Safety Performance Functions for Rural Road Segments and Rural Intersections in Michigan

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16. Abstract
This study involved the development of safety performance functions (SPFs) for rural road segments and intersections in the state of Michigan. The facility types included two-lane and four-lane state trunklines (divided and undivided), rural county roadways (paved and gravel), signalized intersections, and minor-road stop controlled intersections. Data were compiled from several sources for thousands of rural road segments and intersections statewide. These data included traffic crashes, traffic volumes, roadway classification, geometry, cross-sectional features, and other site characteristics for the period of 2011-2015. These data were assembled into separate files based on the facility type, jurisdiction, and federal aid status. The Highway Safety Manual (HSM) base SPFs were then calibrated using the Michigan-specific data, which demonstrated significant variability in terms of the goodness-of-fit of the HSM models across various site types, due in part to the very high proportion of deer crashes on Michigan's rural highways. Consequently, Michigan-specific SPFs were estimated, including simple statewide models that considered only annual average daily traffic (AADT), as well as regionalized models that accounted for regional differences in drivers, weather, topography, and other characteristics. More detailed models were also developed, which considered additional factors such as shoulder width, driveway density, horizontal curvature, median presence, road surface type, and intersection skew. Crash modification factors (CMFs) were estimated, which are used to adjust the SPF crash estimates to account for differences related to the site characteristics. Methods for prediction of crash frequency by collision type and injury severity were also established. Depending on the facility type, this was performed either by using separate SPFs, severity distribution functions (SDFs), or crash distributions. Ultimately, the results of this study provide a number of tools that allow for proactive safety planning activities, including network screening and identification of high-risk sites. These tools have been calibrated such that they can be applied either at the statewide level or within any of MDOT's seven geographic regions to accommodate unique differences across the state. The report also documents procedures for maintaining and calibrating these SPFs over time to account for temporal changes that occur across the network.

17. Key Words
Safety performance function; SPF; intersections; segments; signalized; stop-controlled; crash modification factor; CMF; severity distribution function; SDF

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FINAL REPORT

March 31, 2018

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LIST OF ACRONYMS

3SG	Three-leg signalized
3ST	Three-leg minor leg stop-controlled
4SG	Four-leg signalized
4ST	Four-leg minor leg stop-controlled
2U	Two-lane, two-way MDOT trunkline highway segment
4U	Four-lane, two-way undivided MDOT trunkline highway segment
4D	Four-lane divided MDOT trunkline highway segment
2PF	Two-lane, two-way paved federal aid county highway segment
2PN	Two-lane, two-way paved non-federal aid county highway segment
2GN	Two-lane, two-way gravel non-federal aid county highway segment
AADT	Annual Average Daily Traffic
AASHTO	American Association of State Highway and Transportation Officials
ADA	Americans with Disabilities Act
CMF	Crash Modification Factor
DOT	Department of Transportation
EB	Empirical Bayes
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
GHSA	Governors Highway Safety Association
GIS	Geographic Information System
HSIP	Highway Safety Improvement Program
HSIS	Highway Safety Information System
HSM	Highway Safety Manual
IHSDM	Interactive Highway Safety Design Model
MAP-21	Moving Ahead for Progress in the 21st Century Act
MCGI	Michigan Center for Geographic Information
MDOT	Michigan Department of Transportation
MiGDL	Michigan Geographic Data Library
MMUCC	Model Minimum Uniform Crash Criteria
MPO	Metropolitan Planning Organization
MSP	Michigan State Police
MTA	Median Turn-Around
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
PDO	Property Damage-Only
PR	Physical Road
QA/QC	Quality Assurance/Quality Control
RAP	Research Advisory Panel
RTM	Regression to Mean
RTOR	Right Turn on Red
SDF	Severity Distribution Function
SPF	Safety Performance Function
TRB	Transportation Research Board
TWLTL	Two-way Left-Turn Lane

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EXECUTIVE SUMMARY

Study Objectives and Data Collection

This study involved the estimation of safety performance for rural highways and intersections in Michigan, including two-lane and four-lane state trunklines (divided and undivided), rural county roadways (paved and gravel), signalized intersections, and minor-road stop controlled intersections. This was accomplished through the development of safety performance functions (SPFs) to estimate the number of annual crashes at a given intersection or highway segment, crash modification factors to determine the impacts associated with various roadway and geometric characteristics, and severity distribution functions to predict the crash severity. The development of such models required the compilation of data from across numerous sources for thousands of road segments and intersections statewide. These data included traffic crashes, traffic volumes, roadway classification, geometry, cross-sectional features, and other site characteristics. The primary data sources included:

- Michigan State Police statewide crash database (2011 - 2015),
- MDOT trunkline sufficiency file,
- Michigan Geographic Data Library All Roads shapefile,
- Census boundary shapefile,
- MDOT trunkline signals shapefile,
- MDOT trunkline driveway count file,
- MSU horizontal curve database, and
- Google Earth for manual measurement, where necessary.

In general, data were collected for each facility type across all counties and regions of Michigan, assuming such roadways facilities were present. However, for county road segments, which involved extensive manual collection of data, a statewide analysis was infeasible given the lack of data within certain counties along with project time and resource constraints. Therefore, county road segment data were collected across a sample of 30 counties representing all regions of Michigan. Furthermore, due to the small number of rural signalized intersections statewide, signalized intersections located in a census designated place (CDP) of population less than 5,000 were retained in the sample. The data were assembled into separate files based on the facility type, jurisdiction, and federal aid status, with the number of samples presented in the list that follows:

- Rural segments
    - Two-lane MDOT trunkline - 1556 segments, 5352 miles
    - Four-lane undivided MDOT trunkline - 58 segments, 95 miles
    - Four-lane divided MDOT trunkline - 55 segments, 107 miles
    - Two-lane paved federal aid county - 9912 segments, 4424 miles
    - Two-lane paved non-federal aid county - 2873 segments, 1463 miles
    - Two-lane gravel non-federal aid county - 3983 segments, 2007 miles
- Rural stop controlled intersections
    - Three-leg stop control - 2297 sites
    - Four-leg stop control - 2513 sites
- Rural signal controlled intersections
    - Three-leg signalized - 19 sites
    - Four-leg signalized - 175 sites

Data Analysis

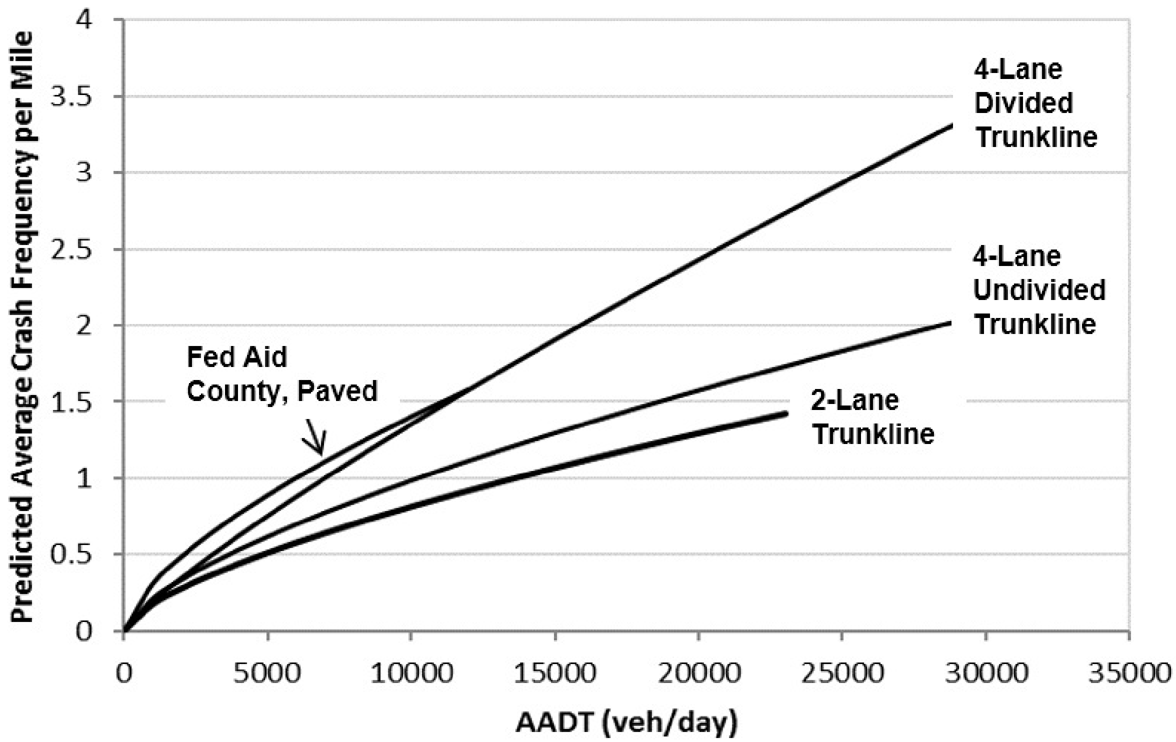
After the data were assembled for rural road segments and intersections in Michigan, a series of preliminary data analyses were conducted to identify general crash trends across each of the facility types. Calibration factors were generated for each corresponding *Highway Safety Manual* (*HSM*) model using the 2011-2015 Michigan crash data for the respective segment and intersection facility type. It was discovered that Michigan rural highway crash data, particularly for segments, contained an overwhelming proportion of deer crashes. This was especially evident in comparison to the crash data used in development of the *HSM* rural highway models, which showed far lower proportions of animal crashes. This caused the base SPFs from the *HSM* to have calibration factors that typically exceeded 1.0 when applied to the Michigan data for each facility type, leading to the conclusion that the *HSM* generally under predicts total crashes on Michigan rural highways. However, removal of deer crashes caused many of the calibration factors to fall below 1.0, suggesting over prediction of Michigan non-deer crashes by the *HSM*. Furthermore, the *HSM* models generally tended to over-predict crashes at stop-controlled intersections, but under-predict crashes at signalized intersections. It was concluded that the *HSM* models display significant variability in terms of the goodness-of-fit across the various rural facility types in Michigan.

To address the shortcomings associated with the calibrated *HSM* models, a series of SPFs were developed using the Michigan-specific data. A series of simple general statewide models were initially developed using average annual daily traffic volumes (AADT) along with regional indicators to account for unobserved differences in drivers, weather, and topography between the various regions of Michigan. Separate models were generated for injury crashes (including fatalities) and property damage only crashes within each of the facility types. Additionally, the roadway segment models were generated both with and without deer-involved crashes.

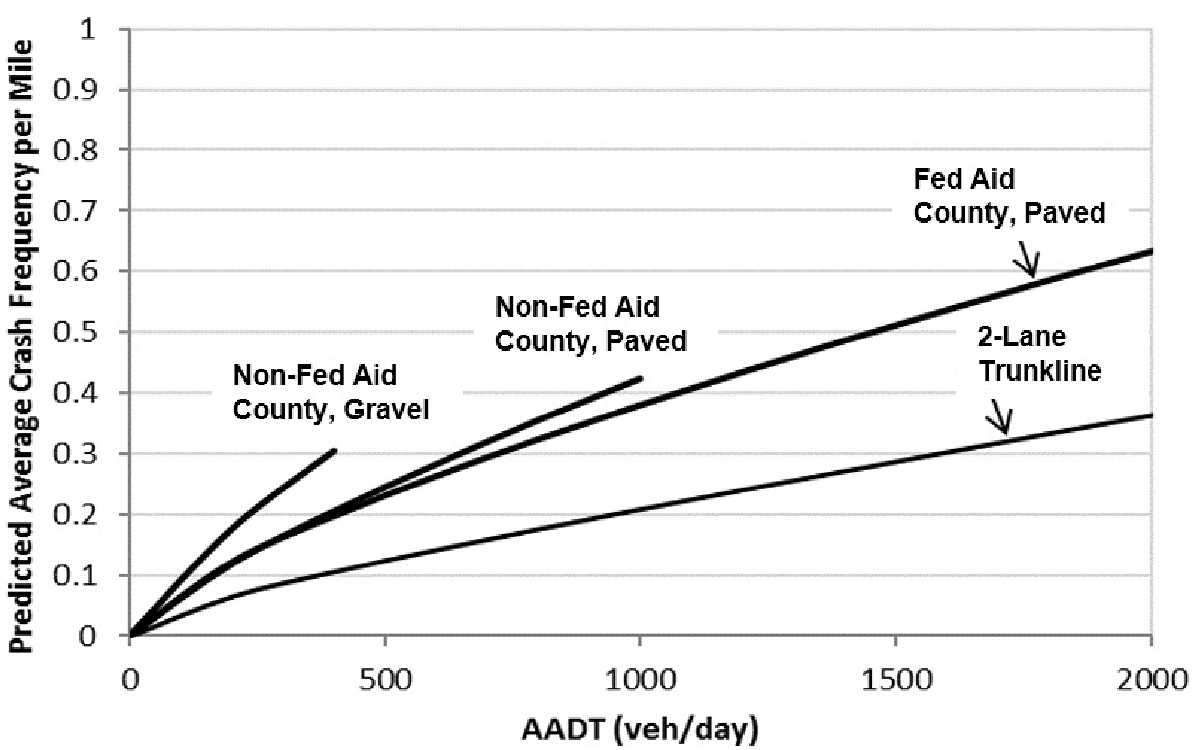
However, in order to provide the greatest degree of crash prediction accuracy, detailed Michigan-specific SPFs were estimated for each rural facility type based on AADT and MDOT region, along with numerous additional roadway related factors. For rural segments, these additional factors included lane width, shoulder width, horizontal curvature, terrain, passing zones, median presence, surface type, and driveway density. For rural intersections, these additional factors included driveways counts, lighting presence, turn lane presence, and intersection skew. To improve the predictive capabilities of the roadway related variables, deer-involved crashes were excluded from the fully-specified rural segment models. Methods for prediction of crash frequency by crash type (i.e., rear-end, head on, angle, run-off-road, etc.) and injury severity were also established. Depending on the facility type, this was performed by using either separate SPFs, severity distribution functions (SDFs), or crash distributions.

Discussion of Results

Comparison of the base SPFs across a common range of traffic volumes for the various rural facility types showed several interesting findings. First, comparison of the rural trunkline road segment SPFs showed four-lane divided trunklines to possess greater rates of single-vehicle midblock crashes compared to four-lane undivided and two-lane trunklines, although little difference was observed in the multi-vehicle midblock crash rates across the three facilities types (2U, 4U, 4D). Turning to the two-lane road segments SPFs, paved county roadways (federal aid and non-federal aid) showed approximately double the midblock crash occurrence rate of trunklines. However, gravel county roadways showed a substantially greater midblock crash occurrence rate than paved county roadways. These findings are reflected in the figures that follow.

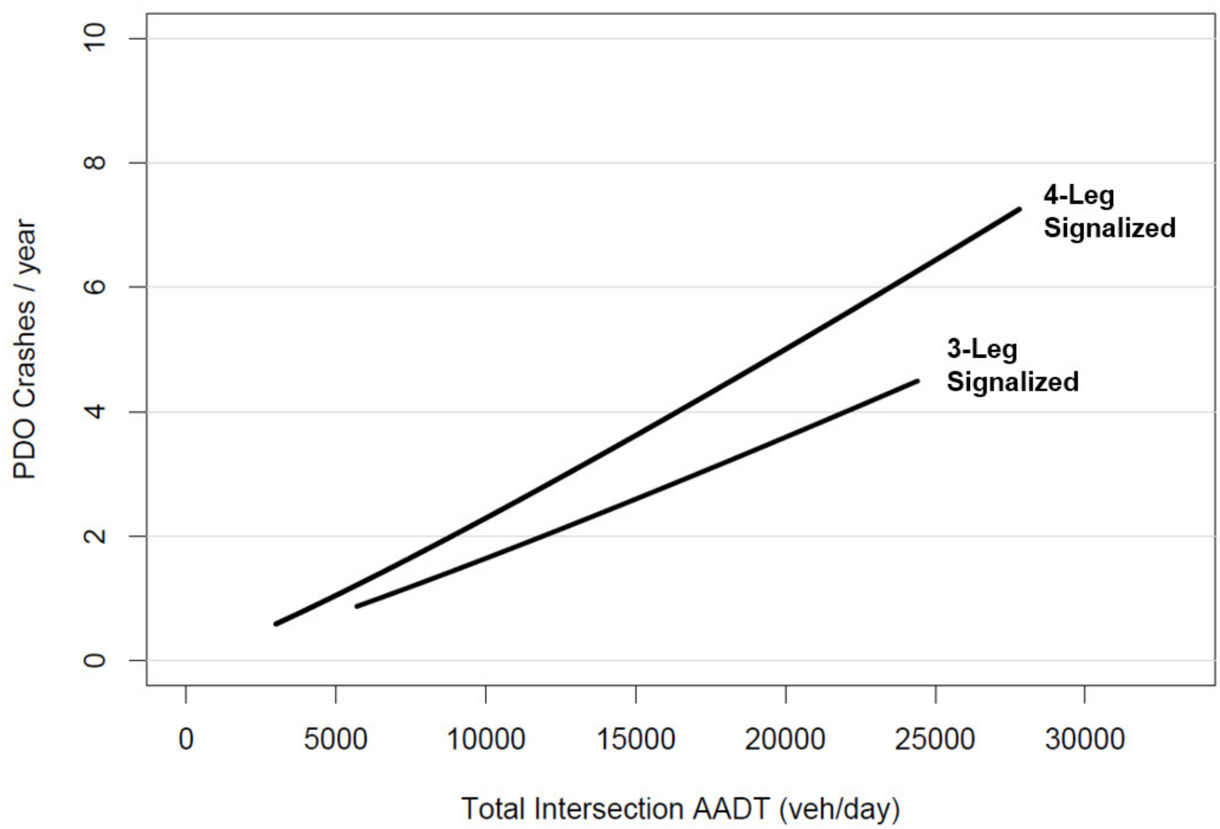


Comparison of Single Vehicle Midblock Crashes (Non-Deer) on Rural Federal Aid Segments



Comparison of Total Midblock Crashes (Non-Deer) on Rural Two-Lane Segments

Turning to comparison of the base intersection SPFs, although the relatively small sample of rural signalized intersections limited the capabilities of the analysis, it was determined that signalized intersections with three legs possessed lower crash occurrence than those with four legs. These findings for property damage crashes are reflected in the following figure. Furthermore, signalized intersections falling within a census designated place had fewer injury crashes than locations outside of a CDP, likely due to the lower speed limits that typically exist within CDPs. Similar to signalized intersections, three-leg stop-controlled intersections also had lower crash occurrence rates than four-leg stop-controlled intersections.



Comparison of Property Damage Crashes at Rural Signalized Intersections

Michigan-specific crash modification factors (CMFs) were also developed, which are used to adjust the crash estimate from the SPF when the characteristics of a particular segment or intersection are not consistent with the base conditions. For segments, it was found that wider paved shoulders are associated with fewer crashes and less severe crashes across all applicable rural segments types. Interestingly, lane width did not have a significant impact on crash occurrence on trunklines or federal aid county roadways, although narrow non-federal aid county roadways (i.e., traveled way less than 18 feet) showed greater crash occurrence and more severe crashes. Increased driveway density was associated with increased crash occurrence, although this effect was more pronounced on trunkline segments. Lastly, an increase in the amount of horizontal curvature on the segment was associated with increases in crash occurrence and crash severity across all rural segment types. Considering four-leg intersections with stop control on the minor roadway, skew angles of greater than 10 degrees were found to increase crash occurrence, particularly for property damage crashes. Furthermore, such intersections with more than two driveways within a 211 ft (0.04 mile) radius of the intersection were also found to have greater crash occurrence and more severe crashes.

Conclusions

The rural road segment and intersection models developed herein will be of great use to transportation professionals, as Michigan-specific SPFs were previously limited to urban segments and intersections. Particularly noteworthy is the inclusion of models specific to county-maintained facilities, as these facilities tend to have lower design standards, lower traffic volumes, and a greater proportion of highly familiar drivers. Furthermore, the non-federal aid models contained in this report were based on data that included gravel roads, for which SPFs and CMFs had not been previously developed, thereby allowing for comparison of the safety performance characteristics between gravel and paved county roadways of similar classification.

Ultimately, the results of this study provide a number of methodological tools that will allow for proactive safety planning activities, including network screening and identification of high-risk sites. These tools have been calibrated such that they can be applied either at the statewide level or within any of MDOT's seven geographic regions, providing additional flexibility to accommodate unique differences across the state. This report also documents procedures for maintaining and calibrating the Michigan-specific SPFs over time. Calibration will allow MDOT to account for changes that occur with time that are not directly reflected by the predictor variables.

1.0 INTRODUCTION

The *Moving Ahead for Progress in the 21st Century Act* (*MAP-21*) required all states to have in place a Highway Safety Improvement Program (HSIP) that "emphasizes a data-driven, strategic approach to improving highway safety on all public roads that focuses on performance" (MAP-21, 2012). Given the prevailing focus on implementing roadway safety practices that are data-driven, recent research has focused on gaining a more thorough understanding of how various factors affect the frequency, type, and severity of traffic crashes at specific roadway sites, such as intersections. Gaining a better understanding of these complex relationships provides traffic safety professionals with the ability to develop better-informed, targeted policies and programs to reduce traffic crashes and the resultant injuries and fatalities.

An important tool in this process is the American Association of State Highway and Transportation Officials (AASHTO) *Highway Safety Manual* (*HSM*) (AASHTO, 2010). Part C of the *HSM* provides a series of predictive models that can be utilized to estimate the frequency of traffic crashes on specific road facilities as a function of traffic volumes, roadway geometry, type of traffic control, and other factors. These models, referred to as safety performance functions (SPFs), are useful for estimating the safety impacts of site-specific design alternatives or for prioritizing candidate locations for safety improvements on a network basis. As a part of this process, these SPFs can also be integrated with decision support tools, such as *Safety Analyst* and the *Interactive Highway Safety Design Model* (*IHSDM*). For example, the Crash Prediction Module (CPM) in the *IHSDM* allows users to estimate the expected crash frequency and severity for a selected project site, the procedures for which closely follow the process described in Chapters 10 and 11 of the *HSM* for rural two-lane two-way and multilane highways, respectively.

While the SPFs presented in the *HSM* provide a useful tool for road agencies, it is recommended that these functions are either calibrated or re-estimated using local data to improve their accuracy and precision (AASHTO, 2010). A variety of states have conducted research to this end, including Colorado, Florida, Georgia, Illinois, Kansas, North Carolina, Oregon, Utah, and Virginia. Collectively, these studies have shown the accuracy of the SPFs from the *HSM* vary considerably from state to state, a result that may be reflective of differences in geography, design practices, driver behavior, weather, crash reporting requirements, or other factors.

This study involves the estimation of SPFs for rural trunkline and non-trunkline segments and intersections throughout Michigan. These SPFs were developed using a robust database, which combines information from the MDOT Sufficiency File, the Michigan State Police (MSP) crash database, and field data from select locations. In addition to the SPFs, modifications to MDOT's *HSM* spreadsheet tool were also proposed. Ultimately, the decision-support tools derived from this research will allow MDOT to more efficiently allocate available resources, perform more effective network surveillance, and make data-driven design decisions.

1.1 Background

The first edition of the *HSM* includes separate families of SPFs (segments and intersections) for three specific facility types: (1) Rural Two-Lane, Two-Way Roads; (2) Rural Multilane Highways; and (3) Urban and Suburban Arterials. Chapters 10, 11, and 12 of the *HSM* provide full details of the SPFs for these respective facility types, which were developed based upon the results of empirical studies. Subsequent research that will be integrated into the second edition of the *HSM* has analyzed other facility types, which include freeways and interchanges, as well as six-lane and one-way urban and suburban arterials.

Within each facility type, separate SPFs have been developed for intersections and road segments. For each location type, these SPFs can be used to estimate the total number of crashes expected during a given time period (typically one-year) under "base" conditions. Similar to the nomenclature from the *Highway Capacity Manual*, these base conditions generally refer to roadways with typical design characteristics (e.g., 12-ft lane widths). The *HSM* SPFs have been statistically estimated such that any variation from these base conditions is then captured in the form of crash modification factors (CMFs), which provide an estimate of the change in predicted crash frequency that would correspond to specific changes in these baseline conditions (e.g., increasing shoulder width). The "base" SPFs provided in the *HSM* have been developed using data from the *Highway Safety Information System* (*HSIS)*. Four separate models have been developed for rural two-lane highways and five separate models have been developed for rural multilane highways, which are described as follows:

- Chapter 10 - Rural Two-Lane Two Way
    - Segments (2U)
    - Unsignalized three-leg intersections (stop control on minor approach) (3ST)
    - Unsignalized four-leg intersections (stop control on minor approaches) (4ST)
    - Signalized four-leg (4SG)
- Chapter 11 - Rural Multilane
    - Rural four-lane undivided segments (4U)
    - Rural four-lane divided segments (4D)
    - Unsignalized three-leg intersections (stop control on minor approach) (3ST)
    - Unsignalized four-leg intersections (stop control on minor approaches) (4ST)
    - Signalized four-leg (4SG)

It should be noted, however, that these models were developed and validated using data for only four states: Washington, California, Minnesota, and Texas. 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. Since the publication of the *HSM*, recent studies have involved the analysis of local data from numerous states. Collectively, these studies have indicated that direct application of the *HSM* SPFs does not typically provide accurate results without calibration or re-estimation using local data. These findings provide motivation for the development of SPFs that are unique to Michigan's rural segments and intersections.

In addition to providing tools to predict the total number of crashes for a given facility, the *HSM* also presents methods for estimating crashes by type and injury severity level. The ability to provide estimates at this disaggregate level is important for several reasons. First, specific safety treatments often have differential effects on crashes by type. For example, the installation of a traffic signal may decrease the frequency of certain crash types (e.g., angle collisions) while increasing other types (e.g., rear-end collisions). Consequently, if reliable estimates are available at the crash type level, road agencies will be able to more precisely estimate potential cost savings that coincide with implementation of a specific treatment. Additionally, the provision of crash estimates by severity level is similarly important since safety treatments are generally given higher priority at those locations that are prone to more severe crashes due to the higher societal costs involved with the resultant injuries and fatalities.

Beyond the statistical issues involved with SPF development, it must be noted that the *HSM* "is written for practitioners at the state, county, metropolitan planning organization (MPO), or local level" (AAHSTO, 2010). This is important to recognize because it is imperative that a balance is struck between the accuracy of a model and its usefulness to practitioners. With that in mind, the *HSM* considers three distinct approaches to disaggregate level crash estimation:

1. In Chapters 10 and 11, the total expected number of crashes are estimated for each location. These totals are then disaggregated based upon aggregate-level proportions provided by default collision type and crash severity distributions.
2. In Chapter 12, separate SPFs are provided to estimate the total expected number of crashes by aggregate crash type (e.g., single- and multi-vehicle, pedestrian, and bicycle-involved). Separate SPFs are also provided for fatal-and-injury (FI) crashes and property-damage-only (PDO) crashes. Chapter 11 of the *HSM* also presents separate SPFs for FI and PDO crashes.
3. More recently, *National Cooperative Highway Research Program (NCHRP) 17-45* (Bonneson et al., 2012) has utilized a third approach, which involves the estimation of the total expected number of crashes for each location. In addition to this estimate, the proportions of crashes by collision type and severity level are also estimated as a function of traffic volumes and road segment characteristics using discrete outcome models. The results of this two-step process are then combined to determine the expected number of crashes at each site by type and severity.

1.2 Study Objectives

This research aims to develop a uniform, consistent approach that can be applied to estimate the safety performance of rural intersections and segments at the aggregate (i.e., total crash) level, as well as to within specific crash types and crash severity categories. The study results provide important guidance to allow MDOT to make informed decisions as to planning and programming decisions for safety projects. The specific objectives of this study are as follows:

1. Review and summarize previous and existing efforts to generate safety performance functions for agencies.
2. Identify sites for the following rural segment and intersection types:
    a. Rural Trunkline Two-Lane Two-Way (2U)

b. Rural Trunkline Four-Lane Undivided (4U)
c. Rural Trunkline Four-Lane Divided (4D)
d. Rural County Two-Lane Two-Way Paved Federal Aid (2PF)
e. Rural County Two-Lane Two-Way Paved Non-Federal Aid (2PN)
f. Rural County Gravel Non-Federal Aid (2GN)
g. Rural Three-Leg Stop Control (3ST)
h. Rural Three-Leg Signalized (3SG)
i. Rural Four-Leg Stop Control (4ST)
j. Rural Four-Leg Signalized (4SG)

3. Develop SPFs for each of the rural segment and intersection types listed above.
4. Define a maintenance cycle and process for updating SPFs.

1.3 Report Structure

This report documents the activities involved in the development of SPFs and CMFs for rural intersections and segments in Michigan. The report is divided into seven chapters. Chapter 2 provides a summary of the state-of-the-art research literature. Chapter 3 describes the data collection process, including details of the data sources and activities involved in database development. Chapter 4 provides a preliminary visual analysis of the data, as well as a brief summary of the statistical methods utilized as a part of this study, and calibration of base models. Chapter 5 presents simple AADT only SPFs and AADT plus regional indicator SPFs for each facility type. Chapters 6 and 7 present fully specified SPFs, CMFs, and severity density functions for segment and intersection facilities, respectively. Chapter 8 discusses calibration and maintenance processes for updating the SPFs over time, as well as provides a demonstration of how crash frequency can be estimated for a given facility. Conclusions and directions for future research are discussed in Chapter 9.

2.0 LITERATURE REVIEW

In the past, the transportation community has used various methods to identify and prioritize sites with potential for safety improvement and select proper countermeasures to achieve that goal. Ranking sites by crash frequency, crash severity, or crash rate are among the most widely used approaches for screening candidate locations. Despite their ample use, several of such methods and their variations have important drawbacks. As far back as 1982, Barbaresso et al. described a ranking process for site selection employed by the Oakland County Road Commission (OCRC) in Michigan, which at the time was an early adopter of safety as its number one priority. The authors recognized that considering only crash frequency tends to favor sites with high traffic volumes while using crash rates tends to favor sites with low traffic volumes (Barbaresso, Bair, Mann, & Smith, 1982). A ranking matrix in effect considered both measures simultaneously in an effort to sort priority sites. However, these methods of site selection are reactionary because they rely on established history of crashes only. More recently, proactive procedures and tools have been developed in order to identify sites potentially before incidents occur.

Hauer et al. have shown that the identification of sites with potential for safety improvement can be an expensive task (Hauer, Kononov, Allery, & Griffith, 2002). Furthermore, suboptimal decisions would add unnecessary costs and result in little or no safety benefit. Time, energy and resources may be wasted as the result of identifying sites with limited potential for safety improvement, or failing to identify sites with the most potential for improvement.

Data-driven screening methods have become widely available with the introduction of the *HSM* (AASHTO, 2010) and the HSIP manual (Herbel, Laing, & McGovern, 2010). These documents provide tools to identify and prioritize sites with potential for improvement, sites that have historically shown more crashes than expected, as guidance on the selection of appropriate countermeasures for safety improvement of those sites.

The goal of this literature review is to present the characteristics of existing safety performance functions developed for assessing the safety performance of rural intersections and segments. These SPFs can be used for identifying and ranking hazardous sites in order to implement countermeasures. The review also includes a discussion of crash modification factors, which characterize how factors, such as geometric and operational variables, relate to the risk of crashes on these facilities.

2.1 Overview of the *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* (AASHTO, 2010).

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

$$N = N_0 \times C \times \prod CMF \qquad (1)$$

Where,

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

2.1.1 Base SPF (N_0)

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 (Harwood, Council, Hauer, Hughes, & Vogt., 2000).

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.

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

Where,

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

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

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

Where,

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

Care needs to be taken when adding variables to avoid overfitting the SPF. The more complex models are often poorer predictors, only accurately predicting crashes on the segments that were used to estimate its parameters, as a lot of noise tends to be incorrectly included as systematic variation in crashes. To avoid this pitfall, researchers Srinivasan, Carter and Bauer, (2013b) suggested using backward elimination in the well documented stepwise model selection process in statistical analysis (Venables & Ripley, 2002). This method identifies significant variables by a stepwise regression approach, including all variables, then eliminating each separately, to determine if each variable significantly degrades the information given by the model.

2.1.2 Crash Modification Factors (CMFs)

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

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

Chapters 10 and 11, Part C of the *HSM* present a set of CMFs for rural segments (two-lane and multilane) and rural intersections. Additional CMFs can also be found the Federal Highway Administration (FHWA) CMF Clearinghouse (University of North Carolina Safety Research Center, 2017). 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 (Wu, Lord, & Zou, 2015). Although it is common practice to estimate the combined effect of multiple CMFs by multiplying the individual CMFs together, this practice relies on the assumption of independence between CMFs. However, that assumption is not necessarily true in every case, and the result could be a significant overestimation or underestimation of the combined effect (Avelar, Dixon, & McDaniel, 2016).

2.1.3 Calibration Factors (C)

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 (2013) found that, on a project level, the development of a typical SPF can take 450-1,050 staff hours, whereas calibration requires only 24-40 staff hours for data collection and preparation. 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, such as: climate, criteria for reporting, topography, animal population, law enforcement, vehicle characteristics, and other factors through jurisdictions (Connors, Maher, Wood, Mountain, & Ropkins, 2013; Srinivasan, Carter, & Bauer, 2013; Lord, Geedipally, & Shirazi, 2016; Geedipally, Lord, & Shirazi, 2017; Shirazi, Geedipally, & Lord, 2017; Wood, Mountain, Connors, Maher, & Ropkins, 2013).

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

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

Where,

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

Similarly, calibration is recommended when applying an SPF to a new jurisdiction, but a calibration between different time periods is also recommended (Dixon, Monsere, Xie, & Gladhill, 2012; Lord, Geedipally, & Shirazi, 2016). When translating SPFs across states, calibration factors are a given, but major physiographic division within a state should also be considered (Rodgers, Wilson, Shaw, & Barton, 2015).

The *HSM* recommends calibrating the models using data from 30-50 locations, which collectively possess at least 100 crashes per year. However, recent research has shown that this number of sites is insufficient for most cases (Alluri, Saha, & Gan, 2016; Shirazi, Lord, & Geedipally, 2016). Several research studies, such as Bahar & Hauer (2014) and Lord, Geedipally, & Shirazi (2016), 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.

2.2 Intersection SPFs

The *HSM* provides information on effectively identifying intersection safety issues in rural areas, choosing the countermeasures that address them, and evaluating the benefits of those treatments. There is an established consensus among traffic safety researchers that a nonlinear relationship exists between traffic exposure and safety. This relationship is reflected by the SPFs calibrated for various classes of roads and intersections (AASHTO, 2010). Few studies and reports have sought to create an SPF model for rural intersections. Among the various types of statistical models used for SPF development, generalized linear models and negative binomial models yield results that are easy to interpret and associate crash frequencies to sets of designated explanatory variables (Young & Park, 2013; Caliendo & Guida, 2012). These models are considered standard for developing SPFs, including the SPFs in the *HSM*, and have been used extensively in many studies (Vogt & Bared, 1998; Vogt A. , 1999; Tegge, Jo, & Ouyang, 2006; Garber, Rivera, & Lim, 2011). This section outlines the recent research on the safety performance of signalized and unsignalized intersections. Table 1 summarizes research on calibrating or developing a jurisdiction-specific SPF for different intersection facilities in different states or countries. Key studies specific to rural intersection safety are described in greater detail later in this document.

Table 1. Summary of Prior Research on Developing or Calibrating Intersection Models

Reference	State or Country	Urban/ Rural	Site Type(s)	Calibrated	Jurisdiction -Specific
(Kweon & Lim, Appropriate Regression Model Types for Intersections in Safety Analyst, 2012)	VA	U	3ST;3SG;4ST;4SG		×
(Kweon & Lim, Appropriate Regression Model Types for Intersections in Safety Analyst, 2012)	VA	R	3ST;3SG;4ST;4SG		×
(Oh, Washington, & Choi, 2004)	S. Korea	R	3SG;4SG		×
(Donnell, Gayah, & Jovanis, 2014)	PA	R	3ST;3SG;4ST;4SG		×
(Dixon & Avelar, 2015)	OR	U	4SG		×
(Monsere, Johnson, Dixon, Zheng, & Schalkwyk, 2011)	OR	R	3ST		×
(Monsere, Johnson, Dixon, Zheng, & Schalkwyk, 2011)	OR	U	4SG		×
(Dixon K. , Avelar, Brown, Mecham, & Schalkwyk, 2012)	OR	R	3ST;4ST;4SG	×	
(Dixon K. , Avelar, Brown, Mecham, & Schalkwyk, 2012)	OR	U	3ST;3SG;4ST;4SG	×	
(Persaud & Nguyen, 1998)	ON Canada	R	3SG; 4SG		×
(Persaud, Lord, & Palmisano, 2002)	ON Canada	U	3ST;3SG;4ST;4SG	×	×
(Lyon, Haq, Persaud, & Kodama, 2005)	ON Canada	U	3SG;4SG	×	×
(Xie & Zhang, 2008)	ON Canada	U	3SG		×
(Persaud, Gross, & Srinivasan, 2012)	ON Canada	U	3SG;4SG	×	×
(Troyer, Bradbury, & Juliano, 2015)	OH	U	3ST;3SG;4ST;4SG	×	
(Sun, Brown, Edara, Claros, & Nam, 2013)	MO	U	3ST;3SG;4ST;4SG	×	
(Sun, Brown, Edara, Claros, & Nam, 2013)	MO	R	3ST;4ST	×	
(Shin, Lee, & Dadvar, 2014)	MD	U	3ST;3SG;4ST;4SG	×	
(Shin, Lee, & Dadvar, 2014)	MD	R	3ST;4ST;4SG	×	
(Savolainen, et al., 2015)	MI	U	3ST; 4ST; 3SG; 4SG		×
(Srinivasan, et al., 2011)	FL	R	3ST;4ST;4SG	×	
(Srinivasan, et al., 2011)	FL	U	3SG;4SG	×	
(Srinivasan & Carter, 2011)	NC	R	3ST;3SG;4ST;4SG	×	
(Srinivasan & Carter, 2011)	NC	U	3ST;3SG;4ST;4SG	×	
(Tegge, Jo, & Ouyang, 2010)	IL	R	3ST;4ST;4SG		×

Note: 3=3-leg intersections; 4=4-leg intersections; ST=stopped-controlled; SG=signalized; R=Rural; U=Urban.

2.2.1 Rural Intersection SPFs

Considering different road characteristics, traffic volumes, weather conditions, etc. across different jurisdictions, it is suggested to develop separate SPFs based on the traffic and crash data of each state (Harwood D. , et al., 2004). To address issues associated with *HSM* model calibration, several states (and countries) have developed their own intersection SPFs, including: Illinois (Tegge, Jo, & Ouyang, 2010), Oregon (Dixon, et al., 2015), Virginia (Kweon & Lim, 2012), and Pennsylvania (Donnell, Gayah, & Jovanis, 2014).

There is a robust historical background regarding crash models for rural intersections. Data collected from the states of Minnesota and Washington on rural two lane highways were used to build crash models for three legged intersections stop-controlled on the minor legs. Negative binomial (NB) and extended NB models concluded that intersection crashes depend primarily on traffic volume (Vogt & Bared, 1998). In this regard, A. Vogt (1999) presented a model which describes the collection, analysis, and modeling of crash and roadway data for three-legged intersections on rural roads in California and Michigan for the years 1993-1995. NB models were developed in this study. A simultaneous-equations model of crash frequency by collision type for rural intersections was developed and presented using crash data for rural intersections in Georgia (Ye, Pendyala, Washington, Konduri, & Oh, 2009). Oh, Washington and Choi (2004) proposed a macro level crash prediction model that can be used to understand and identify effective countermeasures for improving multilane stop-controlled highway intersections in rural areas. Poisson and NB regression models were fit to intersection crash data from Georgia, California, and Michigan in this study. Montella and Mauriello (2012) presented a procedure for ranking rural unsignalized intersections that uses quantitative safety evaluations performed as part of the safety inspection process.

Several studies have investigated crash occurrence at rural three-legged intersections. Stackhouse and Cassidy (1996) sought to understand the effects of warning flashers on the safety of rural intersections. Russell, Rys and Luttrell (2000) identified the factors that contribute to crashes caused by failure to stop and failure to yield the right-of-way at rural two-way stop-controlled intersections on the state highway system. Preston and Schoenecker (1999) and Donnell, Porter and Shankar (2010) performed statistical analysis of crash frequencies and other crash characteristics at isolated rural intersections to see the effects of installing street lighting. Preston, Storm, et al. (2004) studied different causes of crashes at rural intersections in order to support development of technology-based strategies to mitigate high crash rates.

Tegge, Jo and Ouyang (2010) developed SPFs for the following rural intersection subcategories in Illinois using the functional form in Equation 2: 1) Rural Minor Leg Stop Control, 2) Rural All-Way Stop Control, 3) Rural Signalized Intersections, and 4) Rural Undetermined. Each SPF was developed for different severity subcategories, which included fatal (K), injury (A,B) and fatal-injury (FI). The SPF coefficients from Tegge, Jo, and Ouyang (2010) are reported in Table 2.

Table 2. Modeling Coefficients for Rural Intersections in Illinois

Facility	Intercept (β_0)	Maj AADT (β_1)	Min AADT (β_2)	Num. Sites
Type-Fatal (F)				
Rural Minor Leg Stop Control	-7.738	0.215	0.355	14,933
Rural All-Way Stop Control	-25.464	2.520	0.000	351
Rural Signalized Intersection	-16.691	1.501	0.000	199
Rural Undetermined[a]	-7.288	0.240	0.187	5,579
Type-A				
Rural Minor Leg Stop Control	-8.574	0.601	0.293	14,933
Rural All-Way Stop Control	-6.095	0.544	0.000	351
Rural Signalized Intersection	-11.243	1.190	0.000	199
Rural Undetermined[a]	-7.132	0.565	0.067	5,579
Type-B				
Rural Minor Leg Stop Control	-9.220	0.764	0.265	14,933
Rural All-Way Stop Control	-5.927	0.456	0.177	351
Rural Signalized Intersection	-14.389	1.482	0.170	199
Rural Undetermined[a]	-7.547	0.690	0.050	5,579
Type-Fatal and Injury (FI)				
Rural Minor Leg Stop Control	-8.005	0.674	0.272	14,933
Rural All-Way Stop Control	-5.907	0.507	0.171	351
Rural Signalized Intersection	-13.502	1.443	0.151	199
Rural Undetermined[a]	-6.638	0.631	0.065	5,579

[a] intersections where traffic control information is not available
Table based on Tegge, Jo, & Ouyang (2010)

Monsere, et al. (2011) documented two SPFs for Oregon intersections, one for rural 3-legged minor stop-control (R-3ST) intersections, and the other for urban 4-legged signalized intersections (U-4SG) and used data collected at 115 rural 3-legged stop controlled intersections between 2005 and 2007. The dataset involved 165 crashes during this period (with a rate of 0.48 crashes per intersection per year). Of those crashes, 80 were categorized as fatal and injury crashes, while the rest were classified as property damage only (PDO). The researchers noted that the lack of required data and the significant costs of data collection were two major difficulties they faced for developing SPF models for Oregon intersections. Equation 5 shows the R-3ST model that was developed in Monsere et al. (2011)

$$N_{spf} = \exp[-10.5799 + 0.7781 \times \ln(AADT_{major}) + 0.4739 \times \ln(AADT_{minor}) \qquad (5)$$

A study was undertaken by Kweon (2007) to identify high-risk four-leg signalized intersections in Northern Virginia. SPFs were developed in this study for different crash patterns and times of day based on the EB method. Kweon and Lim (2012) developed 11 models (8 panel and 3 cross-sectional) using the Safety Analyst Software (SAS) program for both urban and rural intersections in Virginia for 3ST, 3SG, 4ST, and 4SG facilities to indicate the best safety analysis model. The Virginia data included crashes from 18,356 intersections between 2003 and 2008. The researchers showed that cross-sectional models, either with summed or averaged crash frequencies, significantly underestimate the dispersion parameter of the NB models. It is worth pointing out that the dispersion parameter is a crucial component in the use of the EB method. Lack of precision for this parameter could yield erroneous results.

Donnell, Gayah and Jovanis (2014) have documented SPFs for different facilities in Pennsylvania. As such, SPF models were developed for 3-leg and 4-leg rural intersections with minor street stop-controlled, all-way stop controlled, and signalized intersections. NB regression was used to develop these models. It is worth noting that this research did not use CMFs to account for site geometric variables, but included these variables in the regression model. The SPF included variables such as major and minor AADTs, left and right shoulder width on the major and minor legs, paved width on major legs, and posted speed limit, among others.

Garber, Rivera and Lim (2011) developed SPFs for both total crashes and fatal and injury crashes of urban and rural, 3-leg and 4-leg, and signalized and stop-controlled intersections in Virginia using generalized linear modeling. Major and minor leg AADTs as well as left-turn lanes and presence of lighting were the independent variables considered in their model. All of these studies show that calibrated SPFs based on the *HSM* predictive method have considerably different precisions for different states.

2.2.2 Rural Intersection CMFs

In the safety literature, CMFs have been developed for many geometric and site features and for various jurisdictions (i.e., states, regions, etc.). Most states found that for rural, minor stop-controlled, four-leg intersections, the *HSM* over-predicted the number of crashes. In North Carolina, a calibration factor of 0.68 was determined (Sun, Brown, Edara, Claros, & Nam, 2013). The state of Missouri found similar results to North Carolina, having a range of 0.64 to 0.77 from 2007-2009 (Srinivasan, et al., 2011). This leads to the conclusion that these locations experience fewer crashes than the national average. In the research performed by Oregon, a calibration factor of 0.31 was established, implying that the prediction taken from the *HSM* is over 3 times what Oregon experiences (Xie, Gladhill, Dixon, & Monsere, 2011).

For rural four-leg stop-controlled intersections with lighting, the *HSM* provides a CMF of 0.91, relative to the base condition of no lighting present. Research completed in Minnesota and California found that illuminated intersections are associated with a reduction in nighttime crash frequency of 3.6 percent and 6.5 percent, respectively (Obeidat & Rys, 2016). Intersection sight distance (ISD) and alignment can be a large factor in the safety of a rural intersections (Vogt & Bared, 1998).

As such, the Texas-specific rural intersection models include CMFs describing the characteristics of various site features, both for signalized and un-signalized intersections (Bonneson & Pratt, 2009). The report provides a good summary of existing CMFs for rural intersections and segments as documented in Table 3.

Table 3. Existing CMFs for the Texas Rural Intersection SPF Model

Signalized	Base Conditions	Relation to Safety	Unsigna-lized	Base Conditions	Relation to Safety
Left-Turn Lane	*Major-road legs:* left-turn lane (or bay) on both legs *Minor-road legs:* left-turn lane (or bay) not present	For major approaches, crashes increase with the number of legs not meeting base conditions. For minor approaches, crashes decrease with incorporation of left turn lanes. The proportion of average daily traffic volume on legs play a major role in CMF calculation.	Left-Turn Lane	**Major-road legs**: left-turn lane (or bay) not present	The introduction of left turn lanes of adequate length in major approach decreases crashes. The proportion of average daily traffic volume on legs play a major role in CMF calculation.
Right-Turn Lane	*Major-road legs:* right-turn lane (or bay) not present. *Minor-road legs:* right-turn lane (or bay) not present	Crashes decrease as the number of legs with a right turn lane increases. The proportion of average daily traffic volume on legs play a major role in CMF calculation.	Right-Turn Lane	**Major-road legs**: right-turn lane (or bay) not present	Crashes decrease with the introduction of right turn lanes of adequate length in the major approach. The proportion of average daily traffic volume on legs and presence of left turn lane play a major role in CMF calculation.
Number of Lanes	*Major road:* 2 lanes *Minor road:* 2 lanes	Crashes increase by 1-4 percent when the number of major through lanes are 4 or more with increasing number of minor road through lanes. This is due to increase in intersection conflict area.	Number of Lanes	**Major road**: 2 lanes **Minor road**: 2 lanes	Crashes decrease when number of major through lanes are 4 or more with increasing number of minor road through lanes due to redistribution of traffic patterns.
Driveway Frequency	*Major road:* 2 driveways within 250 ft *Minor road:* 2 driveways within 250 ft	Driveways add turbulence to the traffic stream. Crashes increase when more than two active driveways (≥ 10 veh/d) exist within 250 ft of intersection while both approaches are considered.	Driveway Frequency	**Major road**: 1 driveway within 250 ft **Minor road**: 0 driveways within 250 ft	Number of crashes increases when there are more than 1 active driveway within 250ft of the intersection when both major and minor roads are considered. ADT of major and minor road influence the calculation of CMF.
Truck Presence	11% trucks	CMF depends on the average percent trucks during the peak hour for all intersection movements. Crashes increase when truck presence is more than 11%.	Truck Presence	15% trucks	The number of crashes decreases when the average percent trucks during the peak hour is greater than 15%. CMF developed is appropriate for truck percentages ranging from 0 to 25 percent
Additional CMFs for Unsignalized intersections					
Shoulder Width	*Major road:* 4-ft shoulder width *Minor road:* 4-ft shoulder width	CMF is applicable to shoulder widths ranging from 0 to 10 ft. A reduction in crashes occurs when the shoulder width is greater than 4 ft when average width of the outside shoulders on each leg is considered. ADT of major and minor road are also considered for CMF calculation.			
Median Presence	No median on major road	CMF is only derived for major roads. With left turn bay, CMF remains 1.0 for median width up to 16 ft, and decreases thereafter. For intersections without left turn bay, crashes decrease by introduction of medians starting from width of 5 ft. The median should extend back from the stop line for a distance of 250 ft or more with a width of at least 4 ft.			
Alignment Skew angle	No skew	CMF is applicable to alignment skew angles in the range of 0 to 30 degrees where crashes increase with increasing skew angle. Different CMF curves are available for 4-leg and 3-leg intersections.			

2.3 Segment SPFs

This section summarizes recent research on safety performance for rural segments. Table 4 encapsulates research on calibrating or developing a jurisdiction-specific SPF for different segment facilities in different states or countries. Key studies specific to the safety performance of rural segments are described in greater detail later in this section.

Table 4. Summary of Prior Research on Developing or Calibrating Segment Models

Reference	State or Country	Urban or Rural	Site Type(s) - Rural	Calibrated	Jurisdiction -Specific
(Bauer & Harwood, 2012)	WA	R	R2		
(Bornheimer, Schrock, Wang, & Lubliner, 2011)	KS	R	R2	×	×
(Brimley, Saito, & Schultz, 2012)	UT	R	R2	×	×
(Cafiso, D' Agostino, & Persaud, 2012)	Italy	R	RMD	×	
(Donnell, Gayah, & Jovanis, 2014)	PA	R	R2 and Rural Intersections		×
(Farid, Abdel-Aty, M., Eluru, & Wang, 2016)	FL, CA, OH	R	RMD		
(Garber, Haas, & Gosse, 2010)	VA	R, U	R2		×
(Kweon & Lim, 2014)	VA	R,U	RMU, RMD, RMF		×
(Lu, Haleem, Alluri, Gan, & Liu, 2014)	FL	R,U	RMF		×
(Mehta & Lou, 2013)	AL	R	R2, RMD	×	×
(Park & Aty, 2015)	FL	R	R2		×
(Russo, Busiello, & Dell, 2016)	Italy	R	R2	×	
(Srinivasan & Carter, 2011)	NC	R,U	R2, RMD	×	×
(Srinivasan, et al., 2011)	FL	R,U	R2, RMD	×	×
(Tegge, Jo, & Ouyang, 2010)	IL	R,U	R2, RMU, RMD		×
(Williamson & Zhou, 2012)	IL	R	R2	×	×
(Xie, Gladhill, Dixon, & Monsere, 2011)	OR	R	R2, RMU, RMD	×	×

Note: U = Urban; R = Rural; R2 = Rural Two Lane Two Way Roads; RMU = Rural Multilane Undivided Highways; RMD = Rural Multilane Divided Highways; RMF = Rural Multilane Freeways.

2.3.1 Rural Segment SPFs

A research report on the development of SPFs for two lane roads maintained by the Virginia Department of Transportation developed SPFs for total crashes and combined fatal plus injury crashes through generalized linear modeling using a negative binomial distribution for crashes (Garber, Haas, & Gosse, 2010). Models were developed for urban and rural areas separately for three regions in Virginia. A total of 139,635 sites were identified for use in this study. Each site was a segment of a rural or urban two-lane road without an intersection. A comparative analysis based on the Freeman-Tukey R^2 coefficient was conducted between the relevant Ohio SPFs suggested for use in the *Safety Analyst* User's Manual. The results indicated that the SPFs specifically developed for Virginia fit the Virginia data better.

Tegge, Jo, & Ouyang (2010) developed Illinois-specific SPFs to predict crash frequency based solely on traffic volumes for 12 types of segment and 8 types of intersection peer groups using the statistical program SAS and automated PSI calculation procedure using a computer program. Regression parameters were found for fatal crashes, type A injury crashes, type B injury crashes and fatal and injury SPF peer groups. From the multiple-variable analysis, 37 variables were found to have an impact on the frequency of crashes on Illinois roadways. All of them were statistically significant (based on a 0.10 level of significance) in crash occurrences. Illinois-specific SPFs provided a more accurate representation of the roadways as opposed to usage of SPFs based on other state roadways.

Srinivasan and Carter (2011) calibrated *HSM* predictive models for rural four-lane divided segments along with four types of urban roadway segments and eight types of intersection groups in North Carolina. SPFs for rural two lane roads were developed using AADT and other site characteristics including shoulder width/type and terrain yielding a calibration factor of 0.78. The SPFs developed for this project were anticipated to be used for network screening, project level analysis, and before-after evaluation using the empirical Bayes method.

The development and calibration of SPFs for rural two lane highways in Kansas based on negative binomial regression models was done by Bornheimer, et al. (2011). Road hazard rating was found to be the most significant variable in each model. The equations were compared against SPFs calibrated from the *HSM* using nine validation segments. Removal of animal related crashes, which accounted for 58.9 percent of crashes on Kansas Highways, resulted in improved accuracy of the developed models.

A report by Xie, et al. (2011) on the calibration of *HSM* predictive models for Oregon state highways documented the calibration of SPFs for rural undivided two lane highways, rural undivided highways, and divided multilane highways. The calibration factors for most of the Oregon facilities during the 3-year study period appeared to have values less than 1.00 (0.78) indicating the overestimation of crashes in Oregon by *HSM* SPFs.

A study by Srinivasan, et al. (2011) developed and calibrated *HSM* equations for the state of Florida. District level or population group level calibration factors were used instead of state level factors if localized factors were derived using adequate data. The calibration factors developed for 2005, 2006, 2007 and 2008 were compared with *HSM* equations.

Mehta and Lou (2013) evaluated the applicability of *HSM* predictive methods to Alabama data and developed state-specific statistical models for two-lane, two-way rural roads and four-lane divided highways. *HSM* based SPFs were calibrated using the method recommended by the *HSM* as well as using a special case of negative binomial regression. The new forms of state-specific SPFs were further investigated using Poisson-gamma regression techniques. The prediction capabilities of the two calibrated models and the four newly developed state-specific SPFs were evaluated with a validation data set with the aid of five performance measures. The resulting calibration factors from the two different approaches were 1.522 and 1.392 for two lane two way rural roads and 1.863 and 1.103 for four lane divided highways. This indicates underestimation of crashes by the *HSM* SPFs. The best model described the mean crash frequency as a function of annual average daily traffic, segment length, lane width, year, and speed limit.

Brimley, Saito and Schultz (2012) calibrated the *HSM* SPFs for rural two-lane two-way road segments in Utah and developed new models using negative binomial and hierarchical Bayesian modeling techniques. Four models were developed using the negative binomial regression and applied the EB method for refining the long-term mean estimates for these facilities. The calibration factor of the *HSM* SPF was found to be 1.16. The hierarchical Bayesian technique, which accounts for high levels of uncertainty was useful in determining unsafe segments. The negative binomial model with transformed AADT produced accurate results and required less data than other models.

The recommended model included AADT, segment length, multiple-unit truck percentage, and speed limit. Other variables which were evaluated in model development included driveway density, presence of passing zones (one direction or both), shoulder width, and presence of shoulder rumble strips. The authors found that fewer crashes were predicted when passing maneuvers are restricted, or when truck traffic increases (Brimley, Saito, & Schultz, 2012). The inverse relationship between predicted crashes and increasing truck traffic was unexpected. However, Utah is one of many western states that have a maximum speed limit of 65 mph on rural two-lane two-way highways along with no differential speed limit for trucks.

A state specific SPF for Utah's curved two lane two way segments was developed by Saito, Knecht, & Schultz (2015). Various methods for incorporating horizontal curvature as a parameter in the Utah SPF were considered, ranging from a binary indicator variable, to discrete curve classification (six bins), to radius as a continuous variable. The use of indictor or classification variables were not found to be statistically significant, so radius as a continuous variable was selected, along with AADT, segment length, and multiple-unit truck percentage. Problems were encountered when trying to combine curves and tangents into the same model as the segmentation based on curve or tangent resulted in segment lengths for curves that were much shorter than those for tangents. The SPF for curved segments was calibrated only for curve segment data.

One of the more comprehensive state-specific SPF development efforts was performed by Donnell, et al. (2016) which sought to develop regionalized SPFs for Pennsylvania. Their previous work had produced unique statewide SPFs for rural two-lane two-way segments and intersections. The regionalized SPFs were designed to capture differences across geographic regions. The jurisdictional boundaries of individual counties naturally emerged as the smallest area to consider because they have the most consistency in design features and crash reporting. Different levels of spatial grouping were considered based on engineering district (similar to MDOT's use of TSCs and regions) and by planning organization level (similar to Michigan's MPOs or RPOs). Unique SPFs were calibrated at the district level for rural two-lane two-way roadway segments. The researchers concluded that for rural two-lane two-way intersections, as well as for rural multilane segments and rural multilane intersections, statewide SPFs should be used. In the case of rural multilane segments, district adjustment factors were applied, not unlike the way a calibration factor is applied to the *HSM* to represent local conditions. These findings were attributed to a lack of necessary observations at the district level for the multitude of facility types. Such a finding would likewise apply to Michigan, where certain regions (e.g., Superior) only contain a very small number of rural signalized trunkline intersections. Overall the study showed that statewide SPFs were still better at predicting the safety performance of Pennsylvania segments and intersections than the out of the box *HSM* SPFs. It is unclear if the calibration of *HSM* SPFs was sufficiently performed prior to drawing this conclusion.

Horizontal curvature was incorporated into the Pennsylvania models by use of two variables, one for horizontal curve density in terms of number of curves per mile, and the other for total degree of curvature per mile. The exponential functional form of the variable allowed that a value of 1 would exist whenever either of the variables took a zero value, consistent with the fact that the safety performance of tangent sections would be unaffected by having no curvature present as that is the base condition. Each of the two variables had positive coefficients, meaning that more curves and more degree of curvature (smaller radius of curve) resulted in more predicted crashes. The use of both variables seems to appropriately consider the situation of multiple curves within a single segment. Not considered however, is superelevation, or any other indicator of whether the characteristics of the curve(s) are appropriate for the operational speed of the roadway.

An alternative approach to calibrate prediction models on segments for a rural secondary road network in Italy by Martinelli, Torre, & Vadi (2009) developed the predictive models by using the full model with variables such as AADT, segment length, lane width, shoulder width, horizontal curvature, roadside hazard rating, driveway density, grade rate for vertical curves, and percent grade for straight grades. This study indicated that applying a weighted average of crashes over the segment length performed better than using an actual crash count or a ratio of densities of crashes. It also showed that one specific value for the calibration coefficient may not be sufficient for calibration purposes.

Another study by Mountain, Fawaz and Jarrett (1996) in the United Kingdom used the Poisson regression, log-linear models and the EB method to predict the crash frequency based on data on two-lane rural roads. They concluded that the EB method performed better than other methods as it took into account the difficulty with the regression-to-the-mean effect. A similar study by B. N. Persaud (1994) also adopted the EB method for predicting crashes on rural, two-way two-lane roads in Canada and recognized that the EB method works well using negative binomial regression. This topic was further studied by Persaud, Saleem, et al. (2012). These researchers developed CMFs for treatments aimed at reducing crashes related to traffic signal change intervals. In this study, the three different methods such as the EB before–after method, the comparison group before–after method, and the cross-sectional multiple regression models were compared and were found in agreement about a general safety benefit of this treatment, with indications that crash reductions could be achieved overall.

Hadi, et al. (1995) used a negative binomial regression analysis to assess the impact of the cross-section design elements of two-lane rural roads based on the data of total, fatality, and injury crash rates for a period of four years. The explanatory variables included were AADT, segment length, lane width, shoulder width, speed limit, and the number of intersections. The results revealed that an increase in the median width, inside and/or outside shoulder width, and lane width reduces the number of crashes. Ackaah and Salifu (2011) developed a predictive model for injury crashes based on rural segments of highways in Ghana. The variables considered in this study were traffic volume, speed, and roadway characteristics. A generalized linear model (GLM) with NB error structure was used to estimate the model parameters.

A safety impact study on rural two-lane roads by Labi (2006) confirms that EB analysis effectively corrects for the regression-to-the-mean effect. A prediction model for two-lane rural road segments using data of two-lane rural Spanish national network (Manzo and Orive, 2006) included similar variables to that in the *HSM* model, but also included additional variables such as reduction in design speed between adjacent segments and sight distance.

Zegeer et al. formulated SPFs focused on the effect of travel lane width and shoulder width using data from eight states. They found that wider lanes were associated with crash frequency reductions of 10 to 40 percent, increasing progressively as the distance widened (Zegeer, Deen, & Mayes, 1980). The SPF corresponding to Texas data supported the claim that wider lanes provide a reduction in crash frequency and rural two-way road safety is benefited from the presence of edge lines (Lord & Bonneson, 2007). The three-state study, which included Kansas, Illinois and Michigan, also supports the safety effects of wider lanes by the results. However, Michigan rural two-lane highways did not see as large a reduction in crashes compared to the other states (Park, Carlson, Porter, & Andersen, 2012). Nieto (2017) focused on the development of multiple jurisdiction-specific SPFs for local rural roads with low traffic volume (AADT<2000 vehicles) in Alabama. Separate SPFs were developed for two-lane two-way road segments, three- and four-leg stop controlled intersections, and for different crash severities (total, fatal plus injury, and PDO).

2.3.2 Rural Segment CMFs

Bonneson and Pratt (2009) developed several CMFs for rural segments located in Texas. Table 5 summarizes key CMFs that relate to both two-lane and four-lane highways.

Table 5. CMFs Associated with 2L or 4L Texas Specific Rural Segments

CMF	Base Condition	Relation to Safety
Horizontal Curve Radius	Tangent alignment	This CMF shows that a reduction in all crashes can be observed as the radius of the curve increases. The CMF is multiplied by posted speed limit as a surrogate for representing actual operating speed.
Grade	Flat (0% grade)	Grades influence speed and increasing speed variability with increasing ascending grade results in crashes. Descending grades require vehicle braking and additional maneuverability, thereby increasing chances of crashes. The CMFs developed are for grades of 8 percent or less and their effect is more important on multilane highways than for two-lane highways.
Outside Clearance (no barrier)	30-ft horizontal clearance, 8-ft outside shoulder width	The CMF decreases with increased outside clearances and is applicable to clearance distances up to 30 ft. The effect is more important for two-lane highways. The CMF depends on the proportion of influential crashes based on number of lanes and median type. The values used for outside shoulder width and horizontal clearance should be an average for both travel directions.
Outside Clearance (some barrier)	Roadside barrier not present, 30-ft horizontal clearance, 8-ft outside shoulder width	The treatment is incorporated to decrease crash severity, which may result in an increase in injury and property-damage-only crashes. The resulting reduction in fatal and serious injury crashes increases with available horizontal clearance, and shows less of a reduction compared to the 'no barrier' scenario. The CMF is the combination of the no barrier scenario CMF and the full barrier scenario CMF based on the proportion of the segment length that includes a roadside barrier.
Outside Clearance (full barrier)	Varies with proportion of influential crashes based on number of lanes and median type, min. 30-ft lateral clearance, 8-ft shoulder.	Crashes decrease with increasing distance from edge of traveled way to barrier. The CMF is obtained by multiplying outside clearance CMF when outside barrier is present with outside clearance crash modification factor when outside barrier is present.
Side Slope	1V:4H side Slope (4 ft horizontal run for a 1-ft change in elevation)	The CMF increases with a decrease in horizontal run per unit vertical change. The reduction pattern is different for two lanes and four lanes and CMF depends on proportion of influential crashes based on the number of lanes and median type.

Similar to Table 5, Table 6 shows the Texas CMFs associated with 2L highways only.

Table 6. CMFs Associated with 2L Texas Specific Rural Segments

CMF	Base Condition	Relation to Safety
Spiral Transition Curve	Spiral transition curves not present	Crashes decrease with increasing radius of spiral transition curve. CMF selection is based on horizontal curve length and drastic changes are felt with 0.10 mile curve lengths compared to 0.20 mile.
Lane and Shoulder Width	12-ft lane width, 8-ft shoulder width	CMF is applicable only for highways with paved or gravel shoulders. Increase in lane width decrease crashes. Drastic reduction is seen for 3 ft shoulder width with ADT of greater than 2,000 veh/d. The CMF is a combination based on traffic volume adjustment factor with CMF for high volume (>2,000 veh/d) and low volume (<400 veh/d).
Shoulder Rumble Strips	Shoulder rumble strips not present	Run-off-road (ROR) crashes decrease when rumble strips are present. For undivided highways, the CMF is 0.91 when rumble strips are present. For highways with two-way left-turn lanes or painted medians CMF decreases based on proportion of single-vehicle ROR crashes.
Centerline Rumble Strip	Centerline rumble strip not present	Continuous rumble strip along the centerline can decrease head-on crashes. For undivided highways, CMF is .85 when rumble strips are present.
Two Way Left Turn Lane Median Type	No Two Way Left Turn Lane	The reduction in crashes happens when driveway density is more than 5 driveways/mile. The CMF depends on driveway-related crashes susceptible to correction by TWLTL as a proportion of total crashes which in turn depends on driveway density.
Superelevation	No superelevation deviation	CMF will remain 1.0 when superelevation deviation is within 1%. If the superelevation provided on a curve is significantly less than the amount specified by the applicable design guide, then the potential for a crash may increase. If the deviation exceeds 5 percent, then the CMF value for 5 percent should be used (1.15).
Passing Lane	Climbing lane or passing lane not present	The CMF is applicable to two-lane highways with passing lanes, if the passing lane has a length sufficient to provide safe and efficient passing opportunities. Crashes decrease with number of available lanes and directions.
Driveway Density	5 driveways per mile	Crashes increase when driveway density is more than 5 driveways/mile (two-way total). The CMF is applicable for two-lane highways with a driveway density ranging from 0 to 20 driveways/mi.

Table 7 shows the Texas CMFs associated with 4L highways only in a way similar to Table 6.

Table 7. CMFs Associated with 4L Texas Specific Rural Segments

CMF	Base Condition	Relation to Safety
Lane Width	12-ft lane width	As lane width decreases, the number of crashes increase. CMF applicable range is 9 to 12 ft of lane width. Two CMFs are available, one for four lanes with restrictive median and other for highways with undivided and nonrestrictive median. The proportion of influential crashes based on median type also affects the CMF.
Outside Shoulder Width	8-ft outside shoulder width	Crashes increase for shoulder widths less than 8 ft. This effect was similar for both highways with four lanes and a restrictive median and those that are undivided or have a nonrestrictive median. The proportion of influential crashes based on median type also affects the CMF and is applicable to four-lane highways having a paved outside shoulder with a width ranging from 0 to 10 ft.
Inside Shoulder Width	4-ft inside shoulder width	An inside shoulder width greater than 4 ft decreases the number of crashes as they provide storage space for disabled vehicles and additional room for evasive maneuvers. CMF is applicable to four-lane highways with a restrictive median and an inside shoulder width ranging from 0 to 10 ft. Proportion of influential crashes based on median type also affects the CMF.
Median Width (no barrier)	16-ft median width for nonrestrictive medians, 76-ft median width and 4-ft inside shoulder width for restrictive medians	CMFs decrease drastically from 1.15 for highways with nonrestrictive medians for median widths up to 16 ft. For restrictive medians, CMFs are greater than 1 for median width less than 76 ft. Inside shoulder width affects CMF of highways with restrictive median.
Median Width (some barrier)	Median barrier not present, 76-ft median width, 4-ft inside shoulder width	Three curves are given to find the CMF based on barrier offset distance from shoulders and median. This CMF applies to median widths of 14 ft or more and crashes increase when median width is less than 76 ft.
Median Width (full barrier)	80-ft median width	Cross-median crashes are increased if median width is less than 80ft for highways with median barrier in center of median and median barrier offset is 2 ft from one shoulder. CMF has a constant value of 1.75 if median barrier offset is 2 ft from both shoulders.
Truck Presence	16% trucks	The CMF depends on trucks represented as percentage in ADT. Higher percentage of trucks was found to decrease crashes, as drivers will be more cautious with trucks in traffic stream. CMF was developed for truck percentages ranging from 0.0 to 25 percent. Crashes decrease when truck percentage is greater than 16.

Table 8 summarizes major variables influencing CMFs for four studies that examined the safety performance of rural segments.

Table 8. Summary of CMFs Associated with Rural Segments

Reference	State	Site Types	Factors
Dixon, Avelar, Brown, Mecham, & Schalkwyk (2012)	OR	R2, RMU	Annual average daily traffic, segment length, presence of four travel lanes, proportion of industrial driveways, total number of driveway clusters (roadside), total number of driveways (roadside)
Donnell, Gayah, & Jovanis (2014)	PA	R2	Vertical grade, presence of vertical curvature, lane width, shoulder width, shoulder type, presence of lighting, presence of automated speed enforcement, traffic volume, roadside hazard ratings of 4 or higher, access density, horizontal curve density, degree of curvature per mile, presence of a passing zone, presence of shoulder rumble strips
Mehta & Lou (2013)	AL	R2, RMU	Annual average daily traffic, segment length, lane width, year, and speed limit
Park & Aty (2015)	FL	R2	Shoulder rumble strips, shoulder width

Note: R2 = Rural Two Lane Two Way Roads; RMU = Rural Multilane Undivided Highways.

Qin, Zhi and Vachal (2014) applied the *HSM* methodology to rural two-lane, two-way highway segments in South Dakota. Results showed that the jurisdiction specific crash type distribution for CMFs differed substantially from the crash distribution presented in the *HSM*. The *HSM* method without modification was shown to underestimate crashes in South Dakota by 35 percent. Park, Aty and Lee (2014) developed CMFs for two single treatments (shoulder rumble strips, widening shoulder width) and one combined treatment (shoulder rumble strips + widening shoulder width) using before–after and cross-sectional methods and evaluated the accuracy of the combined CMFs for multiple treatments estimated by the existing methods based on actual evaluated combined CMFs. The results of both before–after and cross-sectional methods show that the two single treatments and the combined treatment produced safety improvement.

Zeng and Schrock (2013) evaluated the safety effects of 10 shoulder design types in winter and non-winter periods. They developed CMFs using cross-sectional methods. The results showed that wider and upgraded shoulders had a significantly lower impact on safety in winter periods than non-winter periods. Park, Lord and Wu (2016) investigated the relative performance of NB and a two-component finite mixture of negative binomial models (FMNB-2) in terms of developing crash modification factors. Combined CMFs of multiple treatments were estimated using the FMNB-2 model. The results indicated that the combined CMFs are not the simple multiplicative of individual CMFs. Adjustment factors (AFs) were then developed and found that current *HSM* method could over- or under-estimate the combined CMFs under particular combination of covariates. A meta-analysis found that shoulder rumble strips are associated with injury crash reductions of around 23 percent using data from five studies (Turner, Affum, Tziotis, & Jurewicz, 2009). Jovanis and Gross (2008) estimated safety effects of shoulder width using case control and cohort methods, with both methods showing a decrease in crashes with increased shoulder width.

Cardoso (2001) developed models for curves and tangents on rural two-lane roads with both unpaved and paved shoulders of the Portuguese national road network. These predictive models examined variables such as AADT, shoulder width, approach speed, curve radius, bendiness, the average gradient, carriageway width, speed reduction on the approach of a curve, and "the difference between the 85th and 15th percentiles of speed distribution on a curve". Fitzpatrick, Schneider and Park (2005) analyzed crashes for a period of three years and developed crash models using NB regression for two-lane rural roads based on data for 3,944 miles of two-lane rural roads in Texas and included AADT, segment length, lane width, and shoulder width as independent variables.

Crash modification factors can also be estimated with the safety performance function. The regression parameters resulting from the statistical estimation to determine the predicted number of crashes can be used to estimate the effects that a specific engineering treatment may have on the number of crashes, though issues exist when such coefficients are derived jointly with several other predictors (Lord & Bonneson, 2007).

2.4 Calibration Factors

The use of calibration factors provides a standardized model to be calibrated for different jurisdictions and road conditions (Saito, Knecht, & Schultz, 2015). Calibration factors for the *HSM* models have been developed for rural intersections and segments in several states. The first two sections below describe studies that attempted to calibrate *HSM* models for rural intersections and segments. The last section covers general issues related to the calibration procedure.

2.4.1 Rural Intersections

Table 9 shows the value of the calibration factor for different rural intersection models (or facilities) in Oregon (Xie, Gladhill, Dixon, & Monsere, 2011; Dixon, Monsere, Xie, & Gladhill, 2012), Florida (Srinivasan, et al., 2011), North Carolina (Srinivasan & Carter, 2011), Maryland (Shin, Lee, & Dadvar, 2014) and Missouri (Sun, Brown, Edara, Claros, & Nam, 2013). As shown in Table 9, the value of the calibration factor tends to be smaller than one, which indicates that the pre-fitted *HSM* models tend to overestimate the number crashes for different types of rural intersections for most cases documented in this table.

The calibration effort in Oregon (Xie, Gladhill, Dixon, & Monsere, 2011; Dixon, Monsere, Xie, & Gladhill, 2012) showed that obtaining the minor AADT flows for rural intersections is a difficult task, as these values are rarely available. To overcome this difficulty, in a more recent effort, researchers developed an AADT estimation model for minor approaches (Dixon, et al., 2015). The model included land-use and demographic variables as well as the characteristics of the main highway to which the minor approach intersects.

Table 9. Rural Intersection Calibration Factors

Facility		Calibration Factor				
		Oregon	**Maryland**	**Florida[a]**	**N. Carolina[b]**	**Missouri**
Rural Two-Lane						
R3ST	3-leg, minor STOP	0.31	0.16	0.80	0.57	0.77
R4ST	4-leg, minor STOP	0.31	0.20	0.80	0.68	0.49
R4SG	4-leg, signalized	0.45	0.26	1.21	1.04	-
Rural Multi-Lane						
MR3ST	3-leg, minor STOP	0.15	0.18	NA	NA	0.28
MR4ST	4-leg, minor STOP	0.39	0.37	NA	NA	0.39
MR4SG	4-leg, signalized	0.15	0.11	0.37	0.49	-

[a] For this sate several yearly calibration factors were derived from 2005 to 2009. Here we report the values derived in 2009.
[b] Both one and three-year period calibration factors were derived for this state. Table 10 shows three-year factor only.

Calibration factors have been derived for several other types of facilities (e.g., urban intersections and segment models) in Oregon, Florida, North Carolina, Maryland and Missouri, as well. However, this document focuses on calibration efforts documented for rural segments and intersections only. Several other states such as Utah (Brimley, Saito, & Schultz, 2012), Illinois (Williamson & Zhou, 2012), and Alabama (Mehta & Lou, 2013) have also performed local calibration of the *HSM* SPFs, although rural intersections were not included in the local calibration.

2.4.2 Rural Segments

Bornheimer, et al. (2011) calibrated the model developed using both the *HSM* procedure and new procedures that address specific qualities of the Kansas highway system. Jalayer, et al. (2015) presented a revised method to develop calibration factors for five types of urban and suburban roadways with consideration of recent changes to the crash recording threshold (CRT) for property damage crashes, which occurred in Illinois in 2009. The study established a revised method to supplement and adopt a standard approach to develop calibration factors in the *HSM*, considering impact of the new CRT. The higher the CRT, the fewer recorded PDO crashes. Before and after the threshold change, calibration factors for four lane divided facilities were 0.68 and 0.55 respectively. Table 10 shows the value of the calibration factor for different rural segment models (or facilities) in North Carolina (Srinivasan & Carter, 2011), Oregon (Xie, Gladhill, Dixon, & Monsere, 2011), Florida (Srinivasan, et al., 2011), and Illinois (Williamson & Zhou, 2012). All the calibration factors are for KABCO crashes. Table 10 shows the value of the calibration factor varies greatly for different states, from a low of 0.36 to more than 4.0.

Table 10. Rural Segment Calibration Factors

Facility	Calibration Factor			
	North Carolina	**Oregon**	**Florida**	**Illinois**
2U	4.04	0.74	1.05	1.58
4U	NA	0.36[a]	NA	NA
4D	NA	0.78[a]	0.70[a]	NA

[a] Referred as multilane rural highways (includes a limited number of 6-lane segments).

2.4.3 General Calibration Issues

Although states usually develop one single calibration factor for the whole state, recent research on urban intersections in Michigan (Savolainen, et al., 2015) showed that the value of the calibration factor could be significantly different in different regions of Michigan. To overcome this issue, the authors estimated several region-specific calibration factors.

As noted above, in the safety literature in general, and the *HSM* in particular, calibration is a tool to incorporate the local conditions of the current jurisdiction into the model that was fitted (or developed) for another jurisdiction. However, although calibrating the models through a scalar factor seems adequate for the overall fit of the model, there is no guarantee that same results will be achieved, even when each variable is analyzed independently (such as AADT), or by group of variables (Dixon & Avelar, 2015). Furthermore, the application of a single scalar factor was found to be biased compared to the recently introduced Bayesian model averaging (BMA) method. Chen, Persaud and Sacchi (2012) investigated this limitation using the BMA method by taking a close look at a series of locally developed and calibrated models. Cumulative residuals (CURE) plots were observed for the AADT variable (Hauer & Bamfo, 1997). Results from this study show that the bias from calibrated models is substantially larger than the BMA models.

2.5 Other Related Topics

This section summarizes two topics that are relevant to this research. Although those findings may not directly influence the next steps of the research project, they may provide some insights on nuances to be considered in developing SPFs for rural intersections and segments.

2.5.1 Temporal Changes to CMFs

Some research has found that the value of CMFs can vary over time. For example, Wang, et al. (2015) analyzed the variations in the CMF values for the signalization and red-light camera installations (RLCs) over time in Florida. The researchers analyzed both rear-end crashes and angle/left-turn crashes. For rear-end crashes, the value of CMFs showed to be low initially (during the early phase of signalization) but then it started to increase after the ninth month of installation. Conversely, for angle and left-turn crashes, the value of the CMFs was found to be initially high, but started decreasing after the ninth month of installation; that research showed that the CMFs ultimately became stable. Sacchi, Sayed and El-Basyouny (2014) modeled this time variation in detail using data collected at signalized intersections in Surrey, Canada.

Although the research on CMF time variations offers some insights, those studies tend to indicate that such a variation occurs in a way that there is convergence to a long term value for the CMF. This body of research may be particularly informative in situations where the countermeasure is evaluated in a short period after installation, or when assessing the time it takes the CMF to converge to a stable value. However, it is not clear to what extent the issue of CMF time variation is applicable to a larger body of countermeasures and their corresponding CMFs.

2.5.2 Crash Distance to Intersection

Recent work by Avelar, Dixon and Escobar (2015) examined the relationship between intersection related crashes and their distance to the intersection. The researchers manually classified 1,534 crashes at 73 intersections in Oregon and tested the performance of several distance-based methods to identify intersection related crashes. This research found that the widely used threshold of 250 ft around the intersection tended to result in a reduced crash frequency at each intersection and could lead to developing SPFs that under-estimate actual crash frequency. Furthermore, that research found evidence that the threshold around the intersection would likely increase as a function of the speed limit. Figure 1 (Avelar, Dixon, & Escobar, 2015) shows the relationship between probabilities of an intersection related crash, distance from intersection, and speed limit.

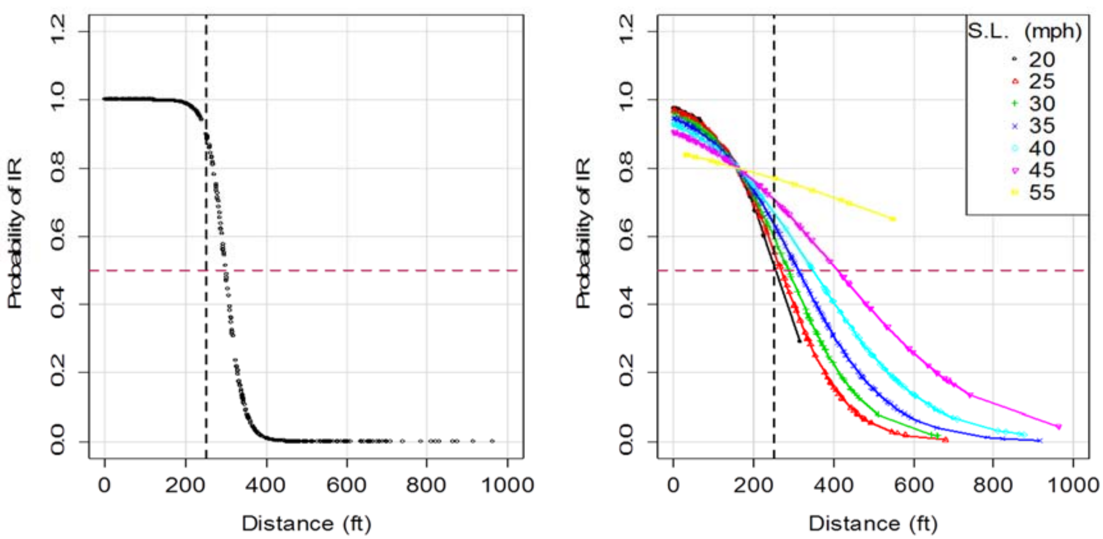


Figure 1. Probability of Intersection Related Crash, Distance from Intersection and Speed Limit

The researchers proposed a wider threshold of 300 ft to mitigate the risk of developing SPFs with under-prediction issues. It should be mentioned, however, that most of the intersections used by Avelar, Dixon and Escobar (2015) were located in urban environments, so it is not clear if the recommended threshold of 300 ft is also applicable at rural intersection.

2.6 Summary

This chapter has summarized recent research regarding SPFs and CMFs at different jurisdictions in the U.S. The overwhelming majority of studies indicate that the *HSM* SPFs should be calibrated or re-estimated to local conditions, as the SPFs provided in the *HSM* tend to provide biased results without calibration or re-estimation using local data. Other studies have compared the performance of calibrated *HSM* SPFs to locally estimated SPFs. Collectively, these studies suggest that locally estimated SPFs tend to provide more accurate results than calibrated *HSM* SPFs.

The research reviewed in this chapter has identified key CMFs for consideration during development of Michigan specific rural SPFs as a part of this project. Table 3, Table 5, Table, 6, Table 7, and Table 8 provide a summary of these key CMFs. The findings from this literature review further justify the development of SPFs that are unique to Michigan's rural segments and intersections. The following chapter summarizes the collection of data specific to Michigan's rural roadways and intersections for purposes of developing Michigan specific SPFs and CMFs. Subsequent chapters will describe the SPF and CMF development process for rural roadways and intersections in Michigan, including calibration of *HSM* models (Chapter 4), development of Michigan AADT-only models with regional indicators (Chapter 5), and development of fully specified Michigan models for rural segments (Chapter 6) and intersections (Chapter 7). The process for periodic maintenance of these models is provided in Chapter 8.

3.0 DATA COLLECTION

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

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

As a part of this study, the research team sought out and assembled data for rural roadway segments and rural intersections from multiple different sources, including state and local agencies. Available geospatial datasets were utilized whenever possible, although some characteristics required manual collection using satellite or street-level imagery. The objective of the data collection task was to quantify relevant roadway characteristics and assemble comprehensive databases for use in SPF development for the following types of rural roadway segments and rural intersections (examples of each are displayed in Figure 2):

a. Rural MDOT Two-Lane Two-Way (2U)
b. Rural County Two-Lane Two-Way Paved Federal Aid (2PF)
c. Rural County Two-Lane Two-Way Paved Non-Federal Aid (2PN)
d. Rural County Gravel Non-Federal Aid (2GN)
e. Rural MDOT Four-Lane Undivided (4U)
f. Rural MDOT Four-Lane Divided (4D)
g. Rural Three-Leg Stop Control (3ST)
h. Rural Three-Leg Signalized (3SG)
i. Rural Four-Leg Stop Control (4ST)
j. Rural Four-Leg Signalized (4SG)

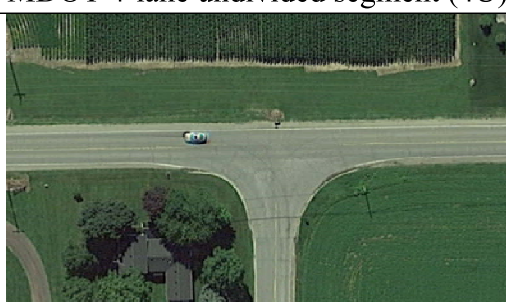
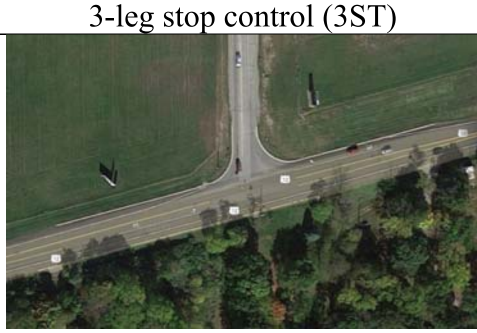
 MDOT 2-lane undivided segments (2U)	 County 2-lane paved fed-aid segment (2PF)
 County 2-lane paved non-fed aid segment (2PN)	 County 2-lane gravel segment (2GN)
 MDOT 4-lane undivided segment (4U)	 MDOT 4-lane divided segment (4D)
 3-leg stop control (3ST)	 4-leg stop control (4ST)
 3-leg signalized (3SG)	 4-leg signalized (4SG)

Figure 2. Rural Facility Types for Michigan SPF Development

Data were initially collected for each of the aforementioned 10 rural facility types from existing data sources that were available either publicly or through MDOT. These data sources included the following databases and files:

- Michigan State Police annual statewide crash database,
- MDOT annual sufficiency rating system file (herein referred to as "sufficiency file"),
- Michigan Geographic Data Library, including the All Roads shapefile and other relevant shapefiles based on the Michigan Geographic Framework,
- Census boundary shapefiles,
- MDOT driveway file,
- MSU's statewide horizontal curve database, and
- MDOT's intersection inventory.

Google Earth satellite imagery was utilized to manually collect additional data for SPF development that was not otherwise included in the existing data sets. Further details of each respective data source is provided in the following sections of this report.

3.1 Michigan Geographic Framework

The Michigan Geographic Framework All Roads shapefile (All_Roads.shp) provided the spatial basis for collection of the necessary roadway and traffic related attributes for county road segments and all intersections. The data collection process was facilitated via the roadway linear referencing system (LRS) used in the Michigan Geographic Framework (MGF). The LRS used in the MGF subdivides the public roadway network into a series of segments identified based on physical road (PR) number and begin/end milepoints, which allowed data from different sources to be uniquely and independently matched to the network based on their relative roadway position.

The initial data collection step was to obtain the basic spatial information pertaining to the Michigan roadway network. This was accomplished by using the "All_Roads.shp" GIS shapefile based on version 16a of the Michigan Geographic Framework (MGF), which was obtained from the Michigan Center for Geographic Information (MCGI) open data portal. The MGF represents a digital base map for the state, consisting of road segments, hydrographic features, urban boundaries, congressional districts, and other relevant boundaries and features for the entire state.

Although the All_Roads.shp file has a total of 39 attribute fields, the following were of particular use for this project:

- PR – Physical road number uniquely identifying road segments in Michigan
- BMP – Beginning mile point for each PR segment
- EMP – Ending mile point for each PR segment
- FCC – Framework Classification Code

The first three attributes (i.e., PR, BMP, and EMP) represent the primary values used in building the LRS for the state, and are subsequently used in identifying and locating events uniquely along Michigan's transportation network (i.e., crashes, AADT, roadway characteristics). Accordingly, the framework commonly serves as a backbone for all GIS mapping tasks. Updates to the framework for the prior year occur annually, and version 16a, which uses 2015 data, was utilized in this study.

Rural designation for segments and intersections in the all roads shapefile was defined on the basis of the designation provided in the Adjusted_Census_Urban_Boundaries.shp file. This file spatially defines each adjusted census urban boundary (ACUB) possessing a minimum population of 5,000, or urbanized area as designated by the U.S. Census, or the entire corporate limits of any incorporated city or village designated as partially urban by the Census (GIS Open Data, 2017). Only those road segments and intersections falling outside of the ACUB designated areas were retained for further analysis.

To further distinguish between rural areas and unincorporated rural communities with less than 5,000 population, a shape file containing census-designated places (CDPs) was obtained and integrated with the all roads shape file in ArcGIS. CDPs are defined as a concentration of population identified by the United States Census Bureau for statistical purposes, exclusive of incorporated cities, towns, and villages. For a list of CDPs and incorporated areas in Michigan, please refer to the Michigan census block maps maintained by the U.S. Census Bureau (2018). The CDP designation was only applied to intersections and county roadway segments. It was not applied to MDOT trunkline segments (2U, 4U, 4D) as these data were assembled using the MDOT sufficiency file as the basis, as described in the following subsection.

3.2 MDOT Sufficiency File

For decades, MDOT has maintained an annual roadway inventory database for state owned roads in Michigan known as the sufficiency file. Each annual sufficiency file contains 129 fields for data items and is divided into homogeneous segments of varying length with segment breaks based on a change in one or more roadway characteristics. Unique segments with homogeneous features are identified through physical road (PR) number, beginning mile point (BMP), and ending mile point (EMP) coordinates, with segmentation generally matching, or at least serving as a subset of that found in the MGF all roads shapefile. The annual MDOT sufficiency files for the period of 2011-2015 were utilized for purposes of this study. Information contained in each annual sufficiency file was used as the basis for assembly of the 2U, 4U, and 4D MDOT rural trunkline segments databases, as each segment within the database was considered a unique, homogeneous segment. 4D segments were provided in the sufficiency file as directional segments, with all attributes (number of lanes, AADT, etc.) populated for the respective direction only. These directional 4D segments were later manually paired together by members of the research team prior to SPF development. Relevant fields from the sufficiency file are listed below as defined from the sufficiency code descriptions (Allen, 2016):

- SURF_WIDTH- predominant surface width of the pavement for the segment measured to the nearest foot.
- NUM_LANES- predominant number of through lanes during peak hour conditions for the segment, this does not include continuous left turn lanes.
- LANE_WIDTH- predominant width of the through traffic lanes for the segment to the nearest foot.
- R_SHDR_WID- predominant width to the nearest foot of the improved shoulder on the right side of the roadway for divided segments, or both sides of the roadway for undivided segments. If the paved shoulder widths are different on either side of an undivided roadway, then the paved width shown is the lesser of the two sides.
- R_SHDR_PVD- predominant width to the nearest foot of the paved portion of the shoulder on the right side of the roadway for divided segments, or both sides of the roadway for undivided segments. If the paved shoulder widths are different on either side of an undivided roadway, then the paved width shown is the lesser of the two sides.

- L_SHDR_WID- predominant width to the nearest foot of the improved shoulder on the left side of the roadway for divided segments.
- L_SHDR_PVD- predominant width to the nearest foot of the paved shoulder on the left side of the roadway for divided segments.
- SPD_LIMIT- predominant posted speed limit for the segment in miles per hour (mph).
- SIGHT_RSTR- the length to the nearest tenth of a mile of no-passing zone distance for one direction of travel for the segment. This variable is only tracked for two-lane two-way segments.
- PCT_RSTR- calculated by dividing the length of no-passing zone on the segment by the length of the segment, then multiply by 100.
- PASS_LANE- indicates the presence of auxiliary passing lane(s) on the segment.
- ACUB - Adjusted census urban boundary indicates whether the segment falls within an urban and/or urbanized area with a population of 5,000 or more qualify as urban.

It should be noted that although such information was not included in the MDOT sufficiency file, nearly all MDOT two-lane two-way rural trunklines with 55 mph speed limits had continuous milled centerline rumble strips present during the study period. Shoulder rumble strips were also typically present for rural trunklines possessing paved shoulders at least 6 ft in width. These rumble strips were installed between 2008 and 2010 as part of MDOT's systemwide implementation program. Rumble strips were typically not installed (i.e., "gapped out") near intersections, commercial driveways, and bridge decks. Trunklines with concrete pavement surfaces also typically do not have centerline rumble strips. However, no attempts were made during this study to identify sections that did not include rumble strips. No county roads included in the study possessed rumble strips.

3.3 Traffic Volume Data

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

- MDOT trunkline AADTs were obtained systemwide for each rural roadway segment directly from the MDOT sufficiency file for each respective year in the study period (2011-

2015). Two-way AADTs were provided for 2U and 4U segments, while one-directional AADTs (equal to one-half of the total segment AADT) were provided for each directional 4D segment. A manual merge process was performed for all paired directional 4D segments to join the AADTs and all other relevant attributes.

- County federal aid roadway AADTs were obtained from the MDOT-maintained GIS shapefile for statewide non-trunkline federal aid (NTFA) roadways, entitled NTFA_Segment.shp. AADTs were obtained for either the year 2014 or 2015 for nearly the entire population of rural federal aid county roadways across all 83 counties statewide.
- County non-federal aid (Non-FA) roadways AADTs, including rural collectors and local roadways, were obtained directly from the county road commission (typically from the Roadsoft asset management system used by transportation agencies in Michigan) or the corresponding regional planning commission, where available. Volume data for rural non-federal aid county roadways were ultimately obtained for 27 counties across all portions of the state, including: Arenac, Baraga, Barry, Charlevoix, Clinton, Dickinson, Eaton, Genesee, Grand Traverse, Gratiot, Ingham, Iosco, Kalamazoo, Kent, Livingston, Luce, Macomb, Marquette, Mason, Mecosta, Muskegon, Oakland, Ogemaw, Roscommon, Schoolcraft, Washtenaw, and Wayne Counties. Because the AADTs for non-federal aid county roadways were obtained directly from the county or regional planning entity, the years for which traffic volumes were available varied from county-to-county.

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

3.4 Traffic Crash Data

The annual statewide crash databases were provided by MDOT for 2011-2015, which was the most recently available five-year period. The crash data were provided as extracts from the MDOT Crash Reporting Information System (CRIS), which is derived from the official statewide crash database maintained by the Criminal Justice Information Center (CJIC) of the Michigan State Police (MSP). The MSP crash database contains details of all reported public roadway crash records in the state of Michigan, sanitized of any personal information. Records in this database are maintained at the crash-, vehicle-, and person-levels with a total of eight separate spreadsheets included in the database as depicted in Figure 3.

Figure 3. Spreadsheets of the Michigan State Police Crash Database

For the purposes of this report, only crash level data was needed from the "1 crash" and "2 crash location" files. These sheets were linked in Microsoft Access using the "crsh_id" field, as shown in Figure 4.

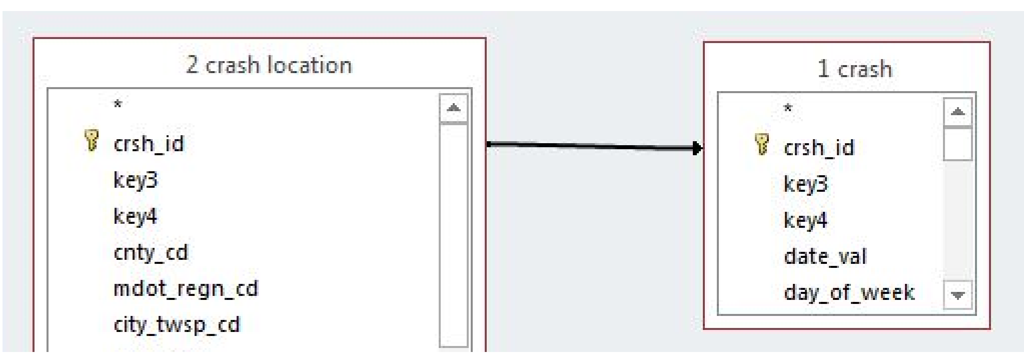


Figure 4. Joining of the Michigan State Police Crash Database Sheets

After joining the two sheets together, the information relevant to the report was exported. The relevant fields are defined below.

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

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

Segment crashes were identified by using the “mdot_area_type_cd” equal to 3, which indicates that the crash occurred on the “mid-block” portion of the segment (i.e., between intersections), and were matched to the appropriate roadway segment based on PR and milepoint for each segment.

Intersection crashes were identified by using "mdot_area_type_cd" equal to 2, which indicates "Intersection", and were matched with each intersection by using a 0.04 mi (211.2 ft) radius around the intersection node. Intersection node identification will be described later in this chapter.

3.5 Additional Roadway Inventory Datasets

Additional roadway inventory dataset were obtained from a variety of sources to supplement the information found in the aforementioned shapefiles. These datasets included information pertaining cross sectional features and roadway geometry that were not otherwise included in the aforementioned framework, traffic volume, or crash databases. The volume, crash, and roadway inventory data were then merged together into a comprehensive datafile, using MGF or sufficiency file for segmentation, for each of the various roadway or intersection types relevant to this study.

3.5.2 MDOT Driveway Inventory

MDOT maintains a trunkline driveway inventory file, which contains recent manually collected information pertaining to the location and type of driveway (i.e., residential, commercial, industrial, other) for each driveway observed on the rural trunkline system. These driveway counts were appended to the appropriate segments found in each of the annual MDOT sufficiency files using the driveway coordinates and the beginning and ending milepoints of each segment. A similar driveway count strategy was replicated for county highway segments during the manual data collection step. The driveway density was then calculated for each segment.

3.5.3 MDOT Trunkline Signals

MDOT also provided the research team with the TL_Signal_Intersections.shp shapefile, which contained the locations of MDOT trunkline intersections with some type of signal. This dataset included 2,819 potential trunkline signal locations. After filtering the locations to the rural "SubType" category, a further inspection of the node locations was performed in Google Earth to confirm whether the location was actually an operational traffic signal at the intersection of two or more intersecting roadways. Cases where no signal was present, mid-block crossings, or flashing beacons at a stop controlled intersection were removed from the dataset. Additionally, rural signal nodes located at interchange ramp terminals were also removed, as these were not considered traditional rural intersections for use towards SPF development. The resulting dataset included only 194 rural MDOT trunkline signal intersections (based on not falling within an ACUB boundary) for further analysis. Rural signalized intersections falling within a CDP were included due to the small sample size.

3.5.6 Horizontal Curves

Horizontal curve information for each segment was obtained through an extraction process initially developed by researchers at Wayne State University and applied to all rural roadways in Michigan, including MDOT trunkline and county roadways. The extraction process estimates the radius and length of horizontal curves based on the All_Roads.shp shapefile using tools and code written for GIS. The information includes number of curves with radii of up to 0.5 miles, length of the curved portion of the segment, fraction of segment length that is curved, and average radii of curves up to 0.5 miles for a segment. The information was organized in cumulative categories, decreasing in order of radii, from 0.5 mile radii to 0.088 mile radii. The curve data were then merged with the roadway inventory data for the respective segment. To account for segment breaks across curves, the curve data were compiled for each radius threshold in the following manner: length of the curved portion of the segment, proportion of the segment on a curve, and the average radii of curves on the segment. Ultimately, horizontal curves with radii of 0.297 mi (1568 ft) and below, which corresponds to a maximum design speed of 65 mph assuming a superelevation of 7 percent (maximum superelevation used by MDOT), were selected for CMF development. This curve design speed was chosen to provide an adequate sample of curved segments and to coincide with the new 65 mph maximum statutory speed limit for rural non-freeway highways in Michigan that was enacted in 2017. Furthermore, any segments with a horizontal radius larger than 1568 ft were ultimately pooled with tangent segments for later analysis.

3.6 Rural Intersection Identification and Database Assembly

In order to identify intersections within Michigan's roadway network, a spatially-based algorithm was developed in ArcGIS to generate nodes based on the occurrence of intersecting lines from the All_Roads.shp file. As shown in

Figure 5 the algorithm includes six main steps. First the full road network was obtained via the All_Roads.shp file, where each public road segment was represented by a unique line in 2-

dimensional GIS space. Points were generated at each vertex of the aggregated roadway network, where vertices have the following general properties:

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

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

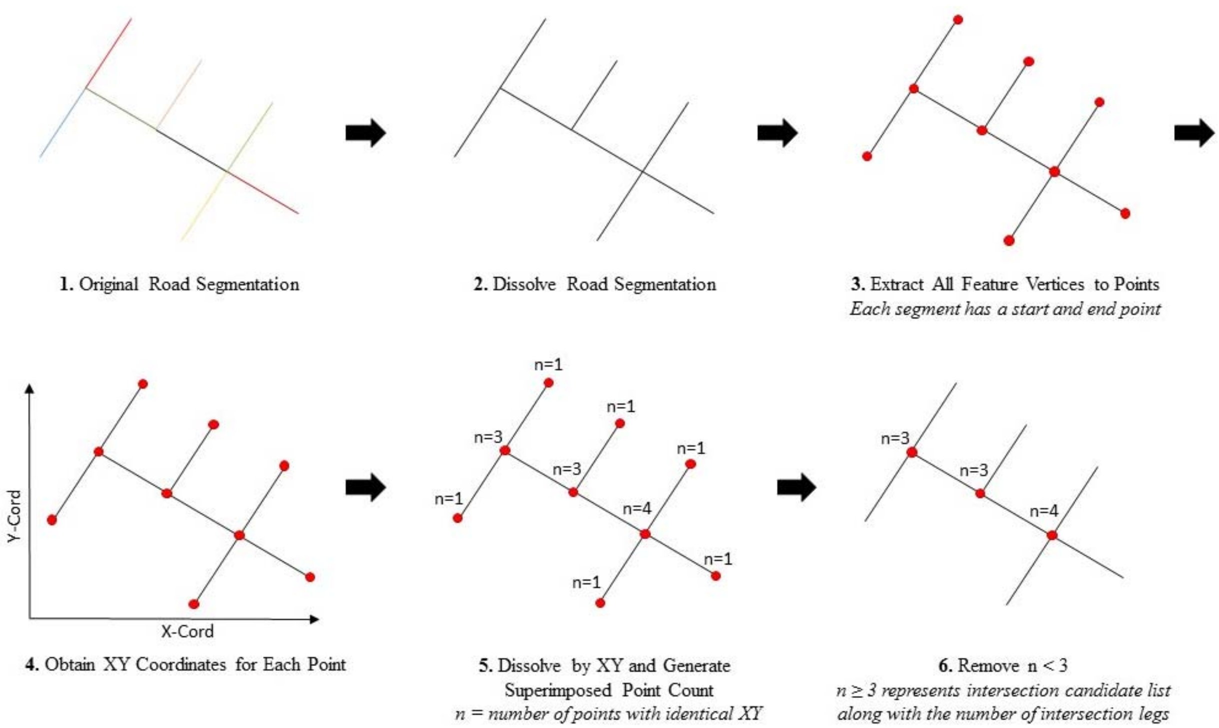


Figure 5. Node Identification Algorithm

Following the node generation process for potential intersections, any intersection node located within an ACUB zone was removed to limit the data solely to rural designated intersections. Stop controlled nodes falling within a CDP were also excluded, although signalized intersections located within a CDP were included due to small sample sizes. Segment information from the All_Roads.shp file were then attached to each node for all corresponding node legs via a one-to-one spatial join with a sensitivity search radius of 5 feet. The spatial join was performed to build a relationship between the node dataset and segment dataset for purposes of joining available traffic volume data to each leg of the node. To determine the availability of traffic volume data, nodes were categorized (MDOT, county federal aid, or county non-federal aid) based on the framework classification code (FCC) of each leg. For a node to be included in the analysis, it was necessary for each major and minor roadway to have at least one leg with traffic volume data. This was only an issue for non-federal aid county roadways, as traffic volume data were available within existing statewide databases for all MDOT trunklines and county federal-aid roadways.

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

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

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

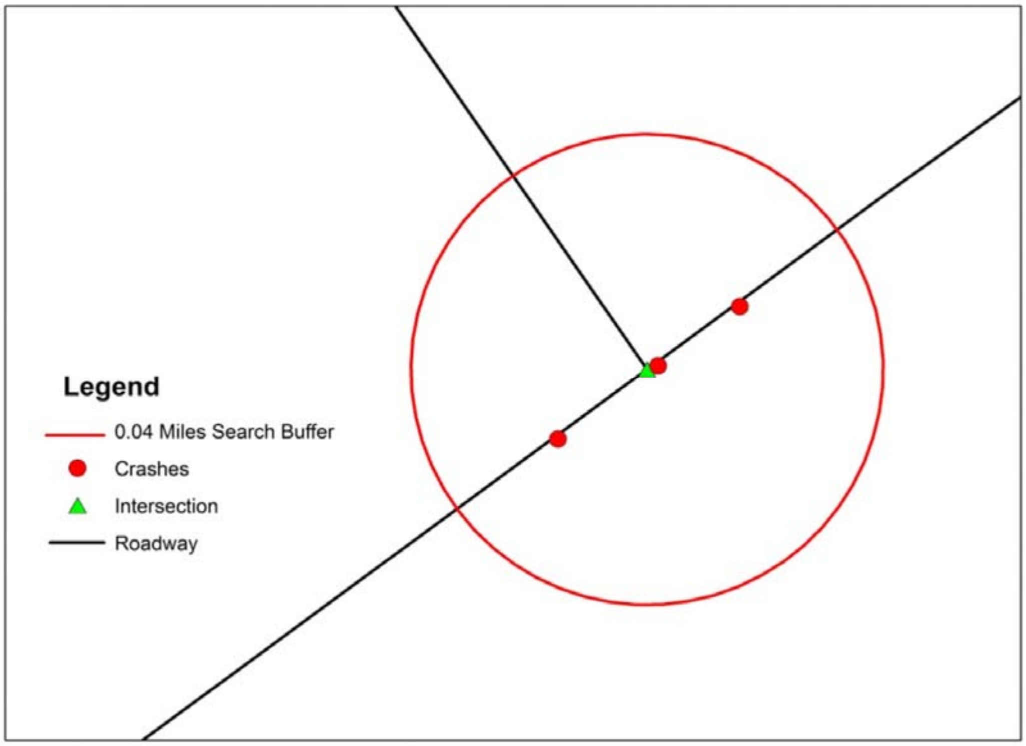


Figure 6. 3-leg Intersection with Crash Search Threshold

Table 11 provides details of the resulting data set, including a count of the number of intersections by type, as well as averages of the major AADT, minor AADT, and total annual crashes. It should be noted that each of Michigan's 83 counties were represented in the 3ST and 4ST datasets.

Table 11. Rural Intersection Summary Statistics

Statistic	3SG	4SG	3ST				4ST			
			MDOT	NTFA	NonFA	TOTAL	MDOT	NTFA	NonFA	TOTAL
Number of Intersections	19	175	664	1212	421	2297	818	1389	306	2513
Average Major Road AADT	9608	9336	4715	2033	544	2536	4803	2200	619	2855
Average Minor Road AADT	3849	3670	1042	730	186	721	1033	743	254	778
Average Annual Crashes per Intersection	3.02	4.11	0.78	0.43	0.10	0.47	1.12	0.72	0.20	0.78

3.7 Rural Segment Database Assembly

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

Following the AADT volume segment assignment, 2011-2015 crashes were matched to the applicable segment in a similar manner using the PR and MP values as presented in each crash record. A secondary criteria was implemented to include only those crashes whose "mdot_area_type_cd" is equal to 3. This particular code represents crashes that not associated with an interchange or intersection (i.e., midblock). Lastly, all assigned crashes were tabulated by year, type, and severity for each segment, exclusive of deer crashes.

The MDOT trunkline segment datasets (2U, 4U, 4D) were assembled using available spatial datasets, using the MDOT sufficiency file as a basis. As all relevant information for SPF development was already present, no additional manual data collection was performed. Directional segment pairs of 4D segments in the sufficiency file were manually identified and paired together. Data for these paired directional segments were combined either by adding or averaging, which depended on the particular attribute.

Finally, all segment datasets were screened to include only segments that were 0.1 miles or more in length, which is the minimum segment length recommended by the *HSM* to adequately represent physical and safety conditions for the facility (AASHTO, 2010). Table 12 provides details of the resulting data set, including a count of the number segments and segment mileage by facility type, as well as averages of the AADT, total annual segment crashes (per mile), non-deer annual segment crashes (per mile), and deer crashes as a proportion of total segment crashes. It can be observed from Table 12, that the proportion of deer crashes ranges from 0.38 to 0.69, depending on facility type, which far exceeds the proportion of deer crashes (0.121) reported for the crash data from Washington State that was used to develop the two-lane two-way SPF found in the *HSM*. This has significant implications on the transferability of the *HSM* segment models for use in Michigan.

Table 12. Rural Segment Summary Statistics

Statistic	MDOT 2U	County Paved FA (2PN)	County Paved Non FA (2PF)	County Gravel Non FA (2GN)	MDOT 4U	MDOT 4D
Number of Segments	1556	9912	2873	3983	58	55
Segment Mileage	5351.6	4423.7	1463.4	2007.2	95.2	106.7
Average AADT	4382	1717	585	241	9373	13518
Average Annual Segment Crashes per mile	2.51	1.49	0.56	0.24	4.19	5.10
Average Annual Non-Deer Segment Crashes per Mile	0.79	0.58	0.22	0.15	1.88	2.51
Deer Crashes as Proportion of Total Segment Crashes	0.69	0.61	0.61	0.38	0.55	0.51

3.8 Additional Manual Data Collection

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

3.8.1 Intersection Data

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

- Number of intersecting legs: Only traditional 3-leg and 4-leg intersections were included.

- Assignment of major and minor approaches: The major and minor approach legs were assigned to each intersection based on highest and lowest segment AADT, respectively.
- Number of stop controlled approaches (stop controlled intersections only): The number of stop controlled approaches for each 3-leg and 4-leg intersection was noted. Intersections for which street level imagery was not available were removed from the dataset, as it was not possible to confirm the presence of stop control on the major and minor approaches. This issue typically only impacted non-federal aid intersections, as Street View imagery was available for all MDOT roadways and many county federal aid roadways.
- Traffic signal type (signalized intersections only): The type of traffic signal support was coded as box span, diagonal span, or mast-arm.
- Number of through traffic lanes: The number of through lanes were determined for each individual approach of the intersection. Shared use lanes (i.e., combined through/turn) were counted as a through lane.
- Turn lane presence: Right and left turn lanes were identified based on presence of pavement markings and/or sign designations. These data were aggregated by the number of approaches with turn lanes. Tapers or widened shoulders were not considered.
- Driveway counts: The number of driveways that were at least partially within at 211 ft radius of the center of the intersection was counted individually for each intersection leg.
- Skew angle: Intersection skew angles were obtained using the heading tool in Google Earth. The *HSM* defines intersection skew angle as the absolute value of the deviation from an intersection angle of 90 degrees. In this definition, skew can range from zero for a perpendicular intersection and to a maximum of 89 degrees. For this study, skew was measured as the smallest angle between any two legs of the intersection. The heading of each leg was measured with respect to the centerline, and the absolute difference of those two headings was then calculated. The skew angle was calculated as the absolute difference of this angle from 90 degrees.
- Flashing beacon presence (stop controlled intersections only).
- Lighting presence (mast-arm or single span wire with hanging light).
- Median presence: Medians were identified along the major leg only.
- Curb presence: Curbs were considered present if they were located on any of the intersection legs within a 211 ft radius of the center of the intersection.

- Sidewalk presence: Sidewalks were considered present if they were located on any of the intersection legs within a 211 ft radius of the center of the intersection.
- Railroad crossing presence: At-grade railroad crossings that fell within a 211 ft radius of the center of the intersection were identified.

In addition to serving as important analytical factors for SPF and CMF development, these manually collected data were in some cases also used for additional screening for identification of appropriate study sites. For example, to provide consistency with the *HSM*, only cases with minor roadway stop control (i.e., one-stop leg for 3-leg intersections and two-stop legs for 4-leg intersections) were retained for further analysis. Furthermore, intersections with high skew angles that were a part of a perpendicular intersection with a bypass curve between adjacent legs were removed from the analysis because the nature of the turning traffic movements is not properly indicated by the major and minor AADT values. This case is common in rural settings where the through movement follows a 90 degree turn, but the tangent legs are retained as minor road approaches.

3.8.2 Segment Data

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

- Driveway count by type: Driveways falling within the segment boundaries were counted and classified as residential or commercial/industrial to match the procedure used to assemble MDOT's trunkline driveway file. Field driveways that did not lead to a structure were not included.
- Surface type: Surface type was classified as paved or gravel.

- Surface width: For paved roadways the surface width (in feet) was measured from paved edge to paved edge. For gravel roadways, the surface width was taken as the predominant extent of width.
- Traveled way width: Width in feet between edgelines (if present) on paved surfaces only.
- Lane width: Calculated as the traveled way width divided by the number of lanes.
- Shoulder width: Calculated as the difference between the surface width and the traveled way width, divided by two.
- Number of lanes: Predominant number of lanes (both directions) within segment boundary.
- Presence of edgelines, centerlines, curbs, two-way left turn lanes, rumble strips, passing lanes, and on-street parking were each individually assessed using aerial imagery, supplemented by street view, where present. Unobservable cases were noted.

3.9 Quality Control/Quality Assurance Verification

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

4.0 PRELIMINARY DATA ANALYSIS

After the data were assembled for rural road segments and intersections in Michigan, a series of preliminary analyses were conducted to examine general trends across all locations for each facility type. This included assessment of the relationships between annual crash frequency and AADT, with scatterplots of these relationships generated for each facility type. After these initial data investigations, calibration factors were generated for each corresponding *HSM* model using the Michigan crash data for the respective segment and intersection facility type.

4.1 Rural Intersections

4.1.1 Rural Three Leg Stop Controlled Intersections (3ST)

The Figure 7 displays the location of three leg stop controlled (3ST) intersection study locations throughout Michigan. Each intersection included only one stop approach, which was located on the minor roadway. The seven MDOT regions are identified in the figure by distinct colors, with county borders also displayed. All 83 counties were represented in the 3ST dataset.

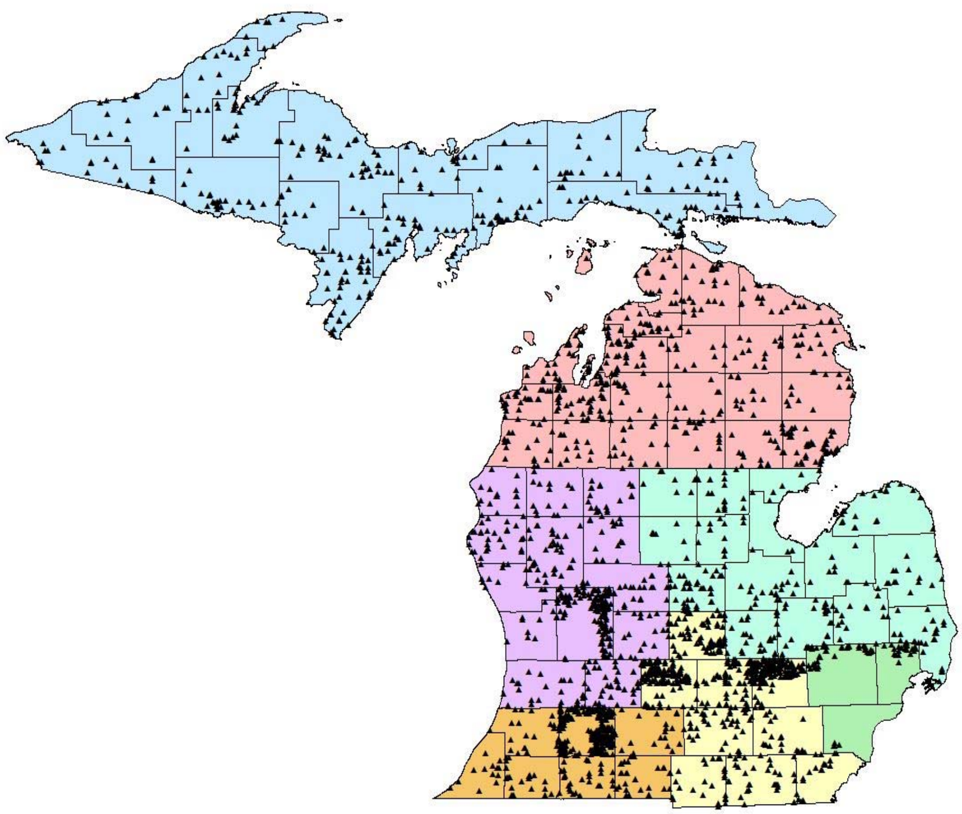


Figure 7. Map of Rural Three-Leg Stop Controlled (3ST) Intersection Locations

Table 13 provides summary statistics (i.e., mean, minimum, maximum, standard deviation) for all relevant variables of interest considered during 3ST SPF development.

Table 13. Descriptive Statistics for Rural 3ST Intersections

Factor	Min	Max	Mean	Std. Dev.
AADT-Major	26.0	32006.0	2535.53	2807.47
AADT-Minor	4.00	6533.00	720.52	871.57
AADT-Total	45.0	32293.0	3256.06	3273.48
MDOT Major Roadway	0.0	1.0	0.29	0.45
County Federal Aid Major Roadway	0.0	1.0	0.53	0.50
County Non-Federal Aid Major Roadway	0.0	1.0	0.18	0.39
Stop/Caution Overhead Flashing Beacon Present	0.0	1.0	0.03	0.16
Lighting Present	0.0	1.0	0.29	0.45
Skew Angle	0.0	80.0	8.68	16.06
Number of Approaches with Left Turn Lane	0.0	3.0	0.08	0.32
Number of Approaches with Right Turn Lane	0.0	2.0	0.11	0.37
Number of Thru Lanes - Major	1.0	2.0	1.03	0.16
Driveway Count	0.0	13.0	1.68	1.77
Median Present on Major	0.0	0.0	0.00	0.00
Railroad Presence	0.0	1.0	0.02	0.13
Sidewalk Ramps	0.0	1.0	0.00	0.06
Curb Present	0.0	1.0	0.31	0.46
Superior Region	0.0	1.0	0.12	0.33
North Region	0.0	1.0	0.17	0.37
Grand Region	0.0	1.0	0.17	0.37
Southwest Region	0.0	1.0	0.17	0.37
University Region	0.0	1.0	0.25	0.43
Bay Region	0.0	1.0	0.10	0.30
Metro Region	0.0	1.0	0.03	0.17
Crashes Per Year (2011-2015)				
Intersection Total	0.0	14.0	0.47	0.92
Intersection FI	0.0	5.0	0.09	0.34
Intersection PDO	0.0	13.0	0.38	0.79

Number of intersections = 2297

The Figure 8 displays the scatter of the annual crash frequency versus the total intersection AADT (major plus minor). Although the AADT has a maximum of just over 32,000, only a small number of intersections possessed traffic volumes greater than 17,000 vehicles per day.

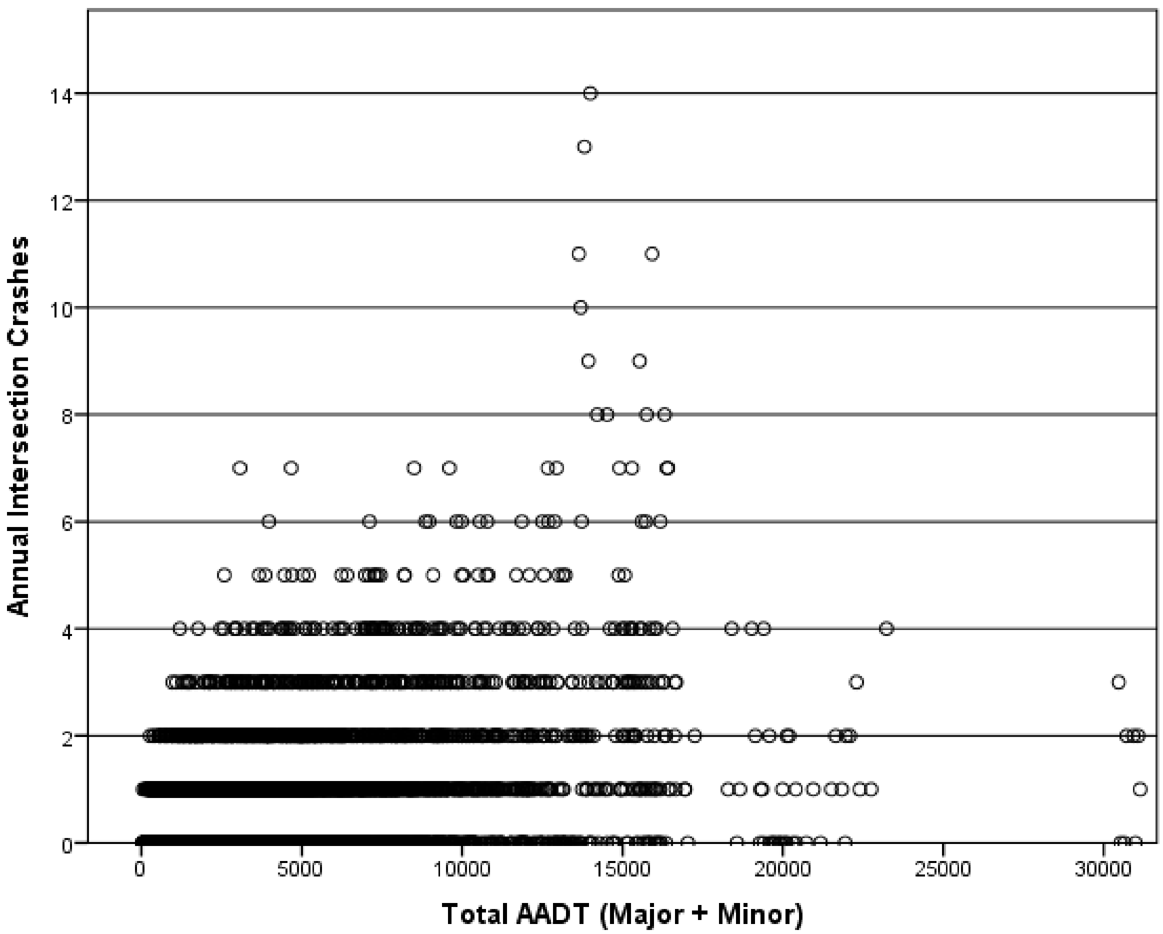


Figure 8. Annual Intersection Crash Frequency vs Total AADT for Rural 3ST Intersections

Table 14 shows crash distributions for 3ST intersections. The tables were formatted to match that of Tables 10-5, 10-6, and 10-15 found in Chapter 10 of the *HSM*. The crash distributions also closely match the format of the information required for entry in the FHWA's *IHSDM* safety tool.

In comparison to the default distributions presented in Chapter 10 of the *HSM*, Michigan's rural 3ST intersection crashes tend to be less severe. In consideration of crash types, a relatively high proportion of single vehicle crashes involved deer, likely contributing to the lower severity compared to the *HSM*. Angle and rear-end collisions are the most prevalent specific categories of multiple-vehicle crashes at 3ST intersections in Michigan, which is consistent with the default distributions in the *HSM*. The proportion of crashes occurring in dark conditions is notably higher than the default distribution in the *HSM*, again, likely due to the high proportion of deer crashes.

Table 14. Crash Severity and Crash Type Distributions for Rural 3ST Intersections

Crash Severity Level, Collision Type, or Light Condition	Count of Intersection Crashes (2011-2015)	Percent of Total Intersection Crashes
Fatal (Type K)	25	0.5%
Incapacitating Injury (Type A)	148	2.7%
Nonincapacitating Injury (Type B)	313	5.8%
Possible Injury (Type C)	598	11.1%
Fatal + Injury (Type K+ABC)	1084	20.1%
Property Damage Only (Type PDO)	4311	79.9%
Single Motor Vehicle	3159	58.6%
Single Motor Vehicle (Deer Excluded)	1764	32.7%
Deer Crashes	1409	26.1%
Multiple Vehicle Crashes	2223	41.2%
Day Crashes	2850	52.8%
Dark Crashes	2545	47.2%
Total Crashes (5 years)	**5395**	**100.0%**

Collision Type	Percent of FI Intersection Crashes	Percent of PDO Intersection Crashes	Percent of Total Intersection Crashes
SINGLE-VEHICLE CRASHES			
Collision with deer	2.0%	32.2%	26.1%
Collision with bicycle	0.6%	0.0%	0.1%
Collision with pedestrian	0.4%	0.0%	0.1%
Overturned	7.9%	2.2%	3.4%
Other single-vehicle crash	32.9%	28.1%	29.1%
Total single-vehicle crash	43.8%	62.6%	58.8%
MULTIPLE-VEHICLE CRASHES			
Angle collision	19.3%	8.4%	10.6%
Head-on collision	9.3%	1.7%	3.2%
Read-end collision	19.6%	17.9%	18.3%
Sideswipe collision	5.3%	5.7%	5.6%
Other multiple-vehicle collision	2.7%	3.7%	3.5%
Total multiple-vehicle collision	56.2%	37.4%	41.2%
Total Crashes	**100.0%**	**100.0%**	**100.0%**

4.1.2 Rural Four Leg Stop Controlled Intersections (4ST)

Figure 9 displays the distribution of four leg stop controlled (4ST) intersection study locations throughout the state of Michigan. Each intersection included two-way stop control on the minor approaches. This type of intersection is the most common of all the intersection types analyzed and 83 counties were represented in the dataset. Due to the large number of 4ST intersections, the preliminary analysis was performed on separate sub-sets based on the jurisdiction of the major roadway at the intersection. Therefore, a sub-set was created for MDOT, county federal aid, and county non-federal aid intersections.

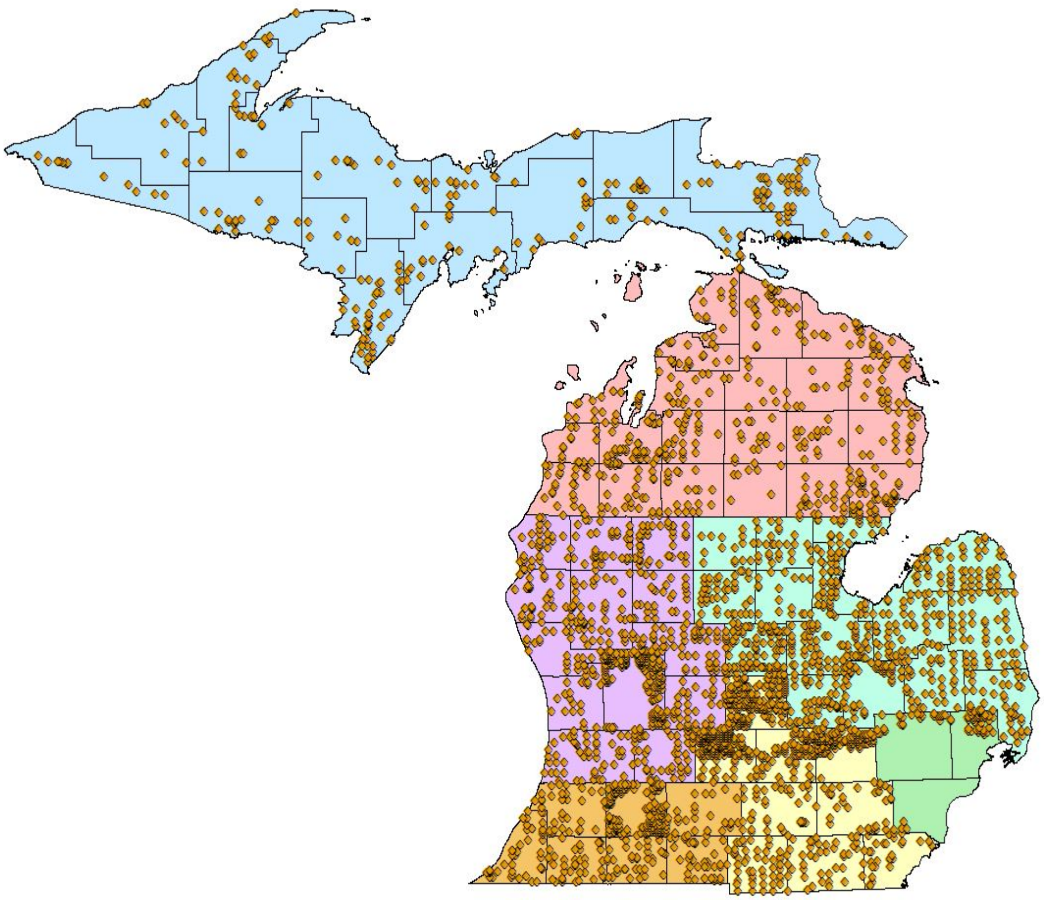


Figure 9. Map of Rural Four Leg Stop Controlled (4ST) Intersections

Table 15 provides summary statistics (i.e., mean, minimum, maximum, standard deviation) for all relevant variables of interest considered during 4ST SPF development for each of the three jurisdiction classifications. It can be observed that 4ST intersections under MDOT jurisdiction clearly possess higher major road traffic volumes than the county intersections.

Table 15. Descriptive Statistics for Rural 4ST Intersections

Factor	Min	Max	Mean	Std. Dev.
AADT-Major	57.0	20274.0	2854.88	2604.13
AADT-Minor	2.00	6829.00	777.94	785.64
AADT-Total	99.0	21471.0	3632.82	3035.87
MDOT Major Roadway	0.0	1.0	0.33	0.47
County Federal Aid Major Roadway	0.0	1.0	0.55	0.50
County Non-Federal Aid Major Roadway	0.0	1.0	0.12	0.33
Stop/Caution Overhead Flashing Beacon Present	0.0	1.0	0.09	0.28
Lighting Present	0.0	1.0	0.35	0.48
Skew Angle	0.0	75.4	5.47	12.24
Number of Approaches with Left Turn Lane	0.0	4.0	0.16	0.65
Number of Approaches with Right Turn Lane	0.0	4.0	0.17	0.56
Number of Thru Lanes - Major	1.0	2.0	1.03	0.16
Number of Thru Lanes - Minor	0.0	1.0	1.00	0.02
Driveway Count	0.0	17.0	2.02	2.15
Median Present on Major	0.0	0.0	0.00	0.00
Railroad Presence	0.0	1.0	0.01	0.12
Sidewalk Ramps	0.0	1.0	0.01	0.10
Curb Present	0.0	1.0	0.31	0.46
Within Census Designated Place	0.0	0.0	0.00	0.00
Superior Region	0.0	1.0	0.08	0.27
North Region	0.0	1.0	0.14	0.35
Grand Region	0.0	1.0	0.21	0.41
Southwest Region	0.0	1.0	0.11	0.31
University Region	0.0	1.0	0.23	0.42
Bay Region	0.0	1.0	0.21	0.40
Metro Region	0.0	1.0	0.02	0.15
Crashes Per Year (2011-2015)				
Intersection Total	0.0	13.0	0.78	1.20
Intersection FI	0.0	6.0	0.24	0.57
Intersection PDO	0.0	11.0	0.55	0.92

Number of intersections = 2513

Figures 10, 11, and 12 show a scatter plot of the annual crash frequency versus the total AADT (major plus minor) for each of the jurisdictional subsets. The relationship between crashes vs. total AADT is somewhat similar for MDOT and county federal aid intersections, although county non-federal aid intersections clearly show fewer crashes per year at equivalent AADTs.

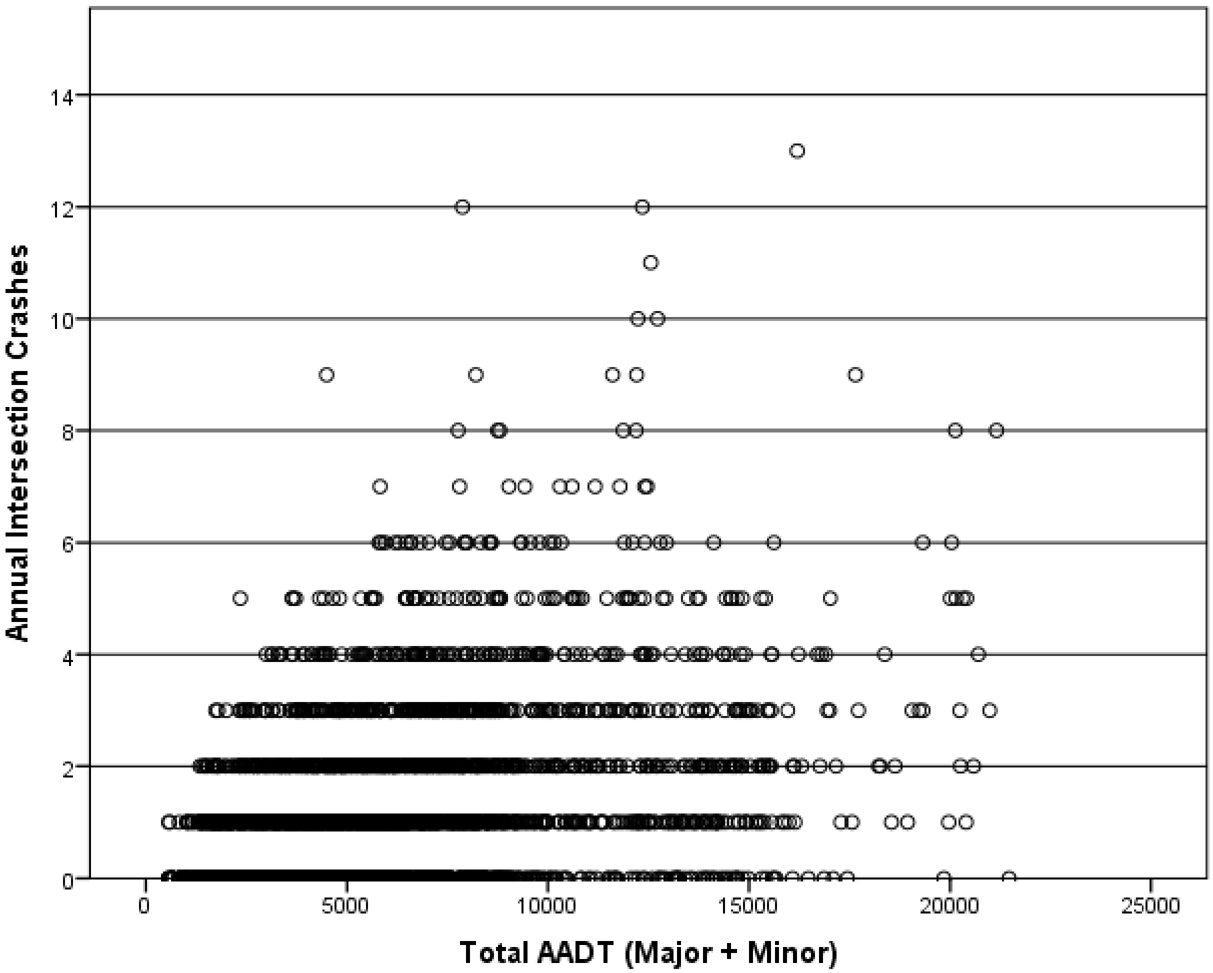


Figure 10. Annual Crash Frequency vs Total AADT for Rural 4ST Intersections, MDOT

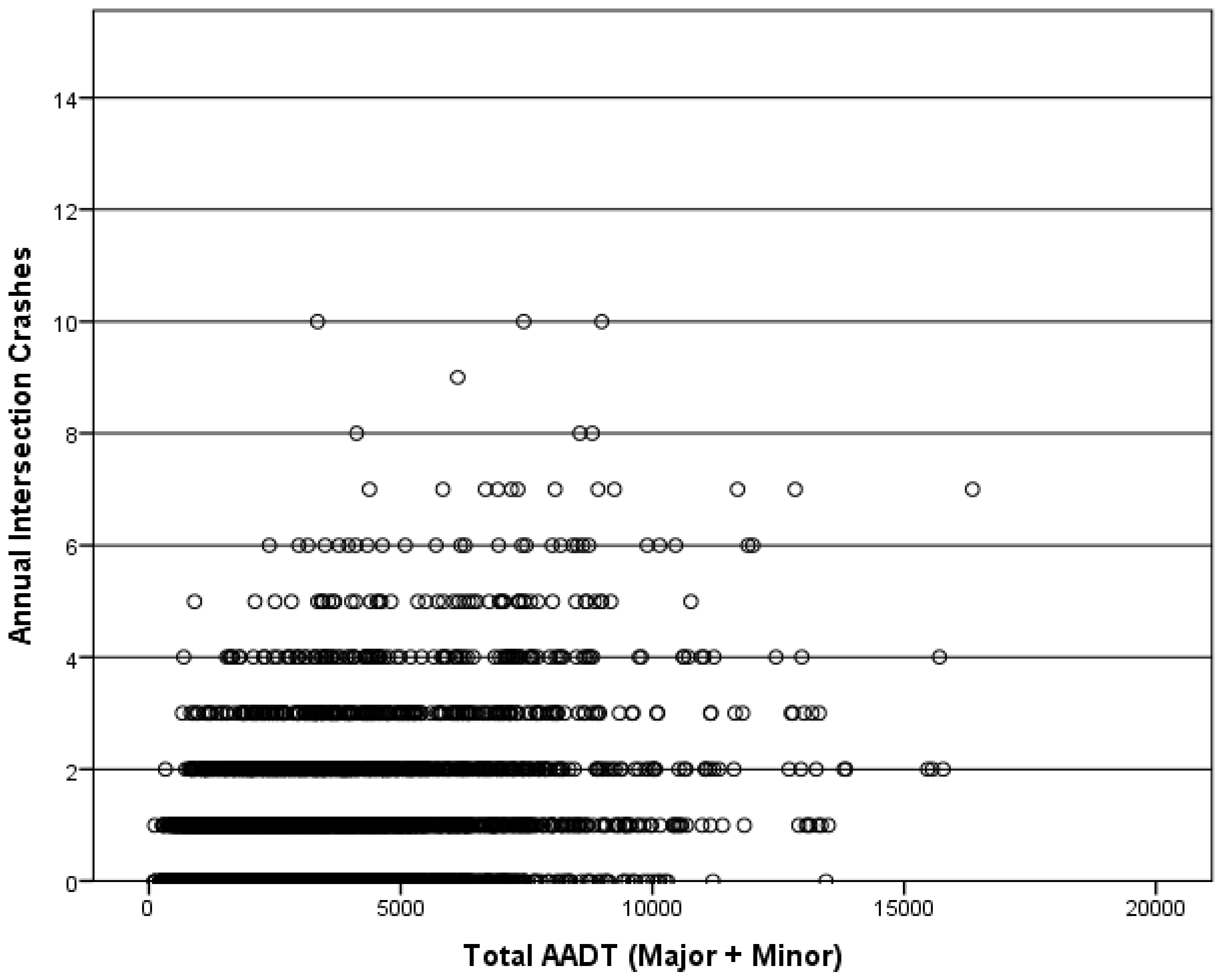


Figure 11. Annual Crash Frequency vs Total AADT for Rural 4ST Intersections, County Federal Aid

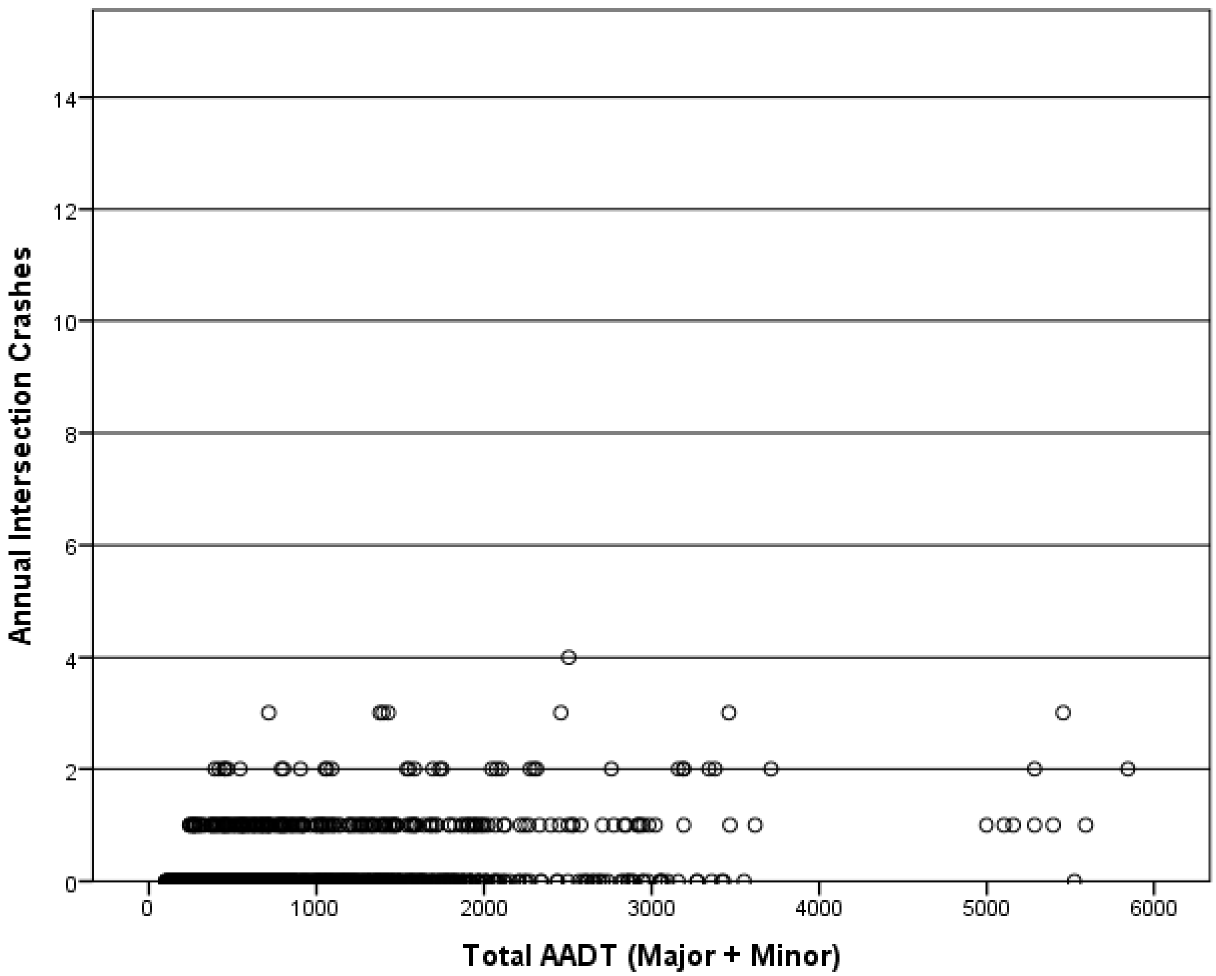


Figure 12. Annual Crash Frequency vs Total AADT for Rural 4ST Intersections, County Non-Federal Aid

Tables 16 through 18 show crash distributions for 4ST intersections for each of the jurisdictional subsets. It can be observed that MDOT intersections have a lower proportion of crashes involving fatalities and/or injuries compared to the other jurisdictions. This is also true for all 4ST rural Michigan intersections in comparison to the default distributions presented in Chapter 10 of the *HSM*. Within the distributions of collisions by type, angle collisions comprised a far greater proportion of intersection crashes at county road intersections compared to MDOT intersections. A potential explanation for this situation is the available intersection sight distance at MDOT intersections as compared to the county road system. This could manifest either in horizontal sight triangles clear of obstructions or vertical sight distance along the approaches.

Table 16. Crash Severity and Crash Type Distributions for Rural 4ST Intersections, MDOT

Crash Severity Level, Collision Type, or Light Condition	Count of Intersection Crashes (2011-2015)	Percent of Total Intersection Crashes
Fatal (Type K)	50	1.1%
Incapacitating Injury (Type A)	191	4.2%
Nonincapacitating Injury (Type B)	347	7.6%
Possible Injury (Type C)	671	14.6%
Fatal + Injury (Type K+ABC)	1259	27.5%
Property Damage Only (Type PDO)	3323	72.5%
Single Motor Vehicle	1626	35.5%
Single Motor Vehicle (Deer Excluded)	652	14.2%
Deer Crashes	978	21.3%
Multiple Vehicle Crashes	2939	64.1%
Day Crashes	2908	63.5%
Dark Crashes	1674	36.5%
Total Crashes (5 years)	**4582**	**100.0%**

Collision Type	Percent of FI Intersection Crashes	Percent of PDO Intersection Crashes	Percent of Total Intersection Crashes
SINGLE-VEHICLE CRASHES			
Collision with deer	1.2%	29.0%	21.3%
Collision with bicycle	0.3%	0.0%	0.1%
Collision with pedestrian	0.8%	0.1%	0.3%
Overturned	2.6%	1.5%	1.8%
Other single-vehicle crash	7.0%	14.4%	12.3%
Total single-vehicle crash	11.9%	44.9%	35.9%
MULTIPLE-VEHICLE CRASHES			
Angle collision	53.8%	21.1%	30.1%
Head-on collision	9.1%	2.0%	4.0%
Read-end collision	19.3%	20.1%	19.9%
Sideswipe collision	3.4%	7.4%	6.3%
Other multiple-vehicle collision	2.5%	4.5%	4.0%
Total multiple-vehicle collision	88.1%	55.1%	64.1%
Total Crashes	**100.0%**	**100.0%**	**100.0%**

Table 17. Crash Severity and Crash Type Distributions for Rural 4ST Intersections, County Federal Aid

Crash Severity Level, Collision Type, or Light Condition	Count of Intersection Crashes (2011-2015)	Percent of Total Intersection Crashes
Fatal (Type K)	71	1.4%
Incapacitating Injury (Type A)	241	4.9%
Nonincapacitating Injury (Type B)	464	9.3%
Possible Injury (Type C)	834	16.8%
Fatal + Injury (Type K+ABC)	1610	32.4%
Property Damage Only (Type PDO)	3357	67.6%
Single Motor Vehicle	1699	34.2%
Single Motor Vehicle (Deer Excluded)	792	15.9%
Deer Crashes	917	18.5%
Multiple Vehicle Crashes	3252	65.5%
Day Crashes	3238	65.2%
Dark Crashes	1729	34.8%
Total Crashes (5 years)	**4967**	**100.0%**

Collision Type	Percent of FI Intersection Crashes	Percent of PDO Intersection Crashes	Percent of Total Intersection Crashes
SINGLE-VEHICLE CRASHES			
Collision with deer	1.2%	26.8%	18.5%
Collision with bicycle	0.2%	0.0%	0.1%
Collision with pedestrian	0.6%	0.1%	0.2%
Overturned	3.2%	1.8%	2.2%
Other single-vehicle crash	8.6%	15.9%	13.5%
Total single-vehicle crash	13.7%	44.5%	34.5%
MULTIPLE-VEHICLE CRASHES			
Angle collision	67.9%	29.6%	42.0%
Head-on collision	6.2%	2.8%	3.9%
Read-end collision	7.8%	12.7%	11.1%
Sideswipe collision	2.2%	6.2%	4.9%
Other multiple-vehicle collision	2.2%	4.2%	3.5%
Total multiple-vehicle collision	86.3%	55.5%	65.5%
Total Crashes	**100.0%**	**100.0%**	**100.0%**

Table 18. Crash Severity and Crash Type Distributions for Rural 4ST Intersections, County Non-Federal Aid

Crash Severity Level, Collision Type, or Light Condition	Count of Intersection Crashes (2011-2015)	Percent of Total Intersection Crashes
Fatal (Type K)	4	1.3%
Incapacitating Injury (Type A)	7	2.3%
Nonincapacitating Injury (Type B)	28	9.2%
Possible Injury (Type C)	48	15.8%
Fatal + Injury (Type K+ABC)	87	28.6%
Property Damage Only (Type PDO)	217	71.4%
Single Motor Vehicle	132	43.4%
Single Motor Vehicle (Deer Excluded)	66	21.7%
Deer Crashes	67	22.0%
Multiple Vehicle Crashes	171	56.3%
Day Crashes	192	63.2%
Dark Crashes	112	36.8%
Total Crashes (5 years)	**304**	**100.0%**

Collision Type	Percent of FI Intersection Crashes	Percent of PDO Intersection Crashes	Percent of Total Intersection Crashes
SINGLE-VEHICLE CRASHES			
Collision with deer	0.0%	30.9%	22.0%
Collision with bicycle	0.0%	0.0%	0.0%
Collision with pedestrian	1.1%	0.0%	0.3%
Overturned	3.4%	0.9%	1.6%
Other single-vehicle crash	10.3%	23.5%	19.7%
Total single-vehicle crash	14.9%	55.3%	43.8%
MULTIPLE-VEHICLE CRASHES			
Angle collision	79.3%	33.2%	46.4%
Head-on collision	1.1%	1.4%	1.3%
Read-end collision	3.4%	5.1%	4.6%
Sideswipe collision	1.1%	1.8%	1.6%
Other multiple-vehicle collision	0.0%	3.2%	2.3%
Total multiple-vehicle collision	85.1%	44.7%	56.3%
Total Crashes	**100.0%**	**100.0%**	**100.0%**

4.1.3 Rural Three Leg Signalized Intersections (3SG)

Figure 13 displays the distribution of three leg signalized (3SG) intersection study locations throughout the state of Michigan. Only 19 rural 3SG intersections were identified across the state, with none in the Superior or Metro regions. Thus, the 3SG study sites were combined with 4SG intersections prior to SPF development, with a CMF subsequently developed for the number of intersection legs.

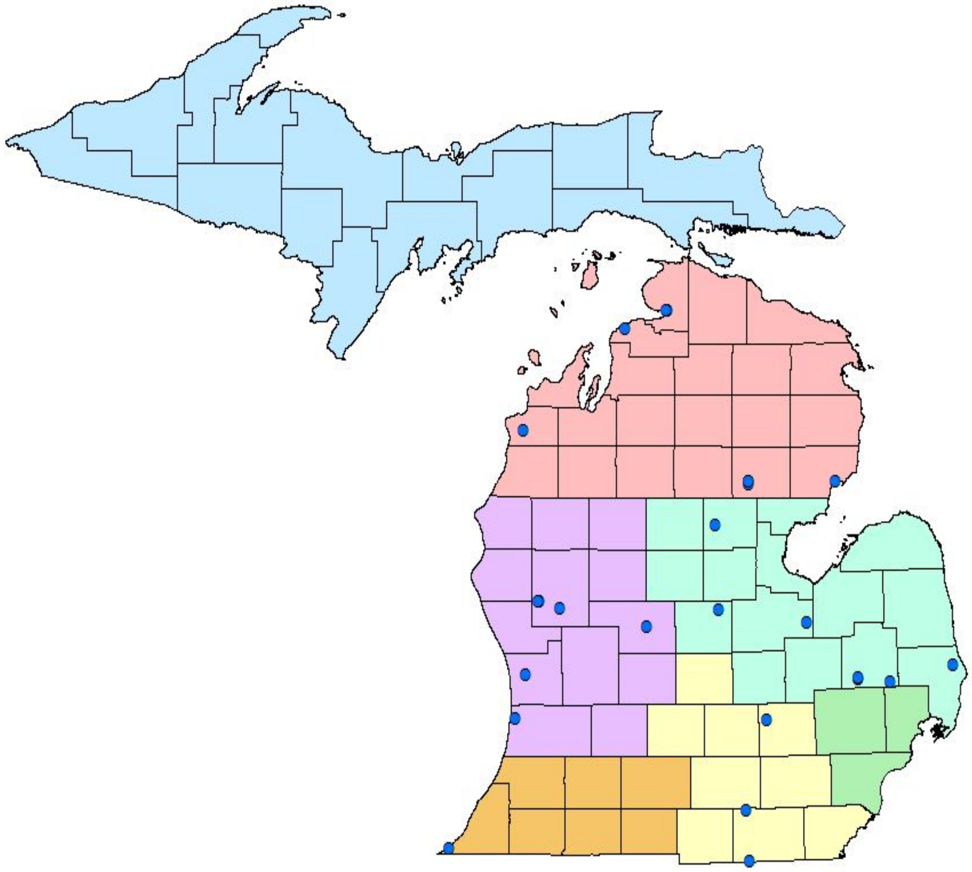


Figure 13. Map of Rural Three Leg Signalized (3SG) Intersections

Table 19 provides summary statistics (i.e., mean, minimum, maximum, standard deviation) for all relevant variables of interest considered during SPF development. Most of the 3SG intersections had lighting and pedestrian signals present in addition to the traffic signal. Nearly all of the 3SG intersections were under MDOT jurisdiction.

Table 19. Descriptive Statistics for Rural 3SG Intersections

Factor	Min	Max	Mean	Std. Dev.
AADT-Major	3726.0	16281.0	9607.95	4139.31
AADT-Minor	141.00	9748.00	3849.49	2552.56
AADT-Total	5589.0	24888.0	13457.44	5457.04
MDOT Major Roadway	0.0	1.0	0.89	0.31
County Federal Aid Major Roadway	0.0	1.0	0.11	0.31
County Non-Federal Aid Major Roadway	0	0.0	0.00	0.00
Lighting Present	0	1.0	0.74	0.44
Skew Angle	0	31.1	1.64	6.99
Number of Approaches with Left Turn Lane	0	2.0	1.42	0.59
Number of Approaches with Right Turn Lane	0	3.0	1.32	0.80
Number of Thru Lanes - Major	1	2.0	1.37	0.48
Driveway Count	0	10.0	4.11	2.67
Median Present on Major	0	0.0	0.00	0.00
Railroad Presence	0	1.0	0.05	0.22
Sidewalk Ramps	0	1.0	0.58	0.50
Pedestrian Signals	0.0	1.0	0.68	0.47
Box Span Signal	0.0	1.0	0.37	0.48
Left Turn Phasing	0.0	1.0	0.11	0.31
RTOR Prohibition	0.0	0.0	0.00	0.00
Curb Present	0.0	1.0	0.21	0.41
Within Census Designated Place	0.0	1.0	0.42	0.50
Superior Region	0.0	0.0	0.00	0.00
North Region	0.0	1.0	0.32	0.47
Grand Region	0.0	1.0	0.16	0.37
Southwest Region	0.0	1.0	0.05	0.22
University Region	0.0	1.0	0.16	0.37
Bay Region	0.0	1.0	0.32	0.47
Metro Region	0.0	0.0	0.00	0.00
Crashes Per Year (2011-2015)				
Intersection Total	0.0	12.0	3.02	2.94
Intersection FI	0.0	4.0	0.63	0.98
Intersection PDO	0.0	10.0	2.39	2.35

Number of intersections = 19

Figure 14 displays the scatter plot of the annual crash frequency versus the total intersection AADT (major plus minor), with the total AADT ranging up to nearly 25,000 vehicles per day.

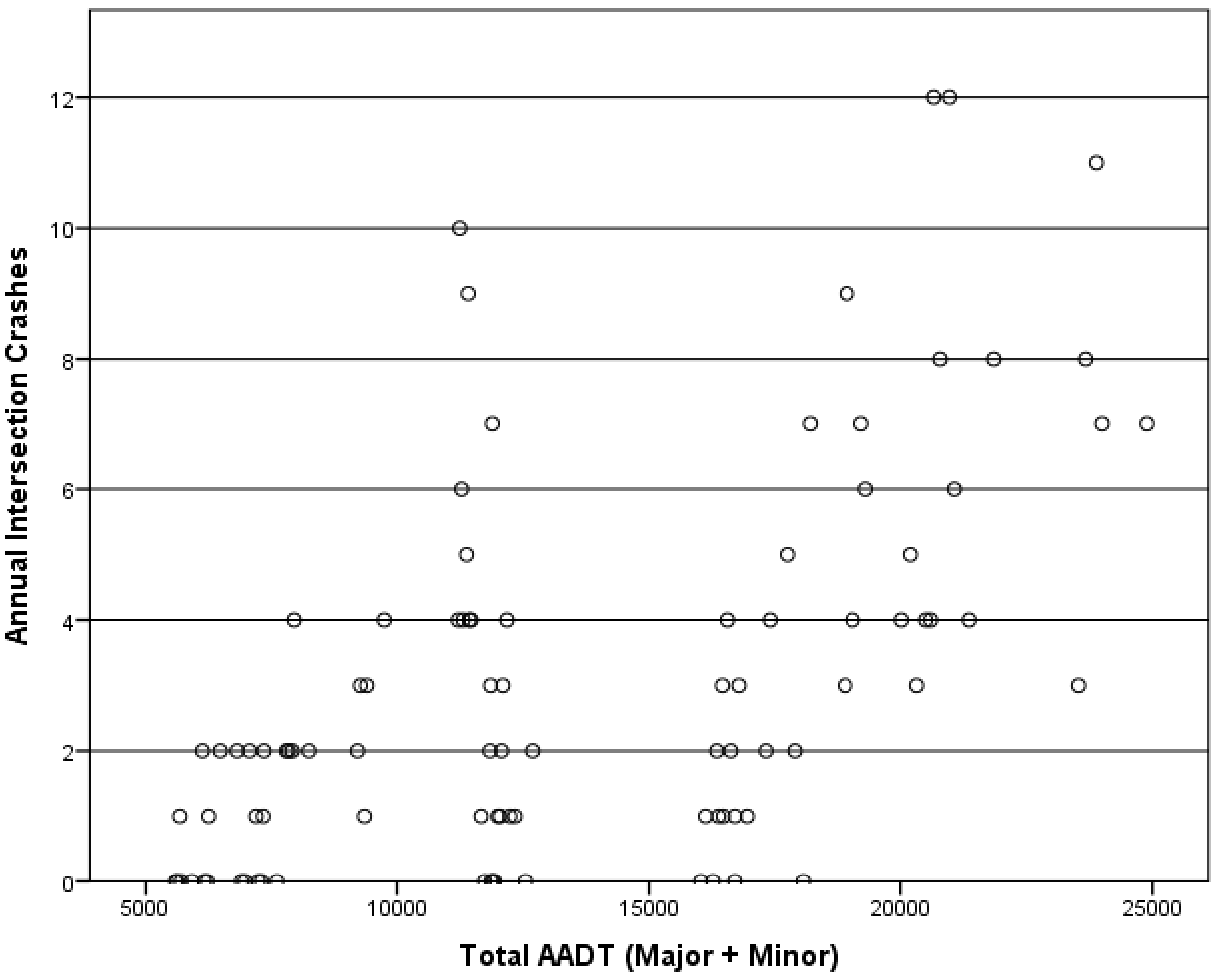


Figure 14. Annual Crash Frequency vs Total AADT for Rural 3SG Intersections

Table 20 shows crash distributions for this intersection type. Three leg signalized intersections do not have a comparable default distribution presented in the *HSM*. This type of intersection has a large proportion of property damage only type of crashes. Many of the collisions involve multiple vehicles, as would be expected at a traffic signal. The majority of multi-vehicle crashes are rear-end type collisions.

Table 20. Crash Severity and Crash Type Distributions for Rural 3SG Intersections

Crash Severity Level, Collision Type, or Light Condition	Count of Intersection Crashes (2011-2015)	Percent of Total Intersection Crashes
Fatal (Type K)	1	0.3%
Incapacitating Injury (Type A)	7	2.4%
Nonincapacitating Injury (Type B)	12	4.2%
Possible Injury (Type C)	40	13.9%
Fatal + Injury (Type K+ABC)	60	20.9%
Property Damage Only (Type PDO)	227	79.1%
Single Motor Vehicle	37	12.9%
Single Motor Vehicle (Deer Excluded)	23	8.0%
Deer Crashes	16	5.6%
Multiple Vehicle Crashes	246	85.7%
Day Crashes	219	76.3%
Dark Crashes	68	23.7%
Total Crashes (5 years)	**287**	**100.0%**

Collision Type	Percent of FI Intersection Crashes	Percent of PDO Intersection Crashes	Percent of Total Intersection Crashes
SINGLE-VEHICLE CRASHES			
Collision with deer	0.0%	7.0%	5.6%
Collision with bicycle	1.7%	0.4%	0.7%
Collision with pedestrian	3.3%	0.0%	0.7%
Overturned	0.0%	0.9%	0.7%
Other single-vehicle crash	6.7%	6.6%	6.6%
Total single-vehicle crash	11.7%	15.0%	14.3%
MULTIPLE-VEHICLE CRASHES			
Angle collision	16.7%	10.1%	11.5%
Head-on collision	11.7%	5.3%	6.6%
Read-end collision	53.3%	52.0%	52.3%
Sideswipe collision	3.3%	13.7%	11.5%
Other multiple-vehicle collision	3.3%	4.0%	3.8%
Total multiple-vehicle collision	88.3%	85.0%	85.7%
Total Crashes	**100.0%**	**100.0%**	**100.0%**

4.1.4 Rural Four Leg Signalized Intersections (4SG)

Figure 15 displays the distribution of the 175 four leg signalized (4SG) study intersections throughout the state of Michigan. The rural 4SG intersections are relatively well dispersed throughout the MDOT regions, with the exception of the Superior and Metro regions.

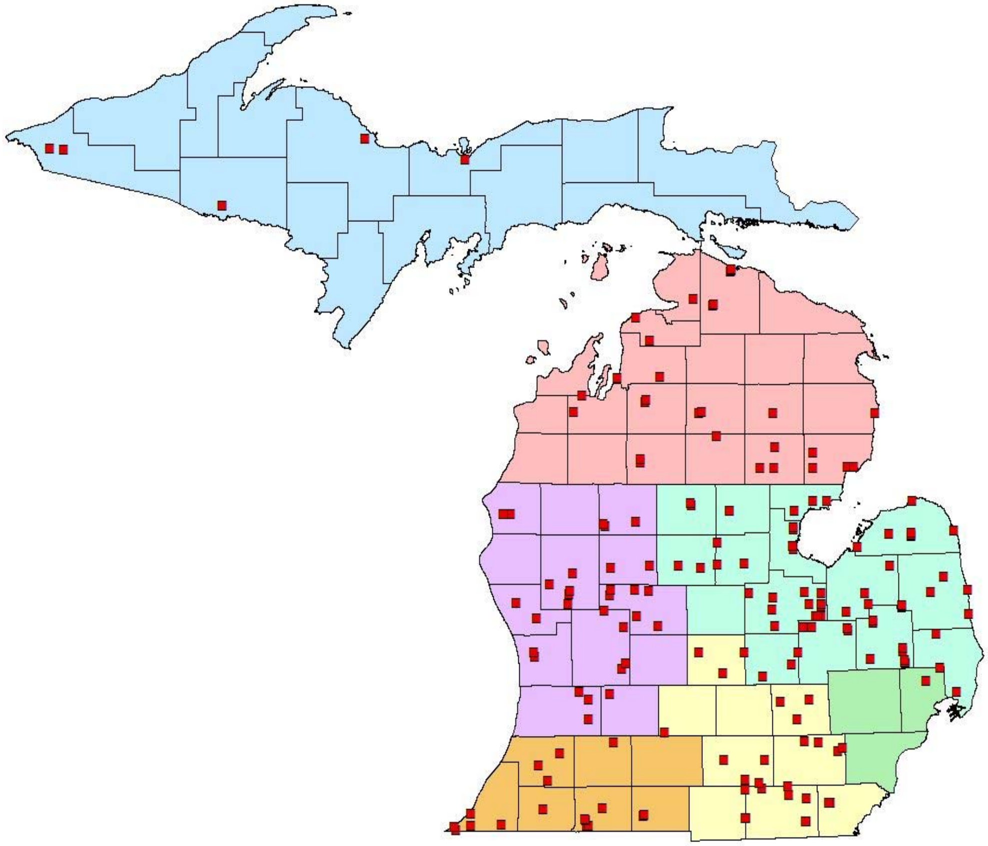


Figure 15. Map of Rural Four Leg Signalized (4SG) Intersections

Descriptive statistics for the evaluated variables in this project are provided in Table 21. About 84 percent of the rural 4SG intersections fall under MDOT jurisdiction, with the remaining rural 4SG intersections possessing a county federal aid roadway as the major roadway. Almost 60 percent of the rural 4SG intersections are within census designated places, such as unincorporated villages or areas outside of cities and towns, although these locations are still designated as rural. Such locations were more likely to possess curbs, sidewalks, and driveways in the proximity of the intersection. Because intersections within CDPs are still generally rural in context and distinctly different from urban intersections, they were retained in the analysis for this project to provide a larger sample population for SPF development.

Table 21. Descriptive Statistics for Rural 4SG Intersections

Factor	Min	Max	Mean	Std. Dev.
AADT-Major	1275.0	21414.0	9336.31	4021.36
AADT-Minor	59.00	12133.00	3669.85	2226.32
AADT-Total	2942.0	28829.0	13006.16	5059.82
MDOT Major Roadway	0.0	1.0	0.84	0.37
County Federal Aid Major Roadway	0.0	1.0	0.16	0.37
County Non-Federal Aid Major Roadway	0.0	0.0	0.00	0.00
Lighting Present	0.0	1.0	0.81	0.40
Skew Angle	0.0	57.0	2.33	8.13
Number of Approaches with Left Turn Lane	0.0	4.0	3.01	1.50
Number of Approaches with Right Turn Lane	0.0	4.0	1.01	1.16
Number of Thru Lanes - Major	1.0	2.0	1.34	0.47
Number of Thru Lanes - Minor	0.0	2.0	1.00	0.15
Driveway Count	0.0	16.0	5.82	3.68
Median Present on Major	0.0	1.0	0.01	0.11
Railroad Presence	0.0	1.0	0.06	0.23
Sidewalk Ramps	0.0	1.0	0.61	0.49
Pedestrian Signals	0.0	1.0	0.63	0.48
Box Span Signal	0.0	1.0	0.32	0.47
Left Turn Phasing	0.0	1.0	0.07	0.25
RTOR Prohibition	0.0	1.0	0.03	0.17
Curb Present	0.0	1.0	0.20	0.40
Within Census Designated Place	0.0	1.0	0.59	0.49
Superior Region	0.0	1.0	0.03	0.17
North Region	0.0	1.0	0.18	0.39
Grand Region	0.0	1.0	0.17	0.38
Southwest Region	0.0	1.0	0.10	0.30
University Region	0.0	1.0	0.15	0.36
Bay Region	0.0	1.0	0.36	0.48
Metro Region	0.0	1.0	0.01	0.11
Crashes Per Year (2011-2015)				
Intersection Total	0.0	22.0	4.11	3.28
Intersection FI	0.0	8.0	0.95	1.21
Intersection PDO	0.0	18.0	3.16	2.72

Number of intersections = 175

Figure 16 shows the scatter plot of the annual crash frequency versus the total AADT. The scatter shows a trend of generally increasing frequency of crashes as the total intersection traffic volume increases.

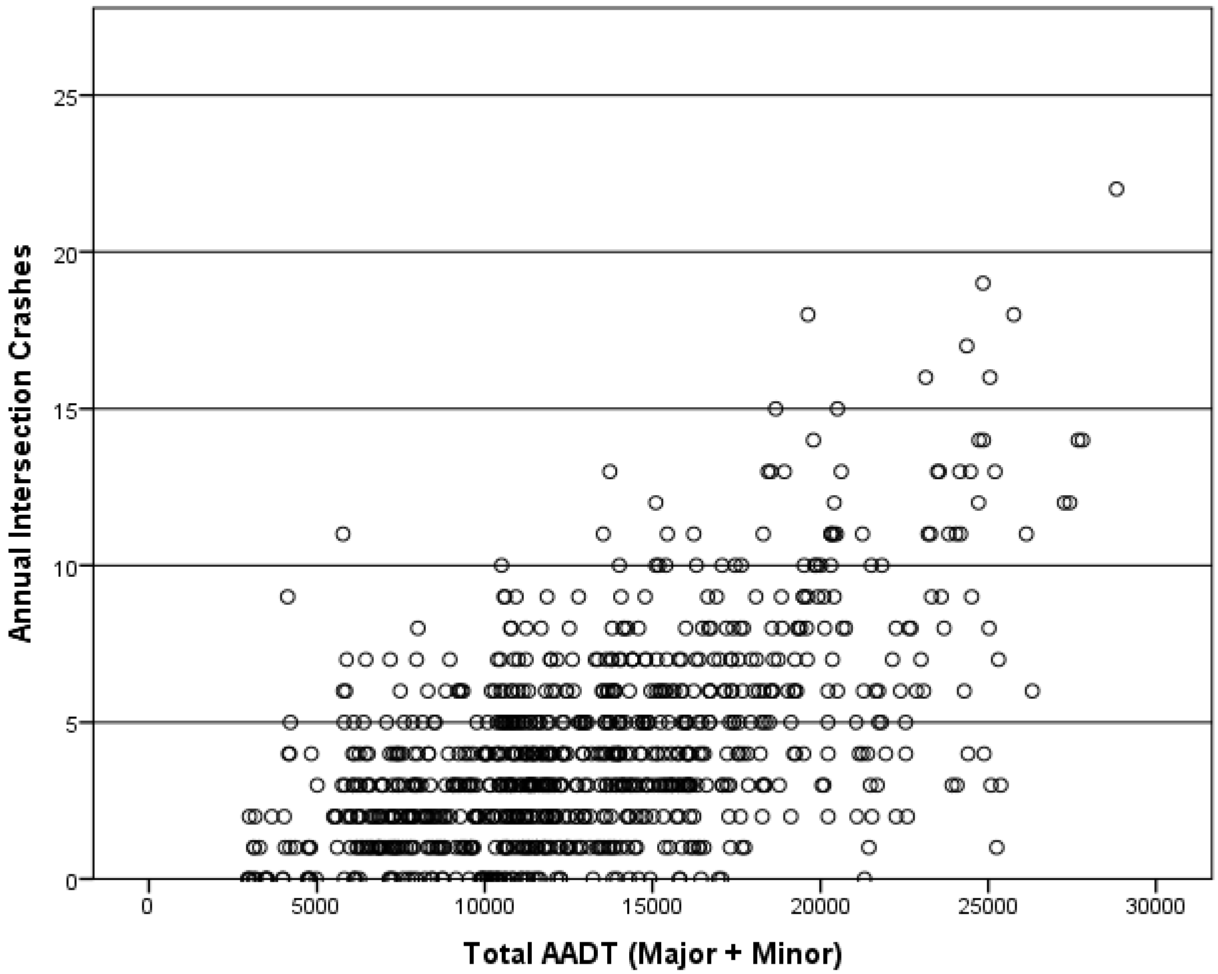


Figure 16. Annual Crash Frequency vs Total AADT for Rural 4SG Intersections

Table 22 shows the crash distributions for this intersection type. Yet again, the proportion of fatal and/or injury crashes in Michigan is lower than default distributions presented in Chapter 10 of the *HSM*.

Table 22. Crash Severity and Crash Type Distributions for Rural 4SG Intersections

Crash Severity Level, Collision Type, or Light Condition	Count of Intersection Crashes (2011-2015)	Percent of Total Intersection Crashes
Fatal (Type K)	11	0.3%
Incapacitating Injury (Type A)	68	1.9%
Nonincapacitating Injury (Type B)	189	5.3%
Possible Injury (Type C)	559	15.5%
Fatal + Injury (Type K+ABC)	827	23.0%
Property Damage Only (Type PDO)	2769	77.0%
Single Motor Vehicle	327	9.1%
Single Motor Vehicle (Deer Excluded)	220	6.1%
Deer Crashes	108	3.0%
Multiple Vehicle Crashes	3207	89.2%
Day Crashes	2696	75.0%
Dark Crashes	900	25.0%
Total Crashes (5 years)	**3596**	**100.0%**

Collision Type	Percent of FI Intersection Crashes	Percent of PDO Intersection Crashes	Percent of Total Intersection Crashes
SINGLE-VEHICLE CRASHES			
Collision with deer	0.1%	3.9%	3.0%
Collision with bicycle	2.2%	0.1%	0.6%
Collision with pedestrian	4.6%	0.1%	1.2%
Overturned	1.0%	0.2%	0.4%
Other single-vehicle crash	3.9%	6.3%	5.7%
Total single-vehicle crash	11.7%	10.5%	10.8%
MULTIPLE-VEHICLE CRASHES			
Angle collision	42.2%	22.5%	27.0%
Head-on collision	16.3%	6.7%	8.9%
Read-end collision	23.8%	40.6%	36.7%
Sideswipe collision	3.1%	14.3%	11.7%
Other multiple-vehicle collision	2.8%	5.4%	4.8%
Total multiple-vehicle collision	88.3%	89.5%	89.2%
Total Crashes	**100.0%**	**100.0%**	**100.0%**

4.2 Rural MDOT Trunkline Segments

4.2.1 MDOT Rural Two-Lane Two-Way Trunkline Segments (2U)

Figure 17 displays the distribution of rural MDOT trunkline two-lane two-way (2U) rural segment locations utilized in this study. All of the study segments were at least 0.1 miles in length, were located outside of urban areas with 5,000 or greater population, and possessed a posted speed limit of 55 mph during the study period, which was the statutory speed limit for rural highways (MDOT or county) in Michigan during the study period. Based on this definition, the sample population of 2U MDOT highways represented nearly all rural two-lane two-way highway segments under MDOT jurisdiction.

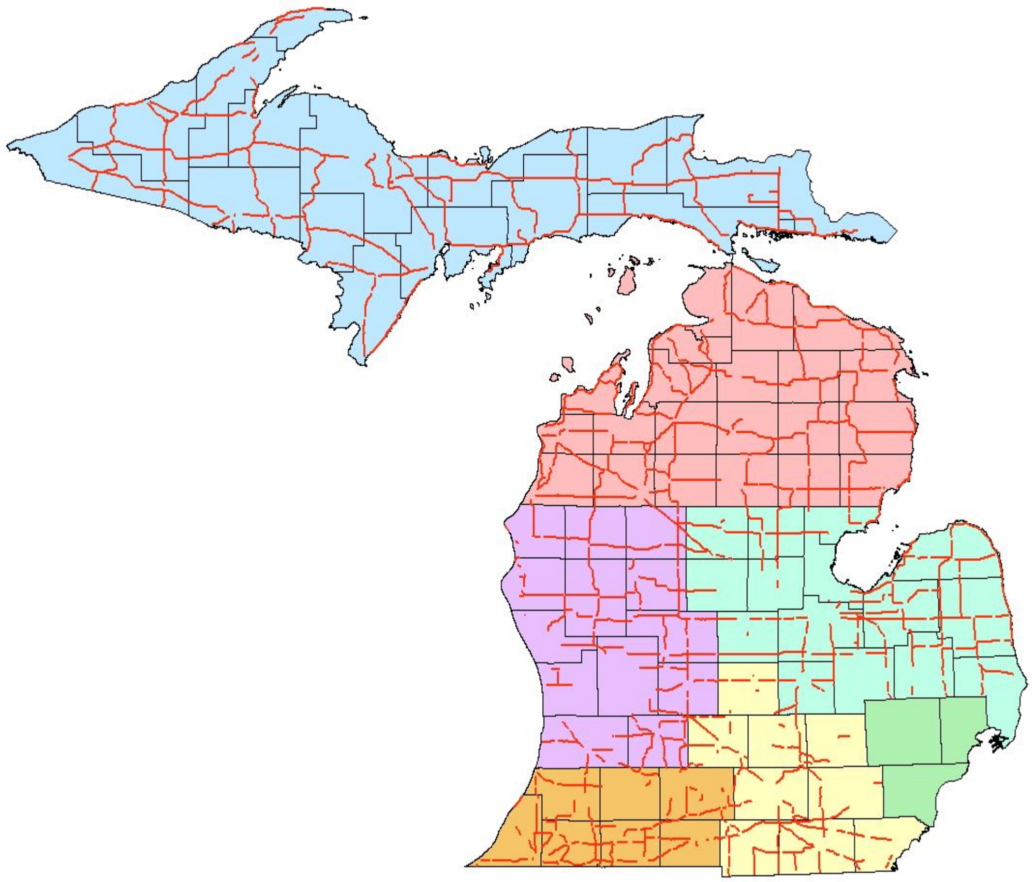


Figure 17. Map of Rural Two-Lane Two-Way (2U) Trunkline Segments

Descriptive statistics for the factors utilized in SPF and CMF development for MDOT 2U segments are provided in Table 23. Crash summary statistics and graphical representations of annual midblock segment crashes versus AADT are displayed in Table 24 and Figure 18, respectively. Table 24 shows crash distributions for 2U segments, which was formatted to match that of Tables 10-3, 10-4, and 10-12 found in Chapter 10 of the *HSM*. In comparison to the default distributions presented in Chapter 10 of the *HSM*, MDOT 2U segments have much lower proportion of severe crashes. This is likely due to a much greater proportion of MDOT 2U segment collisions involving a deer compared to the *HSM* (68.5 percent vs. 12.1 percent, respectively).

Table 23. Descriptive Statistics for Rural 2U Trunkline Segments

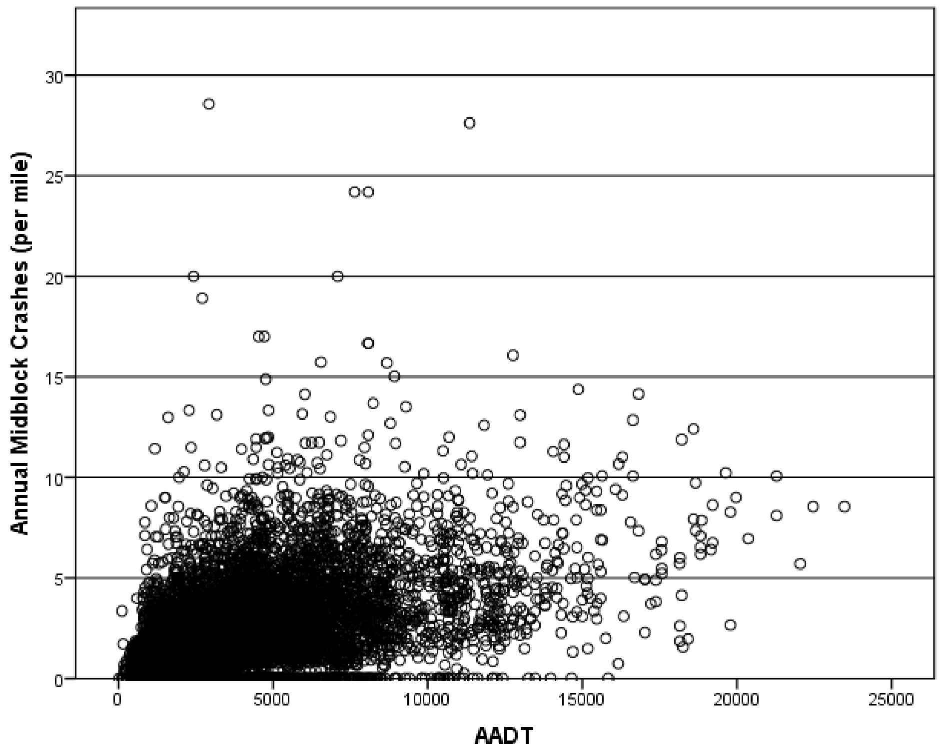
Factor	Min	Max	Mean	Std. Dev.
AADT	23.0	23481.0	4382.15	3016.97
Commercial Vehicle Fraction	0.00	0.50	0.07	0.04
Segment Length (mi)	0.1	21.7	3.44	2.80
Lane Width (ft)	10.0	12.0	11.63	0.50
Paved Shoulder Width (ft)	0.0	12.0	4.77	2.52
Speed Limit (mph)	55.0	55.0	55.00	0.00
Passing Restricted, Percent of Segment	0.0	100.0	21.51	24.26
Passing Lane, Fraction of Segment	0.0	1.0	0.10	0.30
Driveway Density (Residential, Commercial, Industrial)	0.0	85.1	14.51	9.91
Two Way Left Turn Lane, Fraction of Segment	0.0	1.0	0.02	0.13
Terrain Code (0 Flat, 1 Rolling)	0.0	1.0	0.44	0.50
Superior Region	0.0	1.0	0.23	0.42
North Region	0.0	1.0	0.26	0.44
Grand Region	0.0	1.0	0.11	0.31
Bay Region	0.0	1.0	0.16	0.37
Southwest Region	0.0	1.0	0.12	0.33
University Region	0.0	1.0	0.11	0.31
Metro Region	0.0	1.0	0.01	0.12
Horizontal Curvature				
Count w/ radius < 1568 ft (65 mph at e =7%)	0.0	27.0	0.34	1.43
Length w/ radius < 1568 ft (65 mph at e=7%)	0.0	4.6	0.08	0.29
Length fraction w/ radius < 1568 ft (65 mph at e=7%)	0.0	1.0	0.03	0.11
Crashes Per Year (2011-2015)				
Midblock Total	0.0	61.0	8.64	8.74
Midblock FI	0.0	12.0	0.87	1.28
Midblock PDO	0.0	60.0	7.76	8.03
Midblock Deer-Excluded	0.0	31.0	2.72	3.27

Number of segments = 1556

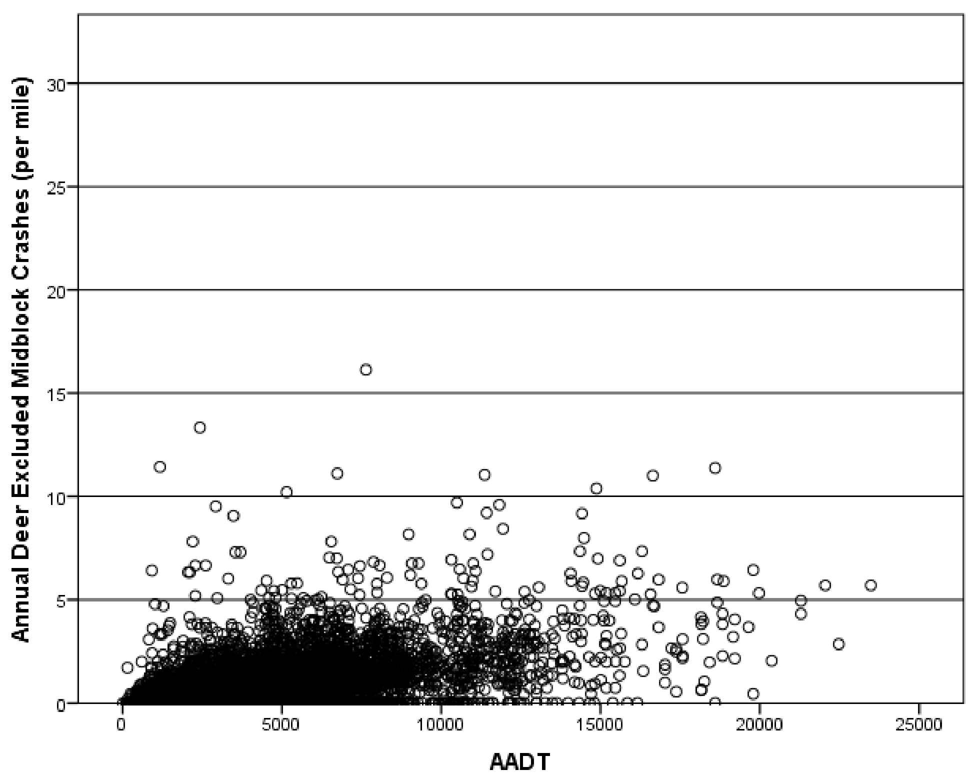
Table 24. Crash Severity and Crash Type Distributions for Rural 2U Trunkline Segments

Crash Severity Level, Collision Type, or Light Condition	Count of Midblock Crashes (2011-2015)	Percent of Total Midblock Crashes
Fatal (Type K)	277	0.4%
Incapacitating Injury (Type A)	994	1.5%
Nonincapacitating Injury (Type B)	1968	2.9%
Possible Injury (Type C)	3539	5.3%
Fatal + Injury (Type K+ABC)	6782	10.1%
Property Damage Only (Type PDO)	60404	89.9%
Single Motor Vehicle	58906	87.7%
Single Motor Vehicle (Deer Excluded)	13132	19.5%
Deer Crashes	46021	68.5%
Multiple Vehicle Crashes	8108	12.1%
Day Crashes	23004	34.2%
Dark Crashes	44182	65.8%
Total Crashes (5 years)	**67186**	**100.0%**

Collision Type	Percent of FI Midblock Crashes	Percent of PDO Midblock Crashes	Percent of Total Midblock Crashes
SINGLE-VEHICLE CRASHES			
Collision with deer	14.2%	74.4%	68.5%
Collision with bicycle	0.9%	0.0%	0.1%
Collision with pedestrian	1.3%	0.0%	0.2%
Overturned	16.2%	2.5%	4.0%
Other single-vehicle crash	28.0%	14.0%	15.1%
Total single-vehicle crash	60.6%	91.0%	87.9%
MULTIPLE-VEHICLE CRASHES			
Angle collision	4.3%	0.8%	1.1%
Head-on collision	8.9%	0.5%	1.3%
Read-end collision	17.3%	4.0%	5.4%
Sideswipe collision	5.9%	2.2%	2.6%
Other multiple-vehicle collision	3.0%	1.5%	1.7%
Total multiple-vehicle collision	39.4%	9.0%	12.1%
Total Crashes	**100.0%**	**100.0%**	**100.0%**



a.) Total Midblock Crashes



b.) Deer Excluded Midblock Crashes

Figure 18. Annual Midblock Crashes per Mile vs AADT for Rural 2U Trunkline Segments

4.2.2 Rural Four-Lane Undivided Trunkline Segments (4U)

Figure 19 displays the distribution of trunkline four-lane undivided (4U) segment study locations throughout the state of Michigan. In all, about 95 miles of rural 4U segments were present in the database. Note that 4U segments did not include short 2U sections with passing lanes on both sides. Additionally, 5-lane segments with two-way left-turn lanes were included in the 4U dataset.

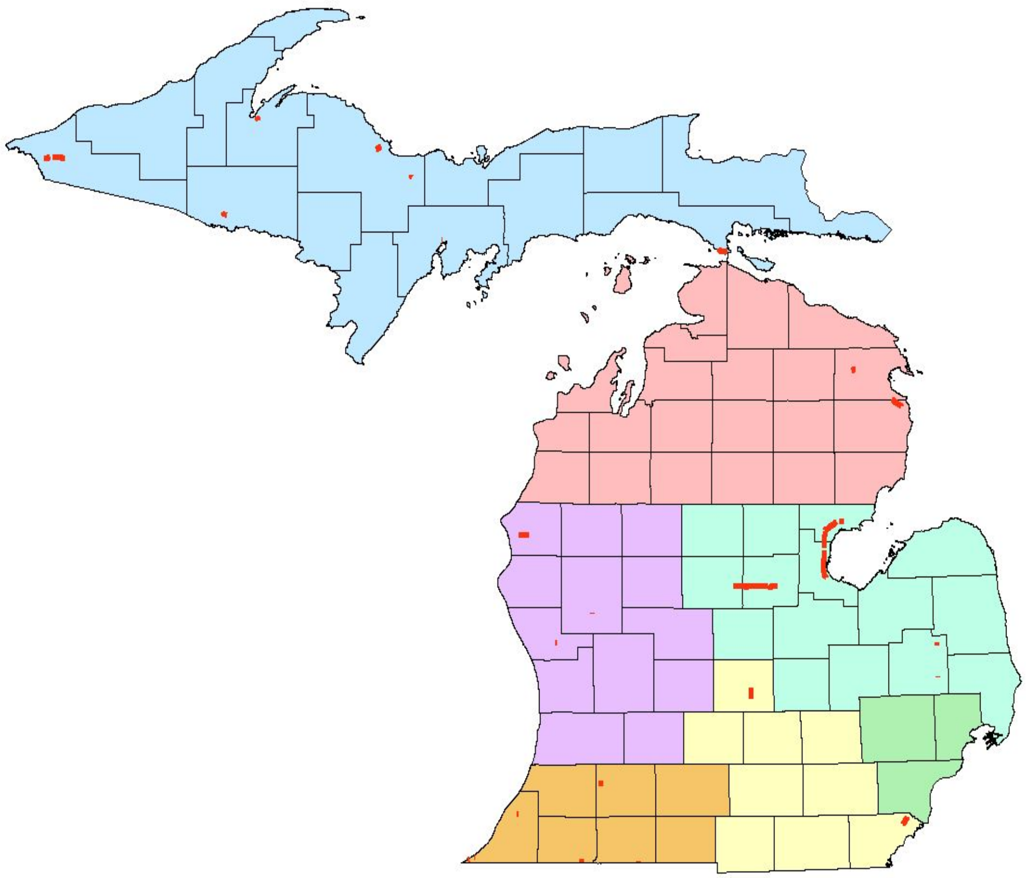


Figure 19. Map of Rural Four-Lane Undivided (4U) Trunkline Segments

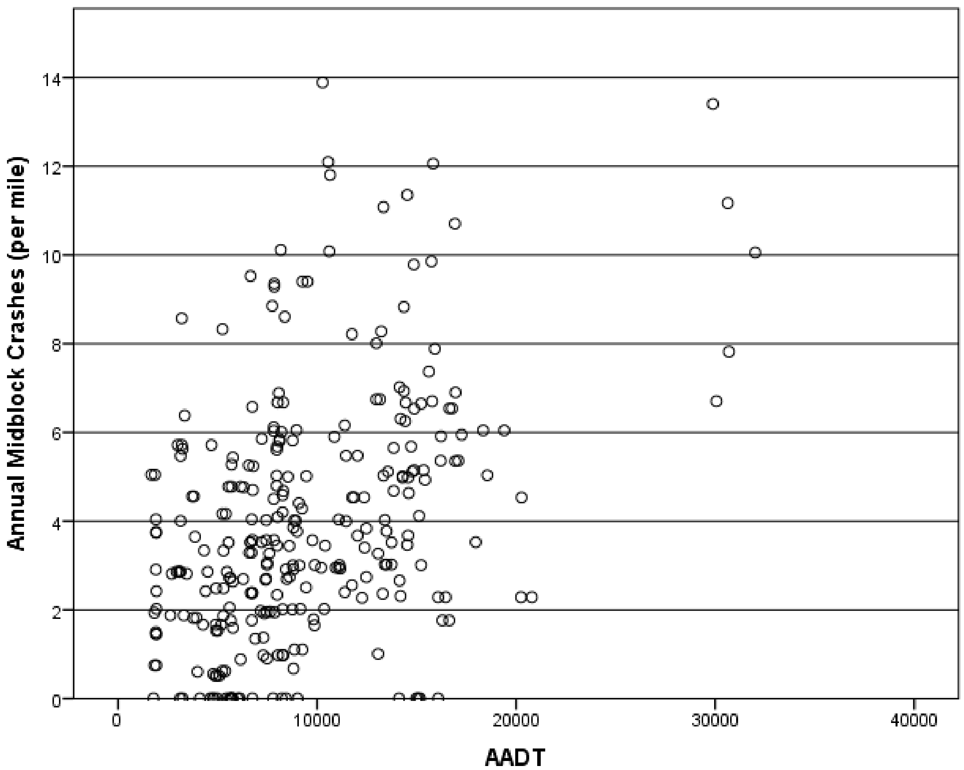
Table 25 provides summary statistics (i.e., mean, minimum, maximum, standard deviation) for all relevant variables of interest considered during 4U SPF development. Few of the rural 4U segments had horizontal curvature present.

Table 25. Descriptive Statistics for Rural 4U Trunkline Segments

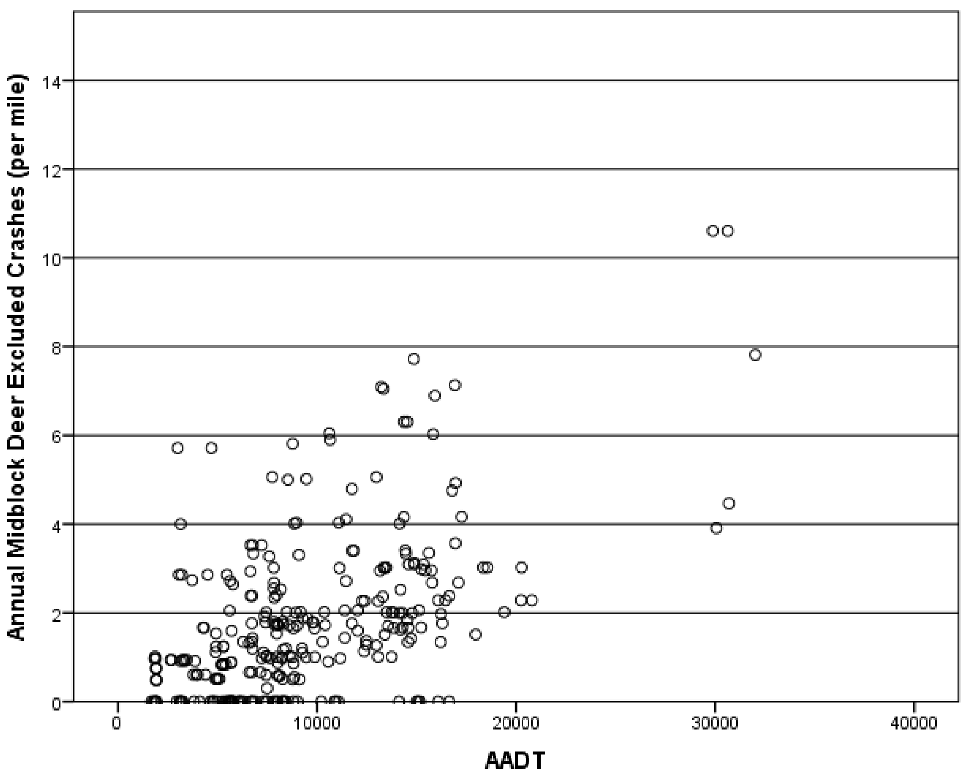
Factor	Min	Max	Mean	Std. Dev.
AADT	1672.0	32006.0	9373.08	5228.63
Commercial Vehicle Fraction	0.01	0.14	0.06	0.03
Segment Length (mi)	0.2	6.3	1.63	1.27
Lane Width (ft)	11.0	12.0	11.87	0.34
Paved Shoulder Width (ft)	0.0	12.0	8.26	3.03
Driveway Density (Residential, Commercial, Industrial)	0.0	63.7	22.03	14.25
Two Way Left Turn Lane Fraction	0.0	1.0	0.50	0.50
Terrain Code (0 Flat, 1 Rolling)	0.0	1.0	0.21	0.41
Superior Region	0.0	1.0	0.30	0.46
North Region	0.0	1.0	0.11	0.31
Grand Region	0.0	1.0	0.04	0.20
Bay Region	0.0	1.0	0.35	0.48
Southwest Region	0.0	1.0	0.13	0.33
University Region	0.0	1.0	0.07	0.25
Metro Region	0.0	0.0	0.00	0.00
Horizontal Curvature				
Count w/ radius < 1568 ft (65 mph at e =7%)	0.0	2.0	0.05	0.29
Length w/ radius < 1568 ft (65 mph at e=7%)	0.0	0.7	0.02	0.09
Length fraction w/ radius < 1568 ft (65 mph at e=7%)	0.0	1.0	0.02	0.14
Crashes Per Year (2011-2015)				
Midblock Total	0.0	32.0	6.83	6.81
Midblock FI	0.0	7.0	0.91	1.26
Midblock PDO	0.0	30.0	5.91	6.14
Midblock Deer-Excluded	0.0	19.0	3.07	3.58

Number of segments = 58

Figure 20 shows the scatter of the annual crash rate versus the AADT, which displays a clear trend between annual segment crash frequency and AADT.



a.) Total Midblock Crashes



b.) Deer Excluded Midblock Crashes

Figure 20. Annual Midblock Crashes per Mile vs AADT for Rural 4U Trunkline Segments

Table 26 shows the crash distribution for this segment type. Once again, the proportion of deer related crashes comprises the majority of all crash types, and causes an overrepresentation of single motor vehicle crashes compared to the *HSM*, especially for property damage only crashes. The most common multiple-vehicle crash type on 4U segments is rear-end collisions. The density of driveways likely contributes to the propensity of rear-end collisions.

Table 26. Crash Severity and Crash Type Distributions for Rural 4U Trunkline Segments

Crash Severity Level, Collision Type, or Light Condition	Count of Midblock Crashes (2011-2015)	Percent of Total Midblock Crashes
Fatal (Type K)	14	0.7%
Incapacitating Injury (Type A)	35	1.8%
Nonincapacitating Injury (Type B)	74	3.7%
Possible Injury (Type C)	143	7.2%
Fatal + Injury (Type K+ABC)	266	13.3%
Property Damage Only (Type PDO)	1727	86.7%
Single Motor Vehicle	1518	76.2%
Single Motor Vehicle (Deer Excluded)	429	21.5%
Deer Crashes	1097	55.0%
Multiple Vehicle Crashes	461	23.1%
Day Crashes	734	36.8%
Dark Crashes	1259	63.2%
Total Crashes (5 years)	**1993**	**100.0%**

Collision Type	Percent of FI Midblock Crashes	Percent of PDO Midblock Crashes	Percent of Total Midblock Crashes
SINGLE-VEHICLE CRASHES			
Collision with deer	9.4%	62.1%	55.0%
Collision with bicycle	0.8%	0.0%	0.1%
Collision with pedestrian	4.1%	0.1%	0.6%
Overturned	9.4%	2.1%	3.1%
Other single-vehicle crash	19.2%	17.9%	18.1%
Total single-vehicle crash	42.9%	82.1%	76.9%
MULTIPLE-VEHICLE CRASHES			
Angle collision	13.5%	2.3%	3.8%
Head-on collision	8.3%	0.9%	1.9%
Read-end collision	21.1%	6.1%	8.1%
Sideswipe collision	8.6%	6.1%	6.5%
Other multiple-vehicle collision	5.6%	2.4%	2.9%
Total multiple-vehicle collision	57.1%	17.9%	23.1%
Total Crashes	**100.0%**	**100.0%**	**100.0%**

4.2.3 Rural Four-Lane Divided Trunkline Segments (4D)

Figure 21 displays the distribution of MDOT trunkline divided four lane (4D) segment study locations throughout the state of Michigan. In all, approximately 106 miles of 4D segments exist on Michigan's were included in the dataset

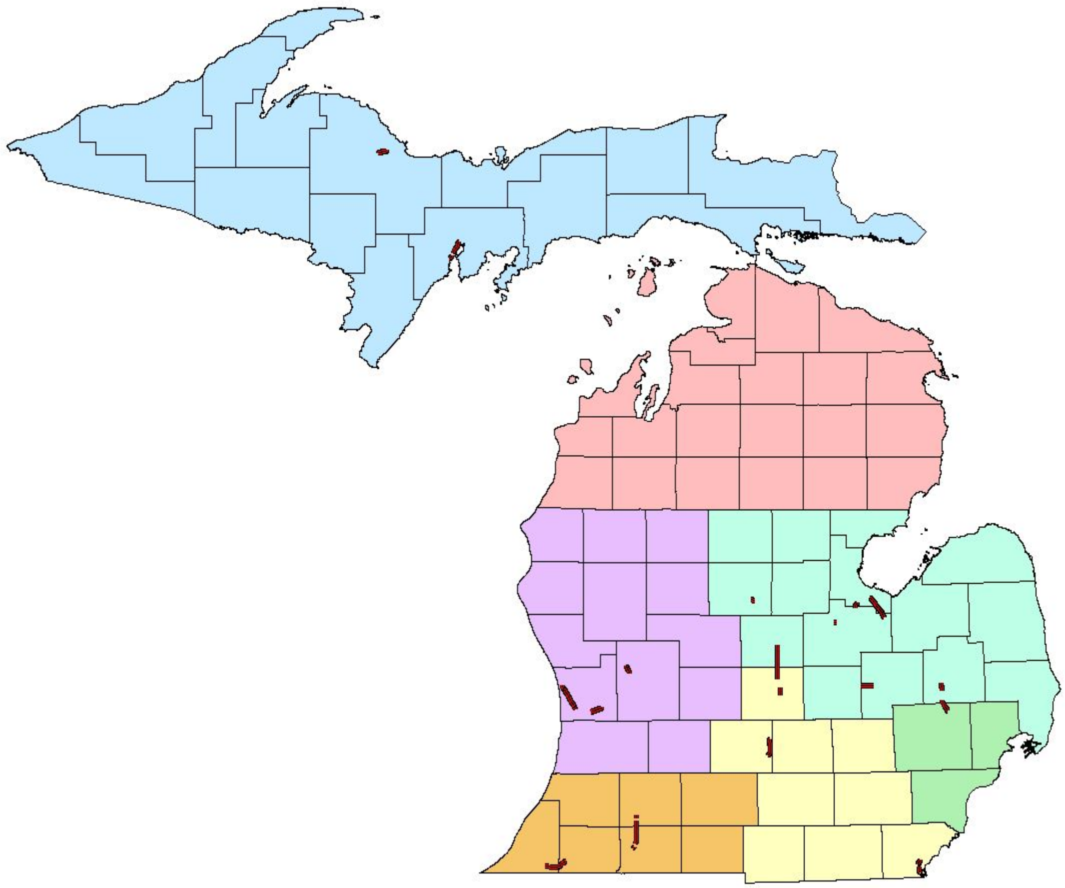


Figure 21. Map of Rural Four-Lane Divided (4D) Trunkline Segments

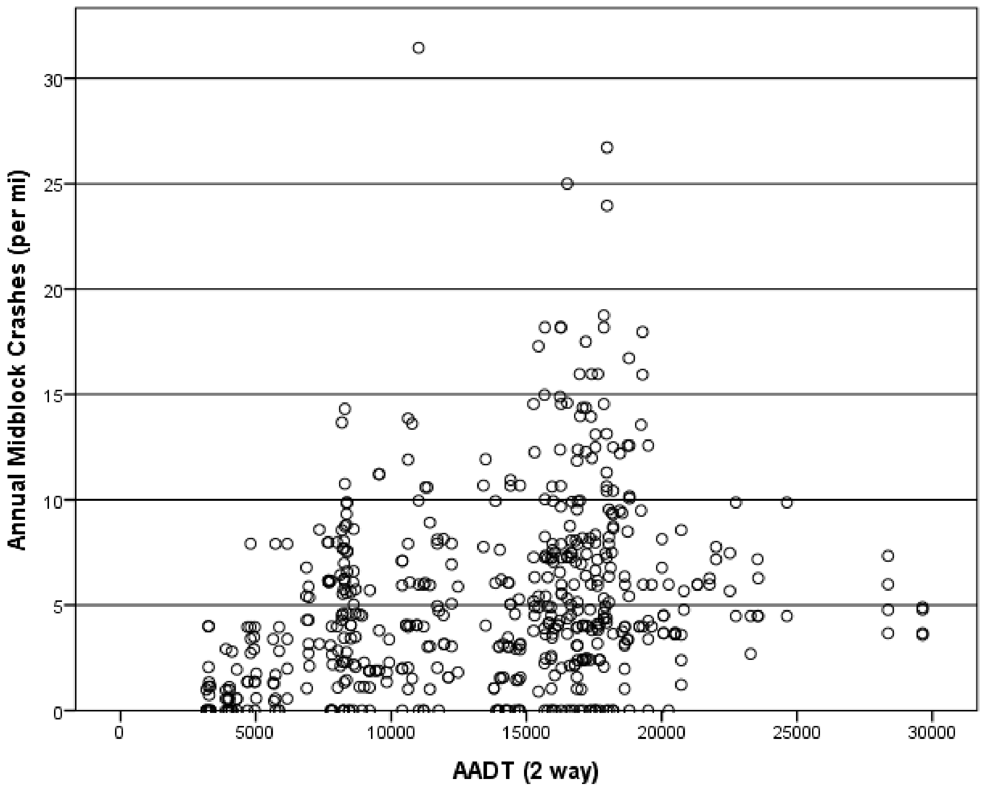
Descriptive statistics for the relevant 4D segment variables are provided in Table 27. The median widths along these segments ranged between 8 feet to 300 feet. The driveway densities for the 4D facilities are notably lower than for the 4U facilities, likely due to comparatively strict access control. Very few cases of horizontal curvature are present on MDOT's 4D segments.

Table 27. Descriptive Statistics for Rural 4D Trunkline Segments (Bi-Directional)

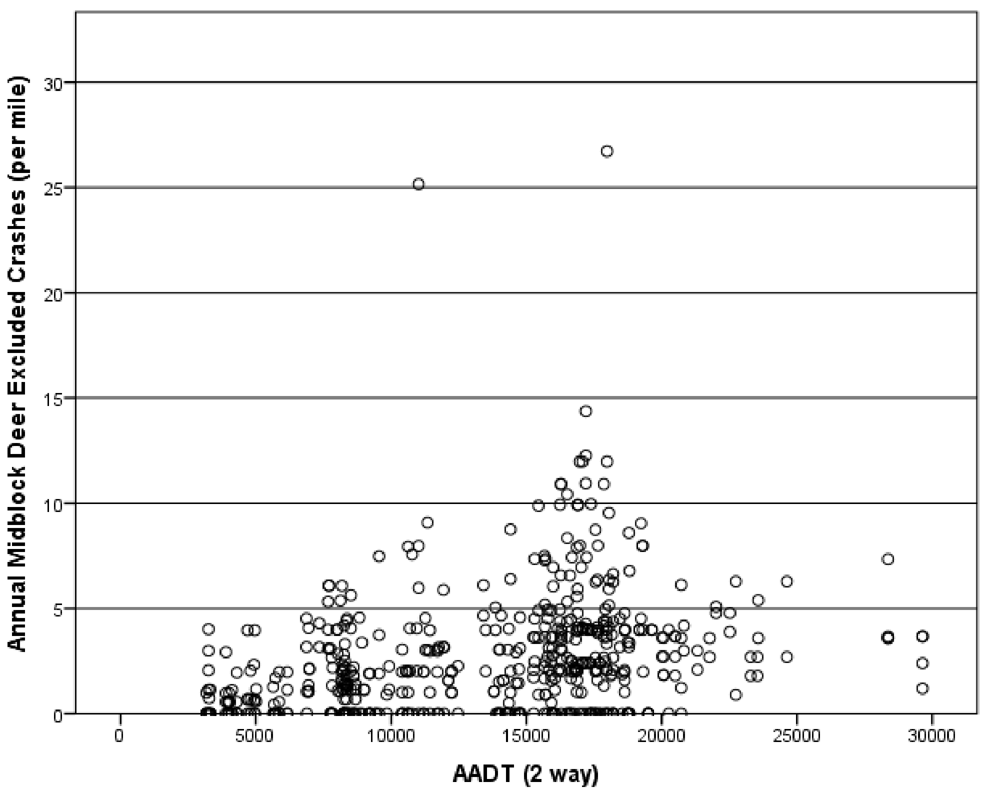
Factor	Min	Max	Mean	Std. Dev.
AADT (2 way)	3172.0	29642.0	13518.40	5495.74
Commercial Vehicle Fraction	0.02	0.12	0.06	0.03
Segment Length (mi)	0.3	6.7	1.93	1.46
Lane Width (ft)	11.0	12.0	11.59	0.49
Paved Shoulder Width (ft)	3.0	9.0	6.87	2.62
Median Width (ft)	8	300.0	44.60	39.25
Speed Limit (mph)	55.0	65.0	56.63	3.69
Driveway Density (Residential, Commercial, Industrial)	0.0	59.4	9.18	11.74
Terrain Code (0 Flat, 1 Rolling)	0.0	1.0	0.02	0.13
Superior Region	0.0	1.0	0.14	0.35
North Region	0.0	0.0	0.00	0.00
Grand Region	0.0	1.0	0.15	0.36
Bay Region	0.0	1.0	0.31	0.46
Southwest Region	0.0	2.0	0.24	0.45
University Region	0.0	1.0	0.16	0.37
Metro Region	0.0	0.0	0.00	0.00
Horizontal Curvature				
Count w/ radius < 1568 ft (65 mph at e =7%)	0.0	1.0	0.01	0.09
Length w/ radius < 1568 ft (65 mph at e=7%)	0.0	0.2	0.00	0.02
Length fraction w/ radius < 1568 ft (65 mph at e=7%)	0.0	0.1	0.00	0.01
Crashes Per Year (2011-2015)				
Midblock Total	0.0	74.0	9.82	11.92
Midblock FI	0.0	12.0	1.23	2.09
Midblock PDO	0.0	62.0	8.59	10.56
Midblock Deer-Excluded	0.0	40.0	4.82	6.09

Number of segments = 55

Figure 22 shows the scatter plot of the annual crash rate versus AADT, with a maximum two-way volume slightly below 30,000, although most segments possessed AADTs below 20,000.



a.) **Total Midblock Crashes**



b.) **Deer Excluded Midblock Crashes**

Figure 22. Annual Midblock Crashes per Mile vs AADT for Rural 4D Trunkline Segments

Table 28 shows the crash distribution for 4D segments. Approximately one-half of the crashes involved deer. Multiple vehicle crashes accounted for a lower proportion on 4D segments than 4U segments. Rear-end collisions were the most common multiple-vehicle crash type.

Table 28. Crash Severity and Crash Type Distributions for Rural 4D Trunkline Segments

Crash Severity Level, Collision Type, or Light Condition	Count of Midblock Crashes (2011-2015)	Percent of Total Midblock Crashes
Fatal (Type K)	7	0.3%
Incapacitating Injury (Type A)	43	1.6%
Nonincapacitating Injury (Type B)	96	3.5%
Possible Injury (Type C)	195	7.2%
Fatal + Injury (Type K+ABC)	341	12.5%
Property Damage Only (Type PDO)	2379	87.5%
Single Motor Vehicle	2177	80.0%
Single Motor Vehicle (Deer Excluded)	799	29.4%
Deer Crashes	1384	50.9%
Multiple Vehicle Crashes	536	19.7%
Day Crashes	1024	37.6%
Dark Crashes	1696	62.4%
Total Crashes (5 years)	**2720**	**100.0%**

Collision Type	Percent of FI Midblock Crashes	Percent of PDO Midblock Crashes	Percent of Total Midblock Crashes
SINGLE-VEHICLE CRASHES			
Collision with deer	15.5%	55.9%	50.9%
Collision with bicycle	0.6%	0.0%	0.1%
Collision with pedestrian	1.5%	0.0%	0.2%
Overturned	17.9%	3.4%	5.2%
Other single-vehicle crash	27.0%	23.5%	23.9%
Total single-vehicle crash	62.5%	82.8%	80.3%
MULTIPLE-VEHICLE CRASHES			
Angle collision	5.9%	1.4%	2.0%
Head-on collision	3.2%	0.4%	0.8%
Read-end collision	21.4%	6.3%	8.2%
Sideswipe collision	4.4%	6.9%	6.5%
Other multiple-vehicle collision	2.6%	2.1%	2.2%
Total multiple-vehicle collision	37.5%	17.2%	19.7%
Total Crashes	**100.0%**	**100.0%**	**100.0%**

4.3 Rural County Road Segments

Figure 23 displays the distribution of county two-lane two-way segment study locations throughout the state of Michigan. A total of 30 counties were represented in the rural county road segment dataset, with representation among all MDOT regions statewide. The following counties were represented in the county road segment database: Arenac, Baraga, Barry, Charlevoix, Clinton, Dickinson, Eaton, Emmet, Genesee, Grand Traverse, Gratiot, Ingham, Iosco, Kalamazoo, Kent, Keweenaw, Livingston, Luce, Macomb, Marquette, Mason, Mecosta, Monroe, Muskegon, Oakland, Ogemaw, Roscommon, Schoolcraft, Washtenaw, and Wayne. In total, 7,894 miles of county highways were included in the SPF development, of which 56.0 percent were paved federal aid segments (from 30 counties), 18.5 percent were paved non-federal aid segments (from 22 counties), and 25.5 percent were gravel roadways (from 27 counties). Due to the differences in design characteristics, traffic volumes, trip distances, driver characteristics, and other factors, separate datasets were created for federal aid and non-federal aid county highways. Non-federal aid county highways were further partitioned into paved and gravel roadway datasets for analysis.

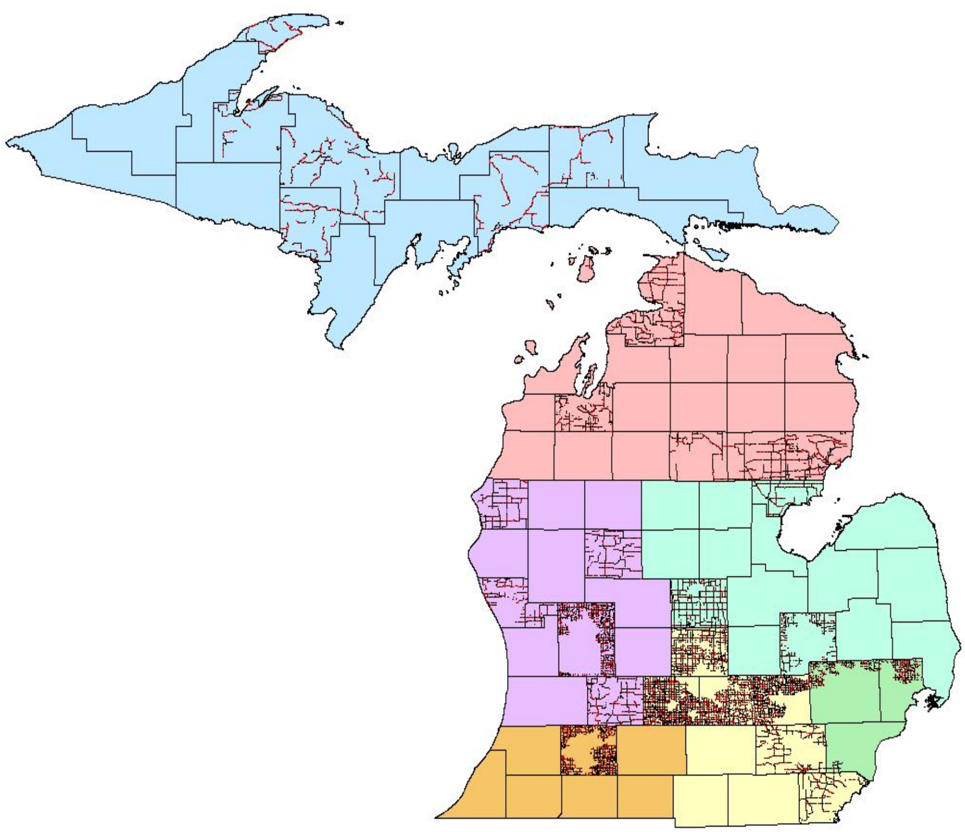


Figure 23. Map of Rural County Highway Segments

Descriptive statistics for the evaluated variables in this project are provided in Tables 29-31. Separate tables are presented for each of the rural county road subsets, including federal aid paved, non-federal aid paved, and gravel road segments.

Table 29. Crash Severity and Type Distributions for Rural Paved Federal Aid County (2PF) Segments

Factor	Min	Max	Mean	Std. Dev.
AADT	10.0	12781.0	1717.10	1676.11
Segment Length (mi)	0.1	8.2	0.45	0.33
Driveway Density (Residential, Commercial, Industrial)	0.00	138.69	14.92	13.96
Lane Width (ft)	9.0	21.0	11.07	0.76
Paved Shoulder Width (ft)	0.0	10.0	1.10	1.55
Curb Present	0.0	1.0	0.00	0.04
TWLTL Present	0.0	0.0	0.00	0.00
Passing Lane Present	0.0	1.0	0.00	0.01
Parking Lane Present	0.0	1.0	0.00	0.01
Centerline Present	0.0	1.0	0.98	0.12
Edgeline Present	0.0	1.0	0.70	0.46
Horizontal Curvature				
Count w/ radius < 1568 ft (65 mph at e =7%)	0.0	13.0	0.16	0.53
Length w/ radius < 1568 ft (65 mph at e=7%)	0.0	2.75	0.03	0.10
Length fraction w/ radius < 1568 ft (65 mph at e=7%)	0.0	1.00	0.07	0.21
Crashes Per Year (2011-2015)				
Midblock Total	0.0	15.0	0.67	1.11
Midblock FI	0.0	8.0	0.08	0.30
Midblock PDO	0.0	15.0	0.59	1.01
Midblock Deer-Excluded	0.0	11.0	0.26	0.62

Number of segments = 9912

Table 30. Crash Severity and Crash Type Distributions for Rural Paved Non-Federal Aid County (2PN) Segments

Factor	Min	Max	Mean	Std. Dev.
AADT	3.0	12628.0	584.60	635.39
Segment Length (mi)	0.1	2.0	0.51	0.30
Driveway Density (Residential, Commercial, Industrial)	0.0	108.1	17.62	13.69
Lane Width (ft)	9.0	17.0	10.61	0.75
Paved Shoulder Width (ft)	0.0	8.0	0.25	0.68
Total Paved Surface Width (ft)	18.0	40.0	21.71	2.10
Curb Present	0.0	1.0	0.00	0.05
TWLTL Present	0.0	0.0	0.00	0.00
Passing Lane Present	0.0	0.0	0.00	0.00
Parking Lane Present	0.0	0.0	0.00	0.00
Centerline Present	0.0	1.0	0.88	0.33
Edgeline Present	0.0	1.0	0.32	0.47
Horizontal Curvature				
Count w/ radius < 1568 ft (65 mph at e =7%)	0.0	5.0	0.15	0.56
Length w/ radius < 1568 ft (65 mph at e=7%)	0.0	0.82	0.02	0.08
Length fraction w/ radius < 1568 ft (65 mph at e=7%)	0.0	1.00	0.05	0.19
Crashes Per Year (2011-2015)				
Midblock Total	0.0	7.0	0.28	0.64
Midblock FI	0.0	3.0	0.04	0.19
Midblock PDO	0.0	7.0	0.25	0.59
Midblock Deer-Excluded	0.0	4.0	0.11	0.36

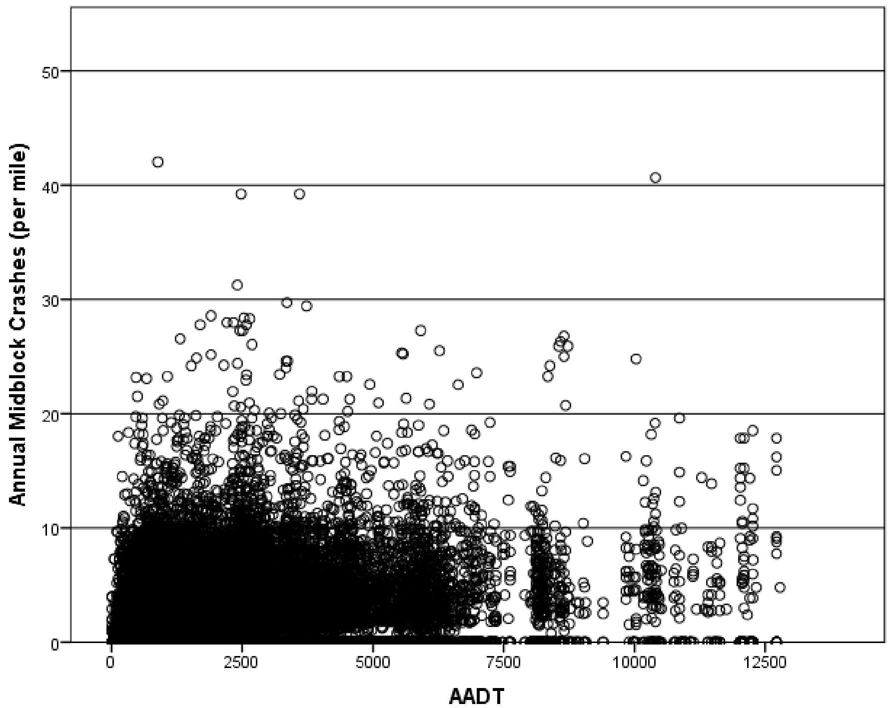
Number of segments = 2873

Table 31. Crash Severity and Crash Type Distributions for Rural Gravel Non-Federal Aid County (2GN) Segments

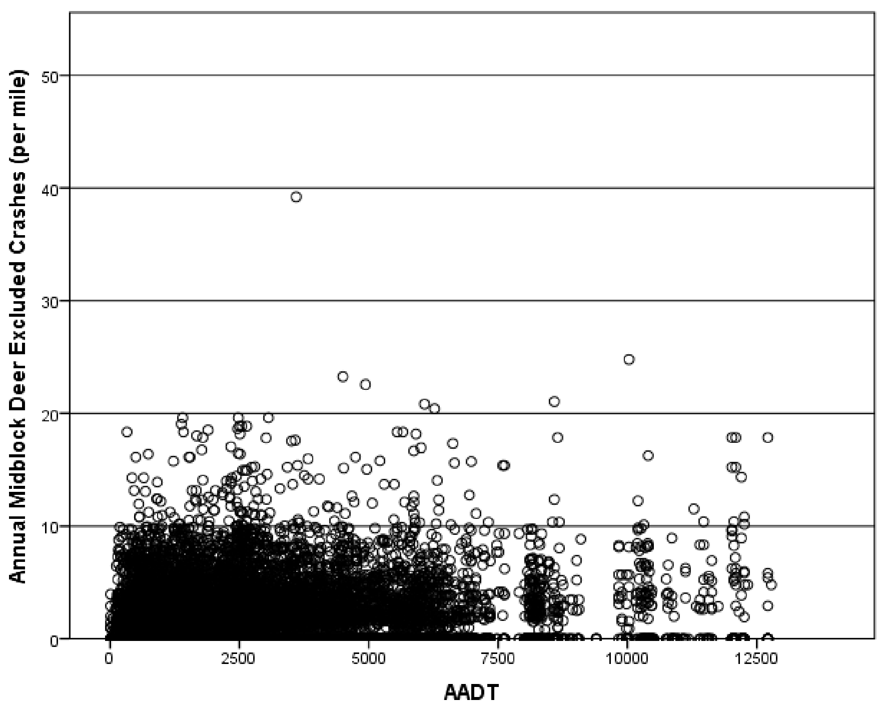
Factor	Min	Max	Mean	Std. Dev.
AADT	4.0	6298.0	241.46	423.53
Segment Length (mi)	0.1	4.6	0.50	0.37
Driveway Density (Residential, Commercial, Industrial)	0.0	93.0	12.44	10.83
Total Surface Width (ft)	12.0	40.0	21.28	3.85
Federal Aid Status (0 = Non Fed Aid, 1 = Fed Aid)	0.0	1.0	0.15	0.36
Horizontal Curvature				
Count w/ radius < 1568 ft (65 mph at e =7%)	0.0	18.0	0.22	0.87
Length w/ radius < 1568 ft (65 mph at e=7%)	0.0	2.79	0.03	0.13
Length fraction w/ radius < 1568 ft (65 mph at e=7%)	0.0	1.00	0.05	0.18
Crashes Per Year (2011-2015)				
Midblock Total	0.0	5.0	0.12	0.37
Midblock FI	0.0	2.0	0.02	0.15
Midblock PDO	0.0	5.0	0.10	0.33
Midblock Deer-Excluded	0.0	5.0	0.08	0.30

Number of segments = 3983

Figures 24-26 display the relationship between the annual total segment crashes and annual non-deer segment crashes versus AADT for each of the three county facility types.

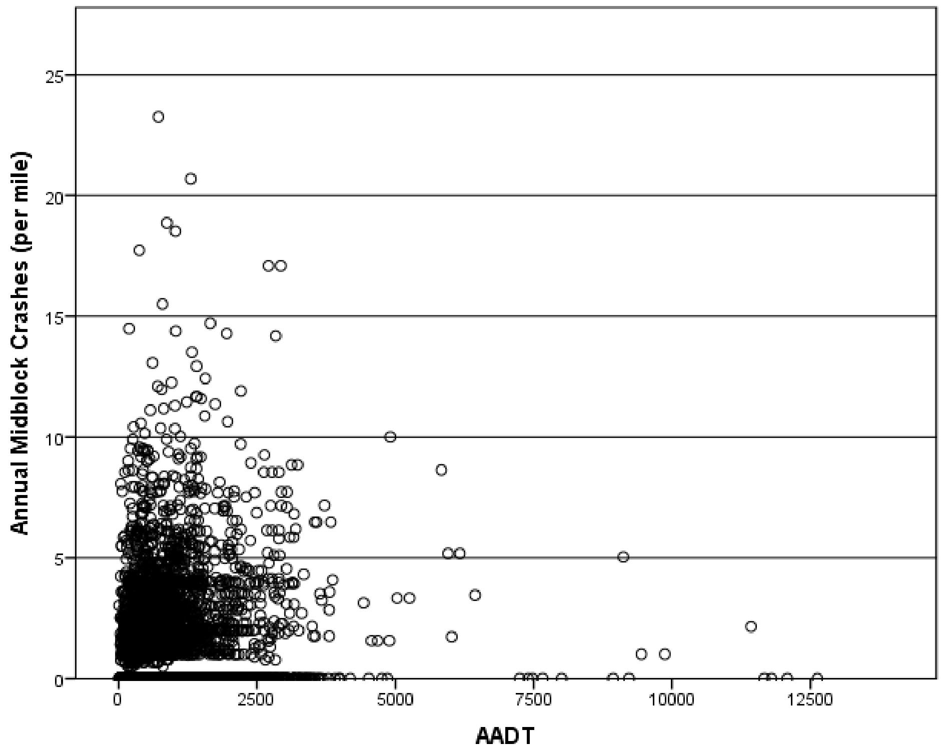


a.) Total Midblock Crashes

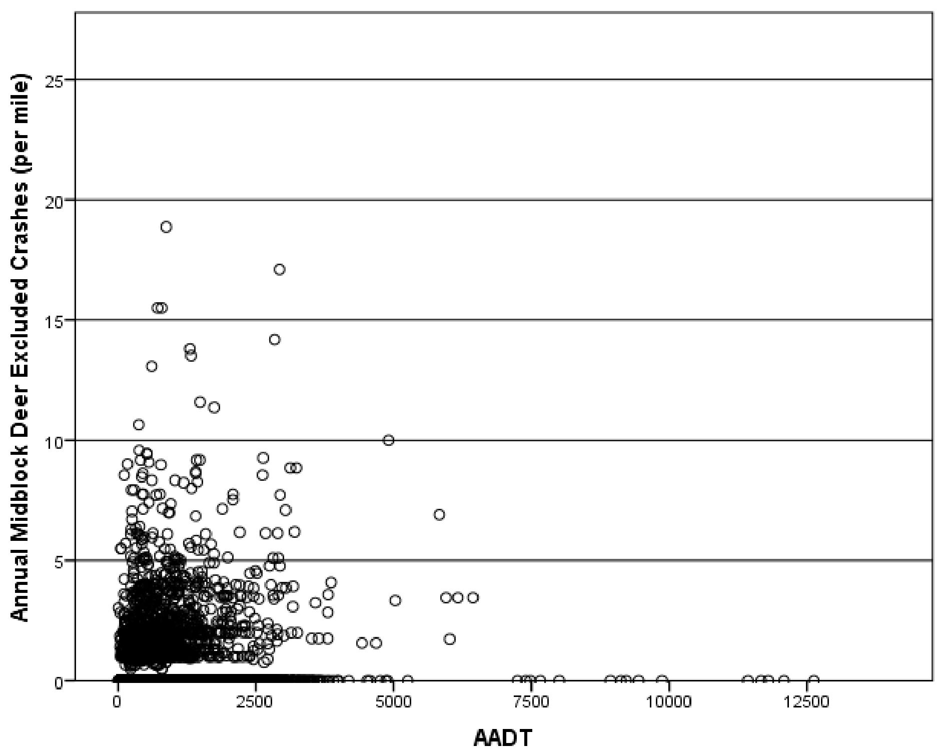


b.) Deer Excluded Midblock Crashes

Figure 24. Annual Midblock Crashes per Mile vs AADT, Rural Paved Federal Aid County (2PF) Segments

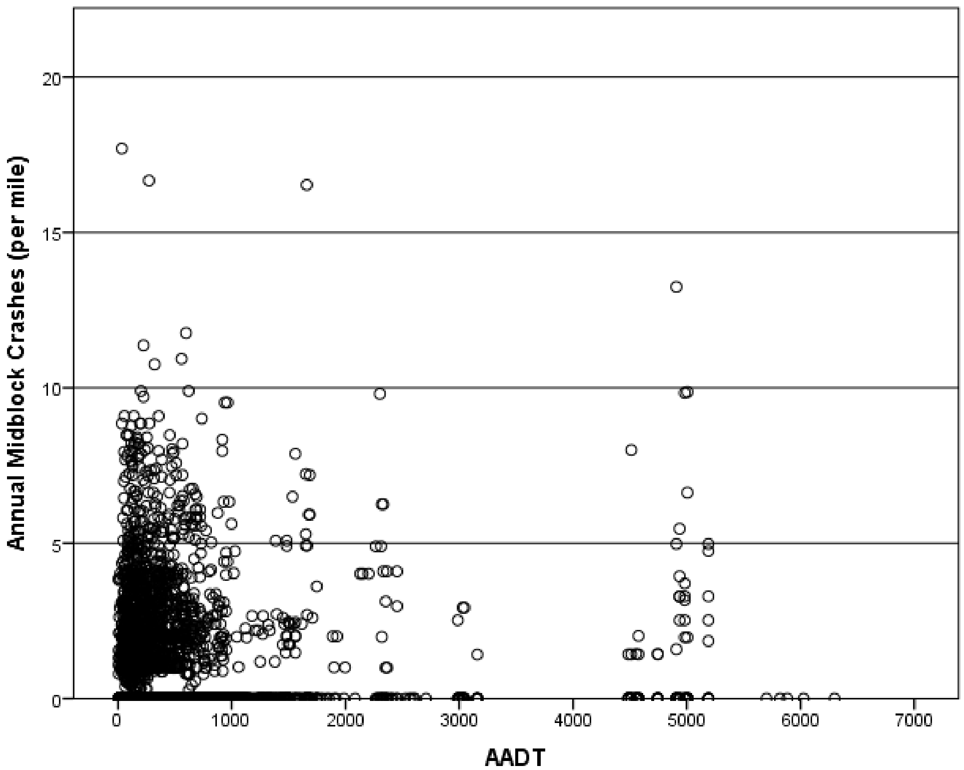


a.) Total Midblock Crashes

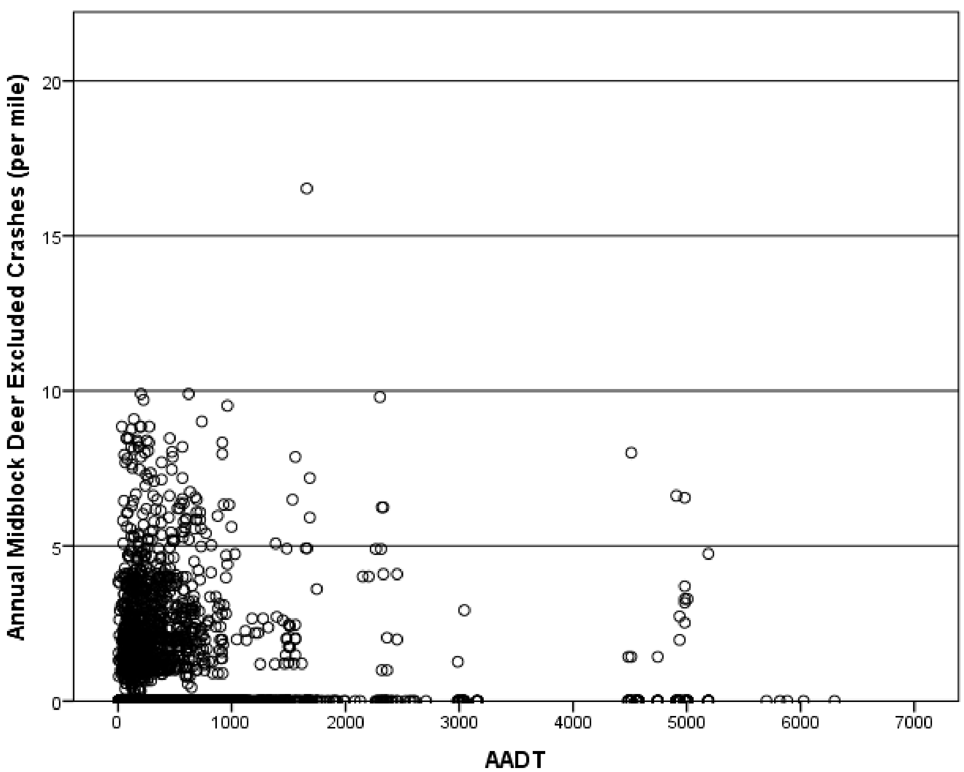


b.) Deer Excluded Midblock Crashes

Figure 25. Annual Midblock Crashes per Mile vs AADT, Rural Paved Non-Federal Aid County (2PN) Segments



a.) Total Midblock Crashes



b.) Deer Excluded Midblock Crashes

Figure 26. Annual Midblock Crashes per Mile vs AADT, Rural Gravel Non-Federal Aid County (2GN) Segments

Tables 32-34 show the crash distributions for this segment type. In comparison to the default distributions presented in Chapter 10 of the *HSM*, Michigan's two-lane two-way county segments have much lower proportions of severe crashes and much greater proportions of animal (deer) crashes. This situation quite similarly relates to the distribution of collision types for MDOT trunkline 2U segments as discussed previously. In direct comparison to state trunkline 2U segments, the two-lane county segments have a higher proportion of other single-vehicle crashes, which includes fixed object collisions, across all crash severities. This type of crash might likely be related to the available clear zone, road hazard rating, or sideslopes, none of which were feasible for collection in this study, but would typically be reflected in the design standards for county roadways compared to MDOT trunkline highways. The over representation of deer crashes on county segments explains why the proportion of multiple-vehicle collisions on Michigan's two-lane county segments is so much lower than the default distributions in the *HSM*.

Table 32. Crash Severity and Crash Type Distributions for Rural Paved Federal Aid County (2PF) Segments

Crash Severity Level, Collision Type, or Light Condition	Count of Midblock Crashes (2011-2015)	Percent of Total Midblock Crashes
Fatal (Type K)	145	0.4%
Incapacitating Injury (Type A)	512	1.6%
Nonincapacitating Injury (Type B)	1255	3.8%
Possible Injury (Type C)	2026	6.1%
Fatal + Injury (Type K+ABC)	3938	11.9%
Property Damage Only (Type PDO)	29061	88.1%
Single Motor Vehicle	29702	90.0%
Single Motor Vehicle (Deer Excluded)	9518	28.8%
Deer Crashes	20280	61.5%
Multiple Vehicle Crashes	3192	9.7%
Day Crashes	11558	35.0%
Dark Crashes	21441	65.0%
Total Crashes (5 years)	**32999**	**100.0%**

Collision Type	Percent of FI Midblock Crashes	Percent of PDO Midblock Crashes	Percent of Total Midblock Crashes
SINGLE-VEHICLE CRASHES			
Collision with deer	10.5%	68.4%	61.5%
Collision with bicycle	1.3%	0.0%	0.2%
Collision with pedestrian	1.2%	0.0%	0.2%
Overturned	19.1%	3.7%	5.6%
Other single-vehicle crash	44.1%	20.1%	23.0%
Total single-vehicle crash	76.2%	92.2%	90.3%
MULTIPLE-VEHICLE CRASHES			
Angle collision	3.1%	1.0%	1.2%
Head-on collision	6.3%	0.4%	1.1%
Read-end collision	8.5%	2.8%	3.5%
Sideswipe collision	4.0%	2.4%	2.6%
Other multiple-vehicle collision	1.9%	1.2%	1.3%
Total multiple-vehicle collision	23.8%	7.8%	9.7%
Total Crashes	**100.0%**	**100.0%**	**100.0%**

Table 33. Crash Severity and Crash Type Distributions for Rural Paved Non-Federal Aid County (2PN) Segments

Crash Severity Level, Collision Type, or Light Condition	Count of Midblock Crashes (2011-2015)	Percentage of Total Midblock Crashes
Fatal (Type K)	24	0.6%
Incapacitating Injury (Type A)	57	1.4%
Nonincapacitating Injury (Type B)	172	4.2%
Possible Injury (Type C)	263	6.4%
Fatal + Injury (Type K+ABC)	516	12.6%
Property Damage Only (Type PDO)	3565	87.4%
Single Motor Vehicle	3656	89.6%
Single Motor Vehicle (Deer Excluded)	1167	28.6%
Deer Crashes	2505	61.4%
Multiple Vehicle Crashes	402	9.9%
Day Crashes	1340	32.8%
Dark Crashes	2741	67.2%
Total Crashes (5 years)	**4081**	**100.0%**

Collision Type	Percent of FI Midblock Crashes	Percent of PDO Midblock Crashes	Percent of Total Midblock Crashes
SINGLE-VEHICLE CRASHES			
Collision with deer	11.2%	68.6%	61.4%
Collision with bicycle	1.0%	0.0%	0.1%
Collision with pedestrian	3.3%	0.0%	0.4%
Overturned	14.7%	2.6%	4.2%
Other single-vehicle crash	51.7%	20.0%	24.0%
Total single-vehicle crash	82.0%	91.3%	90.1%
MULTIPLE-VEHICLE CRASHES			
Angle collision	4.1%	1.3%	1.7%
Head-on collision	4.1%	0.5%	0.9%
Read-end collision	4.8%	2.4%	2.7%
Sideswipe collision	3.1%	2.7%	2.8%
Other multiple-vehicle collision	1.9%	1.7%	1.8%
Total multiple-vehicle collision	18.0%	8.7%	9.9%
Total Crashes	**100.0%**	**100.0%**	**100.0%**

Table 34. Crash Severity and Crash Type Distributions for Rural Gravel Non-Federal Aid County (2GN) Segments

Crash Severity Level, Collision Type, or Light Condition	Count of Midblock Crashes (2011-2015)	Percentage of Total Midblock Crashes
Fatal (Type K)	7	0.3%
Incapacitating Injury (Type A)	66	2.8%
Nonincapacitating Injury (Type B)	172	7.2%
Possible Injury (Type C)	215	9.0%
Fatal + Injury (Type K+ABC)	460	19.4%
Property Damage Only (Type PDO)	1916	80.6%
Single Motor Vehicle	2060	86.7%
Single Motor Vehicle (Deer Excluded)	1222	51.4%
Deer Crashes	843	35.5%
Multiple Vehicle Crashes	305	12.8%
Day Crashes	1068	44.9%
Dark Crashes	1308	55.1%
Total Crashes (5 years)	**2376**	**100.0%**

Collision Type	Percent of FI Midblock Crashes	Percent of PDO Midblock Crashes	Percent of Total Midblock Crashes
SINGLE-VEHICLE CRASHES			
Collision with deer	5.2%	42.7%	35.4%
Collision with bicycle	0.9%	0.1%	0.3%
Collision with pedestrian	1.3%	0.0%	0.3%
Overturned	25.9%	6.7%	10.4%
Other single-vehicle crash	56.5%	37.0%	40.8%
Total single-vehicle crash	89.8%	86.5%	87.1%
MULTIPLE-VEHICLE CRASHES			
Angle collision	2.0%	2.9%	2.7%
Head-on collision	2.2%	1.3%	1.5%
Read-end collision	2.0%	2.4%	2.3%
Sideswipe collision	2.8%	5.0%	4.6%
Other multiple-vehicle collision	1.3%	1.8%	1.7%
Total multiple-vehicle collision	10.2%	13.5%	12.9%
Total Crashes	**100.0%**	**100.0%**	**100.0%**

4.4 Overview of Michigan-Specific SPF Development

After examining the general relationships between crashes and traffic volume within each of the previously described rural intersection and segment facility types, SPFs were developed at four levels of detail for each facility type, as follows:

- Uncalibrated *HSM* – The intersection and segment models from Chapters 10 (two-lane rural highways) and 11 (multilane rural highways) of the *HSM* were applied directly using traffic volume data for the study sites.
- Calibrated *HSM* – The predicted number of crashes based on the SPFs from Chapters 10 and 11 the *HSM* were calibrated based on the observed crashes at the study sites.
- Michigan-specific models with AADT and regional indicators – A series of Michigan-specific general models were developed using only AADT, in addition to models that included AADT plus a series of binary indicator variables for each MDOT region.
- Fully specified Michigan-specific models – A series of detailed models were subsequently developed considering AADT, regional indicator variables, and a diverse range of variables related to the characteristics of the site.

The calibration of the *HSM* models are discussed in Section 4.5 while the development of general Michigan-specific SPFs with AADT and regional indicators are presented in Chapter 5. Fully specified Michigan-specific models are described in Chapters 6 and 7 for segments and intersections, respectively. A general overview of the Michigan-specific SPF development process is provided as follows.

In most cases, including the *HSM* models, SPFs take the form of generalized linear models. As crash data are comprised of non-negative integers, traditional regression techniques (e.g., ordinary least-squares) are generally not appropriate. Given the nature of such data, the Poisson distribution has been shown to provide a better fit and has been used widely to model crash frequency data. In the Poisson model, the probability of intersection or segment i experiencing y_i crashes during a one-year period is given by:

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

where $P(y_i)$ is probability of intersection or segment i experiencing y_i crashes and λ_i is the Poisson parameter for intersection or segment i, which is equal to the expected number of crashes per year, $E[y_i]$. Poisson models are estimated by specifying the Poisson parameter λ_i (expected number of crashes) as a function of explanatory variables, the most common functional form being $\lambda_i = \exp(\beta X_i)$, where X_i is a vector of explanatory variables and β is a vector of estimable parameters.

A limitation of this model is the underlying assumption of the Poisson distribution that the variance is equal to the mean. As such, the model cannot handle overdispersion wherein the variance is greater than the mean. Overdispersion is common in crash data and may be caused by data clustering, unaccounted temporal correlation, model misspecification, or ultimately by the nature of the crash data, which are the product of Bernoulli trials with unequal probability of events (Lord, Washington, & Ivan, 2005). Overdispersion is generally accommodated through the use of negative binomial models (also referred to as Poisson-gamma models).

The negative binomial model is derived by rewriting the Poisson parameter for each intersection as $\lambda_i = \exp(\beta X_i + \varepsilon_i)$, where $EXP\ (\varepsilon_i)$ is a gamma-distributed error term with mean 1 and variance α. The addition of this term allows the variance to differ from the mean as $Var[y_i] = E[y_i] + \alpha E[y_i]^2$. The negative binomial model is preferred over the Poisson model since the latter cannot handle overdispersion and, as such, may lead to biased parameter estimates (Lord & Park, 2008). Consequently, the *HSM* recommends using the negative binomial model for the development of SPFs.

If the overdispersion parameter, k, is equal to zero, the negative binomial reduces to the Poisson model. Estimation of λ_i can be conducted through standard maximum likelihood procedures. While alternatives, such as the Conway-Maxwell model, have the advantage of accommodating both overdispersion and underdispersion (variance is less than the mean) (Lord & Mannering, 2010), the negative binomial model remains the standard in SPF development.

The overdispersion parameter from the negative binomial model is also utilized in the empirical Bayes (EB) method for evaluating the effectiveness of safety improvements as described in the *HSM*. The overdispersion parameter, k, is used to determine the weighted adjustment factor, *w*, which is then used to estimate the expected number of crashes at a given location when combining observed crash data with the number of crashes predicted by an SPF. The formula for this weighting factor is shown as follows.

$$w = \frac{1}{1 + (k \times N_{spf})}$$

Where,

k = overdispersion parameter, and

N_{spf} = predicted number of crashes by SPF.

Upon determining w, the expected number of crashes can then be determined as follows.

$$N_{expected} = w \times N_{spf} + (1 - w) \times N_{observed}$$

Where,

$N_{expected}$ = expected number of crashes determined by the EB method,

w = weighted adjustment factor, and

$N_{observed}$ = observed number of crashes at a site.

For further details of the EB method, the reader is referred to the *HSM* (AASHTO, 2010). As noted previously, several SPFs were developed as a part of this project at varying degrees of complexity. The complexity of the SPFs is reflective, in part, on the underlying data requirements.

One concern that arises from safety evaluation of the county road system in Michigan is the unobserved heterogeneity introduced when collecting data from across various counties and regions of the state. Michigan's county road commissions utilize different design standards. Other factors, such as weather, topography, land use, and driver behavior also vary widely across the various regions of the state. To account for these differences, a county-specific random effect was incorporated into the models for the county roadway segments, thereby allowing the intercept term to vary across locations.

It is also noted that the natural log of segment length was included as an offset in each of the segment models, with a parameter estimate fixed at one, thereby forcing the model to treat crashes as a direct one-to-one relationship with segment length. Furthermore, in order to make direct comparisons between low-volume paved and gravel roads, only non-federal aid roadways were considered and only segments from counties with both gravel and paved roads were included in this study.

4.5 Calibration of *HSM* SPFs for Michigan

Calibration factors were estimated for each corresponding *HSM* model using the 2011-2015 Michigan crash data for each respective facility type. The *HSM* predictive models from Part C, Chapters 10 (two-lane rural highways) and 11 (multilane rural highways) of the *HSM* were applied to the datasets for each of the intersection and segment facility types. The procedure for calibrating the SPFs found in Part C of the *HSM* was followed as described in Appendix A of the *HSM* (AASHTO, 2010). Michigan's *HSM* spreadsheet tool, which includes the *HSM* base models for rural segments and intersections, along with *HSM* and Michigan-specific CMFs, were used to perform the calculation of predicted crashes.

Rather than selecting only those Michigan segments matching the *HSM* base condition, CMFs were utilized to adjust the segment to the base condition for *HSM* crash prediction, thereby allowing for calculation of regional calibration factors. However, it was not possible to apply the horizontal curve CMF from the *HSM* due to the way that the Michigan horizontal curve data were specified. Thus, only tangent segments without horizontal curvature were utilized for calibration, and the CMF related to horizontal curvature was not applied. Similarly, due to a lack of information, CMFs for vertical grade, roadside hazard rating, and side slopes were not applied.

The predicted number of crashes was aggregated for all of the calibration sample sites for the 5-year analysis period. The observed crashes were also aggregated for the calibration sample sites. For segment facilities, total midblock crashes and midblock non-deer crashes were considered for the calibration. For intersection facilities, total intersection crashes was considered for the calibration. The ratio of the total observed crashes to the predicted crashes (from the *HSM* SPFs) for the calibration set was used to compute a calibration factor, which provides a measure of how close the SPFs from the *HSM* fit the Michigan data. The calibration factor for each of the segment models are presented in Tables 35 and 36. The calibration factors for each of the intersection models are presented in Table 37.

Table 35. Calibration Factors for *HSM* Models on MDOT Rural Trunkline Segments

2U	Count of Segments	Segment Mileage	N_observed (Midblock Crashes 2011-2015)	N_observed (Midblock NonDeer Crashes 2011-2015)	N_predicted (HSM 2011-2015)	CALIBRATION FACTOR for Midblock Crashes on Tangent Sections	CALIBRATION FACTOR for Midblock NonDeer Crashes on Tangent Sections
Statewide	946	3,003	39,925	11,861	18,491	**2.16**	**0.64**
Superior	185	658	5,161	1,304	2,192	**2.35**	**0.59**
North	210	705	8,771	2,381	3,768	**2.33**	**0.63**
Grand	161	458	7,757	2,522	3,641	**2.13**	**0.69**
Bay	204	677	11,122	3,105	4,948	**2.25**	**0.63**
Southwest	99	236	3,267	1,254	1,864	**1.75**	**0.67**
University	87	269	3,847	1,295	2,078	**1.85**	**0.62**
Metro	0	0	0	0	0	**Not Applicable**	

4D	Count of Segments	Segment Mileage	N_observed (Midblock Crashes 2011-2015)	N_observed (Midblock NonDeer Crashes 2011-2015)	N_predicted (HSM 2011-2015)	CALIBRATION FACTOR for Midblock Crashes on Tangent Sections	CALIBRATION FACTOR for Midblock NonDeer Crashes on Tangent Sections
Statewide	106	200	2,611	1,303	1,272	**2.05**	**1.02**
Superior	12	17	258	123	91	**2.83**	**1.35**
North	0	0	0	0	0	**Not Applicable**	
Grand	17	41	548	335	362	**1.51**	**0.92**
Bay	36	71	792	351	362	**2.19**	**0.97**
Southwest	28	40	409	274	275	**1.49**	**1.00**
University	14	31	604	220	181	**3.33**	**1.21**
Metro	0	0	0	0	0	**Not Applicable**	

4U	Count of Segments	Segment Mileage	N_observed (Midblock Crashes 2011-2015)	N_observed (Midblock NonDeer Crashes 2011-2015)	N_predicted (HSM 2011-2015)	CALIBRATION FACTOR for Midblock Crashes on Tangent Sections	CALIBRATION FACTOR for Midblock NonDeer Crashes on Tangent Sections
Statewide	55	91	1,910	842	1,495	**1.28**	**0.56**
Superior	17	17	372	150	235	**1.58**	**0.64**
North	4	6	74	21	29	**2.58**	**0.73**
Grand	5	7	182	87	114	**1.60**	**0.77**
Bay	20	45	943	443	872	**1.08**	**0.51**
Southwest	6	7	120	61	126	**0.95**	**0.48**
University	4	9	219	80	119	**1.84**	**0.67**
Metro	0	0	0	0	0	**Not Applicable**	

Table 36. Calibration Factors for *HSM* Models on Michigan Rural County Road Segments

2PF (Paved Fed Aid)	Count of Segments	Segment Mileage	N_observed (Midblock Crashes 2011-2015)	N_observed (Midblock NonDeer Crashes 2011-2015)	N_predicted (HSM 2011-2015)	CALIBRATION FACTOR for Midblock Crashes on Tangent Sections	CALIBRATION FACTOR for Midblock NonDeer Crashes on Tangent Sections
Statewide	8,318	3,558	27,661	9,858	13,078	**2.12**	**0.75**
Superior	634	303	991	304	342	**2.90**	**0.89**
North	1,496	636	4,007	1,343	1,676	**2.39**	**0.80**
Grand	2,032	845	7,103	2,586	2,704	**2.63**	**0.96**
Bay	1,085	465	3,942	1,087	1,736	**2.27**	**0.63**
Southwest	332	159	1,335	561	810	**1.65**	**0.69**
University	2,403	1,033	8,701	3,241	4,649	**1.87**	**0.70**
Metro	336	118	1,582	736	1,162	**1.36**	**0.63**

2PN (Paved NonFed Aid)	Count of Segments	Segment Mileage	N_observed (Midblock Crashes 2011-2015)	N_observed (Midblock NonDeer Crashes 2011-2015)	N_predicted (HSM 2011-2015)	CALIBRATION FACTOR for Midblock Crashes on Tangent Sections	CALIBRATION FACTOR for Midblock NonDeer Crashes on Tangent Sections
Statewide	2545	1293.7	3658	1330	1707	**2.14**	**0.78**
Superior	15	6.2	14	13	4	**Not Applicable**	
North	203	76.1	198	64	120	**1.65**	**0.53**
Grand	418	212.0	522	239	283	**1.85**	**0.85**
Bay	321	139.4	529	190	343	**1.54**	**0.55**
Southwest	513	270.6	565	254	273	**2.07**	**0.93**
University	1061	582.7	1816	564	678	**2.68**	**0.83**
Metro	14	6.8	14	6	6	**Not Applicable**	

2GN (Gravel NonFed Aid)	Count of Segments	Segment Mileage	N_observed (Midblock Crashes 2011-2015)	N_observed (Midblock NonDeer Crashes 2011-2015)	N_predicted (HSM 2011-2015)	CALIBRATION FACTOR for Midblock Crashes on Tangent Sections	CALIBRATION FACTOR for Midblock NonDeer Crashes on Tangent Sections
Statewide	3,054	1,436	1,474	902	541	**2.73**	**1.67**
Superior	2	3	3	2	0	**Not Applicable**	
North	120	46	23	14	14	**1.64**	**1.00**
Grand	268	132	110	76	32	**3.41**	**2.36**
Bay	156	72	92	33	28	**3.32**	**1.19**
Southwest	135	67	30	17	13	**2.34**	**1.33**
University	2,056	939	965	569	349	**2.76**	**1.63**
Metro	317	177	251	191	104	**2.40**	**1.83**

Table 37. Calibration Factors for *HSM* Models at Michigan Rural Intersections

4SG	Count of Intersections	N_observed (Intersection Crashes 2011-2015)	N_predicted (HSM 2011-2015)	CALIBRATION FACTOR for Intersection Crashes
Statewide	175	3,596	2,947	**1.22**
Superior	5	53	89	**0.60**
North	32	609	558	**1.09**
Grand	30	687	501	**1.37**
Bay	63	1,382	1,021	**1.35**
Southwest	17	303	271	**1.12**
University	26	530	476	**1.11**
Metro	2	32	30	**1.06**

4ST	Count of Intersections	N_observed (Intersection Crashes 2011-2015)	N_predicted (HSM 2011-2015)	CALIBRATION FACTOR for Intersection Crashes
Statewide	2,513	9,853	14,010	**0.70**
Superior	198	562	671	**0.84**
North	360	1,301	1,878	**0.69**
Grand	521	2,197	3,235	**0.68**
Bay	516	2,390	3,521	**0.68**
Southwest	278	1,212	1,682	**0.72**
University	583	1,988	2,783	**0.71**
Metro	57	203	239	**0.85**

3ST	Count of Intersections	N_observed (Intersection Crashes 2011-2015)	N_predicted (HSM 2011-2015)	CALIBRATION FACTOR for Intersection Crashes
Statewide	2,297	5,395	6,376	**0.85**
Superior	287	583	498	**1.17**
North	381	1,107	1,248	**0.89**
Grand	388	1,030	1,182	**0.87**
Bay	229	691	913	**0.76**
Southwest	381	780	1,005	**0.78**
University	564	1,056	1,357	**0.78**
Metro	67	148	173	**0.85**

Upon review of the calibration factors for the various *HSM* models, it is evident that the accuracy of the base SPFs from the *HSM* for prediction of crashes in Michigan vary widely by site type. These differences are reflective of several factors, including state-specific differences (e.g., driver characteristics, road design standards, weather, etc.). The most prominent state-specific characteristic is the overabundance of animal crashes attributed to the high deer population in Michigan. Generally, the *HSM* models tend to under-predict total mid-block segment crashes, but over predict deer-excluded mid-block crashes, although consideration must be given to the fact that a certain (albeit much lower) percentage of the *HSM* crash data involved animals. The *HSM* models generally tend to over-predict crashes at stop-controlled intersections, but under-predict crashes at four-leg signalized intersections. As with segments, these differences are reflective of several factors, including state-specific differences (e.g., driver characteristics, road design standards, weather, etc.) and unobserved heterogeneity between sites (e.g., vertical curvature, roadside hazard rating, etc). Some of these differences between the segment and intersection calibration factors may be the consequence of the method used in this study for distinguishing between segment and intersection crashes.

These differences suggest that the accuracy of crash estimation will be improved through the development of Michigan specific SPFs. Development of simple general Michigan-specific SPFs based solely on AADT, in addition to SPFs including AADT plus regional indicator variables are presented in Chapter 5. Development of fully specified Michigan-specific models utilizing AADT, regional indicator variables, and a diverse range of variables related to the characteristics of the site are described in Chapters 6 and 7 for segments and intersections, respectively.

5.0 MICHIGAN-SPECIFIC RURAL SAFETY PERFORMANCE FUNCTIONS WITH AADT AND REGIONAL INDICATORS

Having established that the calibrated SPFs from the *HSM* do not provide consistent fit across the various facility types, crash types, and crash severity levels, a series of Michigan-specific SPFs were subsequently developed. This chapter presents a number of simple general Michigan-specific models that were developed utilizing traffic volume data and regional factors for each facility type, without controlling for geometric or other site-specific conditions. Chapters 6 and 7 present the detailed Michigan-specific models that considered geometric and other site related variables, in addition to traffic volumes and regional factors. The simple SPFs presented in this chapter were developed in the following general forms using standard negative binomial modeling techniques:

- Michigan-specific models with AADT – A series of Michigan-specific models were developed using only the natural log of AADT as a predictor variable and midblock or intersection crashes as the dependent variable. Separate models were developed with and without deer crashes for midblock crashes.
- Michigan-specific models with AADT and regional indicators – Similar models were estimated that included the natural log of AADT, as well as a series of binary indicator variables for each MDOT region, and midblock or intersection crashes as the dependent variable.

As discussed in the Appendix to Part C of the *HSM*, the minimum recommended sample size for SPF development is 30 to 50 sites (segments or intersections) which collectively experience a minimum of 100 total crashes per year (AASHTO, 2010). Furthermore, to the extent possible, it was desirable for this research to provide SPFs that are able to account for differences across each of MDOT's seven geographic regions, meaning that the aforementioned desirable minimum number of sites would apply at the regional level. Table 38 provides information pertaining to the average annual number of crashes by facility type and region for intersections and segments included in the study during the period of 2011 to 2015. Both total and deer excluded crashes are provided for the segments. While a minimum of 30 to 50 sites were desired within each region, there are several regions where a sufficient numbers of sites were not available, as shown in Table 38. This was particularly true for rural signalized intersections (3SG, 4SG) and rural undivided and divided highways (4U, 4D).

Table 38. Facility Statistics and Average Annual Crashes (2011-2015), by MDOT Region

	MDOT Region							
Facility Type	**Superior**	**North**	**Grand**	**Bay**	**SW**	**Univ.**	**Metro**	**Total**
NUMBER OF INTERSECTIONS								
3ST	287	381	388	229	381	564	67	2297
4ST	198	360	521	516	278	583	57	2513
3SG	0	6	3	6	1	3	0	19
4SG	5	32	30	63	17	26	2	175
ANNUAL INTERSECTION CRASHES								
3ST	117	221	206	138	156	211	30	1079
4ST	112	260	439	478	242	398	41	1971
3SG	0	21	5	26	1	4	0	57
4SG	11	122	137	276	61	106	6	719
NUMBER OF SEGMENTS								
2U (MDOT Trunkline)	350	366	246	278	156	154	6	1556
2PF (County Paved FA)	1059	1912	2356	1129	377	2701	378	9912
2PN (County Paved Non FA)	36	261	458	353	584	1165	16	2873
2GN (County Gravel Non FA)	151	227	318	212	144	2413	518	3983
4U	18	4	5	21	7	4	0	58
4D	8	0	8	17	13	9	0	55
SEGMENT MILEAGE								
2U (MDOT Trunkline)	1504	1277	735	895	437	490	13	5352
2PF (County Paved FA)	609	847	992	484	181	1177	135	4424
2PN (County Paved Non FA)	16	102	236	152	310	640	8	1463
2GN (County Gravel Non FA)	172	104	158	101	73	1129	271	2007
4U	19	6	7	47	7	9	0	95
4D	10	0	21	34	20	22	0	107
ANNUAL MIDBLOCK CRASHES - TOTAL								
2U (MDOT Trunkline)	2247	3108	2482	2883	1225	1430	61	13437
2PF (County Paved FA)	345	1117	1612	827	306	2011	382	6600
2PN (County Paved Non FA)	5	52	121	116	132	386	3	816
2GN (County Gravel Non FA)	9	19	28	27	8	273	112	475
4U	79	15	36	200	24	44	0	399
4D	60	0	110	155	76	143	0	544
ANNUAL MIDBLOCK CRASHES - NON DEER								
2U (MDOT Trunkline)	606	931	851	835	471	508	32	4233
2PF (County Paved FA)	127	432	627	235	135	793	194	2544
2PN (County Paved Non FA)	4	21	56	44	64	124	2	315
2GN (County Gravel Non FA)	4	11	19	9	5	174	85	307
4U	33	4	17	96	13	16	0	179
4D	30	0	67	68	51	51	0	267

5.1 Rural Segment SPFs with AADT and Regional Indicator Variables

This section presents the results of separate segment SPFs for FI crash rates, PDO crash rates, and total crash rates for each of the six segment facility types. For each facility type, the results are first presented for the general statewide model(s), followed by a model that has been calibrated at the regional level. The regionally calibrated models account for general differences in safety performance across the seven MDOT regions. For these models, the parameter estimates are provided for AADT and each region. The baseline region varied for each facility type and depended on data availability. Indicator variables for each of the other regions for which data were available were then used to adjust the estimates to fit those regions.

Graphical representations of the SPFs are also provided for AADT only and AADT with regional indicator models. The models are considered valid only for the range of AADT values with which they were estimated. These AADT values for segments can be found in Table 39, rounded to the nearest 25 vehicles.

Table 39. Model AADT Ranges for Rural Segment Facility Types

Facility Type	Min AADT	Max AADT
2U	100	23,500
4U	1,675	32,000
4D	3,175	29,650
2PF	25	12,800
2PN	25	12,625
2GN	25	6,300

5.1.1 MDOT Rural Trunkline Segments (2U, 4U, 4D)

Table 40 and Figure 27 present the SPFs for 2-lane undivided (2U) trunkline segments. For the total midblock crash models, the effect of AADT on the FI crash rate is almost elastic, as shown from the AADT coefficient and the relationship between crashes/mile and AADT. However, the effect of AADT on PDO crashes and crashes of all severity levels is less pronounced, indicating that the majority of crashes are PDO crashes, which is not surprising, as these initial models included deer. Excluding deer from the midblock crash models resulted in a slightly more elastic relationship between AADT and FI crashes, and greatly increased the elasticity between AADT and crash frequency for PDO and total crashes.

Table 40. AADT Only SPF for Midblock Crashes on Rural 2U Trunkline Segments

Variable	FI Crashes			PDO Crashes			All Severities		
	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Total Midblock									
Intercept	-8.495	0.171	-49.590	-3.570	0.086	-41.480	-3.731	0.082	-45.740
AADT	0.867	0.020	42.570	0.539	0.010	51.530	0.571	0.010	57.700
IDP	6.135	-	-	4.082	-	-	4.608	-	-
Deer Excluded Midblock									
Intercept	-9.225	0.189	-48.910	-7.954	0.128	-61.910	-7.697	0.115	-66.940
AADT	0.937	0.022	41.880	0.900	0.015	58.710	0.908	0.014	66.100
IDP	4.831	-	-	5.025	-	-	5.128	-	-

*Note: IDP = inverse dispersion parameter, $\phi = 1/k$ (i.e., $Var(Y) = \mu + \alpha\mu^2 = \mu + \mu^2/\phi$)

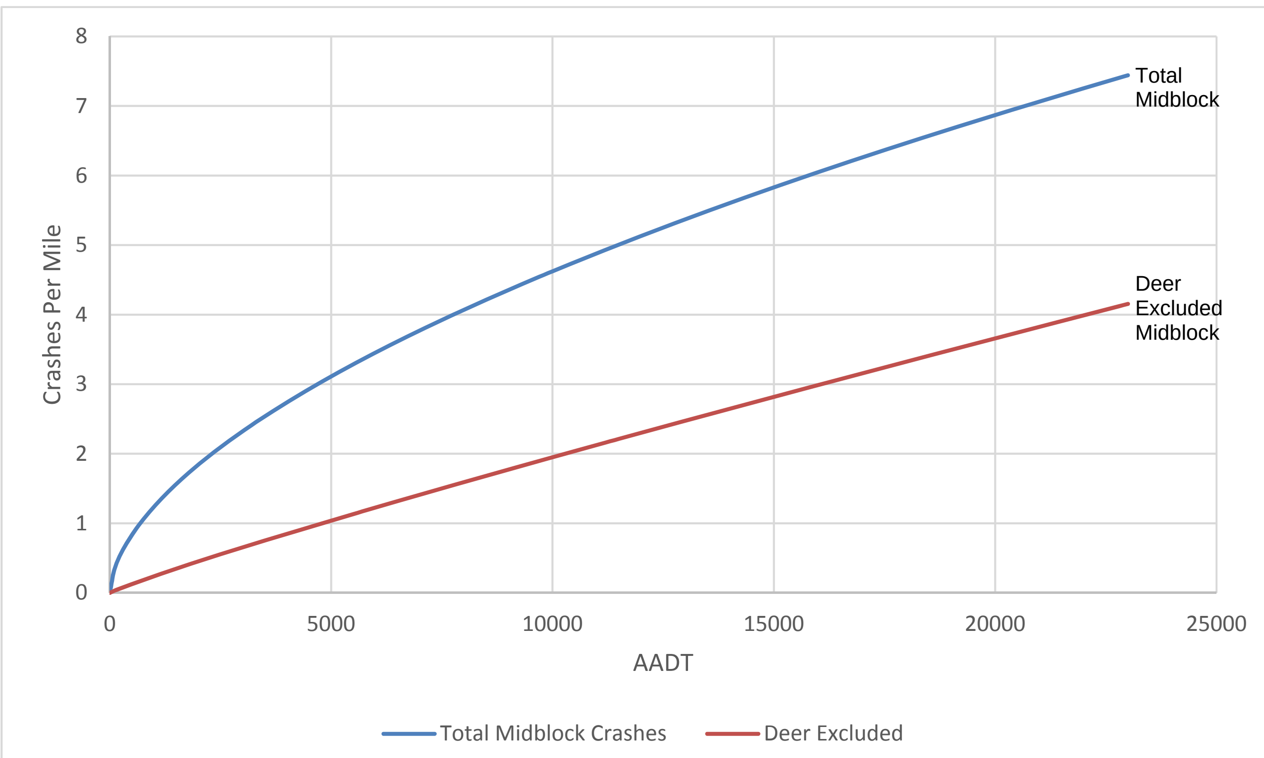


Figure 27. Annual Midblock Crashes per Mile for Rural 2U Trunkline Segments (All Severities)

Table 41 and Figure 28 present the SPFs for midblock crashes (including deer) with regional indicators for 2U trunkline segments. The regional parameter estimates indicate that the Superior and Metro regions had the lowest 2U midblock PDO and total crash rates, while the Bay and Grand regions had the highest rates. In the case of the fatal and injury crash rates, the Superior and North regions had considerably lower rates than the other regions.

Table 41. SPF for Midblock Crashes on Rural 2U Trunkline Segments with AADT and Regional Indicators

	FI Crashes			PDO Crashes			All Severities		
Variable	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Intercept	-7.546	0.231	-32.729	-3.349	0.123	-27.196	-3.412	0.116	-29.511
AADT	0.789	0.023	34.971	0.488	0.012	42.380	0.517	0.011	47.532
Superior Region Effect	-0.479	0.118	-4.068	-0.009	0.074	-0.127	-0.080	0.069	-1.164
North Region Effect	-0.409	0.114	-3.583	0.234	0.073	3.217	0.146	0.067	2.160
Grand Region Effect	-0.152	0.116	-1.315	0.302	0.074	4.056	0.232	0.069	3.361
Bay Region Effect	-0.224	0.114	-1.962	0.359	0.073	4.899	0.277	0.068	4.085
Southwest Region Effect	-0.212	0.116	-1.833	0.161	0.074	2.175	0.101	0.069	1.472
University Region Effect	-0.174	0.116	-1.504	0.169	0.074	2.275	0.116	0.069	1.682
IDP	6.757	-	-	4.367	-	-	4.950	-	-

*Note: IDP = inverse dispersion parameter
Metro Region served as baseline reference category

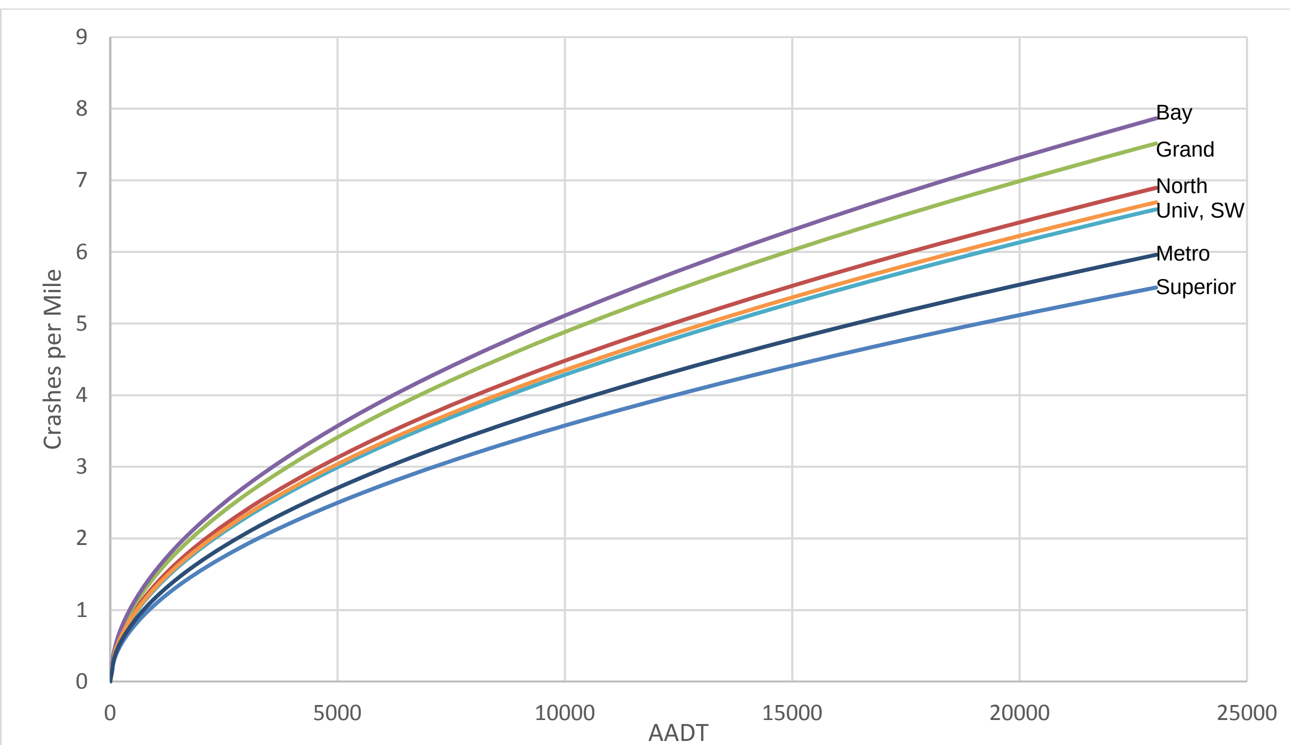


Figure 28. Annual Midblock Crashes per Mile for Rural 2U Trunkline Segments with Regional Indicators (All Severities)

Table 42 and Figure 29 present the relationship of crash rate and AADT for four-lane undivided (4U) segments. For the total midblock crash models, the effect of AADT on the FI crash rate is almost elastic. However, the AADT effect on PDO crashes and total crashes is much less pronounced, likely due to the high proportion of deer crashes. Excluding deer from the midblock crash models resulted in a slightly more elastic relationship between AADT and FI crashes, and greatly increased the elasticity between AADT and crash frequency for PDO and total crashes.

Table 42. AADT Only SPF for Midblock Crashes on Rural 4U Trunkline Segments

	FI Crashes			PDO Crashes			All Severities		
Variable	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Total Midblock									
Intercept	-10.178	1.334	-7.628	-2.639	0.592	-4.458	-3.181	0.561	-5.671
AADT	1.042	0.143	7.288	0.430	0.065	6.629	0.505	0.061	8.229
IDP	7.752	-	-	6.494	-	-	7.407	-	-
Deer Excluded Midblock									
Intercept	-11.614	1.453	-7.992	-7.942	0.851	-9.338	-8.231	0.771	-10.670
AADT	1.185	0.155	7.628	0.897	0.092	9.808	0.963	0.083	11.600
IDP	6.061	-	-	14.286	-	-	11.494	-	-

*Note: IDP = inverse dispersion parameter

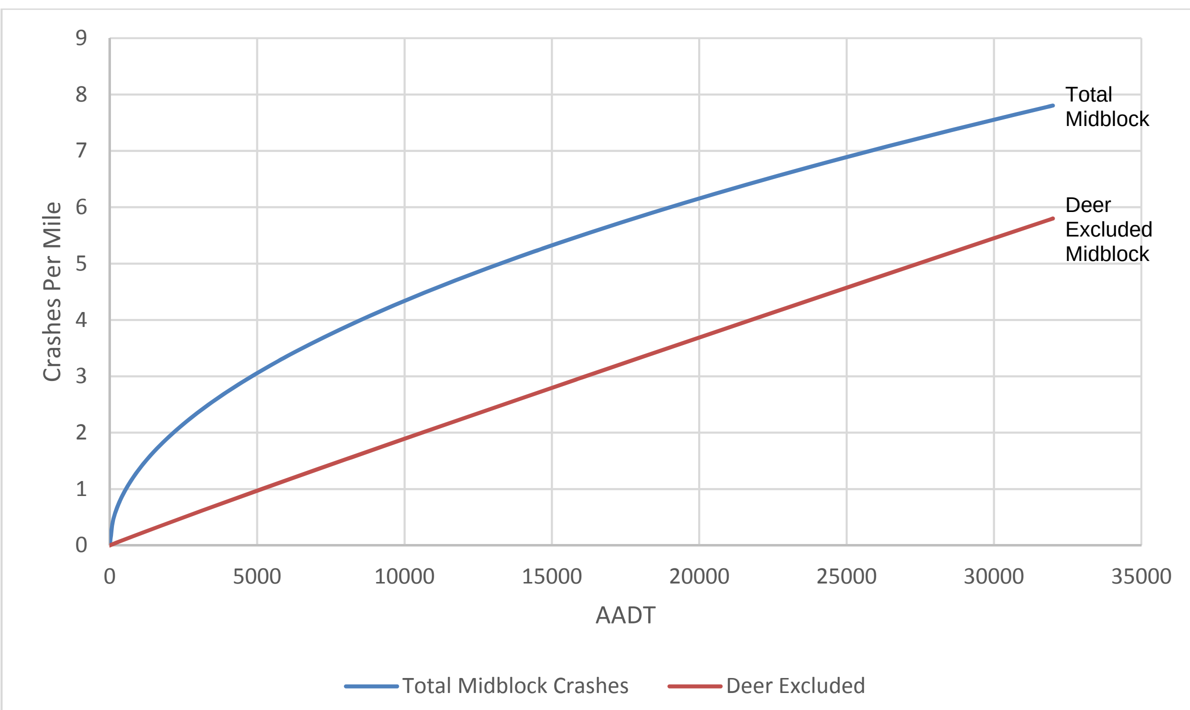


Figure 29. Annual Midblock Crashes per Mile for Rural 4U Trunkline Segments (All Severities)

As shown in Table 43, including the regional indicators did not have a substantial impact on the AADT coefficients for any of the three midblock (deer included) 4U crash models. Also, none of the regional indicators are statistically significant for the FI model. The Southwest region had the lowest PDO and total crash rates, while the University, North, and Superior regions had the highest rates. Metro Region did not contain any rural 4U segments.

Table 43. SPF for Midblock Crashes on Rural 4U Trunkline Segments with AADT and Regional Indicators

Variable	FI Crashes			PDO Crashes			All Severities		
	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Intercept	-10.553	1.348	-7.827	-3.387	0.652	-5.194	-3.857	0.611	-6.308
AADT	1.110	0.148	7.510	0.531	0.071	7.461	0.598	0.067	8.955
Superior Region Effect	-0.218	0.263	-0.827	-0.045	0.132	-0.341	-0.056	0.124	-0.453
North Region Effect	-0.077	0.305	-0.253	0.001	0.154	0.005	-0.005	0.144	-0.037
Grand Region Effect	-0.431	0.508	-0.849	-0.212	0.229	-0.927	-0.233	0.214	-1.089
Bay Region Effect	-0.312	0.234	-1.336	-0.286	0.127	-2.260	-0.270	0.118	-2.294
Southwest Region Effect	-0.446	0.328	-1.360	-0.465	0.167	-2.781	-0.450	0.155	-2.900
IDP	9.901	-	-	7.463	-	-	8.696	-	-

*Note: IDP = inverse dispersion parameter; University Region served as baseline reference category

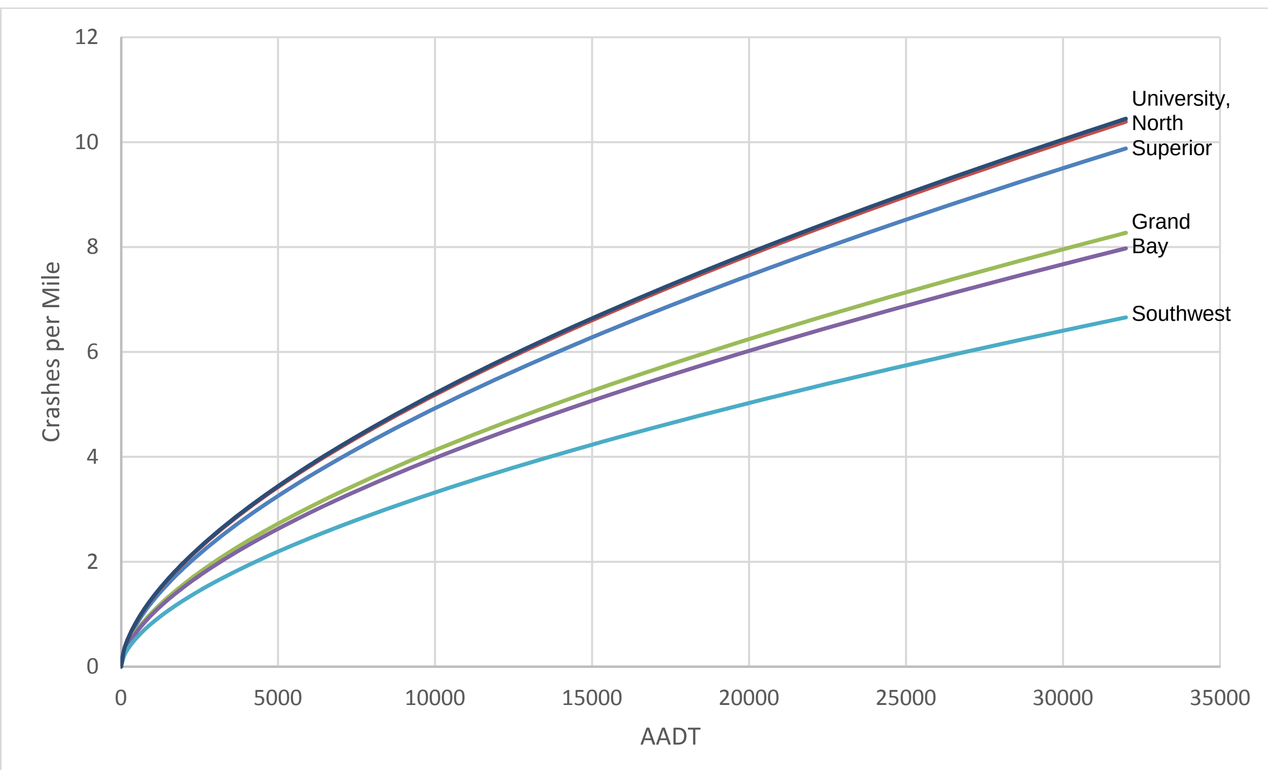


Figure 30. Annual Midblock Crashes per Mile for Rural 4U Trunkline Segments with Regional Indicators (All Severities)

Table 44 and Figure 31 depict the relationship between midblock crash rate and AADT for four-lane divided (4D) trunkline segments. The AADT parameter was very similar across each of the three statewide models. Excluding deer crashes increased the AADT parameters to nearly elastic relationships with PDO and all severity crashes, but caused a slight decrease in the AADT parameter for FI crashes.

Table 44. AADT Only SPF for Crashes on Rural 4D Trunkline Segments

Variable	FI Crashes			PDO Crashes			All Severities		
	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Total Midblock									
Intercept	-7.326	1.140	-6.425	-5.828	0.603	-9.671	-5.679	0.580	-9.788
AADT	0.705	0.129	5.463	0.755	0.069	10.997	0.753	0.066	11.394
IDP	4.926	-	-	3.623	-	-	3.663	-	-
Deer Excluded Midblock									
Intercept	-6.700	1.230	-5.449	-8.952	0.763	-11.740	-7.878	0.687	-11.460
AADT	0.614	0.140	4.403	1.017	0.086	11.810	0.923	0.078	11.860
IDP	3.509	-	-	5.952	-	-	5.556	-	-

*Note: IDP = inverse dispersion parameter

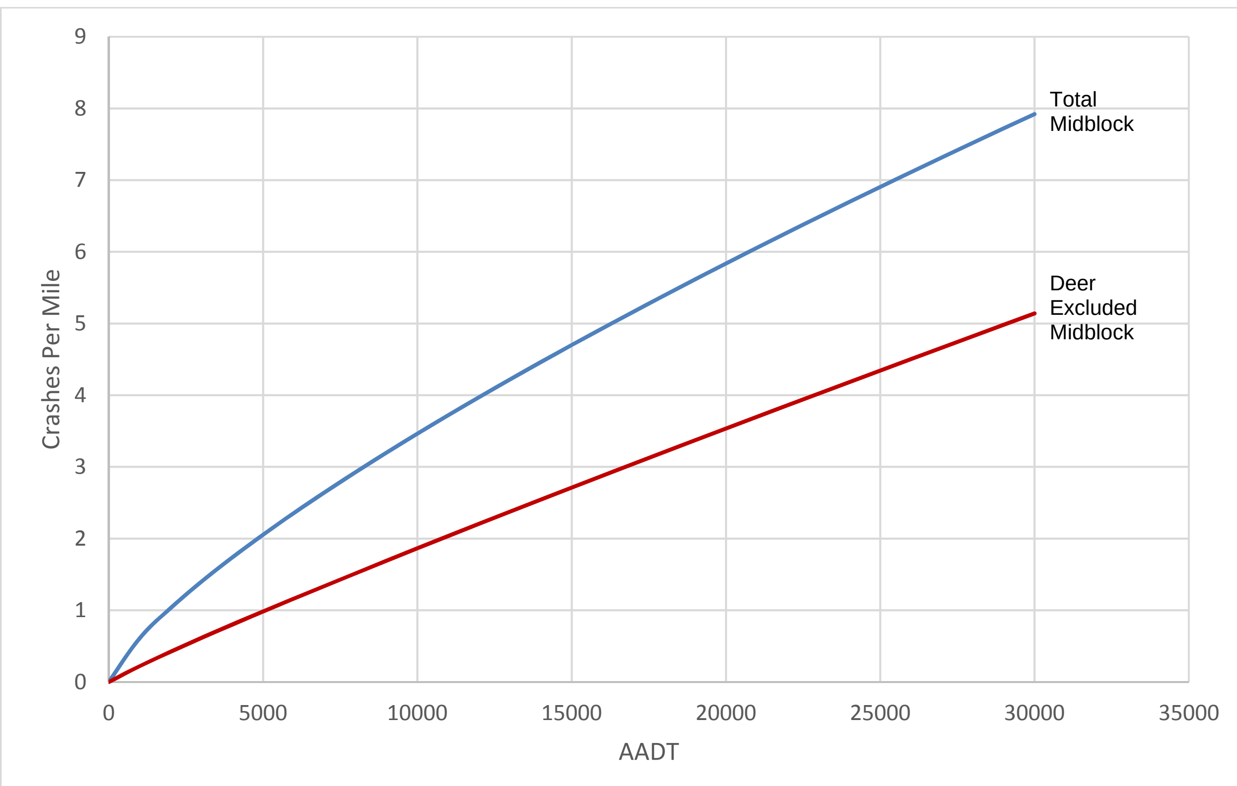


Figure 31. Annual Midblock Crashes per Mile for Rural 4D Trunkline Segments (All Severities)

Table 45 and Figure 32 show the results for the regionally calibrated models for midblock crashes (including deer) on 4D segments. The AADT effects on crash rates follow the same trends in each of the three models. The North, Grand, and Southwest regions experienced the lowest crash rate for total crashes and PDO crashes, while the University and Superior regions showed significantly higher rates. For the FI model, the University Region crash rate was significantly higher than the other regions. Metro Region did not possess any 4D segments.

Table 45. SPF for Crashes on Rural 4D Trunkline Segments with AADT and Regional Indicators

Variable	FI Crashes			PDO Crashes			All Severities		
	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Intercept	-9.025	1.378	-6.551	-7.724	0.672	-11.487	-7.542	0.647	-11.660
AADT	0.846	0.144	5.872	0.946	0.069	13.707	0.934	0.067	13.969
Superior Region Effect	0.533	0.392	1.358	0.447	0.229	1.953	0.485	0.208	2.326
Grand Region Effect	0.292	0.340	0.859	-0.087	0.213	-0.411	-0.014	0.192	-0.072
Bay Region Effect	0.419	0.367	1.142	0.194	0.223	0.873	0.244	0.202	1.204
Southwest Region Effect	0.271	0.313	0.865	-0.117	0.203	-0.579	-0.037	0.181	-0.204
University Region Effect	0.817	0.373	2.190	0.676	0.227	2.981	0.717	0.207	3.471
IDP	6.369	-	-	6.211	-	-	5.882	-	-

*Note: IDP = inverse dispersion parameter
North Region served as baseline reference category

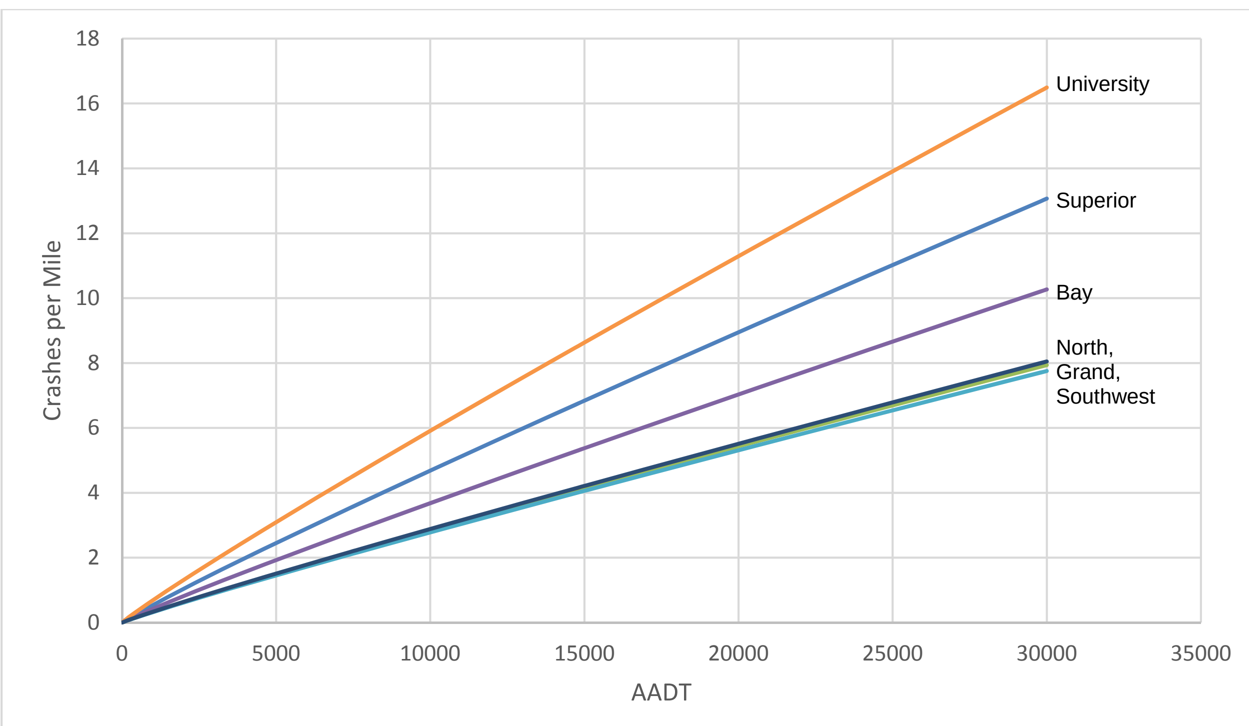


Figure 32. Annual Midblock Crashes per Mile for Rural 4D Trunkline Segments with Regional Indicators (All Severities)

5.1.2 Rural County Road Segments (2PF, 2PN, 2GN)

Table 46 and Figure 33 show the results for the AADT only models for all three crash severities for paved federal aid county segments (2PF) with and without deer crashes. The AADT effects for each of the models showed a relatively inelastic relationship with midblock crashes, although the elasticity was greatly improved for PDO and total crashes when deer were excluded from the midblock crash models.

Table 46. AADT Only SPF for Crashes on Rural 2PF County Segments

Variable	FI Crashes			PDO Crashes			All Severities		
	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Total Midblock									
Intercept	-7.198	0.146	-49.170	-3.580	0.057	-62.400	-3.634	0.054	-66.850
AADT	0.751	0.019	39.030	0.536	0.008	69.110	0.561	0.007	76.370
IDP	2.364	-	-	2.227	-	-	2.481	-	-
Deer Excluded Midblock									
Intercept	-7.568	0.156	-48.460	-6.294	0.100	-62.630	-6.048	0.087	-69.280
AADT	0.785	0.020	38.360	0.744	0.013	56.000	0.755	0.012	65.300
IDP	2.141	-	-	1.675	-	-	1.808	-	-

*Note: IDP = inverse dispersion parameter

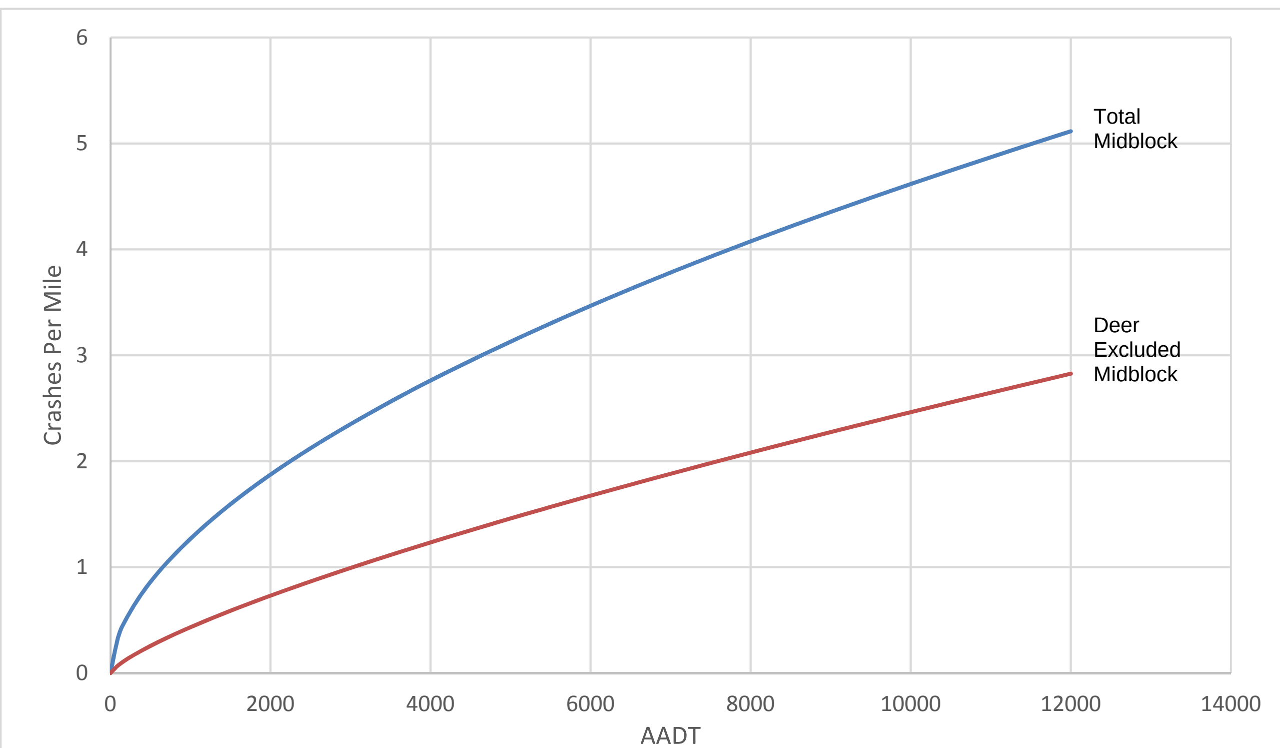


Figure 33. Annual Midblock Crashes per Mile for Rural 2PF County Segments (All Severities)

Table 47 and Figure 34 present the SPF regional indicator results for total midblock crashes (including deer) on paved federal aid (2PF) segments. Superior Region had the lowest total and PDO crash rates while Bay Region had the highest rate. For FI crash rate models, Bay, University, and Superior regions had the lowest crash frequencies, while the Metro Region had a rate that was significantly higher than the others.

Table 47. SPF for Crashes on Rural 2PF County Segments with AADT and Regional Indicators

Variable	FI Crashes			PDO Crashes			All Severities		
	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Intercept	-6.516	0.190	-34.217	-3.324	0.078	-42.400	-3.317	0.074	-44.918
AADT	0.704	0.022	32.706	0.502	0.009	58.054	0.525	0.008	64.194
Superior Region Effect	-0.502	0.099	-5.090	-0.474	0.046	-10.398	-0.491	0.042	-11.573
North Region Effect	-0.350	0.073	-4.778	-0.056	0.036	-1.528	-0.101	0.034	-2.985
Grand Region Effect	-0.322	0.070	-4.588	0.114	0.035	3.236	0.051	0.033	1.564
Bay Region Effect	-0.423	0.080	-5.303	0.171	0.038	4.536	0.093	0.035	2.656
Southwest Region Effect	-0.341	0.092	-3.724	-0.148	0.045	-3.271	-0.183	0.042	-4.351
University Region Effect	-0.333	0.066	-5.086	-0.007	0.034	-0.217	-0.057	0.031	-1.796
IDP	2.513	-	-	2.358	-	-	2.611	-	-

*Note: IDP = inverse dispersion parameter; Metro Region served as baseline reference category

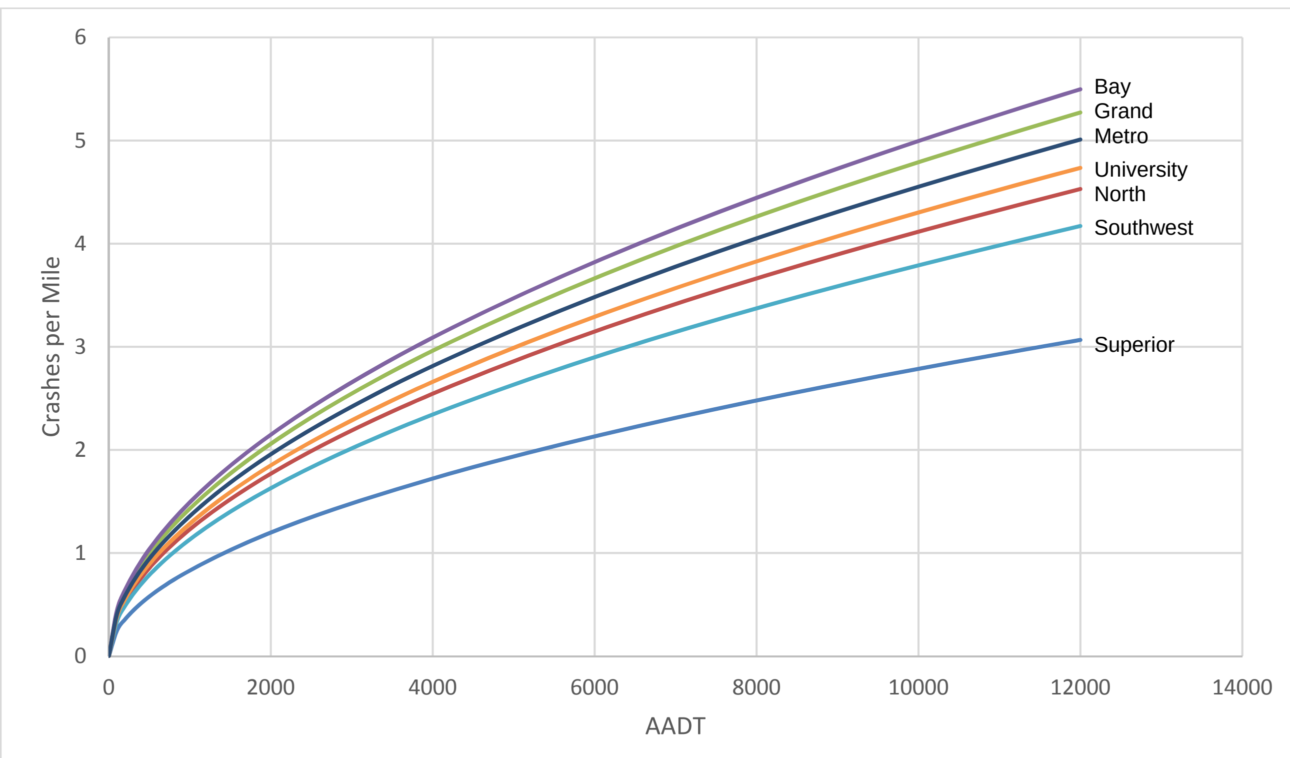


Figure 34. Annual Midblock Crashes per Mile for Rural 2PF County Segments with Regional Indicators (All Severities)

Table 48 describes the relationship between AADT and crashes for different crash severities among the paved non-federal aid (2PN) segments with and without deer crashes. The AADT effects on crash rates are similar for the AADT only models, regardless of severity level, and become slightly more elastic when deer crashes are excluded. This is also presented graphically in Figure 35.

Table 48. AADT Only SPF for Crashes on Rural 2PN County Segments

	FI Crashes			PDO Crashes			All Severities		
Variable	**Value**	**Std. Error**	**z value**	**Value**	**Std. Error**	**z value**	**Value**	**Std. Error**	**z value**
Total Midblock									
Intercept	-7.161	0.329	-21.760	-4.965	0.137	-36.310	-4.876	0.128	-38.080
AADT	0.728	0.050	14.440	0.688	0.021	32.350	0.695	0.020	34.920
IDP	2.506	-	-	1.832	-	-	2.092	-	-
Deer Excluded Midblock									
Intercept	-7.524	0.351	-21.450	-6.399	0.232	-27.540	-6.154	0.198	-31.010
AADT	0.766	0.054	14.310	0.731	0.036	20.430	0.746	0.031	24.420
IDP	2.294	-	-	1.403	-	-	1.610	-	-

*Note: IDP = inverse dispersion parameter

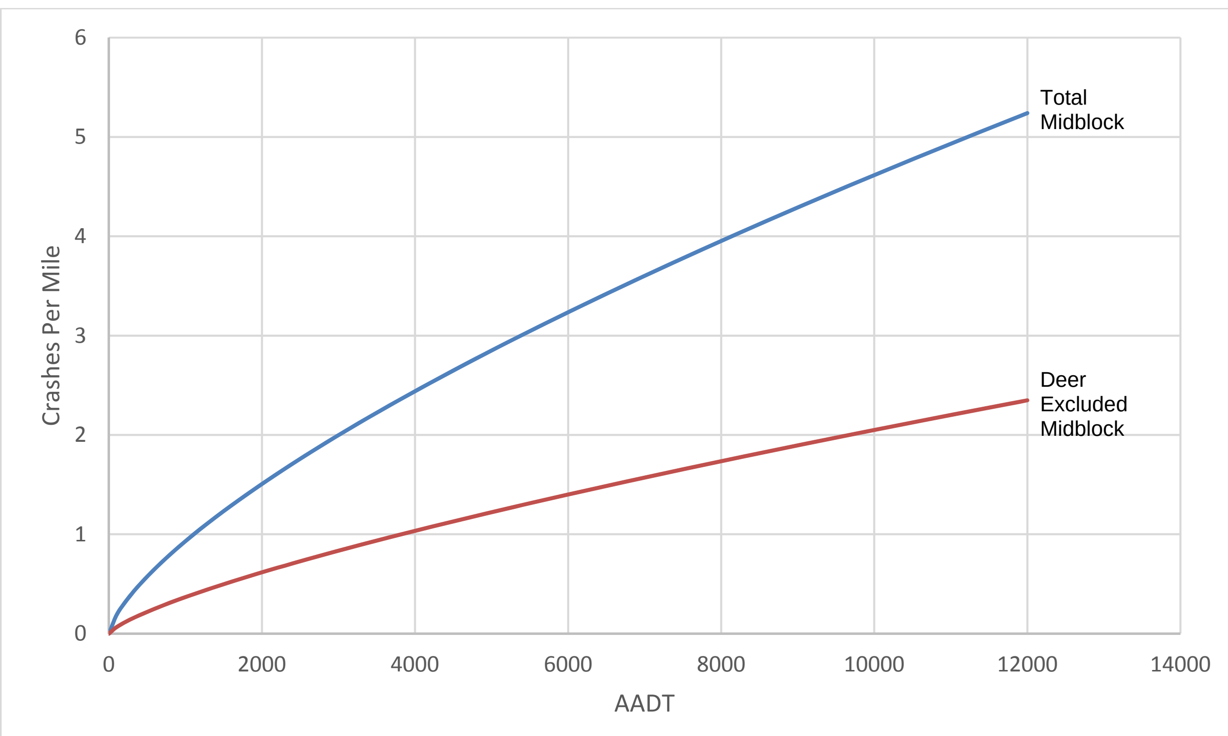


Figure 35. Annual Midblock Crashes per Mile for Rural 2PN County Segments (All Severities)

Table 49 presents the regional SPF results for midblock crashes (including deer) on 2PN segments. Bay and Grand regions showed significantly higher PDO and total midblock crash rates for paved non-federal aid segments, while Superior and Metro regions were significantly lower. However, the Metro Region showed significantly higher FI crash rates than the other regions, while Superior and North regions showed the lowest FI crash rates. This is shown graphically in Figure 36.

Table 49. SPF for Crashes on Rural 2PN County Segments with AADT and Regional Indicators

Variable	FI Crashes			PDO Crashes			All Severities		
	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Intercept	-7.546	0.231	-32.729	-3.349	0.123	-27.196	-3.412	0.116	-29.511
AADT	0.789	0.023	34.971	0.488	0.012	42.380	0.517	0.011	47.532
Superior Region Effect	-0.479	0.118	-4.068	-0.009	0.074	-0.127	-0.080	0.069	-1.164
North Region Effect	-0.409	0.114	-3.583	0.234	0.073	3.217	0.146	0.067	2.160
Grand Region Effect	-0.152	0.116	-1.315	0.302	0.074	4.056	0.232	0.069	3.361
Bay Region Effect	-0.224	0.114	-1.962	0.359	0.073	4.899	0.277	0.068	4.085
Southwest Region Effect	-0.212	0.116	-1.833	0.161	0.074	2.175	0.101	0.069	1.472
University Region Effect	-0.174	0.116	-1.504	0.169	0.074	2.275	0.116	0.069	1.682
IDP	6.757	-	-	4.367	-	-	4.950	-	-

*Note: IDP = inverse dispersion parameter; Metro Region served as baseline reference category

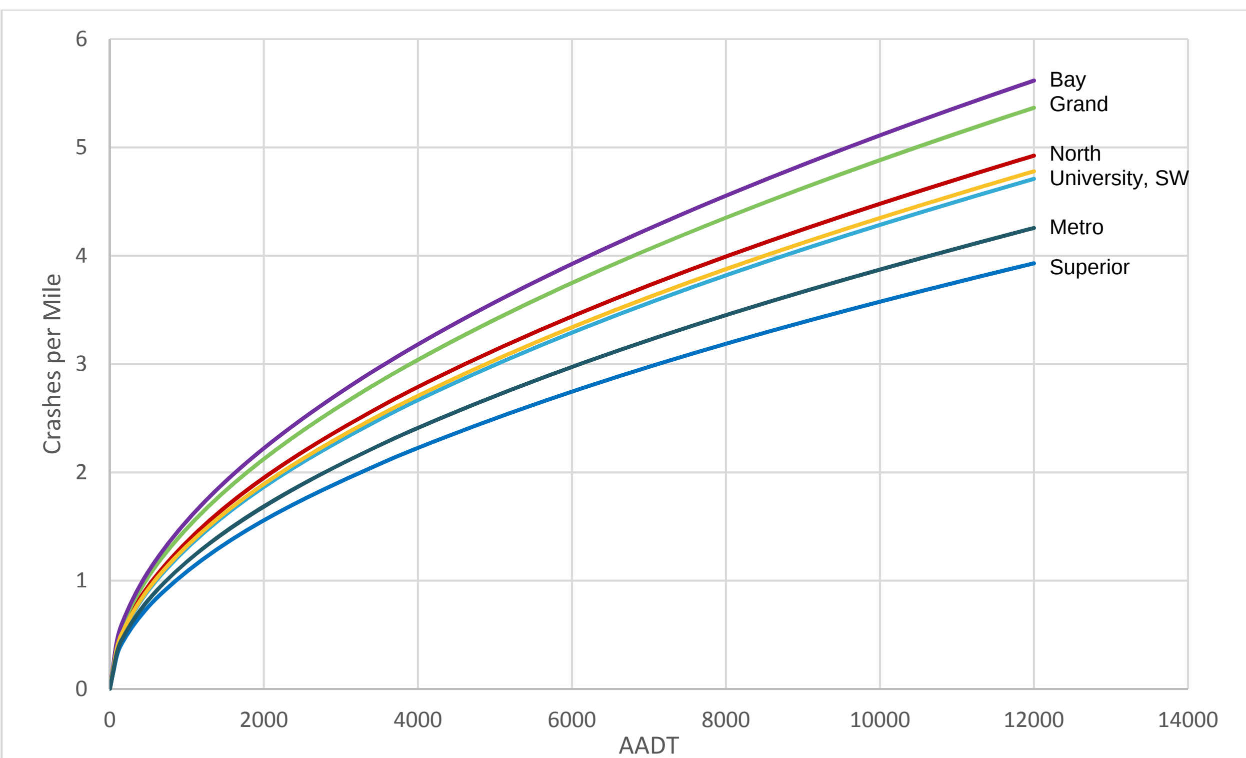


Figure 36. Annual Midblock Crashes per Mile for Rural 2PN County Segments with

Regional Indicators (All Severities)

Table 50 presents the relationship between AADT and the different severity midblock crashes for gravel segments (2GN). The AADT variable showed a similar and relatively inelastic relationship with crashes for each of the three models. Excluding deer from the crashes did not have a large effect on the AADT parameter, likely due to the relatively smaller proportion of deer crashes on these types of segment. This is shown graphically in Figure 37.

Table 50. AADT Only SPF for Crashes on Rural 2GN County Segments

	FI Crashes			PDO Crashes			All Severities		
Variable	**Value**	**Std. Error**	**z value**	**Value**	**Std. Error**	**z value**	**Value**	**Std. Error**	**z value**
Total Midblock									
Intercept	-5.814	0.257	-22.620	-4.642	0.133	-34.770	-4.398	0.121	-36.230
AADT	0.528	0.047	11.310	0.578	0.024	23.810	0.573	0.022	25.890
IDP	1.701	-	-	1.186	-	-	1.248	-	-
Deer Excluded Midblock									
Intercept	-5.765	0.262	-21.990	-5.531	0.177	-31.310	-5.025	0.151	-33.360
AADT	0.509	0.048	10.660	0.640	0.032	20.090	0.608	0.027	22.270
IDP	4.115	-	-	0.662	-	-	0.835	-	-

*Note: IDP = inverse dispersion parameter

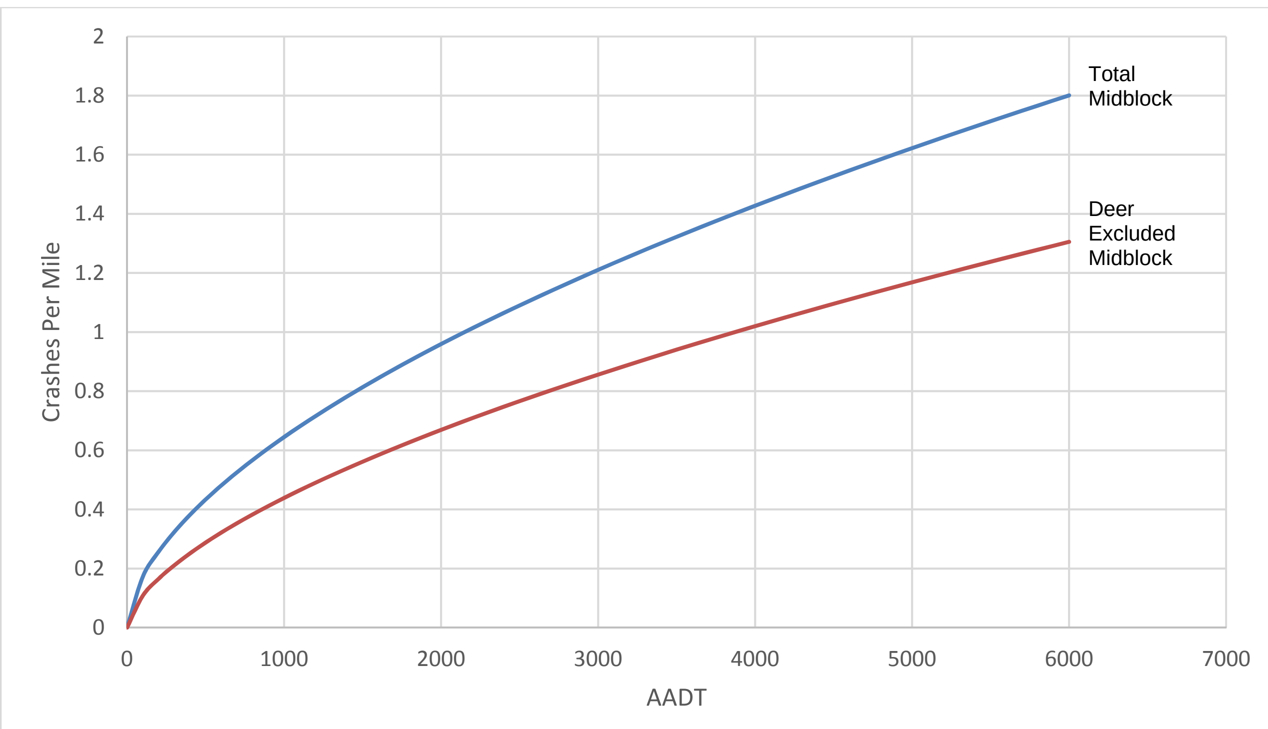


Figure 37. Annual Midblock Crashes per Mile for Rural 2GN County Segments (All Severities)

Including regional indicators to the 2GN midblock crash (including deer) models showed interesting results, which are displayed in Table 51. The Superior region showed dramatically lower midblock crash rates regardless of severity, while Metro Region showed the highest rates across each of the models. The comparatively low crash rates in the Superior region may be due to lower maintenance standards contributing to lower speeds. These findings are shown graphically in Figure 38.

Table 51. SPF for Crashes on Rural 2GN County Segments with AADT and Regional Indicators

Variable	FI Crashes			PDO Crashes			All Severities		
	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Intercept	-5.428	0.294	-18.433	-4.212	0.150	-28.145	-3.970	0.136	-29.197
AADT	0.526	0.048	10.953	0.554	0.024	22.751	0.551	0.022	24.836
Superior Region Effect	-1.803	0.317	-5.682	-2.070	0.184	-11.252	-2.008	0.161	-12.482
North Region Effect	-0.915	0.276	-3.318	-0.616	0.126	-4.901	-0.663	0.115	-5.752
Grand Region Effect	-0.177	0.203	-0.876	-0.380	0.113	-3.356	-0.330	0.100	-3.303
Bay Region Effect	-0.565	0.244	-2.317	-0.190	0.109	-1.733	-0.250	0.101	-2.485
Southwest Region Effect	-0.466	0.336	-1.385	-0.743	0.198	-3.758	-0.677	0.172	-3.929
University Region Effect	-0.340	0.116	-2.934	-0.247	0.060	-4.132	-0.264	0.054	-4.876
IDP	4.329	-	-	2.105	-	-	2.141	-	-

*Note: IDP = inverse dispersion parameter
Metro Region served as baseline reference category

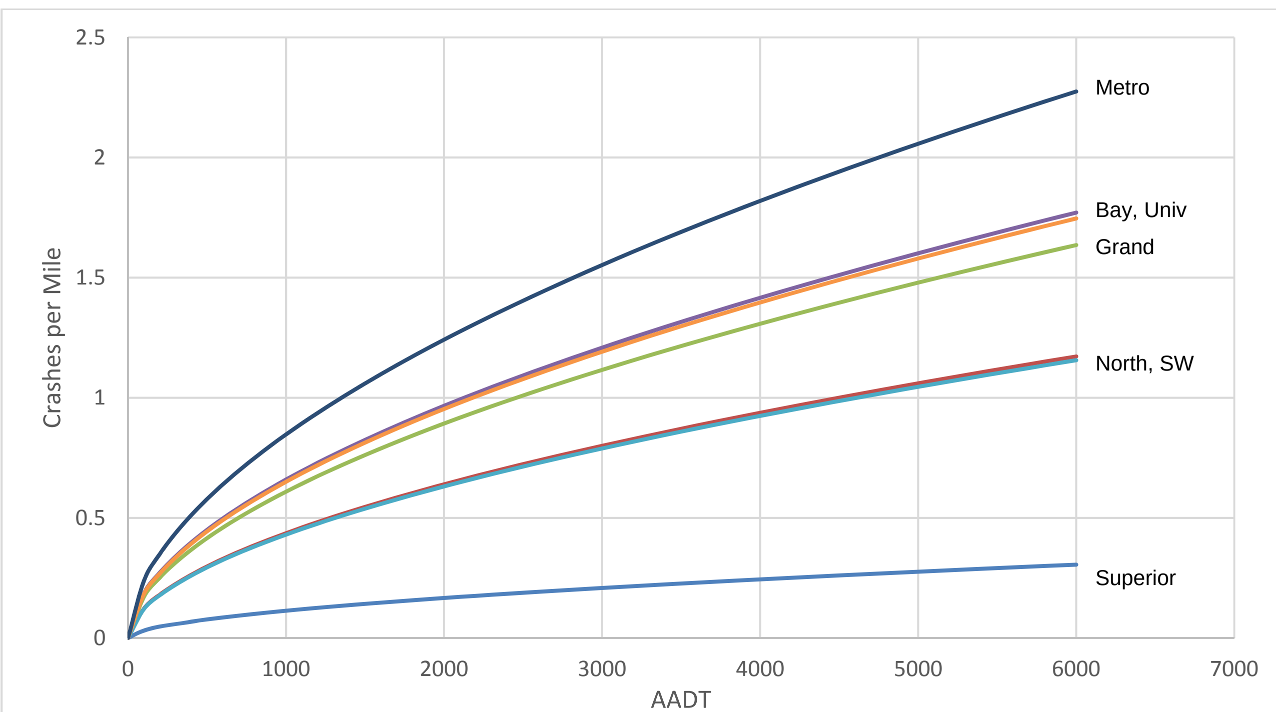


Figure 38. Annual Midblock Crashes per Mile for 2GN Segments with Regional Indicators (All Severities)

5.2 Rural Intersection SPFs with AADT and Regional Indicator Variables

This section presents the results of segment SPFs for FI crash rates, PDO crash rates, and total crash rates for each of the four intersection facility types. For each facility type, the results are first presented for the general statewide model(s), followed by a model that has been calibrated at the regional level. The regionally calibrated models account for general differences in safety performance across the seven MDOT regions. For these models, the parameter estimates are provided for AADT and each region. The baseline region varied for each facility type and depended on data availability. Indicator variables for each of the other regions for which data were available were then used to adjust the estimates to fit those regions.

Graphical representation of the SPFs are provided for AADT only and AADT with the regional indicator models. The statewide graphics display the models for major roadway AADTs, with minor road AADTs fixed at the 25th, 50th, and 75th percentile values, rounded to the nearest 100. The regional models are only presented for the 50th percentile minor road AADTs. The models are considered valid only for the range of AADT values with which they were estimated. These AADT values for rural intersections can be found in Table 52, rounded to the nearest 25 vehicles.

Table 52. Model AADT Ranges for Rural Intersection Facility Types

Facility Type	Min AADT Major	Max AADT Major	Min AADT Minor	Max AADT Minor
3ST	25	32,000	25	6,550
4ST	50	20,275	25	6,850
3SG	3,725	16,300	125	9,750
4SG	1,275	21,425	50	12,150

5.2.1 Rural Stop Controlled Intersections (3ST, 4ST)

Table 53 and Figure 39 present the SPFs for 3-leg minor road stop controlled (3ST) intersections. For the statewide intersection crash models, the effect of AADT is largely inelastic and consistent across major and minor AADT and crash severity levels.

Table 53. AADT Only SPF for Crashes at Rural 3ST Intersections

	FI Crashes			PDO Crashes			All Severities		
Variable	**Value**	**Std. Error**	**z value**	**Value**	**Std. Error**	**z value**	**Value**	**Std. Error**	**z value**
Intercept	-8.939	0.303	-29.520	-6.811	0.161	-42.240	-6.729	0.146	-45.980
$AADT_{maj}$	0.452	0.041	11.010	0.436	0.022	19.560	0.439	0.020	21.750
$AADT_{min}$	0.493	0.034	14.630	0.402	0.018	22.530	0.419	0.016	25.910
IDP	1.387	-	-	1.600	-	-	1.866	-	-

*Note: IDP = inverse dispersion parameter

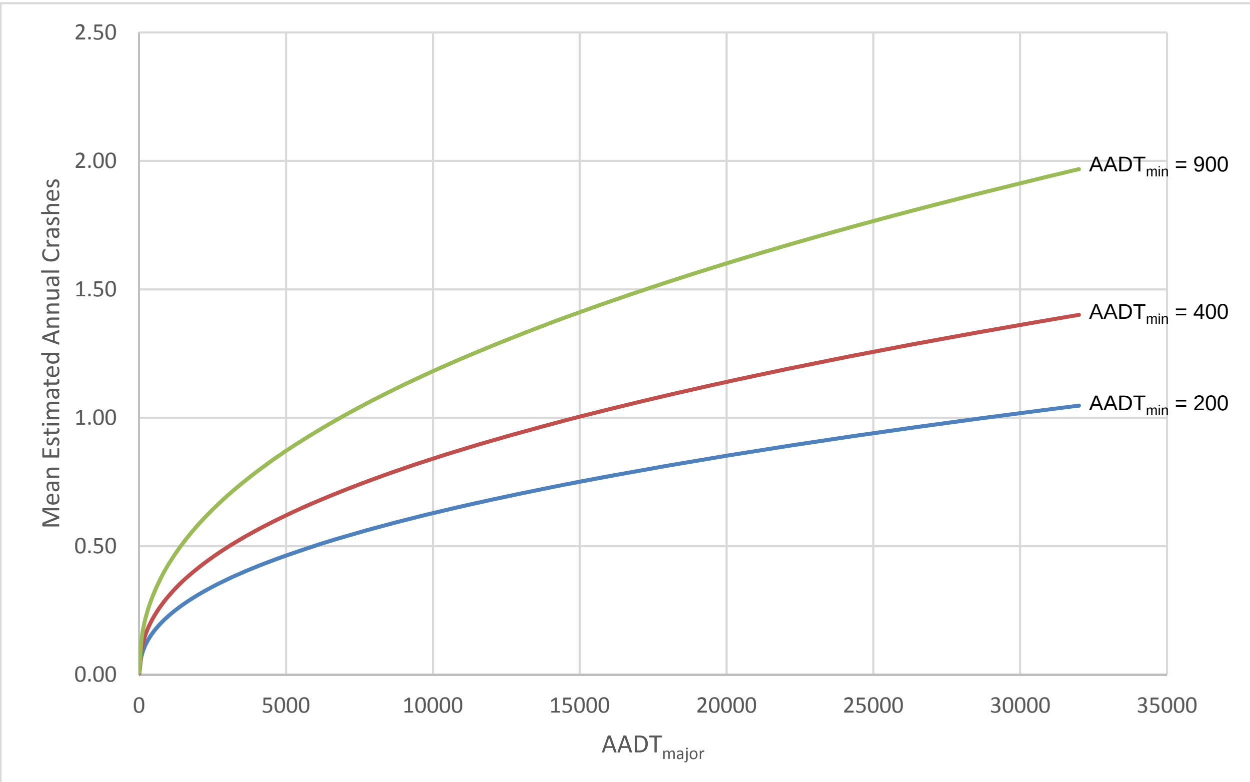


Figure 39. Annual Crashes for Rural 3ST Intersections (All Severities)

Including the regional effect in the 3ST models, which is shown in Table 54 and Figure 40, showed North Region to have significantly lower FI crash rates and Superior Region to have greater PDO and total crash rates. Bay Region had a significantly lower total 3ST intersection crash rate. The effect of major and minor AADT remained largely consistent with the statewide models.

Table 54. SPF for Crashes at Rural 3ST Intersections with AADT and Regional Indicators

Variable	FI Crashes			PDO Crashes			All Severities		
	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Intercept	-9.146	0.386	-23.674	-7.144	0.210	-34.063	-7.029	0.189	-37.093
$AADT_{maj}$	0.493	0.044	11.187	0.470	0.024	19.851	0.475	0.021	22.110
$AADT_{min}$	0.506	0.034	14.848	0.412	0.018	22.820	0.429	0.016	26.220
Superior Region Effect	0.047	0.215	0.217	0.272	0.121	2.243	0.222	0.109	2.041
North Region Effect	-0.401	0.202	-1.988	0.040	0.115	0.344	-0.048	0.103	-0.464
Grand Region Effect	-0.123	0.199	-0.617	-0.079	0.116	-0.682	-0.087	0.103	-0.839
Bay Region Effect	-0.346	0.206	-1.676	-0.202	0.120	-1.688	-0.234	0.107	-2.188
Southwest Region Effect	-0.023	0.205	-0.114	0.006	0.119	0.050	-0.001	0.106	-0.006
University Region Effect	-0.274	0.201	-1.363	0.009	0.115	0.078	-0.048	0.103	-0.467
IDP	1.431	-	-	1.647	-	-	1.919	-	-

*Note: IDP = inverse dispersion parameter
Metro Region served as baseline reference category

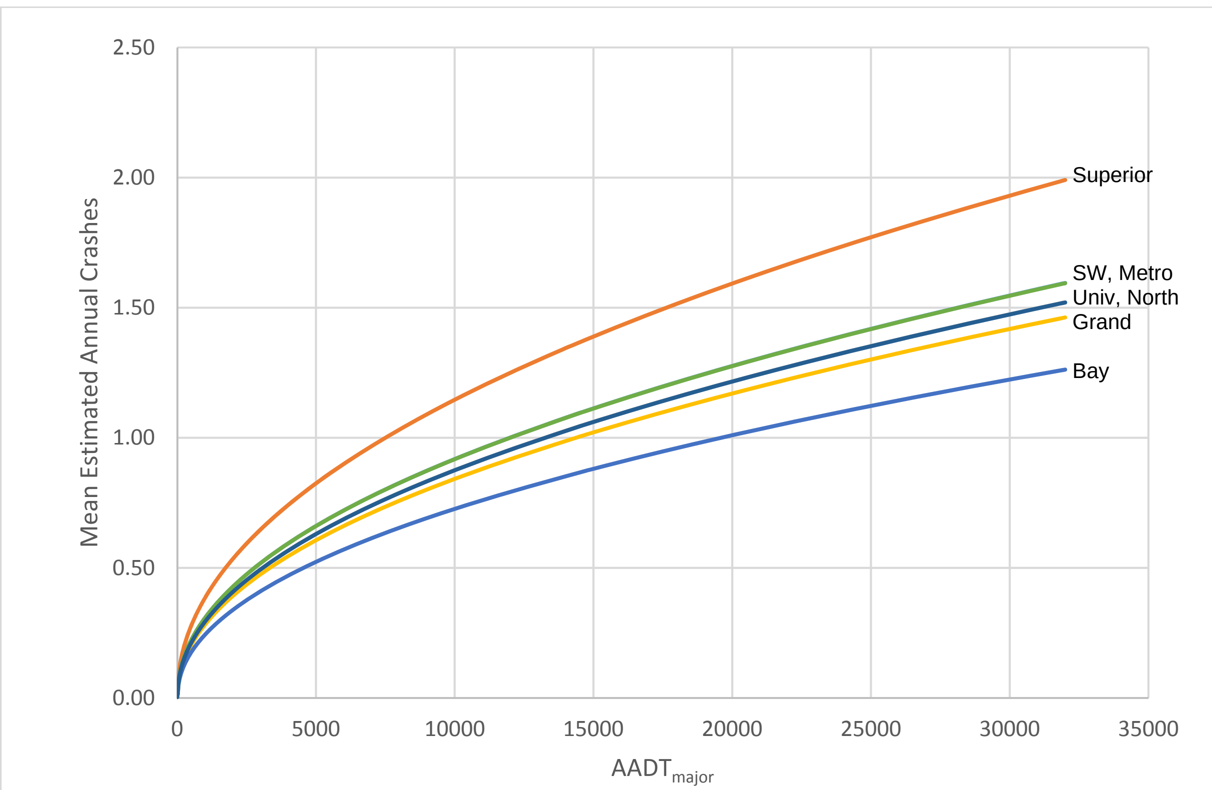


Figure 40. Annual Crashes (All Severities) for Rural 3ST Intersections with Regional Indicators ($AADT_{min}$ = 400)

Table 55 and Figure 41 present the SPFs for 4-leg minor road stop controlled (4ST) intersections. For the statewide intersection crash models, the effect of major road AADT is even more inelastic than for 3ST intersections, although the minor road AADT showed improved elasticity with respect to crash prediction. These results were relatively consistent across each of the three severity levels.

Table 55. AADT Only SPF for Crashes at Rural 4ST Intersections

Variable	FI			PDO			All Severities		
	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Intercept	-8.257	0.207	-39.810	-6.586	0.133	-49.350	-6.495	0.118	-55.000
$AADT_{maj}$	0.321	0.027	11.780	0.369	0.018	20.790	0.359	0.016	22.940
$AADT_{min}$	0.659	0.026	25.020	0.483	0.017	28.910	0.533	0.015	35.920
IDP	0.583	-	-	0.320	-	-	0.349	-	-

*Note: IDP = inverse dispersion parameter

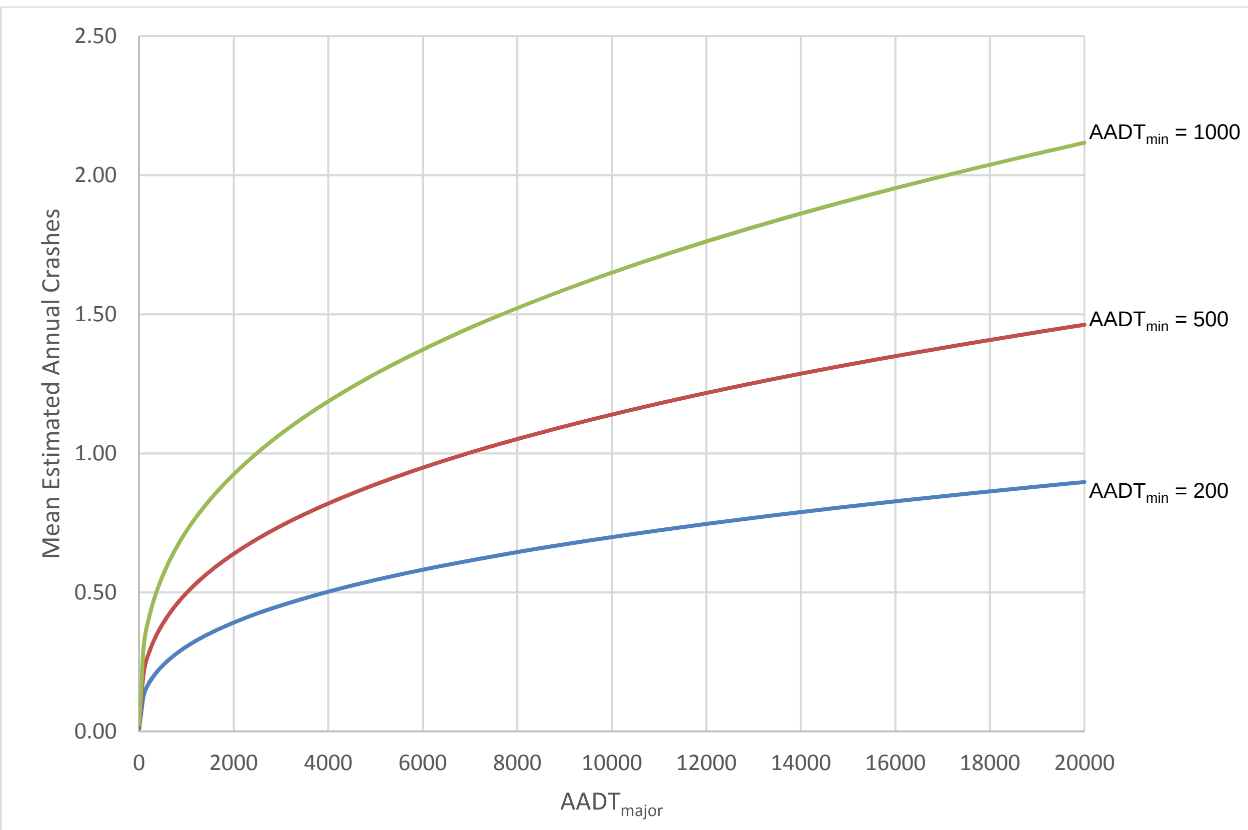


Figure 41. Annual Crashes for Rural 4ST Intersections (All Severities)

Similar to the 3ST results, including the regional effect in the 4ST models, shown in Table 56 and Figure 42, showed North, Grand, and Bay regions to have significantly lower PDO and total intersection crash rates and Superior, Metro, and Southwest regions to have greater PDO and total crash rates. No significant differences were observed for FI 4ST intersection crashes. The effect of major and minor AADT remained largely consistent with the statewide models.

Table 56. SPF for Crashes at Rural 4ST Intersections with AADT and Regional Indicators

Variable	FI			PDO			All Severities		
	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Intercept	-8.149	0.263	-30.931	-6.834	0.170	-40.267	-6.633	0.150	-44.193
$AADT_{maj}$	0.333	0.029	11.579	0.421	0.019	22.469	0.400	0.017	24.211
$AADT_{min}$	0.650	0.027	24.466	0.489	0.017	29.146	0.535	0.015	35.806
Superior Region Effect	-0.233	0.177	-1.313	0.116	0.107	1.091	0.022	0.096	0.233
North Region Effect	-0.277	0.159	-1.746	-0.247	0.099	-2.488	-0.263	0.089	-2.963
Grand Region Effect	-0.235	0.154	-1.522	-0.297	0.097	-3.075	-0.290	0.087	-3.353
Bay Region Effect	-0.096	0.153	-0.626	-0.335	0.097	-3.470	-0.269	0.086	-3.117
Southwest Region Effect	-0.013	0.160	-0.081	-0.026	0.101	-0.257	-0.031	0.090	-0.341
University Region Effect	-0.091	0.155	-0.588	-0.106	0.097	-1.096	-0.111	0.087	-1.276
IDP	1.751	-	-	3.300	-	-	2.959	-	-

*Note: IDP = inverse dispersion parameter
Metro Region served as baseline reference category

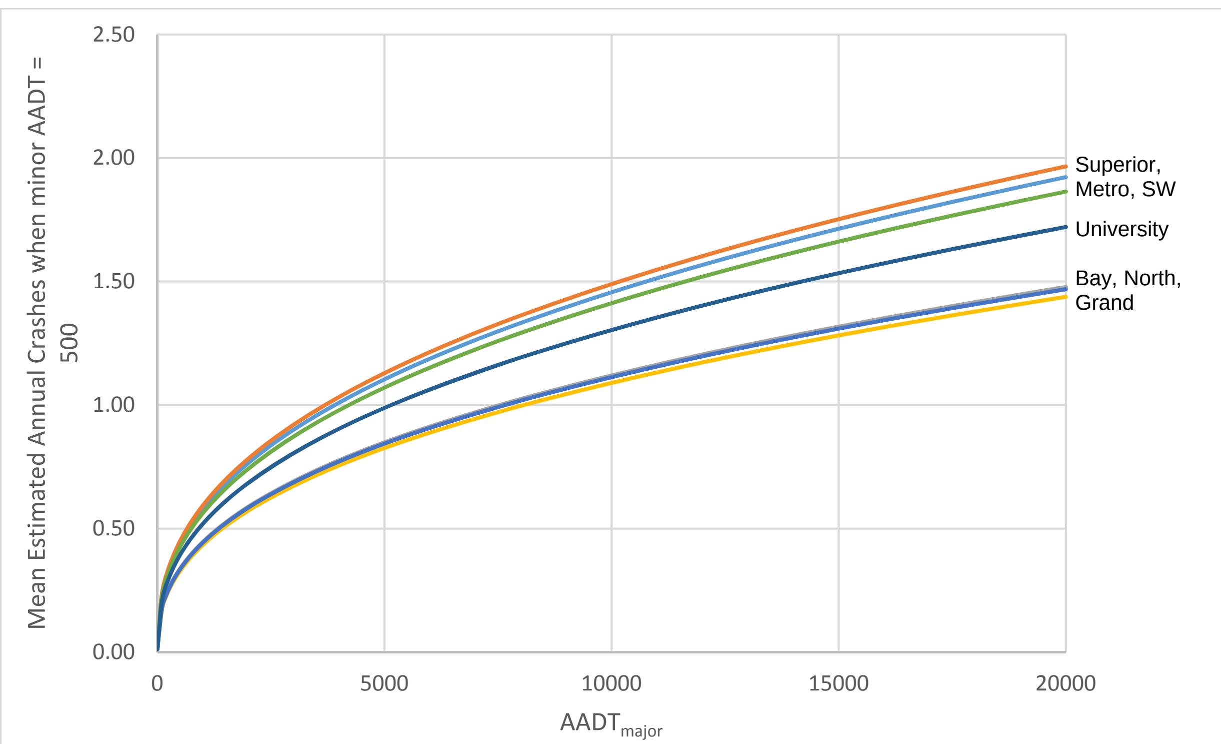


Figure 42. Annual Crashes (All Severities) for Rural 4ST Intersections with Regional Indicators ($AADT_{min}$ = 500)

5.2.2 Rural Signalized Intersections (3SG, 4SG)

Table 57 and Figure 43 present the SPFs for 3-leg signalized intersections (3SG). Only the statewide models are presented here as the sample was too small to provide meaningful results across the various regions. For the statewide intersection crash models, the effect of major and minor road AADT is highly inelastic and provides very little predictive capability. This is likely at least partially due to the small sample size of rural 3-leg signalized intersections in Michigan.

Table 57. AADT Only SPF for Crashes at Rural 3SG Intersections

	FI			PDO			All Severities		
Variable	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Intercept	-3.627	2.223	-1.631	-1.350	1.395	-0.968	-1.236	1.365	-0.905
$AADT_{maj}$	0.174	0.179	0.975	0.157	0.115	1.363	0.157	0.113	1.399
$AADT_{min}$	0.207	0.162	1.277	0.108	0.097	1.112	0.123	0.095	1.290
IDP	1.142	-	-	1.675	-	-	1.560	-	-

*Note: IDP = inverse dispersion parameter

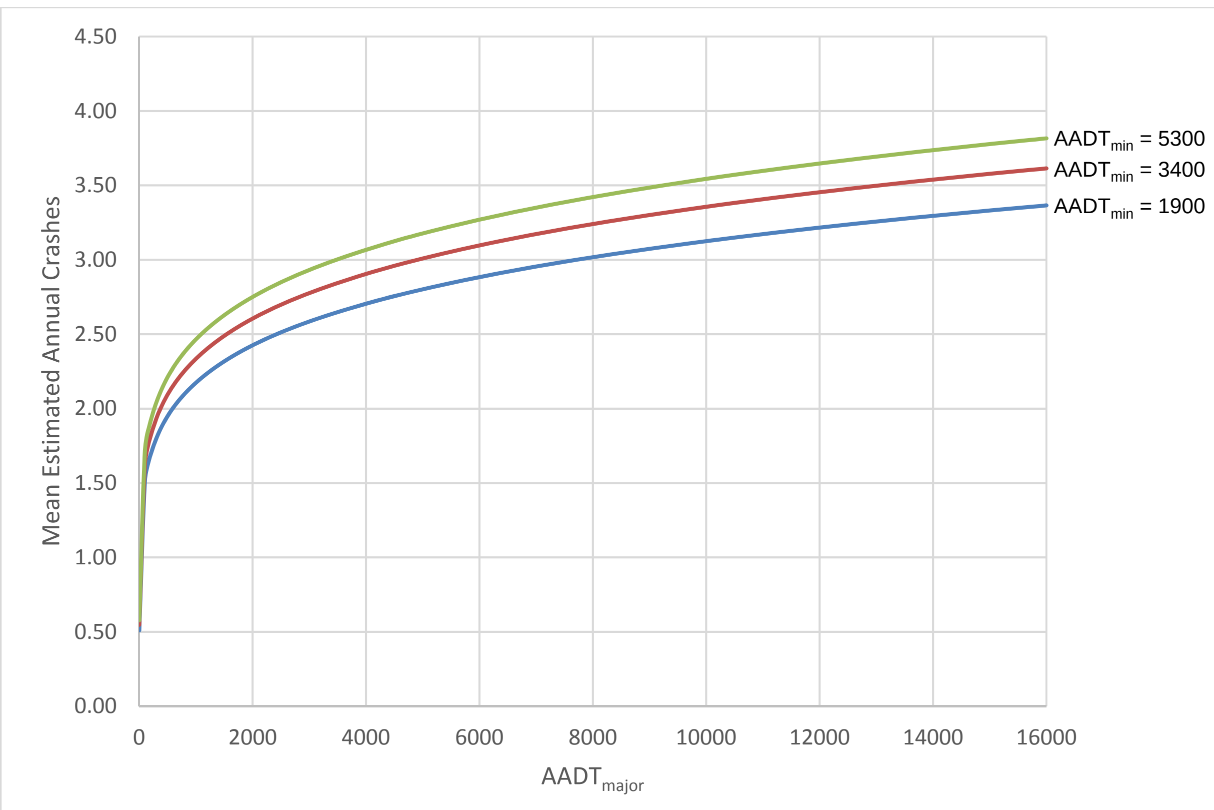


Figure 43. Annual Crashes for Rural 3SG Intersections (All Severities)

Table 58 and Figure 44 present the SPFs for 4-leg signalized intersections (4SG). Similar to the 3SG intersection models, the effect of major and minor road AADT is highly inelastic and provides very little predictive capability.

Table 58. AADT Only SPF for Crashes at Rural 4SG Intersections

Variable	FI			PDO			All Severities		
	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Intercept	-3.954	0.582	-6.795	-2.481	0.367	-6.750	-2.217	0.337	-6.571
$AADT_{maj}$	0.263	0.050	5.232	0.246	0.032	7.769	0.245	0.029	8.446
$AADT_{min}$	0.198	0.051	3.853	0.183	0.032	5.659	0.184	0.030	6.174
IDP	2.404	-	-	3.279	-	-	3.497	-	-

*Note: IDP = inverse dispersion parameter

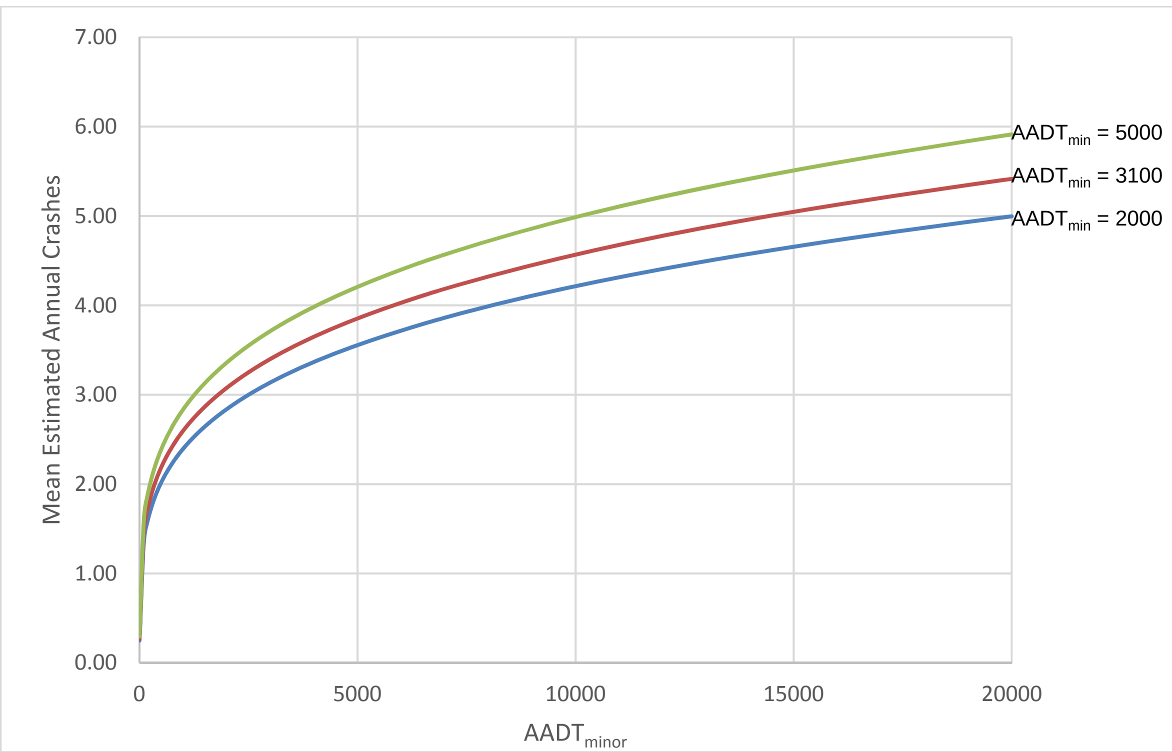


Figure 44. Annual Crashes for Rural 4SG Intersections (All Severities)

Including the regional effect in the 4SG models, shown in Table 59 and Figure 45, showed the Southwest region to have significantly higher crash rates across all severities and Metro Region to have the lowest rates. The effect of major and minor AADT remained largely inelastic, which was consistent with the statewide models.

Table 59. SPF for Crashes at Rural 4SG Intersections with AADT and Regional Indicators

Variable	Fatal and Injury Crashes			Property Damage Only Crashes			All Crash Severities		
	Value	Std. Error	z value	Value	Std. Error	z value	Value	Std. Error	z value
Intercept	-5.244	0.814	-6.446	-2.987	0.495	-6.034	-2.906	0.457	-6.364
$AADT_{maj}$	0.319	0.060	5.301	0.276	0.039	7.161	0.284	0.035	8.013
$AADT_{min}$	0.206	0.052	4.005	0.181	0.033	5.534	0.184	0.030	6.151
Superior Region Effect	0.446	0.605	0.737	0.148	0.331	0.448	0.200	0.308	0.650
North Region Effect	0.389	0.500	0.779	0.246	0.269	0.914	0.274	0.252	1.089
Grand Region Effect	0.694	0.497	1.398	0.257	0.269	0.955	0.342	0.251	1.361
Bay Region Effect	0.729	0.492	1.481	0.212	0.265	0.800	0.310	0.248	1.251
Southwest Region Effect	1.130	0.510	2.216	0.431	0.281	1.536	0.581	0.262	2.216
University Region Effect	0.911	0.499	1.827	0.300	0.271	1.107	0.431	0.254	1.700
IDP	2.703	-	-	3.311	-	-	3.597	-	-

*Note: IDP = inverse dispersion parameter
Metro Region served as baseline reference category

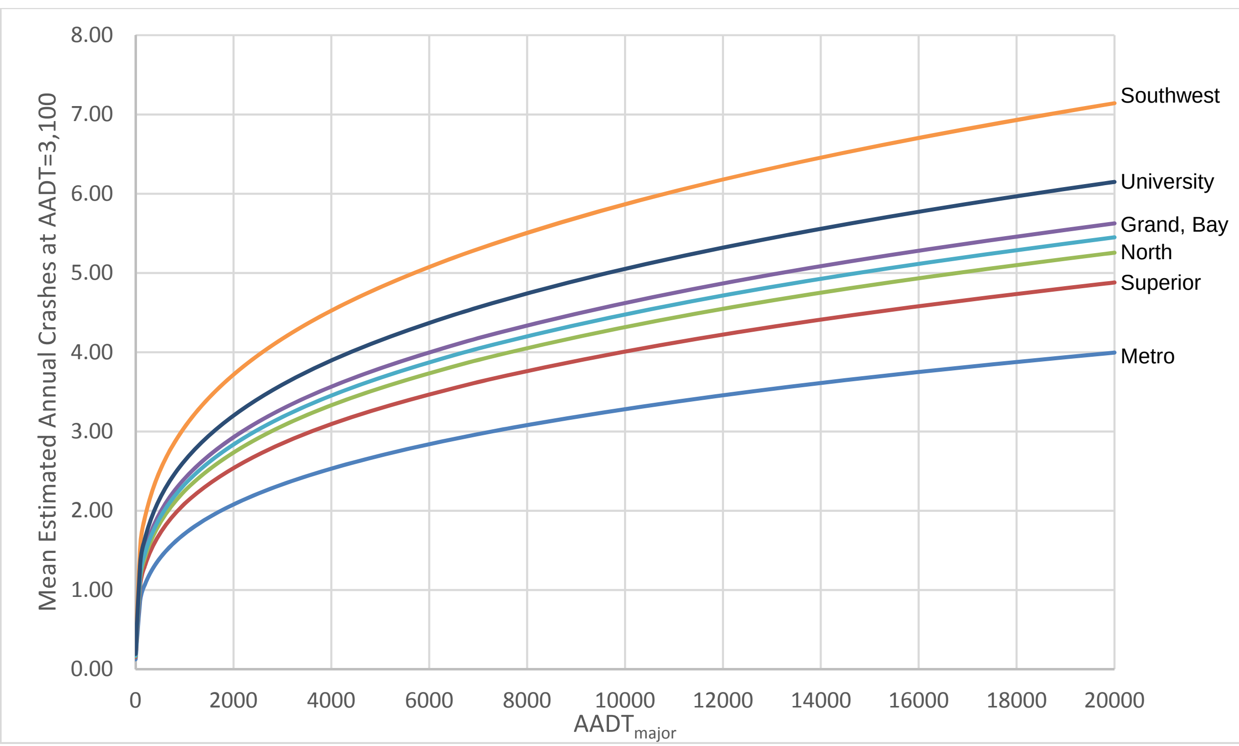


Figure 45. Annual Crashes (All Severities) for Rural 4SG Intersections with Regional Indicators ($AADT_{min}$ =3,100)

6.0 FULLY-SPECIFIED MICHIGAN RURAL SEGMENT SPFS WITH AADT, REGIONAL INDICATORS, AND GEOMETRIC VARIABLES

After estimating the segment models considering only traffic volumes and MDOT region, more detailed models were specified that considered the full database developed by the research team using the complete datasets of traffic and inventory data as described in section 3.0 of this report. These fully-specified models were developed in a format similar to those presented in Chapters 10 and 11 of the *HSM*. This chapter outlines the format of these SPFs, which are estimated in combination with CMFs where sufficient data are available. Several preliminary models were developed for each of the six segment facility types. The preliminary analysis as described in section 4.0 of this report helped inform the investigation of parameters to be included in the SPFs. Where possible, the base conditions for the CMFs were specified in the same manner as the *HSM* (e.g., base shoulder width of 6 ft for 2U segments). However, in many cases the parameters were specified differently from the form provided in the *HSM*.

6.1 Functional Form

The predicted average crash frequency for each rural roadway segment facility type is computed as the sum of predicted average crash frequency of all crash types that occurred on the segment. For segment crashes, this included all non-deer crashes that occurred on the segment and included the midblock (i.e., non-intersection) area type code. Deer crashes were excluded from the segment SPF/CMF development process due to the high frequency of occurrence and the subsequent impact on the predictive capabilities of the resulting SPFs and CMFs. The predicted average crash frequency is computed using the predictive model, where a model is the combination of an SPF and several CMFs. The SPF is used to estimate the average crash frequency for the stated base conditions. The CMFs are used to adjust the SPF estimate when the attributes of the subject site are not consistent with the base conditions. The predicted average crash frequency of a roadway segment is calculated as shown below.

$$N_{br} = N_{mvr} + N_{svr}$$

With,

$N_{mvr} = N_{spfmv} \times (CMF_1 \times \ldots . \times CMF_p)$, and
$N_{svr} = N_{spfsv} \times (CMF_1 \times \ldots . \times CMF_p)$,

where,

N_{br}	=	predicted average crash frequency of an individual segment (excluding deer-vehicle collisions),
N_{mvr}	=	predicted average crash frequency of multiple-vehicle crashes (excluding deer-vehicle collisions) for a segment,
N_{svr}	=	predicted average crash frequency of single-vehicle crashes (excluding deer-vehicle collisions) for a segment,
N_{spfmv}	=	predicted average crash frequency of multiple-vehicle crashes (excluding deer-vehicle collisions) for base conditions,
N_{spfmv}	=	predicted average crash frequency of single-vehicle crashes (excluding deer-vehicle collisions) for base conditions, and
$CMF_1 \times \ldots . \times CMF_p$	=	crash modification factors at a site with geometric features, p.

SPFs and CMFs are provided for the following rural highway segment types:

- Two-lane MDOT trunkline segments (2U),
- Four-lane undivided MDOT trunkline segments (4U),
- Four-lane divided MDOT trunkline segments (4D),
- Two-lane paved federal aid county segments (2PF),
- Two-lane paved non-federal aid county segments (2PN), and
- Two-lane gravel non-federal aid county segments (2GN).

6.2 Model Calibration

The predictive model calibration process consisted of the simultaneous calibration of multiple-vehicle and single-vehicle crash models and CMFs using the aggregate model represented by the equations above. The simultaneous calibration approach was needed because some CMFs were common to multiple-vehicle and single-vehicle crash models. The database assembled for calibration included two replications of the original database. The dependent variable in the first replication was set equal to the multiple-vehicle crashes. The dependent variable in the second replication was set equal to the single-vehicle crashes. The results of the multivariate regression model calibration are presented in the following sections.

The Non-Linear Mixed (NLMIXED) procedure in the SAS software was used to estimate the proposed model coefficients. This procedure was used because the proposed predictive model is both nonlinear and discontinuous. The log-likelihood function for the NB distribution was used to determine the best-fit model coefficients.

6.3 Safety Performance Functions for Rural Highway Segments

6.3.1 Two-Lane Rural Trunkline Segments (2U)

The following regression model form was used to predict the average crash frequency at an individual roadway segment:

$$N_j = (N_{spfmv} I_{mv} + N_{spfsv} I_{sv}) \times CMF_{sw} \times CMF_{dw} \times CMF_{hc} \times CMF_{roll} \times CMF_{rstr}$$

with,

$N_{spfmv} = n \times L \times e^{b_{mv} + b_{mv1} \ln(AADT) + b_{r1} I_{r1} + b_{r2} I_{r2} + b_{r3} I_{r3} + b_{r4} I_{r4} + b_{r5} I_{r5} + b_{r6} I_{r6}}$,

$N_{spfsv} = n \times L \times e^{b_{sv} + b_{sv1} \ln(AADT) + b_{r1} I_{r1} + b_{r2} I_{r2} + b_{r3} I_{r3} + b_{r4} I_{r4} + b_{r5} I_{r5} + b_{r6} I_{r6}}$,

$CMF_{sw} = e^{b_{sw}(W_{sw} - 6)}$,

$CMF_{dw} = e^{b_{dw}(n_{dw} - 15)}$,

$CMF_{hc} = e^{b_{hc}(p_{hc})}$,

$CMF_{roll} = e^{b_{roll}(I_{roll})}$, and

$CMF_{rstr} = e^{b_{rstr}(p_{rstr})}$,

where,

N_j	= predicted annual average crash frequency for model j (j=*mv, sv*),
N_{mv} =	= predicted annual average multiple-vehicle crash frequency,
N_{sv}	= predicted annual average single-vehicle crash frequency,
I_{mv}	= multiple-vehicle crash indicator variable (=1.0 if multiple-vehicle crash data, 0.0 otherwise),
I_{sv}	= single-vehicle crash indicator variable (=1.0 if single-vehicle crash data, 0.0 otherwise),
n	= number of years of crash data,
$AADT$	= annual average daily traffic (veh/day),
I_{r1}	= Superior Region indicator variable (=1.0 if site is in Superior Region, 0.0 if it is not),
I_{r2}	= North Region indicator variable (=1.0 if site is in North Region, 0.0 if it is not),
I_{r3}	= Grand Region indicator variable (=1.0 if site is in Grand Region, 0.0 if it is not),
I_{r4}	= Bay Region indicator variable (=1.0 if site is in Bay Region, 0.0 if it is not),
I_{r5}	= Southwest Region indicator variable (=1.0 if site is in Southwest Region, 0.0 if it is not),
I_{r6}	= University Region indicator variable (=1.0 if site is in University Region, 0.0 if it is not),
CMF_{sw}	= paved shoulder width crash modification factor,
CMF_{dw}	= driveway density crash modification factor,
CMF_{hc}	= horizontal curve crash modification factor,
CMF_{roll}	= rolling terrain crash modification factor,
CMF_{rtsr}	= passing restriction crash modification factor,
W_{sw}	= average paved shoulder width (ft),
n_{dw}	= driveway density (driveways/mile),

p_{hc} = fraction of the segment which is curved for curves under 0.297 miles in radius,
I_{roll} = indicator variable for rolling terrain (=1.0 if it is rolling, 0.0 otherwise),
p_{rstr} = fraction of the segment where passing is restricted (%) and
b_i = calibration coefficient for variable i.

The inverse dispersion parameter, K (which is the inverse of the over-dispersion parameter k), is allowed to vary with the segment length. The inverse dispersion parameter is calculated using the following equation.

$$K = L \times e^{\delta,j};\ j = mv, sv$$

where,
K = inverse dispersion parameter, and
δ = calibration coefficient for inverse dispersion parameter.

Table 60 summarizes the results for fatal and injury, and PDO crashes on two-lane trunkline segments. The t-statistics indicate a test of the hypothesis that the coefficient value is equal to 0.0. Those t-statistics with an absolute value that is larger than 1.96 indicate that the hypothesis can be rejected with the probability of error in this conclusion being less than 0.05. For those few variables where the absolute value of the t-statistic is smaller than 1.96, it was decided that each variable should be retained in the model, as the trends were found to be consistent with previous research findings. The indicator variables for some regions in the state were found to be significant. For the same conditions, when compared to other regions, the Superior and North regions experience the least number of fatal and injury crashes, while the Grand and Southwest regions experience the highest number of PDO crashes. The trend could not be explained by difference in road design between the regions. It is likely due to the differences between regions that are due to unobserved variables such as driver behavior, weather, vertical grade, and crash reporting differences.

Table 60. Calibrated Coefficients for Two-Lane Rural Trunkline Segments (2U)

	FI Non-Deer Crashes			PDO Non-Deer Crashes		
Parameter	Est	Std. err	t-stat	Est	Std. err	t-stat
Intercept for MV crashes (b_{mv})	-14.333	0.360	-39.79	-13.461	0.280	-48.00
AADT on MV crashes (b_{mv1})	1.421	0.042	34.18	1.389	0.033	42.08
Intercept for SV crashes (b_{sv})	-6.868	0.281	-24.46	-6.891	0.172	-40.07
AADT on SV crashes (b_{sv1})	0.563	0.033	17.14	0.698	0.021	33.83
Added effect of Superior Region (b_{r1})	-0.186	0.036	-5.13	0.000	--	--
Added effect of North Region (b_{r2})	-0.186	0.036	-5.13	0.000	--	--
Added effect of Grand Region (b_{r3})	0.000	--	--	0.145	0.025	5.85
Added effect of Bay Region (b_{r4})	0.000	--	--	0.000	--	--
Added effect of Southwest Region (b_{r5})	0.000	--	--	0.145	0.025	5.85
Added effect of University Region (b_{r6})	0.000	--	--	0.000	--	--
Shoulder width (b_{sw})	-0.024	0.007	-3.68	-0.020	0.005	-4.29
Driveway density (b_{dw})	0.021	0.002	8.98	0.022	0.002	11.04
Horizontal curve (b_{hc})	0.714	0.246	2.90	0.484	0.182	2.66
Rolling terrain (b_{roll})	0.071	0.035	2.05	0.118	0.024	4.92
Passing restriction (b_{rstr})	0.005	0.001	6.09	0.003	0.001	5.54
Inverse DP for MV crashes (δ_{mv})	1.069	0.204	5.23	0.622	0.102	6.08
Inverse DP for SV crashes (δ_{sv})	0.650	0.167	3.89	0.899	0.087	10.35

DP = dispersion parameter

6.3.2 Four-Lane Rural Trunkline Segments (4U, 4D)

The following regression model form was used to predict the average crash frequency at an individual roadway segment.

$$N_j = (N_{spfmv} I_{mv} + N_{spfsv} I_{sv}) \times CMF_{rsw} \times CMF_{lsw} \times CMF_{dw} \times CMF_{hc}$$

with,

$N_{spfmv} = n \times L \times e^{b_{mv}+b_{mv1}\ln(AADT)+b_{r1}I_{r1}+b_{r2}I_{r2}+b_{r3}I_{r3}+b_{r4}I_{r4}+b_{r5}I_{r5}+b_{r6}I_{r6}}$,

$N_{spfsv} = n \times L \times e^{b_{sv}+b_{sv1}\ln(AADT)+b_{r1}I_{r1}+b_{r2}I_{r2}+b_{r3}I_{r3}+b_{r4}I_{r4}+b_{r5}I_{r5}+b_{r6}I_{r6}}$,

$CMF_{rsw} = e^{b_{rsw}(W_{rsw}-6)}$,

$CMF_{lsw} = e^{b_{lsw}(W_{lsw}-2)}$,

$CMF_{dw} = e^{b_{dw}(n_{dw}-20)}$, and

$CMF_{hc} = e^{b_{hc}(p_{hc})}$,

where,

N_j = predicted annual average crash frequency for model *j* (*j=mv, sv*),

N_{mv} = predicted annual average multiple-vehicle crash frequency,

N_{sv} = predicted annual average single-vehicle crash frequency,

I_{mv} = multiple-vehicle crash indicator variable (=1.0 if multiple-vehicle crash data, 0.0 otherwise),

I_{sv} = single-vehicle crash indicator variable (=1.0 if single-vehicle crash data, 0.0 otherwise),

n = number of years of crash data,

$AADT$ = annual average daily traffic (veh/day),
I_{r1} = Superior Region indicator variable (=1.0 if site is in Superior Region, 0.0 if it is not),
I_{r2} = North Region indicator variable (=1.0 if site is in North Region, 0.0 if it is not),
I_{r3} = Grand Region indicator variable (=1.0 if site is in Grand Region, 0.0 if it is not),
I_{r4} = Bay Region indicator variable (=1.0 if site is in Bay Region, 0.0 if it is not),
I_{r5} = Southwest Region indicator variable (=1.0 if site is in Southwest Region, 0.0 if it is not),
I_{r6} = University Region indicator variable (=1.0 if site is in University Region, 0.0 if it is not),
CMF_{rsw} = paved right shoulder width crash modification factor,
CMF_{lsw} = paved left shoulder width crash modification factor,
CMF_{dw} = driveway density crash modification factor,
CMF_{hc} = horizontal curve crash modification factor,
W_{rsw} = average paved right shoulder width (ft),
W_{lsw} = average paved left shoulder width (ft),
n_{dw} = driveway density (driveways/mile),
p_{hc} = fraction of the segment which is curved for curves under 0.5 miles in radius, and
b_i = calibration coefficient for variable *i*.

Table 61 summarizes the results for fatal and injury, and PDO crashes on four-lane trunkline segments. The indicator variables for some regions in the state were found to be significant. For the same conditions, when compared to other regions, the University region experiences the highest number of fatal and injury crashes, while the Bay region experiences the lowest number of PDO crashes. The trend could not be explained by differences in road design between the regions. It is likely due to the differences between regions that are due to unobserved variables such as driver behavior, weather, vertical grade, and crash reporting differences.

Table 61. Calibrated Coefficients for Four-Lane Rural Trunkline Segments (4U & 4D)

	FI Non-Deer Crashes			PDO Non-Deer Crashes		
Parameter	**Est**	**Std. err**	**t-stat**	**Est**	**Std. err**	**t-stat**
Intercept for MV crashes on 4U (b_{mv})	-14.380	2.651	-5.42	-14.467	1.621	-8.92
AADT on MV crashes on 4U (b_{mv1})	1.412	0.287	4.92	1.503	0.174	8.65
Intercept for SV crashes on 4U (b_{sv})	-10.091	2.513	-4.02	-6.056	1.148	-5.28
AADT on SV crashes on 4U (b_{sv1})	0.883	0.271	3.26	0.639	0.126	5.10
Intercept for MV crashes on 4D (b_{mv})	-10.749	2.568	-4.19	-14.689	1.772	-8.29
AADT on MV crashes on 4D (b_{mv1})	0.997	0.279	3.58	1.538	0.190	8.08
Intercept for SV crashes on 4D (b_{sv})	-9.170	1.820	-5.04	-7.675	1.215	-6.32
AADT on SV crashes on 4D (b_{sv1})	0.841	0.193	4.36	0.845	0.129	6.51
Added effect of Superior region (b_{r1})	0.000	--	--	0.000	--	--
Added effect of North region (b_{r2})	0.000	--	--	0.000	--	--
Added effect of Grand region (b_{r3})	0.000	--	--	0.000	--	--
Added effect of Bay region (b_{r4})	0.000	--	--	-0.197	0.074	-2.67
Added effect of Southwest region (b_{r5})	0.000	--	--	0.000	--	--
Added effect of University region (b_{r6})	0.388	0.143	2.72	0.000	--	--
Right shoulder width (b_{rsw})	-0.037	0.035	-1.06	-0.020	0.018	-1.11
Left shoulder width (b_{lsw})	-0.064	0.051	-1.26	-0.050	0.033	-1.52
Driveway density on 4U (b_{dw})	0.0136	0.009	1.56	0.017	0.005	3.71
Driveway density on 4D (b_{dw})	0.010	0.014	0.74	0.010	0.008	1.03
Horizontal curve (b_{hc})	0.902	0.567	1.59	0.429	0.339	1.27
Inverse DP for MV crashes 4U (δ_{mv})	0.396	0.448	0.88	2.443	0.962	2.54
Inverse DP for SV crashes 4U (δ_{sv})	4.961	13.215	0.38	21.535	13.301	1.62
Inverse DP for MV crashes 4D (δ_{mv})	0.886	0.588	1.51	1.551	0.430	3.61
Inverse DP for SV crashes 4D (δ_{sv})	6.877	31.666	0.22	1.649	0.384	4.29

DP = dispersion parameter

6.3.3 Paved Federal Aid Rural County Segments (2PF)

The following regression model form was used to predict the average crash frequency at an individual roadway segment.

$$N_j = (N_{spfmv} I_{mv} + N_{spfsv} I_{sv}) \times CMF_{sw} \times CMF_{dw} \times CMF_{hc} \times e^u$$

With,

$N_{spfmv} = n \times L \times e^{b_{mv} + b_{mv1} \ln(AADT)}$,
$N_{spfsv} = n \times L \times e^{b_{sv} + b_{sv1} \ln(AADT)}$,
$CMF_{sw} = e^{b_{sw}(W_{sw} - 6)}$,
$CMF_{dw} = e^{b_{dw}(n_{dw} - 15)}$, and
$CMF_{hc} = e^{b_{hc}(p_{hc})}$,

where,

N_j = predicted annual average crash frequency for model *j* (*j=mv, sv*),
N_{mv} = predicted annual average multiple-vehicle crash frequency,
N_{sv} = predicted annual average single-vehicle crash frequency,
I_{mv} = multiple-vehicle crash indicator variable (=1.0 if multiple-vehicle crash data,

0.0 otherwise),

I_{sv} = single-vehicle crash indicator variable (=1.0 if single-vehicle crash data, 0.0 otherwise),

n = number of years of crash data,

$AADT$ = annual average daily traffic (veh/day),

CMF_{sw} = paved shoulder width crash modification factor,

CMF_{dw} = driveway density crash modification factor,

CMF_{hc} = horizontal curve crash modification factor,

u = county level effect,

W_{sw} = average paved shoulder width (ft),

n_{dw} = driveway density (driveways/mile),

p_{hc} = fraction of the segment which is curved for curves under 0.297 miles in radius,

b_i = calibration coefficient for variable i.

To minimize the influence of county-to-county differences in design and maintenance practices or other factors, a county level random effect was included in the regression model. The parameter "u" is used to represent the random effect and is assumed to follow a normal distribution as below:

$$u \sim Normal\ (0, e^S)$$

where,

e^S = variance of the normal distribution.

Table 62 summarizes the results for fatal and injury, and PDO crashes on paved federal aid county segments. The variance of the normal distribution is statistically significant which shows that there is a significant difference in crash occurrence between the counties. The trend could be due to differences in road design or maintenance practices, driver behavior, weather, vertical grade, and/or crash reporting.

Table 62. Calibrated Coefficients for Paved Federal Aid Rural County Segments (2PF)

	FI Non-Deer Crashes			PDO Non-Deer Crashes		
Parameter	Est	Std. err	t-stat	Est	Std. err	t-stat
Intercept for MV crashes (b_{mv})	-11.929	0.381	-31.28	-9.784	0.269	-36.41
AADT on MV crashes (b_{mv1})	1.163	0.049	23.69	0.986	0.035	28.12
Intercept for SV crashes (b_{sv})	-7.061	0.233	-30.27	-6.017	0.153	-39.39
AADT on SV crashes (b_{sv1})	0.663	0.031	21.59	0.655	0.020	32.28
Shoulder width (b_{sw})	-0.029	0.015	-1.90	--	--	--
Driveway density (b_{dw})	0.010	0.003	3.80	0.018	0.002	10.21
Horizontal curve (b_{hc})	0.869	0.089	9.72	0.712	0.064	11.08
Inverse DP for MV crashes (δ_{mv})	1.668	0.311	5.37	1.637	0.136	12.03
Inverse DP for SV crashes (δ_{sv})	1.435	0.132	10.84	1.549	0.062	25.14
County level effect (S)	-3.105	0.302	-10.29	-2.240	0.156	-14.36

DP = dispersion parameter

6.3.4 Paved and Gravel Non Federal Aid Rural County Segments (2PN, 2GN)

The following regression model form was used to predict the average crash frequency at an individual non-federal aid roadway segment. Different from the trunkline and federal aid county segment SPFs, single and multi vehicle crashes were considered collectively rather than separately during parameter estimation. The non-federal aid segment model was calibrated using maximum AADT thresholds of 1,000 and 400 for paved and gravel roadways, respectively.

$$N = N_{spf} \times CMF_{pav} \times CMF_{tw} \times CMF_{dw} \times CMF_{hc} \times e^{u}$$

With,

$N_{spf} = n \times L \times e^{b_0 + b_1 \ln(AADT)}$,
$CMF_{pav} = e^{b_{pav}(I_{pav})}$,
$CMF_{tw} = e^{b_{tw}(I_{tw})}$,
$CMF_{dw} = e^{b_{dw}(I_{dw})}$, and
$CMF_{hc} = e^{b_{hc}(p_{hc})}$,

where,

N = predicted annual average crash frequency,
n = number of years of crash data,
$AADT$ = annual average daily traffic (veh/day),
CMF_{pav} = paved surface crash modification factor,
CMF_{tw} = traveled-way width crash modification factor,
CMF_{dw} = driveway density crash modification factor,
CMF_{hc} = horizontal curve crash modification factor,
u = county level effect,
I_{pav} = indicator variable for paved surface (=1.0 if paved, 0.0 if gravel),
I_{tw} = indicator variable for traveled-way width (=1.0 if traveled way is at least 18 ft, 0.0 otherwise),
I_{dw} = indicator variable for driveway density (=1.0 if driveway density is at least 5 driveways per mile, 0.0 otherwise),
p_{hc} = fraction of the segment which is curved for curves under 0.297 miles in radius, and
b_i = calibration coefficient for variable i.

To minimize the influence of reporting threshold variability among counties, the "county" variable was treated as random effect in the regression model. Table 63 summarizes the results for fatal and injury, and PDO crashes on paved federal aid county segments. The variance of the normal distribution is statistically significant which shows that there is a significant difference among the counties. The trend could be due to differences in road design or maintenance practices, driver behavior, weather, vertical grade, and/or crash reporting.

Table 63. Calibrated Coefficients for Non-Federal Aid Rural County Segments (2PN & 2GN)

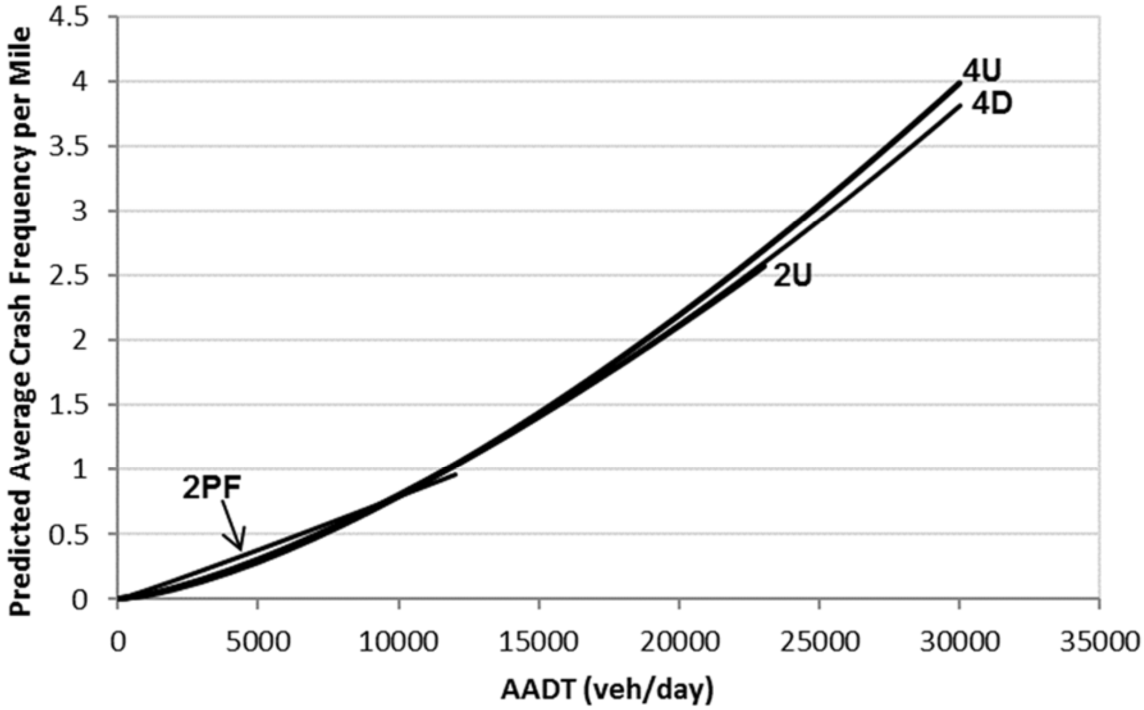
	FI Non-Deer Crashes			PDO Non-Deer Crashes		
Parameter	Est	Std. err	t-stat	Est	Std. err	t-stat
Intercept (b_0)	-6.911	0.317	-18.61	-6.413	0.276	-23.28
AADT (b_1)	0.782	0.071	10.98	0.799	0.050	15.87
Paved surface (b_{pav})	-0.536	0.127	-4.23	-0.333	0.123	-2.70
Traveled-way width (b_{tw})	-0.361	0.174	-2.08	-0.159	0.137	-1.17
Driveway density (b_{dw})	0.127	0.126	1.01	0.090	0.086	1.04
Horizontal curve (b_{hc})	1.059	0.213	4.98	0.995	0.152	6.56
Inverse DP (δ)	1.593	0.213	4.98	1.396	0.183	7.62
County level effect (S)	-3.789	0.909	-4.17	-2.272	0.373	-6.09

DP = dispersion parameter

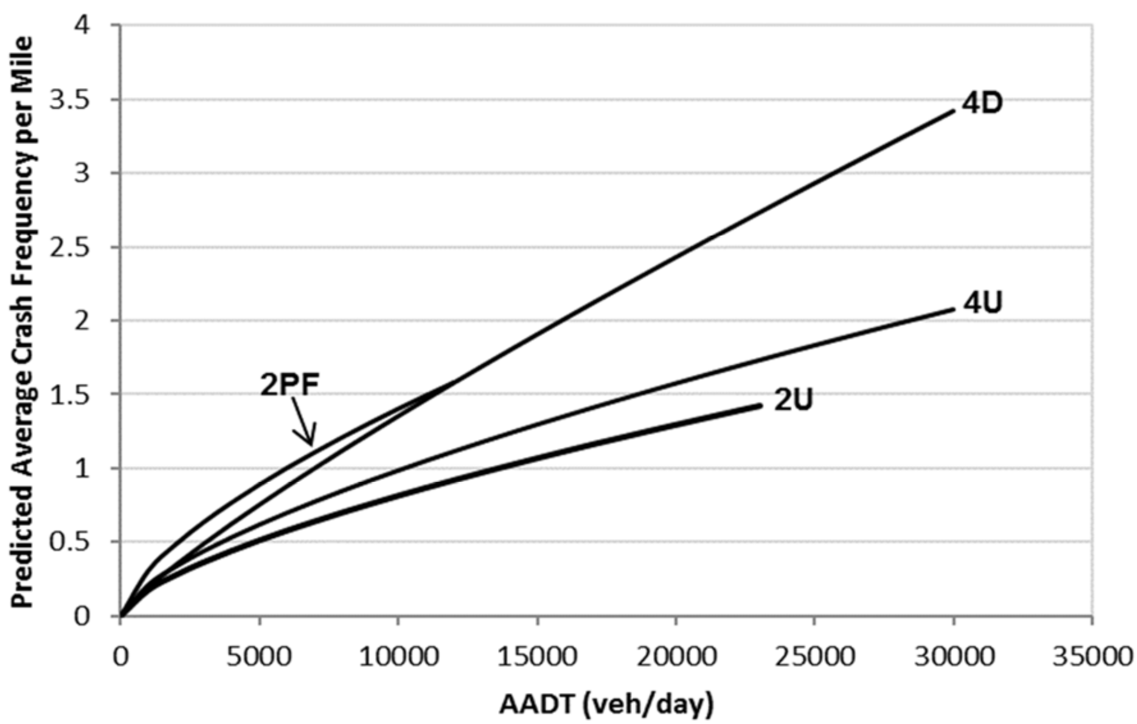
6.3.5 Comparison of Rural Segment SPF Results

For trunkline and paved federal aid county segments, the relationship between crash frequency (FI plus PDO crashes) and traffic volume for the calibrated SPFs at the base conditions is illustrated in Figure 46a for multiple vehicle crashes and Figure 46b for single vehicle crashes. For all two-lane segments, the relationship between crash frequency (FI plus PDO crashes) and traffic volume for the calibrated SPFs at the base conditions, is illustrated in Figure 47.

Comparison of the base SPFs across the various rural facility types displayed in Figures 46 and 47 showed several interesting findings. First, comparison of rural trunkline and paved federal aid county road segments (Figure 46a) showed little difference in the base multi-vehicle SPFs across the various facilities types (2U, 4U, 4D, 2PF), regardless of the number of lanes or jurisdiction. However, when considering the base SPFs for single-vehicle crashes (Figure 46b), which occurred at a greater frequency than multi-vehicle crashes, two-lane paved federal aid county roadways showed single vehicle crash occurrence rates that were approximately double that of two-lane trunkline highways across the common range of traffic volumes. Although rural four-lane undivided trunklines showed marginally higher single-vehicle crash occurrence rates compared to two-lane trunklines, four-lane divided trunklines showed substantially greater rates of single-vehicle crashes across the common range of traffic volumes. Turning to two-lane segments only (Figure 47) paved county roadways (federal aid and non-federal aid) showed approximately double the crash occurrence rate of trunklines, while gravel roadways showed a substantially greater crash occurrence rate than paved county roadways across the equivalent range of traffic volumes.



a) Multiple-Vehicle Crashes



b) Single-Vehicle Crashes

Figure 46. Comparison of Crashes on Trunkline and Paved Federal Aid Rural Segments

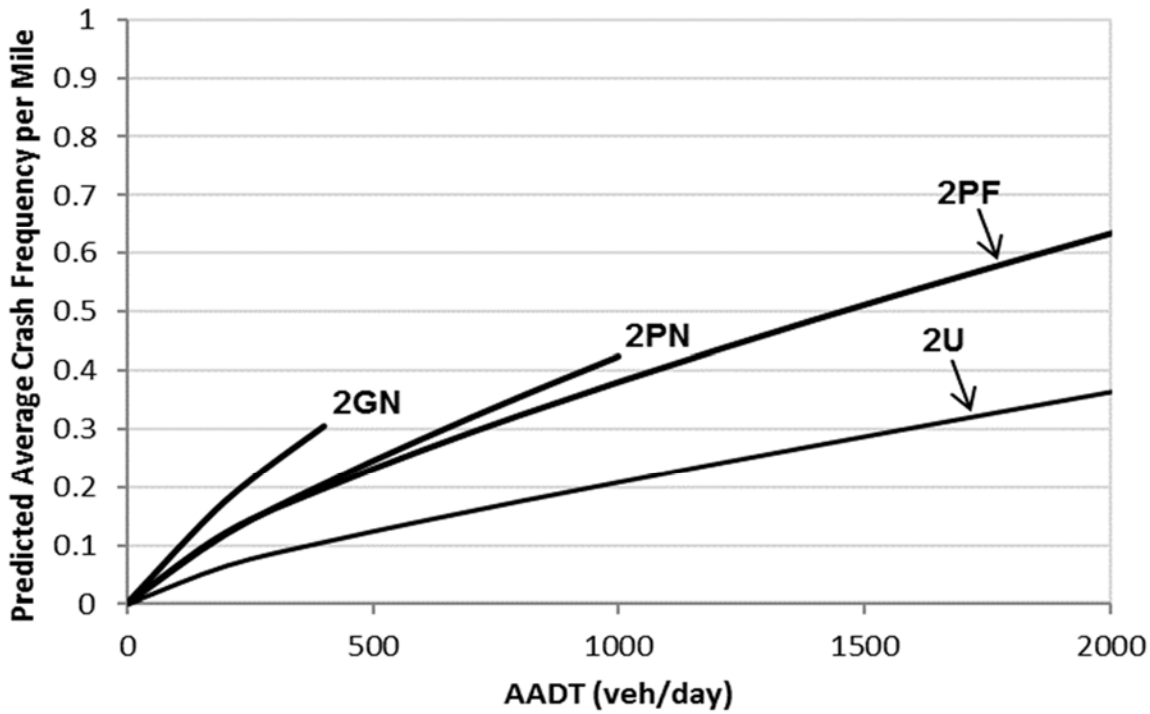


Figure 47. Comparison of Total Crashes on Two-Lane Rural Segments, by Classification and Surface Type

6.3.6 Distribution of Crashes by Collision Type

To estimate crash frequency across various collision types for trunkline or federal aid county rural roadway segments, the crash frequency predicted by the FI or PDO SPF may be multiplied by the crash type proportions obtained from the respective 2011-2015 crash datasets, as displayed in Tables 64 and 65 for trunkline and county segments, respectively.

Table 64. Distribution of Crashes by Collision Type and Severity Level, Rural Trunkline Segments

Category	Collision Type	Proportion of Crashes by Severity Level and Segment Type					
		2U		4U		4D	
		FI	PDO	FI	PDO	FI	PDO
Single Vehicle (Deer Excluded)	Bicycle	0.01	0.00	0.01	0.00	0.01	0.00
	Pedestrian	0.02	0.00	0.05	0.00	0.02	0.00
	Overturned	0.19	0.10	0.10	0.06	0.21	0.08
	Fixed object/other SV	0.33	0.55	0.21	0.47	0.32	0.53
Multiple Vehicle	Angle	0.05	0.03	0.15	0.06	0.07	0.03
	Head-on	0.10	0.02	0.09	0.02	0.04	0.01
	Read-end	0.20	0.16	0.23	0.16	0.25	0.14
	Sideswipe	0.07	0.09	0.09	0.16	0.05	0.16
	Other MV	0.03	0.06	0.06	0.06	0.03	0.05

Table 65. Distribution of Crashes by Collision Type and Severity Level, Rural County Segments

Category	Collision Type	Proportion of Crashes by Severity Level and Segment Type					
		2PF		2PN		2GN	
		FI	PDO	FI	PDO	FI	PDO
Single Vehicle (Deer Excluded)	Bicycle	0.01	0.00	0.01	0.00	0.01	0.00
	Pedestrian	0.01	0.00	0.04	0.00	0.01	0.00
	Overturned	0.21	0.12	0.17	0.08	0.27	0.12
	Fixed object/other SV	0.49	0.64	0.58	0.64	0.60	0.65
Multiple Vehicle	Angle	0.03	0.03	0.05	0.04	0.02	0.05
	Head-on	0.07	0.01	0.05	0.02	0.02	0.02
	Read-end	0.09	0.09	0.05	0.08	0.02	0.04
	Sideswipe	0.04	0.08	0.03	0.09	0.03	0.09
	Other MV	0.02	0.04	0.02	0.05	0.01	0.03

6.4 Crash Modification Factors for Rural Highway Segments

The CMFs for geometric design features of segments are presented below. The CMFs are used to adjust the SPF for segments to account for differences between the base conditions and the local site conditions. Several CMFs were calibrated in conjunction with the SPFs. These were calibrated using the FI SPFs only to alleviate issues associated with the PDO crash data, specifically underreporting. Collectively, the CMFs describe the relationship between various geometric factors and crash frequency. Many of the CMFs found in the literature are typically derived from (and applied to) the combination of multiple-vehicle and single-vehicle crashes. That is, one CMF is used to indicate the influence of a specified geometric feature on total crashes. In contrast, the models developed for this project include several CMFs that are calibrated for a specific crash type.

In general, it was found that wider paved shoulders are associated with fewer crashes and less severe crashes across all applicable rural segments types. Interestingly, lane width did not have a significant impact on crash occurrence on trunklines or federal aid county roadways, although narrow non-federal aid county roadways (i.e., traveled way less than 18 feet) showed greater crash occurrence and more severe crashes. Increased driveway density was associated increased crash occurrence, although this effect was more pronounced on trunkline segments. Lastly, an increase in horizontal curvature on the segment was associated with increases in crash occurrence and crash severity across all rural segment types. The specific CMFs are described in the following sections.

6.4.1 Two-Lane Rural Trunkline Segments

CMF_{sw}- Shoulder Width. The base condition for this CMF is a 6.0-ft paved shoulder width. The shoulder width used in this CMF is an average of two roadbeds on the segment. This CMF applies to both MV and SV segment crashes. The shoulder CMF is described using the following equation.

$$CMF_{sw} = e^{-0.024(W_{sw}-6.0)}$$

CMF_{dw}- Driveways. The driveway CMF is applicable to multiple-vehicle crashes only. The base condition for the driveway CMF is 15 driveways per mile. The driveway CMF is described using the following equation.

$$CMF_{dw} = e^{0.021(n_{dw}-15)}$$

CMF_{hc}- Horizontal Curve. The base condition for this CMF is no horizontal curves possessing a radius less than 0.297 miles (1,570 ft) exist on the segment. This CMF applies to both MV and SV segment crashes. The horizontal curve CMF is described using the following equation.

$$CMF_{hc} = e^{0.714(p_{hc})}$$

The CMF is derived to be applicable to a segment that has a mix of uncurved and curved lengths. The variable p_{hc} is computed as the ratio of the length of curves under 0.297 miles in radius on the segment to the length of the segment. When the variable p_{hc} is equal to 1.0, then the CMF is 2.0, which means a segment that is totally on a curve under 0.297 miles in radius experiences double the crashes to that of a straight segment.

CMF_{roll}- Terrain. The base condition for this CMF is a level terrain. This CMF applies to both MV and SV segment crashes. The CMF for terrain type is provided in the following table.

Table 66. Terrain CMF for Two-Lane Rural Trunkline Segments

Terrain	CMF
Level	1.00
Rolling	1.07

CMF_{rstr}- Passing Restriction. The base condition for this CMF is no restriction on passing throughout the segment. This CMF applies to both MV and SV segment crashes. The sight restriction CMF is described using the following equation.

$$CMF_{rstr} = e^{0.005(p_{rstr})}$$

The CMF is derived to be applicable to a segment that has a mix of no-passing and passing zones. The variable p_{rstr} is computed as the ratio of the length of no-passing areas on the segment to the length of the segment multiplied by 100. When the variable p_{rstr} is 100 percent then the CMF is 1.65, which means a segment that has total passing restriction experiences 65 percent more crashes than the segment with no restriction.

6.4.2 Four-Lane Rural Trunkline Segments

CMF_{rsw}- Right Shoulder Width. The base condition for this CMF is a 6.0-ft right shoulder width and it is applicable to both undivided and divided roadway segments. The shoulder width used in this CMF is an average of two roadbeds on the segment. This CMF applies to both MV and SV segment crashes. The right shoulder width CMF is described using the following equation.

$$CMF_{rsw} = e^{-0.037(W_{rsw}-6.0)}$$

CMF_{lsw}- Left Shoulder Width. The base condition for this CMF is a 2.0-ft inside shoulder width and it is applicable to divided roadway segments only. The shoulder width used in this CMF is an average of two roadbeds on the segment. This CMF applies to both MV and SV segment crashes. The right shoulder width CMF is described using the following equation.

$$CMF_{rsw} = e^{-0.064(W_{rsw}-2.0)}$$

CMF_{dw}- Driveways. The driveway CMF is applicable to multiple-vehicle crashes only. The base condition for the driveway CMF is 20 driveways per mile. The driveway CMF for 4U segments is described using the following equation.

$$CMF_{dw} = e^{0.0136(n_{dw}-20)}$$

The driveway CMF for 4D segments is described using the following equation.

$$CMF_{dw} = e^{0.010(n_{dw}-20)}$$

CMF_{hc}- Horizontal Curve. The base condition for this CMF is no horizontal curves with radius less than 0.5 miles (2,640 ft) on the segment. This CMF applies to both MV and SV segment crashes. The horizontal curve CMF is described using the following equation.

$$CMF_{hc} = e^{0.902(p_{hc})}$$

The variable p_{hc} is computed as the ratio of the length of curves under 0.5 miles in radius on the segment to the length of the segment. When the variable p_{hc} is 1.0 then the CMF is 2.46, which means a segment that is totally on a curve under 0.5 miles in radius experiences 146 percent more crashes than that of a straight segment.

6.4.3 Paved Federal Aid Rural County Segments

CMF_{sw}- Shoulder Width. The base condition for this CMF is a 6.0-ft paved shoulder width. The shoulder width used in this CMF is an average of two roadbeds on the segment. This CMF applies to both MV and SV segment crashes. The shoulder CMF is described using the following equation.

$$CMF_{sw} = e^{-0.029(W_{sw}-6.0)}$$

CMF_{dw}- Driveways. The driveway CMF is applicable to multiple-vehicle crashes only. The base condition for the driveway CMF is 15 driveways per mile. The driveway CMF is described using the following equation.

$$CMF_{dw} = e^{0.010(n_{dw}-15)}$$

CMF_{hc}- Horizontal Curve. The base condition for this CMF is no horizontal curves with radius less than 0.297 miles (1,570 ft) on the segment. This CMF applies to both MV and SV segment crashes. The horizontal curve CMF is described using the following equation.

$$CMF_{hc} = e^{0.869(p_{hc})}$$

The variable p_{hc} is computed as the ratio of the length of curves under 0.297 miles in radius on the segment to the length of the segment. When the variable p_{hc} is 1.0 then the CMF is 2.38, which means a segment that is totally on a curve under 0.297 miles in radius experiences 138 percent more crashes than that of a straight segment.

6.4.3 Non-Federal Aid Rural County Segments

CMF_{pav}- Surface Type. The base condition for this CMF is a gravel surface. The CMF for surface type is provided in the following table.

Table 67. Surface Type CMF for Non-Federal Aid Rural County Segments

Surface Type	CMF
Gravel	1.00
Paved	0.59

CMF_{tw}- Traveled-way Width. The base condition for this CMF is less than 18 ft traveled-way. The CMF for traveled-way width is provided in the following table.

Table 68. Traveled-Way Width CMF for Non-Federal Aid Rural County Segments

Traveled-Way Width	CMF
< 18 ft	1.00
$\geq$ 18 ft	0.70

CMF_{dw}- Driveways. The base condition for this CMF is fewer than 5 driveways per mile. The CMF for driveways is provided in the following table.

Table 69. Driveway CMF for Non-Federal Aid Rural County Segments

Driveway Density	CMF
< 5 driveways/mile	1.00
$\geq$ 5 driveways/mile	1.14

CMF_{hc}- Horizontal Curve. The base condition for this CMF is no horizontal curves with radius less than 0.297 miles (1,570 ft) on the segment. This CMF applies to both MV and SV segment crashes. The horizontal curve CMF is described using the following equation.

$$CMF_{hc} = e^{0.869(p_{hc})}$$

The variable p_{hc} is computed as the ratio of the length of curves under 0.297 miles in radius on the segment to the length of the segment. When the variable p_{hc} is 1.0 then the CMF is 2.88, which means a segment that is totally on a curve under 0.297 miles in radius experiences 188 percent more crashes than that of a straight segment.

6.5 Severity Distribution Functions for Rural Highway Segments

This section documents the development of severity distribution functions (SDF) for both MDOT trunkline and county segments. An SDF is represented by a discrete choice model. In theory, it could be used to predict the proportion of crashes in each of the following severity categories: fatal (K), incapacitating injury (A), non-incapacitating injury (B), or possible injury (C). The SDF can be used with the safety performance functions to estimate the expected crash frequency for each severity category. It may include various geometric, operation, and traffic variables that will allow the estimated proportion to be specific to an individual segment.

The multinomial logit (MNL) model was used to predict the probability of crash severities. Given the characteristics of the data, the MNL is the most suitable model for estimating a SDF. A linear function is used to relate the crash severity with the geometric and traffic variables. SAS's non-linear mixed modeling procedure (NLMIXED) was used for the evaluation of MNL model. The probability for each crash severity category is given by the following equations.

$$P_K = \frac{e^{V_K}}{1+e^{V_K}+e^{V_A}+e^{V_B}}$$

$$P_A = \frac{e^{V_A}}{1+e^{V_K}+e^{V_A}+e^{V_B}}$$

$$P_B = \frac{e^{V_B}}{1+e^{V_K}+e^{V_A}+e^{V_B}}$$

$$P_C = 1-(P_K+P_A+P_B)$$

Where,

P_j = probability of the occurrence of crash severity *j*, and

V_j = systematic component of crash severity probability for severity *j*.

The database assembled for calibration included crash severity level as a dependent variable and the geometric and traffic variables of each site as independent variables. Each row (site characteristics) is repeated to the frequency of each severity level. Thus, a segment with 'n' crashes will be repeated 'n' number of times. It should be noted that the segments without injury (plus fatal) crashes are not included in the database. The total sample size of the final dataset for model calibration will be equal to total number of injury (plus fatal) crashes in the data. Due to the small sample size, fatal and incapacitating injury crashes are combined into one category. During the model calibration, the "possible injury" category is set as the base scenario with coefficients restricted at zero.

6.5.1 Two-Lane Rural Trunkline Segments (2U)

A model for estimating the systematic component of crash severity V_j for two-lane trunkline segments is described by the following equations.

$$V_{KA} = ASC_{KA} + b_{sw,KA} \times I_{sw} + b_{hc,KA} \times p_{hc} + b_{r,KA} \times I_r$$
$$V_B = ASC_B + b_{sw,B} \times I_{sw} + b_{hc,B} \times p_{hc} + b_{r,B} \times I_r$$

where,

I_{sw} = paved shoulder width indicator variable (=1.0 if width > 3ft, 0.0 otherwise),
p_{hc} = fraction of the segment which is curved for curves under 0.297 miles in radius,
I_r = region indicator variable (=1.0 if Bay or University region, 0.0 otherwise),
ASC_j = alternative specific constant for crash severity *j*, and
$b_{k,j}$ = calibration coefficient for variable *k* and crash severity *j*.

Table 70 summarizes the estimation results of MNL model for the two-lane trunkline segments. An examination of the coefficient values and their implication on the corresponding crash severity levels are documented in a subsequent section.

Table 70. Parameter Estimation for Two-Lane Rural Trunkline Segments (2U) SDF

Coefficient	Variable	Fatality and Incapacitating Injury (KA)		Non-Incapacitating Injury (B)	
		Value	t-statistic	Value	t-statistic
ASC	Alternative specific constant	-0.555	-2.86	-0.537	-13.72
b_{sv}	Shoulder Width	-0.315	1.64	--	--
b_{hc}	Horizontal Curve	0.619	1.22	0.923	2.08
b_r	Bay or University Region	-0.228	-3.08	-0.184	-2.82
Observations		5,871 crashes (KA=1,191; B=1,682; C=2,998)			

Note: Possible injury is the base scenario with coefficients restricted at zero.

6.5.2 Four-Lane Rural Trunkline Segments (4U, 4D)

Due to the small sample size, a reliable model could not be developed for predicting the probability of each severity level for four-lane trunkline segments. It is therefore recommended to use fixed proportions based on the observed data. The default proportion for severity levels are shown in Table 71.

Table 71. Default Severity Level Proportions for Four-Lane Rural Trunkline Segments (4U, 4D)

Crash Severity Level	Crash Frequency	Percent of All FI Segment Crashes
Fatal and Incapacitating Injury (KA)	74	18.6
Non-incapacitating Injury (B)	107	26.9
Minor Injury (C)	216	54.5

6.5.3 Paved Federal Aid Rural County Segments (2PF)

A model for estimating the systematic component of crash severity V_j for paved federal aid county segments is described by the following equations.

$$V_{KA} = ASC_{KA} + b_{sw,KA} \times I_{sw} + b_{lw,KA} \times I_{lw} + b_{pm,KA} \times I_{pm}$$
$$V_{B} = ASC_{B} + b_{sw,B} \times I_{sw} + b_{lw,B} \times I_{lw} + b_{pm,B} \times I_{pm}$$

Where,

I_{sw} = paved shoulder width indicator variable (=1.0 if width >= 4 ft, 0.0 otherwise),

I_{lw} = lane width indicator variable (=1.0 if width >= 10 ft, 0.0 otherwise),

I_{pm} = pavement marking presence indicator variable (=2.0 if both centerline and edgelines are present, =1.0 if only centerline is present, 0.0 if no markings),

ASC_j = alternative specific constant for crash severity *j*, and

$b_{k,j}$ = calibration coefficient for variable *k* and crash severity *j*.

Table 72 summarizes the estimation results of MNL model for the paved federal aid county segments. An examination of the coefficient values and their implication on the corresponding crash severity levels are documented in a subsequent section.

Table 72. Parameter Estimation for Paved Federal Aid Rural County Segments (2PF) SDF

Coefficient	Variable	Fatality and Incapacitating Injury (KA)		Non-Incapacitating Injury (B)	
		Value	t-statistic	Value	t-statistic
ASC	Alternative specific constant	-0.070	-0.13	0.105	0.23
b_{sv}	Shoulder Width	-0.315	-2.06	-0.243	-2.06
b_{lw}	Lane Width	-0.597	-1.13	-0.544	-1.18
b_{pm}	Pavement Marking Presence	-0.196	-1.82	--	--
Observations		3,525 crashes (KA=620; B=1,121; C=1,784)			

Note: Possible injury is the base scenario with coefficients restricted at zero.

6.5.3 Paved and Gravel Non Federal Aid Rural County Segments (2PN, 2GN)

A model for estimating the systematic component of crash severity V_j for non-federal aid county segments (paved or gravel) is described by the following equations.

$$V_{KA} = ASC_{KA} + b_{tw,KA} \times W_{tw}$$
$$V_B = ASC_B + b_{tw,B} \times W_{tw}$$

where,

W_{tw} = traveled-way width (ft),

ASC_j = alternative specific constant for crash severity *j*, and

$b_{k,j}$ = calibration coefficient for variable *k* and crash severity *j*.

Table 73 summarizes the estimation results of MNL model for non-federal aid county segments. An examination of the coefficient values and their implication on the corresponding crash severity levels are documented in a subsequent section.

Table 73. Parameter Estimation for Non-Federal Aid Rural County Segments (2PN, 2GN) SDF

Coefficient	Variable	Fatality and Incapacitating Injury (KA)		Non-Incapacitating Injury (B)	
		Value	t-statistic	Value	t-statistic
ASC	Alternative specific constant	-0.168	-0.19	0.788	1.15
b_{tw}	Traveled-way Width	-0.041	-1.00	-0.050	-1.57
Observations		606 crashes (KA=101; B=218; C=287)			

Note: Possible injury is the base scenario with coefficients restricted at zero.

6.6 Predicted Severity Probabilities for Rural Highway Segments

This section describes the change in probability of each crash severity for a given change in a particular variable.

6.6.1 Two-Lane Rural Trunkline Segments (2U)

Shoulder Width. The shoulder width varied from 0 ft to 12 ft. The 2U SDF model coefficients in Table 70 indicate that the roads with wider shoulders have a low probability of occurrence of high severity crashes. As seen in Table 74, the probability of fatal and incapacitating injury crashes is 25.7 percent for roads with shoulders less than or equal to 3 ft, when compared to 20.1 percent for roads with shoulders greater than 3 ft.

Table 74. Crash Severity Distribution based on Shoulder Width, Rural 2U.

Shoulder Width	Crash Severity		
	KA	B	C
<=3 ft	25.7%	26.7%	47.6%
> 3 ft	20.1%	28.7%	51.2%

Horizontal Curve. This variable is computed as the ratio of the length of curves under 0.297 miles in radius on the segment to the length of the segment. The model coefficients in Table 70 indicate that as the proportion of the segment with horizontal curves of radii less than 0.297 miles increases, the probability of high severity crashes increases. As seen in Table 75, the probability of fatal and severe injury crashes (i.e., K, A, and B) is 48.5 percent for segments with no horizontal curves, when compared to 67.9 percent for a segment totally on a horizontal curve.

Table 75. Crash Severity Distribution based on Horizontal Curve Presence, Rural 2U.

Proportion of Segment on horizontal curve	Crash Severity		
	KA	B	C
0.0	20.2%	28.3%	51.5%
0.2	21.1%	31.4%	47.5%
0.4	21.8%	34.6%	43.5%
0.6	22.5%	37.9%	39.6%
0.8	23.0%	41.2%	35.8%
1.0	23.4%	44.5%	32.1%

Region. This variable indicates whether the segment is in Bay or University regions. The model coefficients in Table 70 indicate that the crashes in Bay or University regions are likely to be less severe than other regions. Table 76 suggests that the probability of severe crashes (i.e., K, A, and B) in Bay and University regions is 45.6 percent when compared to 50.6 percent in other regions.

Table 76. Predicted Probabilities for Different Regions, Rural 2U

Region	Crash Severity		
	KA	B	C
Bay or University	18.6%	27.0%	54.4%
Other	21.1%	29.5%	49.4%

6.6.2 Paved Federal Aid Rural County Segments (2PF)

Shoulder Width. The shoulder width varied from 0 ft to 10 ft. The model coefficients in Table 72 indicate that roads with wider shoulders have a lower probability of occurrence of high severity crashes. As seen in Table 77, the probability of fatal and severe injury crashes (i.e., K, A, and B) is 50.2 percent for roads with shoulders less than 4 ft, when compared to 43.5 percent for roads with shoulders greater than or equal to 4 ft.

Table 77. Crash Severity Distribution based on Shoulder Width, Rural 2PF.

Shoulder Width	Crash Severity		
	KA	B	C
<4 ft	17.9%	32.3%	49.8%
>= 4 ft	14.8%	28.7%	56.5%

Lane Width. The lane width varied from 9 ft to 15 ft. The model coefficients in Table 72 indicate that the roads with wider lanes have a lower probability of high severity crashes. As seen in Table 78, the probability of fatal or severe injury crashes (i.e., K, A, and B) is 63.1 percent for roads with lanes below 10 ft, compared to 49.3 percent for roads with shoulders greater than or equal to 10 ft.

Table 78. Crash Severity Distribution based on Lane Width, Rural 2PF.

Shoulder Width	Crash Severity		
	KA	B	C
< 10 ft	23.2%	39.9%	37.0%
>= 10 ft	17.5%	31.8%	50.7%

Pavement Marking Presence. This variable indicates whether the centerline and edgeline are present. The model coefficients in Table 72 indicate that the roads with visible pavement markings have a low probability of occurrence of high severity crashes. As seen in Table 79, the probability of fatal and incapacitating injury crashes is 17.1 percent for roads with visible centerline and edgelines, when compared to 23 percent for roads with both markings not present.

Table 79. Crash Severity Distribution Based on Pavement Marking Presence, Rural 2PF.

Pavement Markings	Crash Severity		
	KA	B	C
Both centerline and edgeline present	17.1%	32.0%	50.9%
Only centerline present	20.0%	30.9%	49.1%
No markings present	23.0%	29.6%	47.1%

6.6.3 Paved and Gravel Non Federal Aid Rural County Segments (2PN, 2GN)

Traveled-Way Width. The effect of traveled-way width on crash severity was considered in the calibrated model. The traveled-way width varied from 14 ft to 37 ft. The model coefficients in Table 73 indicate that as the traveled-way width increases, the crash severity decreases. As seen in Table 80, the probability of fatal and severe injury crashes (i.e., K, A, and B) decreases from 61 percent to 37.8 percent when the traveled-way width changes from 14 ft to 34 ft respectively.

Table 80. Crash Severity Distribution based on Traveled-Way Width, Rural 2GN & 2PN

Traveled-way Width	Crash Severity		
	KA	B	C
14 ft	18.5%	42.5%	39.0%
18 ft	17.5%	38.9%	43.6%
22 ft	16.5%	35.3%	48.2%
26 ft	15.3%	31.7%	53.0%
30 ft	14.2%	28.2%	57.6%
34 ft	12.9%	24.9%	62.1%

7.0 FULLY-SPECIFIED MICHIGAN RURAL INTERSECTION SPFS WITH AADT, REGIONAL INDICATORS, AND GEOMETRIC VARIABLES

After estimating the fully specified Michigan segment models considering the complete datasets of traffic and inventory data as described in section 3.0 of this report, similar fully specified models were developed for intersection facilities. These fully-specified models were again developed in a format similar to those presented in Chapters 10 and 11 of the *HSM*. This chapter outlines the format of these SPFs, which are estimated in combination with CMFs where sufficient data are available. Several preliminary models were developed for each of the three intersection facility types. The preliminary analysis as described in section 4.0 of this report helped inform the investigation of parameters to be included in the SPFs. Where possible, the base conditions for the CMFs were specified in the same manner as the *HSM*. However, in many cases the parameters were specified differently from the form provided in the *HSM*.

7.1 Functional Form

The predicted average crash frequency for each intersection is computed as the sum of predicted average crash frequency of all crash types of a given severity that occurred at the intersection during the period of analysis. A predictive model was developed to obtain the predicted average crash frequency as the combination of a base SPF and a set of corresponding CMFs. The SPF provides an estimate of the average crash frequency at the stated base conditions while the CMFs adjust the base SPF estimate to reflect attributes that vary from the base conditions. The predicted average crash frequency of an intersection is calculated as shown below.

$$N_{ri} = N_{base} \times (CMF_1 \times \ldots . \times CMF_p)$$

Where,

N_{ri} = predicted average crash frequency of an individual intersection,

N_{base} = predicted average crash frequency of an individual intersection and for base conditions, and

$CMF_1 \times \ldots . \times CMF_p$ = crash modification factors at a site with specific p attributes.

This is the general functional form recommended and used by the *Highway Safety Manual* (AASHTO, 2010). SPFs (inclusive of deer crashes) were developed (with CMFs as appropriate) for the following rural intersection site types:

- Four-leg signalized intersections (4SG)
- Three-leg signalized intersections (3SG)
- Four-leg stop-controlled intersections (4ST)
- Three-leg stop-controlled intersections (3ST)

7.2 Model Calibration

The framework to calibrate the model is generalized linear models (GLMs) as proposed by McCullagh and Nelder (McCullagh & Nelder, 1989). The predictive model calibration process consisted in obtaining maximum likelihood estimates of the model parameters corresponding to the SPFs and CMFs for the intersection facility types listed above. Separate models were developed for fatal plus injury (FI) crashes and for PDO crashes (PDO) following the general functional form described in the equation above.

The predictive model uses the negative binomial distribution (NB) to describe the distribution of observed crashes. This distribution can handle the Poisson- overdispersion typically found in crash data. Although there are several alternatives for modeling, the standard NB treatment of Poisson overdispersion in most statistical packages specifies the dispersion parameter such that it links the crash variance and expectation using a quadratic function. This specification is known as the NB2 model (Hilbe, 2011). The expected number of crashes is linked to a set of predictors as follows.

$$E(N_{ri}) = e^{\beta_0 + \boldsymbol{X}' . \boldsymbol{\beta}}$$

Where,

N_{ri}	= number of rural intersection crashes,
$E(N_{ri})$	= denotes the long term expectation of N_{ri},
X	= vector of explanatory variables,
β	= vector of coefficients to be estimated, and
β_0	= intercept term (to be estimated).

The NB2 model has a dispersion parameter that relates to the variance of the number of crashes as a quadratic function of the expectation:

$$V(N_{ri}) = E(N_{ri}) + \kappa \cdot E(N_{ri})^2$$

Where,

$V(N_{ri})$ = variance of the Number of rural intersection crashes, and

κ = dispersion parameter; other variables as previously defined.

There are instances where parameterizing the dispersion parameter of the NB distribution is desirable because the data may be dispersed differently at different levels of some independent variable. The calibration process considered such additional parameterization as a general functional form of an independent variable:

$$\kappa = f(X)$$

Where X is an independent variable along which the dispersion varies for a given crash expectation. Only polynomials up to the third degree were considered for this work as alternatives to the default constant parameter for specifying the dispersion. Model selection was driven by parsimony metrics and by goodness of fit considerations. Open source statistical software and packages were used to estimate the generalized linear model coefficients (The R Development Core Team, 2013; Fox & Weisberg, 2011).

7.3 Safety Performance Functions for Rural Intersections

7.3.1 Four- and Three-leg Signalized Rural Intersections (4SG, 3SG)

Because the total number of signalized rural intersections was small (n=194), the modeling was conducted pooling four-leg (n=175) and three-leg (n=19) intersections together. Because of the reduced sample, only base condition models were developed with no additional CMFs. The following regression model form was used to predict the average crash frequency at an individual intersection:

$$N = N_{base}$$

with,

$$N_{base} = n \times (AADT_{Total})^{b_{tot\,AADT}} \times (p_{minor\,AADT})^{b_{p.minor\,AADT}} \times e^{b_0 + b_{CDP} \cdot I_{CDP} + b_{r1} \cdot I_{r1} + b_{r2} \cdot I_{r2} + b_{r3} \cdot I_{r3} + b_{r4} \cdot I_{r4} + b_{r5} \cdot I_{r5} + b_{r6} \cdot I_{r6} + b_{3-leg} \cdot I_{3-leg}},$$

where,

N = predicted annual average crash frequency,

N_{base} = predicted annual average crash frequency for base conditions,

n = number of years of crash data,

$AADT_{Total}$ = total annual average daily traffic entering the intersection (=AADT$_{Major}$+ AADT$_{Minor}$), veh/day,
$p_{minorAADT}$ = proportion of minor AADT (=AADT$_{Minor}$/AADT$_{Total}$),
I_{r1} = Superior Region indicator variable (=1.0 if Superior Region, 0.0 otherwise),
I_{r2} = North Region indicator variable (=1.0 if North Region, 0.0 otherwise),
I_{r3} = Grand Region indicator variable (=1.0 if Grand Region, 0.0 otherwise),
I_{r4} = Bay Region indicator variable (=1.0 if Bay Region, 0.0 otherwise),
I_{r5} = Southwest Region indicator variable (=1.0 if Southwest Region, 0.0 otherwise),
I_{r6} = University Region indicator variable (=1.0 if University Region, 0.0 otherwise),
I_{CDP} = indicator variable for census designated place (=1.0 if within a CDP, 0.0 otherwise),
I_{3-leg} = indicator variable for 3-leg intersection (=1.0 if it is 3-leg intersection, 0.0 otherwise), and
b_i = calibration coefficient for variable *i*.

The inverse dispersion parameter, *K* was allowed to vary with the CDP variable. The inverse dispersion parameter is calculated using the following equation.

$$K = g_o + g_{CDP} \cdot I_{CDP}$$

Where,

K = inverse dispersion parameter,
g_o = calibration coefficient for CDP = 0 or constant inverse dispersion parameter,
g_{CDP} = calibration coefficient for CDP = 1.

The dispersion parameter can be calculated as follows:

$$\kappa = K^{-1} = (g_o + g_{CDP} \cdot I_{CDP})^{-1}$$

Table 81 summarizes the results for fatal and injury, and PDO crashes on 3- and 4-leg rural intersections. The z-statistics correspond to the Wald test of the hypothesis that the coefficient value is equal to 0.0. Those z-statistics with an absolute value larger than 2.0 indicate that the hypothesis can be rejected, as the probability of type I error (i.e., “false positive”) is less than 0.05. For those few variables where the absolute value of the z-statistic is smaller than 2.0, it was decided that the variable was important to the model and its trend was found to be consistent with previous research findings (even if the specific value was not known with a great deal of certainty as applied to this database). The indicator variable for the North region was found to be significant in the FI model. When compared to other regions, the North region experience fewer fatal and injury crashes compared to the other regions. The trend is likely due to unobserved differences between regions that are due to unobserved variables such as differing design and maintenance practices, terrain, and weather.

The number of intersection legs and whether the intersection fell within a census designated place each had an effect on FI crashes, while the number of intersection legs also affected PDO crashes. Three-leg intersections had significantly fewer FI and PDO crashes compared to four-leg intersections, while intersections within a CDP had fewer FI crashes than locations outside of CDPs. Each of these effects were intuitive, as three-leg intersections have fewer conflict points and locations within CDPs are more likely to have speed limits that fall below the 55 mph statutory limit for rural highways, thereby leading to fewer FI crashes (and not necessarily fewer PDO crashes).

Table 81. Calibrated Coefficients for Signalized Rural Intersections (4SG and 3SG)

	FI Crashes			PDO Crashes		
Parameter	**Est**	**Std. err**	**z-stat**	**Est**	**Std. err**	**z-stat**
Intercept (b_0)	-10.745	1.190	-9.029	-9.576	0.859	-11.151
Total AADT ($b_{totAADT}$)	1.146	0.125	9.190	1.127	0.091	12.435
Proportion of Minor AADT ($b_{p.minor\ AADT}$)	-0.050	0.055	-0.912	-0.018	0.042	-0.441
Added effect of CDP (b_{CDP})	-0.448	0.098	-4.555	0.000	--	--
Added effect of Superior region (b_{r1})	0.000	--	--	0.000	--	--
Added effect of North region (b_{r2})	-0.273	0.125	-2.182	0.000	--	--
Added effect of Grand region (b_{r3})	0.000	--	--	0.000	--	--
Added effect of Bay region (b_{r4})	0.000	--	--	0.000	--	--
Added effect of Southwest region (b_{r5})	0.000	--	--	0.000	--	--
Added effect of University region (b_{r6})	0.000	--	--	0.000	--	--
Added effect of 3-leg intersection (b_{3-leg})	-0.273	0.125	-2.182	-0.332	0.125	-2.665
Constant inverse dispersion parameter (g_o)	--	--	--	5.91	0.906	6.52
Inverse dispersion parameter for CDP=0 (g_o)	5.49	1.45	3.80	--	--	--
Inverse dispersion parameter for CDO=1 ($g_o + g_{CDP}$)	6.81	1.79	3.80	--	--	--

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

The following regression model form was used to predict the average crash frequency at an individual 4-leg stop-controlled intersection.

$$N = N_{base} \times CMF_{skew} \times CMF_{dw}$$

With,

$$N_{Base} = n \times \left(AADT_{Major}\right)^{b_{Major\ AADT}} \times (AADT_{Minor})^{b_{Minor\ AADT}} \times$$

$e^{b_0+b_{r1}\cdot I_{r1}+b_{r2}\cdot I_{r2}+b_{r3}\cdot I_{r3}+b_{r4}\cdot I_{r4}+b_{r5}\cdot I_{r5}+b_{r6}\cdot I_{r6}+b_{r7}\cdot I_{r7}}$,

$CMF_{Skew} = e^{b_{skew}(1_{[skew>10°]})}$, and

$CMF_{dw} = e^{b_{dw}(1_{[n_{dw}>2]})}$,

where,

N	= predicted annual average crash frequency,
N_{base}	= predicted annual average crash frequency for base conditions,
n	= number of years of crash data,
$AADT_{Major}$	= annual average daily traffic on major road (veh/day),
$AADT_{Minor}$	= annual average daily traffic on minor road (veh/day),
I_{r1}	= Superior Region indicator variable (=1.0 if Superior Region, 0.0 otherwise),
I_{r2}	= North Region indicator variable (=1.0 if North Region, 0.0 otherwise),
I_{r3}	= Grand Region indicator variable (=1.0 if Grand Region, 0.0 otherwise),
I_{r4}	= Bay Region indicator variable (=1.0 if Bay Region, 0.0 otherwise),
I_{r5}	= Southwest Region indicator variable (=1.0 if Southwest Region, 0.0 otherwise),
I_{r6}	= University Region indicator variable (=1.0 if site University Region, 0.0 otherwise),
I_{r7}	= Metro Region indicator variable (=1.0 if Metro Region, 0.0 otherwise),
CMF_{Skew}	= leg skew angle crash modification factor,
CMF_{dw}	= driveway count crash modification factor,
$Skew$	= largest skew angle between two intersection approaches (degrees),
$1_{[skew>10°]}$	= step function (=1 if $Skew$>10 degrees, =0 otherwise),
n_{dw}	= number of driveways within 211 ft of intersection center,
$1_{[n_{dw}>2]}$	= step function (=1 if n_{dw}>2 driveways, =0 otherwise), and
b_i	= calibration coefficient for variable i.

Table 82 summarizes the results for fatal and injury, and PDO crashes on four-leg stop-controlled rural intersections. Note, as opposed to the signalized intersections, stop controlled intersections contained a sufficiently large sample of locations. Because of this, locations falling within a CDP were excluded from the stop controlled intersection datasets in order to isolate truly rural intersections. The indicator variables for some regions were found to be significant. Assuming all other conditions to be equal, the Bay region experiences the highest number of fatal and injury crashes, while the Superior region experiences the lowest number of fatal and injury crashes, compared to the rest of the regions. In the case of PDO crashes, both the University and Metro regions experience the highest number of PDO crashes, compared to the other regions. The trend is likely due to unobserved differences between regions that are due to unobserved variables such as differing design and maintenance practices, terrain, and weather.

Four-leg stop-controlled intersections with skew angles greater than 10 degrees were found to have a marginally greater FI crashes, and significantly greater PDO crashes. Furthermore, intersections with greater than two driveways within a 211 ft radius of the intersection were found to have a significantly greater frequency of FI crashes and marginally greater PDO crashes.

Table 82. Calibrated Coefficients for Four-leg Stop-Controlled Rural Intersections (4ST)

	FI Crashes			PDO Crashes		
Parameter	**Est**	**Std. err**	**z-stat**	**Est**	**Std. err**	**z-stat**
Intercept (b_0)	-8.607	0.258	-33.306	-7.178	0.169	-42.548
AADT Major ($b_{AADT_{Major}}$)	0.414	0.035	11.983	0.497	0.023	22.007
AADT Minor ($b_{AADT_{Minor}}$)	0.582	0.033	17.86	0.397	0.021	19.257
Added effect of Superior region (b_{r1})	-0.283	0.114	-2.484	0.000	--	--
Added effect of North region (b_{r2})	0.000	--	--	0.000	--	--
Added effect of Grand region (b_{r3})	0.000	--	--	0.000	--	--
Added effect of Bay region (b_{r4})	0.123	0.058	2.117	0.000	--	--
Added effect of Southwest region (b_{r5})	0.000	--	--	0.000	--	--
Added effect of University region (b_{r6})	0.000	--	--	0.094	0.041	2.254
Added effect of Metro region (b_{r7})	0.000	--	--	0.257	0.116	2.217
Added effect of intersection skew angle (b_{skew})	0.092	0.062	1.483	0.213	0.040	5.307
Added effect of number of driveways (b_{dw})	0.110	0.052	2.113	0.034	0.035	0.974
Constant inverse dispersion parameter (g_o)	2.057	0.181	11.36	4.001	0.303	13.205

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

The following regression model form was used to predict the average crash frequency at an individual three-leg stop-controlled intersection.

$$N = N_{base}$$

With,

$$N_{Base} = n \times \left(AADT_{Major}\right)^{b_{Major\ AADT}} \times (AADT_{Minor})^{b_{Minor\ AADT}} \times e^{b_0 + b_{r1}I_{r1} + b_{r2}I_{r2} + b_{r3}I_{r3} + b_{r4}I_{r4} + b_{r5}I_{r5} + b_{r6}I_{r6} + b_{r7}I_{r7}},$$

where,

N = predicted annual average crash frequency,
N_{base} = predicted annual average crash frequency for base conditions,
n = number of years of crash data,
$AADT_{Major}$ = annual average daily traffic on major road (veh/day),
$AADT_{Minor}$ = annual average daily traffic on minor road (veh/day),
I_{r1} = Superior Region indicator variable (=1.0 if Superior Region, 0.0 otherwise),
I_{r2} = North Region indicator variable (=1.0 if North Region, 0.0 otherwise),
I_{r3} = Grand Region indicator variable (=1.0 if Grand Region, 0.0 otherwise),

I_{r4} = Bay Region indicator variable (=1.0 if Bay Region, 0.0 otherwise),
I_{r5} = Southwest Region indicator variable (=1.0 if Southwest Region, 0.0 otherwise),
I_{r6} = University Region indicator variable (=1.0 if University Region, 0.0 otherwise),
I_{r7} = Metro Region indicator variable (=1.0 if Metro Region, 0.0 otherwise), and
b_i = calibration coefficient for variable i.

Table 83 summarizes the results for fatal and injury, and PDO crashes on three-leg stop-controlled rural intersections. The indicator variables for some regions in the state were found to be significant. Everything else equal, the Bay and Metro regions experience the highest number of fatal and injury crashes, while the Superior and North regions experience the lowest number of PDO crashes. The trend is likely due to unobserved differences between regions that are due to unobserved variables such as differing design and maintenance practices, terrain, and weather. No additional geometric or site related effects were observed.

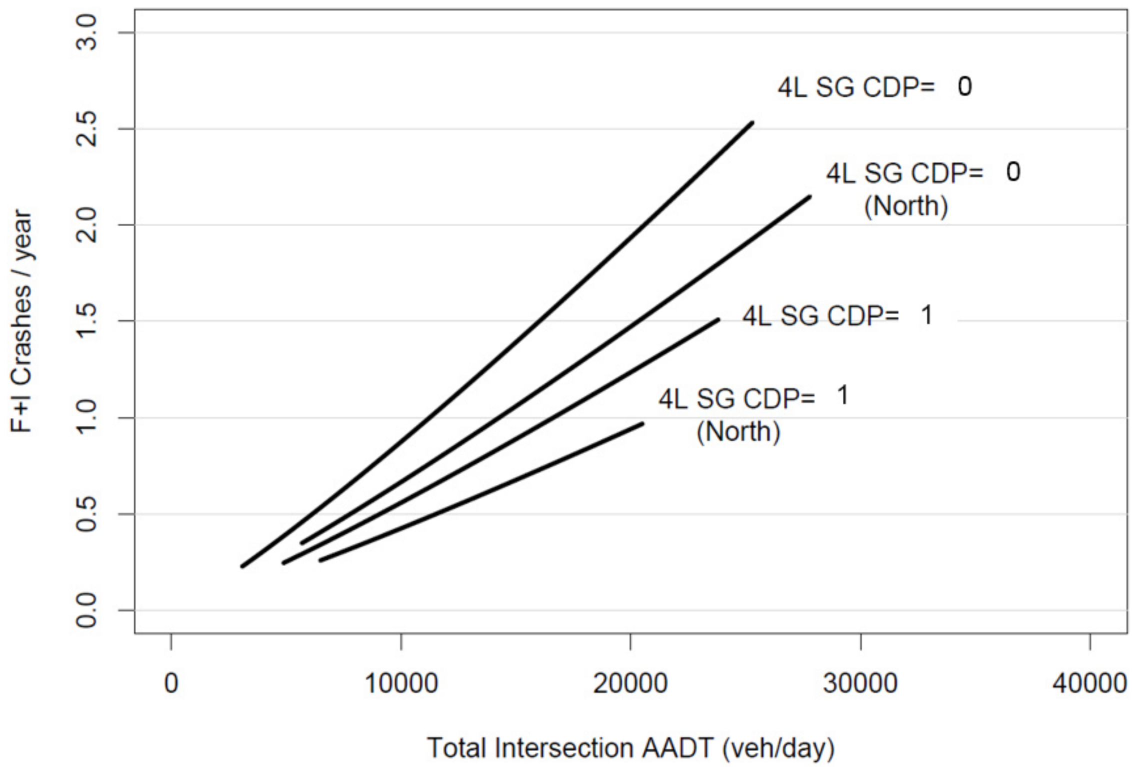
Table 83. Calibrated Coefficients for Three-leg Stop-Controlled Rural Intersections (3ST)

	FI Crashes			PDO Crashes		
Parameter	Est	Std. err	z-stat	Est	Std. err	z-stat
Intercept (b_0)	-9.664	0.337	-28.670	-7.226	0.187	-38.722
AADT Major ($b_{AADT_{Major}}$)	0.617	0.045	13.843	0.550	0.026	21.289
AADT Minor ($b_{AADT_{Minor}}$)	0.385	0.037	10.476	0.310	0.022	14.189
Added effect of Superior region (b_{r1})[b]	0.000	--	--	0.130	0.047	2.785
Added effect of North region (b_{r2})[b]	0.000	--	--	0.130	0.047	2.785
Added effect of Grand region (b_{r3})[a]	0.215	0.083	2.589	0.000	--	--
Added effect of Bay region (b_{r4})	0.000	--	--	0.000	--	--
Added effect of Southwest region (b_{r5})	0.000	--	--	0.000	--	--
Added effect of University region (b_{r6})	0.000	--	--	0.000	--	--
Added effect of Metro region (b_{r7})[a]	0.215	0.083	2.589	0.000	--	--
Constant inverse dispersion parameter (g_o)	2.283	0.396	5.765	2.555	0.200	12.775

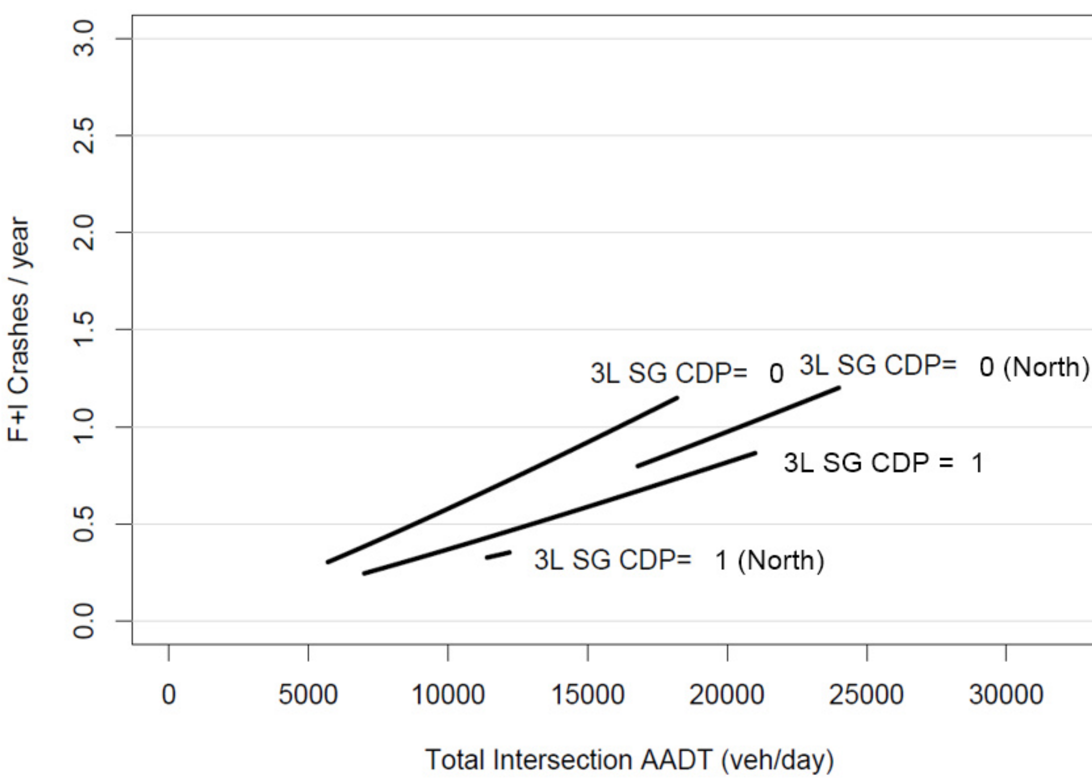
Notes:
[a] Single average estimate for both regions
[b] Single average estimate for both regions

7.3.4 Comparison of Rural Signalized Intersection SPF Results

For base conditions of four-leg signalized rural intersections, the relationship between FI crash frequency and traffic volume, as obtained from the calibrated models, are illustrated in Figure 48.



a.) 4-leg



b.) 3-leg

Figure 48. Comparison of FI Crashes on Signalized Rural Intersections

Similar to Figure 48, Figure 49 shows the corresponding relationships between PDO crashes and traffic volumes at rural signalized intersections.

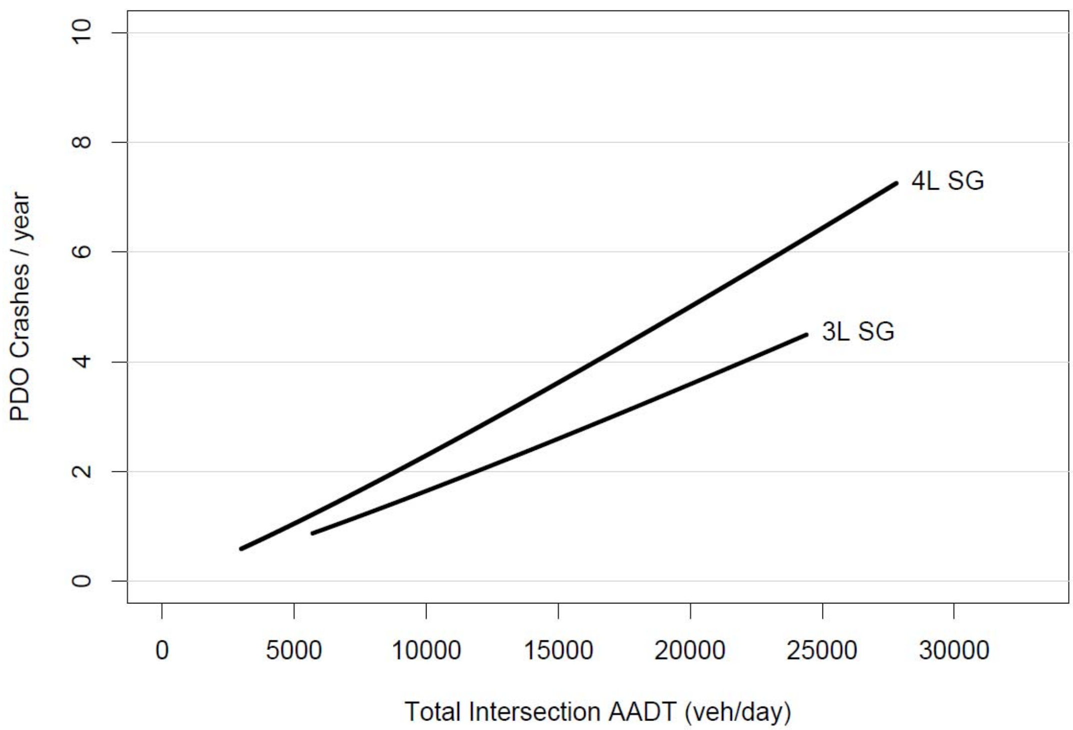
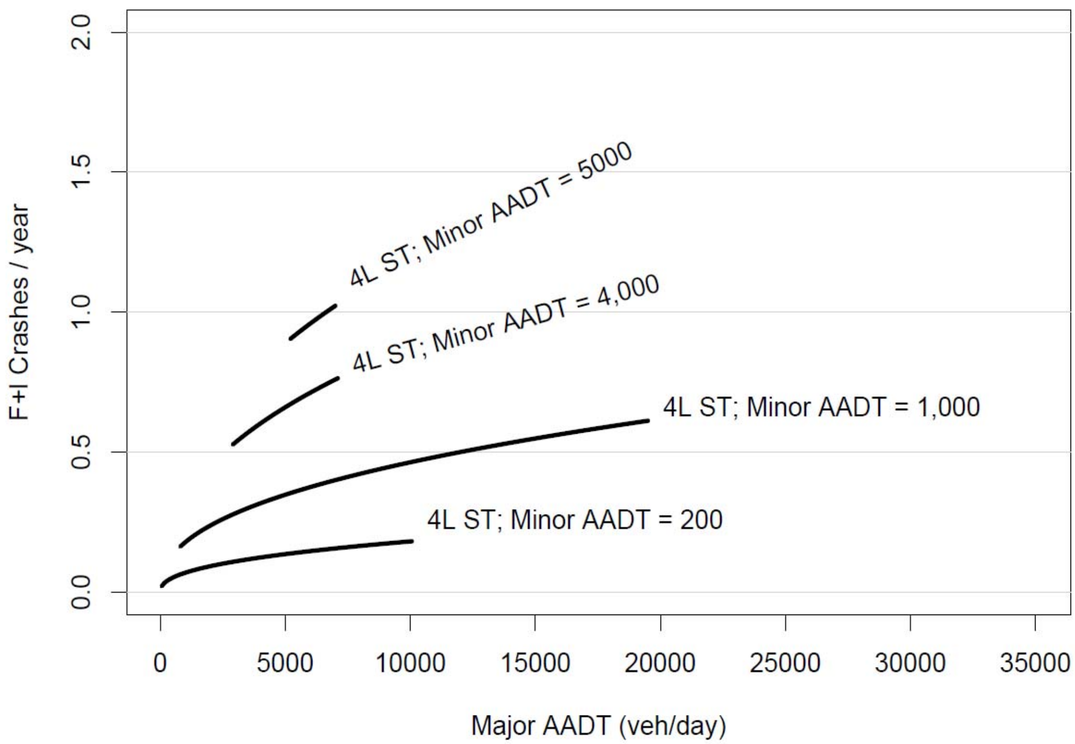


Figure 49. Comparison of PDO Crashes on Signalized Rural Intersections

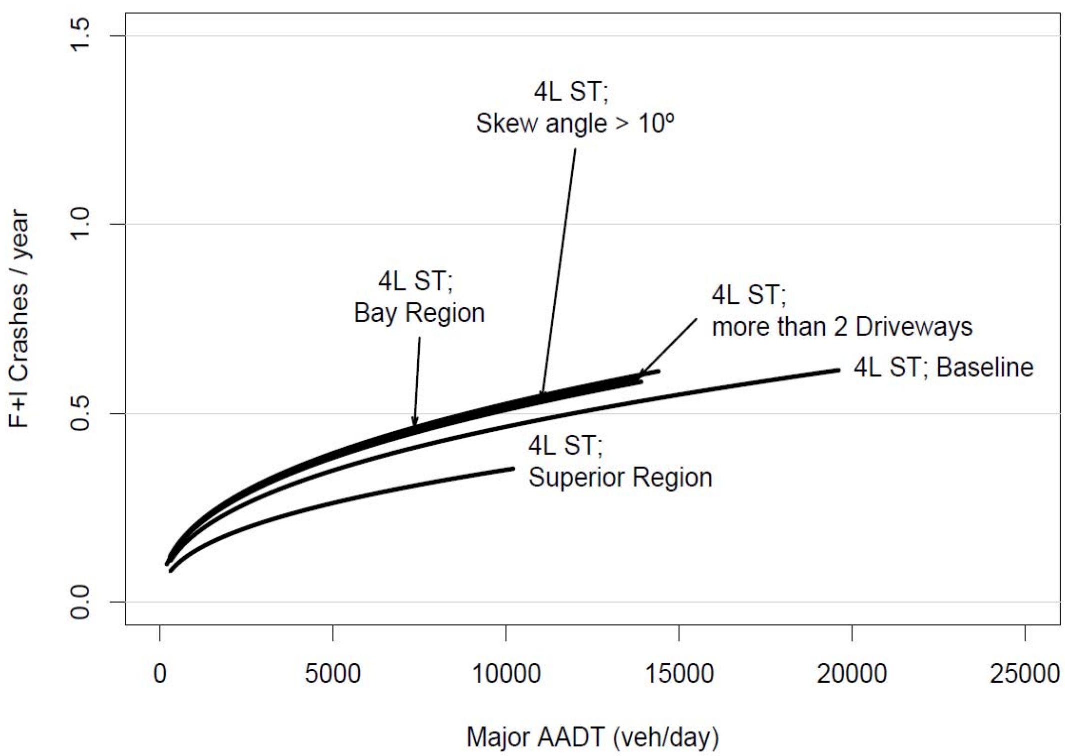
The total crash frequency for a given intersection can be obtained by the adding the corresponding predictions from the FI and PDO models.

7.3.5 Comparison of Rural Stop-Controlled Intersection SPF Results

For four-leg stop-controlled rural intersections, the relationship between FI crash frequency and traffic volume for base conditions, as obtained from the calibrated models, is shown in Figure 50.



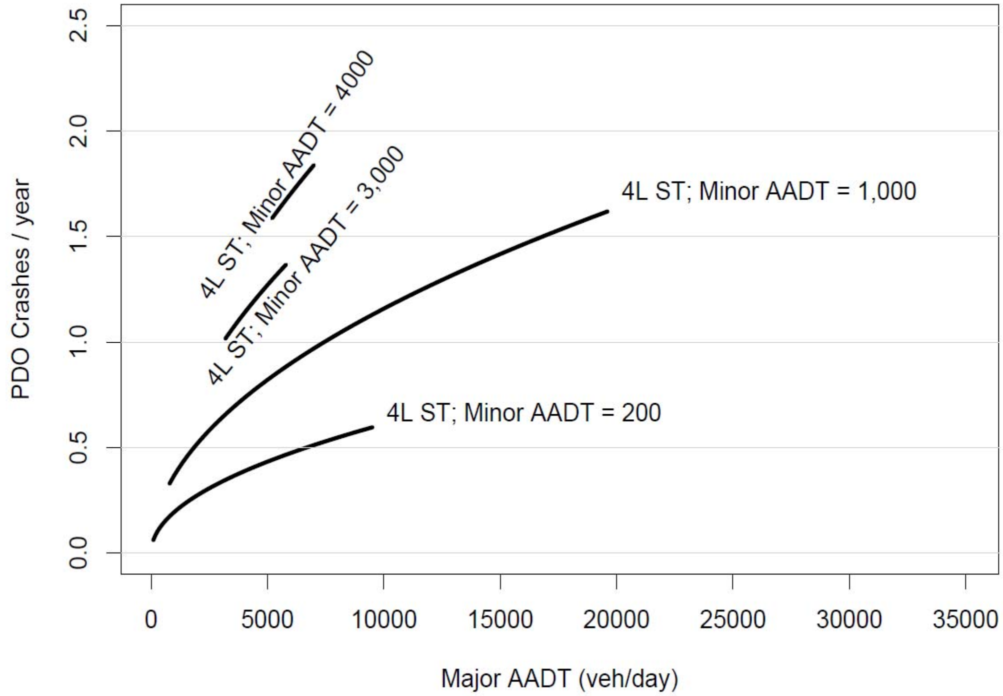
a) No skew, no driveways, and various values of minor AADT



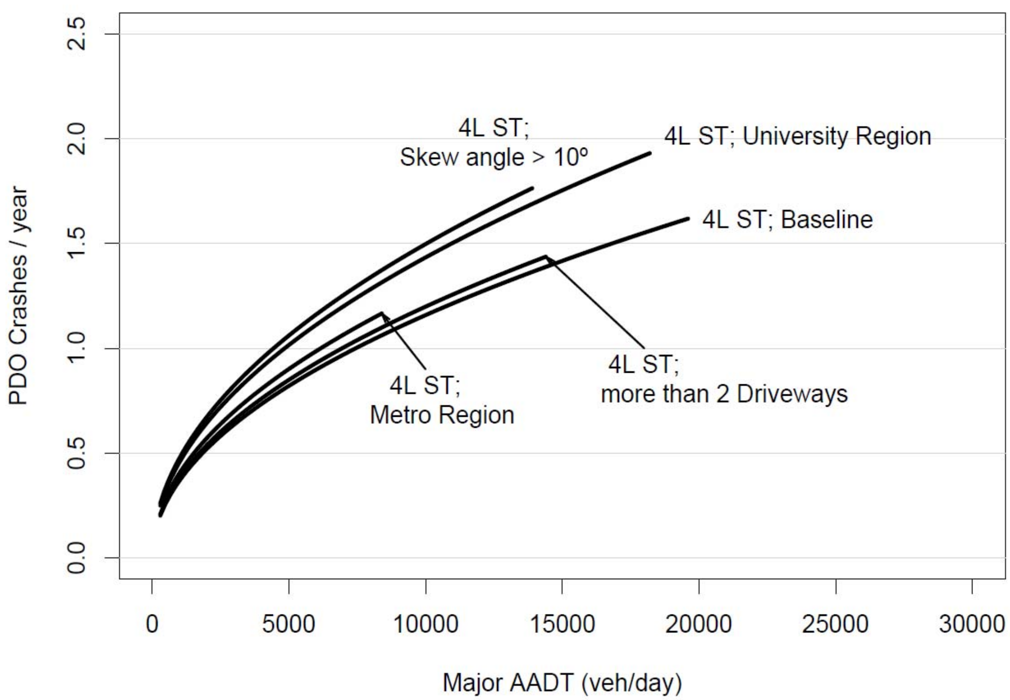
b) Other base conditions with minor AADT=1,000 veh/day

Figure 50. Comparison of FI Crashes on 4-leg Stop-Controlled Rural Intersections

Similar to Figure 50, Figure 51 shows the corresponding relationships between PDO crashes and traffic volumes at four-leg stop-controlled rural signalized intersections.



a) No skew, no driveways, and various values of minor AADT



b) Other base conditions with minor AADT=1,000 veh/day

Figure 51. Comparison of PDO Crashes on 4-leg Stop-Controlled Rural Intersections

For three-leg stop-controlled rural intersections, the relationship between FI crash frequency and traffic volume for base conditions, as obtained from the calibrated models, is shown in Figure 52.

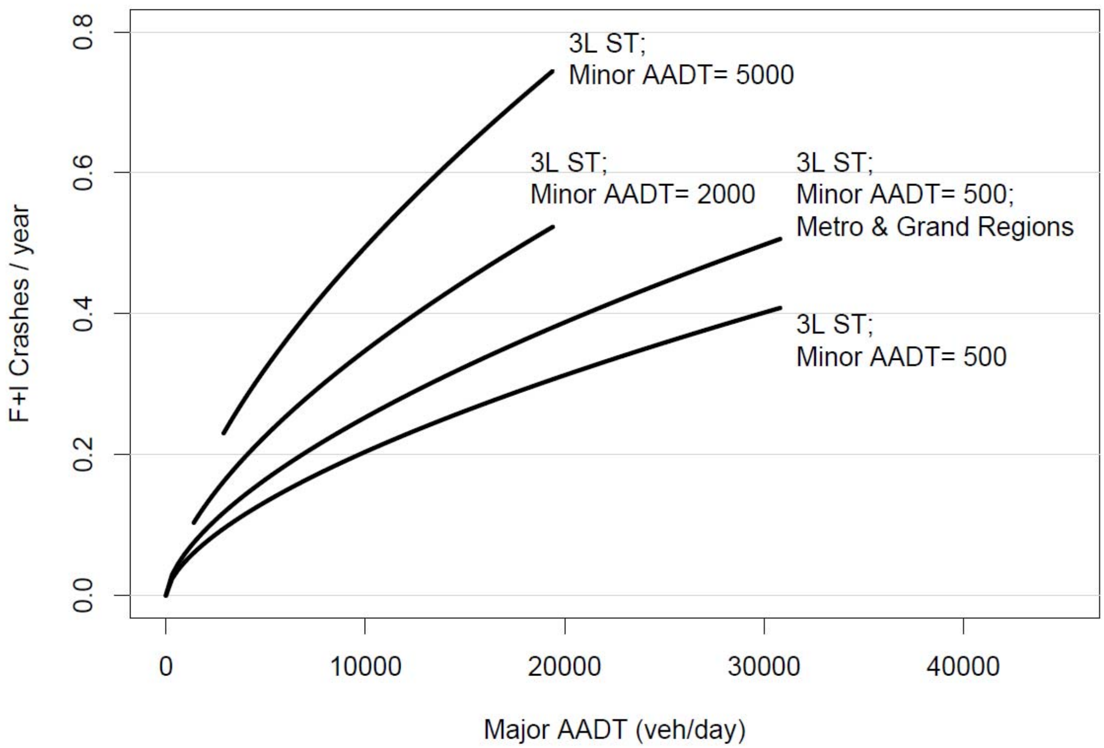


Figure 52. Comparison of FI Crashes on 3-leg Stop-Controlled Rural Intersections

Similar to Figure 52, Figure 53 shows the corresponding relationships between PDO crashes and traffic volumes at four-leg stop-controlled rural signalized intersections.

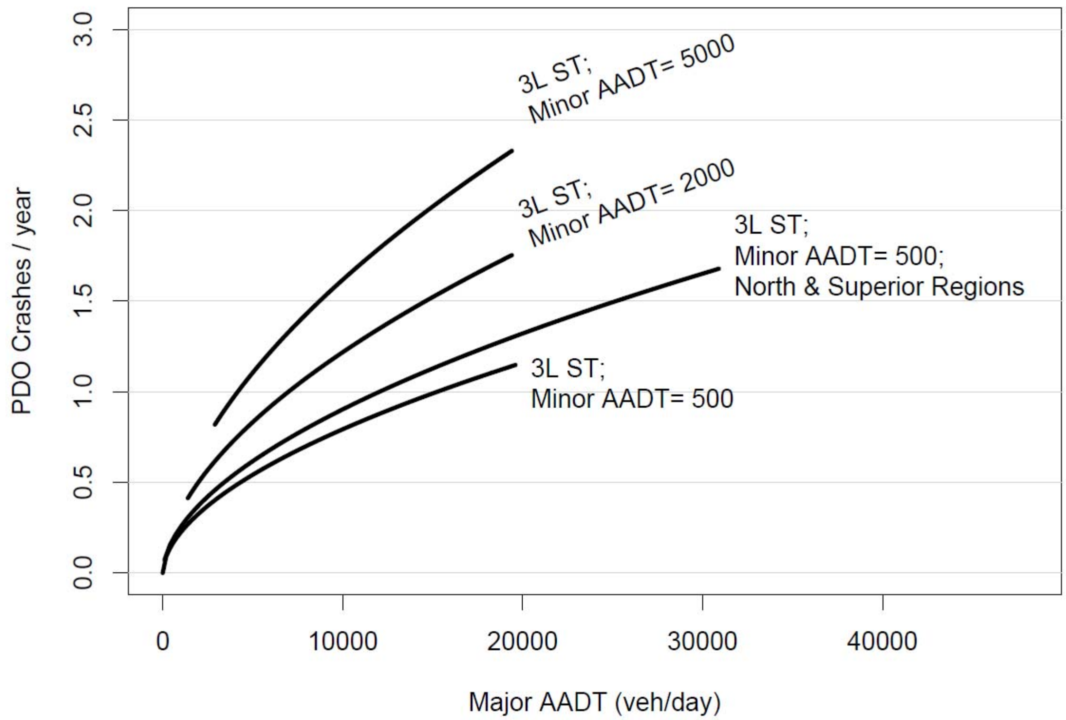


Figure 53. Comparison of PDO Crashes on 3-leg Stop-Controlled Rural Intersections

7.3.6 Distribution of Crashes by Collision Type

To estimate crash frequency across various collision types for rural signalized or stop-controlled intersections the crash frequency predicted by the FI or PDO SPF may be multiplied by the crash type proportions obtained from the respective 2011-2015 crash datasets, as displayed in Tables 84 and 85 for signalized and stop-controlled intersections, respectively.

Table 84. Distribution of Crashes by Collision Type and Severity Level, Rural Signalized Intersections

Category	Collision Type	Proportion of Crashes by Severity Level and Intersection Type			
		3SG		4SG	
		FI	PDO	FI	PDO
Single Vehicle	Deer	0.00	0.07	0.00	0.04
	Bicycle	0.02	0.00	0.02	0.00
	Pedestrian	0.03	0.00	0.05	0.00
	Overturned	0.00	0.01	0.01	0.00
	Fixed object/other SV	0.07	0.07	0.04	0.06
Multiple Vehicle	Angle	0.17	0.10	0.42	0.23
	Head-on	0.12	0.05	0.16	0.07
	Read-end	0.53	0.52	0.24	0.41
	Sideswipe	0.03	0.14	0.03	0.14
	Other MV	0.03	0.04	0.03	0.05

Table 85. Distribution of Crashes by Collision Type and Severity Level, Rural Stop-Controlled Intersections

Category	Collision Type	Proportion of Crashes by Severity Level and Intersection Type							
		3ST		4ST-MDOT		4ST-Fed Aid County		4ST-Non-Fed Aid County	
		FI	PDO	FI	PDO	FI	PDO	FI	PDO
Single Vehicle	Deer	0.02	0.32	0.01	0.29	0.01	0.27	0.00	0.31
	Bicycle	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Pedestrian	0.00	0.00	0.01	0.00	0.01	0.00	0.01	0.00
	Overturned	0.08	0.02	0.03	0.02	0.03	0.02	0.03	0.01
	Fixed object/other SV	0.33	0.28	0.07	0.14	0.09	0.16	0.10	0.24
Multiple Vehicle	Angle	0.19	0.08	0.54	0.21	0.68	0.30	0.79	0.33
	Head-on	0.09	0.02	0.09	0.02	0.06	0.03	0.01	0.01
	Read-end	0.20	0.18	0.19	0.20	0.08	0.13	0.03	0.05
	Sideswipe	0.05	0.06	0.03	0.07	0.02	0.06	0.01	0.02
	Other MV	0.03	0.04	0.03	0.05	0.02	0.04	0.00	0.03

7.4 Crash Modification Factors for Rural Four-Leg Stop-Controlled Rural Intersections

The CMFs for geometric design features of segments are presented below. The CMFs are used to adjust the SPF for intersections to account for differences between the base conditions and the local site conditions. Several CMFs were calibrated in conjunction with the SPFs. These were calibrated using the FI SPFs only because of the issues associated with the PDO crash data, such as underreporting. Collectively, they describe the relationship between various geometric factors and crash frequency. Of the three sets of SPFs developed for rural intersections, only the SPF for four-leg stop controlled intersections had CMFs calibrated along with the base condition models. Those CMFs are described and summarized as follows.

CMF_{skew}- Skew Angle. The base condition for the skew angle CMF is a skew angle of 0 degrees. The skew angle CMF for skew angle is provided in Table 86.

Table 86. Skew Angle CMF for 4ST Rural Intersections

Skew Angle Range	CMF
0-10 degrees	1.00
>10 degrees	1.10

CMF_{dw}- Driveways. The base condition for driveways CMF is no driveways within 211 ft of the center of the intersection. The driveways CMF is provided in Table 87.

Table 87. Driveways CMF for 4ST Rural Intersections

Skew Angle Range	CMF
0-2 driveways	1.00
>2 driveways	1.12

8.0 CALIBRATION, MAINTENANCE, AND USE OF SPFS

8.1 SPF Calibration Overview

When applied to different jurisdictions or over different time periods, SPFs need to be calibrated to reflect differences due to temporal or spatial trends. This calibration is achieved through the estimation of a calibration factor C_x. The recommended crash prediction algorithm takes the following form:

$$N_{predicted} = N_{spf,x} \times (CMF_{1x} \times CMF_{2x} \times \ldots \times CMF_{yx}) \times C_x \text{ ,}$$

where:

$N_{predicted}$ = predicted average crash frequency for a specificyear for a site of type x,
$N_{spf,x}$ = predicted average crash frequency determined for base conditions of the SPF developed for site type x,
CMF_{yx} = Crash modification factors specific to SPF for site type x, and
C_x = calibration factor to adjust SPF for local conditions for site type x.

Calibration capabilities are built into existing software support packages, such as the *Interactive Highway Safety Design Model* (*IHSDM*), which includes a calibration utility within its administration tool to assist agencies in implementing the calibration procedures described in *HSM*. The *IHSDM* also allows state agencies to develop and implement their own SPFs, in addition to modifying the crash severity and crash type distribution values (FHWA 2017).

8.2 SPF Calibration Procedure

Calibration can be used to account for changes in safety performance over time, which may be reflective of effects outside of the factors included in the SPFs developed as a part of this study. The calibration process is relatively straight-forward and can be applied following the steps outlined in Appendix A from Part C of the *HSM.* This procedure is briefly described on the following pages.

1. Identify facility type for which the applicable SPF is to be calibrated. For the case of the Michigan specific SPFs documented in this report, eight specific rural facility types are identified. This study considered both segments and intersections and included MDOT and county roadways including paved and gravel road surfaces (county only). All segments were two directional facilities of two to four lanes, including median divided facilities for the four lane roadways. The intersections were classified as three-leg minor road stop controlled, three-leg signalized, four-leg minor road stop controlled, or four-leg signalized. Due to small sample size, the three and four leg signalized intersections were included together during SPF development.
2. Select sites for calibration of the predictive model for each facility type. The *HSM* procedure recommends using 30-50 sites for a given facility type. The *HSM* also recommends that for jurisdictions attempting calibration that do not have enough sites of a particular type to use all sites within that jurisdiction of said type. For calibration purposes, sites should be selected without regard for the crash experience at individual sites, as selecting sites based on crash experience will potentially result in high or low calibration values. The selected sites should represent a total of at least 100 crashes. Sites should be selected so that they are representative of intersections for the entire area for which the calibration will be applied but do not need to be stratified by traffic volume or other site characteristics. The *HSM* states that site selection for calibration need only occur once, as the same sites may be used for calibration in subsequent years.
3. Obtain data for each facility type available to a specific calibration period. For annual calibration, one year of data should be used. Crashes for all severity levels should be included in the calibration.
    a. Observed crashes at each intersection or on each segment
    b. Major street AADT (intersections)
    c. Minor street AADT (intersections)
    d. Two-way AADT (segments)
    e. Roadway jurisdiction
    f. MDOT region or county
    g. Number of lanes (segments)
    h. Number of through lanes on the major and minor street
    i. Whether or not left-turn lanes are present on major leg approaches
    j. Lane width (segments)
    k. Centerline and edgeline presence (segments)
    l. Paved shoulder width (segments)
    m. Pavement surface type (county segments)
    n. Presence of a median
    o. Presence of lighting
    p. Number of driveways (on the segment or near the intersection)
    q. Presence of a curve with 65 mph or less design/advisory speed (segments)
    r. Terrain type, rolling or flat (segments)
4. Apply the applicable SPF to predict the total predicted average crash frequency for each site during the calibration period as a whole. This is done using the equations in sections 5.3 and 5.4 of this report. Following the example of shown in Section 6.5, the following steps should be taken for each intersection in the calibration set.
5. Calculate the number of expected fatal and injury multiple-vehicle crashes prior to the

application of CMFs, N_{spfmv}

6. Calculate the number of expected fatal and injury single-vehicle crashes prior to the application of CMFs, N_{spfsv}
7. Calculate the CMFs for fatal and injury vehicular crashes, $CMF_1 \times \ldots . \times CMF_p$
8. Sum N_{spfmv} and N_{spfsv}, and apply the CMFs to calculate N_{bi} for fatal and injury crashes
9. Calculate the number of expected PDO multiple-vehicle crashes prior to the application of CMFs, N_{spfmv}
10. Calculate the number of expected PDO single-vehicle crashes prior to the application of CMFs, N_{spfsv}
11. Calculate the CMFs for PDO crashes, $CMF_1 \times \ldots . \times CMF_p$
12. Sum N_{spfmv} and N_{spfsv}, and apply the CMFs to calculate N_{bi} for PDO crashes
13. Add the fatal and injury N_{bi} with the PDO N_{bi} to obtain the predicted total of all automobile-only crashes
14. Apply the pedestrian and bicycle proportions to the total automobile-only N_{bi}, to obtain the predicted number of pedestrian and bicycle involved crashes
15. Add the pedestrian and bicycle crashes to N_{bi} to obtain the predicted amount of total crashes
16. Compute calibration factors for use with each SPF. The purpose of the calibration factor is to scale the SPF to more accurately match the type of facility it is being used on. If an SPF predicts fewer total crashes than actually occur for the sum of all crashes of the calibration data set, a calibration factor greater than one is required. If the SPF predicts more crashes than actually occur for the calibration year, then a calibration factor less than one is need to reduce the predicted crashes. The calibration factors for a particular facility type, C_i, are computed with the following equation:

$$C_i = \frac{\Sigma_{observed\ crashes}}{\Sigma_{predicted\ crashes}}$$

8.3 Example Calibration

To illustrate this point, consider the following example: A set of 30 calibration sites experience a total of 100 crashes during the calibration year. The appropriate SPF predicts that the calibration sites should experience 105.099 crashes during the calibration year. The calibration factor of this facility type is calculated by

$$C_i = \frac{100}{105.099} = 0.951$$

This calibration factor can then be applied when predicting crashes for intersections or segments of the appropriate facility type. This concept is illustrated in Table 88.

Table 88. Example Calibration

Hypothetical Intersection or Segment	Hypothetical Observed Crashes	Hypothetical Predicted Crashes ($N_{spf,x}$)	Calibrated Predictions (C_x*$N_{spf,x}$)
1	4	2.983	2.839
2	3	3.283	3.124
3	3	2.983	2.839
4	2	3.583	3.409
5	1	3.283	3.124
6	0	3.883	3.695
7	6	4.183	3.980
8	3	3.583	3.409
9	4	3.283	3.124
10	2	3.583	3.409
11	1	3.583	3.409
12	2	3.883	3.695
13	3	2.533	2.410
14	5	4.483	4.266
15	1	2.983	2.839
16	8	3.283	3.124
17	9	3.133	2.981
18	0	3.433	3.267
19	3	2.683	2.553
20	6	4.783	4.551
21	3	4.183	3.980
22	5	4.183	3.980
23	3	3.283	3.124
24	0	3.283	3.124
25	4	3.583	3.409
26	6	4.483	4.266
27	4	2.683	2.553
28	4	2.983	2.839
29	5	3.583	3.409
30	0	3.433	3.267
Total	100	105.099	100
Calibration Factor (C_x)		0.951	

8.4 Long Term Maintenance and SPF Re-estimation

In the future, MDOT may wish to re-estimate the SPFs developed in this research. In order to accomplish this task, data should be collected and organized as described in Section 3 of this report. Data available in *Safety Analyst* may be sufficient to estimate SPFs when used in conjunction with crash data from the Michigan State Police. In lieu of the discontinuation of the sufficiency file maintained by MDOT, manual data collection may be necessary if available data sources do not contain geometric data. This research found the following variables to significantly influence crashes within at least one of the facility types:

- Segments
  - AADT
  - Driveway Density
  - Horizontal Curvature
  - Paved Shoulder Width
  - Traveled Way Width
  - Terrain (level vs. rolling)
  - No Passing Zone Length
  - Surface Type (paved vs. gravel)
- Stop Controlled Intersections
  - Skew Angle
  - Number of Driveways
- Signalized Intersections
  - Census Designated Place
  - Number of Intersecting Legs (3 vs. 4)

These characteristics provide a starting point for data collection to re-estimate the SPFs, however changes in driver behavior and roadway characteristics may lead to additional characteristics becoming significant in the future. In addition to roadway characteristics, for select facility types, this research found variation in estimated crash frequency between MDOT regions, making the inclusion of MDOT region in the data set relevant, depending on the facility type.

Once the dataset has been assembled, statistical analysis software must be utilized to estimate the effects of each roadway characteristic on each facility type. Negative binomial models, the standard for SPF development, should be used. A functional form of the model must be identified. Recall that separate models have been developed for single-vehicle and multiple-vehicle crashes at FI and PDO severity levels. For example, for a given severity level, the general equation for the predicted number of crashes on MDOT 2U segments is shown below.

$$N_j = (N_{spfmv} I_{mv} + N_{spfsv} I_{sv}) \times CMF_{sw} \times CMF_{dw} \times CMF_{hc} \times CMF_{roll} \times CMF_{rstr}$$

With the equations for multiple vehicle and single vehicle midblock segment crashes based on the natural log of AADT and the MDOT regional indicators as shown below.

$$N_{spfmv} = n \times L \times e^{b_{mv} + b_{mv1} \ln(AADT) + b_{r1} I_{r1} + b_{r2} I_{r2} + b_{r3} I_{r3} + b_{r4} I_{r4} + b_{r5} I_{r5} + b_{r6} I_{r6}}$$

$$N_{spfsv} = n \times L \times e^{b_{sv} + b_{sv1} \ln(AADT) + b_{r1} I_{r1} + b_{r2} I_{r2} + b_{r3} I_{r3} + b_{r4} I_{r4} + b_{r5} I_{r5} + b_{r6} I_{r6}}$$

Ultimately, the results of the statistical analysis will yield parameter estimates, or coefficients, as well as significance levels and information regarding the accuracy of the parameter estimation. The parameter estimates will serve as the "b" values in the SPF equations, provided they are significant at 95 percent confidence interval or their inclusion can otherwise be justified using engineering judgement. The equation above illustrates that AADT is generally log-transformed, which has been shown to provide improved fit.

The effects of other roadway characteristics, such as shoulder width, driveway density, and horizontal curvature for segments, and skew angle and driveway counts for stop controlled intersections, are accounted for through the creation of CMFs. In Chapter 3, it was mentioned that the "base" scenario is represented with a CMF of 1.0 for a specific roadway characteristic. Based on engineering judgement, it may be desirable to transform the data collected for any specific roadway feature so that a particular case is used as the base scenario. For example, in this research it was determined that a 6 ft shoulder width was base scenario for a 2U trunkline highway segment, so all segments with 6 ft shoulders would have a CMF of 1.0. To accomplish this, the shoulder width for each site was transformed by subtracting 6 ft from the actual value. For an example of the form of a CMF, consider the shoulder width:

$$CMF_{sw} = e^{-0.024(W_{sw} - 6.0)}$$

Re-estimation/long-term maintenance of the SPFs will require careful data collection and analysis. The resulting SPFs can only be as good as the data they are based upon. The SPFs presented in this report are the result of extensive data collection and analysis, and ultimately serve as a guideline for the re-estimation of Michigan-specific SPFs in the future.

9.0 SUMMARY AND CONCLUSIONS

This study involved the estimation of safety performance for rural highways and intersections in Michigan, including two-lane and four-lane state trunklines (divided and undivided), rural county roadways (paved and gravel), signalized intersections, and minor-road stop controlled intersections. This was accomplished through the development of safety performance functions to estimate the number of annual crashes at a given intersection or highway segment, crash modification factors to determine the impacts associated with various roadway and geometric characteristics, and severity distribution functions to predict the crash severity. The development of such models required the compilation of data from across numerous sources for thousands of road segments and intersections statewide. These data included traffic crashes, traffic volumes, roadway classification, geometry, cross-sectional features, and other site characteristics. The primary data sources included:

- Michigan State Police statewide crash database (2011 - 2015),
- MDOT trunkline sufficiency file,
- Michigan Geographic Data Library All Roads shapefile,
- Census boundary shapefile,
- MDOT trunkline signals shapefile,
- MDOT trunkline driveway count file,
- MSU horizontal curve database, and
- Google Earth for manual measurement, where necessary.

In general, data were collected for each facility type across all counties and regions of Michigan, assuming such roadways facilities were present. However, for county road segments, which involved extensive manual collection of data, a statewide analysis was infeasible given the lack of data within certain counties along with project time and resource constraints. Therefore, county road segment data were collected across a sample of 30 counties representing all regions of Michigan. Furthermore, due to the small number of rural signalized intersections statewide, signalized intersections located within a census designated place of population less than 5,000 were retained in the sample. The data were assembled into separate files based on the facility type, jurisdiction, and federal aid status, with the number of samples presented in the list that follows:

- Rural segments
    - Two-lane MDOT trunkline (2U): 1556 segments, 5352 miles
    - Four-lane undivided MDOT trunkline (4U): 58 segments, 95 miles
    - Four-lane divided MDOT trunkline (4D): 55 segments, 107 miles
    - Two-lane paved federal aid county (2PF): 9912 segments, 4424 miles
    - Two-lane paved non-federal aid county (2PN): 2873 segments, 1463 miles
    - Two-lane gravel non-federal aid county (2GN): 3983 segments, 2007 miles
- Rural intersections
    - Stop controlled
        - Three-leg stop control (3ST): 2297 sites
        - Four-leg stop control (4ST): 2513 sites
    - Signal controlled
        - Three-leg signalized (3SG): 19 sites
        - Four-leg signalized (4SG): 175 sites

After the data were assembled for rural road segments and intersections in Michigan, a series of preliminary data analyses were conducted to identify general crash trends across each of the facility types. Calibration factors were generated for each corresponding *HSM* model using the 2011-2015 Michigan crash data for the respective segment and intersection facility type. It was discovered that Michigan rural highway crash data, particularly for segments, contained an overwhelming proportion of deer crashes. This was especially evident in comparison to the crash data used in development of the *HSM* rural highway models, which showed far lower proportions of animal crashes. This caused the base SPFs from the *HSM* to have calibration factors that typically exceeded 1.0 when applied to the Michigan data for each facility type, leading to the conclusion that the *HSM* generally under predicts total crashes on Michigan rural highways. However, removal of deer crashes caused many of the calibration factors to fall below 1.0, suggesting over prediction of Michigan non-deer crashes by the *HSM*. Furthermore, the *HSM* models generally tended to over-predict crashes at stop-controlled intersections, but under-predict crashes at signalized intersections. It was concluded that the *HSM* models display significant variability in terms of the goodness-of-fit across the various rural facility types in Michigan.

To address the shortcomings associated with the calibrated *HSM* models, a series of SPFs were developed using the Michigan-specific data. A series of simple general statewide models were initially developed using AADT along with regional indicators to account for unobserved differences in drivers, weather, and topography between the various regions of Michigan. Separate models were generated for injury crashes (including fatalities) and property damage only crashes within each of the facility types. Additionally, the roadway segment models were generated both with and without deer-involved crashes.

However, in order to provide the greatest degree of crash prediction accuracy, detailed Michigan-specific SPFs were estimated for each rural facility type based on AADT and MDOT region, along with numerous additional roadway related factors. For rural segments, these additional factors included lane width, shoulder width, horizontal curvature, terrain, passing zones, median presence, surface type, and driveway density. For rural intersections, these additional factors included driveways counts, lighting presence, turn lane presence, and intersection skew. To improve the predictive capabilities of the roadway related variables, deer-involved crashes were excluded from the fully-specified rural segment models. Methods for prediction of crash frequency by crash type (i.e., rear-end, head on, angle, run-off-road, etc.) and injury severity were also established. Depending on the facility type, this was performed by using either separate SPFs, severity distribution functions, or crash distributions.

Comparison of the base SPFs across a common range of traffic volumes for the various rural facility types showed several interesting findings. First, comparison of the rural trunkline road segment SPFs showed four-lane divided trunklines to possess greater rates of single-vehicle midblock crashes compared to four-lane undivided and two-lane trunklines, although little difference was observed in the multi-vehicle midblock crash rates across the three facilities types (2U, 4U, 4D). Turning to the two-lane road segments SPFs, paved county roadways (federal aid and non-federal aid) showed approximately double the midblock crash occurrence rate of trunklines. However, gravel county roadways showed a substantially greater midblock crash occurrence rate than paved county roadways. Please refer to Chapter 6, particularly Figures 46 and 47, for further details pertaining to these findings.

Turning to comparison of the base intersection SPFs, although the relatively small sample of rural signalized intersections limited the capabilities of the analysis, it was determined that signalized intersections with three legs possessed lower crash occurrence than those with four legs. Furthermore, signalized intersections falling within a census designated place had fewer injury crashes than locations outside of a CDP, likely due to the lower speed limits that typically exist within CDPs. Similar to signalized intersections, three-leg stop-controlled intersections also had lower crash occurrence rates than four-leg stop-controlled intersections. Please refer to Chapter 7 for further details pertaining to these findings.

Michigan-specific CMFs were also developed, which may be used to adjust the crash estimate from the SPF when the characteristics of a particular segment or intersection are not consistent with the base conditions. For segments, it was found that wider paved shoulders are associated with fewer crashes and less severe crashes across all applicable rural segments types. Interestingly, lane width did not have a significant impact on crash occurrence on trunklines or federal aid county roadways, although narrow non-federal aid county roadways (i.e., traveled way less than 18 feet) showed greater crash occurrence and more severe crashes. Increased driveway density was associated with increased crash occurrence, although this effect was more pronounced on trunkline segments. Lastly, an increase in the amount of horizontal curvature on the segment was associated with increases in crash occurrence and crash severity across all rural segment types. Considering four-leg intersections with stop control on the minor roadway, skew angles of greater than 10 degrees were found to increase crash occurrence, particularly for property damage crashes. Furthermore, such intersections with more than two driveways within a 211 ft (0.04 mile) radius of the intersection were also found to have greater crash occurrence and more severe crashes.

The rural road segment and intersection models developed herein will be of great use to transportation professionals, as Michigan-specific SPFs were previously limited to urban segments and intersections. Particularly noteworthy is the inclusion of models specific to county-maintained facilities, as these facilities tend to have lower design standards, lower traffic volumes, and a greater proportion of highly familiar drivers. Furthermore, the non-federal aid models contained in this report were based on data that included gravel roads, for which SPFs and CMFs had not been previously developed, thereby allowing for comparison of the safety performance characteristics between gravel and paved county roadways of similar classification.

Ultimately, the results of this study provide a number of methodological tools that will allow for proactive safety planning activities, including network screening and identification of high-risk sites. These tools have been calibrated such that they can be applied either at the statewide level or within any of MDOT's seven geographic regions, providing additional flexibility to accommodate unique differences across the state. This report also documents procedures for maintaining and calibrating the Michigan-specific SPFs over time. Calibration will allow MDOT to account for changes that occur with time that are not directly reflected by the predictor variables. As MDOT continues to build its data system, the use of additional geographically-referenced geometric, operational, and traffic control data will allow for further refinements to these analytical tools.

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