehicles per day	0.443	1.558	0.019	<0.001
Horizontal curve design speed					
>55 mph	Baseline				
50-54.9 mph	Curved proportion of segment	0.581	1.787	0.143	<0.001
45-49.9 mph	Curved proportion of segment	0.863	2.370	0.148	<0.001
40-44.9 mph	Curved proportion of segment	0.393	1.482	0.243	0.105
<40 mph	Curved proportion of segment	1.207	3.343	0.340	<0.001
10-ft lane	Baseline				
11-ft lane	Width in feet	-0.096	0.908	0.042	0.021
12-ft lane	Width in feet	-0.157	0.855	0.047	0.001
13-ft lane	Width in feet	-0.096	0.909	0.088	0.273
0 to 1 ft shoulder	Baseline				
2-ft shoulder	Width in feet	-0.058	0.944	0.053	0.277
3 to 8 ft shoulder	Width in feet	-0.133	0.876	0.037	<0.001
0-to-4.9 driveways per mile	Baseline				
5-to-14.9 driveways per mile	Binary indicator variable	0.345	1.411	0.039	<0.001
15-to-24.9 driveways per mile	Binary indicator variable	0.428	1.534	0.044	<0.001
≥25 driveways per mile	Binary indicator variable	0.326	1.386	0.047	<0.001
Overdispersion parameter		1.400			
AIC		27,636.7			
Log likelihood		-13,803.4			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion; mph = miles per hour; ft = foot

Appendix C: Mixed Effects Models without Length Offset

Table 58: Mixed Effects Negative Binomial Model Results for Paved Federal Aid Segments (No Length Offset)

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-5.949	0.003	0.151	<0.001
Segment length	Natural log of, miles	0.936	2.550	0.020	<0.001
AADT	Natural log of, vehicles per day	0.677	1.968	0.020	<0.001
Horizontal curve design speed					
>55 mph	Baseline				
50-54.9 mph	Curved proportion of segment	0.699	2.011	0.136	<0.001
45-49.9 mph	Curved proportion of segment	1.061	2.888	0.149	<0.001
40-44.9 mph	Curved proportion of segment	0.966	2.626	0.224	<0.001
<40 mph	Curved proportion of segment	1.409	4.091	0.324	<0.001
10-ft lane	Baseline				
11-ft lane	Width in feet	0.014	1.014	0.041	0.729
12-ft lane	Width in feet	0.048	1.050	0.048	0.314
13-ft lane	Width in feet	0.123	1.131	0.088	0.161
0 to 1 ft shoulder	Baseline				
2-ft shoulder	Width in feet	-0.048	0.953	0.048	0.323
3 to 8 ft shoulder	Width in feet	0.042	1.043	0.036	0.250
0-to-4.9 driveways per mile	Baseline				
5-to-14.9 driveways per mile	Binary indicator variable	0.119	1.126	0.036	0.001
15-to-24.9 driveways per mile	Binary indicator variable	0.178	1.195	0.040	<0.001
≥25 driveways per mile	Binary indicator variable	0.262	1.299	0.043	<0.001
Site random effect				0.555	
County random effect				0.254	
Overdispersion parameter		0.045			
AIC		49,256.7			
Log likelihood		-24,610.3			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion; mph = miles per hour; ft = foot

Table 59: Mixed Effects Negative Binomial Model Results for Paved Non-Federal Aid Segments (No Length Offset)

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-6.848	0.001	0.310	<0.001
Segment length	Natural log of, miles	1.017	2.764	0.059	<0.001
AADT	Natural log of, vehicles per day	0.802	2.229	0.047	<0.001
Horizontal curve design speed					
>55 mph	Baseline				
50-54.9 mph	Curved proportion of segment	0.275	1.317	0.432	0.524
45-49.9 mph	Curved proportion of segment	0.279	1.322	0.569	0.624
40-44.9 mph	Curved proportion of segment	0.959	2.610	0.450	0.033
<40 mph	Curved proportion of segment	1.442	4.230	0.665	0.030
11-ft lane	Baseline				
12- or 13-ft lane	Width in feet	-0.066	0.936	0.110	0.548
9- or 10-ft lane	Width in feet	0.043	1.044	0.070	0.539
0-ft shoulder	Baseline				
1-ft shoulder	Width in feet	0.060	1.062	0.088	0.495
2-ft shoulder or wider	Width in feet	0.096	1.101	0.166	0.561
0-to-4.9 driveways per mile	Baseline				
5-to-14.9 driveways per mile	Binary indicator variable	0.092	1.096	0.112	0.410
15-to-24.9 driveways per mile	Binary indicator variable	0.068	1.070	0.117	0.560
≥25 driveways per mile	Binary indicator variable	0.311	1.365	0.116	0.007
Site random effect				0.638	
County random effect				<0.001	
Overdispersion parameter		0.022			
AIC		8,420.4			
Log likelihood		-4,193.2			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion; mph = miles per hour; ft = foot

Table 60: Mixed Effects Negative Binomial Model Results for Unpaved Segments (No Length Offset)

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-5.792	0.003	0.667	<0.001
Segment length	Natural log of, miles	0.944	2.571	0.051	<0.001
AADT	Natural log of, vehicles per day	0.601	1.823	0.052	<0.001
Horizontal curve design speed					
>55 mph	Baseline				
50-54.9 mph	Curved proportion of segment	1.721	5.592	0.365	<0.001
45-49.9 mph	Curved proportion of segment	1.357	3.886	0.310	<0.001
40-44.9 mph	Curved proportion of segment	1.244	3.469	0.380	0.001
<40 mph	Curved proportion of segment	1.278	3.590	0.334	<0.001
Surface width	Width in feet, natural log of	0.087	1.091	0.235	0.711
0-to-4.9 driveways per mile	Baseline				
5-to-14.9 driveways per mile	Binary indicator variable	0.168	1.182	0.087	0.053
15-to-24.9 driveways per mile	Binary indicator variable	0.019	1.019	0.099	0.846
≥25 driveways per mile	Binary indicator variable	0.167	1.181	0.108	0.122
County random effect				0.732	
Overdispersion parameter		0.026			
AIC		8,945.3			
Log likelihood		-4,459.7			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion; mph = miles per hour; ft = foot

Appendix D: Mixed Effects Models with Modified Curve Variables

Table 61: Mixed Effects Negative Binomial Model Results for Paved Federal Aid Segments (Binary Curve Variables)

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-5.947	0.003	0.156	<0.001
Segment length	Offset, natural log of, miles				
AADT	Natural log of, vehicles per day	0.681	1.976	0.021	<0.001
Horizontal curve design speed					
>55 mph	Baseline				
50-54.9 mph	Curved proportion of segment	0.614	1.848	0.223	0.006
45-49.9 mph	Curved proportion of segment	1.149	3.154	0.218	<0.001
40-44.9 mph	Curved proportion of segment	0.932	2.539	0.383	0.015
<40 mph	Curved proportion of segment	-12.272	0.000	593.110	0.983
10-ft lane	Baseline				
11-ft lane	Width in feet	0.027	1.027	0.043	0.537
12-ft lane	Width in feet	0.059	1.061	0.050	0.240
13-ft lane	Width in feet	0.133	1.142	0.091	0.145
0 to 1 ft shoulder	Baseline				
2-ft shoulder	Width in feet	-0.055	0.946	0.050	0.271
3 to 8 ft shoulder	Width in feet	0.048	1.049	0.038	0.200
0-to-4.9 driveways per mile	Baseline				
5-to-14.9 driveways per mile	Binary indicator variable	0.113	1.120	0.037	0.002
15-to-24.9 driveways per mile	Binary indicator variable	0.194	1.214	0.041	<0.001
≥25 driveways per mile	Binary indicator variable	0.291	1.338	0.044	<0.001
Site random effect				0.558	
County random effect				0.239	
Overdispersion parameter		0.040			
AIC		46,161.7			
Log likelihood		-23,063.9			

Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion; mph = miles per hour; ft = foot

Table 62: Mixed Effects Negative Binomial Model Results for Paved Federal Aid Segments (Quasi-Binary Curve Variable for <40 mph Curve Design Speed)

Factor	Description	Est	Exp(B)	Std error	P-value
Intercept		-5.951	0.003	0.156	<0.001
Segment length	Offset, natural log of, miles				
AADT	Natural log of, vehicles per day	0.681	1.976	0.021	<0.001
Horizontal curve design speed					
>55 mph	Baseline				
50-54.9 mph	Curved proportion of segment	0.614	1.848	0.223	0.006
45-49.9 mph	Curved proportion of segment	1.149	3.155	0.218	<0.001
40-44.9 mph	Curved proportion of segment	0.931	2.537	0.383	0.015
*<40 mph**	*Curved proportion of segment*	*1.080*	*2.944*	*0.500*	*0.031*
10-ft lane	Baseline				
11-ft lane	Width in feet	0.026	1.026	0.043	0.542
12-ft lane	Width in feet	0.059	1.061	0.050	0.240
13-ft lane	Width in feet	0.133	1.142	0.091	0.145
0 to 1 ft shoulder	Baseline				
2-ft shoulder	Width in feet	-0.055	0.947	0.050	0.275
3 to 8 ft shoulder	Width in feet	0.049	1.051	0.038	0.189
0-to-4.9 driveways per mile	Baseline				
5-to-14.9 driveways per mile	Binary indicator variable	0.114	1.121	0.037	0.002
15-to-24.9 driveways per mile	Binary indicator variable	0.194	1.214	0.041	<0.001
≥25 driveways per mile	Binary indicator variable	0.292	1.339	0.044	<0.001
Site random effect				0.558	
County random effect				0.240	
Overdispersion parameter		0.040			
AIC		46,189.9			
Log likelihood		-23,077.9			

*The quasi-curve variable only applies to <40 mph curve design speed segments, all other curve variables are binary
Note: Est = parameter estimate, Std = standard, AIC = Akaike information criterion; mph = miles per hour; ft = foot

REFERENCES

REFERENCES

[1] National Center for Statistics and Analysis, "Rural/urban comparison of traffic fatalities: 2018 data (Traffic Safety Facts. Report No. HOT HS 812 957)," National Highway Traffic Safety Adinistration, Washington, D.C., 2020.

[2] US. Department of Transportation, Federal Highway Administration, "HSIP History," 3 June 2009. [Online]. Available: https://safety.fhwa.dot.gov/hsip/gen_info/hsip_history.cfm.

[3] AASHTO, Highway Safety Manual, First Edition, Washington, D.C.: American Association of State Highway and Transportation Officials, 2010.

[4] American Association of State Highway and Transportation Officials, Highway Safety Manual, 1st Edition, Supplement, Washington, D.C.: American Association of State Highway and Transportation Officials, 2014.

[5] B. K. Brimley, M. Saito and G. G. Schultz, "Calibration of the Highway Safety Manual Safety Performance Function: Development of New Models for Rural Two-Lane Two-Way Highways," *Transportation Research Board, Journal of the Transportation Research Board, No. 2279,* pp. 82-89, 2012.

[6] C. Bornheimer, S. D. Schrock, M. Wang and H. Lubliner, "Developing a Regional Safety Performance Function for Rural Two-Lane Highways," in *91st Annual Meeting of the Transportation Research Board*, Washington, D.C., 2012.

[7] S. Srinivasan, P. Haas, N. S. Dhakar, R. Hormel, D. Torbic and D. Harwood, "Development and Calibration of Highway Safety Manual Equations for Florida Conditions," Florida Department of Transportation, Publication TRC-FDOT-82013-2011, 2011.

[8] R. A. Tegge, J. Jo and Y. Ouyang, "Development and Application of Safety Performance Functions for Illinois," Illinois Department of Transportation, Publication FHWA-ICT10-066, 2010.

[9] H. Lubliner and S. D. Schrock, "Calibration of the Highway Safety Manual Prediction Method for Rural Kansas Highways," in *91st Annual Meeting of the Transportation Research Board*, Washington, D.C., 2012.

[10] R. Srinivasan and D. Carter, "Development of Safety Performance Functions for North Carolina," North Carolina Department of Transportation, Publication FHWA/NC/2010-09, 2011.

[11] K. Dixon, C. Monsere, F. Xie and K. Gladhill, "Calibrating the Future Highway Safety Manual Predictive Methods for Oregon State Highways," Oregon Department of Transportation, Publication FHWA-OR-RD-12-07, 2012.

[12] N. J. Garber, P. R. Haas and C. Goose, "Development of Safety Performance Functions for Two-Lane Roads Maintained by the Virginia Department of Transportation," FHWA, Virginia Department of Transportation, Publication FHWA/VTRC 10-R25, 2010.

[13] Michigan State Police, "Crash Database," Lansing, 2011-2015.

[14] P. Alluri and J. Ogle, "Effects of State-Specific SPFs, AADT Estimations, and Overdispersion Parameters on Crash Predictions Using SafetyAnalyst," in *91st Annual Meeting of the Transportation Research Board*, Washington, D.C., 2012.

[15] P. T. Savolainen, T. J. Gates, D. Lord, S. Geedipally and E. Rista, "Michigan Urban Trunkline Intersections Safety Performance Functions (SPFs) Development and Support," Michigan Department of Transportation, Publication RC-1628, 2015.

[16] T. Gates, 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," Michigan Department of Transportation, Report SPR-1645, 2018.

[17] Michigan Department of Transportation, Michigan Road Design Manual, Lansing, MI: Michigan Department of Transportation, 2020.

[18] S. Y. Stapleton, A. Ingle, M. Chakraborty, T. J. Gates and P. T. Savolainen, "Safety Performance Functions for Rural Two-Lane County Road Segments," in *97th Annual Meeting of the Transportation Research Board*, Washington, D.C., 2018.

[19] J. P. Gooch, V. V. Gayah and E. T. Donnell, "Quantifying the safety effects of horizontal curves on two-way, two-lane rural roads," *Accident Analysis & Prevention, No. 92,* pp. 71-81, 2016.

[20] D. W. Harwood, F. M. Council, E. Hauer, W. E. Hughes and A. Vogt., "Prediction of the Expected Safety Performance of Rural Two-Lane Highways," Federal Highway Administration, U.S. Department of Transportation, 2000.

[21] R. Srinivasan, D. Carter and K. Bauer, "Safety Performance Function Decision Guide: SPF Calibration vs SPF Development," Federal Highway Administration, Washington, USA,, 2013.

[22] W. N. Venables and B. D. Ripley, Modern Applied Statistics with S. Fourth Edition, New York: Springer, 2002.

[23] University of North Carolina Safety Research Center, "Crash Modification Factor Clearinghouse," 15 March 2017. [Online]. Available: http://www.cmfclearinghouse.org.

[24] L. Wu, D. Lord and Y. Zou, "Validation of Crash Modification Factors Derived from Cross-Sectional Studies with Regression Models," *Transportation Research Record: Journal of the Transportation Research Board,* vol. 2514, pp. 88-96, 2015.

[25] R. Avelar, K. Dixon and D. McDaniel, "An Evaluation of the Independence Assumption when Combining Crash Modification Factors," in *TRB 95th Annual Meeting*, Washington D.C., 2016.

[26] R. D. Connors, M. Maher, A. Wood, L. Mountain and K. Ropkins, "Methodology for Fitting and Updating Predictive Accident Models with Trend," *Accident Analysis and Prevention,* vol. 56, pp. 82-94, 2013.

[27] D. Lord, S. Geedipally and M. Shirazi, "Improved Guidelines for Estimating the Highway Safety Manual Calibration Factors," College Sation, TX, 2016.

[28] S. Geedipally, D. Lord and M. Shirazi, "Exploring the Need for Having Region-Specific Calibration Factors," in *TRB 96th Annual Meeting Compendium of Papers*, Washington D.C, 2017.

[29] M. Shirazi, S. Geedipally and D. Lord, "A Procedure to Determine When Safety Performance Functions Should be Recalibrated," *Journal of Transportation Safety and Security,* vol. 9, no. 4, pp. 457-469, 2017.

[30] A. G. Wood, L. J. Mountain, R. D. Connors, M. J. Maher and K. Ropkins, "Updating Outdated Predictive Accident Models," *Accident Analysis & Prevention,* vol. 55, pp. 54-66, 2013.

[31] K. Dixon, C. Monsere, F. Xie and K. Gladhill, "Calibrating the Future Highway Safety Manual Predictive Methods for Oregon State Highways," 2012.

[32] M. Rodgers, A. Wilson, A. Shaw and M. Barton, "Applying the Highway Safety Manual to Georgia," Georgia Department of Transportation, 2015.

[33] P. Alluri, D. Saha and A. Gan, "Minimum Sample Sizes for Estimating Reliable Highway Safety Manual (HSM) Calibration Factors," *Journal of Transportation Safety & Security,* vol. 8, no. 1, pp. 56-74, 2016.

[34] M. Shirazi, D. Lord and S. Geedipally, "Sample-Size Guidelines for Recalibrating Crash Prediction Models: Recommendation for the Highway Safety Manual," *Accident Analysis & Prevention,* vol. 93, pp. 160-168., 2016.

[35] G. B. Bahar and E. Hauer, "User's Guide to Develop Highway Safety Manual Safety Performance Function Calibration Factors," NCHRP, Washington, D.C., 2014.

[36] M. Saito, C. Knecht and G. Schultz, "Crash Prediction Modeling for Curved Segments of Rural Two-Lane Two-Way Highway in Utah," Utah Department of Transportation, 2015.

[37] F. Xie, K. Gladhill, K. Dixon and C. Monsere, "Calibration of Highway Safety Manual Predictive Models for Oregon State Highways," *Transportation Research Record: Journal of the Transportation Research Board,* pp. 19-28, 2011.

[38] S. Srinivasan, P. Haas, N. Dhakar, R. Hormel, D. Torbic and D. Harwood, "Development and Calibration of Highway Safety Manual Equations for Florida Conditions," Florida Department of Transportation, 2011.

[39] R. Srinivasan and D. Carter, "Development of Safety Performance Functions for North Carolina," North Carolina Department of Transportation, Chapel Hill., 2011.

[40] H. Shin, Y. Lee and S. Dadvar, "The Development of Local Calibration Factors for Implementing the Highway Safety Manual in Maryland," Maryland State Highway Administration, Hanover, MD, 2014.

[41] C. Sun, H. Brown, P. Edara, B. Claros and K. Nam, "Calibration of the Highway Safety Manual for Missouri," Research and Innovative Technology Administration, Washington, D.C., 2013.

[42] K. Dixon, C. Monsere, R. Avelar, J. Barnett, P. Escobar, S. Kothuri and Y. Wang, "Improved Safety Performance Functions for Signalized Intersections," Oregon Department of Transportation, 2015.

[43] B. Brimley, M. Saito and G. Schultz, "Calibration of Highway Safety Manual Safety Performance Function: Development of New Models for Rural Two-Lane Two-Way Highways," *Transportation Research Record No. 2279, Transportation Research Board of the National Academies, Washington, D.C.,,* pp. pp. 82-89, 2012.

[44] M. Williamson and H. Zhou, "Develop Calibration Factors for Crash Prediction Models for Rural Two-Lane Roadways in Illinois," *Procedia-Social and Behavioral Sciences,* vol. 43, pp. 330-338, 2012.

[45] G. Mehta and Y. Lou, "Calibration and Development of Safety Performance Functions for Alabama," *Transportation Research Record: Journal of the Transportation Research Baord,* vol. 2398, pp. 75-82, 2013.

[46] C. Bornheimer, S. D. Schrock, M.-H. Wang and H. Lubliner, "Developing a Regional Safety Performance Function for Rural Two-Lane Highways," 2012.

[47] M. Jalayer, H. Zhou, M. Williamson and J. J. LaMondia, "Developing Calibration Factors for Crash Prediction Models with Consideration of Crash Recording Threshold Change," *Transportation Research Record,* vol. 2515, pp. 57-62, 2015.

[48] P. Savolainen, 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," Michigan Department of Transportation, Lansing, MI, 2015.

[49] K. Dixon and R. Avelar, "Validation Technique Applied to Oregon Safety Performance Function Arterial Segment Models," *Transportation Research Record, the Journal of the Transportation Research Board,* vol. 2515, pp. 115-123, 2015.

[50] Y. Chen, B. Persaud and E. Sacchi, "Improving Transferability of Safety Performance Functions by Bayesian Model Averaging," *Transportation Research Record,* vol. 2280, pp. 162-172, 2012.

[51] E. Hauer and J. Bamfo, "Two Tools for Finding what Function Links the Dependent Variable to the Explanatory Variables," in *Proceedings of the ICTCT 1997 Conference*, Lund, Sweden, 1997.

[52] H. Wu, Z. Han, M. R. Murphy and Z. Zhang, "Empirical Bayes Before-After Study on Safety Effect of Narrow Pavement Widening Projects in Texas," *Transportation Research Record: Journal of the Transportation Research Board, No. 2515,* pp. 63-69, 2015.

[53] F. Gross, P. P. Jovanis and E. Kimberly, "Safety Effectiveness of Lane and Shoulder Width Combinations on Rural, Two-Lane, Undivided Roads," *Transportation Research Record,* pp. 42-49, 2009.

[54] S. Labi, S. Chen, P. V. Preckel, Y. Qiao and W. Woldemariam, "Rural two-lane highway shoulder and lane width policy evaluation using multiobjective optimization," *Transpormetrica A: Transport Science,* vol. 13, no. 7, pp. 631-656, 2017.

[55] S. Chen, T. U. Saeed, M. Alinizzi, S. Lavrenz and S. Labi, "Safety sensitivity to roadway characteristics: A comparison across highway classes," *Accident Analysis and Prevention,* vol. 123, pp. 39-50, 2019.

[56] K. Wang, J. N. Ivan, N. Ravishanker and E. Jackson, "Multivariate poisson lognormal modeling of crashes by type and severity on rural two lane highways," *Accident Analysis and Prevention,* vol. 99, pp. 6-19, 2017.

[57] C. Lee, M. Abdel-Aty, J. Park and J.-H. Wang, "Development of crash modification factors for changing lane width on roadway segments using generalized nonlinear models," *Accident Analysis and Prevention,* vol. 76, pp. 83-91, 2015.

[58] S. R. Geedipally, T. J. Gates, S. Y. Stapleton, A. J. Ingle and R. E. Avelar, "Examining the Safety Performance and Injury Severity Characteristics of Rural County Roadways," *Transportation Research Record,* vol. 2673, no. 10, pp. 405-415, 2019.

[59] F. Gross and P. P. Jovanis, "Estimation of Safety Effectiveness of Changes in Shoulder Width with Case Control and Cohort Methods," *Transportation Research Record,* vol. 2019, pp. 237-245, 2007.

[60] F. Gross and E. T. Donnell, "Case-control and cross-sectional methods for estimating crash modification factors: Comparisons from roadway lighting and lane and shoulder width safety effect studies," *Journal of Safety Research,* vol. 42, pp. 117-129, 2011.

[61] D. W. Harwood, F. M. Council, E. Hauer, W. E. Hughes and A. Vogt, "Prediction of the Expected Safety Performance of Rural Two-Lane Highways," FHWA, Office of Safety Research and Development, Publication FHWA-RD-99-207, 2000.

[62] J. Gluck, H. S. Levinson and V. Stover, "NCHRP Report 420: Impact of Access Management Techniques," Transportation Research Board, Washington, D.C., 1999.

[63] R. E. Avelar, K. K. Dixon, L. S. Brown, M. E. Mecham and I. van Schalwyk, "Influence of Land Use and Driveway Placement on Safety Performance of Arterial Highways," *Transportation Research Record,* vol. 2398, pp. 101-109, 2013.

[64] M. Chakraborty and T. J. Gates, "Association between Driveway Land Use and Safety Performance on Rural Highways," *Transportation Research Record,* pp. 1-11, 2020.

[65] M. D. Wooldridge, K. Fitzpatrick, D. W. Harwood, I. B. Potts, L. Elefteriadou and D. J. Torbic, "Geometric Design Consistency on High Speed Rural Two-Lane Roadways," Transportation Research Board, Washington, D.C., 2003.

[66] K. W. Terhune and M. R. Parker, "An Evaluation of Accident Surrogates for Safety Analysis of Rural Highways, Final Report," FHWA-RD-86-128, Washington, D.C., 1986.

[67] C. V. Zegeer, J. R. Stewart, F. M. Council, D. W. Reinfurt and E. Hamilton, "Safety Effects of Geometric Improvements on Horizontal Curves," *Transportation Research Record,* vol. 1356, pp. 11-19, 1992.

[68] K. L. Fink and R. A. Krammes, "Tangent Length and Sight Distance Effects on Accident Rates at Horizontal Curves on Rural Two-Lane Highways," *Transportation Research Record,* vol. 1500, pp. 162-168, 1995.

[69] W. H. Schneider IV, P. T. Savolainen and D. N. Moore, "Effects of Horizontal Curvature on Single-Vehicle Motorcycle Crashes Along Rural Two-Lane Highways," *Transportation Research Record,* vol. 2197, pp. 91-98, 2010.

[70] C. Xin, Z. Wang, P.-S. Lin, C. Lee and R. Guo, "Safety Effects of Horizontal Curve Design on Motorcycle Crash Frequency on Rural, Two-Lane, Undivided Highways in Florida," *Transportation Research Record,* vol. 2637, pp. 1-8, 2017.

[71] B. Wang, S. Hallmark, P. Savolainen and J. Dong, "Crashes and near-crashes on horizontal curves along rural two-lane highways: Analysis of naturalistic driving data," *Journal of Safety Research,* vol. 63, pp. 163-169, 2017.

[72] H. Jeong and Y. Liu, "Horizontal Curve Drive Performance and Safety Affected by Road Geometry and Lead Vehicle," in *Proceedings of the Human Factors and Ergonomics Society 2017 Annual Meeting*, Austin, TX, 2017.

[73] K. Fitzpatrick, L. Elefteriadou, D. W. Harwood, J. Collins, J. McFadden, I. B. Anderson, R. A. Krammes, N. Irizarry, K. Parma, K. M. Bauer and K. Passetti, "Speed Prediction Models for Two-Lane Rural Highways," Federal Highway Administration, U.S. Department of Transportation, Report FHWA-RD-99-171, Washington, D.C., 2000.

[74] I. B. Anderson, K. M. Bauer, D. W. Harwood and K. Fitzpatrick, "Relationship to Safety of Geometric Consistency Measures for Rural Two-Lane Highways," *Transportation Research Record,* vol. 1658, pp. 43-51, 1999.

[75] K. M. Bauer and D. W. Harwood, "Safety Effects of Horizontal Curve and Grade Combinations on Rural Two-Lane Highways," *Transportation Research Record,* vol. 2398, pp. 37-49, 2013.

[76] T. Saleem and B. Persaud, "Another look at the safety effects of horizontal curvature on rural two-lane highways," *Accident Analysis and Prevention,* vol. 106, pp. 149-159, 2017.

[77] C. Zegeer, R. Stewart, F. Council and T. R. Neuman, "Accident Relationships of Roadway Width on Low-Volume Roads," *Transportation Research Record: Journal of the Transportation Research Board, No. 1445,* pp. 160-168, 1994.

[78] F. Brieger, R. Hagen, D. Vetter, C. F. Dormann and I. Storch, "Effectiveness of light-reflecting devices: A systematic reanalysis of animal-vehicle collision data.," *Accident Analysis & Prevention, Vol. 97,* pp. 242-260, 2016.

[79] S. A. Barnum and G. Alt, "The Effect of Reduced Roadside Mowing on Rate of Deer-Vehicle Collisions," in *91st Annual Meeting of the Transportation Research Board*, Washington, D.C., 2012.

[80] Normandeau Associates, Inc., "Deer-Vehicle Crash, Econolical, and Economic Impacts of Reduced Roadwide Mowing: Final Report," Federal Highway Administration, Washington, D.C., 2012.

[81] M. Khalilikhah and K. Heaslip, "Improvement of the performance of animal crossing warning signs," *Journal of Safety Research, Vol. 62,* pp. 1-12, 2017.

[82] K. Gkritza, R. R. Souleyrette, M. J. Baird and B. J. Danielson, "Empirical Bayes Approach for Estimating Urban Deer-Vehicle Crashes Using Police and Maintenance Records," *Journal of Transportation Engineering,* vol. 140, no. 2, pp. 1-7, February 2014.

[83] M. Bil, R. Andrasik, T. Bartonicka, Z. Krivankova and J. Sedonik, "An evaluation of odor repellent effectiveness in prevention of wildlife-vehicle collisions," *Journal of Environmental Management, Vol. 205,* pp. 209-214, 2018.

[84] F. Castiov, "Testing Potential Repellants for Mitigation of Vehicle-Induced Mortality of Wild Ungulates in Ontario," Laurentian University, Master's Thesis, Sudbury, Ontario, 1999.

[85] J. H. Hedlund, P. D. Curtis, G. Curtis and A. F. Williams, "Methods to Reduce Traffic Crashes Involving Deer: What Works and What Does Not," *Traffic Injury Prevention, Vol. 5, no. 2,* pp. 122-131, 2004.

[86] A. El Hani and M. R. Conover, "Comparative Analysis of Deer Repellants," in *National Wildlife Research Center Repellents Conference*, 1995.

[87] C. Druta, A. S. Alden and B. M. Donaldson, "Evaluation of a Buried Sensing Cable for Roadside Animal Detection," in *97th Annual Meeting of the Transportation Research Board*, Washington, D.C., 2018.

[88] R. Ament, D. Galarus, D. Richter, K. Bateman, M. Huijser and J. Begley, "Roadkill Observation Collection System (ROCS): Phase III Development. Western Transportation Institute," Western Transportation Institute, Report FHWA-CFL/TD-12-001, Washington, D.C., 2012.

[89] J. Young 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,* pp. 517-527, 2013.

[90] C. Caliendo and M. Guida, "Microsimulation Approach for Predicting Crashes at Unsignalized Intersections Using Traffic Conflicts," *Journal of Transportation Engineering, Vol. 138, no. 12,* pp. 1453-1467, 2012.

[91] A. Vogt, "Crash Models for Rural Intersections: Four-Lane by Two-Lane Stop-Controlled and Two-Lane by Two-Lane Signalized," FHWA-RD.99-I28, 1999.

[92] N. J. Garber and G. Rivera, "Safety Performance Functions for Intersections on Highways Maintained by the Virginia Department of Transportation," Virginia Department of Transportation, Report FHWA/VTRC 11-CR1 , Richmond, VA, 2010.

[93] A. Vogt and J. Bared, "Accident Models for Two-Lane Rural Segments and Intersections," *Transportation Research Record,* vol. 1635, pp. 18-29, 1998.

[94] C. Monsere, T. Johnson, K. Dixon, J. Zheng and I. Schalkwyk, "Assessment of Statewide Intersection Safety Performance," Oregon Department of Transportation (ODOT), SPR 667, FHWA-OR-RD-18, 2011.

[95] M. S. Obeidat and M. J. Rys, "Intersection Lighting Impacts on Nighttime Crashes Reduction and Safety Improvement," in *TRB 2016 Annual Meeting*, Washington D.C., 2016.

[96] J. A. Bonneson and M. P. Pratt, "Roadway Safety Design Workbook," FHWA/TX-09/0-4703-P2, College Station, TX, 2009.

[97] D.-G. Kim, S. Washington and J. Oh, "Modeling Crash Types: New Insights into the Effects of Covariates at Rural Intersections," *Journal of Transportation Engineering,* vol. 132, no. 4, pp. 282-292, 2006.

[98] D.-G. Kim, "The significance of endogeneity problems in crash models: An examination of left-turn lanes in intersection crash models," *Accident Analysis and Prevention,* vol. 38, pp. 1094-1100, 2006.

[99] T. Hall and A. P. Tarko, "Adequacy of negative binomial models for managing safety on rural local roads," *Accident Analysis and Prevention,* vol. 128, pp. 148-158, 2019.

[100] J. Oh, S. Washington and K. Choi, "Development of Accident Prediction Models for Rural Highway Intersections," *Transportation Research Record,* vol. 1897, pp. 18-27, 2004.

[101] S. A. Biancardo, F. Russo, W. Zhang and R. Veropalumbo, "Design Criteria for Improving Safety Performance of Rural Intersections," *Journal of Advanced Transportation,* vol. 2019, pp. 1-11, 2019.

[102] E. Nightingale, N. Parvin, C. Seiberlich, P. T. Savolainen and M. Pawlovich, "Investigation of Skew Angle and Other Factors Influencing Crash Frequency at High-Speed Rural Intersections," *Transportation Research Record,* vol. 2636, pp. 9-14, 2017.

[103] W. Kumfer, D. Harkey, B. Lan, R. Srinivasan, D. Carter, A. P. Nujjetty, A. M. Eigan and C. Tan, "Identification of Critical Intersection Angle through Crash Modification Functions," *Transportation Research Record,* vol. 2673, no. 2, pp. 531-543, 2019.

[104] X. Qin, Z. Chen and R. R. Shaon, "Developing jurisdiction-specific SPFs and crash severity portion functions for rural two-lane, two-way intersections," *Journal of Transportation Safety & Security,* vol. 11, no. 6, pp. 629-641, 2018.

[105] K. Dixon, "Highway Safety Manual 1st Edition, Volume 2, Chapter 10 -- Predictive Method for Rural Two-Lane, Two-Way Roads -- Analysis Spreadsheet," American Association of State Highway Transportation Officials, College Station, TX, 2019.

[106] D. Lord, "Modeling Motor Vehicle Crashes Using Poisson-gamma Models: Examining the Effects of Low Sample Mean Values and Small Sample Size on the Estimation of the Fixed Dispersion Parameter," *Accident Analysis and Prevention,* vol. 38, no. 4, pp. 751-766, 2006.

[107] D. Lord and P. Y. Park, "Investigating the Effects of the Fixed and Varying Dispersion Parameters of Poisson-gamma Models on Empirical Bayes Estimates," *Accident Analysis and Prevention,* vol. 40, pp. 1441-1457, 2008.

[108] State of Michigan, "Michigan Geographic Framework All Roads Shapefile v16a," GIS Open Data, 25 March 2016. [Online].

[109] F. L. Mannering, V. Shankar and C. R. Bhat, "Unobserved heterogeneity and the statistical analysis of highway accident data," *Analytic Methods in Accident Research,* vol. 11, pp. 1-16, 2016.

[110] M. A. Mohammadi, V. A. Samaranayake and G. H. Bham, "Crash frequency modeling using negative binomial models: An application of generalized estimating equation to longitudinal data," *Analytic Methods in Accident Research,* vol. 2, pp. 52-69, 2014.

[111] H. Huang and H. C. Chin, "Modeling road traffic crashes with zero-inflation and site-specific random effects," *Stat Methods Appl,* vol. 19, pp. 445-462, 2010.

[112] S. R. Geedipally, D. Lord and S. S. Dhavala, "The negative binomial-Lindley generalized linear model: Characteristics and application using crash data," *Accident Analysis & Prevention,* vol. 45, pp. 258-265, 2012.

[113] Y. Zou, J. E. Ash, B.-J. Park, D. Lord and L. Wu, "Empirical Bayes estimates of finite mixture of negative binomial regression models and its application to highway safety," *Jounal of Applied Statistics,* vol. 45, no. 9, pp. 1652-1669, 2017.

[114] R. Yu, M. Quddus, X. Wang and K. Yang, "Impact of data aggregation approaches on the relationships between operating speed and traffic safety," *Accident Analysis and Prevention,* vol. 120, pp. 304-310, 2018.

[115] M.-I. M. Imprialou, M. Quddus, D. E. Pitfield and D. Lord, "Re-visiting crash–speed relationships: A new perspective in crash modelling," *Accident Analysis and Prevention,* vol. 86, pp. 173-185, 2016.

[116] L. Ewan, A. Al-Kaisy and F. Hossain, "Safety Effects of Road Geometry and Roadside Features on Low-Volume Roads in Oregon," *Transportation Research Record,* vol. 2580, pp. 47-55, 2016.

[117] S. P. Washington, M. G. Karlaftis and F. L. Mannering, Statistical and Econometric Methods for Transportation Data Analysis, 2nd ed., Boca Raton: CRC Press, 2011.

[118] C. Sun, P. Edara, H. Brown, B. Claros and K. Nam, "Calibration of the Highway Safety Manual for Missouri," Mid-America Transportation Center, 2013.

[119] A. B. Northmore and E. Hildebrand, "Aggregated North American safety performance functions for signalized and stop-controlled intersections," *Canadian Journal of Civil Engineering,* vol. 47, pp. 749-758, 2019.

[120] A. M. Figueroa Medina and A. P. Tarko, "Speed Factors on Two-Lane Rural Highways in Free-Flow Conditions," *Transportation Research Record: Journal of the Transportation Research Board,* no. 1912, pp. 39-46, 2005.

[121] M. Pearce, "Deer Trail Tricks: Use a few simple adjustments to bring the bucks your way," 18 September 2007. [Online]. Available: https://www.outdoorlife.com/articles/hunting/2007/09/deer-trail-tricks. [Accessed 25 July 2018].

[122] J. Houser, "3 Ways To Make Deer Walk Where You Want Them To," 12 October 2015. [Online]. Available: https://www.grandviewoutdoors.com/big-game-hunting/3-ways-to-make-deer-walk-where-you-want-them-to/. [Accessed 2018 July 25].

[123] Federal Highway Administration, "Highway Safety Improvement Program," *Federal Register,* vol. 73, no. 248, pp. 78959-78969, 24 December 2008.

[124] Federal Highway Administration, "Guidance on NHS Design Standards and Design Exceptions," U.S. Department of Transportation, 6 March 2019. [Online]. Available: https://www.fhwa.dot.gov/design/standards/qa.cfm.

[125] Federal Highway Administration, "Office of Highway Policy Information," 30 August 2019. [Online]. Available: https://www.fhwa.dot.gov/policyinformation/statistics/2018/hm10.cfm.

[126] E. Hauer, Observational Before-After Studies in Road Safety, 1st ed., Bingley: Emerald Group, 1997.

[127] Michigan Department of Transportation Bureau of Highway Development, *Standard Plan for Superelevation and Pavement Crowns,* Lansing: Michigan Department of Transportation, 2009.

[128] Federal Highway Administration, Manual on Uniform Traffic Control Devices, Washington, D.C.: U.S. Department of Transportation, 2009.

[129] Michigan Department of Transportation, "Definitions: Federal-aid Highways, Federal-aid Systems and Federal-aid Eligible," State of Michigan, [Online]. Available: https://www.michigan.gov/mdot/0,4616,7-151-11151_11155-208501--,00.html.

[130] Michigan State Police, *Crash Database,* 2017.

[131] State Farm, "Deer Drive Damage Costs Up!," 2 October 2017. [Online]. Available: https://newsroom.statefarm.com/deer-collision-damage-claim-costs-up/. [Accessed 27 July 2018].