SAFETY PERFORMANCE OF RURAL INTERSECTIONS WITH ATYPICAL DESIGN CHARACTERISTICS

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ABSTRACT

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The results described in this dissertation describe the safety performance at rural minor stop-control intersections with atypical design characteristics. Statistical modelling is used to predict average crash frequency using 10 years of recent crash history. The model specification uses attributes such as the average annual daily traffic (AADT) on the major and minor road approaches, among other characteristics, to account for the exposure to crashes of various defined types and severities.

A series of random intercept negative binomial models for crash occurrence were generated from a sample of 299 offset-T intersections and 301 four-leg intersections in Michigan. The modeling technique uses a random effect for each site (location). The effects of offset distance and direction were analyzed and incorporated into the models. Compared to conventional four-leg intersections, offset-T intersections exhibited 35 percent more crashes regardless of the offset distance or direction. Single motor vehicle crashes occurred more frequently at offset-T intersections, and increased as the offset distance increased. Rear-end crashes also occurred more frequency at offset-T intersections, with left offsets having more crash occurrence than right offsets. However, angle crashes were 40 to 69 percent lower at offset-T intersections due to the elimination of the direct crossing maneuver.

Investigation into curved corner intersections utilized random intercept negative binomial models for crash occurrence by incorporating geographic region as a random effect. A model was generated from a sample of 227 three-leg sites and 65 four-leg sites among curved corner

intersection geometry only. Reliance on the availability of minor road AADT so severely limited the sample population that a linear regression estimation model for minor road AADT was calibrated in order to proceed with modeling. At curved corner intersections, installing a combined/merged intersection approach near the midpoint of the curve is a potential countermeasure that can be expected to reduce the average intersection crash frequency by 25 percent for three-leg configurations. A larger radius of curvature is also very favorable for safety performance. Each 100-foot increase in the radius of a three-leg or four-leg curved corner intersection is estimated to reduce crash occurrence by 5 percent and 8 percent respectively.

The safety influence of intersection skew angle was used to develop crash modification functions at three-leg and four-leg stop-controlled intersections. Skew angle was investigated both as a continuous variable, with observed values ranging from 0 to 80 degrees, and categorized into ranges. Both three-leg and four-leg intersections exhibited an initially increasing trend of crash rates followed by a decreasing trend as skew angle increased. A categorical model best described the skew relationship using discrete skew angle ranges. Among three-leg intersections, a skew angle between 17 to 27 degrees experienced 22 percent more crashes than perpendicular intersections. Among four-leg intersections, a skew angle between 17 to 27 degrees experienced 40 percent more crashes, while intersections with a skew angle greater than 45 degrees did not have significantly different crash occurrence than perpendicular intersections.

The procedures described in this study are consistent with the Highway Safety Manual (HSM) and subsequent state of the art research for the procurement of safety performance models for any variety of circumstances. An effort is made to summarize the outcomes in practically applicable terminology so that the conclusions of this study can lend toward a safer transportation future.

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1.0 INTRODUCTION

Despite constituting only a small portion of the roadway infrastructure, intersections continue to represent a major safety concern within the nation's highway system. In total, about 40 percent of all traffic crashes occur at intersections or are intersection-related. Crashes at intersections account for about 22 percent of traffic-related fatalities and 45 percent of traffic-related injuries [1]. These crashes often occur because of the conflicts between crossing paths and turning maneuvers when two or more roads intersect. The problem of intersection crashes transcends both rural and urban areas as well as signalized and un-signalized types of traffic control. Crashes in rural areas often have more severe outcomes than in urban areas due to higher vehicle speeds and longer emergency response times. This study pertains to stop-controlled intersections located along high-speed two-lane two-way highways in "rural" areas. Rural areas are defined in the Highway Safety Manual (HSM) based on Federal Highway Administration (FHWA) guidelines which classify rural areas as those having a population of less than 5,000 people [2].

A variety of intersection geometries have evolved in use; among the most common found in rural settings are four-leg cross and three-leg T intersections. Examples of these types are shown in Figure 1. This study pertains to four atypical intersection types prevalent enough to sample, yet characteristically distinct from the conventional intersection types. The four atypical intersection types studied herein are:

1) offset-T;

2) curved corner;

3) skewed; and

4) multi-leg (5+) with five or more-legs.

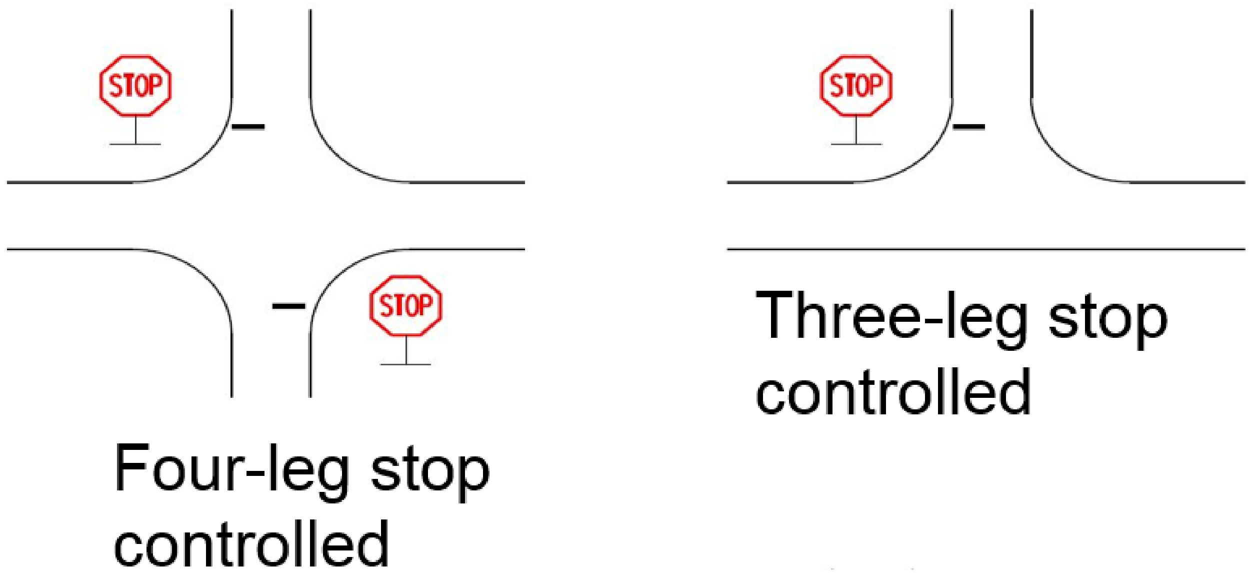

Figure 1. Conventional four-leg and three-leg minor road stop-controlled intersections.

Much emphasis has been placed on making data-driven decisions for the selection of targeted intersection safety investments. In the past, project selections have been based on locations that have established a history of crashes. The point of choosing locations for safety improvements based purely on prior history is greatly challenged by the issue of regression to the mean. Attempts have been made to more proactively identify locations which have the potential to become crash locations actually before the crashes occur. In order to achieve this ambition, a predictive model is desired to estimate future crashes based on characteristic features of the roadway facility [3].

The first edition of the Highway Safety Manual (HSM) published by AASHTO in 2010 provides safety performance functions (SPFs) that can be used to predict crashes at facilities, such as rural two-lane two-way segments and intersections [2]. The HSM is currently used by numerous state departments of transportation and local agencies for project selection and planning. However, the equations presented in the current edition of the HSM do not cover all of the complexities of different situations. As a result, the predictive capability of the SPF models may be limited when applied to unique situations such as the intersections considered in this study. The HSM suggests developing new SPFs to deal with specific situations.

1.1 Background

Chapter 10 of the HSM presents the predictive method for rural two-lane, two-way facilities, addressing both segments and intersections. An estimate of the expected average crash frequency of an individual site is based upon predictive models and can also incorporate observed crash data using the Empirical Bayes (EB) Method [2]. SPFs are developed to estimate the total expected number of crashes under base conditions, which are subsequently multiplied by crash modification factors (CMFs) to adjust for non-base conditions, and finally multiplied by a calibration factor to adjust estimates for local conditions.

1.1.1 Offset-T Intersections

Offset-T intersections are a special situation where two three-leg intersections adjoin the major road from opposite directions and are separated by a short distance such that the influence area of the two intersections overlap. The operational and safety characteristics of the two intersections are interdependent and crashes occurring in the region between the two intersections could be attributed to either intersection. It is therefore appropriate to consider evaluating the pair of intersections as a single intersection site. This type of intersection is expected to have more turning movements associated with the minor road traffic. For example, what would be a crossing maneuver at a conventional four-leg stop-controlled intersection is a combination of left and right turns. The sequence of turns is related to the geometry. Two conditions exist, one in which the minor road approach begins with a left turn herein referred to as an L-R, and one in which the minor road approach begins with a right turn herein referred to as an R-L. Figure 2 shows the definition of an offset-T by the direction of the first turn.

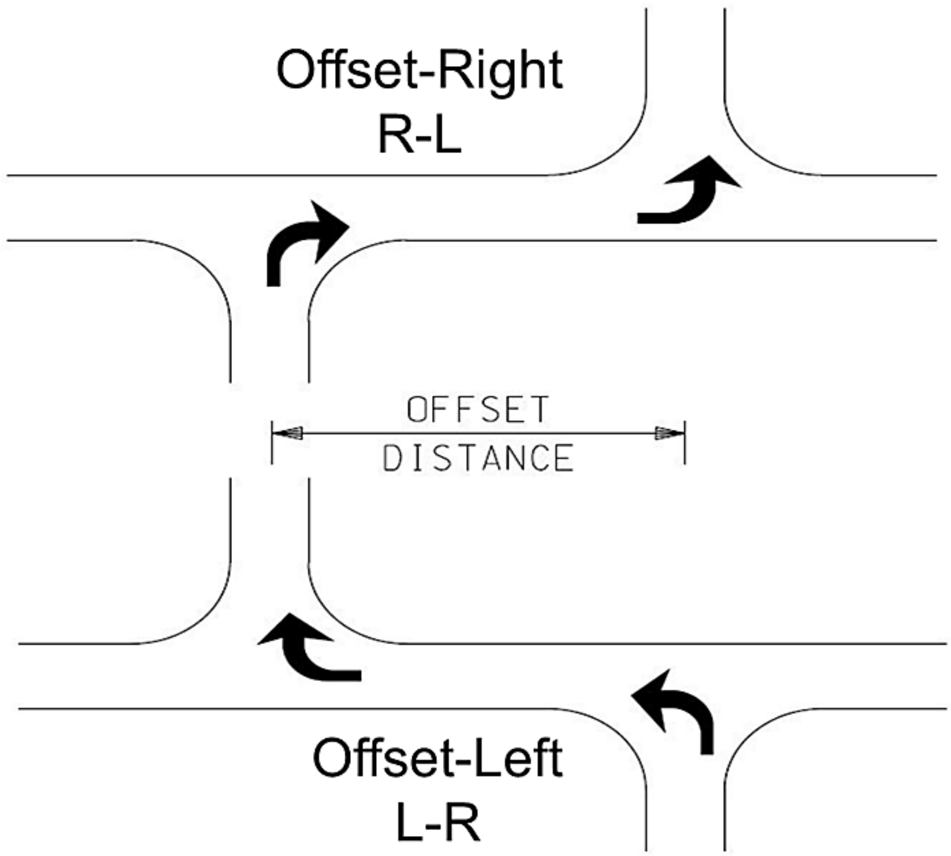

Figure 2. Offset-T intersection defined by direction and distance.

A likely reason for offset-T intersections in rural areas is an artifact of the rectangular survey system, also known as the public land survey system (PLSS). The PLSS is used throughout most of the United States west of the original 13 colonies. This study focuses on offset-Ts that geometrically exist due to historic land boundary lines. The original rectangular survey used guide meridians and standard parallels to partition large blocks 24 miles on each side. Later surveys would establish township boundaries six miles on each side and sections one-mile square. As meridians converge gradually toward the earth's poles, cases arose when surveyors would "close corners", which referred to survey correction adjustments made at intersecting section lines. Land boundaries are often set and described from the survey section lines, and in most cases in the west and mid-western states, rural roadways closely follow the section lines too. Roadways that follow the section lines are subject to adjustments whenever a large offset is encountered between section lines that tie to an established township or range line. This is especially prevalent for minor or local roads that intersect with a primary or arterial highway that follows along a township boundary or county line.

1.1.2 Curved Corner Intersections

Curved corner intersections are a special situation where three or more tangent roadway segments intersect, yet the major route turns from the starting direction of one approach segment to an orthogonal direction of the departing segment as depicted in Figure 3. Curved corner intersections in rural situations most often occur where an existing grid of roadways along section lines has developed a pattern of traffic with a primary turn at the intersection. This situation is really an evolution of channelization at intersections, which separates the major movements from conflicts and/or incurred delays. For various reasons, the development of primary roads in rural situations often must jog or turn to another direction. These reasons range from natural physical obstructions to cemeteries and property disputes, or simply to find the shortest route to the next town.

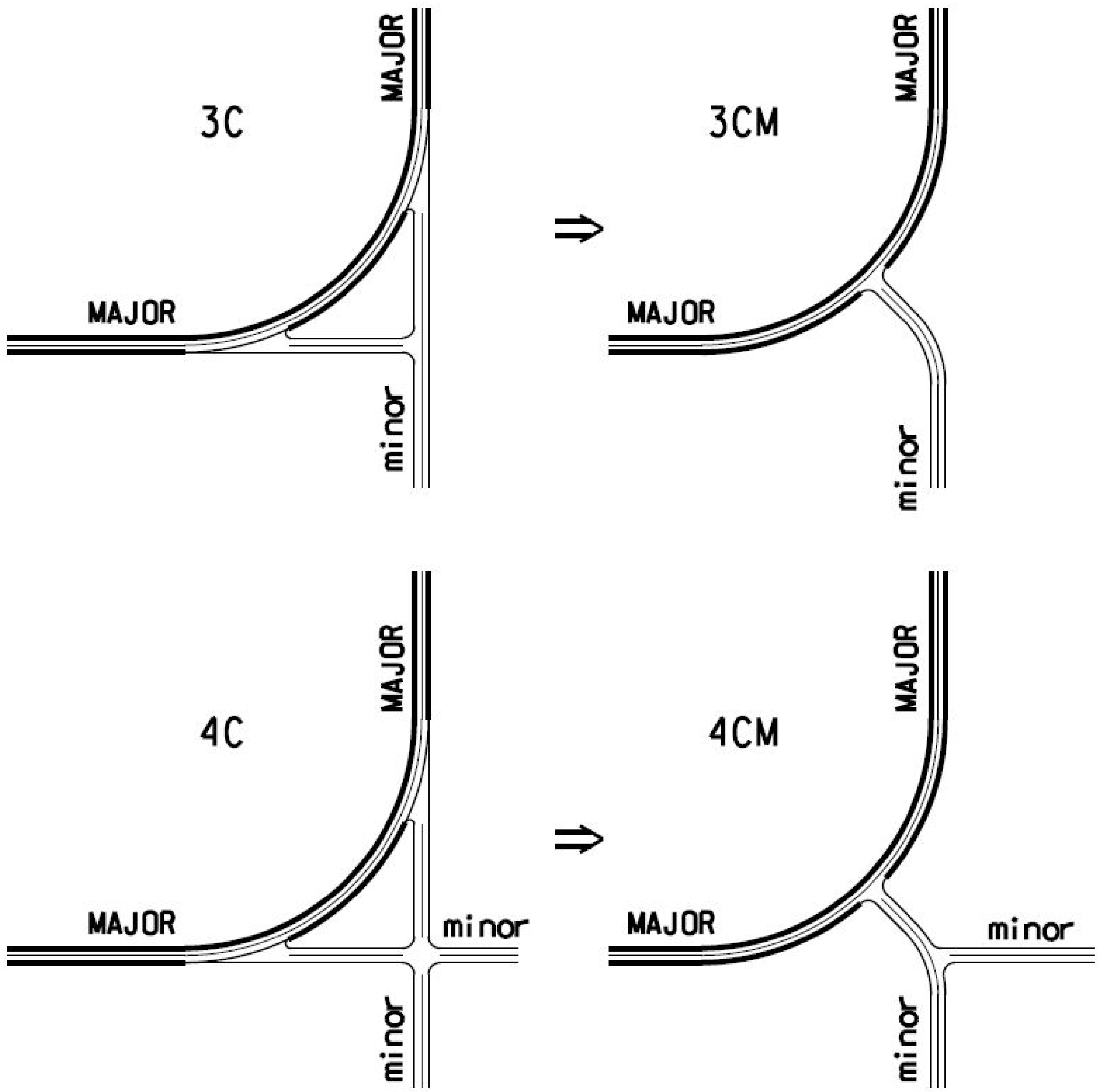

Figure 3. Geometric alterations at curved corner intersections.

Route turns occur among various classifications of roadways and different intersection geometric and control types. Traffic control for route turns often signs for and sometimes gives right-of-way to continuation of the major through movement at the intersection. In the case of curved corner intersections, for the convenience of the major flow traffic, a segment of curved roadway connects the two orthogonal major flow approaches. The radius of the curved roadway varies based on the posted or advisory speed, similar to any other ordinary highway curve.

Superelevation is commonly used for the curved roadway portion to compensate for small radius of curvature, which is most often still well below the posted speed limit on the major roadway segment approaching the curve. The curved roadway portion is often treated with chevrons, curve arrows, and advisory curve speed signs throughout the vicinity of the intersection points.

Since many routes in the west and mid-western states follow along already established section lines, the route turns at curved corner intersections form out of an otherwise nearly perpendicular intersection to create a composite of intersections favoring the major flow traffic. In this case, the intersecting tangent approaches connect to the bypassing curved segment. Two highly skewed three-leg intersections are tangent to each of the major flow approach legs, and a third (usually orthogonal) intersection is located geometrically at the point of intersection of the major flow approach legs. Since these three intersections are in close proximity and inter-dependent on each other, it is appropriate to consider evaluating the combination of intersections as a single intersection site.

Geometric changes at these types of intersections have been considered as a countermeasure to treat sub-standard geometric conditions as well as improve safety and operations. A conventional treatment is illustrated in Figure 3. The alteration reduces the skew for minor road approach traffic, thus improving sight lines at the intersection with the major road. In the case of one minor road approach leg, the modification reduces the number of intersections and subsequently the number of conflict points from 15 to 4. In the case of two minor road approach legs, the modification reduces the total number of intersecting points as well as the number of conflicting traffic crossing points from 32 to 12. This treatment has been observed among several state highway jurisdiction roadways, but it is less commonly observed among county jurisdiction or lower functional classification roadways.

1.1.3 Skewed Intersections

Despite the predominately rectilinear grid of rural roadways prevalent throughout much of the west and mid-western states, several other regions of the country as well as specific routes in states such as Michigan follow headings that result in skewed intersections. Intersection skew is defined in the HSM as an angle of less than 90 degrees between the legs of the intersection [2]. Figure 4 shows the measurement of skew which is recorded as the absolute value of the difference between 90 degrees and the actual intersection angle. Formative research by Harwood et. al. initially described the nominal or base condition of skew as 0 degrees, thus the skew angle could have a positive or negative sign which indicated an acute or obtuse angle respectively. Ultimately however, the researchers' proposal to use the absolute value of skew angle was included in the HSM [4]. The skew angle, and whether it is an acute or obtuse angle certainly affects the field of vision for vehicles at the intersection approach. This may limit the ability to see oncoming traffic more from the acute side than the other direction. In addition, skewed intersections may require more distance to cross, resulting in an increased exposure time to conflicting traffic. Visual limitations resulting from skew not only affect operation of vehicles from a human factors stand point, but could also encumber automated vehicles reliant on sensors with unobstructed sight lines.

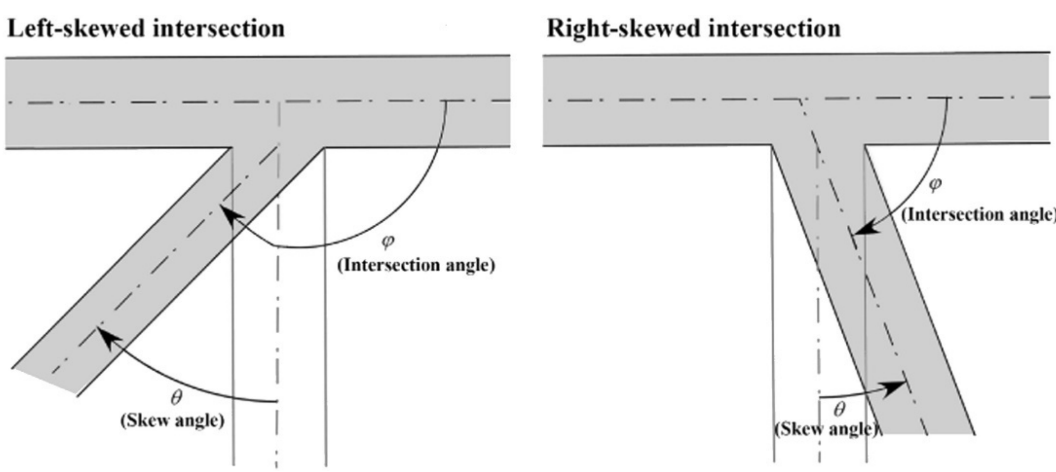

Figure 4. Defined intersection angle and skew angle at intersections [5].

1.1.4 Stop-Controlled with Five or More-leg Intersections

Another dimension to intersections with skew involves intersections with more than four approach legs. The addition of a fifth or sixth leg to an intersection results in non-perpendicular angles for some approaches. Intersections with more than four legs are herein described as multi-leg 5+ intersections. Further, it can be explained that these intersections will have either five or six legs. The configuration of stop-control at these multi-leg 5+ intersections could be all-way stop-control, or three-way or four-way stop-control allowing a free movement along the major road. Other site-specific circumstances occurring at these intersections may involve the presence of nearby driveways, lighting, turn lanes, and flashing beacons. For being a very unique type of intersection, there are numerous variations of site specifics circumstances. This has made the quantification of safety performance quite challenging and very limited at multi-leg intersections with more than four approach legs.

In most cases, the additional leg is a very low volume minor road approach, even compared with the other minor road approaches. Often traffic volume is not recorded on these most minor approaches at an intersection. The characteristics of four-leg and skewed intersections is essentially compounded in the occurrence of multi-leg 5+ intersections. One treatment of interest at multi-leg 5+ intersections is installation of a rural roundabout. Another treatment might include an all way stop, or a traffic signal. The element of free flow on the major road through movement defines the conditions herein tested as minor road stop-control for these two-lane two-way roads. There is an easily understandable principle in recognizing the major road through traffic movement, by means of looking at a National Functional Classification (NFC) map, or looking at adjacent segments' traffic volume. To solve the mystery of predicting minor road approach volumes involves the most current database of functional, geometric, and operational characteristics. This database includes a sub-set of increased rural road speed limits (e.g. 65 mph) as well as the most recently available American Community Survey (ACS) census data.

a) Five-leg intersection b) Six-leg intersection

Figure 5. Aerial imagery example of a rural five-leg and six-leg intersections in Michigan.

1.1.5 Highway Safety Manual

SPFs are part of the core methods documented in the HSM, and they are building blocks for more 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. 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 [2]. 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.

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

Where,

N = predicted annual average crash frequency for the site;

N_0 = predicted average crash frequency determined for base conditions;

CMF = set of crash modification factors specific to the site; and

C = calibration factor to adjust the SPF for local conditions.

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 [4].

The set of fixed values is referred to as the base conditions of the base SPF. These conditions may include such variables as 12-ft lanes and 6-ft 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.

$$N_0 = \mathrm{e}^{\beta_0 + \beta_1 \times ln\left(\mathrm{AADT_{Major}}\right) + \beta_2 \times ln\left(\mathrm{AADT_{Minor}}\right)} \tag{2}$$

Where,

$\mathrm{N_0}$ = predicted average crash frequency at base conditions;

$\mathrm{AADT_{major}}$ = annual average daily traffic (AADT) for the major road;

$\mathrm{AADT_{minor}}$ = annual average daily traffic (AADT) for the minor road; and

$\beta_0, \beta_1, \beta_2$ = estimated parameters.

Care needs to be taken when adding variables to avoid overfitting the SPF. The more complex models are often poorer predictors, as a lot of noise tends to be included. Researchers Srinivasan, Carter and Bauer, suggested using backward elimination in the well documented stepwise model selection process in statistical analysis [6]. 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 model.

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 at 90 degrees of each other, applying this SPF to a location with one approach with a significant 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 presents a set of CMFs for rural segments (two-lane and multilane) and rural intersections. Additional CMFs can also be found the Federal

Highway Administration (FHWA) CMF Clearinghouse [7].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 [8]. 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 implications could be to overestimate or underestimate the combined effect significantly [9]. This document summarizes relevant CMFs for rural intersections and segments in the following sections.

To take advantage of the value of the multiple SPFs presented in the HSM, such SPFs can be calibrated to local conditions. The calibration intends to account for the variation of crash data between different jurisdictions and for factors that were not involved in the model. Srinivasan, Carter and Bauer found that, on a project level, the development of a typical SPF can take 450 to 1050 staff hours, whereas calibration is only 24 to 40 staff hours for data collection and preparation [10]. When using an already existing SPF taken from the HSM (part C) or Safety Analyst, calibration is essential because, crash frequencies fluctuate for a variety of reasons that cannot be accounted for when developing the SPF. These local conditions include: climate, criteria for crash reporting, topography, animal population, law enforcement, vehicle characteristics, and other factors throughout jurisdictions [11, 10, 12, 13, 14, 15]. The calibration factor is estimated using Equation 3 and is multiplied to the base SPF as a scaling factor.

$$C = \frac{\sum_{i=1}^{n} N_{obs,i}}{\sum_{i=1}^{n} N_{pre,i}} \tag{3}$$

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 used in the calibration process.

Similar to using a calibration factor when applying an SPF to a new jurisdiction, a calibration factor is recommended when applying an SPF to different time periods [12]. When translating SPFs across states, calibration factors are a recommended, but major physiographic divisions within a state should also be considered [16]. 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 30-50 locations is insufficient for most cases [17, 18]. Several research studies, such as [19] and [12] have provided further or improved guidelines to calibrate the models for local conditions. Considering the caveats of the calibration procedure, it is preferable to develop new predictive models if enough data are available.

1.2 Research Problem Statement and Objectives

The situations described in the aforementioned intersection types are out of the ordinary. However, atypical intersections are still prevalent enough in rural areas that a driver in rural Michigan for example would never be more than 30 miles in absolute distance from any atypical intersection. In fact, some counties may possess several atypical intersections, while others may not. There is a lack of research evaluating the safety performance of the four atypical intersection types identified in this study. Although the HSM provides SPFs for conventional three-leg and four-leg rural intersections with stop-control on the minor roadway, these models were developed and validated using data for only three states: Washington, California, and Minnesota. Given differences in Michigan's drivers, roadways, and environmental conditions, it is unclear how well these SPFs would predict safety performance for rural intersections and segments in Michigan. Further, many of the highways where atypical intersections occur are owned and maintained by counties or local agencies, which limits the usefulness of the HSM SPFs and other models generated using data from state-highways.

Even as the Michigan Department of Transportation (MDOT) has recently commissioned state specific SPFs for rural intersections, along with CMFs and regional calibration factors, the models are still applicable only to conventional three-leg and four-leg intersections. In many ways limited information on atypical intersections has restrained the development of SPFs. There was not found any SPF to adequately address any of the atypical intersection types studied. Although some CMFs may address portions of the situation (e.g. skew), the interaction of several other factors needs to be clearly sorted out. With the comprehensive collection of site-specific data proposed in this study, the uniqueness of atypical intersections can be modeled and the influence of different characteristics can be investigated and better understood. At a more detailed level, understanding the influence atypical intersections have on specific crash types is a knowledge gap this study seeks to fulfill. For example, the crossing maneuver at a conventional four-leg intersection would require a left and right turn in sequence at an offset-T intersection. This changes the exposure to different types of crashes and may relate to the severity of those crashes as well.

For offset-T intersections, the separation distance between the offset three-leg T intersections has not been well defined in terms of its impact on safety. Further, while the CMF for converting a four-leg intersection into two three-leg intersections is provided within the HSM, it is only applicable to urban stop-controlled situations [2]. Intersections at curved corner sites do not have any CMFs available in published research. The influence of the radius of the curved segment at these sites is not yet defined. For intersections near a railroad crossing, the safety impacts of different crossing controls and train traffic characteristics have not been applied beyond the railroad crossing itself. At highly skewed intersections, the idealized monotonic relationship between skew angle and crash risk has been challenged. A better understanding of the influence of skew is needed. The outcome of a variety of geometric modifications at atypical intersections also has not previously been clearly quantified.

To address these gaps in the available safety performance models, research is proposed to develop a series of SPFs for rural stop-controlled intersections that considers numerous site-specific characteristics. This problem involves a vast amount of data collection from different sources that must be carefully assembled into a coherent data set. A sufficient number of sample sites must be procured to allow for rigorous statistical analysis and model development. Finally, the apparent outcomes must be presented in a manner in which they can be most easily incorporated into the workflow of practitioners in order for the research to have a functional impact.

The first objective of this research is to assemble a comprehensive data set from numerous different sources using a methodology that is repeatable. Common data features at all intersection types consists of traffic, pavement surface, functional classification, number of lanes, type of control, etc. However, not only do many of these features come from different sources, each source (e.g. a county road agency) may only have a geographically limited set of information. Different sources and different data features have various formats that all need to be rectified to stitch together a comprehensive data set. For the sake of efficiency, common data features may apply to any or all atypical intersection types studied. Maintenance or updating the data is also part of this objective. Over the course of the research project, more recent year's data becomes available. The architecture of the data set must allow for updates or additions when needed.

The second objective is to model the safety performance of each atypical intersection type in order to gain a clearer understanding of what characteristics influence crash frequency and severity of selected crash types. Distinguishing characteristics of these intersections include the geometry, radius of curvature, driving surface type, skew angle, AADT of the intersection approaches, and potentially many more. The analytical methods proposed in this study will generate a series of SPFs using mixed effects negative binomial modeling techniques. Since statewide locations often have varying design standards, maintenance practices, and weather conditions, a site-specific or region-specific random effect (intercept) is included in the models to account for this unobservable heterogeneity within the data. The modeling effort also includes designation of CMFs to estimate the change in crash frequency associated with converting conditions within each intersection type or between intersection types. As an example, modification of the curve radius at curved corner intersection, or converting a rural offset-T intersection into a conventional four-leg intersection. In this way the efficacy of conventional treatments can be evaluated and priorities can be established.

The third objective of this research is to quantifiably recommend CMFs that can be adopted into the field of practice. In order to achieve this objective, the methods and results of this analysis must be clearly documented and reviewed. Three journal articles on the atypical intersection types have already been published. The outcome of review and publication strengthens the quality of the CMFs recommended. Other factors that affect CMF quality include: number of sites, number of crashes, actual traffic volume sources, model form, statistical significance, and consideration of bias or correlation among independent variables. The dissertation will thoroughly document these factors to the extent that the highest quality rating could be achieved for CMFs submitted to the CMF Clearinghouse. Along with documentation of CMFs, the dissertation will also catalog several SPFs for predicting the frequency of intersection related crashes reported annually.

The anticipated outcomes for this research investigation include a series of SPFs that can help to accurately predict the expected number of crashes at atypical rural intersection sites. The SPFs can be used by state and local transportation agencies for various activities such as network screening to identify and rank sites, or safety studies and countermeasure evaluation for site planning and design. Within each investigation, it is anticipated to discover what characteristics of these type of intersections influence safety performance. The recommendations generated will help to determine suitable treatments and quantified CMFs at these atypical intersection types.

1.3 Dissertation Organization

This dissertation documents the activities involved in the development of safety performance functions (SPFs) and crash modification factors (CMFs) for the identified types of atypical rural intersections in Michigan. The dissertation is divided into nine chapters:

- Chapter 2 provides a summary of the state-of-the-art research literature relevant to each category of what are considered atypical intersection geometries.
- Chapter 3 describes the general data collection and methodology that is common to all investigations. This includes details of the data sources and activities involved in database development.
- Chapters 4, 5, 6, and 7 provide a data summary, modeling results, and conclusions for offset-T intersections, curved corner intersections, skewed intersections, and multi-leg intersections respectively.

- Chapter 8 provides a data summary, modeling results, and conclusions for estimation of minor road approach AADT.
- Chapter 9 provides a summary of conclusions and recommendations.

2.0 LITERATURE REVIEW

A comprehensive literature review has been conducted regarding intersection crash prediction modeling. The literature review is organized by the intersection types of interest in this study.

2.1 Offset T Intersections

A number of prior studies have evaluated the safety effectiveness of implementing offset-T intersections in various related situations. The findings of several studies from the 1970's and 1980's suggest that the effect of offsetting intersections depends on the proportion of the minor road traffic compared to the total entering volume of traffic. When the urban minor road traffic is heavy, comprising greater than 30 percent of the total entering traffic, the effect of converting to an offset intersection is a reduction of up to 33 percent in all injury crashes [20]. Further, the number of property damage only (PDO) crashes is also reduced by about 10 percent for heavy urban minor road traffic. However, when urban minor road traffic is light, comprising less than 15 percent of the total entering traffic, injury crashes were found to increase by 35 percent and PDO crashes increased by 15 percent when converting a four-leg intersection into an offset-T [20]. The applicability of these CMFs to urban intersections should be considered in light of often lower operating speeds, but also higher amounts of total entering traffic. The number of conflict points encountered at a four-leg intersection is 32, while an offset-T has only 18 conflict points. The reduction in conflict points makes the task of minor road traffic crossing a major road theoretically safer at offset-T intersections.

The installation of an offset-T intersection has been promoted as a countermeasure for a highly skewed four-leg intersection. Sight distance concerns as well as related operational problems can occur at skewed intersections. This can result in an abundance of right-angle crashes, particularly involving vehicles approaching from the acute angle. Drivers may find it difficult to scan the approach on an acute angle, and vehicles turning right at an acute angle may encroach on vehicles approaching from the opposite direction. At skewed intersections, drivers may have more difficulty judging gaps when turning. Turning in intersections, and thus creating offset-Ts is a countermeasure suggested to deal with extreme skew at crossings. The Michigan Department of Transportation (MDOT) has a geometric design guide which documents several alternative treatments at highly skewed intersections. The preferred option is to introduce curves on the minor road approach to create a near perpendicular four-leg intersection. However as noted in MDOT GEO-640-C, when the crossroad has light through traffic and a lack of available land makes turned in approaches impractical, two three-leg T intersections are proposed [21]. It is interesting to note that the guidance qualifies this option as applicable for "light" minor road through traffic, suggesting that numerous crossing maneuvers for the minor road is less desirable at an offset-T configuration than a four-leg intersection. The FHWA also provides guidance towards the implementation of offset-T intersections as a countermeasure to skewed intersections [22]. In comparison to a four-leg intersection with skew, two three-leg intersections with an offset distance mitigates the safety concerns related to intersection skew. In addition, the crossing distance for pedestrians is shortened for offset-T intersection geometry, a consideration that is more likely a concern in urban settings or at signalized intersections.

The installation of offset-T intersections on rural high-speed divided highways was evaluated by Maze et al. [23]. The concept of reducing conflict points at the intersection is key to the justification. The use of a three-leg intersection eliminates far-side conflicts associated with minor road crossing maneuvers and minor road left turn maneuvers which are especially high risk on high-speed highways. Conversion of an existing four-leg divided highway intersection to an offset-T requires realignment of the minor road approaches in order to accommodate access for minor road through traffic. The availability of land for the relocation is often the biggest issue with creating and offset-T configuration. Another type of channelization geometry can also accomplish this on divided highways without realignment of the minor road approaches, such as the J-turn intersection (also known as restricted crossing U-turn or RCUT). In either case, conversion from a four-leg crossing to an offset-T or J-turn may potentially lead to increased rear-end and sideswipe collisions related to the required weaving maneuvers [23]. For this reason, the use of turn lanes and tapers are recommended to be included in the reconfiguration on divided highways.

The direction of offset has been evaluated as it regards to safety and operational performance in a study by Mahalel et al. [24]. Offset-Ts with an L-R design were found to have greater reductions in injury crashes than those with an R-L design. When the offset-T is created as a realignment of a highly skewed intersection, the choice of offset direction is not often an option. However, when given the choice of offset direction, Mahalel et al. suggested the R-L layout for mostly operational reasons. The critical gap for making an initial right turn from the minor road approach is less than making an initial left turn. Thus the R-L would afford higher minor road capacity and incur less intersection delay [24]. The opposite sentiment is espoused in the AASHTO Green Book; when addressing offset-T intersections the potential for a vehicle making a left turn from the major road to slow down or stop major flow through traffic is noted as a concern with R-L offset configurations [25]. Similarly, this concern manifests with the potential for interlocking left turns from the major road to each of the minor road approaches when considering the R-L design. When the major road is a divided highway, the R-L configuration is preferred because it has higher capacity, less delay time, and interlocking left turns is not an issue because of the median [23].

Guidance for the amount of offset between un-signalized offset-T intersections was provided in a study by Bared and Kaisar [26]. Citing previous work by Mahalel et al. it was shown that there was no interference by minor road crossing traffic movements when the distance separating minor road approaches is less than or equal to 200 feet (60m) for an R-L design and 260 feet (80m) for an L-R design [24]. This concept plays out at specified traffic volumes for two-lane two-way major roads with a 50 mph speed limit when the offset distance is small enough that minor road crossing traffic can maneuver without impeding either direction of major road traffic. The concept was furthered by Bared and Kaisar by deriving guidelines for the maximum offset between minor road approaches that would still minimize the interference with major road traffic flow due to the decelerating or accelerating minor road vehicle. The derivation assumed that minor road traffic would not accept headways smaller than the critical gap for the first turn being made. Without the provision of left or right turn lanes on the major road, the maximum recommended offset between minor road approaches is 154 feet for the R-L design and 227 feet for the L-R design [26]. This study also asserted that on an aggregate level the benefit of converting a four-leg cross intersection to an offset-T would be a reduction of 20 to 30 percent in total crashes for rural two-lane two-way facilities.

Conversion of two offset-T intersections into a four-leg intersection is a safety strategy that has been proposed for unsignalized intersections with "very high" through volumes on the minor road [27] [28]. This strategy is expected to reduce crashes involving left turns from the major road as well as rear-end collisions on the major road. The safety benefit of this strategy is contrary to the CMF for urban area types as promulgated in the CMF Clearinghouse [7]. The focus of this paper is on the safety performance of offset-T intersections at rural two-lane two-way intersections in comparison to conventional four-leg cross intersections without substantial skew in the approach geometry.

2.2 Curvature at Intersections

Chapter 10 of the HSM documents a CMF for intersection skew, which is involved in parts of the curved corner intersection. There have been several studies that develop SPFs and CMFs for a variety of unique and specific situations, although none were found for the case of curved corner intersections in particular. Several recent studies have explored horizontal curve CMFs for rural two-lane two-way highways [29] [30] [31] [32] [33]. These include measures of the radius of curve or the proportion of the segment length that is curved. In any case the factor that involves curvature leads to more crashes than a tangent segment. Other studies have explored treatments at horizontal curves, some of which such are static and dynamic curve warning signs [34]. This has not been explored in cases of intersections however. The curved corner intersections may have curve warning signs, advisory speed, target arrow, chevrons, delineators, etc, regardless of the intersection control signage (i.e. stop and yield) that are present. The characteristics of an intersection on a curve are hard to disassociate with the curve. The FHWA maintains the CMF Clearinghouse, a web-based database of CMFs that provides supporting documentation to assist users in estimating the impacts of various safety countermeasures [7]. There were not found to be any CMFs in the clearinghouse related to the situation described in this study as a curved corner intersection geometry.

2.3 Skew at Intersections

Intersection skew angle is one of the foundational characteristics that was associated with intersection safety performance in studies that lead to the development of the HSM. A FHWA report by Harwood, et. al, calibrated the crash relationship to intersection skew angle using 324 four-leg stop-controlled intersections in Minnesota [4]. As a direct relationship, a 1 degree increase in skew angle was translated to a 0.54 percent increase in crash frequency among four-leg intersections. Similarly, for three-leg intersections, a 0.40 percent increase in crash frequency was predicted as the skew increases by 1 degree. While at the time a different effect was postulated for acute and obtuse skew angles, it was not ultimately included in the formulation.

While the preferred design is conventionally accepted to be perpendicular intersecting approaches, skewed intersections remain quite common due in most part to the orientation of the approaching roadway segments. Numerous highway agencies provide design guidance on the "improvement" of intersection skew in terms of creating a more perpendicular approach. For example, AASHO's first *Policy on Intersections at Grade* from 1940 states "…it is desirable that intersecting roads meet at right angles or nearly so, both for economy and for safety" and then goes on to provide graphical examples of alignment modifications to procure intersecting angles closer to perpendicular [35]. The Michigan Road Design Manual states that "the angle of intersection between the approach road and the trunkline should not be less than 60° or more than 120°, with desirable values between 75° and 105°" [36]. The latter policy in effect limits skew angle to not more than 30 degrees, and desirably less than 15 degrees in either direction. The effect of skew is associated with inhibiting intersection sight distance based on the sight line of the driver and the necessary distance along a crossing highway that must be visible to allow decisions for crossing and turning maneuvers as well as traffic control.

In an evaluation of 35 intersections of Sicilia, Italy prototypical crash scenarios are described for three-leg skewed intersections with respect to the direction of the skew [5]. All of the intersections in the study by Distefano and Leonardi had skew angles between 15 and 20 degrees. The researchers suggest that acute and obtuse angles impact safety differently. Right skewed intersections produce an acute angle from the minor road approach to oncoming traffic from the right side. This situation is more prone to result in angle type and rear-end type crashes involving minor road traffic with major traffic approaching from the acute angled side. The most plausible explanation for this observation is that the driver's field of vision is decreased for seeing traffic approaching from the acute angle side. A passenger or portions of the vehicle itself can cause a blind spot for right skewed minor road approaches [37]. This is less likely a problem at left skewed minor road approaches since the driver may rotate their head or lean to direct their gaze at oncoming traffic. Another effect of skew is that drivers making right turns around the acute angle radius may encroach on the lanes of oncoming traffic, this is especially a concern for large vehicles. Overall it is argued that intersections with increasing skew in either direction could result in more crashes.

A study of 919 three-leg and four-leg rural stop-controlled intersections in South Dakota developed crash severity proportion models. Instead of applying a fixed crash severity distribution to all sites of the same intersection facility type, Qin et. al. proposed a severity proportion function based on intersection characteristics and found that the proportion of fatal and injury crashes at four-leg intersections significantly increases as skew angle increases [38]. However skew angle was not significantly related to fatal and injury crash proportion for the population of three-leg intersections studied. Since the skew angle was not used as a parameter to model the crash frequency in the study by Qin et. al., no inference is made about the effect of skew on crash frequency.

According to the Institute of Transportation Engineers (ITE) unsignalized intersection improvement guide, as the angle between the two adjacent legs becomes more acute, it is increasingly difficult for the driver (especially seniors) to view oncoming traffic, which makes the turning maneuver more hazardous [28]. Extreme skew angles are expected to have the greater influence on crashes. In addition, skewed intersections may require more distance to cross, resulting in an increased exposure time to conflicting traffic for all modes of transportation involved. The targeted crash types identified at skewed intersections include angle, rear-end, head-on, as well as pedestrian and bicycle crashes. The suggested treatment is to realign the intersection approach to reduce or eliminate the skew angle.

Nightingale et. al. published a study of 9,711 three-leg and 8,343 four-leg rural stop-controlled intersections in Iowa, of which 39.5 percent and 15.5 percent were skewed respectively [39]. The study used five years of crash history to calibrate SPFs and translated intersection skew angle as a crash modification factor with a monotonic relationship to crash frequency. The results of the study were very similar albeit slightly lower than the HSM. For three-leg intersections, a 0.3 percent increase in crash frequency for 1 degree increase in skew, and a 0.4 percent increase in crash frequency for a 1 degree increase in skew at four-leg intersections. The study noted that angle crashes at four-leg intersections also increased as skew increased, and that the through traffic movement on the minor road was more affected by the skew angle for this crash type [39].

Other researchers suggest that the relationship between crashes and skew is not monotonically increasing, or that within a range of skew angles crash frequency increases and then decreases somewhat parabolically. Harkey et. al. derived crash modification functions for skew at rural and urban three-leg and four-leg intersections based on data from Minnesota and Ohio [40]. The researchers evaluated several functional forms of the relationship to find a better fitting CMF to what was observed in comparison to annual average total crash rate throughout the range of intersection angles. The suggested CMF is derived from a flexible form model that includes the intersection angle interacted with the annual average daily traffic (AADT). A perpendicular intersection defines the baseline condition and a CMF value of one. The flexible form model increases up to a critical intersection angle and then decreases, eventually falling below 1.0, which indicates that the most highly skewed intersections are predicted to experience fewer crashes than perpendicular intersections. The CMFs currently listed in the CMF Clearinghouse for changing the minimum intersection angle consist of an average of the flexible form models separately calibrated on the Minnesota and Ohio data [7]. In the case of rural three-leg intersections on two-lane two-way roads a Hoerl curve model is recommended by Harkey et. al. The Hoerl curve is a composite function by multiplying the basic power function by the exponential function [41]. In this case intersection angle is thereby a parameter in the composite function twice. While this may not have a causal theoretical explanation, the Hoerl curve is useful for curve fitting. Afterall, the functional form of the relationship is an important consideration for developing crash prediction models, and assuming a monotonic relationship for simplicity or theoretical logic may provide misleading results.

2.4 Multi-leg (5+) with Five or More-leg Intersections

The AASHTO Green Book defines multi-leg intersections as those with five or more intersection legs and adds that they "should be avoided wherever practical" [25]. Besides this terse guidance, it is suggested that all intersecting legs share a common paved area where traffic volumes are light and stop-control is used. However, for other minor road intersections, a few geometric reconfiguration examples are offered to improve operational efficiency and remove some of the conflicting movements from the major intersection. The type of reconfigurations suggested involve realigning one or two of the minor intersection legs or combining two minor legs into a subsidiary adjacent intersection. The 1954 edition of the AASHO "Blue Book", *A Policy on*

Geometric Design of Rural Highways was the first national policy document to provide some graphical examples of realignment at multileg intersections as shown in the following figure [35].

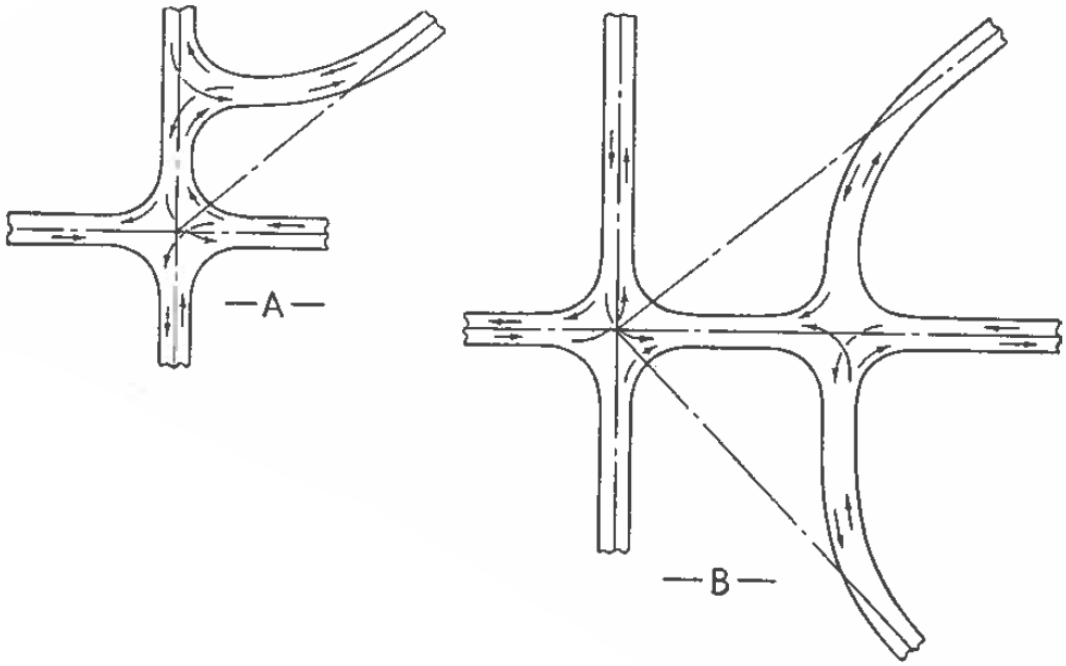

Figure 6. Realignment of multi-leg intersection examples [35].

Very limited literature was found regarding the safety performance of multi-leg intersections, although certain portions of this type of intersection geometry certainly include intersection skew as previously discussed. One reference study in the CMF Clearinghouse lists a countermeasure for changing the number of five-leg intersections; however, the referenced CMF only applies to vehicle-pedestrian crashes in urban areas based on a study from New York City [7]. The limited body of research into multi-leg intersections is indicative of how relatively rare these types of sites are, especially in rural locations.

2.5 Minor AADT Estimation

Traffic volume is considered to be the paramount characteristic for intersection crash estimation because it represents the exposure of the facility. Considering Equation 2, both the major and minor road AADT are conventionally included in intersection crash prediction models. The interaction between turning movements and/or the popularity of minor road turns in any direction verses crossing maneuvers is typically not microscopically evaluated, instead macroscopic measures are employed due primarily to data limitations. It would be overwhelmingly cumbersome for analysts to collect traffic turning movements at every intersection, so the basis of the models developed for crash prediction use aggregated major and minor road AADT to represent the exposure of the intersection to traffic. Even still, there are numerous intersections that have no available or reliable minor road traffic volume to use. Quite often these minor road approaches will be considered too small or inconsequential to the operational and safety performance of the overall network to invest effort into data collection. As a result, methods for minor road AADT estimation have emerged as a means to forge ahead with the analysis using information that describes the facility well enough to make a reliable estimation of the minor road traffic exposure.

In a paper presented at the 2015 Transportation Research Board (TRB) annual meeting, multiple linear regression was used to cost effectively estimate AADT on low volume minor road approaches in the state of Wyoming using socio-economic, demographic, and road geometric factors [42]. In this study, the surface type, land use, highway access, tax revenue, and roadway width were found to be statistically significant predictors of the minor road AADT. Road surface was categorized as either paved or unpaved. The influence of population density was incorporated using U.S. Census data aggregated at the census block group level. A multiple linear regression model achieved a coefficient of determination, R-square, of 0.64 meaning that 64 percent of the variation in AADT could be described by the model. Subsequent studies have also employed this methodology. Multiple linear regression was used to predict AADT on low volume roadways in Louisiana to provide a cost-effective alternative for traffic data collection. The model employed by Yeboah et. al [43] included the number of lanes, median household income, income density, and household density. The primary measures of effectiveness used to test the accuracy and validity of the models is the R-square, MAPE (mean absolute percent error), and %RMSE (percent root mean squared error). The lower values for MAPE and %RMSE are indicators of better model fit.

The use of GIS (geographic information systems) to estimate AADT was developed by Lowry and Dixon, combining geospatial analysis and linear regression [44]. In the tools developed, connectivity importance index was used to describe internal and external trip probabilities. It is important to note that this model applies to a small urban network; Moscow Idaho, and thus the connectivity of more expansive rural networks was not explicitly included in the derivation. As explained in the report: “A simple approach to spatial extrapolation is to use characteristics of the roadway and surrounding area to create a model from one location that can be transferred to another location.” [44]. The implementation of machine learning techniques has been applied to prediction of AADT mainly focused on the use of historical data. Machine learning is an artificial intelligence technique that relies on pattern recognition algorithms. A study of 1,350 rural four-leg stop-controlled intersections in the province of Alberta, Canada employed a deep neural network to estimate AADT of minor road approaches. The resulting model includes the functional classification and AADT of the major road approach to estimate the AADT of the minor road approach [45]. The R-square for a multiple linear regression model was 0.66, while the R-square for models using deep neural networks ranged from 0.67 to 0.94. An artificial neural network with a random forest was used to estimate a model for rural two-lane two-way minor road intersections in the state of Washington using data available from the Highway Performance Monitoring System (HPMS). The resulting model included the major road AADT as well as the functional classification of the major road minus the functional classification of the minor road to estimate minor road AADT with an R-square of 0.57 [46]. Machine learning was used to estimate low-volume roadway AADT in the state of Vermont using population density and work employment density as predictors. The best fitting machine learning model using random forest improved the accuracy of AADT for low-volume roadways from 0.45 to 0.77 with regard to the R-square value. The use of census data at the block group and tract levels were found to have higher correlations with AADT than those disaggregated at the census block level or aggregated to the county level.

3.0 DATA COLLECTION AND METHODOLOGY

This section describes the general applicability of data collected to facilitate these investigations. Additional information specific to the unique intersection types is further explained within each chapter. Data sources were accessed or requested from multiple federal, state, and local jurisdictions. Data was assembled representing AADT traffic, roadway inventory (number of lanes, turn lanes), operations (stop control, lighting, flashing beacon), and jurisdictional (functional classification, maintaining agency). All of these characteristics were initially hypothesized to potentially impact the safety performance of intersections. Visual inspection of each site location was conducted manually using satellite aerial imagery. The number of intersecting legs was verified, as well as the stop-control on the approaches. Intersections for which street level imagery was not available were removed from the dataset if it was not possible to confirm the presence of a stop-control on the minor approaches. The aerial imagery was used to cursorily verify that the major geometric conditions remained consistent throughout the years of data applied to each site. There was no intent to perform before and after comparisons of treatments or countermeasures

3.1 Intersection Data

The Michigan Geographic Framework (MGF) All Roads shapefile provided the spatial basis for collection of the necessary roadway and traffic-related attributes for the intersections included within this study. A spatially-based algorithm was developed in ArcGIS to generate nodes based on the occurrence of intersecting lines within the All Roads shapefile. Figure 7 depicts the six main steps followed to identify all intersection nodes with a numerical count of the number of intersecting legs. Further details about this process are described in a research report by Gates et. al [47]. Segment vertices were converted to points, where the X (longitude) and Y (latitude) coordinates represent the location of the intersection node. From the available intersection locations, the sample was filtered to include only two-lane two-way highways. The number of intersecting legs, assignment of major and minor road approaches, and stop-control was verified using satellite imagery and street level imagery.

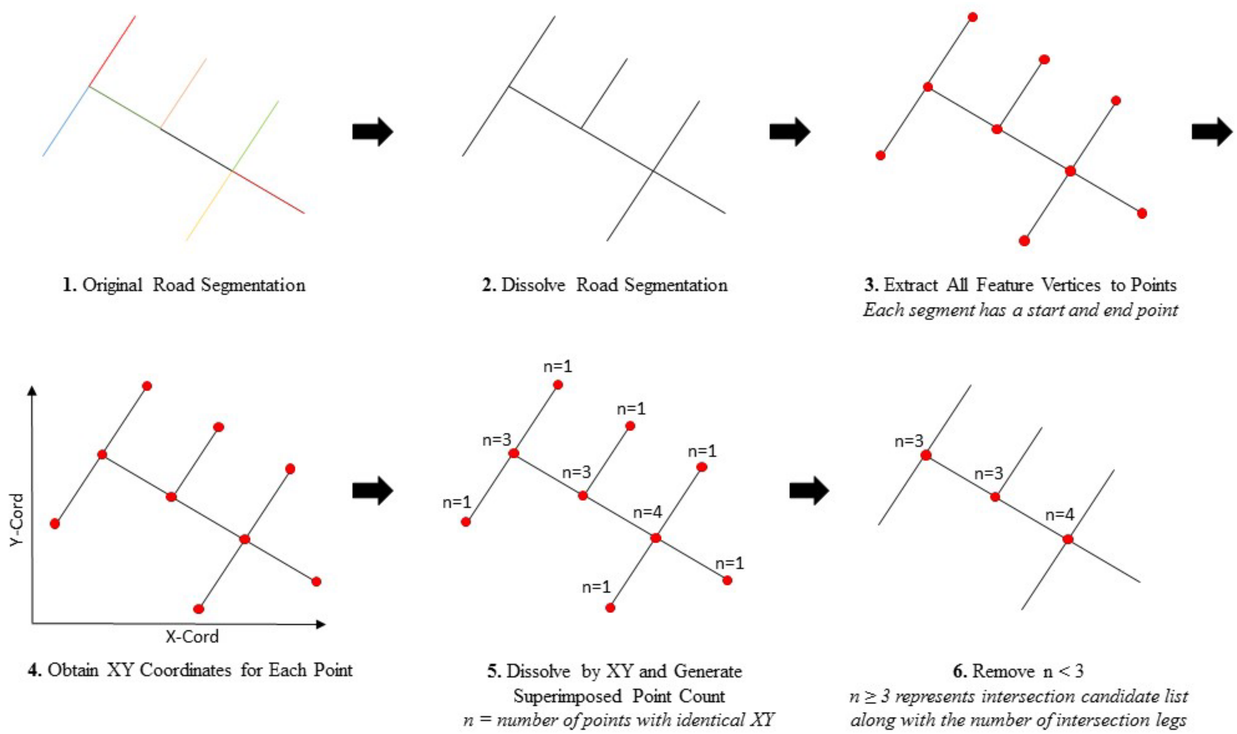

Figure 7. Node identification algorithm employed by this study [47].

This study pertains to intersections located in "rural" areas which are classified as having a population less than 5,000 people. Following the node generation process for potential intersections, any intersection node located within Michigan's Adjusted Census Urban Boundary (ACUB) zone was removed to limit the data solely to rural designated intersections. To further isolate high-speed highways, intersections inside of villages and census designated places were also excluded.

The skew angle of the intersection was measured using the heading tool in Google Earth. The heading of each leg was measured with respect to the centerline, and the absolute difference of those two headings was then calculated as the intersection angle. The skew angle was then calculated as the absolute difference of the smallest intersection angle from 90 degrees. The HSM defines intersection skew angle as the absolute value of the deviation from an intersection angle of 90 degrees. For this study, skew was measured as the smallest angle between any two adjacent legs of the intersection. The skew was not recorded for tangents to the curved segment of curved corner intersections as a site type. Use of satellite imagery was very important for this task, since measurements based only from the framework might not accurately reflect the actual skew on the immediate intersection approach.

Radius of curvature for the curved segment at intersections was measured using the ruler tool in Google Earth as illustrated in Figure 8. This process allowed for an accurate estimation of the radius. The centerline of the roadway was used for the measurement based on the aerial photo rather than the framework lines.

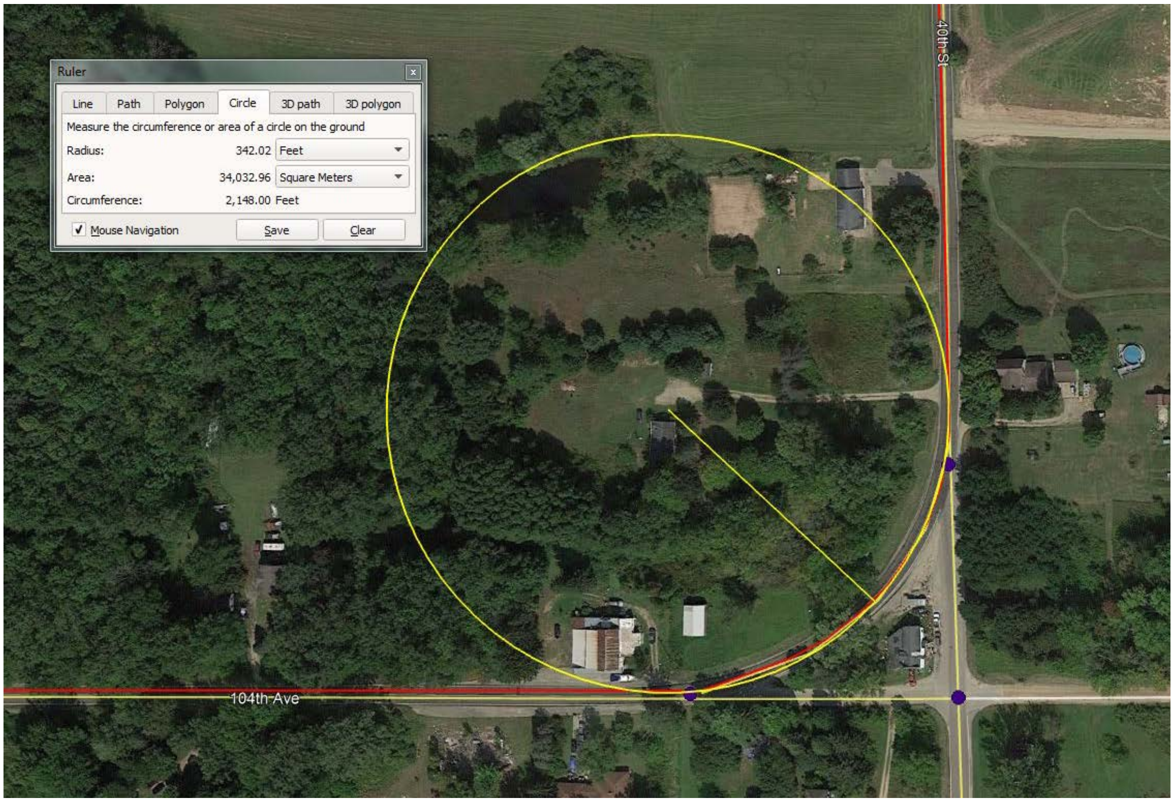

Figure 8. Measurement of curved segment radius using Google Earth ruler tool.

3.2 Segment Data

3.2.1 Annual Average Daily Traffic

The availability of AADT data was considered a necessity in order to proceed with site selection. Major road AADT and minor road AADT should be available for each project site. In many circumstances, the minor road AADT was not available from any data source. These sites were retained in the dataset with the known limitation that they could either not be included to develop models based on minor road AADT as a parameter or that minor road AADT would need to be estimated. In the study of curved corner intersections, the latter case was applied. For the other site types, only known or reported traffic volumes were used. The AADT volumes were obtained from three primary sources for use in this study. The particular volume data source was dependent on the roadway jurisdiction and federal aid classification, which are further described as follows:

- Michigan Department of Transportation (MDOT) “trunkline” AADTs were obtained system wide for all state maintained rural major arterials.
- County federal aid roadway AADTs were obtained from the statewide non-trunkline federal aid (NTFA) dataset, consisting of major and minor arterials and major collectors.
- County non-federal aid (Non-FA) roadway AADTs were obtained directly from the county road agency or regional planning commission.

The opportunity to expand the analysis to routes that involve Non-FA minor collectors and local roadways was only possible through information gathering from numerous local sources. This feat overcame a substantial limitation of prior studies that are only based on federal aid routes for which traffic data is maintained. This study covers a period of 10 years from 2010 to 2019. Growth factors were applied to adjust all obtained traffic data to match the year to which annual crashes were associated. The growth rates were not always positive, and were based on historic trends in annual vehicle miles traveled as reported by MDOT through Highway Performance Monitoring System (HPMS) related efforts. Growth rates for other county non-federal aid roadways were determined based on reported annual traffic growth rates that were aggregated to the county level in various local traffic databases. 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 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 identified as a complete intersection.

3.2.2 Roadsoft and PASER Data

Roadsoft is an asset management software used by transportation agencies throughout Michigan. The inventory data from Roadsoft was collected from several participating county road agencies and provides useful information about the traffic volume as well as the number of lanes, and traffic control for intersections. PASER is a pavement surface evaluation rating system based on a visual survey evaluating the condition of roadway segments. The visual survey results in a database including surface type, qualitative surface condition Michigan's Transportation Asset Management Council (TAMC) adopted the PASER method in combination with Roadsoft for collecting, storing, and analyzing statewide pavement ratings.

3.3 Crash Data

In addition to characteristics of the facility, historical crash data were obtained from the annual databases maintained by the Michigan State Police. The crash history for 10 years from 2010 to 2019 was collected for each site. Panel data consisting of individual years of crash data and facility characteristic data were assembled for each intersection, thus a site would occur in the database 10 times, once for each intersection-year. The crash data was mapped using X & Y coordinates provided in the individual crash records. The buffers, previously mentioned, around each intersection node were dissolved resulting in a single shape at each intersection site. The buffers as dissolved were then used to select by location only those crashes that existed inside the buffer shapes. The individual crash records produced by this selection were exported into a new data set. From within the new data set, each crash was assigned to the intersection site by appending the unique site identifier to the crash record listing.

As previously mentioned, crash information was matched to the intersection inventory information using spatial location information associated with each crash report. Crashes were summarized and categorized by type and severity. In the analysis of intersections, only intersection crashes are desired. Intersection crashes were isolated by filtering the “mdot_area_type_cd” equal to 2 (i.e. intersection crash) from the crash record information. This crash area type is coded by MDOT in refinement of the raw crash information provided by the Michigan State Police. Conventionally, crashes occurring within a 250 feet radius from the center of the intersection have been coded as intersection-related [48]. The intent of extending at such a distance is to capture crashes that are intersection-related. However, certain crash circumstances within the spatial vicinity of the intersection are not necessarily intersection related (e.g. driveway and animal type crashes). Among curved corner intersection sites, numerous single-vehicle run-off-road and fixed object type of crashes were also filtered out as a result of using the MDOT area type code for “intersection”. In addition, throughout the study several driveway related crashes, either single or multiple vehicle, are also excluded by using the MDOT area type code for “intersection”.

3.4 Spatial Analysis

ArcGIS permits data from different sources to be overlaid and matched based upon a linear referencing system which was defined in association with the MGF. A spatial join was performed to build a relationship between the node dataset and segment dataset for purposes of joining available segment traffic volume data to each leg of the intersection node. Once the data was matched and assembled, an algorithm of sorting and filtering was applied in order to narrow down the data set to match the targeted facility of rural intersections. Spatial buffers were evaluated in ArcGIS to identify nodes whose buffers overlap with another node, as shown in Figure 9. Each intersection has a unique X & Y coordinate at the centroid of the intersection. The buffer distance used in this study is 250 ft from the centroid of any intersection. All overlapping buffers were joined together at each site and assigned a single site identifier.

a) Offset-T intersection b) Curved corner intersection

Figure 9. Example of nodes and buffers at intersection sites.

3.5 Analysis and Modeling

The statistical package R was used to develop random effect negative binomial regression models for a combination of variables predicting the frequency of intersection related crashes reported annually. These safety performance functions (SPFs) take the form of generalized linear models. Since 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 is known to provide a better fit and is used widely to model crash frequency data. In the Poisson model, the probability of intersection *i* experiencing y_i crashes during a one-year period is computed by Equation 4:

$$P(y_i) = \frac{e^{-\lambda_i} \times {\lambda_i}^{y_i}}{y_i!} \qquad (4)$$

Where,

$P(y_i)$ = probability of intersection *i* experiencing y_i crashes, and

λ_i = expected number of crashes per year of intersection *i* .

In Equation 4, the expected number of crashes for the intersection (λ_i) is the Poisson model parameter and is calibrated as a function of explanatory variables based on observed history. A limitation of this model is the underlying assumption of the Poisson distribution that the variance is equal to the mean. As such, the Poisson model alone cannot handle overdispersion which is common particularly in rural intersection crash data that may be caused by: data clustering, unaccounted temporal correlation, model misspecification, or ultimately by the nature of the crash data as random rare events. Overdispersion is generally accommodated through the use of negative binomial models. The negative binomial model is preferred over the simple Poisson model since the latter cannot handle overdispersion and, as such, may lead to biased parameter estimates.

The HSM recommends using the negative binomial distribution for the development of SPFs due to its ability to account for the Poisson variance overdispersion that is common in crash data distributions [2]. One concern when evaluating SPFs across a broad statewide network is unobserved heterogeneity. Within the context of this study, each site is observed ten times (once per year from 2010 to 2019). These repeated measurements introduce correlation in the crash counts within the individual sites over time, as individual sites are likely to experience more (or less) crashes than other similar sites due to site-specific factors that may not be included in the model. To account for this, a site-specific random effect (intercept) was incorporated into the analysis, which was performed using the statistical package R. The RENB allows the intercept term to vary across individual observations, while still applying the basic functional form of the NB model. Depending on the groups specified as the random effect, the RENB attempts to capture some of the variation geographically and jurisdictionally. The expected number of crashes can be estimated using the general functional form:

$$N_{spf} = e^{(\beta_0 + \boldsymbol{\beta} * \mathbf{X} + \varepsilon + \eta)} \tag{5}$$

Where,

N_{spf} = predicted intersection-related crashes per year,

β_0 = intercept term,

$\boldsymbol{\beta}$ = vector of coefficients,

$\mathbf{X}$ = vector of explanatory variables,

ε = gamma-distributed error term for negative binomial, and

η = random effect for observation groups

In Equation 5, both exp(ε) and exp(η) are gamma-distributed with a mean one and variance α. The random effect on the intercept adds a term η, however the mean value of the intercept is unchanged.

The inclusion of a variable in the model was typically determined based on a test of significance of the model coefficient for that variable. The significance level was judged based on a 95 percent confidence interval. Other random effects on the intercept were tested for statewide defined regions as well as the analysis year. A region-specific random effect was included in this study. The region codes defined by MDOT encompass 7 different regions in their governance that also possess distinct traffic characteristics and weather conditions, as well as other distinctive population demographics. Assessment of the differences between log-likelihoods of the models with and without the random effects were assessed along with assessment of the Akaike information criterion (AIC). The random effect for year provided model results that were nearly identical to the fixed effect negative binomial model without year. The random effect for site improved upon the fixed effect model based on comparison of the AIC along with a modest difference in the log-likelihood.

4.0 OFFSET T INTERSECTIONS

The contents of this chapter were first published as Safety Performance of Rural Offset-T Intersections [49] and have been reformatted to fit this dissertation.

4.1 Data Summary

The first step in this investigation consisted of identifying two-lane two-way rural highway intersections where an offset-T exists. Candidate intersections were identified based on prior experience, spatial evaluation, and expert searching techniques targeting likely characteristics. The most common circumstance for rural offset-T intersections in Michigan occurs when county highways following section lines meet at closing corners, where survey adjustments had been made. Section line roads, which occur every mile, typically have closing corners at their intersection with township or range lines, which occur every six miles. Offset-T intersections are likely to occur at closing corners in rural areas, which as described previously, are an artifact of historical surveys. In order to identify offset-T intersections using this technique, aerial maps were visually searched following along township or range lines. When these lines coincided with primary roads, the lower-class section line roads may be stop-controlled, and occasionally offset. Figure 10 shows an example of a single offset-T site consisting of two three-leg intersections separated by an offset distance. The pair of three-leg stop-controlled intersections and the small segment of roadway separating them were considered collectively as a single offset-T intersection site in this analysis.

Offset-T intersections may also occur due to other reasons, such as railroads or natural features near the intersecting point, which necessitates offsetting one or both of the intersection legs, often introducing curvature or skew on the intersection approach. However, due to the desire to isolate the effects of the offset characteristics, intersections with skew or curvature on the approaches were excluded from the study.

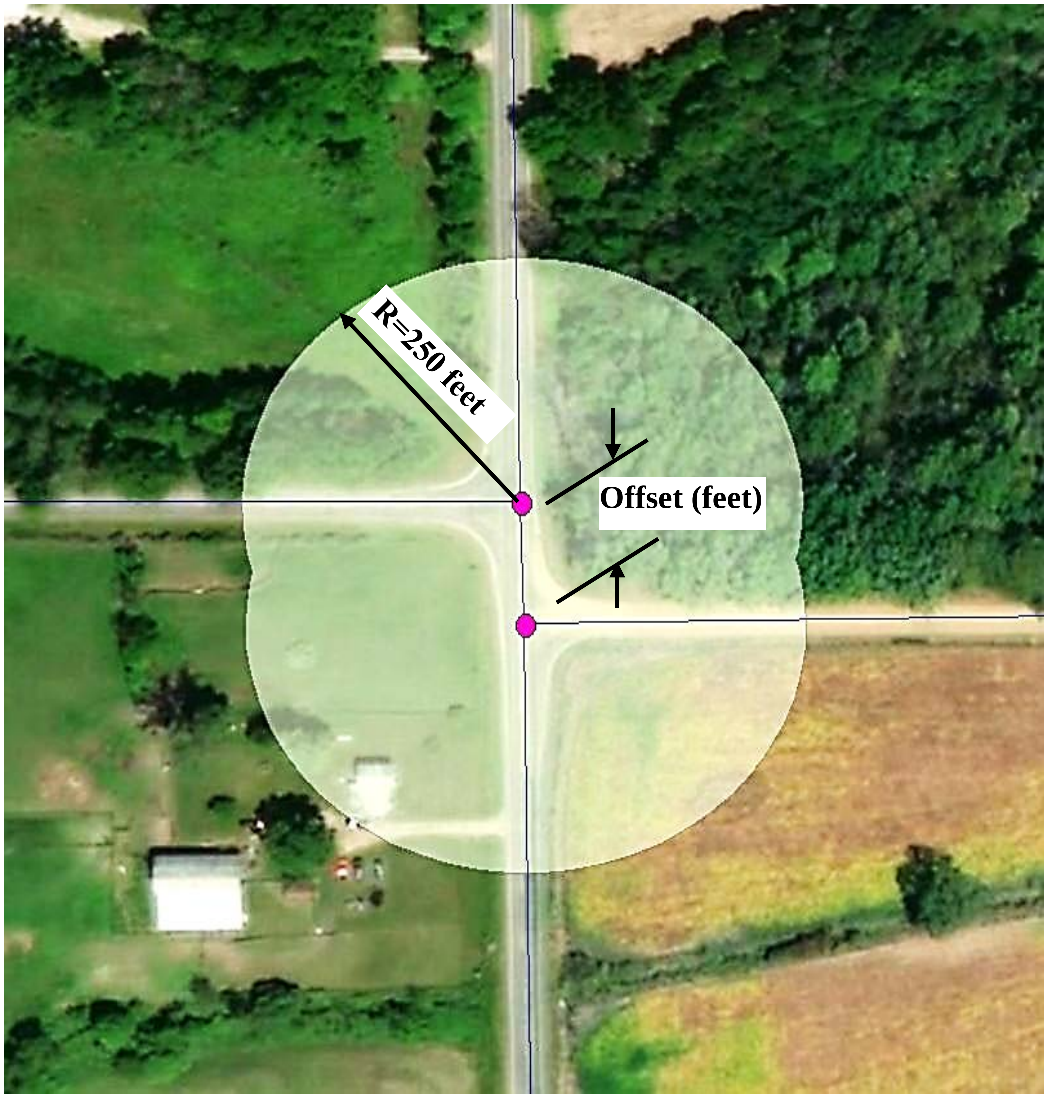

Figure 10. Example offset-T intersection with buffer and offset.

A total of 299 offset-T intersections sites were identified. An additional 301 four-leg two-way stop-controlled intersections were selected to provide a baseline for comparison. The comparison sample of four-leg intersections were drawn in one of two ways. First, where possible, four-leg intersections were selected from within the general proximity of each offset-T site to help control for driver population and other spatially-affected attributes (e.g., weather, road design, road maintenance, etc). This general proximity usually meant searching 1 or 2 miles in any direction along either the major or minor roadway. Second, other four-leg intersections were selected to provide a similar range of major and minor AADT values as the population of offset-T intersections. These intersections were randomly drawn from a geographically diverse pool of previously identified sites after filtering to a range of appropriate traffic volumes. The geographic distribution of the offset-T and four-leg intersections included in this study is shown in Figure 11.

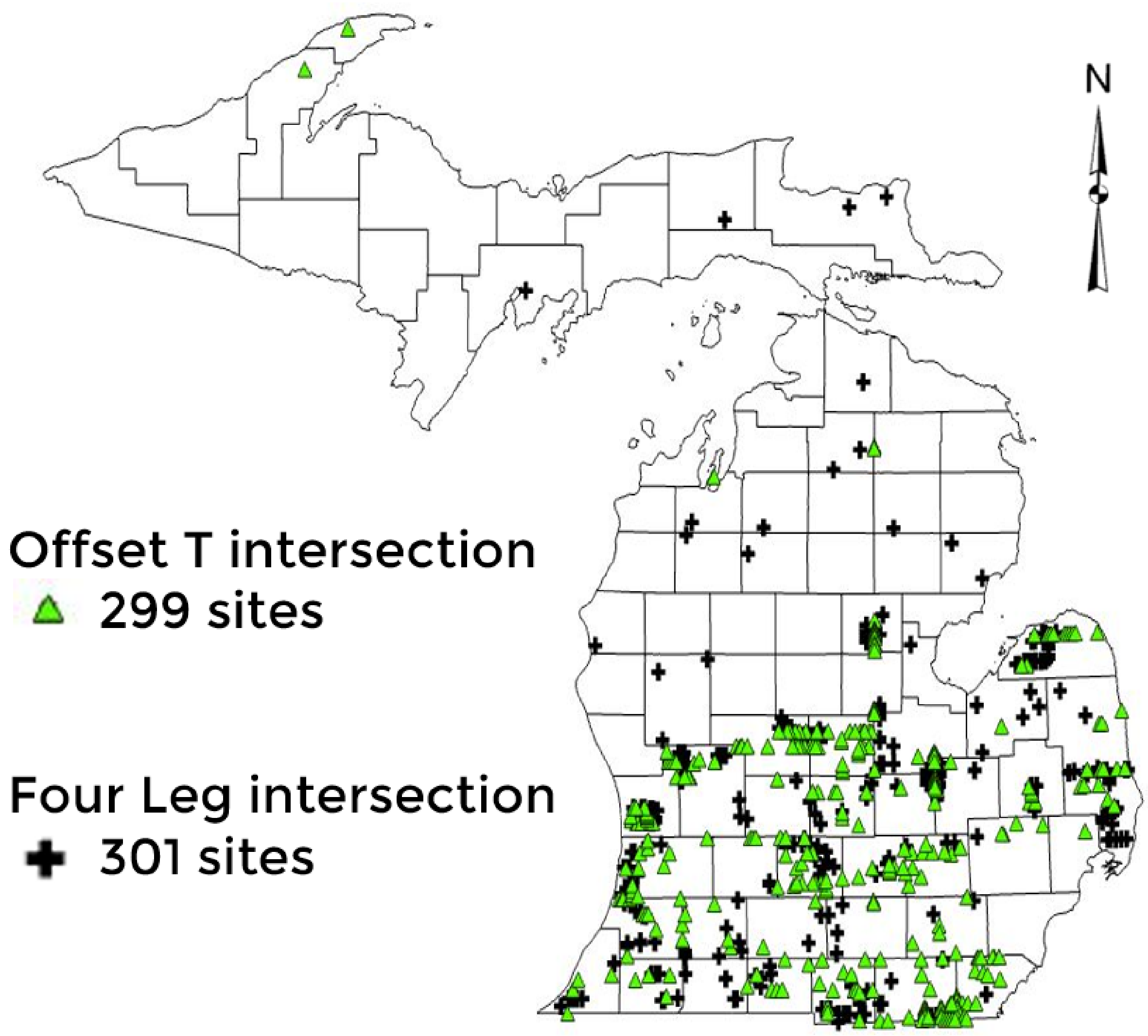

Figure 11. Geographic distribution of offset-T study intersections in Michigan with county lines shown.

4.1.1 Site Data Collection

Visual inspection of each site location was conducted manually using Google Earth aerial imagery. The initial verification step was to confirm that all intersecting roadways were two-lane two-way. From there, the number of intersecting legs was confirmed, along with the presence of stop-control on the minor approaches (all-way stop-control locations were removed). Intersections for which street level imagery was not available were removed from the dataset if it was not possible to confirm the presence of stop-control on the minor approaches only. The aerial imagery was used to verify that the intersection geometric conditions remained consistent throughout the years of data applied to each site. Intersections which appeared to have been converted from offset-T to four-leg were omitted from analysis, as the small sample of such intersections was too small to provide meaningful results.

Each intersection has a unique X & Y coordinate at the centroid of the intersection. Conventionally, crashes occurring within a 250 feet radius from the center of the intersection have been coded as intersection related. However more recent investigations suggest that site specific circumstances should be considered when determining the intersection safety influence area [48]. For offset-T intersections, this would include extending the buffer distance to include the area along the primary roadway between the offset-T intersections to account for crashes affected by the geometry of the offset (e.g., vehicles traveling through on the offset approach). The buffer distance used in this study was 250 feet from the centroid of any intersection. For purposes of this study, it was decided that the maximum distance separating two offset-T intersections was 500 feet, beyond which the two intersections were considered as separate three-leg intersections from a safety and operational standpoint. Offset distance is measured as the distance in feet separating the centerline of each minor road approach intersecting with the major road. The direction of offset was recorded on the basis of the first turn necessary for the minor road approach to complete a crossing maneuver at the intersection as illustrated in Figure 2. No offset distance was recorded below 20 feet; any intersection with less than 20 feet of offset separation was excluded since the alignment of the approaches allowed for crossing maneuvers to be performed in a manner that was similar to a four-leg cross intersection. As stated previously, each intersection included in this sample was without curvature or skew.

4.1.2 Descriptive Statistics

A total of 1,665 crashes occurred at the 299 offset-T sites during the 10-year sampling period, while 1,688 crashes occurred at 301 four-leg intersection sites during the same period. A large proportion of the property damage crashes involved collision with an animal, the most common of which were deer. As roadway and traffic related attributes typically show poor association with deer crashes [33], any crashes coded primarily as animal type were excluded from further analysis. The distribution of crashes by severity level (excluding animal crash) is shown in Table 1.

Upon removal of the animal crashes, a total of 1,174 crashes occurred at the 299 offset-T sites during the ten-year sampling period, while 1,127 crashes occurred at 301 four-leg intersection sites during the same period. Table 1 closely matches the format of, and shows similarity with, the default distributions presented in Table 10-5 of the HSM Chapter 10 [2]. The offset-T and four-leg intersections used for this study have a lower proportion of fatal and injury crashes and a higher proportion of property damage only type crashes than the default distribution in the HSM, even with exclusion of animal crashes. The crash severity distributions are similar between the two intersection categories evaluated here, although offset-T intersections have a lower proportion of fatal and each category of injury crashes compared to four-leg intersections.

Table 1. Distribution of Crash Severity for Offset-T Rural Two-lane Two-way Minor Road Stop-Controlled Intersection Study in Michigan.

	Intersection crash severity distributions (2010-2019)			
	Offset-T intersections		**4-leg intersections**	
Crash severity level	**Frequency**	**Pct. of total**	**Frequency**	**Pct. of total**
Fatal (K)	6	0.5	24	2.1
Incapacitating injury (A)	52	4.4	74	6.6
Nonincapacitating injury (B)	101	8.6	109	9.7
Possible injury (C)	182	15.5	218	19.3
Fatal + injury (KABC)	341	29.0	425	37.7
Property damage only (PDO)	833	71.0	702	62.3
Total	**1174**	**100.0**	**1127**	**100.0**

Note: Each category excludes animal crashes.

Table 2 shows the distribution of collision types for the study intersections and is formatted similar to Table 10-6 of the HSM Chapter 10 [2]. The majority (62.8 percent) of fatal and injury (FI) crashes at four-leg intersections were angle crashes. At offset-T intersections, angle crashes account for less than a quarter (23.8 percent) of fatal and injury crashes, which is more similar to the default distribution for three-leg stop-controlled intersections in the HSM. This finding is consistent with previous investigations which conclude that either offset-T or three-leg intersections have fewer angle crashes than four-leg intersections [2] [20] [23] [24] [27] [28] [50]. Not surprisingly, rear-end crashes and single vehicle crashes were more prominent at offset-T sites, likely due to the unique geometry. The category for "other single-vehicle crash" includes ran-off-road crashes that did not involve the vehicle overturning, such as collision with a fixed object.

Table 2. Distribution of Collision Type and Manner of Collision for Offset-T Rural Two-lane Two-way Minor Road Stop-Controlled Intersection Study in Michigan.

	Percentage of crashes by collision type (2010-2019)					
	Offset-T intersections			4-leg intersections		
Collision Type	**FI**	**PDO**	**Total**	**FI**	**PDO**	**Total**
Single-vehicle crashes						
Collision with bicycle	0.6	0.1	0.3	1.2	0.0	0.4
Collision with pedestrian	1.2	0.0	0.3	0.7	0.1	0.4
Overturned	7.9	5.6	6.3	4.5	3.0	3.5
Other single-vehicle crash	33.1	51.1	45.9	13.6	34.9	26.9
Total single-vehicle crash	42.8	56.9	52.8	20.0	38.0	31.2
Multiple-vehicle crashes						
Angle collision	23.8	13.3	16.4	62.8	29.5	42.1
Head-on collision	8.8	2.5	4.3	5.4	2.8	3.8
Read-end collision	18.2	15.7	16.4	7.8	13.5	11.4
Sideswipe collision	5.0	7.2	6.6	2.6	12.7	8.9
Other multiple-vehicle collision	1.5	4.3	3.5	1.4	3.4	2.7
Total multiple-vehicle collision	57.2	43.1	47.2	80.0	62.0	68.8
Total Crashes	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Note: Each category excludes animal crashes. FI = fatal and injury; PDO = property damage only.

Summary statistics for the variables in this study are provided in Table 3. For offset-T intersections, the mean major road traffic volume was 1,619 vehicles per day (vpd) with a minor road average traffic volume of 333 vpd. Considering the major roadway jurisdiction at the offset-T sites, 11 percent were MDOT, 47 percent were county federal aid, and the remaining 42 percent were county non-federal aid. The offset-T minor road approaches were almost exclusively county jurisdiction, 8 percent federal aid and 92 percent non-federal aid. Among four-leg intersections, the mean major road traffic volume was 1,675 vpd with a minor road average traffic volume of 380 vpd. Considering the major roadway jurisdiction at the four-leg intersections, 11 percent were MDOT, 71 percent were county federal aid, while the remaining 18 percent were county non-federal aid. Twenty-two percent of the four-leg minor road approaches were county federal aid and the remaining 78 percent were county non-federal aid jurisdiction. The population of study sites has a similar distribution of traffic volumes between the intersection types. The distribution of offset distance ranges from 20 feet to 500 feet, with a median value of 105 feet. The proportion of left and right offsets were relatively balanced within the sample population of offset-T intersections (52 percent were L-R, 48 percent were R-L). Several binary variables were created (0=No, 1=Yes) in order to classify offset distance and direction into discrete ranges.

Table 3. Descriptive Statistics for Offset-T Rural Two-lane Two-way Minor Road Stop-Controlled Intersection Study in Michigan.

Variable	Min.	25th%	50th%	75th%	Max.	Mean	SD	Variance
Offset-T intersections (*n=299 sites)*								
Major Rd AADT (vpd)	89	365	825	2,514	9,058	1,619	1,781	3,170,608
Minor Rd AADT (vpd)	24	56	121	389	4,427	333	503	253,444
Offset Distance (feet)	20	62	105	202	500	144	110	12,108
Offset Left 20 to 80 feet	0	0	0	0	1	0.20	0.40	0.16
Offset Left 81 to 160 feet	0	0	0	0	1	0.15	0.36	0.13
Offset Left 161 to 500 feet	0	0	0	0	1	0.16	0.37	0.14
Offset Right 20 to 80 feet	0	0	0	0	1	0.16	0.37	0.14
Offset Right 81 to 160 feet	0	0	0	0	1	0.17	0.37	0.14
Offset Right 161 to 500 feet	0	0	0	0	1	0.15	0.36	0.13
Total Crashes	0	0	0	1	9	0.39	0.80	0.64
Fatal and Injury Crashes	0	0	0	0	4	0.11	0.37	0.14
Property Damage Crashes	0	0	0	0	7	0.28	0.64	0.40
Single Motor Vehicle Crashes	0	0	0	0	5	0.21	0.51	0.26
Angle Crashes	0	0	0	0	3	0.06	0.28	0.08
Rear-end Crashes	0	0	0	0	4	0.06	0.29	0.08
Four-leg stop-controlled intersections (*n=301 sites)*								
Major Rd AADT (vpd)	89	607	1,211	2,280	9,601	1,675	1,468	2,153,987
Minor Rd AADT (vpd)	22	101	208	502	3,240	380	406	165,046
Total Crashes	0	0	0	1	6	0.37	0.76	0.58
Fatal and Injury Crashes	0	0	0	0	4	0.14	0.42	0.18
Property Damage Crashes	0	0	0	0	4	0.23	0.54	0.29
Single motor vehicle Crashes	0	0	0	0	3	0.12	0.37	0.13
Angle Crashes	0	0	0	0	6	0.16	0.51	0.26
Rear-end Crashes	0	0	0	0	3	0.04	0.22	0.05

Note: Min. = minimum; Max. = maximum; SD = standard deviation; vpd = vehicles per day; AADT = annual average daily traffic; Crashes are displayed as per site, per year (2010-2019), exclusive of animal crashes.

4.2 Modeling and Results

Models were developed for total crashes, single motor vehicle crashes, rear-end crashes, and angle crashes. A model developed for fatal and injury crashes did not contain any significant coefficients for offset-T related variables.

Initially, offset distance alone was considered as a continuous variable; however, no discernable relationship could be found to directly link offset distance to the total crash frequency. Given the consideration by Bared and Kaiser [26] of a maximum offset distance for which there is no minor road traffic interference, it was decided to categorize the offset distance as being above or below different thresholds. Numerous thresholds were tested to determine the most significant effect of offset distance and direction on crashes. Eventually offset thresholds of 80 feet and 160 feet were utilized, which corresponds to the distance traveled by a major road vehicle over 1 and 2 seconds, respectively, at the rural statutory speed limit of 55 mph. These thresholds provide relative balance between the categories by dividing the population of offset-Ts in either direction roughly into thirds. Additional upper bound thresholds for offset distance were tested at increments including 240 feet and 320 feet, but did not provide improved significance in the results.

The base SPF for prediction of annual intersection crash frequency includes the major road AADT and the minor road AADT. Characteristics of the offset-T intersections are evaluated in comparison to the four-leg intersections, which represent the baseline condition. Therefore, the characteristics of the offset-T translate as CMFs to incorporate the effects of the offset-T compared to a four-leg cross intersection. A natural log transformation of the AADT is performed in the model calibration so that the AADT can be directly input into the simplified SPF. The functional form of the random intercept negative binomial model from Equation 5 is expanded to represent the SPF as shown in Equation 6.

$$N_{spf} = e^{\beta_0}\left(AADT_{Major}{}^{\beta_1}\right)\left(AADT_{Minor}{}^{\beta_2}\right)e^{\beta_i X_i} \tag{6}$$

Where,

N_{spf}	= predicted intersection-related crashes per year,
β_0	= intercept term,
$AADT_{Major}$	= AADT (vehicles per day) on the major road,
$AADT_{Minor}$	= AADT (vehicles per day) on the minor road,
β_1	= coefficient term related to major road AADT,
β_2	= coefficient term related to minor road AADT,
β_i	= vector of coefficient terms related to intersection characteristics, and
X_i	= vector of binary indicator variables for intersection characteristics

The calibrated coefficients for the SPF are provided in Table 4. Separate SPFs have been developed for total crashes as well as targeted crash types. The overdispersion parameter is provided with each model to weight the predicted and observed crash frequency during application of the Empirical Bayes method consistent with the 2010 HSM methods [2].

Table 4. Random Intercept Negative Binomial Model Results for Rural Offset-T Intersection Study in Michigan.

Parameter	Estimate	Standard error	p-value
Total crashes			
Intercept	-6.852	0.3312	<0.001
Ln(Major Rd AADT)	0.417	0.0501	<0.001
Ln(Minor Rd AADT)	0.449	0.0461	<0.001
No Offset = baseline condition	-	-	-
Offset Left 20 to 160 feet	0.302	0.1053	0.004
Offset Right 81 to 500 feet	0.304	0.107	0.005
Overdispersion	0.078	-	-
Random effect for Site	-	0.0089	-
AIC	7132.7	-	-
Log-likelihood	-3559.3		
Single motor vehicle crashes			
Intercept	-5.649	0.3555	<0.001
Ln(Major Rd AADT)	0.241	0.0545	<0.001
Ln(Minor Rd AADT)	0.271	0.0523	<0.001
No Offset = baseline condition	-	-	-
Offset 20 to 80 feet	0.518	0.1331	<0.001
Offset 81 to 160 feet	0.690	0.1314	<0.001
Offset 161 to 500 feet	0.786	0.1256	<0.001
Overdispersion	0.078	-	-
Random effect for Site	-	0.0091	-
AIC	5262.9	-	-
Log-likelihood	-2623.5		
Angle crashes			
Intercept	-8.374	0.5495	<0.001
Ln(Major Rd AADT)	0.155	0.0849	0.068
Ln(Minor Rd AADT)	0.846	0.0756	<0.001
No Offset = baseline condition	-	-	-
Offset 40 to 160 feet	-0.519	0.1563	<0.001
Offset 161 to 500 feet	-1.161	0.2093	<0.001
Overdispersion	0.127	-	-
Random effect for Site	-	0.0110	-
AIC	3380.4	-	-
Log-likelihood	-1683.2		

Table 4 (cont'd)

Parameter	Estimate	Standard error	p-value
Rear-end crashes			
Intercept	-15.287	0.9528	<0.001
Ln(Major Rd AADT)	1.296	0.1205	<0.001
Ln(Minor Rd AADT)	0.363	0.085	0.003
No Offset = baseline condition	-	-	-
Offset Left 20 to 160 feet	0.598	0.2028	0.032
Offset Right 81 to 500 feet	0.440	0.2112	0.038
Overdispersion	0.584	-	-
Random effect for Site	-	0.0092	-
AIC	1677.8	-	-
Log-likelihood	-831.9		

Note: Each category excludes animal crashes.

4.2.1 Effect of Offset Distance and Direction on Total Crashes

The parameter coefficients for total crashes at offset-Ts summarized in Table 4 show greater crash occurrence compared to conventional four-leg intersections regardless of the offset distance or direction. Offsets left between 161 and 500 feet and offsets right between 20 and 80 feet showed no significant difference in crash occurrence compared to four-leg intersections. For the total crash model presented herein, these sites were excluded from the analysis population. Considering offset distance and direction, the significant parameter coefficients have nearly identical values. In these ranges, offset-T configurations show 35 percent greater total crash occurrence compared to conventional four-leg intersections. Figure 12 shows the model results plotted using a minor road AADT value of 400 veh/day. Two HSM based models are shown for comparison. Both HSM models are calibrated according to the procedures described in Appendix A of Part C for rural intersections [2]. The HSM-4ST model represents a baseline four-leg stop-controlled intersection. The HSM-2x3ST model represents two baseline three-leg stop-controlled intersections; composed by doubling the calibrated model for three-leg from the HSM. The calibration factor for both HSM models was determined using the observed and predicted crashes at the four-leg study sites. A total of 1127 non-animal crashes were observed and the baseline predicted crashes were 1786 resulting in a calibration factor of 0.631 that was used to plot the HSM models.

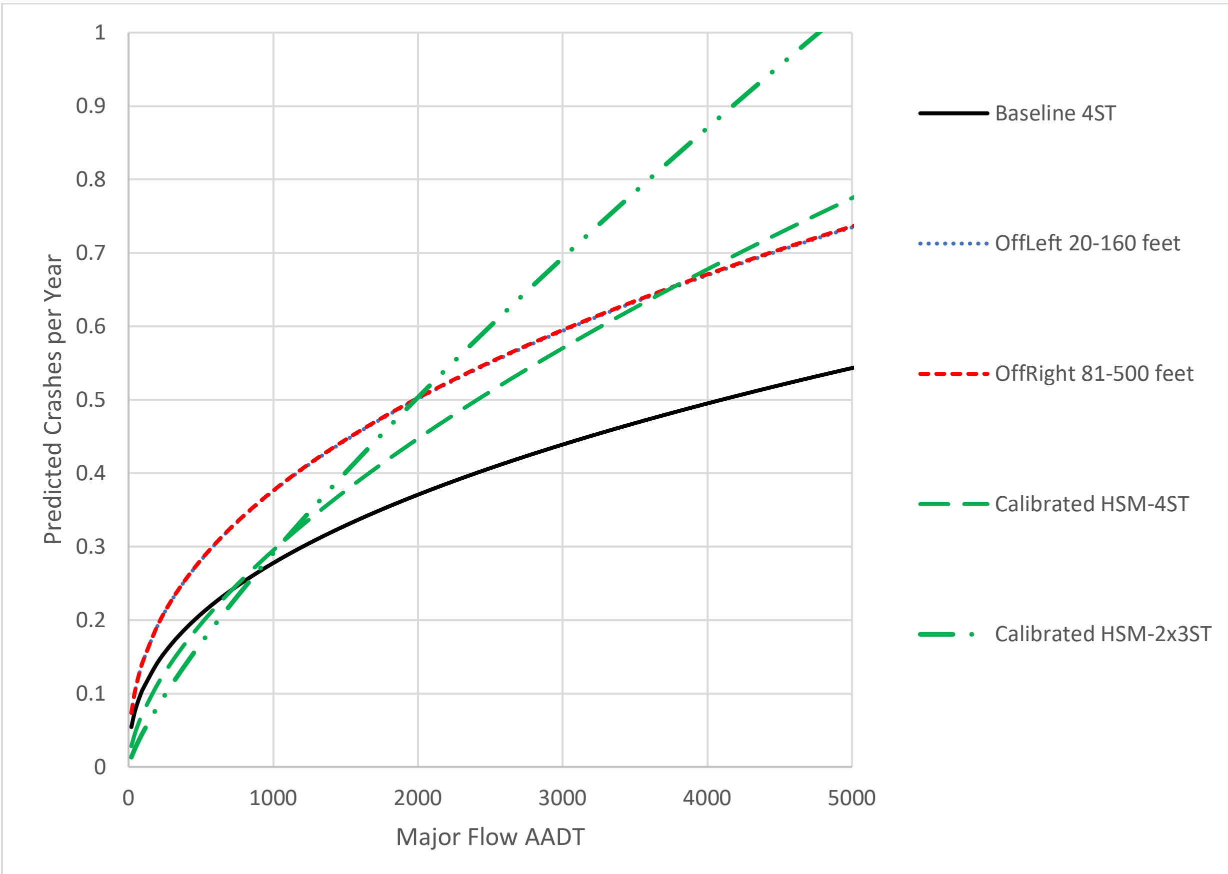

Figure 12. Model results for total non-animal crashes with minor roadway AADT=400 veh/day.

Offset left is considered preferred in AASHTO geometric design guidance because it eliminates the possibility for left turns on the major road to interlock [25]. However, in consideration of the relatively low traffic volumes of the intersections involved with this study, interlocking left turns are very unlikely for these rural sites. The initial left turn for L-R minor road crossing maneuver conflicts with both directions of major road traffic which could introduce more risk of conflict in the crossing maneuver than an R-L condition, which crosses with only one conflicting direction of major road traffic at a time.

Below an offset distance of 80 feet, vehicles making a crossing maneuver in either direction may tend to weave across the major road instead of making distinct left and/or right turns. This may manifest as vehicles “shoot the gap” in major road traffic rather than carefully selecting a safe crossing gap. The acceptable gap for making a left turn from the minor road approach is larger than the acceptable gap for making a right turn or straight crossing maneuver [25]. While the trend in total crashes at offset-Ts appears consistently higher than comparable four-leg intersections, there is a tradeoff in the type of crashes involved. Therefore, it is more informative to investigate specific crash types involved as a function of offset distance and direction, which is described in the section that follows.

4.2.2 Effect of Offset Distance and Direction on Crash Types

The offset distance and direction were specifically evaluated for their effect on various crash types at offset-T intersections. Separate SPFs were developed to enumerate the effect of offset-T intersections on the following crash types: single vehicle, rear-end, and angle. Offset-Ts are shown in Table 2 to have nearly twice as many single motor vehicle crashes as comparable four-leg intersections. This effect starts at the smallest offset range and grows as the offset distance increases. For example, offsets 20 to 80 feet show 68 percent more single vehicle crashes while offsets 161 to 500 feet show 119 percent more. This effect was observed regardless of the direction of the offset. One explanation of this effect is that the larger offset distance involved includes a larger spatial area, or segment length, between the two intersections. The susceptibility of single motor vehicle crashes increases with greater exposure length. In addition, the geometry of offset-

Ts which require all minor traffic to turn at the intersection increases the susceptibility of ran-off-road and fixed object crashes circumstantial to the turn.

Considering multiple vehicle crashes, offset-Ts are estimated to have up to 82 percent more rear-end type crashes than comparable four-leg intersections. This finding is illustrated in Figure 13, which shows model results for offset-T rear-end crashes. The calibrated HSM models in Figure 12 and 12 use the same calibration factor as for total crashes as well as the distribution of crash types from Table 2; this methodology of applying calibration and crash distribution to estimate specific crash types follows section 10.8 of the HSM [2]. Similar to the total crash model, offset-T sites left between 161 and 500 feet and right between 20 and 80 feet were excluded from the analysis population for rear-end crashes. Offset-T intersections are most susceptible to rear-end crashes when the offset distance is less than 161 feet to the left, or 2 seconds of sight distance. The parameter coefficients shown in Table 4 suggest that this effect also occurs for offset-T configuration to the right whenever greater than 81 feet, or 1 second of sight distance. The increase in rear-end crashes is believed to be caused by interference that minor road crossing maneuvers have on major flow through traffic. For example, a crossing maneuver for an R-L configuration consists of an initial right turn followed by a left turn. The second (or left) turn is made from within the major road through traffic lane in absence of a separate left turn lane or passing flare. This exposes minor road crossing traffic to rear-end collisions and head-on left-turn collisions subsequent to the gap selected for their initial right turn maneuver. The addition of left or right turn lanes on the major road could be considered as a countermeasure, however not enough sample locations were available to test the efficacy of turn lanes within this study. A few locations of offset-T intersections in this study were discovered to have turn lanes, and it was plainly obvious from the traffic volumes that substantial turning movements were being served by their presence.

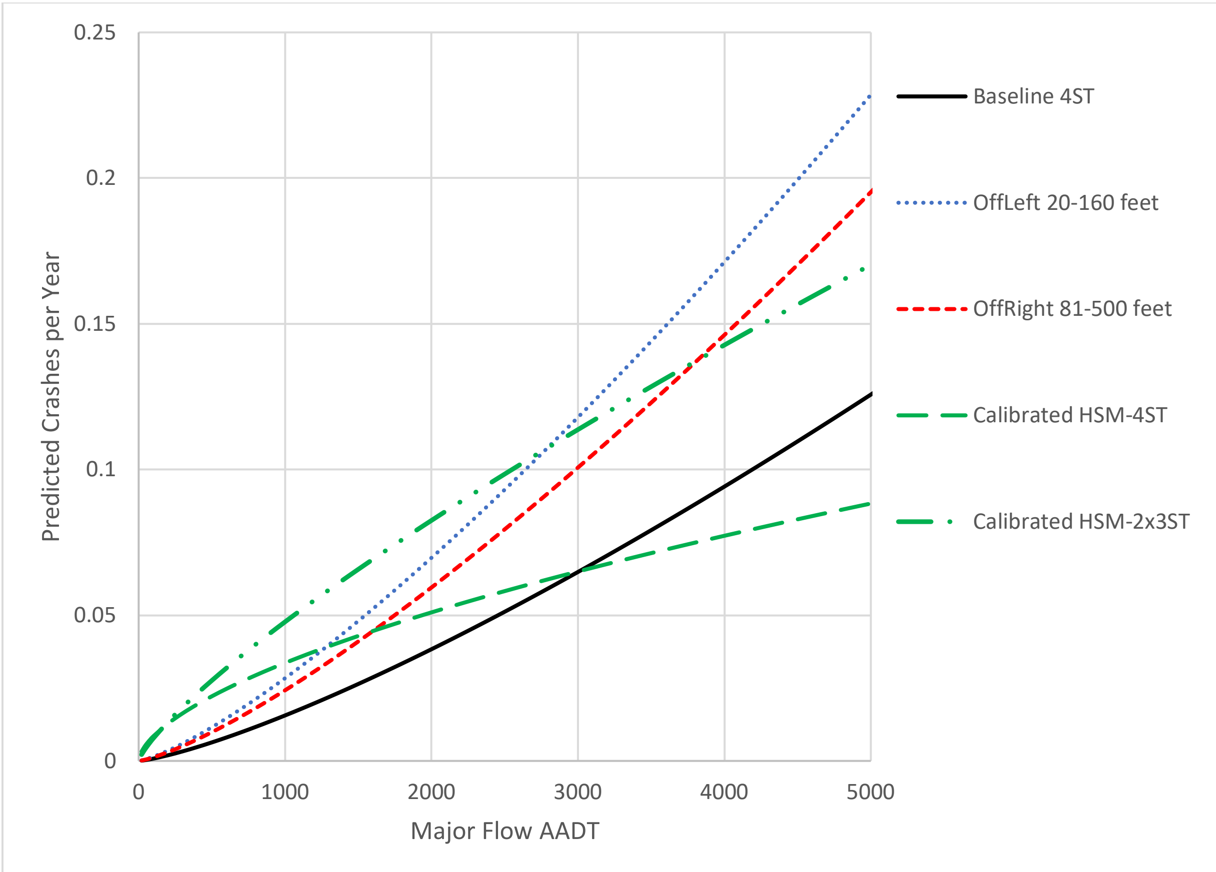

Figure 13. Model results for rear-end crashes with minor roadway AADT=400 veh/day.

Angle crashes were the only crash type for which the offset-T configuration consistently showed lower crash occurrence than four-leg intersections, and this finding can be observed in Figure 14. The geometry of offset-T intersections reinforces the priority of the major roadway by requiring all minor approach traffic to slow down and turn, greatly reducing the opportunity for minor road drivers proceeding through the intersection without stopping. This inherent elimination of direct crossing maneuvers from the minor approaches characteristically reduces the likelihood of angle collisions, which is reflected in the model results. Ultimately, the parameter estimates suggest that larger offset distances lead to fewer angle crashes, regardless of whether the offset is to the left or right. Any offset distance between 40 and 160 feet, or half second to two seconds of sight distance, had 40 percent fewer angle crashes than conventional four-leg intersections. Angle crashes at offset-T intersections with separation beyond 161 feet occurred 69 percent less often than conventional four-leg intersections. It is also worth noting that there were zero observed angle crashes at R-L configuration beyond 300 feet offset distance.

Offsets from 20 to 40 feet performed mostly the same as comparable four-leg intersections with angle crash parameter estimates that were near zero and non-significant. This finding helps to identify a lower threshold in offset distance where the susceptibility to angle crashes is the same as comparable four-leg intersections. On the other hand, offsets left from 20 to 160 feet showed an increase in rear-end, single vehicle, and total crashes compared to four-leg intersections. Therefore, the type of site that is the most apparent candidate for conversion to a conventional four-leg intersection is narrow offset left less than 40 feet, as it possesses the greatest potential for safety benefits (e.g., reduction in total, rear-end, and single vehicle crashes) with the least consequences (e.g., no increase in angle crashes).

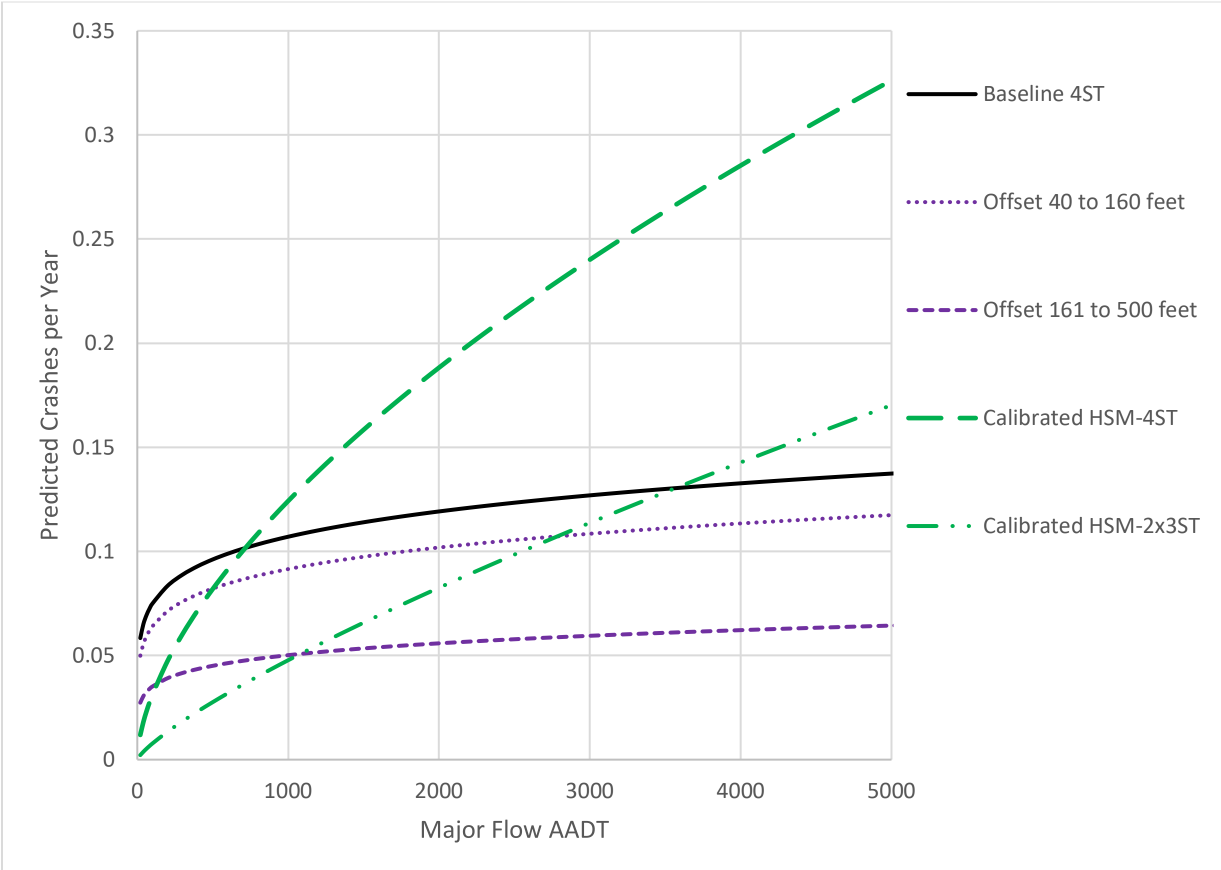

Figure 14. Model results for angle crashes with minor roadway AADT=400 veh/day.

4.2.3 Crash Modification Factors

CMFs represent the estimated change in average crash frequency of a site associated with a change in one specific condition. In the models presented in this study, the base condition for comparison was a rural four-leg stop-controlled intersection with no skew or curvature on the approaches. For those crash types evaluated in this study, except angle collisions, crash occurrence was higher for offset-T compared to four-leg intersections, which suggests that conversion of offset-T to four-leg would be prudent for road agencies to consider from a safety standpoint. Thus, the corresponding CMFs presented in Table 5 are arranged to illustrate the potential effect of converting an existing offset-T intersection into a four-leg intersection. The table is formatted in a way consistent with the CMF Clearinghouse. To determine the CMF, *e*, was raised to the power of the estimated parameter, β, for each statistically significant (p-value <0.05) category of offset direction and distance. The inverse of the result reflects the change from an existing offset-T configuration into a four-leg configuration.

Table 5. CMFs for Converting an Offset-T Intersection into a Four-Leg Intersection.

CMF	**Crash Type**	**Crash Severity**	**Area Type**	**Comment**
0.74	All	All	Rural	Existing was Offset Left 20 to 160 feet
0.74	All	All	Rural	Existing was Offset Right 81 to 500 feet
0.60	Single Vehicle	All	Rural	Existing was Offset 20 to 80 feet
0.50	Single Vehicle	All	Rural	Existing was Offset 81 to 160 feet
0.46	Single Vehicle	All	Rural	Existing was Offset 161 to 500 feet
1.68	Angle	All	Rural	Existing was Offset 40 to 160 feet
3.19	Angle	All	Rural	Existing was Offset 161 to 500 feet
0.55	Rear-end	All	Rural	Existing was Offset Left 20 to 160 feet
0.64	Rear-end	All	Rural	Existing was Offset Right 81 to 500 feet

Note: Each category excludes animal crashes.

4.3 Conclusions and Recommendations

Offset-T intersections represent a special geometric configuration where two three-leg intersections adjoin the major road from opposite directions within a short separation distance. The prevalence of offset-T intersections in rural areas coupled with the lack of research evaluating their safety performance led to the development of a series of SPFs for rural stop-controlled intersections that considered the effects of the offset direction (L-R vs. R-L) and separation distances up to 500 feet. Additionally, CMFs were developed to estimate the change in crash frequency associated with converting a rural offset-T intersection into a conventional four-leg intersection.

A series of mixed effect negative binomial models for crash occurrence were generated based on 10 years of crash data from a sample of 299 offset-T intersections and 301 four-leg intersections with minor stop-control along rural two-lane highways in Michigan. Compared to conventional four-leg intersections, offset-T intersections exhibited 35 percent more crashes regardless of the offset distance or direction. Considering crash types, single motor vehicle crashes occurred more frequently at offset-T intersections, and increased as the offset distance increased. Rear end crashes also occurred more frequency at offset-T intersections, with offsets left being more susceptible to rear-end crashes than offsets right. Angle crashes were 40 to 69 percent lower at offset-T intersections due to the elimination of the direct crossing maneuver.

The conversion of an offset-T intersection into a four-leg intersection is a countermeasure than can reduce crash occurrence by 26 percent, within a range of offset direction and distance, which corresponds to a CMF of 0.74. When targeting single motor vehicle crash types, a 40 to 54 percent reduction is estimated from converting an offset-T intersection into a four-leg intersection. Likewise, rear-end crashes can be reduced by up to 45 percent with such a conversion. The tradeoff involved in converting offset-T intersections to four-leg intersections involves acceptance of higher angle crash risk, due to the accommodation of direct crossing maneuvers from the minor roadway.

It must be noted that the conversion of an offset-T intersection into a four-leg intersection may introduce additional issues. First, realignment of offset minor road approaches into a four-leg intersection necessitates introduction of reverse curvature (to achieve a perpendicular alignment) or excessive skew on at least one of the approaches, each of which may increase crash occurrence and are not accounted for in the CMFs. Furthermore, any change in the geometric footprint of an intersection will likely incur a right-of-way purchase. A potentially less costly alternative to mitigate the increased total and rear-end crash risk at offset-T sites is to add turn lanes, passing flares, or full width paved shoulders in the vicinity of the two intersections. This countermeasure would still maintain the benefit of reduced angle crash occurrence, which offset-Ts experience at nearly every combination of offset distance and direction. Unfortunately, it was not possible to assess the safety performance of turn lanes or passing flares within this evaluation because very few sites had such features. Therefore, this study establishes a baseline for safety operation of offset-Ts without the influence of turn lanes.

5.0 CURVED CORNER INTERSECTIONS

The contents of this chapter were first published as Safety Performance of Rural Curved Corner Intersections with Regional Effects [51] and have been reformatted to fit this dissertation.

5.1 Data Summary

Intersection sites within Michigan's roadway network, were spatially identified based on overlapping node buffers. The maximum distance separating any two nodes at a curved corner intersection would be 500 ft, after which point the three intersections would be considered as separate intersections. The use of this threshold alone for site selection would eliminate the possibility of a curve radius exceeding 500 ft. Next visual searches using satellite imagery of the candidate nodes confirmed locations where a curve corner intersection exists. Previous research undertaken on rural three-leg and four-leg stop-controlled intersections in Michigan had identified, and excluded, intersections that were in close proximity to another intersection [47]. This study considers the combination of three intersections to be a single site area. Therefore, two three-leg stop-controlled intersections and one three or four-leg stop-controlled intersection, and the curved segment of roadway connecting them are considered collectively as a single site in this analysis. Figure 15 shows an example of a single curved corner intersection site consisting of three three-leg intersections and a segment of curved roadway connecting the tangents of the major flow route.

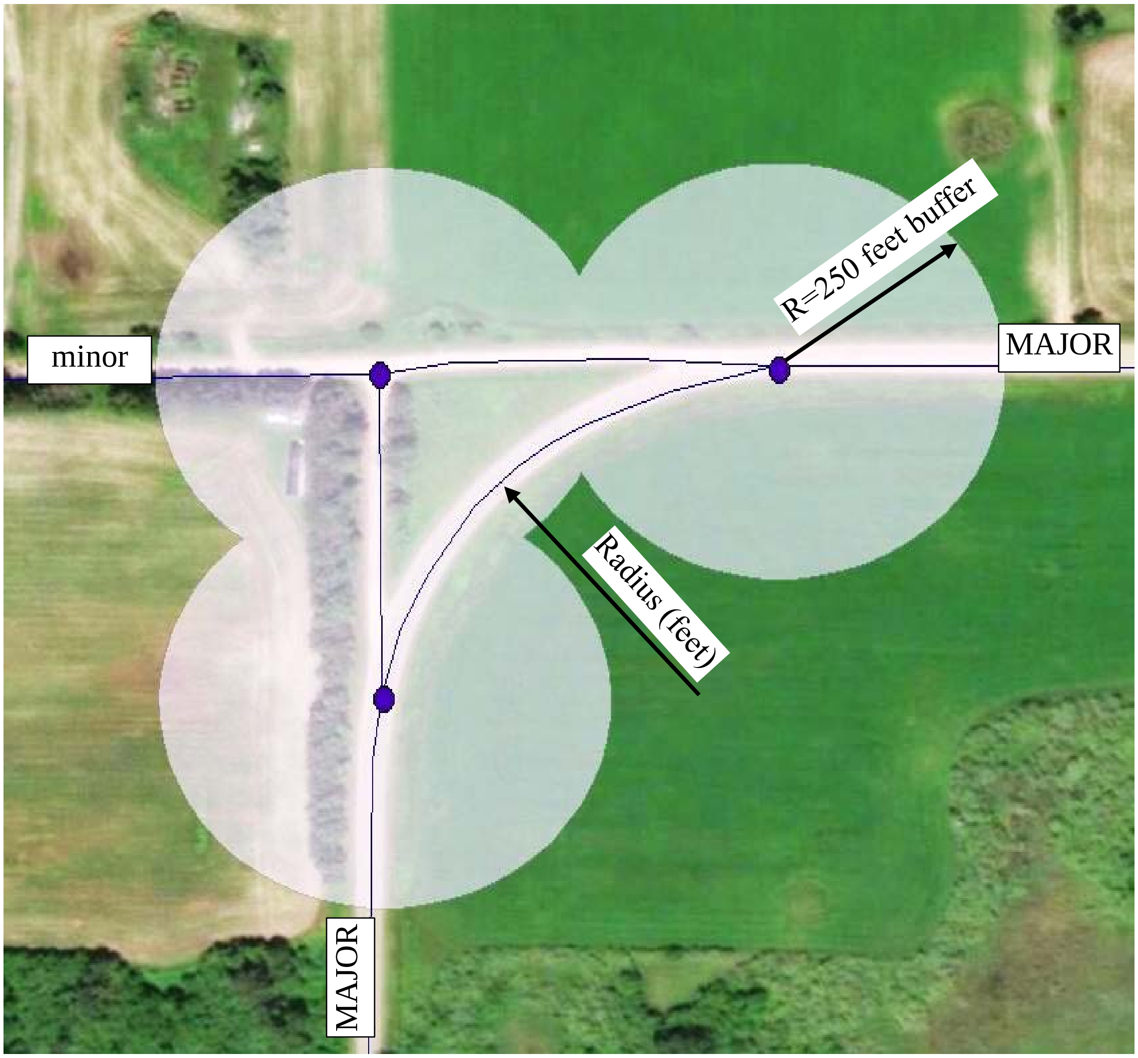

Figure 15. Example rural three-leg, 3C, curved corner intersection with buffer and curve radius.

Since the curved corner intersections exist at places where the major route turns, maps were visually searched for route turns when following the primary arterial roadways. Quite simply, a visual scan of a county road map helps to quickly identify numerous potential locations. County primary arterial routes often turn or jog in direction to align with the most direct or shortest path to popular destinations. These type of direction changes in the major route can also be related to the rectangular survey system on which many of the rural highways follow. A total of 292 curved corner intersections were identified within the state of Michigan to represent the study population. The geographic distribution of study sites is shown in Figure 16. At least one curved corner intersection was identified in 51 of the state's 83 counties. Additionally, the study sites are present in all seven of the MDOT's regions. The regions are administrative boundaries that also coincide with different climactic zones as well as population characteristics throughout the diverse state.

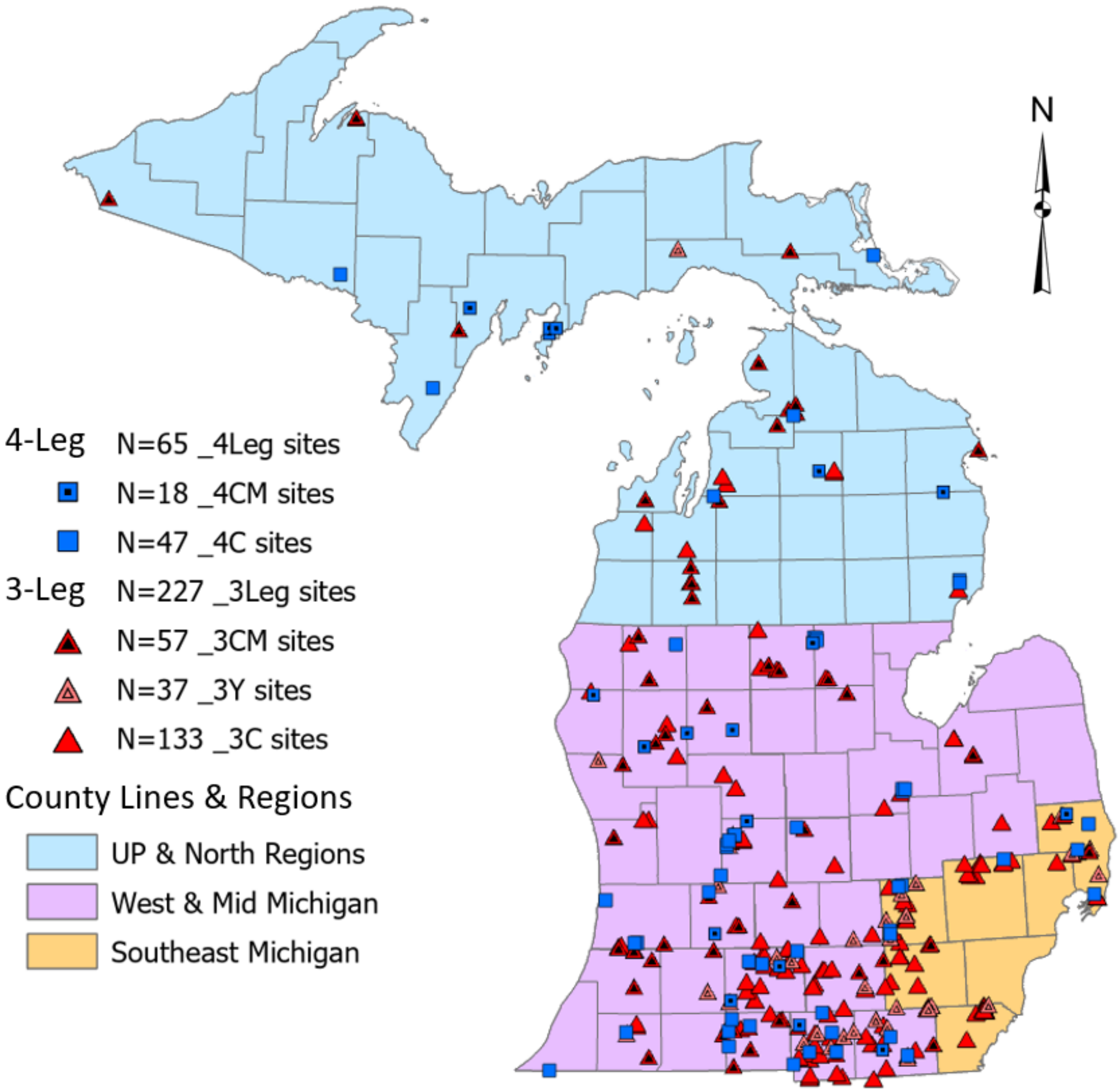

Figure 16. Geographic distribution of curved corner study intersections in Michigan with county lines and region shown.

5.1.1 Site Data Collection

To further detail the data collection, an assignment of the study sites was made to different categories or types as defined based on the geometric scenarios encountered. The different types of curved corner intersections were defined as shown in Figure 17, consisting of the following types: 3C, 4C, 3Y, 4Y, 3CM, and 4CM. The 3Y or 4Y type of configuration are unique in that they may exist when the major road continues through the intersection with or without traveling the curved roadway segment. Only two instances of 4Y type intersections were encountered throughout the entire state, and thus this intersection type was excluded from the analysis.

The type of intersection geometry where the minor road approaches are merged into a single intersection with the major road is defined as a type 3CM or 4CM intersection based on the number of approach legs. This type of intersection is common as a treatment, or countermeasure to create a single intersection on a curve. It generally removes the highly skewed intersections in favor of a single intersection. This treatment consolidates turning movements and reduces the total number of vehicle conflict points.

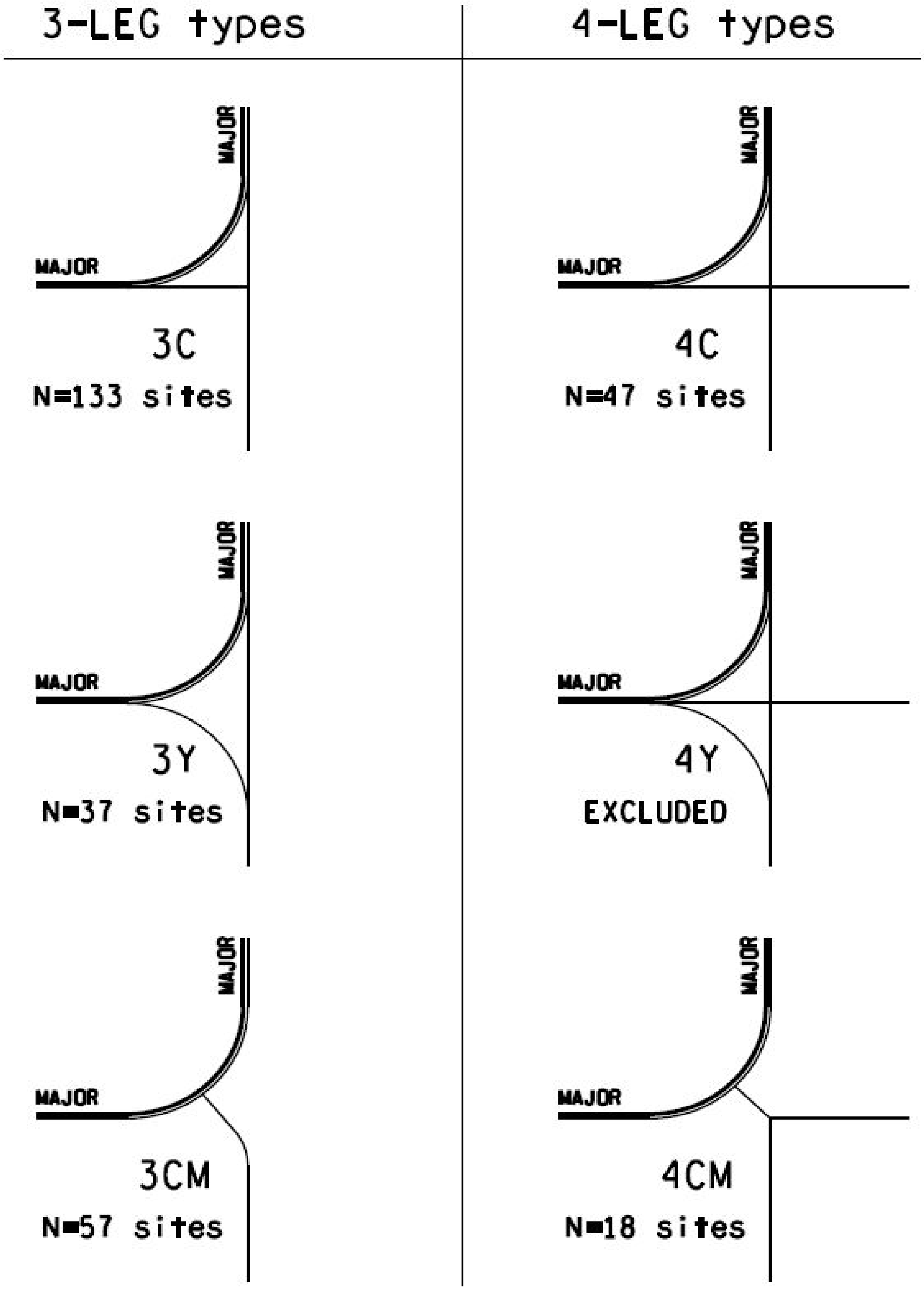

Figure 17. Curved Corner Intersection Types and Number of Study Sites in Michigan.

5.1.2 Descriptive Statistics

Once the data was assembled, the distribution of crashes by severity type was determined as shown in Table 6. This table closely matches the format of the information presented in Tables

10-5 and 10-15 of the HSM Chapter 10 [2]. The crash severity data shows general similarity with the HSM default distributions. A total of 1,801 crashes occurred within the 250-foot buffered vicinity of the 292 intersection sites used in this study during the 10-year sampling period. Upon filtering to the intersection area type code included in the crash data, 1,022 crashes remained. Even still, a large proportion of the mostly property damage crashes that remained involved primarily a crash with an animal (e.g. most likely a deer in Michigan). Upon removal of the animal crashes, a total of 870 intersection non-animal crashes occurred among the 292 intersection sites during the 10-year sampling period. The curved corner intersections used for this study have fewer fatal plus injury crashes and more property damage only type crashes as compared to the default distributions in the HSM. In comparison to 4,810 three-leg and four-leg conventional rural minor road stop-controlled intersections throughout Michigan, the curved corner sites have broadly similar crash severity distributions [47].

Table 6. Distribution of Crash Severity for Curved Corner Two-lane Two-way Minor Road Stop-Controlled Intersection Study in Michigan.

	Intersection crash severity distributions (2010-2019)					
	Three-leg intersections			**Four-leg intersections**		
	Curved corner		**Statewide**	**Curved corner**		**Statewide**
Crash severity level	**Frequency**	**Pct. of total**	**Pct. of total**	**Frequency**	**Pct. of total**	**Pct. of total**
Fatal (K)	7	1.0	0.5	1	0.5	1.3
Incapacitating injury (A)	23	3.4	2.7	7	3.5	4.5
Nonincapacitating injury (B)	74	11.1	5.8	19	9.5	8.5
Possible injury (C)	99	14.8	11.1	36	17.9	15.8
Fatal + injury (KABC)	203	30.3	20.1	63	31.3	30.0
Property damage only (PDO)	466	69.7	79.9	138	68.7	70.0
Total	**669**	**100.0**	**100.0**	**201**	**100.0**	**100.0**

Note: Each category excludes animal crashes.

The distribution of collision types and severity levels is shown in Table 7, which closely matches the format of the information presented in Table 10-6 of the HSM Chapter 10. Overturn crash types were much more frequently observed at the study curved corner sites than the default distributions in the HSM. This result is observed even after non-intersection related overturn type crashes have been removed, yet it is not unexpected that the presence of an intersection on a curved roadway segment has higher propensity of overturn crashes than at conventional three-leg or four-leg intersections. The same can be said for run-off-road and fixed-object crash types, which were not separately coded in the available crash data, but are aggregated in the category of other single-vehicle crashes in the summary Table 7. For the comparison of collision types, intersection types 3C, 3Y, and 4C were aggregated and compared with 3CM and 4CM intersection types. This categorization provides the most meaningful distinction between the curved corner geometric alternatives. The 3CM and 4CM intersection types have notably more proportion of single-vehicle crashes and fewer angle and head-on crashes than the other curved corner types. In a comparison with a larger population of statewide Michigan intersections, the study sites at curved corner intersections likewise have much more overturn, run-off-road, and fixed-object crashes than conventional three-leg and four-leg stop-controlled intersections [47]. All of the curved corner types also have much fewer angle and rear-end crashes when compared to rural three-leg and four-leg stop-controlled intersections in Michigan as well as HSM distributions.

Table 7. Distribution of Collision Type and Manner of Collision for Curved Corner Two-lane Two-way Minor Road Stop-Controlled Intersection Study in Michigan.

	Percentage of crashes by collision type (2010-2019)								
	Types 3C, 3Y, and 4C			Types 3CM and 4CM			Statewide Three and Four Leg		
Collision Type	**FI**	**PDO**	**Total**	**FI**	**PDO**	**Total**	**FI**	**PDO**	**Total**
Single-vehicle crashes									
Collision with bicycle	0.0	0.0	0.0	0.0	0.0	0.0	0.3	0.0	0.1
Collision with pedestrian	0.5	0.0	0.1	0.0	0.0	0.0	0.6	0.1	0.2
Overturned	16.6	8.2	10.8	21.8	6.2	10.8	4.3	1.8	2.5
Other single-vehicle crash	48.8	61.0	57.2	60.0	66.2	64.3	14.7	20.3	18.8
Total single-vehicle crash	65.9	69.2	68.1	81.8	72.4	75.1	21.3	51.8	43.7
Multiple-vehicle crashes									
Angle collision	10.8	9.3	9.8	3.6	8.5	7.0	50.7	19.0	27.4
Head-on collision	12.2	3.4	6.1	5.5	5.4	5.4	7.8	19.0	27.4
Read-end collision	4.2	8.9	7.0	1.8	4.6	3.8	14.5	16.8	16.1
Sideswipe collision	4.2	7.4	6.4	5.5	7.7	7.0	3.4	6.3	5.5
Other multiple-vehicle collision	2.7	1.9	2.6	1.8	1.5	1.6	2.4	4.1	3.6
Total multiple-vehicle collision	34.1	30.8	31.9	18.2	27.7	24.9	78.7	48.2	56.3
Total Crashes	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**	**100.0**

Note: Each category excludes animal crashes. FI = fatal and injury; PDO = property damage only.

Summary statistics for the evaluated variables in this study are provided in Table 8. Many variables take a binary format (0=No, 1=Yes), in which case the mean value indicates what proportion of the sites takes on the affirmative value. The mean major road traffic volume was 1,442 veh/day. The mean value for minor road AADT was 373 veh/day, inclusive of observed and estimated traffic volumes. Ninety-one percent of the sites have a paved major road, while 51 percent of sites have a paved minor road. The mean radius of curvature among all of the sites is 326 feet, with a median radius of 290 feet. The distribution of radius for each intersection configuration is provided in Table 4. It can be observed that only the 3CM and 4CM intersection configurations tended to have radius of curvature larger than 500 feet. The most frequently observed radius of curvature lies within the range between 250 feet and 300 feet.

Table 8. Descriptive Statistics for Curved Corner Two-lane Two-way Minor Road Stop-Controlled Intersection Study in Michigan.

Parameter	Min.	Max.	Mean	Median	SD	Variance
Major road AADT (vpd)	96	9,142	1,442	981	1,402	1,965,681
Minor road AADT (vpd)	28	4,061	373	250	499	248,913
Observed minor road AADT (vpd)	28	4,061	751	418	864	746,395
Estimated minor road AADT (vpd)	64	1,063	249	226	155	24,095
3Y type	0	1	0.13	0	0.33	0.11
3C type	0	1	0.46	0	0.50	0.25
4C type	0	1	0.16	0	0.37	0.14
4CM type	0	1	0.06	0	0.24	0.06
3CM type	0	1	0.20	0	0.40	0.16
Radius (feet)	81	1,296	326	290	181	32,791
UP & North Region	0	1	0.13	0	0.34	0.11
West and Mid-Michigan Region	0	1	0.65	0	0.48	0.23
SEMCOG Region	0	1	0.22	0	0.41	0.17
Major surface paved	0	1	0.91	1	0.28	0.08
Minor surface paved	0	1	0.51	1	0.50	0.25
Crashes per site per year	0	5	0.35	0	0.70	0.49

Note: Min. = minimum; Max. = maximum; SD = standard deviation; vpd = vehicles per day; AADT = annual average daily traffic; Crashes are displayed as per site, per year (2010-2019), exclusive of animal crashes

Table 9. Distribution of Radius in feet for Curved Corner Two-lane Two-way Minor Road Stop-Controlled Intersection Study in Michigan.

Intersection Type	Min.	10th %	25th %	30th %	40th %	50th %	60th %	75th %	80th %	90th %	Max.	Mean
3Y	81	100	143	168	190	210	245	280	300	325	346	214
3C	150	210	250	256	276	300	323	370	403	465	906	326
4C	122	195	240	245	260	315	340	378	390	424	830	332
4CM	200	263	325	325	346	410	488	547	560	1,064	1,110	496
3CM	85	110	165	175	205	245	300	440	500	805	1,296	342

Note: Min. = minimum; Max. = maximum

5.2 Modeling and Results

The HSM recommends using the negative binomial (NB) distribution for the development of SPFs due to its ability to account for the Poisson variance overdispersion that is common in crash data distributions [2]. One concern when evaluating SPFs across a broad statewide network is unobserved heterogeneity, which in large part contributes to overdispersion. Within the context of this study, each site is observed ten times (once per year from 2010 to 2019). These repeated measurements could introduce serial correlation in the crash counts over time. The consideration of random effects negative binomial (RENB) was evaluated to address location-specific and time-series effects for median crossover crashes [52]. Shankar, et al. note that including spatial and temporal effects in a fixed effects NB was statistically adequate if not superior to specifying a RENB. More recently Tang, et al. compared the prediction accuracy of NB and random parameter NB models for two-lane rural highway segments and found the NB model to be superior when applied to sites outside of the sample [53]. The approach presented herein is to develop the basic NB model and progressively compare specification of fixed effects and random effects to better understand the consequences of either modeling technique.

The RENB allows the intercept term to vary across individual observations, while still applying the basic functional form of the NB model. Depending on the groups specified as the random effect, the RENB attempts to capture some of the variation geographically and jurisdictionally. The expected number of crashes can be estimated using the general functional form:

$$N_{spf} = e^{(\beta_0+\boldsymbol{\beta}*\mathbf{X}+\varepsilon+\eta)} \quad (7)$$

Where,

N_{spf} = predicted intersection-related crashes per year,

β_0 = intercept term,

$\boldsymbol{\beta}$ = vector of coefficients,

$\mathbf{X}$ = vector of explanatory variables,

ε = gamma-distributed error term for negative binomial, and

η = random effect for observation groups

In Equation 7, both exp(ε) and exp(η) are gamma-distributed with a mean one and variance α. The random effect on the intercept adds a term η, however the mean value of the intercept is unchanged. A region-specific random effect was included in this study. The region codes defined by MDOT encompass 7 different regions in their governance that also possess distinct traffic characteristics and weather conditions, as well as other distinctive population demographics. The inclusion of a variable in the model is determined based on a test of significance for the model coefficient for that variable. The threshold for significance often based on a 95 percent confidence interval to be regarded as a high-quality predictor in the model. The differences between log-likelihoods of the models with and without the random effects were assessed along with the Akaike information criterion (AIC). Smaller scores for either of these metrics suggest stronger statistical fit.

A model was created amongst the three-leg sites separately from the four-leg sites. The reason for this distinction is entirely dependent on the number of approach legs at the intersection site. The base condition for this evaluation is the combined/merged approach, type 3CM or 4CM. Therefore, in relative comparison, 3Y and 3C sites are compared with their geometric alternative of a 3CM type of configuration, and 4C sites are compared with 4CM. The general functional form of the RENB model from Equation 2 is expanded to represent the SPF as shown in Equation 8.

$$N_{spf} = e^{\beta_0}\left(AADT_{Major}{}^{\beta_1}\right)\left(AADT_{Minor}{}^{\beta_2}\right)e^{\boldsymbol{\beta_i X_i}} \tag{8}$$

Where,

N_{spf} = predicted intersection-related crashes per year,

β_0 = intercept term,

$AADT_{Major}$ = AADT (vehicles per day) on the major road,

$AADT_{Minor}$ = AADT (vehicles per day) on the minor road,

β_1 = coefficient term related to major road AADT,

β_2 = coefficient term related to minor road AADT,

β_i = vector of coefficient terms related to intersection characteristics, and

X_i = vector of explanatory variables for intersection characteristics

The calibrated coefficients for the SPF are provided in Table 10. The overdispersion parameter is provided with each model to weight the predicted and observed crash frequency during application of the Empirical Bayes method consistent with the 2010 HSM methods [2]. The RENB models display the standard error of the random effect.

Table 10. Model Results for Rural Curved Corner Intersection Study in Michigan.

	Three-leg intersections				**Four-leg intersections**			
	Base model	**Radius variable included**	**Region fixed effects**	**Region random effect**	**Base model**	**Radius variable included**	**Region fixed effects**	**Region random effect**
Parameter	**NB**	**NB**	**NB**	**RENB**	**NB**	**NB**	**NB**	**RENB**
Intercept	-7.117 (0.381) ***	-7.038 (0.384) ***	-6.494 (0.432) ***	-6.857 (0.426) ***	-6.530 (0.733) ***	-6.456 (0.721) ***	-5.938 (0.796) ***	-6.338 (0.759) ***
Ln(major road AADT)	0.615 (0.056) ***	0.636 (0.057) ***	0.583 (0.062) ***	0.604 (0.065) ***	0.580 (0.119) ***	0.640 (0.119) ***	0.577 (0.123) ***	0.603 (0.124) ***
Ln(minor road AADT)	0.200 (0.055) ***	0.198 (0.055) ***	0.214 (0.564) ***	0.210 (0.057) ***	0.242 (0.098) **	0.231 (0.096) **	0.258 (0.095) ***	0.248 (0.096) ***
3CM type	Base	Base	Base	Base	na	na	na	na
3Y type	0.564 (0.145) ***	0.474 (0.149) ***	0.322 (0.158) **	0.405 (0.171) **	na	na	na	na
3C type	0.391 (0.118) ***	0.348 (0.119) ***	0.221 (0.127) *	0.291 (0.137) **	na	na	na	na
4CM type	na	na	na	na	Base	Base	Base	Base
4C type	na	na	na	na	-0.335 (0.149) **	-0.486 (0.159) ***	-0.525 (0.161) ***	-0.514 (0.161) **
Radius	na	-0.00055 (0.0003) **	-0.00052 (0.0003) **	-0.00053 (0.0002) **	na	-0.00089 (0.0004) **	-0.00072 (0.0004) *	-0.00079 (0.0004) **
SEMCOG Region	na	na	Base	na	na	na	Base	na
UP & North Region	na	na	-0.523 (0.200) ***	na	na	na	-0.795 (0.273) ***	na
West and Mid-Michigan Region	na	na	-0.203 (0.102) **	na	na	na	-0.210 (0.197)	na
Overdispersion	0.508 (0.123)	0.496 (0.122)	0.485 (0.121)	0.492 (0.121)	0.0000 (0.000)	0.0000 (0.001)	0.0000 (0.000)	0.0003 (0.001)
Random effect for MDOT Region	na	na	na	(0.0023)	na	na	na	(0.0098)
AIC	2889.4	2886.5	2882.4	2887.9	855.9	851.9	845.7	851.6
Log-likelihood	-1438.7	-1436.3	-1432.2	-1436.0	-422.9	-419.9	-414.8	-418.8

Note: Base = baseline condition; Standard errors are in parentheses; *** = significant on 99 percent level; ** = significant on 95 percent level; * = significant on 90 percent level; AIC = Akaike information criterion; na = not applicable.

A comparison was made between the types of curved intersections. Figure 18 shows the prediction of the RENB models using the statistic median radius of 290 feet and minor road AADT of 250 veh/day. It is clear that 3CM intersections on average have fewer predicted crashes, and the deference between a 3C or 3Y site and the 3CM can be inferred from the parameter coefficient, all other aspects being the same. The 3C configuration is the most likely candidate to be converted to a 3CM configuration, which is predicted to reduce the average frequency of crashes by 25 percent. The 3Y configuration is a bit harder to anticipate which legs are the major approaches, but converting to a 3CM could likewise reduce average crash frequency by 33 percent. The conversion of a 4C configuration into a 4CM configuration however is not predicted to produce a safety benefit as the 4CM configuration is predicted to have more intersection (non-animal) crashes than any other configuration. Attempts to estimate a model for fatal and injury crashes only, or individual crash types of interest did not pass the threshold for test of significance on important parameters. A suggested explanation for the poor, in relative sense, safety performance of 4CM intersections is the inadequate separation distance between the intersection on the curve at the major road and the intersection between the orthogonal minor approach legs. The conversion of 4C intersections into 4CM should be investigated further and may be more appropriately studied using a before and after comparison.

Overall, the three-leg and four-leg models have many similarities. For example, the parameter coefficient for major and minor road AADT remain mostly consistent among the models. This is interpreted as a good result, meaning that the effect of those factors in the model is not mixed up with the inclusion of other parameters. The best three-leg and four-leg models were those specified with fixed regional effects as judged by the AIC and log-likelihood. However, the differences in these metrics are very small from one model to the other. Notably the four-leg models all have an overdispersion parameter near zero, meaning that the model is nearly identical to a Poisson model, which in effect can be considered a special case of the NB distribution.

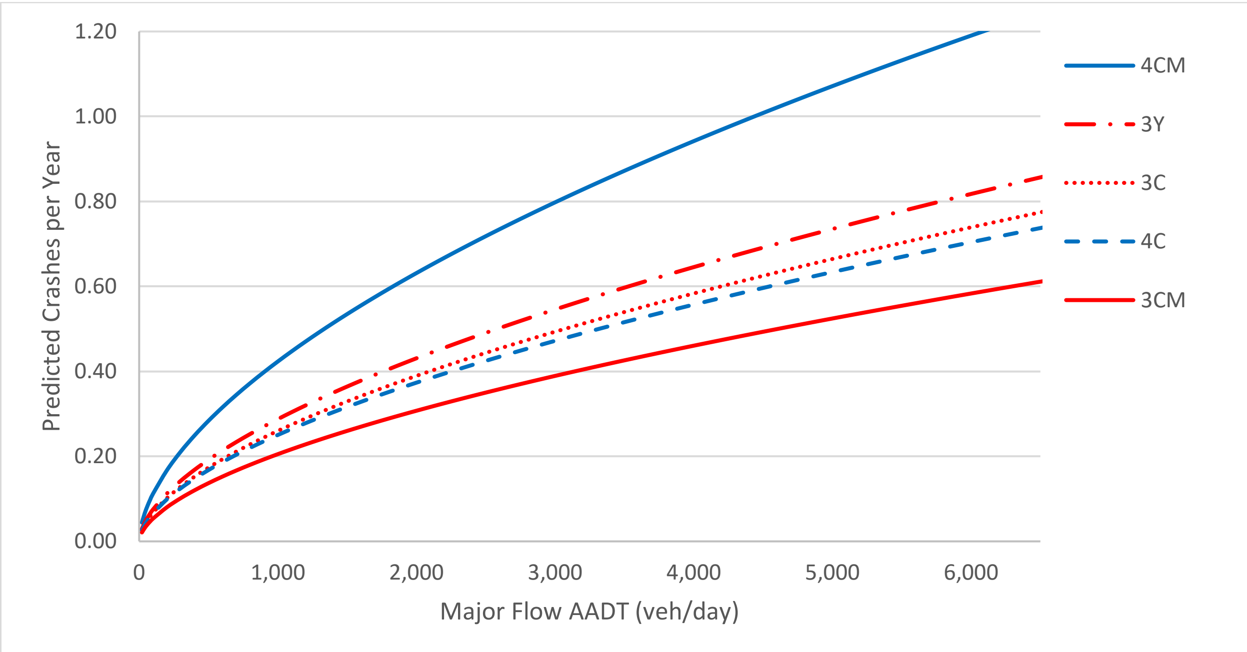

Figure 18. Model results for intersection (non-animal) crashes with radius of curve = 290 feet and minor road AADT = 250 veh/day.

5.2.1 Effect of Radius of Curvature

The radius of curvature on the curved segment was investigated as a parameter in the SPF models both as a continuous variable, with observed values ranging from 81 to 1,296 feet, and categorized into bins, or ranges, based on the distribution within sample site locations. A few transformations of the radius parameter were considered including the natural-log of the radius, the inverse radius, and similarly the degree of curvature. Ultimately the specification of radius as a continuous variable was sought in order to define a CM-Function whereby any existing radius or change to an existing radius could be evaluated. The CM-Function is less constrained than a categorical or step function and “is preferable if the cause-effect relationship with crashes can be determined with confidence” [54]. In all of the model combinations examined, larger radius of curvature leads to lower crash frequency. The influence of larger radius of curvature will lead to higher travel speeds on the major roadway. However, larger radius of curvature also improves the sight lines at combined/merged minor road approaches and increases the separation between intersecting legs for all curved corner configurations.

Interpreting the model results can be done by exponentiating the radius parameter and coefficient with a natural log base as shown in Equation 9. This indicates the unit change in predicted crash frequency for each unit change in radius. This is a very small number considering one foot at a time, but put into perspective increasing the curve radius by 100 feet at a three-leg intersection would decrease the predicted crash frequency by 5 percent. Likewise, at a four-leg intersection increasing curve radius by 100 feet decreases the predicted crash frequency by 8 percent. Figure 19 shows the CM-Function for curve radius, that is the relationship between change in predicted crash frequency plotted over a range of radius values from which the model was calibrated. Note that without specifying an intercept, the CM-Function for radius would take a value of one at zero radius, equivalent to saying the base condition is the smallest radius possible or no change in radius.

$$CMF_{Radius} = e^{[\beta_3 R]} \tag{9}$$

Where,

CMF_{Radius} = crash modification factor for the effect of radius on intersection-related crashes,

β_3 = coefficient term related to radius, and

R = radius of curve in feet

To directly calculate the predicted crash frequency at a curved corner site, the existing radius may be directly inputted into the appropriate parameter of Equation 8. To calculate the effect of changing the radius from an existing value to a proposed radius value, the difference between the existing and proposed radius would be inputted as the parameter *R* in Equation 9, where a positive difference indicates increasing the radius. This formulation can be most effective for evaluating site modifications where the radius may be improved (increased) with or without a change to the geometric configuration of the curved corner intersection.

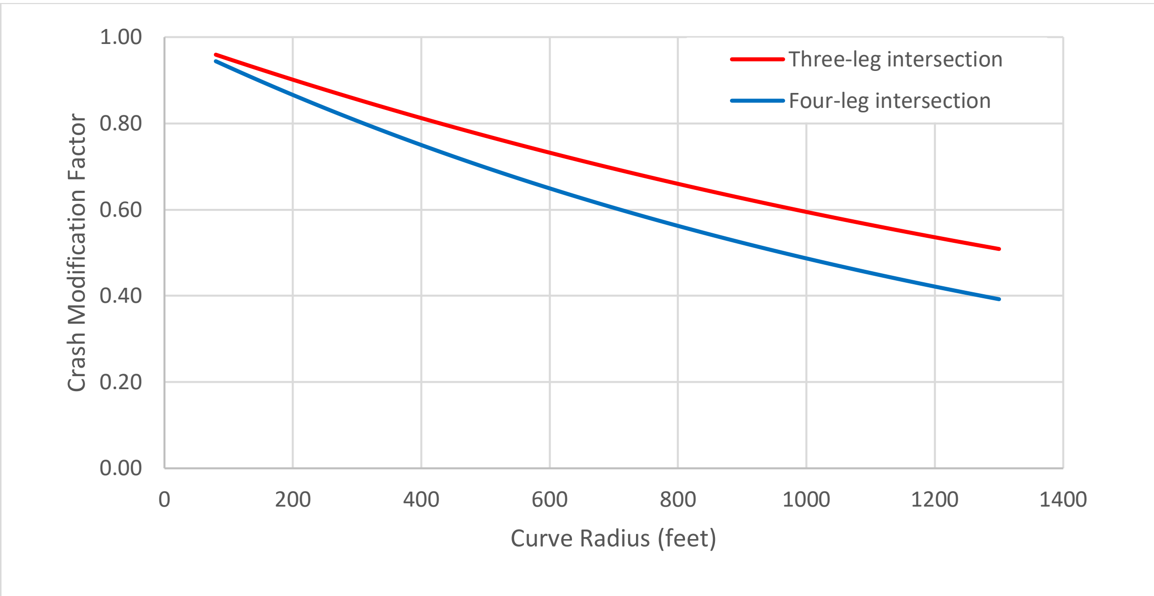

Figure 19. Crash modification factor for radius of curvature at curved corner intersection types.

5.2.2 Region Specific Effects

One of the objectives of this study was to evaluate the use random effects as a way to address unobservable heterogeneity within the data. Of particular interest are possible geographic and jurisdictional heterogeneity that could also pertain to travel patterns, driver population, and climatic differences. A model with fixed effects for the three distinct regions is compared with a model using the three regions as a random effect grouping. The RENB model therefore allows the intercept term to vary across different regions, yet the mean value of the intercept is reported for the model calibration result. This characteristic of the RENB model offers portability such as application outside of the state where it was calibrated, in this case Michigan. If a practitioner was offered the NB model with region specific fixed effects and found that their site did not reside in any of the specified regions, it would be inappropriate to assume the base condition. Essentially if location specificity is set as a fixed effect, then the model cannot be used outside of the locality for which it was calibrated.

The model with fixed effects for region has the strongest statistical fit of the models compared, having the smallest AIC and log-likelihood. However, the differences in these metrics are not large in comparison. The base condition for the regional fixed effects model is the SEMCOG (Southeast Michigan Council of Governments) region, which includes seven counties near the metro Detroit area. Although large areas of these counties are urbanized, rural areas do exist, and 22 percent of the sites were located within that region. The SEMCOG region sites had the greatest average crash frequency. Michigan's upper peninsula and the northern half of the lower peninsula are represented by a region that is much less densely populated and experiences much greater snowfall accumulation in comparison with the other regions. Predicted crash frequency in the UP & North region is 40 percent lower for three-leg intersections and 55 percent lower at four-leg curved corner intersections. The remaining region of the state was aggregated as West & Mid Michigan, which has a predicted crash frequency 18 percent lower than the base condition. However, at four-leg curved corner intersections, this effect was not statistically significant. Plausible explanations can be reasoned for the fixed effect of regions, in short, they appear sensible. However, the RENB model is recommended because it offers portability of the model without compromising the accuracy of the prediction.

5.2.3 Effect of Major and Minor roadway surface

Information about the pavement surface in the vicinity of the intersection was analyzed; however, during model development these factors were eliminated. Ninety-one percent of the sites had a paved major road surface. In fact, all of the 4CM sites had a paved major road surface. Certainly paved major road surface provides better braking, side friction, and maneuverability compared to an unpaved surface. This would result in higher travel speeds on the major roadway, and it more likely helps to compensate for the geometry of the curved corner segment. Absent variability, the parameter for paved major road surface was not statistically significant and was excluded from the model. A paved minor roadway surface was present in half of the sample population. However, the presence of a paved minor roadway was already incorporated into the minor road AADT estimation, Equation 1, which applied to three quarters of the sites. Since there is a strong correlation between minor road AADT and paved minor road surface, and one was used to predict the other, it would be inappropriate to include paved minor road surface as a variable in the model.

5.2.4 Crash Modification Factors

CMFs represent the estimated change in average crash frequency of a site associated with a change in one specific condition. In the models presented in this study, the base condition for comparison was a rural curved corner intersection with a combined/merged approach. However this base condition is also the most likely outcome of geometric improvements at curved corner intersections. The corresponding CMFs presented in Table 11 are arranged to illustrate the potential effect of converting an existing curved corner intersection into the baseline intersection configuration. The table is formatted in a way consistent with the CMF Clearinghouse. To determine the CMF Euler's number, *e,* was raised to the power of the estimated parameter, *β,* for each statistically significant category. The inverse of the result reflects the change from an existing curved corner configuration into the baseline combined/merged approach configuration. The CMFs are computed using the coefficients from the RENB model in order to be consistent with the recommendation regarding region specific effects. The CM-Function for changing the radius of curvature at curved corner intersections is described in the prior section, effect of radius of curvature.

Table 11. CMFs for Converting a Curved Corner Intersection into a Combined / Merged Approach.

CMF	**Crash Type**	**Crash Severity**	**Area Type**	**Comment**
0.67	Intersection	All	Rural	Existing was 3Y, converted to 3CM
0.75	Intersection	All	Rural	Existing was 3C, converted to 3CM
1.67	Intersection	All	Rural	Existing was 4C, converted to 4CM

Note: Each category excludes animal crashes.

The evaluation of CMF quality for cross-sectional studies, such as this one, considers sample size, study design and statistical methods, and statistical significance in a rating system described in NCHRP 17-72 [7]. The previous sections in this report detail much of this information. That being said, the CMF for converting a 4C type to a 4CM type has a counterintuitive effect and should be investigated further. Other limitations for CMFs derived from cross-sectional studies include inappropriate functional form, omitted variable bias, and correlation among variables. To the extent possible these limitations were addressed by concisely specifying the models. However, considering several functional forms for the CM-Function related to curve radius by way of the parameter transformations is a way that the relationship could be further explored.

5.3 Conclusions and Recommendations

The objective of this research was to create an SPF for rural intersections specific to the geometry represented as a curved corner intersection. In total, 292 curved corner intersection sites within the state of Michigan were represented in the study population. A multiple linear regression model was calibrated to predict minor road AADT for use in developing the SPFs. After an evaluation of several potential independent variables, it was found that a model including AADT for the major and minor road approaches, radius of curvature, and intersection configuration type was most appropriate for predicting the total frequency of (non-animal) intersection related crashes. A comparison between the intersection types shows that the 3CM configuration has the lowest predicted crash frequency, with the fewest number of intersection conflict points, and turning movements consolidated to a single junction. The 3CM and 4CM configurations both provide improved intersection lines of sight by eliminating highly skewed approaches. Conversion of an existing 3Y intersection into a 3CM is predicted to reduce crash frequency by 33 percent, while conversion of a 3C intersection into a 3CM is predicted to reduce crash frequency by 25 percent.

A larger radius of curvature was also found to favorably affect the safety performance of curved corner intersections. For three-leg curved corner intersections, increasing the curve radius by 100 feet results in an estimated 5 percent fewer crashes. At four-leg curved corner intersections, increasing the curve radius by 100 feet results in an estimated 8 percent fewer crashes. A model with fixed effects for three distinct regions was comparable to a RENB model with a random effect for the region grouping. The RENB model is recommended because it offers portability such as application outside of the state where it was calibrated, without compromising the accuracy of the prediction. The impact of this research will result in more accurate predictions of crash frequency which can be used to better prioritize safety investments.

6.0 SKEWED INTERSECTIONS

In addition to having a sample population of intersection with skew, it is necessary to obtain an equivalent population of intersections with no skew. These perpendicular intersections will establish the baseline condition for comparison with skewed intersections. The comparison population must consist of intersections with similar distributions of major and minor traffic volume as well as similar spatial distribution. To the extent possible, a conventional perpendicular intersection is drawn from a nearby location to a skewed intersection and along the same major route such that the sites compare as similarly as possible except for the amount of skew. The types of skewed intersections considered include three-leg separately from four-leg intersections.

Site specific data collection includes the following characteristics:

- Verify minor road stop-control
- Presence of lighting
- Presence of turn lanes
- Driveway count within 200 feet of intersection legs (major and minor)
- Angle of intersection skew
- Major road orientation

The site data must be spatially matched to other attributes using GIS (geographic information systems). This includes other locational features such as county and region as well as jurisdictional features such as National Functional Classification (NFC), federal aid eligibility, and surface type for the major and minor intersection approaches. In addition, 10 years of crash history are spatially matched to the selected nodes. Once the spatial mapping is complete, the data is summarized in spreadsheets. From there crash data summary tables are presented in a format consistent with the crash distributions presented in the HSM. This consistent format also allows easy incorporation into other tools such as IHSDM software. Finally, variables are coded for modeling, which includes the skew angle as a continuous variable as well as categorized into different discrete ranges.

The following contents of this chapter were first published as Crash Modification Functions for Rural Skewed Intersections [55] and have been reformatted to fit this dissertation.

6.1 Data Summary

This chapter presents the findings of a study to develop CMFs and similarly crash modification functions that relate crash frequency to intersection skew angle at rural two-lane two-way intersections. Using a cross-sectional analysis, an extensive sample of sites were observed throughout 10 years of crash history to develop models for the influence of skew angle. The skew angle is defined as the angle from which an intersection deviates from perpendicular. Whereas the term “intersection angle” would take a value of 90 degrees at a perpendicular approach, the skew angle is zero when approaches meet perpendicularly. The collected data was used with generalized linear modeling to develop several SPFs for predicting the frequency of intersection related crashes reported annually. A CMF relates changes in the skew angle to the expected crash frequency.

6.1.1 Site Data Collection

In order to confine the cross-sectional analysis to variation in skew angle alone, locations with turn lanes, lighting, flashing beacons, or traffic signals were excluded. The geographic distribution of study sites is shown in Figure 20. At least one intersection was identified in all of the state’s 83 counties. Administrative regions from the MDOT were aggregated to form three geographic regions that also broadly associate with different climatic zones as well as population demographics throughout the diverse state. Intersection locations where a curved roadway segment connects the major flow of through traffic from orthogonal directions, effectively the major road curves at the intersection, were also excluded because these have been separately studied as curved corner sites [51]. A total of 1,498 three-leg and 1,564 four-leg rural minor road stop-controlled intersections were identified along two-lane two-way roadways in the state of Michigan. Among these, 404 three-leg sites and 280 four-leg sites have some amount of minor road skew at the intersection; the remaining intersections have no skew or are perpendicular.

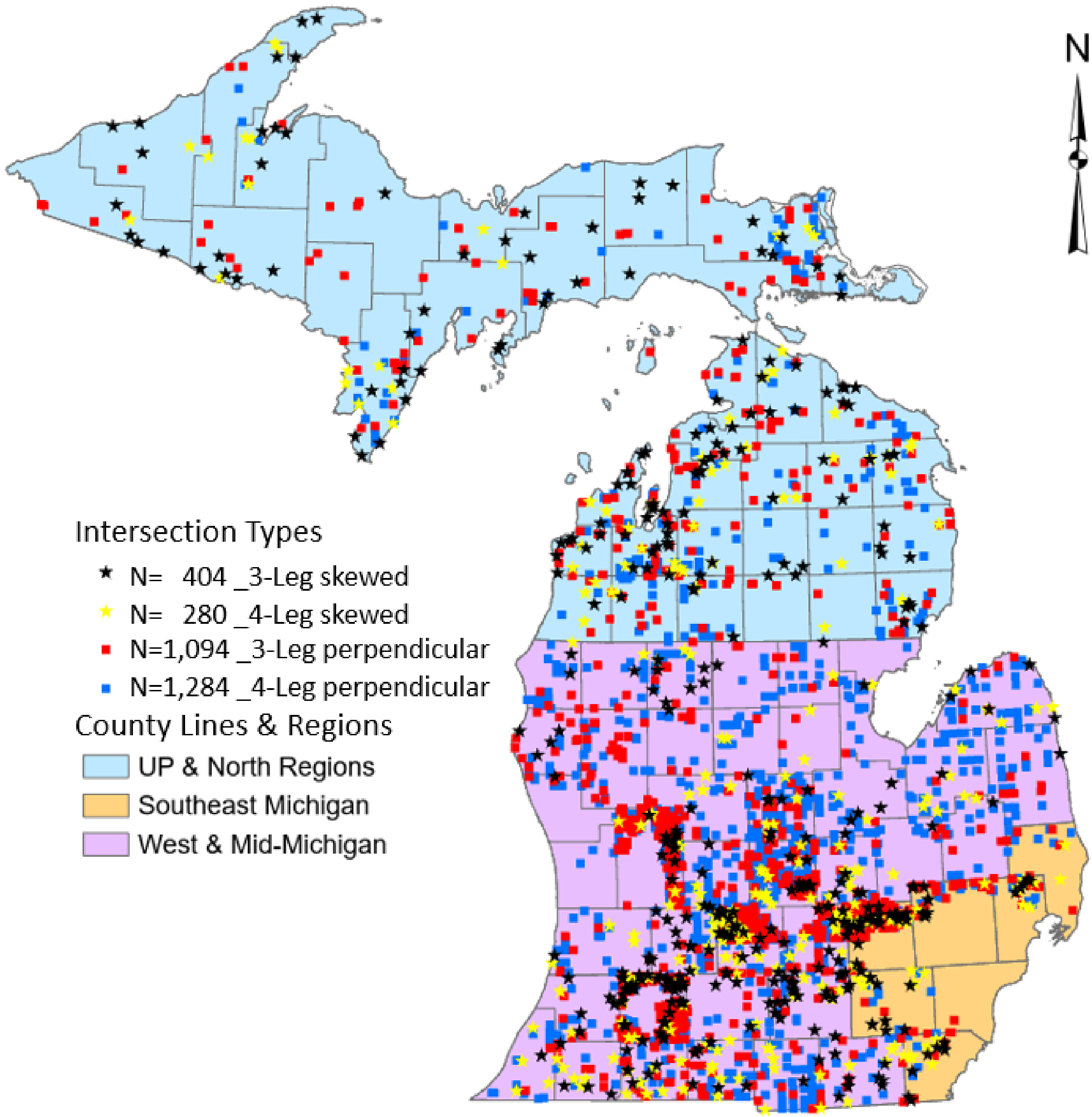

Figure 20. Geographic distribution of skewed study intersections in Michigan county lines and regions shown.

6.1.2 Descriptive Statistics

Once the data was assembled, the distribution of crashes by severity type was determined as shown in Table 12. This table closely matches the format of the information presented in Tables 10-5 and 10-15 of the HSM Chapter 10. Consistent with findings from previous statewide intersection safety research, Michigan's rural three-leg and four-leg intersection crashes tend to be less severe than the HSM default distributions [47]. This finding especially stands out considering that numerous crashes coded "animal" as the primary involvement were removed from this analysis at the onset. Most animal crashes that are reported in Michigan involve deer and mostly incur property damage only; however, they are not intersection related and so were removed. Among 1,498 three-leg intersections, a total of 3,307 intersection non-animal crashes occurred during the 10-year sampling period. A total of 6,191 intersection non-animal crashes occurred among the 1,564 four-leg intersection sites during the same period.

The three-leg intersections show lower proportions in all categories of fatal and injury severities compared to four-leg intersections, with an average annual crash frequency of 0.22 crashes per year, while four-leg intersections' crash frequency was nearly double at 0.40 crashes per year. While not surprising, this observation can often be attributed to fewer crossing conflict points at three-leg intersections, and less exposure to traffic. Looking at intersections with any amount of skew in comparison to perpendicular geometry, four-leg skewed intersections have a notably higher average crash frequency, while crash severity distributions appear similar regardless of skew.

Table 12. Distribution of Crash Severity for Skewed Rural Two-lane Two-way Minor Road Stop-Controlled Intersection Study in Michigan.

	Percentage of intersection crashes by greatest severity (2010-2019)			
	Three-leg intersections		**Four-leg intersections**	
Crash severity level	**with skew**	**perpendicular**	**with skew**	**perpendicular**
Fatal (K)	1.1	0.6	1.4	2.0
Incapacitating injury (A)	3.5	3.8	4.2	6.6
Nonincapacitating injury (B)	10.1	9.0	11.7	12.3
Possible injury (C)	14.4	13.9	18.1	19.6
Fatal + injury (KABC)	29.1	27.3	35.4	40.4
Property damage only (PDO)	70.9	72.7	64.6	59.6
Total percentage	**100.0**	**100.0**	**100.0**	**100.0**
Total number of crashes	1,055	2,252	1,479	4,712
Total number of sites	404	1,094	280	1,284

Note: Each category excludes animal crashes.

The distribution of collision types and severity levels is shown in Table *13*, which closely matches the format of the information presented in Table 10-6 of the HSM Chapter 10. The three-leg intersections studied experienced significantly more single vehicle crashes than the default distributions in the HSM. Within the available crash data, run-off-road and fixed-object crash types, were not separately coded and were so aggregated in the category of other single-vehicle crashes in the summary Table *13*. Adverse winter weather conditions in Michigan could be an explanation for some of the abundance of single vehicle crashes in comparison to the HSM distributions. Within the multiple vehicle crash types, angle and rear-end collisions are the most common, which is consistent with the HSM distributions. Looking more closely at three-leg intersections with skew compared to perpendicular appears to have very similar crash distributions. Some subtle differences are noticed in that skewed three-leg intersections experienced fewer proportion of angle crashes and more proportion of head-on crashes. While head-on crashes at three-leg intersections would typically only occur between major road traffic streams, the influence of skew on acute angle right turns could lead to lane encroachment resulting in a head-on or sideswipe-opposite crash depending on the position of impact.

The four-leg intersections studied were generally consistent with the HSM distributions, especially in the categories of single vehicle crashes. The studied sites experienced a greater proportion of angle crashes and a lesser proportion of rear-end crashes than the HSM distribution. However, the proportion of total multiple vehicle crashes remained consistent. Looking specifically at four-leg intersections with skew compared to perpendicular, there are fewer proportion of angle crashes at skewed intersections. In general, the crash distributions within the intersection types remains quite consistent regardless of having skew or not. This finding differs from much of the prior research literature that tended to suggest skew leads to more severe, angle, and rear-end oriented crashes.

Table 13. Distribution of Collision Type and Manner of Collision for Skewed Rural Two-lane Two-way Minor Road Stop-Controlled Intersection Study in Michigan.

	Percentage of intersection crashes by collision type (2010-2019)											
	Three-leg with skew			**Three-leg perpendicular**			**Four-leg with skew**			**Four-leg perpendicular**		
Collision Type	**FI**	**PDO**	**Total**	**FI**	**PDO**	**Total**	**FI**	**PDO**	**Total**	**FI**	**PDO**	**Total**
Single-vehicle crashes												
Collision with bicycle	0.7	0.0	0.2	0.8	0.0	0.2	0.2	0.0	0.1	0.5	0.0	0.2
Collision with pedestrian	0.0	0.4	0.3	0.5	0.0	0.2	0.4	0.1	0.2	0.4	0.2	0.3
Overturned	11.4	5.7	7.4	10.4	4.1	5.8	4.4	2.0	2.8	3.3	2.6	2.9
Other single-vehicle crash	45.6	49.1	48.0	39.7	53.2	49.5	11.6	24.2	19.8	8.5	25.7	18.7
Total single-vehicle crash	57.7	55.2	55.9	51.4	57.3	55.7	16.6	26.3	22.9	12.7	28.5	22.1
Multiple-vehicle crashes												
Angle collision	12.3	9.6	10.4	18.9	12.5	14.3	58.8	37.3	44.8	65.1	36.7	48.2
Head-on collision	8.1	2.7	4.3	7.3	2.0	3.5	5.2	1.8	3.0	5.6	3.0	4.1
Read-end collision	15.0	19.2	18.0	14.3	17.6	16.7	13.0	18.1	16.3	9.9	17.6	14.5
Sideswipe collision	4.9	7.0	6.4	5.5	6.7	6.3	2.9	9.1	6.9	2.6	8.2	5.9
Other multiple-vehicle collision	2.0	6.3	5.0	2.6	3.9	3.5	3.5	7.4	6.1	4.1	6.0	5.2
Total multiple-vehicle collision	42.3	44.8	44.1	48.6	42.7	44.3	83.4	73.7	77.1	87.3	71.5	77.9
Total Crashes	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Note: Each category excludes animal crashes. FI = fatal and injury; PDO = property damage only.

Summary statistics for the evaluated variables in this study are provided in Table 14. Many categorical variables take a binary format (0=No, 1=Yes), in which case the mean value indicates what proportion of the sites take on the affirmative value. A logical upper limit for skew angle was observed as 80 degrees among four individual three-leg intersection sites. One of the four-leg intersection sites had a maximum skew angle of 72 degrees. Geometrically skew angles greater than these become impractical and none were observed. In total 27 percent of the three-leg and 18 percent of the four-leg intersection sites had some amount of skew. While the skew angle remains a continuous variable, it was categorized initially in increments of ten degrees in order to display the distribution. It is evident that very few skewed intersection sites exist at the most extreme skew angles. Based on limited sample size for the most extreme skew, the study results should not be extrapolated beyond the maximum observed skew angle.

Table 14. Descriptive Statistics for Skewed Rural Two-lane Two-way Minor Road Stop-Controlled Intersection Study in Michigan.

	Three-leg intersections				Four-leg intersections			
Parameter	**Min.**	**Max.**	**Mean**	**SD.**	**Min.**	**Max.**	**Mean**	**SD.**
AADT-major road (veh/day)	28	15,521	1,815	1,949	60	14,443	2,067	1,949
AADT-minor road (veh/day)	4	6,985	512	660	11	7,150	596	593
MDOT-major road jurisdiction	0	1	0.17	0.37	0	1	0.18	0.38
NTFA-major road jurisdiction	0	1	0.56	0.50	0	1	0.63	0.48
NonFA-major road jurisdiction	0	1	0.27	0.45	0	1	0.19	0.39
West and Mid-Michigan region	0	1	0.64	0.48	0	1	0.75	0.43
UP and North region	0	1	0.21	0.41	0	1	0.15	0.36
Southeast Michigan region	0	1	0.15	0.36	0	1	0.10	0.30
Skew angle (degrees)	0	80	6.77	14.06	0	72	4.34	11.23
Skew = 0 degrees	0	1	0.73	0.44	0	1	0.82	0.38
Skew > 0 to 10 degrees	0	1	0.06	0.23	0	1	0.04	0.19
Skew >10 to 20 degrees	0	1	0.07	0.26	0	1	0.05	0.22
Skew >20 to 30 degrees	0	1	0.06	0.23	0	1	0.03	0.18
Skew >30 to 40 degrees	0	1	0.04	0.18	0	1	0.03	0.16
Skew >40 to 50 degrees	0	1	0.03	0.16	0	1	0.02	0.15
Skew >50 to 60 degrees	0	1	0.01	0.09	0	1	0.00	0.07
Skew >60 to 70 degrees	0	1	0.01	0.08	0	1	0.00	0.05
Skew >70 to 80 degrees	0	1	0.01	0.08	0	1	0.00	0.02
Non-animal crashes per site per year	0	10	0.22	0.57	0	10	0.40	0.80

Note: Min. = minimum; Max. = maximum; SD = standard deviation.

Crash rate was calculated for each intersection site in order to better understand the impact of exposure to traffic amount on the observed crash frequency. The crash rate for intersections is computed according to Equation 10, and is reported in units of annual crashes per 100 million entering vehicles (MEV). Intersection AADT is computed as the summation of the major road and minor road AADT for each site and is used to represent the daily entering vehicle traffic volume. As previously mentioned, a ten-year time period was used in this study.

$$R_{int} = \frac{C \times 10^6}{DEV \times 365 \times T} \tag{10}$$

Where,

R_{int} = intersection crash rate (crashes per 100 million entering vehicles),

C = summation of intersection-related crashes during time period,

DEV = daily entering vehicle traffic volume (veh/day)

T = time period

The individual intersection crash rates were averaged in aggregated categories of skew angle in ten-degree increments. The average crash rates are plotted in Figure 21. The four-leg intersections exhibited consistently higher crash rates than three-leg intersections, with the highest average crash rate occurring in the range from 20 to 30 degrees. After the peak, the four-leg average crash rates mostly declined. The three-leg intersections had a peak average crash rate in the category range of skew from 10 to 20 degrees. Beyond that point, the average crash rates more gradually decline as the skew angle increases to the maximum observed skew. Trendlines were fitted to the crash rate plot in order to characterize the shape of the relationship. The three-leg relationship is fitted as a linear declining trendline. The four-leg relationship is fitted as a fourth order polynomial. For both three-leg and four-leg intersections, the average crash rate in categories of skew greater than 40 degrees is lower than that for perpendicular intersections of the same type.

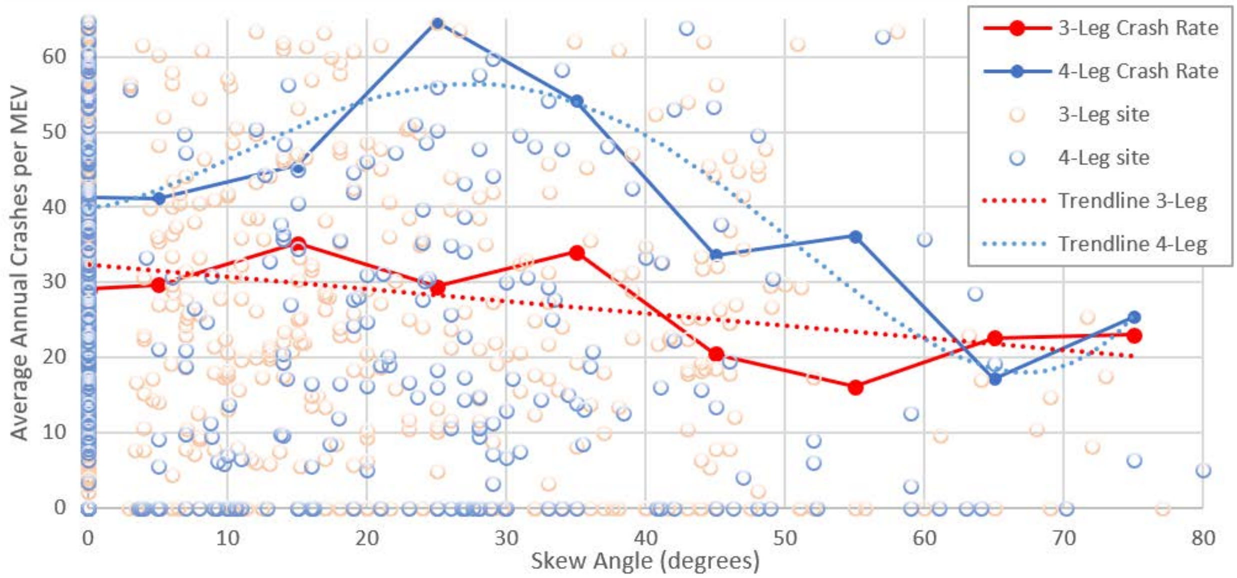

Figure 21. Annual average total crash rate by skew angle category and number of legs.

During the analysis, various aggregations of skew were considered to form categorical variables or binned ranges of skew. Bin ranges were considered using intervals sized from 4 to 15 degree increments. Smaller intervals generally produced more volatile average crash rates. Increasing the size of bin ranges was necessary for higher skew angles in order to capture an adequate sample size. The binned ranges were determined by looking at the breakpoints in the crash rate trends shown in Figure 21 and similarly constructed graphs for various bin interval ranges. Further, the categories were formed to include an adequate number of sites and observed crashes in order to calibrate a statistically significant SPF. Table 15 shows the distribution of intersection AADT within the skew category ranges that were forwarded in the analysis. The first bin range for skew up to 17 degrees relates with a limit that state and national policies often consider a desirable maximum amount of skew. The second bin from 17 to 27 degrees encompasses the peak average crash rates observed, while the last two bin ranges were carefully divided to capture an adequate sample size without biasing the results. Various aggregations were evaluated throughout the modeling with attention to the statistical significance of the parameter coefficients estimated. It can be observed that the aggregated category for skew angle greater than 45 degrees also has higher average intersection AADT than other skew categories. So while average crash frequencies (crashes per site) may appear consistently higher among skewed sites, computed intersection crash rates based on traffic volume exposure are actually lower at the most highly skewed sites. This situation most likely results from high volume major roads intersecting with very low volume minor roads at the most highly skewed sites.

Table 15. Distribution of Intersection AADT and Non-animal Crashes by Skew Angle Category.

	Three-leg intersections			Four-leg intersections		
Skew Angle	**N (sites)**	**Average Intersection AADT (veh/day)**	**Number of non-animal crashes**	**N (sites)**	**Average Intersection AADT (veh/day)**	**Number of non-animal crashes**
Skew = 0 degrees	1,094	2,131	2,252	1,284	2,517	4,712
Skew > 0 to 17 degrees	154	2,539	370	111	3,271	492
Skew >17 to 27 degrees	95	2,768	306	59	3,123	377
Skew >27 to 45 degrees	112	2,892	262	81	3,341	465
Skew >45 to 80 degrees	43	4,123	117	29	3,944	145
Total	**1,498**	**2,327**	**3,307**	**1,564**	**2,663**	**6,191**

6.2 Modeling and Results

The HSM recommends using the negative binomial (NB) distribution for the development of SPFs due to its ability to account for the Poisson variance overdispersion that is common in crash data distributions [2]. The approach presented herein is to develop several SPFs as NB models with different functional forms for the skew relationship. In this way, the researchers seek to better understand the consequences of the functional form chosen, and ultimately to recommend a CMF based on goodness of fit to the sample data. Models were created amongst the three-leg sites separately from the four-leg sites. The SPFs include the primary relationship with major and minor approach AADT, with other explanatory variables added to adjust for differences from the base condition. The base condition is a skew angle of zero (perpendicular intersection) on a roadway where the major road is federal aid eligible. The expected number of crashes can be estimated using the general NB functional form:

$$N_{spf} = e^{(\beta_0 + \boldsymbol{\beta} * \mathbf{X} + \varepsilon)} \tag{11}$$

Where,

N_{spf} = predicted intersection-related crashes per year,

β_0 = intercept term,

$\boldsymbol{\beta}$ = vector of coefficients,

$\mathbf{X}$ = vector of explanatory variables,

ε = negative binomial error term, and

In Equation 11, exp(ε) is gamma-distributed with a mean one and variance α. One concern when evaluating SPFs across a broad statewide network is unobserved heterogeneity, which in large part contributes to overdispersion. Various spatial groupings were evaluated to help describe locational differences. The initial region codes defined by MDOT encompass 7 different regions in their governance that also possess distinct traffic characteristics and weather conditions, as well as other distinctive population demographics. Subsequent aggregations of the regions were selected based on the analyst's knowledge of the state of Michigan, in an attempt to categorize more homogeneous regions with respect to weather, demographic, and traffic characteristics. The inclusion of a variable in the model is determined based on a test of significance for the model coefficient for that variable. The threshold for significance is often based on a 95 percent confidence interval to be regarded as a high-quality predictor in the model. In the analysis of skew relationships, non-significant coefficients mean that the coefficient is not significantly different than the base condition which is a perpendicular intersection. The differences between log-likelihoods of the models were assessed along with the Akaike information criterion (AIC). Smaller scores for either of these metrics suggest stronger statistical fit.

6.2.1 Safety Performance Functions

The first SPF developed assumes a monotonic relationship with the skew angle. In this case, the general NB model from Equation 11 is expanded to represent the SPF as shown in Equation 12. The monotonic relationship is assumed for the skew angle CMF in the HSM and has been widely adopted by subsequent studies. A positive coefficient indicates crash frequency increases with increasing skew, while a negative coefficient indicates crash frequency decreases with increasing skew.

$$N_{spf} = e^{\beta_0} \times \left({AADT_{Major}}^{\beta_1}\right) \times \left({AADT_{Minor}}^{\beta_2}\right) \times e^{(\beta_3 * skew + \boldsymbol{\beta_i X_i})} \qquad (12)$$

Where,

N_{spf}	= predicted intersection-related crashes per year,
β_0	= intercept term,
$AADT_{Major}$	= AADT (vehicles per day) on the major road,
$AADT_{Minor}$	= AADT (vehicles per day) on the minor road,
β_1	= coefficient term related to major road AADT,
β_2	= coefficient term related to minor road AADT,
β_3	= coefficient term related to skew angle,
skew	= skew angle (degrees),
$\boldsymbol{\beta_i}$	= vector of coefficient terms related to intersection characteristics, and
$\boldsymbol{X_i}$	= vector of explanatory variables for intersection characteristics

The calibrated coefficients for all of the SPFs are provided in *Table 16*. The overdispersion parameter is provided with each model, as well as goodness of fit metrics. The second SPF developed uses categorical binary variables to evaluate ranges of skew angle as were defined in Table 15. The categorical function is essentially a stepwise function where mutually exclusive binary variables are employed in the same manner as the vector of coefficients and variables in Equation 12. Skew angle is not directly included in the function, and the discontinuous steps are represented as constant factors, or CMFs, applicable to a specific range of skew angles.

A third SPF was developed using a flexible form model similar to that employed by Harkey et. al. for the intersection angle CMFs in the CMF Clearinghouse [40]. From the plot of intersection crash rate versus the skew angle in Figure 21, it is apparent that the relationship to skew is not monotonic, especially among four-leg intersections studied. The flexible form model consists of an upward facing convex function. The skew angle is included in the model directly, as in Equation 12 and through a multiplicative interaction with the AADT of the major and minor approaches using the sine of the skew angle. Equation 13 shows the arrangement of the flexible form model. Each of the terms have been previously defined.

$$N_{spf} = e^{\beta_0} \times \left(AADT_{Major}{}^{\beta_1}\right) \times \left(AADT_{Minor}{}^{\beta_2}\right) \times [1 + \sin(skew)]^{(\beta_1+\beta_2)} \times e^{(\beta_3 * skew + \boldsymbol{\beta_i X_i})} \tag{13}$$

The derivation of how to model the skew interaction with AADT is shown in a FHWA report by Harkey et. al. [40], which used the cosine function on the intersection angle; however, this will be equivalent to using the sine function on the skew angle. Specifically the term *1+sin(skew)* is used in the model such that for perpendicular intersections when the *sin*(0 degrees) equals zero and the term becomes 1.0 and when skew is theoretically maximum, the *sin*(90 degrees) equals one and the term becomes 2.0. Another difference between the flex form model employed by Harkey et. al. and this one is that major and minor approach AADT is herein used in place of intersection and minor approach AADT. It is not entirely clear why intersection AADT would be included with minor approach AADT, since the minor AADT is also already part of the intersection AADT. In this study the inclusion of major and minor approach AADT separately is more consistent with the primary intersection SPF format.

A fourth SPF was developed using a Hoerl curve for the relationship to skew angle. The Hoerl curve is a composite of function using both the skew angle and the natural log of the intersection angle as explanatory variables. In this situation, intersection angle was used rather than skew angle because the natural log of a zero skew is an undefined value. However, intersection angle is easily equated as 90 minus skew angle. The Hoerl curve portion of the model is shown in Equation 14, and the full SPF with the skew angle effects included is shown in Equation 15.

$$Hoerl = e^{(\beta_3 * skew + \beta_4 * \ln(Int.angle))} \tag{14}$$

$$N_{spf} = e^{\beta_0} \times \left(AADT_{Major}{}^{\beta_1}\right) \times \left(AADT_{Minor}{}^{\beta_2}\right) \times e^{(\beta_3 * skew + \boldsymbol{\beta_i X_i})} \times \left(Int.angle^{\beta_4}\right) \tag{15}$$

Where each of the previous term definitions apply with the addition of the following,

β_4 = coefficient term related to intersection angle,

Int.angle = intersection angle, equivalent to 90 minus skew angle (degrees),

Table 16. Model Results for Rural Skewed Intersection Study in Michigan.

Parameter	Three-leg intersections				Four-leg intersections			
	Skew Mono-tonic	**Skew Categori-cal**	**Skew Flex Form**	**Skew Hoerl Curve**	**Skew Mono-tonic**	**Skew Categori-cal**	**Skew Flex Form**	**Skew Hoerl Curve**
Intercept	-7.331 (0.203) ***	-7.345 (0.203) ***	-7.346 (0.203) ***	-7.567 (1.101) ***	-7.707 (0.158) ***	-7.717 (0.158) ***	-7.717 (0.158) ***	-14.823 (2.131) ***
Ln(major road AADT)	0.389 (0.027) ***	0.385 (0.027) ***	0.388 (0.027) ***	0.389 (0.027) ***	0.427 (0.020) ***	0.429 (0.020) ***	0.428 (0.020) ***	0.427 (0.020) ***
Ln(minor road AADT)	0.500 (0.021) ***	0.505 (0.021) ***	0.502 (0.021) ***	0.501 (0.021) ***	0.569 (0.017) ***	0.567 (0.017) ***	0.569 (0.017) ***	0.568 (0.017) ***
Federal aid major	Base	Base	Base	Base	Base	Base	Base	Base
NONFA-major	-0.342 (0.075) ***	-0.336 (0.075) ***	-0.338 (0.075) ***	-0.341 (0.075) ***	-0.227 (0.061) ***	-0.223 (0.061) ***	-0.224 (0.061) ***	-0.224 (0.061) ***
Skew angle	-0.004 (0.001) ***	na	-0.014 (0.001) ***	-0.003 (0.004)	0.002 (0.001) **	na	-0.010 (0.001) ***	0.027 (0.007) ***
Skew 0 degrees	na	Base	na	na	na	Base	na	na
Skew >0 to 17 degrees	na	-0.049 (0.063)	na	na	na	-0.007 (0.049)	na	na
Skew >17 to 27 degrees	na	0.202 (0.069) ***	na	na	na	0.335 (0.057) ***	na	na
Skew >27 to 45 degrees	na	-0.115 (0.073) **	na	na	na	0.085 (0.052) *	na	na
Skew >45 to 80 degrees	na	-0.360 (0.073) ***	na	na	na	-0.061 (0.089)	na	na
Ln(Int.angle)	na	na	na	0.052 (0.238)	na	na	na	1.581 (0.472) ***
West and Mid-Michigan region	Base	Base	Base	Base	Base	Base	Base	Base
UP and North region	-0.117 (0.050) **	-0.118 (0.050) **	-0.124 (0.050) ***	-0.118 (0.050) **	-0.291 (0.045) ***	-0.293 (0.045) ***	-0.293 (0.045) ***	-0.293 (0.045) ***
Southeast Michigan region	0.150 (0.058) ***	0.146 (0.058) ***	0.148 (0.058) ***	0.150 (0.058) ***	0.168 (0.043) ***	0.155 (0.043) ***	0.160 (0.043) ***	0.151 (0.043) ***
Overdispersion	0.596 (0.061)	0.581 (0.060)	0.597 (0.061)	0.597 (0.061)	0.118 (0.017)	0.117 (0.017)	0.118 (0.017)	0.118 (0.017)
AIC	15334	15322	15331	15336	23267	23245	23258	23256
Log-likelihood	-7659	-7650	-7658	-7659	-11625	-11611	-11621	-11619

Note: Base = baseline condition; Standard errors are in parentheses; *** = significant on 99 percent level; ** = significant on 95 percent level; * = significant on 90 percent level; AIC = Akaike information criterion; na = not applicable.

The best three-leg and four-leg models, as judged by the AIC and log-likelihood, are the categorical models. However, the differences in these metrics are very small from one model to the other. It is also observed from the model results in Table 16 that the coefficients for every parameter included besides skew angle are very consistent between models. This is a reassuring outcome indicating that functionally, the relationship with skew angle is the variation between the models evaluated.

Cumulative residual (CURE) plots were generated to examine the model fit as a function of the skew angle as shown in Figure 22. The predicted values were sorted by increasing skew angle before the cumulative residual was computed. The intercept with the vertical axis at zero skew is the accumulated residual considering perpendicular intersections only. Ideally the cumulative residual should oscillate about a horizontal line; long sloped increasing runs correspond to regions of consistent underestimation by the model, as residuals are accumulated between the actual minus predicted values. Confidence limits are typically portrayed as upper and lower bounds at 95 percent or two standard deviations from the mean by assuming that the residuals are approximately normally distributed. Cumulative residuals frequently outside of the confidence envelope would indicate notable bias in the SPF. Since four models are being overlaid in each CURE plot, the upper and lower bounds herein were only displayed for the categorical model which is ultimately suggested to have the best fit. For three-leg intersections, the categorical model appears to fit best, as the cumulative residual stays mostly within the confidence envelope throughout the evaluated skew angles. For four-leg intersections, the categorical model adds the least cumulative residual throughout the range of skew angles and stays entirely within the confidence envelope, indicating the best performance among the models. All of the other models have some spikes or prolonged segments that protrude outside of the confidence envelope.

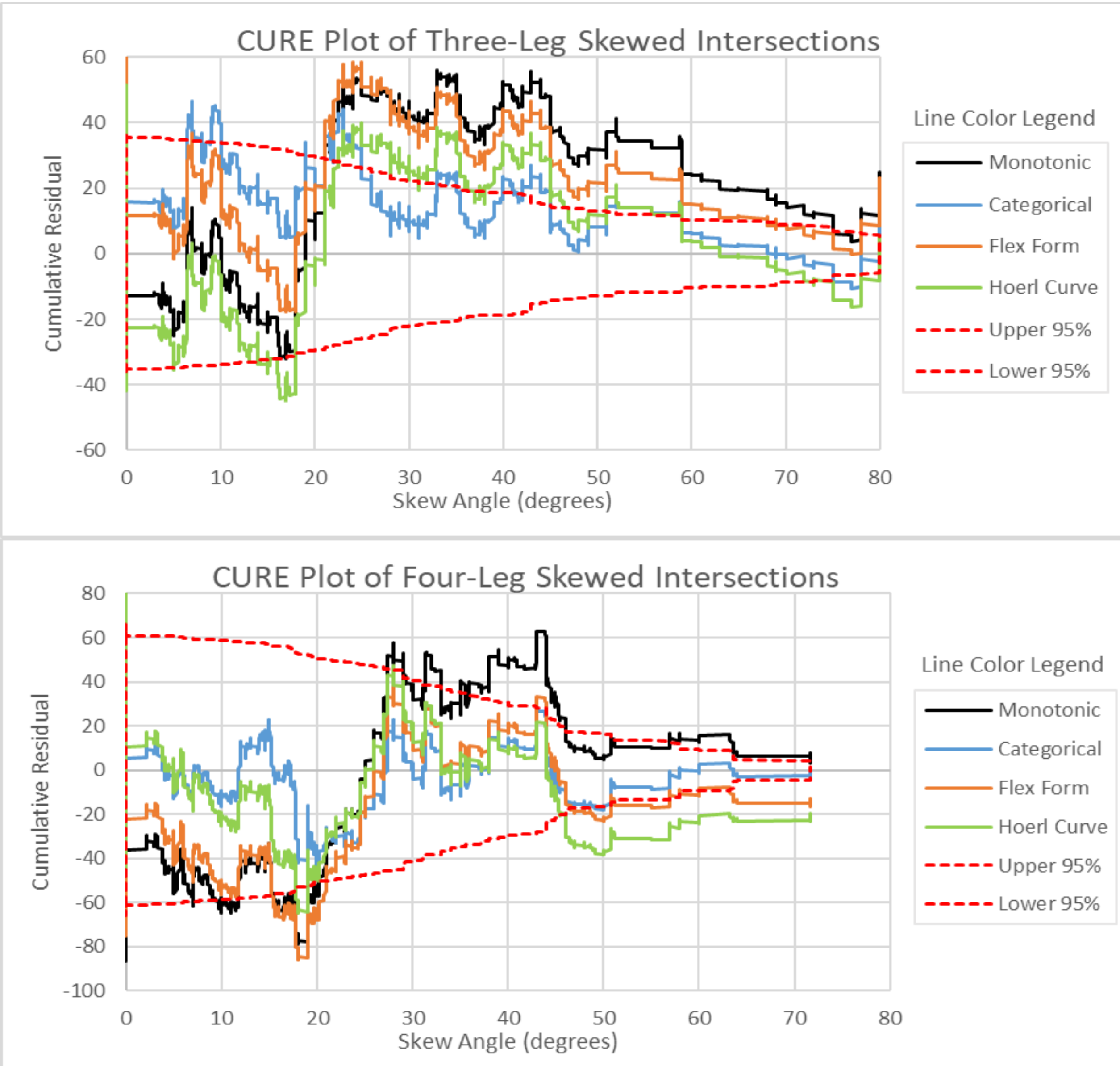

Figure 22. CURE plots of different model prediction vs. skew angle.

6.2.2 CM-Function for Skew

CMFs represent the estimated change in average crash frequency of a site associated with a change in one specific condition. While CMFs are generally regarded as a single constant multiplier, the term CMF is often loosely used to describe a CM-Function, which is a continuous version of the CMF. The CM-Function is less constrained than a categorical or step function and "is preferable if the cause-effect relationship with crashes can be determined with confidence" [54]. The coefficients from the SPF models are used to derive the CMF or CM-Function to show the relationship between crashes and skew angle. Recall that the skew angle was investigated as a parameter in the SPF models both as a continuous variable, with observed values ranging from 0 to 80 degrees, and categorized into bins, based on the distribution within sample site locations. A few transformations of the skew parameter were considered such as the flexible form model with skew interaction with AADT, and the Hoerl curve including the natural-log of the intersection angle. The CM-Function is derived to have a nominal value of 1.0 for the base condition of zero skew angle or perpendicular intersection. The derivations of a CM-Function from the flexible form model and Hoerl curve model are shown in Equations 16 and 17 respectively. Each of the previous term definitions apply.

$$CMF_{Flex-form} = \frac{[1+\sin(skew)]^{(\beta_1+\beta_2)} \times e^{\beta_3 * skew}}{[1+\sin(0)]^{(\beta_1+\beta_2)} \times e^{\beta_3 * 0}} = \frac{[1+\sin(skew)]^{(\beta_1+\beta_2)} \times e^{\beta_3 * skew}}{1} \quad (16)$$

$$CMF_{Hoerl-curve} = \frac{e^{(\beta_3 * skew + \beta_4 * \ln(Int.angle))}}{e^{(\beta_3 * 0 + \beta_4 * \ln(90))}} = \frac{e^{(\beta_3 * skew + \beta_4 * \ln(Int.angle))}}{90^{\beta_4}} \quad (17)$$

The denominator in Equation 16 is one regardless of the coefficients. Figure 23 and 24 show the CM-Functions for three-leg and four-leg intersections respectively. The monotonic relationship was not plotted, as that model was calibrated mostly to compare with the modeling format displayed in the 2010 HSM. Although a statistically significant monotonically increasing relationship to skew was calibrated for four-leg intersections, it does not fit the data considering annual average crash rate shown in Figure 21. A curve was added to compare the CM-Functions developed in this study of Michigan intersections to those portrayed in the CMF Clearinghouse which are currently based on studies of Minnesota and Ohio intersections.

The models developed for three-leg intersections mostly exhibit decreasing predicted crash occurrence as skew angle increases. A few justifications are offered to explain this trend. Although turning movements were not specifically obtained, examination of aerial photos at the most highly skewed three-leg sites showed wear patterns that suggest the minor road traffic primarily departs toward the direction of the obtuse angle turn. In similar fashion turns from the major road to the minor road appear to bias the obtuse angle turn as well. Likewise looking at larger roadway networks, a shorter travel path or cut-off road is sometimes observed which negates the need to "backtrack" and avoids the acute angle turn to, or, from a highly skewed minor road approach. Another explanation involving driver behavior suggests that the alertness level of the driver will increase when encountering unique and extremely skewed intersections. This safety compensation may result in the presumably bad sites performing better. Increased alertness at extremely skewed intersections is not a characteristic inherited by autonomous vehicles. Only the categorical model portrays the initial upward trend in average annual crash rate observed through the range of skew angles from 17 to 27 degrees. At three-leg intersections, this statistically significant parameter suggests 22 percent higher predicted crash occurrence than perpendicular intersections. Since the parameter coefficient for skew angles greater than zero to 17 degrees is not statistically significant and close to zero, this suggests that intersections in that range of skew perform similarly to perpendicular intersections, a finding that agrees with current state guidelines identifying a desired maximum skew of 15 degrees.

At four-leg intersections with a skew angle between 17 to 27 degrees the predicted crash occurrence is 40 percent higher than perpendicular intersections. None of the other categories of skew angle at four-leg intersections has a statistically significant parameter coefficient at a 95 percent confidence level. The models all indicate that a marginal change from any skew angle greater than 27 degrees to an angle remaining greater than 17 degrees is potentially detrimental to safety. In addition, the categorical models clearly indicate that intersections with a range of skew between 17 to 27 degrees would benefit the most from a reduction in skew angle. Based on the graphical comparison of the CM-Functions and the average annual crash rates, the categorical models most accurately reflect the skew relationship. The Hoerl curve shows the modeled crash influence at high skew angles is quite dramatically lower than can be justified in comparison to average annual crash rates, indicating that the shape of the model is being overly influenced by a limited number of extreme skew angle sites. The flexible form model is tied to a sine function of the skew angle and thus conforms to the requisite shape within skew angles from 0 to 90.

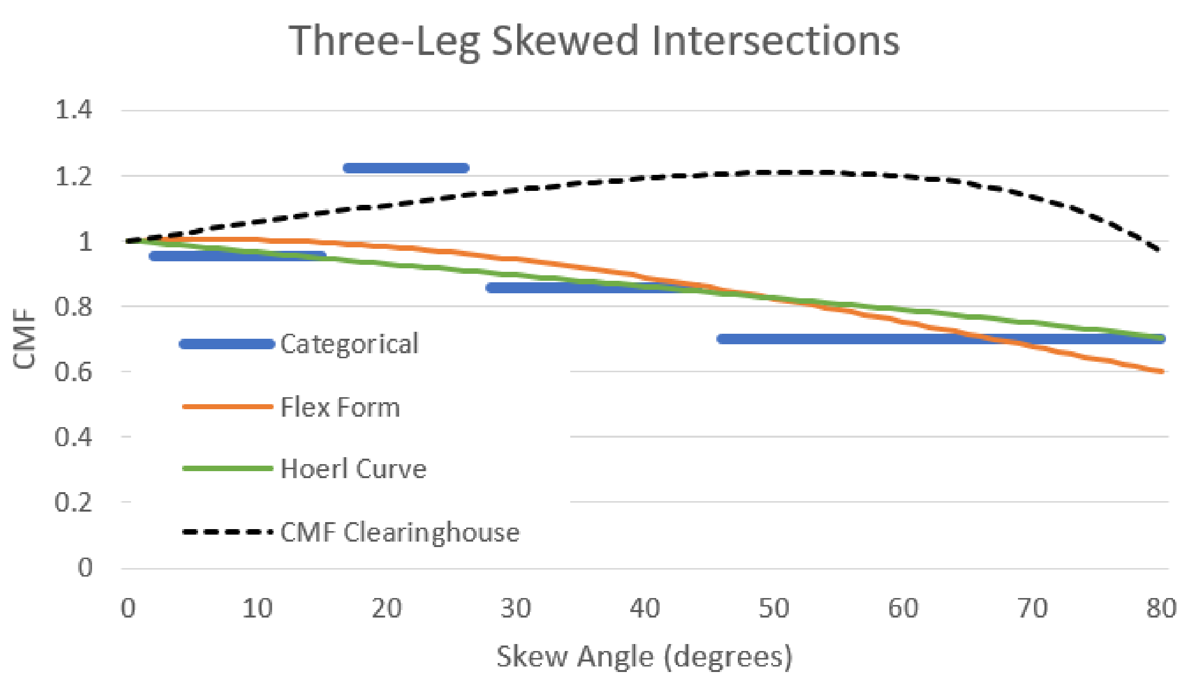

Figure 23. Crash modification functions for skew angle three-leg intersection types.

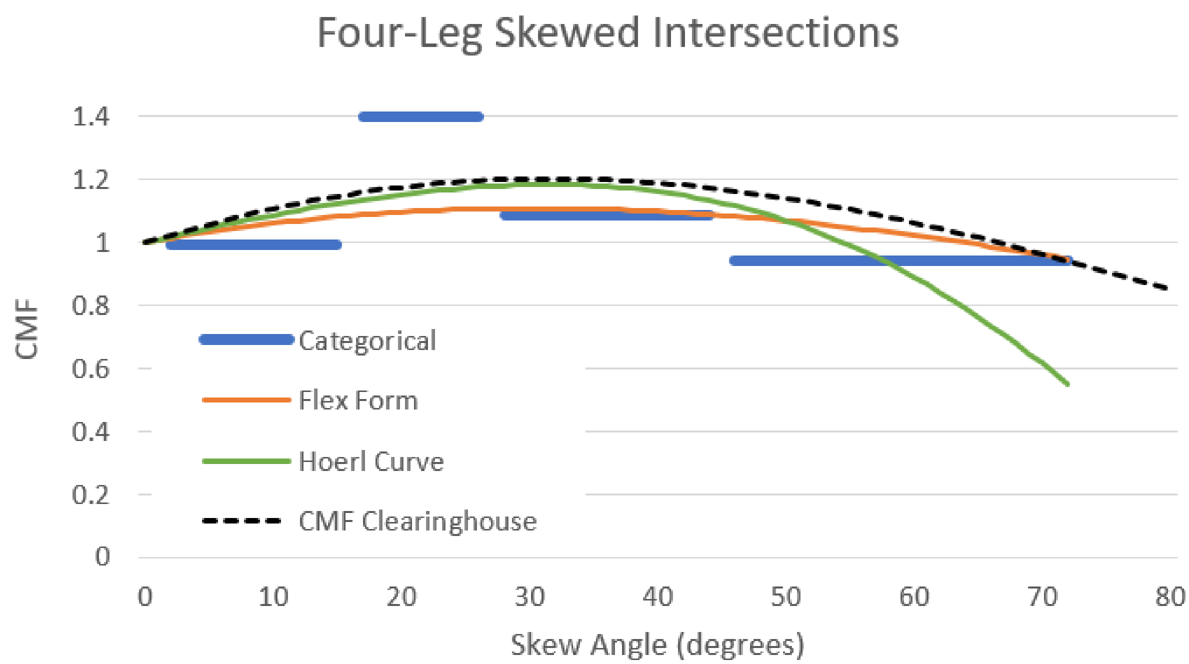

Figure 24. Crash modification functions for skew angle four-leg intersection types.

6.2.3 Region Specific Effects

Of particular interest are possible geographic and jurisdictional heterogeneity that could also pertain to travel patterns, driver population, and climatic differences. The SPFs were developed with fixed effects for the three distinct regions. The base condition for the regional fixed effect is the West and Mid-Michigan region, which is an aggregation of several counties representing a broad portion of the state that is middle range in terms of urbanization and weather characteristics. The Southeast Michigan region was created to match the area of SEMCOG (Southeast Michigan Council of Governments) region, which includes seven counties near the metro Detroit area. Although large areas of these counties are urbanized, rural areas do exist, and 13 percent of the sites were located within that region. The Southeast Michigan region consistently had a 16 percent higher crash occurrence at both types of intersections. Michigan's upper peninsula and the northern half of the lower peninsula are represented by a region that is much less densely populated and experiences much greater snowfall accumulation in comparison with the other regions. Crash frequency in the UP and North region was 11 percent lower for three-leg intersections and 25 percent lower at four-leg intersections in comparison to West and Mid-Michigan (base condition).

6.2.4 Crash Modification Factors for Federal Aid Status

In the models presented in this study, the base condition for comparison were intersections for which the major highway is part of the federal aid system. This includes state operated highways, called "trunklines" in Michigan, as well as major and minor arterials and major collectors eligible for federal aid that are operated by local agencies. Non-federal aid three-leg intersections had 29 percent lower crash occurrence, while non-federal aid four-leg intersections had 20 percent lower crash occurrence. This echoes the findings of a study by Stapleton et. al. into the safety performance of low volume rural stop-controlled intersections in Michigan [50]. The perceived safety benefit of non-federal aid intersections could possibly be attributed to a greater proportion of more familiar "local" drivers, despite otherwise lesser design standards and maintenance status.

6.3 Conclusions and Recommendations

The objective of this research was to explore SPFs for rural two-lane two-way minor stop-controlled intersections with specific attention to the characterizing the functional relationship to skew angle. The evaluation of crash type and severity distributions did not indicate substantial differences between intersections with skew and those with perpendicular orientation. CM-Functions are derived from the fitted parameters dealing with intersection skew. At three-leg intersections, a categorical model provided the best statistical fit, which predicted 22 percent more crashes at intersections with a skew angle between 17 to 27 degrees. However, for three-leg intersections with greater than 27 degrees skew angle, the categorical model predicts a reduction in crashes of up to 30 percent. Although this finding is counterintuitive, it may indicate that drivers compensate by being more alert and cautious at highly skewed intersections. Among four-leg intersections, a categorical model also provided the best statistical fit. Intersections with a skew angle between 17 to 27 degrees are predicted to experience 40 percent more crashes, while intersections with a skew angle greater than 45 degrees do not have a significantly different predicted crash occurrence than perpendicular intersections. A flexible form model for four-leg intersections peaks at a 30 degree skew angle, with an estimated 11 percent increase in predicted crash frequency compared to the baseline. Likewise, a Hoerl curve model for four-leg intersections peaks at a 31 degree skew angle with an estimated 18 percent increase in predicted crash frequency. The shape of these models is more consistent in comparison to annual average crash rate than a monotonic assumption. Therefore, the application of non-monotonic models results in more accurate predictions of crash frequency which can be used to better prioritize safety investments.

While a concentrated effort was made to isolate skew angle as the only variable characteristic in this cross-sectional analysis, some undetected differences may exist between the numerous sites evaluated. For consistency any sites with turn lanes, lighting, or flashing beacons were excluded from this study. Treatments such as turn lanes, lighting, flashing beacons, and vertical sight distance enhancement may be beneficial at skewed intersections; however, since these are often applied to the worst performing sites, their safety benefit is better observed in before-after studies than cross-sectional analysis. A limitation of this study is not knowing, or modeling, the directional traffic volumes of each approach, which AADT segment information simply does not provide. Some of the most highly skewed intersections likely satisfy a destination or directional preference in traffic movements. Thus, it is posited that at highly skewed intersections drivers will have a preferential intersection geometry for major and minor road traffic turning toward the direction of the obtuse angle approach. Benefits might include higher turning speed, convenience of route selection, and shorter overall travel distance. In this manner, highly skewed intersections serve their purpose in directional routing and should not be assumed to have the worst safety performance based purely on having the highest skew angle. The 684 skewed intersection study locations in Michigan disprove an implicit monotonic relationship between crashes and skew angle.

7.0 STOP-CONTROLLED WITH FIVE OR MORE-LEG INTERSECTIONS

7.1 Data Summary

Site identification commenced by using spatial analysis techniques, node leg counting, as described in section 3.1, which initially resulted in 856 sites that are located inside the "All_Roads.shp" shapefile within the Michigan Geographic Framework (MGF) network having five or more intersection legs. Only intersections with minor road stop-control are desired for this study. The vast majority of the mulit-leg 5+ intersections (those with five or more intersecting approach legs) are located in urban areas. These often consist of boulevard transitions, where a local minor (i.e., residential) street intersects with a collector street, etc. Ultimately the urban situations are characterized by the traffic control characteristics, the driver population, and road and vehicle parameters which may distinctly differ from rural locations. Focusing on rural locations entailed erasing all of the nodes inside of Adjusted Census Urban Boundaries (ACUB) and Census Designated Place (CDP) boundaries. The ACUB boundary broadly covers urban and suburban areas where the population exceeds 5,000 persons. The decision to also exclude intersections located within CDP boundaries was made to further isolate what could truly be defined as rural multi-leg 5+ intersections. The CDP boundaries represent settled concentrations of population that may not be incorporated under the laws of the state. These boundaries "usually coincide with visible features or the boundary of an adjacent incorporated place or another legal entity boundary, have no legal status, nor do these places have officials elected to serve traditional municipal functions" [56]. The CDP boundaries quite often overlap with villages, towns, and small cities, besides other incorporated places. The characteristics of intersections inside CDP boundaries generally consists of reduced speed limits, higher potential for pedestrian activity, and proximity to population density that renders the area as urbanized from a very local perspective.

Upon filtering to sites outside of ACUB and CDP boundaries; only 89 sites remained, so rural multi-leg 5+ intersections are indeed rare.

7.1.1 Site Data Collection

The primary data element to obtain for intersection crash analysis is preeminently traffic volume, which is most likely characterized as an AADT on the major and minor roads of an intersection. Few of the 89 rural multi-leg 5+ intersection sites in Michigan have traffic volume data available; in particular, only 23 sites have a verified major road traffic volume reported by any of the available sources described in section 3.2.1. The prior MDOT Rural SPF research project excluded intersections with greater than four legs before data collection, so no prior information about these sites is available [47]. Even among sites that do have AADT values on the major road, most do not have any minor road AADT of record, not even on one remaining minor road approach. Since exposure to the unusual geometry at multi-leg 5+ intersections likely only, or most prevalently, is encountered by minor road approach traffic; then it seems quite necessary that an SPF would include exposure to both the major and minor AADT as parameters. With such a limited number of sites, and a desperate need for more detailed traffic information, the potential for robust statistical regression modeling of multi-leg 5+ intersection types is not currently feasible. Further exploration inclusive of turning movement counts should be considered to perform data collection adequate for regression modeling. In chapter 8 of this dissertation a minor road AADT estimation model is described, which may be extended for use at multi-leg 5+ intersections.

The 23 rural multi-leg 5+ intersection sites that were identified as having at least a major road traffic volume are depicted in Figure 25. Of these 23 intersections: 15 have 5-legs, and 8 have 6-legs; which is depicted in the symbology legend of the figure. Acquisition of facility characteristics was accomplished in the same manner as described in the chapter 3 of this dissertation. Crash history was matched to and summarized at each site location for 10 years of recent history (2010-2019). This time frame remains an ardent sample for pre-Covid transportation safety modeling, as the data is not affected by statewide shut-downs and executive orders of the state of Michigan Governor during the year 2020.

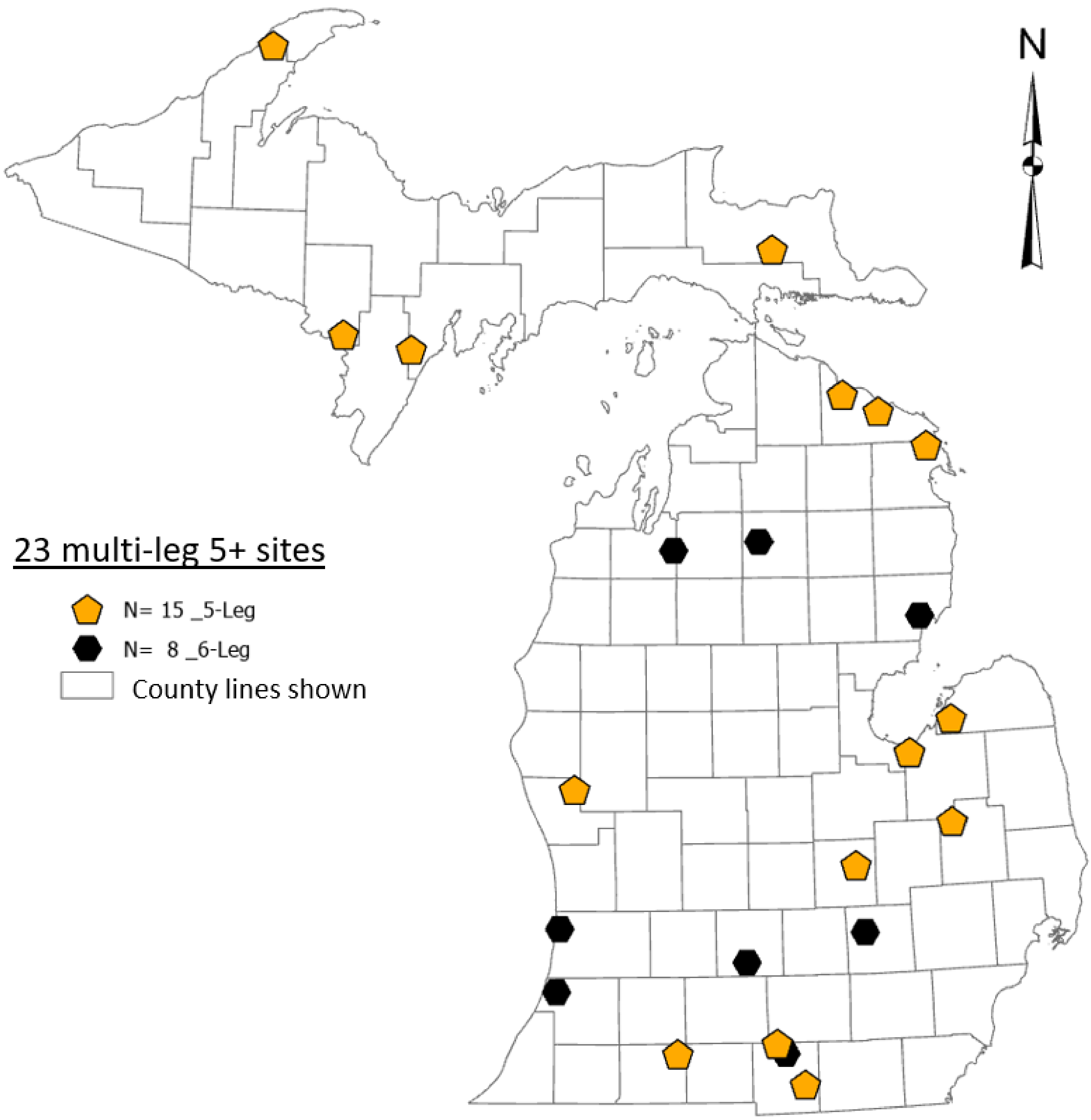

Figure 25. Geographic location of rural multi-leg 5+ minor road stop-controlled intersections in Michigan with county lines shown.

7.1.2 Descriptive Statistics

Table 17 shows the distribution of crash severity at multi-leg 5+ intersections in comparison to 1,564 previously studied four-leg intersections with and without skew, as initially described in section 6.1. The six-leg intersections are represented by 8 site locations at which a total of 100 intersection non-animal crashes occurred during the 10-year sampling period. This equates to an average crash frequency of 1.25 crashes per year. The five-leg intersections are represented by 15 site locations at which a total of 95 intersection non-animal crashes occurred during the 10-year sampling period. This equates to an average crash frequency of 0.63 crashes per year. The small sample of unique multi-leg 5+ sites have a remarkably higher average crash frequency compared to 0.53 and 0.37 crashes per year among skewed and perpendicular four-leg intersections respectively. The distribution of crashes by greatest severity indicates that five-leg intersections have a greater proportion of severe crashes than four-leg intersections. This is particularly evident if fatal and injury (i.e. KABC) crashes are combined, recognizing the rare non-occurrence of any fatal crashes at the 15 five-leg locations during the 10 years of crash history. However, although six-leg intersections have a much higher average crash frequency, those site locations experienced a lower proportion of severe crashes than other four or five-leg intersections. The distribution of collision types and severity levels is shown in Table 18 and is formatted similar to HSM tables.

Table 17. Distribution of Crash Severity for Rural Minor Road Stop-Controlled Intersection Multi-leg 5+ Study in Michigan.

Percentage of intersection crashes by greatest severity (2010-2019)				
	Multi-leg 5+		Four-leg intersections	
Crash severity level	**5-leg**	**6-leg**	**with skew**	**perpendicular**
Fatal (K)	0.0	1.0	1.4	2.0
Incapacitating injury (A)	9.5	4.0	4.2	6.6
Nonincapacitating injury (B)	14.7	6.0	11.7	12.3
Possible injury (C)	20.0	18.0	18.1	19.6
Fatal + injury (KABC)	44.2	29.0	35.4	40.4
Property damage only (PDO)	55.8	71.0	64.6	59.6
Total percentage	**100.0**	**100.0**	**100**	**100**
Total number of crashes	95	100	1,479	4,712
Total number of sites	15	8	280	1,284

Note: Each category excludes animal crashes.

Table 18. Distribution of Collision Type and Manner of Collision for Rural Minor Road Stop-Controlled Intersection Multi-leg 5+ Study in Michigan.

	Percentage of intersection crashes by collision type (2010-2019)											
	5-leg			**6-leg**			**Four-leg with skew**			**Four-leg perpendicular**		
Collision Type	**FI**	**PDO**	**Total**	**FI**	**PDO**	**Total**	**FI**	**PDO**	**Total**	**FI**	**PDO**	**Total**
Single-vehicle crashes												
Collision with bicycle	0.0	0.0	0.0	3.4	0.0	1.0	0.2	0.0	0.1	0.5	0.0	0.2
Collision with pedestrian	2.4	0.0	1.1	0.0	0.0	0.0	0.4	0.1	0.2	0.4	0.2	0.3
Overturned	4.8	5.7	5.3	6.9	2.8	4.0	4.4	2.0	2.8	3.3	2.6	2.9
Other single-vehicle crash	28.6	28.3	28.4	6.9	18.3	15.0	11.6	24.2	19.8	8.5	25.7	18.7
Total single-vehicle crash	35.8	34.0	34.7	17.2	21.1	20.0	16.6	26.3	22.9	12.7	28.5	22.1
Multiple-vehicle crashes												
Angle collision	38.2	22.8	29.3	24.1	23.9	24.0	58.8	37.3	44.8	65.1	36.7	48.2
Head-on collision	2.4	5.7	4.2	19.8	4.2	8.8	5.2	1.8	3.0	5.6	3.0	4.1
Read-end collision	14.3	18.9	15.8	28.6	40.9	37.2	13.0	18.1	16.3	9.9	17.6	14.5
Sideswipe collision	7.1	9.4	8.4	10.3	9.9	10.0	2.9	9.1	6.9	2.6	8.2	5.9
Other multiple-vehicle collision	2.1	9.3	7.5	0.0	0.0	0.0	3.5	7.4	6.1	4.1	6.0	5.2
Total multiple-vehicle collision	64.2	66.0	65.3	82.8	78.9	80.0	83.4	73.7	77.1	87.3	71.5	77.9
Total Crashes	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**	**100**

Note: Each category excludes animal crashes. FI = fatal and injury; PDO = property damage only.

7.2 Crash Data Analysis

A few situations are noteworthy in the comparison of collision types and severities. First, there is a significantly higher proportion of other single-vehicle crash types at five-leg intersections than four-leg intersections, both skewed and perpendicular. This trend of having more single-vehicle crashes was similarly observed among the other atypical intersection types: offset-T and curved corner. A second noteworthy observation is that angle collisions occur at a much lower proportion among multi-leg 5+ intersections than four-leg intersections. Since angle collisions would be considered one of the most potentially dangerous in terms of injury severity, this observation is somewhat gratifying. However, the frequency of crash occurrence at six-leg intersections is more than double that at four-leg intersections. So while the proportion of angle collisions may be lower, the frequency of angle collisions at six-leg intersections may actually be higher than four-leg intersections. Third, while the six-leg intersections have a lower proportion of angle collisions, there is a much greater proportion of other multi-vehicle crash types such as head-on, rear-end, and sideswipe collisions. A closer investigation into the type of crashes at multi-leg 5+ intersections is depicted in Figure 26, which is a frequency distribution of the crash type codes for fatal & injury crashes aggregated separately from property damage only crashes.

The most frequently observed crash type, accounting for 22 percent of the total crashes at multi-leg 5+ intersections, is fixed-object. This type of crash involves only a single motor vehicle in collision with a permanent roadside object (e.g., guardrail, tree, light post, mailbox) that is located outside of the traveled way of the road. Fixed-object collisions may result from complex or dis-beneficial roadway geometry, but may also be influenced by adverse road whether conditions. Of the fixed-object collisions observed at the multi-leg 5+ intersections in this study, 15 out of 42 (36 percent) occurred during rain, snow, or blowing snow as the defined weather condition in the crash report. Further, 18 out of 42 (43 percent) of the fixed-object collisions occurred during dark conditions, either lit or un-lighted. The circumstances of navigating a multi-leg 5+ intersection in darkness or rain and snowy weather may help to explain the abundance of fixed-object crashes.

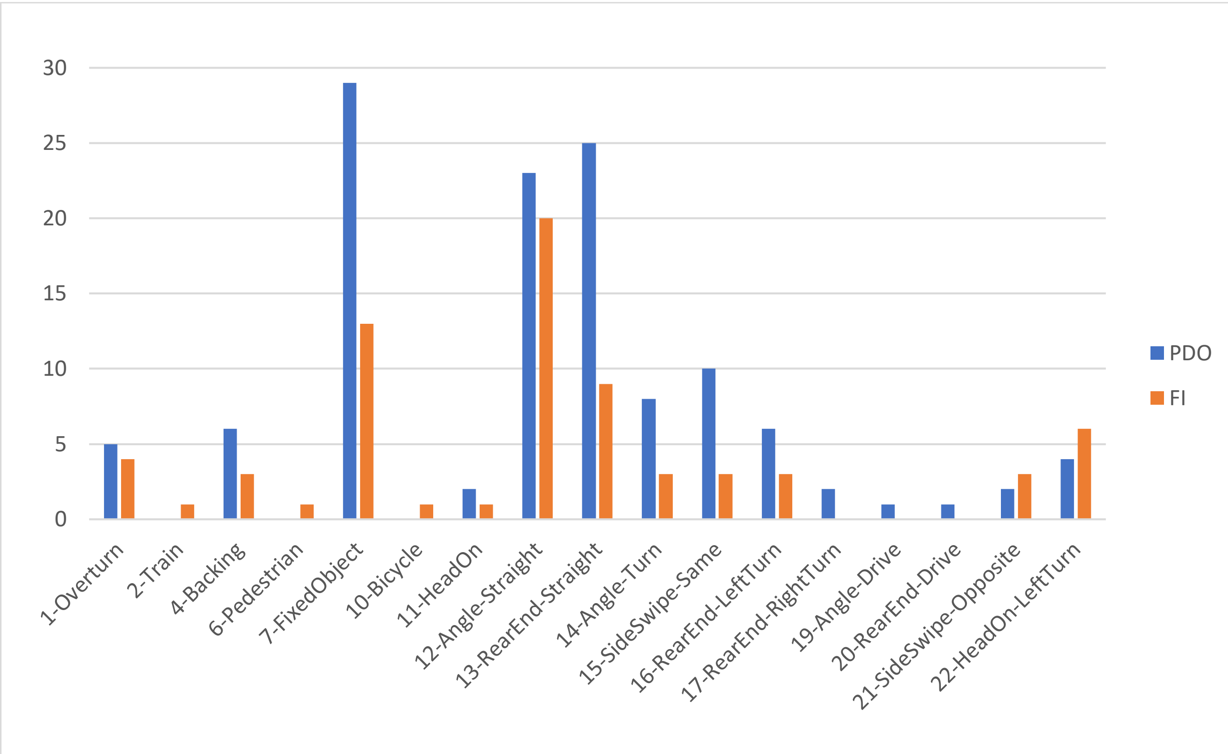

Figure 26. Crash type distribution for rural multi-leg 5+ minor road stop-controlled intersection study in Michigan.

In total, 11 out of 42 (26 percent) of the fixed-object collisions occurred at the same intersection location, depicted in Figure 27, during the 10 years of crash history. This location is one of a few sites where the major road through traffic movement is also on a curve through the multi-leg 5+ intersection. The geometry of the curve and superelevation of the major road through the intersection may be contributing factors to the preponderance of fixed-object crashes. While this location does not have turn lanes, other similar multi-leg 5+ intersections do include passing flares, turn lanes, or widened shoulders between the merged legs.

Figure 27. Example five-leg intersection in Jackson County, Michigan.

The most common multiple-vehicle crash types at multi-leg 5+ intersections are angle and rear-end collisions. These types of crashes are consistent with four-leg intersections as well. The six-leg intersections have a significantly greater proportion of rear-end crashes. The overall end to end length of the intersection vicinity at six-leg intersections is the largest, and may contribute to increased exposure to rear-end type collisions. In addition, there are more turning options available to major road traffic, which may result in rear-end collisions. Potential countermeasures to mitigate the risk of rear-end collisions include passing flares, turn lanes, or widened shoulders between the merged legs.

7.3 Conclusions and Recommendations

Several factors complicate the safety analysis of multi-leg 5+ intersections. Seven of the 23 sites (30 percent) are located in close proximity to unincorporated places. Although not located within CDP boundaries, these unincorporated places are only represented as a point location in GIS, yet have visible concentrated population and the multi-leg 5+ intersection is the central crossroad in the area. These locations are most likely to include nearby driveways, or even continuous open driveway frontage in the vicinity of the intersection often for commercial land uses. The site locations near unincorporated places may include reduced speed limit zones as well. With a confluence of differentiating characteristics and a very small sample size lacking basic traffic data, regression modeling was not feasible.

Multi-leg 5+ intersections clearly exhibit a higher crash frequency than comparable four-leg sites, but the defining characteristics are so variable that no single parameter can be attributed as the cause. The general consensus from policy guidance recommends that the minor diagonal leg is realigned to join another minor roadway approach creating two adjacent intersections. Better access management for locations with continuous driveway frontage may also help to mitigate the occurrence of crashes at multi-leg 5+ intersections. Another option for geometric improvement at multi-leg 5+ intersections is the installation of a roundabout. One instance was found in the sample where a six-leg intersection was converted to a rural roundabout; however, a more detailed before and after study is necessary to enumerate the implications of such a modification.

8.0 MINOR ROAD AADT ESTIMATION

8.1 Data Summary

Estimation of rural minor roadway traffic volumes will be more convenient for state and local agencies by utilizing simple available data sources such as Highway Performance Management System (HPMS) and census data. This investigation arose out of a desire to expand the number of sample sites available for the aforementioned atypical intersection types. The methodology to identify intersections was followed as outlined in all of the earlier chapters. In fact, the data collection for the population of rural minor road stop-controlled intersections was foundational in performing the analyses described in this dissertation. Using the intersection and roadway source data described in prior studies 4,798 rural stop-controlled intersections were identified that have both major and minor approach AADT available. The importance of a wide variety of traffic data sources is introduced in section 3.2.1 (Annual Average Daily Traffic). Traffic data was obtained from state agencies, as well as county agencies and metropolitan planning organizations. The undertaking to assemble so many sites with minor road AADT was enormous, but helped connect with local resources such as regional planning organizations and county road commissions. The geographic distribution of the study sites is shown in Figure 28. Although the data was independently collected from websites and resources, it was promptly sorted and mapped using spreadsheets and GIS mapping.

The sites are broadly distributed among all of the state's 83 counties. All of the intersections were geospatially filtered to "rural" areas using Michigan's adjusted census urban boundary shapefile. A random draw of one third (33 percent) of the population was set aside as validation sites. The remaining population (67 percent) was considered the calibration sample. The methodology is to use the calibration sample to create the model and estimate all parameter coefficients. Then only the validation sample is used to compare the performance of different model alternatives. In this manner, the validation sites are set aside and excluded from being used for model calibration. A similar method is frequently used in machine learning techniques to "train" an algorithm and then separately validate with separate data.

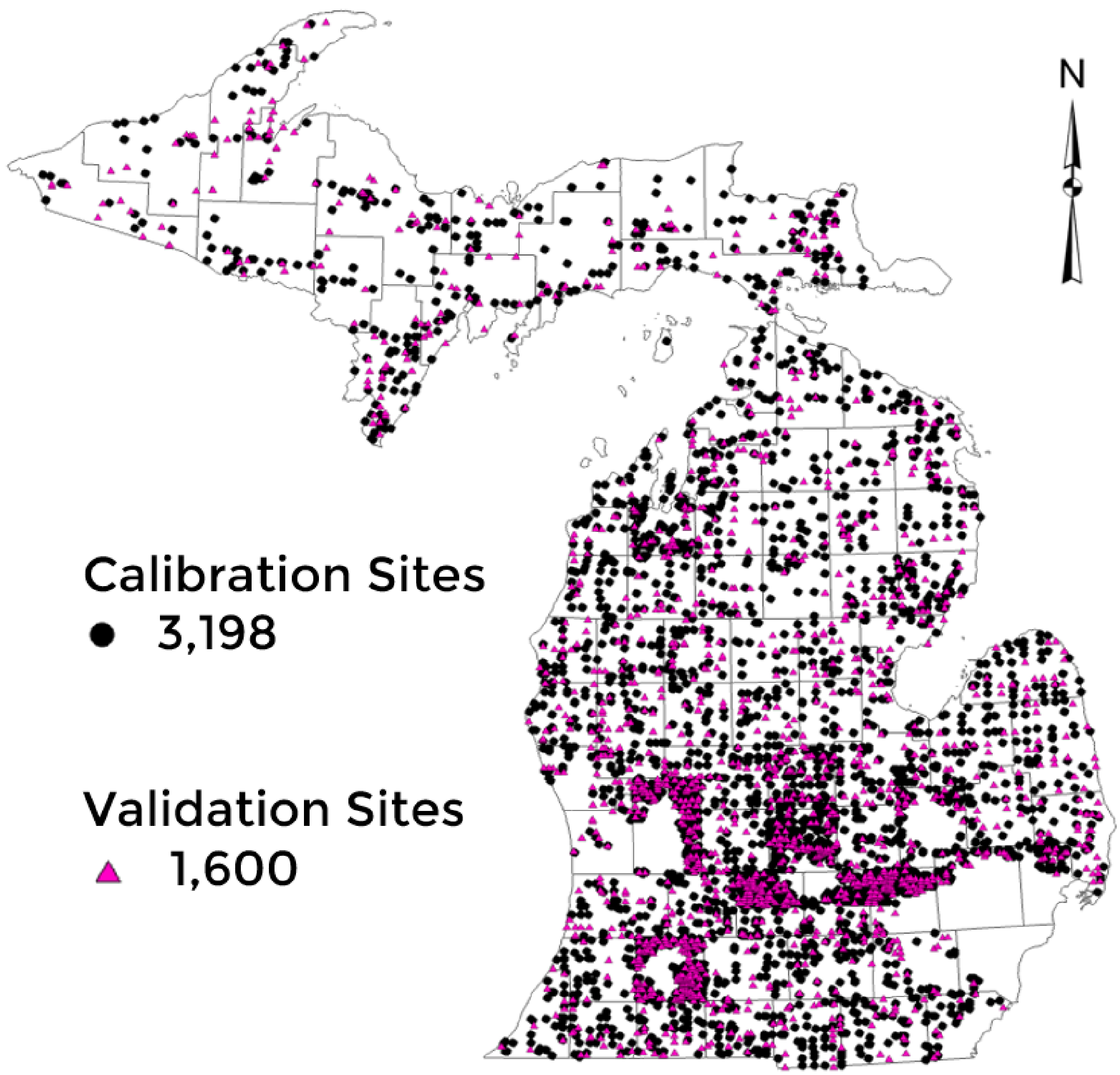

Figure 28. Geographic distribution of calibration and validation sites for minor AADT estimation of rural minor road stop-controlled intersection study in Michigan.

8.1.1 Site Data Collection

The spatial location of each site is mapped using coordinates, and the assignment of major and minor road AADT is assigned to each node. A review of AADT values was performed in order to check the assignment the major or minor approaches. Higher functional classification would generally correlate with the major road approach, as would higher AADT. Very rare circumstances may exist however, where the higher AADT road stops, or where minor road AADT is equivalent to the major road AADT. In each of these cases, aerial imagery was explored to confirm the assignment of stop-control at the intersection sites.

The AADT value has been normalized in the sample of representative sites to reflect the year 2010, which corresponds to the year of the census data. This is achieved by consistently applying growth factors to adjust all obtained traffic data to match the year 2010. The growth rates were not always positive, and were based on historic trends in annual vehicle miles traveled as reported by MDOT through Highway Performance Monitoring System (HPMS) related efforts. Table 19 shows growth factors that are computed in a spreadsheet database. Growth rates for other county non-federal aid roadways were determined based on reported annual traffic growth rates that were aggregated to the county level in various local traffic databases. In this manner, the most accurate growth factor could be applied based either on locally reported AADT trends or statewide. A logarithmic transformation is typically used for continuous variables in the estimation of models to minimize unbalanced variables such as the target estimate minor road approach AADT, and the actual major road AADT.

Table 19. Example of Traffic Growth Factors Based on Annual Vehicle Miles Traveled Trends.

Traffic Volume Data															
Move To Year		2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017
Annual VMT		101.8	103.2	104.0	104.6	100.9	95.9	97.6	94.8	94.3	95.1	93.4	97.8	99.2	99.2
Perc. Change		0.00%	1.38%	0.78%	0.58%	-3.54%	-4.96%	1.77%	-2.87%	-0.53%	0.85%	-1.79%	4.71%	1.43%	0.00%
Count Year	2004	**1.000**	1.014	1.022	1.028	0.991	0.942	0.959	0.931	0.926	0.934	0.917	0.961	0.974	0.974
	2005	0.986	**1.000**	1.008	1.014	0.978	0.929	0.946	0.919	0.914	0.922	0.905	0.948	0.961	0.961
	2006	0.979	0.992	**1.000**	1.006	0.970	0.922	0.938	0.912	0.907	0.914	0.898	0.940	0.954	0.954
	2007	0.973	0.987	0.994	**1.000**	0.965	0.917	0.933	0.906	0.902	0.909	0.893	0.935	0.948	0.948
	2008	1.009	1.023	1.031	1.037	**1.000**	0.950	0.967	0.940	0.935	0.943	0.926	0.969	0.983	0.983
	2009	1.062	1.076	1.084	1.091	1.052	**1.000**	1.018	0.989	0.983	0.992	0.974	1.020	1.034	1.034
	2010	1.043	1.057	1.066	1.072	1.034	0.983	**1.000**	0.971	0.966	0.974	0.957	1.002	1.016	1.016
	2011	1.074	1.089	1.097	1.103	1.064	1.012	1.030	**1.000**	0.995	1.003	0.985	1.032	1.046	1.046
	2012	1.080	1.094	1.103	1.109	1.070	1.017	1.035	1.005	**1.000**	1.008	0.990	1.037	1.052	1.052
	2013	1.070	1.085	1.094	1.100	1.061	1.008	1.026	0.997	0.992	**1.000**	0.982	1.028	1.043	1.043
	2014	1.090	1.105	1.113	1.120	1.080	1.027	1.045	1.015	1.010	1.018	**1.000**	1.047	1.062	1.062
	2015	1.041	1.055	1.063	1.070	1.032	0.981	0.998	0.969	0.964	0.972	0.955	**1.000**	1.014	1.014
	2016	1.026	1.040	1.048	1.054	1.017	0.967	0.984	0.956	0.951	0.959	0.942	0.986	**1.000**	1.000
	2017	1.026	1.040	1.048	1.054	1.017	0.967	0.984	0.956	0.951	0.959	0.942	0.986	1.000	**1.000**

Census tract data is matched to the node database using the 2010 Census Data [57]. Figure 29 shows an example of census tract data matched to the framework in ArcGIS. The National Functional Classification (NFC) data come from statewide framework data. Other agency specific county, non-trunkline, and trunkline segment databases each had surface type as a parameter from segment analysis conducted for statewide rural SPF research [47]. Much of the surface type information was initially populated using PASER road surface rating system data. Segments were then verified using manual inspection of aerial photography. Occurrences such as the one depicted in Figure 29 illustrate the need for careful decision making in the geoprocessing steps. It is not uncommon that roadways are used as the boundary lines for census tracts. Since an intersection site location may exist on the boundary of intersecting census tracts, the data is aggregated using summarization statistics to find the average population density, household density, and occupied household density of all tracts that the node is touching. This method of averaging was chosen because contributing population statistics could come from either direction at the intersection of the roadways. It was not feasible to ascertain weighting factors to ascribe the influence of different traffic analysis zones, because no real origin-destination level traffic information is available.

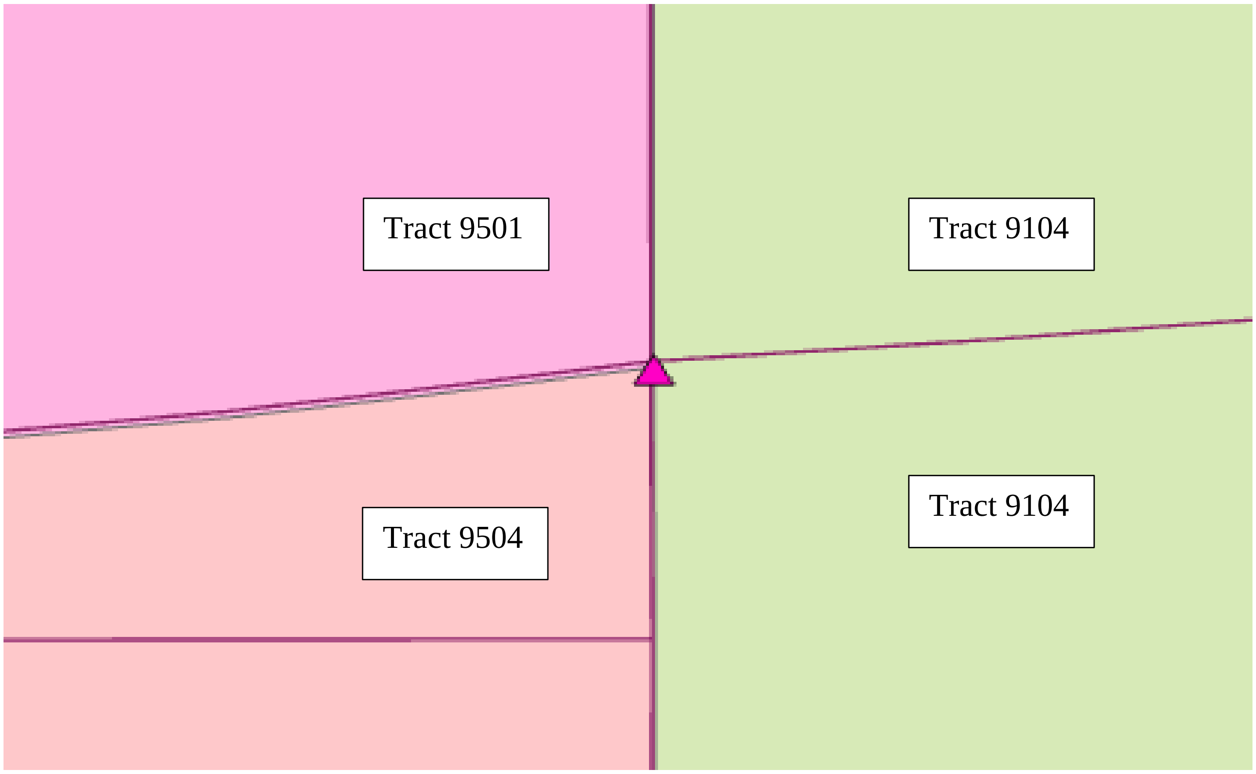

Figure 29. Example of census tract data matched to the framework in ArcGIS.

8.1.2 Descriptive Statistics

Due to the magnanimous size of the statistical sample, numerous permutations of calibration sets can be filtered by constraining major and minor road AADT ranges, or by setting geospatial filters. The resulting outcome is a customizable data set that can be used to calibrate statistically strong models that are better suited to fit the needs of specific project constraints. Table 20 shows the descriptive statistics for the total sample as well as the randomly assigned validation and calibration sub-datasets. The calibration data set consists of 3,198 sites with an average minor road AADT of 714 veh/day and a median minor road AADT of 481 veh/day. Likewise, the validation data set consists of 1,600 sites with an average minor road AADT of 706 veh/day and a median minor road AADT of 496 veh/day. Approximately 76 percent of the minor road approaches have a paved roadway surface extending beyond 250 feet from the intersection approach, and 93 percent of the major roads have a paved surface.

Table 20. Descriptive Statistics for Rural Two-lane Two-way Minor Road Stop-Controlled Intersection Study in Michigan.

Variable	Min.	25th%	50th%	75th%	Max.	Mean	SD.	Variance
Total Sample n=4,798 sites								
Major Rd AADT (veh/day)	34	831	1,839	3,680	21,113	2,635	2,560	6,553,580
Minor Rd AADT (veh/day)	26	205	485	950	6,000	711	729	530,972
Ln(Major.AADT)	4	7	8	8	10	7.39	1.08	1.17
Ln(Minor.AADT)	3	5	6	7	9	6.07	1.07	1.15
Population Density (persons/sq mile)	3	39	67	111	728	87.59	75.27	5665.19
Housing Density (units/sq mile)	3	20	31	48	339	39.46	31.82	1012.72
NFC Major	3	4	5	5	7	4.79	1.07	1.14
NFC Minor	3	5	6	7	7	5.97	1.02	1.05
NFC Major = 3	0	0	0	0	1	0.11	0.31	0.09
NFC Major = 4	0	0	0	1	1	0.26	0.44	0.19
NFC Major = 5	0	0	0	1	1	0.49	0.50	0.25
NFC Major = 6	0	0	0	0	1	0.03	0.16	0.03
NFC Major = 7	0	0	0	0	1	0.12	0.32	0.10
NFC Minor = 3	0	0	0	0	1	0.00	0.05	0.00
NFC Minor = 4	0	0	0	0	1	0.03	0.16	0.03
NFC Minor = 5	0	0	0	1	1	0.44	0.50	0.25
NFC Minor = 6	0	0	0	0	1	0.05	0.22	0.05
NFC Minor = 7	0	0	0	1	1	0.48	0.50	0.25
Major Surface Paved	0	1	1	1	1	0.93	0.25	0.06
Minor Surface Paved	0	1	1	1	1	0.76	0.43	0.18
Calibration n=3,198 sites								
Major Rd AADT (veh/day)	40	820	1,789	3,661	21,113	2,628	2,615	6,837,209
Minor Rd AADT (veh/day)	26	205	481	951	6,000	714	739	545,529
Ln(Major.AADT)	4	7	7	8	10	7.38	1.09	1.19
Ln(Minor.AADT)	3	5	6	7	9	6.07	1.08	1.16
Population Density (persons/sq mile)	3	39	68	111	728	87.56	74.37	5531.54
Housing Density (units/sq mile)	3	20	32	49	339	39.44	31.34	982.50
NFC Major	3	4	5	5	7	4.79	1.07	1.14
NFC Minor	3	5	6	7	7	5.99	1.03	1.05

Table 20. (cont'd)

Variable	Min	25th%	50th%	75th%	Max	Mean	Std Dev	Variance
Calibration sites (con't)								
NFC Major = 3	0	0	0	0	1	0.10	0.31	0.09
NFC Major = 4	0	0	0	1	1	0.27	0.44	0.20
NFC Major = 5	0	0	0	1	1	0.48	0.50	0.25
NFC Major = 6	0	0	0	0	1	0.03	0.16	0.03
NFC Major = 7	0	0	0	0	1	0.12	0.32	0.11
NFC Minor = 3	0	0	0	0	1	0.00	0.05	0.00
NFC Minor = 4	0	0	0	0	1	0.03	0.16	0.03
NFC Minor = 5	0	0	0	1	1	0.43	0.50	0.25
NFC Minor = 6	0	0	0	0	1	0.05	0.22	0.05
NFC Minor = 7	0	0	0	1	1	0.48	0.50	0.25
Major Surface Paved	0	1	1	1	1	0.93	0.26	0.07
Minor Surface Paved	0	1	1	1	1	0.76	0.43	0.18
Validation n=1,600 sites								
Major Rd AADT (veh/day)	34	850	1,948	3,726	16,863	2,647	2,447	5,990,193
Minor Rd AADT (veh/day)	26	203	496	949	5,266	706	709	502,147
Ln(Major.AADT)	4	7	8	8	10	7.42	1.07	1.14
Ln(Minor.AADT)	3	5	6	7	9	6.07	1.07	1.15
Population Density (persons/sq mile)	3	38	64	112	728	87.64	77.05	5936.01
Housing Density (units/sq mile)	3	20	31	48	324	39.52	32.77	1073.77
NFC Major	3	4	5	5	7	4.78	1.06	1.12
NFC Minor	3	5	6	7	7	5.95	1.02	1.04
NFC Major = 3	0	0	0	0	1	0.11	0.31	0.10
NFC Major = 4	0	0	0	1	1	0.26	0.44	0.19
NFC Major = 5	0	0	0	1	1	0.49	0.50	0.25
NFC Major = 6	0	0	0	0	1	0.03	0.17	0.03
NFC Major = 7	0	0	0	0	1	0.11	0.32	0.10
NFC Minor = 3	0	0	0	0	1	0.00	0.04	0.00
NFC Minor = 4	0	0	0	0	1	0.03	0.16	0.03
NFC Minor = 5	0	0	0	1	1	0.46	0.50	0.25
NFC Minor = 6	0	0	0	0	1	0.05	0.21	0.04
NFC Minor = 7	0	0	0	1	1	0.46	0.50	0.25
Major Surface Paved	0	1	1	1	1	0.93	0.25	0.06
Minor Surface Paved	0	1	1	1	1	0.77	0.42	0.18

Note: Min. = minimum; Max. = maximum; SD = standard deviation.

It can be observed from Table 20 that the distributions of the several parameters measured in the calibration and validation datasets are similar and consistent with the distribution in the total sample. Figure 30 shows a scatter plot of all the sites minor AADT vs. major AADT. It can be distinctively observed that minor AADT will very rarely exceed the major AADT. In addition, the broad distribution of minor and major AADTs illustrates the challenge in calibrating a minor road AADT estimation model. While machine learning techniques are frequently cited in the literature for the selection of parameters to include in the model, a consistent combination of parameters was often observed. In this analysis, minor road approach AADT is estimated as a function of the NFC on the minor roadway, the average population density where the intersection is located, the minor road surface type, and the major road approach AADT.

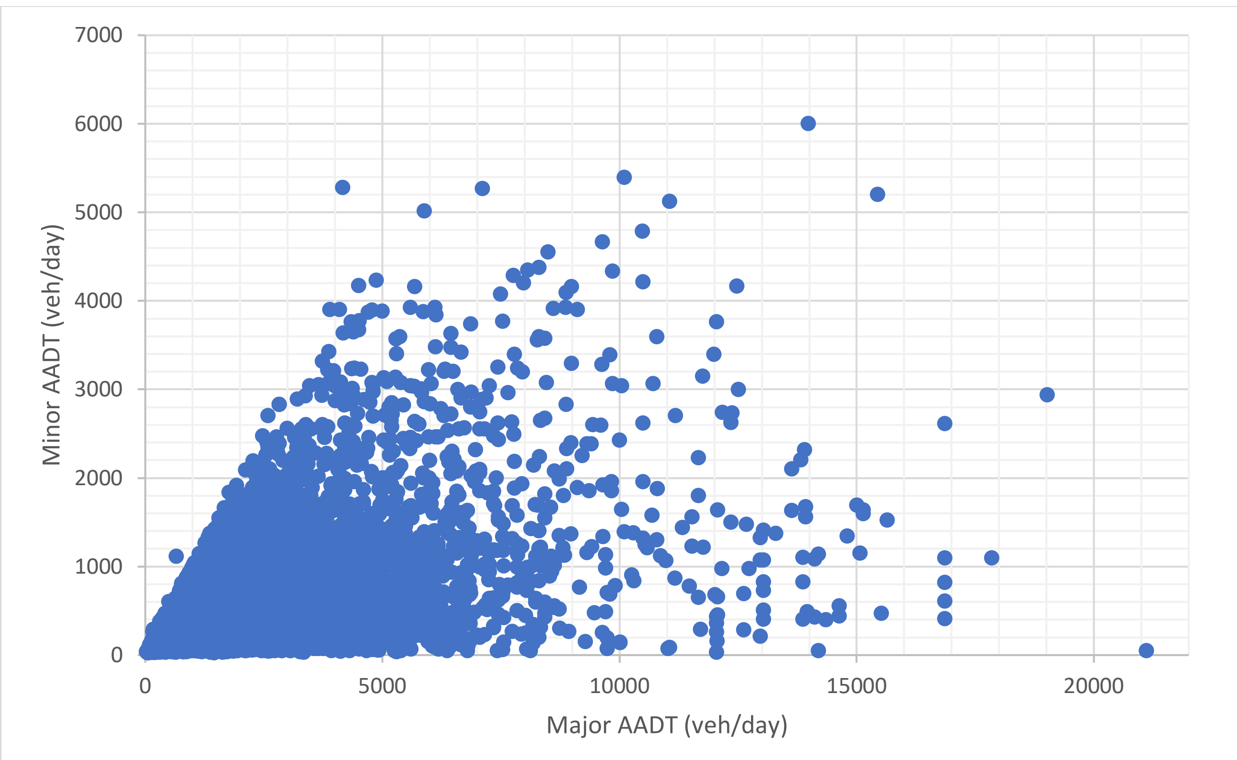

Figure 30. Scatter plot of all sample sites minor AADT vs. major AADT for rural two-lane two-way minor road stop-controlled intersection study in Michigan.

8.2 Modeling and Results

Multiple linear regression is employed under the assumption that the minor AADT can be predicted as a linear function of several independent variables and that errors from the prediction parameters are uncorrelated and normally distributed. The linear assumption is graphically inspected through various scatter plots, such as Figure 30. Models that were investigated in the literature review helped to identify socio-economic and demographic variables for similar statewide modeling applications. Using the entire calibration dataset, the minor road AADT estimation model shown in Equation 18 was developed using multiple linear regression.

$$Minor.AADT = e^{(2.34+1.63X_1+1.26X_2+0.56X_3+0.35X_4+0.90X_5+0.002X_6)} * Major.AADT^{0.349} \quad (18)$$

Where,

Minor.AADT = estimated minor road AADT (veh/day),

X_1 = binary indicator for minor road national functional class 3,

X_2 = binary indicator for minor road national functional class 4,

X_3 = binary indicator for minor road national functional class 5,

X_4 = binary indicator for minor road national functional class 6,

X_5 = binary indicator for minor road paved surface,

X_6 = average population density (people/square mile) of the census tract(s) where the intersection is located,

Major.AADT = actual major road AADT (veh/day).

The parameter coefficient estimates and test of significance results are shown in Table *21*. The model has an adjusted R-square of 0.60, which is consistent with the outcome of other multivariable AADT estimation models explored in the literature review. In this model the baseline minor road national functional class is 7, which is also very consistent with the statewide minor road sites observed in this study. One notable observation from the resulting model is that minor road surfaces that are paved have on average 145 percent more traffic than unpaved minor road surfaces. Also, a 1 percent increase in the average population density of the surrounding census tracts is directly related to a 0.2 percent increase in minor road AADT. Since population density is measured as people per square mile, it can be an effective estimator of activity of the roadway within a traffic analysis zone. However, a limitation on the use of population density should be recognized in statewide analysis because certain zones in Michigan's upper and lower peninsulas will contain a wide range from 3 to 728 people per square mile in rural areas based on the position, size, and shape of the census tracts. Household density and occupied household density were also evaluated as potential indicators; however, the population density was a more significant indicator and improved the overall fit of the model.

Table 21. Multiple Linear Regression Model Rural Two-lane Two-way Minor Road Stop-controlled Intersection Study in Michigan.

Parameter	Estimate	Std. error	p-value
Intercept (Constant)	2.336	0.085	<0.001
Minor.NFC = 3	1.630	0.261	<0.001
Minor.NFC = 4	1.263	0.077	<0.001
Minor.NFC = 5	0.559	0.029	<0.001
Minor.NFC = 6	0.348	0.055	<0.001
Minor.NFC = 7 (base condition)	-	-	-
Minor.Surface.Paved	0.897	0.033	<0.001
Minor.Surface.Unpaved (base condition)	-	-	-
Average population density (people/square mile)	0.002	0.000	<0.001
Ln(Major.AADT)	0.349	0.013	<0.001

The National Functional Classification (NFC) of the minor road was determined to be a better predictor than the NFC of the major road. The range of NFC represents a range of categories in terms of accessibly and mobility of the roadway. The service characteristics of rural roadways involves the types of vehicles, weather maintenance, load restrictions, and commercial driveway access that will be provided by the facility. Interstate and other freeway, NFC categories 1 and 2 respectively, are not part of this sample population. Within the range of rural two-lane two-way highways that are included in this study the NFC is defined as follows:

- 3 = Other Principal Arterial
- 4 = Minor Arterial
- 5 = Major Collector
- 6 = Minor Collector
- 7 = Local Road

There is a nearly direct inverse linear relationship between the parameter coefficient and the minor road NFC within the minor road AADT estimation model as shown in Figure 31. When exponentiated in the model, the sensitivity of the parameter coefficient is compared with the base condition, which in this case is a minor road approach NFC = 7 or a “local road”. This means an intersection with a minor NFC = 3, which would likely be another state trunkline or county primary route, is estimated to have 5.1x times the baseline traffic volume. Similarly, an intersection with a minor collector road (NFC = 5) is estimated to have 75 percent more traffic volume than a local road. Although the minor road surface will also correlate with the minor NFC, there is no standard, rule, or ordinance that mandates a paved vs. unpaved surface just based on the NFC. The NFC and paved surface are both indicators of the popularity of the minor road and improved the quality of fit of the model. Other significant indicators included as previously mentioned are the average population density of the census tract where the intersection is located, and the AADT of the highest major road approach.

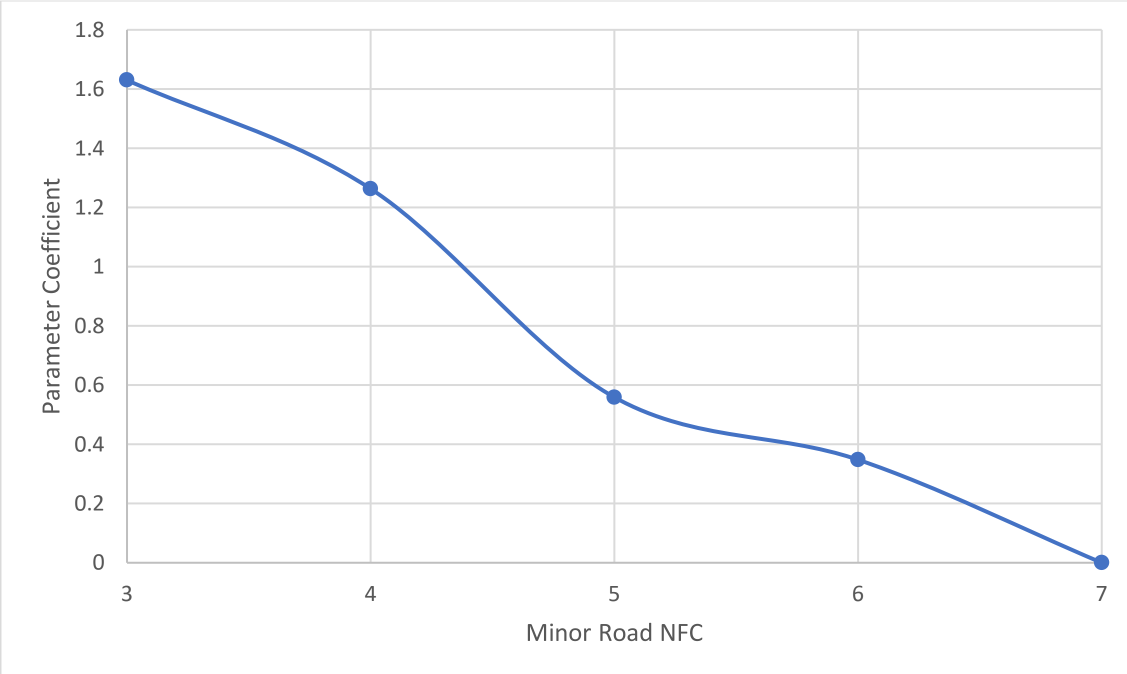

Figure 31. Parameter coefficient for minor road national functional classification (NFC) at AADT estimation of rural minor road stop-controlled intersection study in Michigan.

8.2.1 Measures of Fit

Measures of effectiveness are useful to understand the trustworthiness of a model. The coefficient of determination or R-square represents the proportion of variance for the dependent variable that is explained by the independent variables. As mentioned earlier, the adjusted R-square for the model is 0.60. While linear calibration techniques will cause the sum of squares to be minimized, a look as the residuals can be informative. Figure 32 shows a plot of the residuals of the estimated minor road AADT plotted on the vertical axis against the actual minor road AADT for the 1,600 validation sites that were randomly selected. The residual plot shows a consistent upward trend, such that beyond 2,000 veh/day actual minor road AADT the model almost always underpredicts. This underprediction at the higher ranges of minor road AADT illuminates the reason why a model should be calibrated for a constrained range of major and minor AADT ranges. Figure 33 shows a cumulative residual (CURE) plot which is constructed by sorting the actual minor road AADT values from smallest to largest before computing the residual and cumulative residual. The CURE plot initially goes negative, which indicates that the estimated AADT is overpredicted for a brief lower range. However, after approximately 700 veh/day actual AADT, the slope of the CURE plot reverses direction which indicates that the model underpredicts the estimated AADT for much of the remaining range.

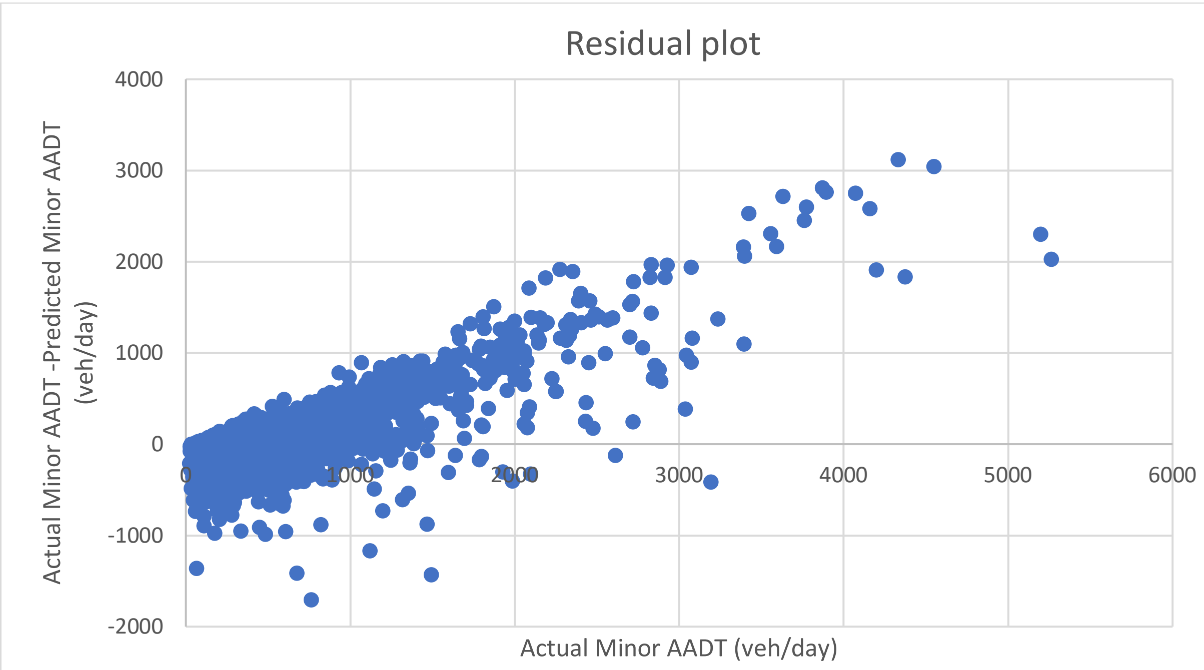

Figure 32. Residual plot for validation data set at AADT estimation of rural minor road stop-controlled intersection study in Michigan.

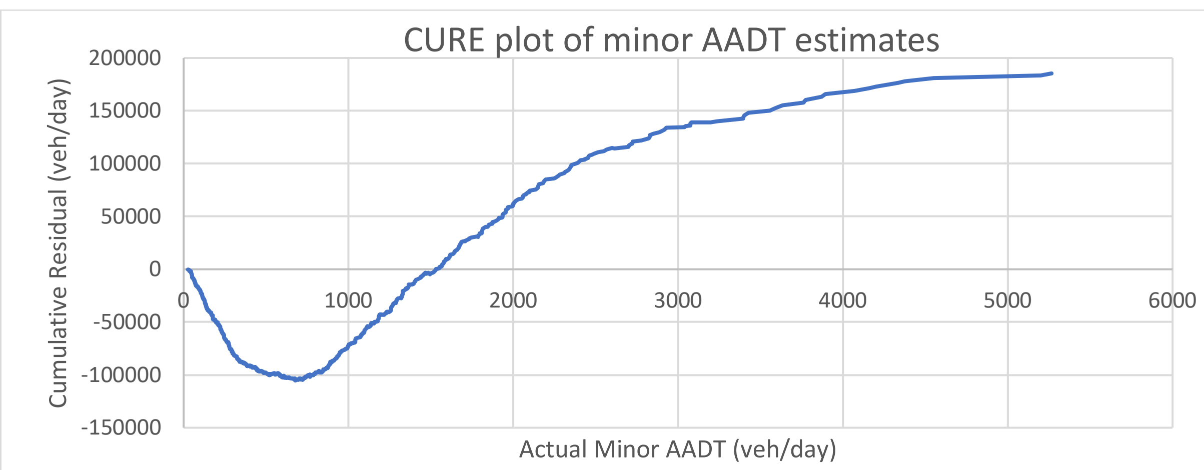

Figure 33. CURE plot for validation data set at AADT estimation of rural minor road stop-controlled intersection study in Michigan.

Another goodness of fit metric that was computed was mean absolute error (MAE), which is computed by taking the average of the absolute value of all residuals. The MAE for the validation set is 309 veh/day and can be interpreted as on average how far off the estimated minor road AADT is from the actual value. Root mean squared error (RMSE) is computed by squaring the residuals, then taking the square root of the average. The RMSE for the validation set as 506 veh/day. The RMSE has the effect of penalizing large errors. Finally, a mean absolute percent error (MAPE) was computed for the validation set as 71 percent. The MAPE is also a measure of how accurate the prediction is and is calculated as the average absolute percent error. Since the validation data set ranged from 26 to 5,266 veh/day minor road AADT and consistent underprediction was observed in the CURE plot, it is not unexpected that the prediction accuracy metrics described above are not overwhelmingly impressive.

8.2.2 Case Study

The fact that so many sites were available made possible circumstances such as mentioned in section 5.2 (Modeling and Results) as applied to curved corner intersections. Although major road AADT and minor road AADT are desired for each site; nearly three quarters of the curved corner intersection sites did not have an available minor road AADT from any data source. In this case, a minor road AADT estimation model was calibrated using a subset of 2,784 rural three-leg and four-leg intersection sites throughout Michigan. The calibration sites for the curved corner intersection minor road estimation were confined to major and minor AADT ranges that matched the population of observed or actual values. Therefore, the calibration sites had actual major road AADT less than 10,000 veh/day and actual minor road AADT less than 1,500 veh/day which aligns with the ranges of actual AADTs observed from the curved corner sites that did have sufficient traffic data. This is an example of the use of this far more extensive database for minor road AADT estimation to calibrating an equation more specific to the sample distribution. In the case of curved corner intersections, the model uses the same variables and provides different parameter estimates.

The estimated minor road AADT model using Equation 18 was applied to a case study on the 220 curved corner intersection sites that did not have a minor road AADT. Using the inputted characteristics of the curved corner sites described in section 5.2. the estimated minor road AADT value, ranges from 55 to 1,616 veh/day. The 95th percentile estimated minor road AADT is 565 veh/day; with a frequency distribution shown in the following Figure 34. Since each of the 220 curved corner intersection sites was represented in the analysis 10 times, once for each year of crash data, and since major road AADT did have variability due to traffic year adjustments, the frequency distribution represents 2,220 site-years. It is clear from Figure 34 that the vast majority of the predicted minor road AADTs are well below 800 veh/day which does well reflect the observed curved corner sites which have unquestionably very low minor road approach traffic.

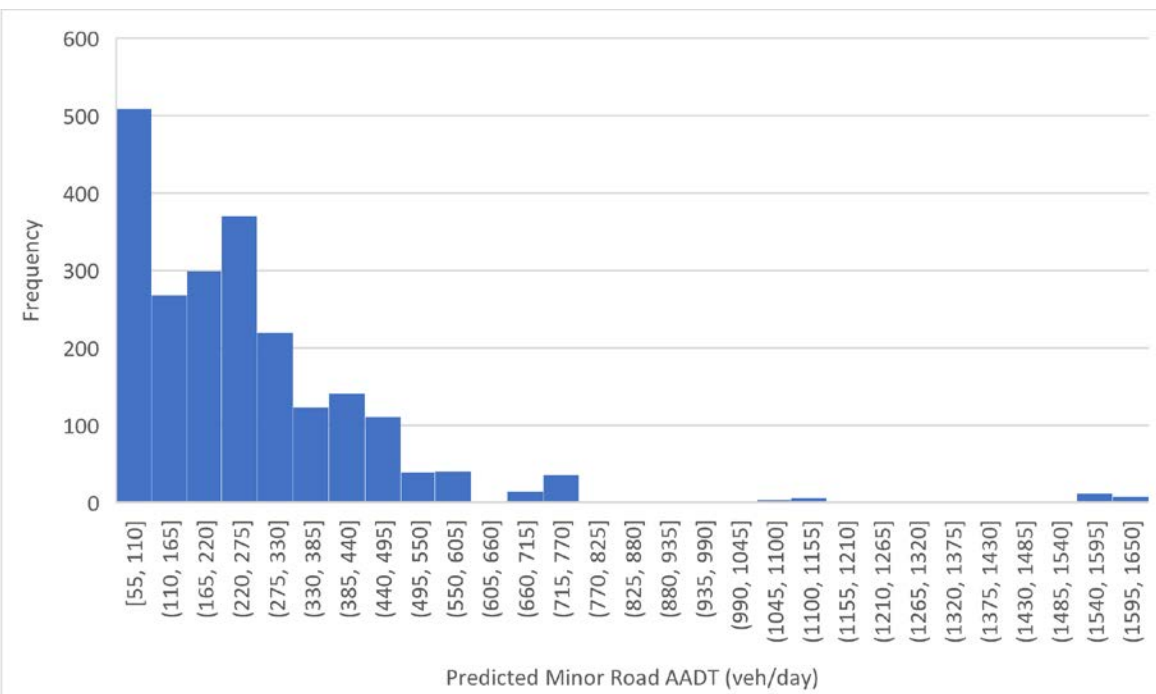

Figure 34. Frequency distribution of estimated minor road AADT for 2,200 curved corner intersection site-years.

Since one quarter, or 72, of the curved corner intersection sites did have actual minor road AADT available, these were used in validation to compute goodness of fit measures for the model. The validation set of actual minor road AADTs ranged from 28 to 4,061 veh/day with an average value of 751 veh/day. In comparison, predicted minor road AADTs for the validation set ranged from 93 to 2,409 veh/day with an average value of 441 veh/day. The MAE for the validation set is 400 veh/day, the RMSE is 675 veh/day, and the MAPE is 62 percent. Again, since the range of estimated minor road AADTs is well below 800 veh/day, a residual plot and CURE plot was investigated with attention to this range as shown in Figure 35 and 35.

Figure 35. Residual plot for case study validation of curved corner intersection sites in Michigan.

While the residual plot still shows consistent underprediction of the minor road AADT, the CURE plot indicates early overprediction up until about 350 veh/day. Prolonged horizontal runs in the CURE plot indicate ranges where the cumulative residual is not changing much, for example from 100 to 400 veh/day and again from 500 to 650 veh/day. This indicates a well performing model in those ranges, with lower residuals and absolute error than other ranges of the model. A sharp vertical decline such as around 100 veh/day indicates an area where the CURE plot is influenced by outliers, in this case overpredicting the minor road AADT by upwards of 300 percent is portrayed as a nearly vertical step in the cumulative residuals. Prolonged inclined upward runs in the CURE plot, such as from 650 to 800 veh/day, indicate areas of consistent underprediction, resulting in the accumulation of residuals. The prediction accuracy performance metrics were also evaluated on the validation set filtered just to the range of actual minor road AADT below 800 veh/day. The MAE for this range of the validation set is 137 veh/day, the RMSE is 179 veh/day, and the MAPE is 64 percent. This evaluation illustrates a much tighter and perhaps more trustworthy fit for the estimated minor road AADTs in this case study which were generally below 800 veh/day anyway.

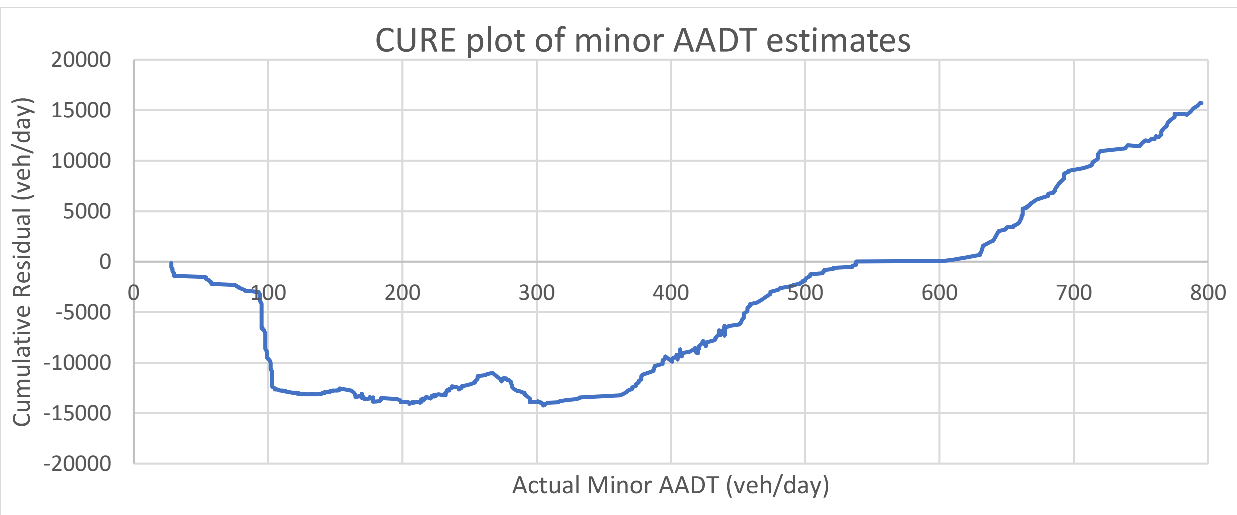

Figure 36. CURE plot for case study validation of curved corner intersection sites in Michigan.

8.3 Conclusions and Recommendations

A multiple linear regression model is developed to predict the average annual daily traffic (AADT) on minor road approaches to rural stop-controlled intersections. The highest minor approach AADT is directly related to the NFC, presence of a paved surface, the highest major approach AADT, and population density. The performance metrics used by most researchers to test the accuracy and validity of models is R-squared, MAE, RMSE, and MAPE. The initial model successfully predicts about 60 percent of the variance in the minor approach AADT. The validation set is critical to computing MAE, RMSE, and MAPE percentages.

The initial analysis can be extended to incorporate land cover, land use, or zoning indicators. Various model forms may be considered besides linear regression, even to the reaches of artificial intelligence. Other analysis ideas include stratifying the models to specific minor approach AADT ranges. The concept is that if one already knows they are estimating for a minor approach likely to be less than 500 veh/day the model is different than for higher anticipated minor approach AADTs. This appears to be a chicken and egg quandary, but actually the anticipation of some strata (e.g. low, medium, high) may already exist if not masked by the NFC and presence of paved surface. The issue also encompasses the influence of major AADT on the estimated minor AADT. There are numerous instances of high major AADT routes with very little minor AADT, yet there are also numerous instances of nearly if not equal AADT on the major and minor approaches. Stratifying the models so that they apply to specific ranges may produce discontinuities at the threshold boundaries for the models. Another future area of interest may involve methods for blending the thresholds or implementing a transition function to resolve discontinuities. Ultimately the model developed is adequate for prediction among rural routes in Michigan, but extension to other states across the nation should be approached with caution.

9.0 CONCLUSIONS

This dissertation presents the findings from an investigation into rural intersection types that are of atypical geometry, and thus, have often been excluded from roadway safety analysis and modeling efforts. Select atypical intersection configurations are, however, common enough to warrant a detailed analysis to assess the impacts of these geometric configurations on safety performance. The findings for these atypical intersection types are calibrated in the midwestern state of Michigan, USA; and should be considered in other national and international situations by applying appropriate judgement of the engineer/analyst. The objectives of this research were achieved by assembling a comprehensive data set from numerous different sources using a methodology that is repeatable for continuing updates. The safety performance of atypical intersection types was modeled using distinguishing characteristics to gain an understanding of what influences the risk of crashes and severity of selected types of crashes. A variety of analytical methods were applied, such as negative binomial regression, fixed and random effects, and multi-linear regression. Different functional forms were explored in modeling the relationships, since a monotonic increasing or decreasing functions may not adequately represent the relationships modeled. CMFs are quantified, which represent adjustments for non-base conditions.

The atypical intersection geometries evaluated in this study consist of offset-T, curved corner, highly skewed, and multi-leg with five or more intersection legs. All of the intersections studied are minor road stop-controlled, along two-lane two-way rural highways. In general, the atypical intersections pose an increased crash risk as compared to conventional three-leg and four-leg intersections. However, just as the geometry of atypical intersections is unique, their safety influence is also varied. These locations possessed a greater proportion of single-vehicle crashes which often result in less severe injuries. The influence of geographic location was also shown to impact safety performance, with locations in Michigan’s Upper Peninsula and North regions consistently experiencing lower average crash frequencies and Southeast Michigan experiencing higher average crash frequencies. Geographical and jurisdictional heterogeneity could pertain to travel patterns, driver population, and climactic differences, as well as population density, design standards, and road maintenance practices. The alignment of atypical intersections is often an artifact of boundary constraints, yet the geometry is often adapted to favor the major flow or major traffic turning movements. Majority rules, however, is not an excuse to risk motor-vehicle safety and the specific implications at atypical intersection types are described as follows.

Compared to conventional four-leg intersections, offset-T intersections exhibited 35 percent more crashes regardless of the offset distance or direction. Additionally, there were more single-vehicle crashes than comparable four-leg intersections, and this trend increases at offset-T intersections as the offset distance increased. Rear end crashes also occurred more frequency at offset-T intersections, with offsets left being more susceptible to rear-end crashes than offsets right. Offset-T intersections experienced 40 to 69 percent lower proportion of angle crashes than comparable four-leg intersections. The conversion of an offset-T intersection into a four-leg intersection is a countermeasure that could be expected to reduce crash occurrence by 26 percent. However, the tradeoff involved in converting offset-T intersections to four-leg intersections involves acceptance of higher angle crash risk, due to the accommodation of direct crossing maneuvers from the minor roadway.

At curved corner intersections, the installation of a combined/merged intersection approach (i.e. 3CM) near the midpoint of the curve is a potential countermeasure that could be expected to reduce the average intersection crash frequency by 25 to 33 percent at three-leg curved corner intersections. Among four-leg curved corner intersections, the conversion to a combined/merged intersection approach (i.e. 4CM) coincides with an expected increase in total non-animal crashes. Although this finding is counterproductive, a limitation in the sampling of 4CM sites based on the size of curve radius may warrant a broader analysis. A close investigation of curve size showed that a larger radius of curvature favorably affected the safety performance of curved corner intersections. At three-leg curved corner intersections, increasing the curve radius by 100 feet results in an estimated 5 percent fewer crashes. At four-leg curved corner intersections, increasing the curve radius by 100 feet results in an estimated 8 percent fewer crashes.

Intersection skew angle, as measured as deviance from perpendicular, presents a complex non-monotonic relationship. At three-leg intersections, a categorical model for skew angle predicts 22 percent more crashes at intersections with a skew angle between 17 to 27 degrees than conventional perpendicular T intersections. Four-leg intersections with a skew angle between 17 to 27 degrees are predicted to experience 40 percent more crashes, while intersections with a skew angle greater than 45 degrees do not have a significantly different predicted crash occurrence than perpendicular intersections. Various functional forms were considered to better model the relationship. The best fitted models suggest that at highly skewed intersections drivers have preferential intersection geometry for major and minor road traffic turning toward the direction of the obtuse angle approach. Benefits might include higher turning speed, convenience of route selection, and shorter overall travel distance. In this manner, highly skewed intersections serve their purpose in directional routing and should not be assumed to have the worst safety performance based purely on having the highest skew angle.

Multi-leg 5+ intersections experience a higher frequency of crashes than comparable four-leg intersections. This includes a greater proportion of head-on, rear-end, and sideswipe collision types, but comparably lower proportion of angle collisions than four-leg perpendicular intersections. However, with a higher overall frequency of crashes, the occurrence of angle collisions particularly at six-leg intersections may actually be higher than four-leg intersections. Traffic data at multi-leg 5+ intersections was generally lacking, and considering the very small sample size prevented the application of robust statistical modeling.

A multiple linear regression model was developed to predict the average annual daily traffic (AADT) on minor road approaches to rural stop-controlled intersections. The highest minor approach AADT is directly related to the NFC, presence of a paved surface, the highest major approach AADT, and population density. The performance metrics indicate that the initial model successfully predicts about 60 percent of the variance in the minor approach AADT. The mean absolute error (MAE) for the validation set is 309 veh/day, and the root mean squared error (RMSE) is 506 veh/day. The mean absolute percent error (MAPE) was computed for the validation set as 71 percent. With a validation data set ranging from 26 to 5,266 veh/day minor road AADT, there was a consistent underprediction of minor road AADT beyond approximately 700 veh/day actual minor AADT. The minor road AADT estimation dataset is vast and is most useful when applied to low expected minor road AADT ranges, or calibrated to a particular range or interest.

9.1 Recommendations

Rural offset-T intersections with low minor road traffic are good candidates for conversion to a four-leg conventional intersection if the cost (including right-of-way) is feasibly low. Whenever an offset-T intersection is encountered, consider that a potentially less costly alternative to mitigate the increased total and rear-end crash risk at offset-T sites is to add turn lanes, passing flares, or full width paved shoulders in the vicinity of the two intersections. This countermeasure would still maintain the benefit of reduced angle crash occurrence, which offset-Ts experience at nearly every combination of offset distance and direction.

Whenever a three-leg curved corner intersection is encountered, consider the conversion to a combined/merged (i.e. 3CM) intersection approach. Four-leg curved corner intersection types should be further studied. At any type of curved corner intersection, increasing the radius of curvature on the major route is always a good thing!

Whenever a skewed intersection is encountered with a skew angle between 17 and 27 degrees: reduce the skew angle to below 17 degrees. This simple countermeasure applies to three-leg and four-leg intersections alike. The most highly skewed intersections should be investigated using traffic turning movement counts to see if the skewed geometry actually benefits heavy directional traffic movements.

At multi-leg 5+ intersections, the general consensus from policy guidance recommends that the minor diagonal leg is realigned to join another minor roadway approach creating two adjacent intersections. The installation of a roundabout may also be considered, although a more detailed before and after analysis is necessary to enumerate the implications of such a modification.

This information documented in this dissertation should be incorporated into Interactive Highway Safety Design Model (IHSDM) and widely accepted in safety analysis. The proposed CMFs should be entered into the CMF Clearinghouse for future reference by road safety practitioners.

9.2 Future Work

This research has uncovered new possibilities and expanded capabilities to make connections between GIS, safety, highway design, and traffic engineering. As data availability and portability continues to develop, more accurate analysis of safety performance can be made at conventional and atypical intersection types. As the adoption of autonomous and semi-autonomous vehicles expands, safety performance may be steered towards what the vehicle knows or sees rather than what the driver sees. Explanations consisting of ‘cautious driver behavior’ at atypical intersections may not apply equally to autonomous vehicles. The development of a vast comprehensive GIS data set will help to inform autonomous vehicles as well as safety analysts to pursue a safer transportation future.

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