ASSESSING SAFETY PERFORMANCE OF ROADWAY CHARACTERISTICS IN RURAL AND URBAN CONTEXTS

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ABSTRACT

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Evaluating the safety performance of roadway segments and intersections typically involves associating traffic crashes, injuries, and fatalities to various roadway and traffic characteristics, which typically vary broadly between rural and urban contexts. In rural areas, roadway geometric characteristics often play a critical role in the safety performance of a given roadway, while myriad other factors, including driveways and intersections, tend to have a greater influence on urban roadway safety. However, certain geometric aspects, such as the characteristics of the horizontal curvature and the impact of driveway land-use type have not been well-explored in prior roadway safety research. There has also been limited research on the safety performance for roadways of lower functional classifications, such as minor arterial and collector roadways, which comprise a substantial portion of the nationwide roadway network but are often designed to lower standards and possess driver and trip characteristics that typically differ from those of principal arterials. Therefore, assumptions made on the general effect of the predictor variables from typical safety performance functions may not apply to lower roadway classes. This research sought to explore those gaps in the roadway safety research domain. To accomplish this objective, roadway characteristics were collected along with traffic volume and crash data for greater than 13,000 miles of two-lane roadways in rural, urban, and suburban areas from across the state of Michigan for the period of 2011 through 2018. A series of safety performance functions were developed using a mixed-effects negative binomial modeling structure, which included fixed-effects and random-effects to account for the unobserved

heterogeneity associated with varying design standards and site characteristics. The results indicated that driveway density significantly influences crash occurrence across all land-use categories for paved highways, although no impact was observed on unpaved roads. Commercial driveways possessed a stronger effect on crash occurrence than residential driveways or industrial driveways. In urban areas, posted speed limit had a significant positive association with crash frequency, and this effect increased when the speed limit exceeded 40 mph. The effect of speed limit was stronger on urban minor arterial segments (compared to collectors) and for fatal and injury crashes (compared to property damage only). This research also assessed the safety impacts associated with horizontal curve characteristics on rural highway segments, including curve type, curve direction, curve-approaching, curve-following, and inner-curve tangent distances, and curve design speed on rural two-lane undivided highways. Similar to prior research, curves with design speeds lower than the posted speed limit showed elevated crash occurrence. Most notably, compound and reverse curves were associated with greater crash occurrence compared to simple curves, with the greatest impact by the reverse curves. The increased approaching tangent distance for the simple curve or the first of a series of compound or reverse curves increased crash likelihood, perhaps due to the decreased driver expectancy for curvature with increasing tangent distance. However, increased inner-curve tangent distance was found to be associated with decreased crash occurrence. Lastly, the left-turning curves were found to be associated with greater crash occurrence than that on the right-turning curves.

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1. INTRODUCTION

Research on road safety has attracted considerable interest due to the heavy societal toll including lost productivity and costs of healthcare associated with traffic crashes. The high economic impact of motor vehicle crashes, $242 billion in 2010 in the United States., provides motivation for transportation agencies to proactively pursue traffic safety improvements (*1*). Recent worldwide highway safety reports indicate that, road traffic injuries are the leading cause of death for children and young adults aged 5-29 years (*2*) and by 2030, highway-related crashes will be among the top five leading causes of death (*3*). In 2019, there were 33,244 fatal motor vehicle crashes resulting in 36,096 fatalities. Of these fatal crashes, 44.1 percent occurred in rural areas, and 55.4 percent occurred in urban areas (*4*). In terms of fatalities, rural and urban areas accounted for 45.3 percent and 54.3 percent, respectively, of all fatalities in 2019 (*5*).

According to the 2016 American Community Survey (*6*) from the U.S. Census Bureau (*7*), an estimated 19 percent of the U.S. population lived in rural areas, and as Federal Highway Administration (FHWA) indicates, only 30 percent of the total vehicle miles traveled (VMT) in 2019 were in rural areas (*8*). However, in the same year, the fatality rate per 100 million miles traveled was almost 2 times higher in rural areas than in urban areas (1.66 in rural areas compared with 0.86 in urban areas) (*5*). Also, data shows that the majority of fatal crashes in the U.S. occur on two-lane highways (*9*).

In Michigan, between 2009 and 2019, both total and fatal crashes have increased by 8.0 percent and 12.0 percent, respectively, with the increase in fatal crashes outpacing the increase nationwide, while the increase in VMT during this time was only about 6.5 percent. Urban fatal crashes have generally comprised the majority of crashes in Michigan, unlike the rest of the country where until recently, the majority of fatal crashes occur in rural areas. Moreover, non-intersection segment/midblock crashes have consistently accounted for over 65 percent of the total crashes statewide in Michigan (*10*). Although midblock crashes are usually not directly influenced by junctions, they are greatly influenced by factors related to roadway geometry, cross-section, roadside attributes, among other characteristics.

1.1 Roadway Functional Class and Traffic Safety

Roadways in the U.S. have historically been classified functionally based on two primary criteria: land access and mobility. The significance of these two characteristics is different according to the road type, as indicated by the AASHTO Green Book, 2001 (*11*). In general, the mobility function decreases as access increases. AASHTO (*12*) specifies the three basic types of roadways based on traffic volumes, design characteristics, and method of financing. These classifications are arterials, collector, and local roads/streets. While arterials have high mobility level and they connect major trip generators which demand long trip length and high traffic volumes, collector roads collect traffic from lower category, connect local and arterial highways, and serve subordinate traffic generators. Lastly, the local roads are characteristic of low volume public facilities, and their primary function is to provide access to adjacent land. Shortest distances, low speed and volumes, lowest level of mobility and the highest land access are the basic characteristics of these types of roads.

While understanding the impacts of the roadway and traffic environments on safety, one has to comprehend the functions and characteristics of different classes of roads. For non-freeway, non-major arterials roadways, this understanding in even more crucial. This is because, unlimited access directly from businesses and residences to roads of lower functional classes create a wide range of circumstances in the mix of access and movement functions and pose different kinds of safety concerns by creating more locations for potential conflicts of vehicular movements. The proper "function" of any roadway is determined by consideration and evaluation of numerous complex factors including length of trips traveled on the road, speed of operation, degree of access control, degree of land service, freedom of movement, service to activity centers or traffic generators, system continuity, and traffic volume, among others.

1.2 Rural vs Urban Road Safety

There is a wide range of potential explanations for the differences in road safety performance between rural and urban areas, which includes: rural drivers may drive more miles than their urban counterparts (*13*); rural roads may be less safe than urban roads; rural crashes may be more severe than urban crashes; rural crash victims may not receive medical attention as quickly as urban crash victims; and the quality of the medical response may not be as good (*14*). Most recent data shows that rural traffic fatalities decreased by 10 percent from 18,089 in 2010 to 16,340 in 2019, whereas urban traffic fatalities increased by 34 percent from 14,659 in 2010 to 19,595 in 2019 (*5*).

Highways owned and maintained by counties are an important part of the rural road system in many states, especially those in the Midwest and Great Lakes regions of the U.S. The same is true in Michigan, where approximately only 8 percent of all public roadways (totaling approximately 122,000 miles) are owned by the state jurisdiction, while 74 percent are owned by county road agencies (*15*). More than 57 percent of all traffic crashes in Michigan in 2019 occurred on facilities owned by agencies other than the state (*16*). Several factors contribute to the high rural crash risk, including roadway geometry, travel speed, lack of lighting, weather, maintenance, and physical conditions of the roadways, among others. Higher crash rates on rural roads than that on urban roads led to the establishment of the High Risk Rural Roads (HRRR) program in SAFETEA-LU (*17*).

On the other hand, with the majority of the U.S. population living in the urban and suburban areas, urban roadways remain a critical aspect of roadway safety. Particularly, urban arterials and collectors, which typically possess speed limits 50 mph or lower, are an important part of the roadway system, and generally carry substantially high volumes of traffic and provide more frequent access to roadside developments. Urban and suburban road segments account for about 29 percent of all road-miles in the U.S (*18*) and almost 31 percent of the total road miles in Michigan (*19*). In 2019, urban roads in the U.S. experienced almost 70 percent of the total vehicle miles traveled (*20*) and majority of fatalities (55.4 percent) compared to rural roadways (*9*), a trend which has been sustained since 2016 (*5*).

According to the National Highway Traffic Safety Administration (NHTSA), approximately 59 percent of fatalities occurred in urban regions in Michigan in 2019 (*5*). Modeling crash risk in urban areas is generally more complicated than in rural areas due to the complexity of the driving environment and the difficulty obtaining data to fully characterize the road and surrounding environment. Urban areas contain a plethora of factors contributing to increased environmental complexity that are not captured by traditional data sources. Roadside development in urban areas is often much denser than in rural areas, bringing with it increased access points, parking areas (on-street and/or off-street), transit stops, and traffic signals, thereby increasing the complexity of the roadway environment.

Additionally, majority of rural fatal crashes occurred on roads where the speed limit was 55 mph or higher, the opposite of urban fatal crashes. Specifically, 66 percent of drivers involved in urban fatal crashes in 2019 were on roadways where the posted speed limits were 50 mph or less. In rural fatal crashes, 72 percent of drivers involved were on roadways where the posted speed limit was 55 mph or higher (*5*). Furthermore, in 2019, urban areas accounted for majority of the pedestrian (82 percent in urban area vs 18 percent in rural area) and bicyclist (78 percent in urban areas vs 22 percent in rural areas) fatalities by large margins (*5*). More than half (54.3 percent) of alcohol-impaired driving fatalities were in urban areas (*5*).

1.3 Problem and Knowledge Gap

A comprehensive literature review, which is provided in the following section (Chapter 2), has identified the knowledge gaps in the extant body of work based on which the objectives of this research were formulated.

Access management can be defined as the "systematic control of all access points to a roadway", including their design and operation (*21*). Previous research identified the major factors that affect safety of accesses including design and spacing of driveways, land-use, roadway geometry, proximity to intersections and interchanges, median configuration, and signalized intersection spacing and signal coordination, traffic volumes, speed limits, and vehicle configurations (*22–24*). An effective access management technique that has been widely used for road safety measures is to reduce the overall number and density of access points. The American Association of State Highway and Transportation Officials (AASHTO) states "the number of crashes is disproportionately higher at driveways than at other intersections; thus their design and location merit special consideration." (*25*).

Although it is widely understood that driveway entry/exit volumes vary based on the development or land-use type (e.g., commercial driveways typically carry greater traffic than residential driveways), rarely are entering/exiting volume counts taken regularly at driveways. Thus, in lieu of traffic volume data, greater precision would be provided to safety performance models when specified based on driveway development or land-use type.

The *Highway Safety Manual* (*HSM*) provides guidance for considering driveway density as a crash modification factor (CMF) for use with safety performance functions (SPFs) for both urban and rural roads (*26*). Specific development and utilization categories are provided for the *HSM* driveway CMFs for urban/suburban roadways. However, only a vague description is provided for rural two-lane roadways, suggesting that "driveways serving all types of land-use" and "all driveways that are used by traffic on at least a daily basis" are to be considered when determining driveway density for use in the CMF. Unfortunately, there has been limited research investigating the differences in safety performance across various driveway types on rural roads with respect to the type of development or land-use that they serve.

With regard to other roadway characteristics, horizontal curves are a necessary design component of the highway system, although they are widely known to pose significant safety concerns. A study from early 2000s estimated more than 10 million horizontal curves on two-lane highways alone in the U.S (*27*). Prior research has indicated that traffic crashes occur more frequently and are more severe on horizontal curves compared to straight segments (*28*), and fatal crash rates are three times greater on horizontal curves than straight segments (*29*).

Additionally, single motor vehicle crashes are even more overrepresented on horizontal curves (*30*) due to numerous reasons, as pointed out by previous studies, including relatively high speed and low design standards of horizontal alignments, complex riding maneuvers required to negotiate curves, and reduced sight distance on curves, among others, on rural two-lane highways (*31*, *32*). Collectively, these statistics along with the predominance of horizontal curves on rural roads indicate the need for a thorough understanding pertaining to the safety performance associated with horizontal curves characteristics on rural highways. This is particularly important on rural secondary roadways, including those owned and maintained by counties, which are often designed and maintained to lower standards and include different driver populations and trip characteristics compared to arterial highways.

Although the *HSM* provides details related to calibration of safety performance functions (SPFs) for rural highways and crash modification factors (CMFs) for horizontal curves, these SPFs/CMFs were generated based on data obtained from state highways. Hence, assumptions made on the general effects of the factors included in the models may not apply to secondary roadways. Also, while prior work has investigated the relationship between crash occurrence and aggregate curve characteristics, including number of curves, curve radius, and length of curve (*33*–*35*), several important alignment-related aspects have received little attention. Moreover, as more and more states are increasing their statutory maximum speed limits on rural highways, additional research is warranted to provide guidance on the selection of rural two-lane highway segments for speed limit increases, particularly with respect to roadway geometry.

In the context of urban roadways, research focus has generally been on higher functional class roads (*36*, *37*). This is also the case with *HSM* where the SPFs were generated based largely on data obtained from higher functional classes (i.e., primary arterials), which are typically owned by the state DOTs. Therefore, assumptions made on the general effect of the predictors, such as traffic volume or roadway characteristics, may not apply to lower urban/suburban roadway classes such as minor arterials and collectors, which are often owned by local agencies (e.g., city or county) (*38*).

1.4 Research Problem Statement and Objectives

This research will explore various roadway characteristics and their associations with the safety performance on rural and urban non-freeway roads. This work aims to specifically address the existing research gaps related to the safety performance characteristics of roadways with functional classifications lower than freeways and principal arterials, including secondary roadways under county or city jurisdiction, which are often designed and maintained to lower standards and include different driver populations, trip characteristics, and travel speeds compared to state-owned roadways. The analysis will generally consider two-lane two-way undivided arterial and collector roadways, although local roadways will also be considered for only rural highways. The research objectives have been developed based on a review of the literature and the data availability for analysis. In total, three specific research objectives have been developed for the research proposed here, as follows.

1.4.1 Objective 1: Determine the association between driveway land-use and safety performance on rural two-lane two-way undivided state and county highways.

While driveway density has been explored with respect to the impacts on highway safety, little is known about the safety performance across various classifications of driveway land-use, especially for rural county roads. For states with a highly rural road network, including Michigan, it is imperative to understand how the development type of driveways impacts highway safety across roadway jurisdictions and functional classifications. To address this knowledge gap, the relationship between driveway land-use and safety for rural two-lane highways has been evaluated utilizing data from both state and county roadways and across various functional classifications. This includes development of safety performance functions for two-lane rural roadways in Michigan that consider driveway density across various land-use categories along with other roadway, traffic, and geometric characteristics. This objective has utilized and developed further on the data originally obtained for the Development of Safety Performance Functions for Rural Segments in Michigan project. This objective has resulted in a manuscript presented at the TRB Annual Meeting in January 2020, and published in the Transportation Research Record in November 2020 as follows:

Chakraborty M, Gates TJ. *Association between Driveway Land-Use and Safety Performance on Rural Highways*. Transportation Research Record. November 2020. doi:10.1177/0361198120965232 (*35*).

1.4.2 Objective 2: Determine the association between horizontal curve characteristics and safety performance on rural two-lane two-way undivided state and county highways.

While prior work has investigated the relationship between crash occurrence and aggregate horizontal curve characteristics, including number of curves, curve radius, and length of curve, several important alignment-related aspects remain uninvestigated. For states with a highly rural road network, including Michigan, with a predominance of horizontal curves where particularly single motor vehicle crashes are overrepresented, it is crucial to gain a thorough understanding pertaining to the safety performance associated with horizontal curves characteristics on rural highways. To address this knowledge gap, research was carried out to assess the safety impacts of horizontal curve characteristics including curve type, curve direction, curve-approaching, curve-following, and inner-curve tangent distances, and curve design speed associated with single-vehicle crashes on rural two-lane undivided highways, by developing safety performance functions with curve-specific, roadway, traffic characteristics. Same as Objective 1, this objective too has utilized and developed further on the data originally obtained for the Development of Safety Performance Functions for Rural Segments in Michigan project. A manuscript is prepared based on this objective to be submitted to the Accident Analysis and Prevention journal.

1.4.3 Objective 3: Determine the association between roadway characteristics and safety performance on urban and suburban lower functional class (minor arterials and collectors) two-lane two-way undivided county and city roadways.

The literature review also revealed limitations with respect to safety performance on urban and suburban roadways. While considerable research has been performed for higher class (and typically higher volume) urban roadways, typically owned by state agencies, this work has typically not considered lower class urban and suburban roadways, particularly those owned by cities and counties. Urban roadways owned by cities and counties are typically of lower speed and possess drivers and trip characteristics that differ from their state-owned analogs. Furthermore, the road design and land-use characteristics vary greatly between urban core, general urban, and suburban areas, although distinction between urban and suburban context are often not characteristics are often not considered. This research objective aims to determine the relationship between various roadway characteristics, including those related to roadway geometry and other cross-sectional attributes, and crash occurrence on urban and suburban two-lane two-way undivided roadways maintained by cities and counties. In terms of the roadway functional classifications, this objective will include minor arterials, and collector roads that are owned by county and city road agencies. This objective has utilized and developed further on the data originally obtained for NCHRP 17-76 – Guidelines for Setting Speed Limits project and collected from municipal and county jurisdictions within Washtenaw County in Michigan. This objective has resulted in a manuscript that has been presented at the TRB Annual Meeting in January 2022, and accepted for publication in the Transportation Research Record as follows: Chakraborty M, Gates TJ. *Assessing Safety Performance on Urban and Suburban Roadways of Lower Functional Classification: A Comparison of Minor Arterial and Collector Roadway Segments* (*38*).

1.5 Organization of the Dissertation

This dissertation document consists of seven chapters. Having detailed the topics being investigated and outlined the research objectives in this chapter, the remaining chapters are focused on the following topics.

- Chapter 2 presents a detailed review of the state-of-the-art research literature and the summary of previous findings on the impacts of various roadway-related factors considered in this research including driveway/access density, horizontal curve characteristics, traffic volume, posted speed limits, lane width, and additional roadway cross-sectional features such as parking, crosswalk etc.
- Chapter 3 elaborates the methodology carried out for this analysis. This includes the details of data analyzed and the data collection procedure, and the statistical method utilized to carry out the analysis.
- Chapter 4 provides the detailed results of the models developed for the association between driveway land-use and safety performance on rural two-lane two-way undivided state and county highways.

- Chapter 5 provides the detailed results of the models developed for the association between horizontal curve characteristics and safety performance on rural two-lane two-way undivided state and county highways.
- Chapter 6 provides the detailed results of the models developed for the association between roadway characteristics and safety performance on urban and suburban two-lane two-way undivided county and city roadways.
- Conclusions, contributions, limitations, and recommendations for future research are discussed in Chapter 7.

2. LITERATURE REVIEW

Previous studies identified a myriad of factors that may impact roadway safety (*39–46*), particularly motor vehicle crash occurrence (*47–49*). These factors can be classified as roadway characteristics, crash characteristics, vehicle characteristics, occupant attributes, and environmental conditions, among others. The following subsections provide a review of previous research focusing on the factors that were investigated in this research (*34*, *50–56*).

2.1 Driveway/Access Density

Driveway-related crashes on public road segments are most commonly caused by either improper gap selection at the access point or collision with queued vehicles waiting to turn into the driveway (*57*). Though these conflict areas exist irrespective of the driveway density, an increasing driveway density tends to inflate the problem, as the conflict areas of multiple driveways may overlap and interact with each other when the gaps between driveways decreases.

The effects of access density on road safety has been investigated in many past studies (*22*, *26*, *36*, *58–60*), usually showing an increase in crashes with an increase in access density. Gattis (2010) argued that driveway-related crashes on public road segments are most commonly due to either improper gap selection at the access point or collision with queued vehicles waiting to turn into the driveway (*57*). Figure 1 shows the crash modification factors (CMFs) for access density on rural two-lane roads as provided by *HSM* (*26*).

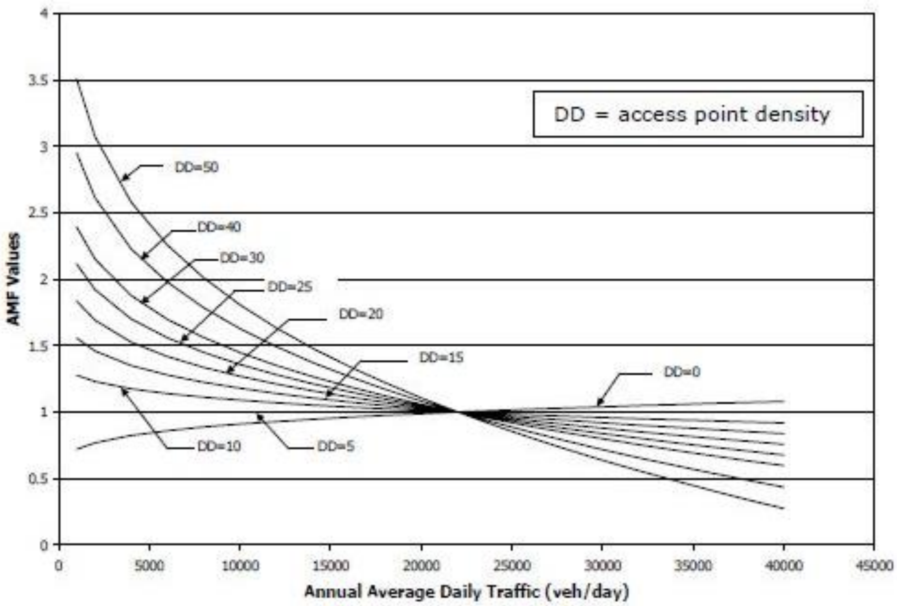


Figure 1: Potential crash effects of access point density on rural two-lane roads.

McLean (1997) concluded that increasing the access density from 10 to 20 per mile led to a 30 percent increase in crashes while increasing access points to 40 per mile was associated with a more than 60 percent increase in crashes (*61*). With a similar objective, Papayannoulis et al. (1999) suggested that increasing the access frequency from 10 to 20 access points per mile would increase crash rates by 40 percent while increasing to 60 access points per mile would triple the crash rate as compared with 10 access points per mile. Each additional access point increases the crash rate by about 4 percent (*23*). Harwood et al. (2000) estimated a crash prediction model for two-lane rural roads (*36*), and driveway density was found to be one of the main factors associated with crash frequency. Another study by Levinson, and Gluck (1997) identified access points as the main source of crashes and congestion on roadways and found that crash rates increase as a result of more access points (*62*).

Gluck et al. (1999) analyzed roadways in eight states including Delaware, Illinois, Michigan, New Jersey, Oregon, Texas, Virginia, and Wisconsin. Findings revealed that the area type was significant since crash rates for rural areas were significantly lower than those for urban/suburban areas. In general, each additional access point per mile increases the crash rate by about 4 percent. Undivided road segments have higher crash rates followed by segments with two-way-left-turn-lane (TWLTL) and non-traversable medians. In urban and suburban areas, overall crash rates for access densities of over 60 points per mile were about 2.2 times that for densities of 20 or fewer access points per mile. Each access point/driveway added would increase the annual crash rate by 0.11 to 0.18 on undivided highways. In rural areas, the increase in access density from less than 15 access points to over 30 access points per mile resulted in a 65 percent increase in the overall crash rate. Access point/driveway added would increase the annual crash rate by 0.07 on undivided highways (*63*).

A comprehensive study by Fitzpatrick et al. (2008) developed CMFs for driveway density using the data from rural two-lane and four-lane highways in Texas. The study recommended that unlike *HSM* and other prior studies on the safety impacts of driveway density, the base condition for driveway density should be assumed to be three driveways per mile as the greatest percentage change occurred between driveway density groups representing zero to three driveways per mile and greater than three driveways per mile, with a 40 percent difference. When the models were developed by including AADT as one continuous variable, for two-lane highways, shoulder width and driveway density were significant. In addition, when AADT is added by grouping them into different ranges, it was found that, for two-lane highways with AADT <400, driveway density was again a significant variable, although right shoulder width was not significant. For AADT between 400 and 2,000, shoulder width was significant; however, driveway density was not. For AADT above 2,000, both driveway density and shoulder width were significant. This finding indicates that driveway density may be a more statistically significant factor than shoulder width for determining the number of crashes along a segment when AADT is <400. The results from categorizing by ADT indicate that there may be an interaction effect between AADT and driveway density on crash frequency (*51*). Figure 2 shows the adjusted AMFs of driveway density for different ranges of AADTs for rural two-lane highways (*51*).

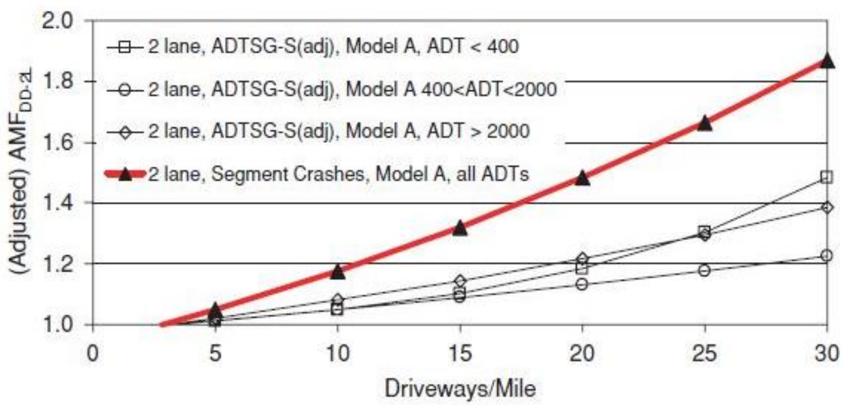


Figure 2: Rural two-lane highway AMFs for driveway density by using AADT groups (adjusted to segment crashes).

An important aspect of urban roads of lower functional classes is the high degree of connectivity to roadside development, which result in greater access densities. This level of development requires careful access management to address the issues of mobility and safety. Based on land-use and parking lot size, the *HSM* has defined seven different types of driveways for use with the urban/suburban arterial SPFs, including major and minor commercial, major and minor industrial-institutional, major and minor residential, and others (*26*). Driveways having more than 50 parking spaces are defined as major driveways, whereas minor driveways are defined as those with less than 50 parking spaces. The crash prediction models in *HSM* require the driveway type and density information as inputs (*26*). However, the understanding of the actual impacts of different types of driveways on the crash frequency in rural areas is not clear and scant in the literature.

A recent study evaluated the safety impact of different access management techniques in urban areas using random coefficient simultaneous equation models. Driveway density was among the significant factors associated with crash rates. The longer the distance between driveways, the fewer the potential crashes were. Additionally, land-use, especially the commercial land type, influences the safety on segments (*60*).

In some other studies, the safety impact of access density has also been found to vary, reflecting differences in road geometry, operating speeds, and driveway and traffic volumes (*51*, *63–65*). A study by Li (1993) found that an increase from 16 to 40 per mile resulted in an estimated 85 percent increase in the crash rates (*66*). Garber and White (1996) found that number of accesses along with average driveway spacing, AADT per lane, average speed influenced the crash rate for urban principal arterials in Virginia (*67*).

Although it is widely understood that driveway entry/exit volumes vary based on the development or land-use type (e.g., commercial driveways typically carry greater traffic than residential driveways), rarely are entering/exiting volume counts taken regularly at driveways. Thus, in lieu of traffic volume data, greater precision would be provided to safety performance models based on driveway development or land-use type. The *HSM* provides guidance for considering driveway density as a CMF for use with safety performance functions (SPFs) for both urban and rural roads (*26*). Specific development and utilization categories are provided for the *HSM* driveway CMFs for urban/suburban roadways, as described before. In general, the CMFs in *HSM* show that industrial and commercial driveways tend to be associated with more strongly crash occurrence for driveway-related crashes than other types of driveways in urban environments, as shown in Figure 3 (*26*). However, only a vague description is provided for rural two-lane roadways, suggesting that “driveways serving all types of land-use” and “all driveways that are used by traffic on at least a daily basis” are to be considered when determining driveway density for use in the CMF.

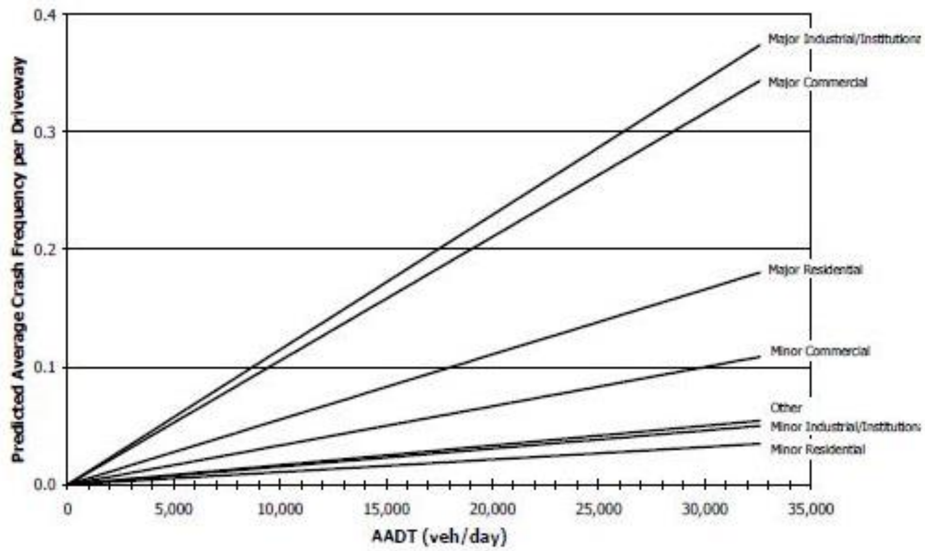


Figure 3: Safety performance functions (SPFs) for multi-vehicle driveway-related crashes on two-lane undivided urban arterials.

Among the limited studies providing insights on the safety impacts of driveway land-use types, Avelar et al. (2013) assessed safety performance of various driveway configurations for both rural and urban highways in Oregon. The proposed models exhibited different ranges of effects for urban and rural conditions, but type of land-use proved a prominent factor for both the urban and the rural models, but it demonstrated different degrees of safety impacts of driveways based on their land-use. Similar to *HSM*, results show that the associations between industrial and commercial driveways with crash frequency are more pronounced than other types of driveways in urban environments. This analysis showed that the land-use of rural driveways seems to influence safety, but it also depends on the spatial distribution of driveways that is captured by driveway clusters. For a fixed number of driveways, more crashes are expected when the driveways are isolated than when the driveways are clustered (*68*).

Dixon et al. (2012) developed SPFs to evaluate the safety impacts of various driveway configurations on rural and urban arterial state highways in Oregon. The proposed models exhibited different effects for urban and rural conditions, but land-use type was found to be a key factor for both the urban and the rural models. Results indicated that while commercial and industrial driveways are positively associated with crashes in the urban environment, industrial driveways have the greatest adverse safety effects among all driveway types in rural environments. Moreover, there were fewer crashes with clustered driveways compared to that with isolated driveways on rural highways (*22*).

A study by Hauer et al. (2004) revealed a significant relationship between non-intersection crashes and traffic volume, number of commercial driveways and speed limit on urban four-lane undivided roads (*69*). Bindra et al. (2009) suggested that it is essential to account for land-use information in prediction models pertaining to driveway density or frequency (*70*). Similarly, Zhu et al. (2010) found driveway type as one of the significant factors that influence single-vehicle fatal crashes (*71*).

Another relevant study developed a method to quantify the impact of different access types and access density on crash types, frequencies, and severities. A cross-sectional comparison was carried out to compare the average crash frequency and crash rates of different driveway types. Statistical analysis revealed a relationship between driveway type and crash rates, where impacts were the highest for commercial driveways with drive-thru service and lowest for the residential driveways (*72*).

Deng et al. (2006) analyzed the association between different factors and crash severity on two-lane highways in Connecticut. Results in this study showed that among all access types, business or office-use driveways were the most significant predictors for crash severity. Contrary to expectation, the retail-use and minor driveways were positively associated with crash severity. When the number of retail-use driveways was less than 5 per segment, crash severity was negatively associated with the number of retail-use driveways. However, when retail-use driveways were greater than 5 per segment, the association between crash severity and number of driveways showed the opposite trend. The frequency of office-use driveways exhibited a negative association with severity of crashes, while a large number of retail-use driveways were associated with high crash severity. These findings suggest that the safety impacts of driveways may fairly vary depending on the land-use context (*73*).

Li (1993) examined the safety impact of access type and density, traffic volume, and road geometry on two-lane rural arterial highways in British Columbia. In this study, accesses were categorized into four groups such as public road intersection, business access, private access, and roadside pullout. The results of this analysis indicated that all access types were significantly associated with crashes. The combined effects of private access and horizontal curvature intensify the impact of accesses on crashes. Hence, relative weighting for each access type in terms of their impact on safety was determined. With public road intersections having the most significant impact on safety, business accesses were weighted as 0.50 of public road intersections, whereas the private accesses were weighted as 0.10 of public road intersections. Additionally, with an increase in the average degree of horizontal curvatures, private accesses and roadside pullouts demonstrated an increased adverse effect on crashes (*66*).

McLean (1997) suggested that each additional private driveway per km in both urban and rural areas results in increased crash rates by about 1.5 percent and 2.5 percent for two-lane and four-lane roads respectively. These translate to an increase of crash rates by 2.4 percent and 4.0 percent per private driveway per mile. In urban areas, each commercial driveway had effects on crash rates approximately 5 times greater than that of a private driveway (*61*).

Williamson et al. (2015) determined that with an increase of driveway density one unit, the crash frequency increased by 0.119 units for rural two-lane two-way highways. For both two-lane and four-lane undivided urban and suburban arterials, major industrial driveways were the most sensitive driveway land-use type with a 0.120 reduction in crash frequency per unit decrease. For urban and suburban four-lane divided arterials, major industrial driveways proved to be the most sensitive with a 0.046 reduction in the crash frequency per unit decrease (*74*).

2.2 Horizontal Curvature

Horizontal curves are a necessary part of the highway system, and are among the most critical geometric design elements related to the influence of driver behavior and crash risk, and statistics have consistently shown that curves pose significant safety concerns (*75*). Several previous studies have examined the relationship between safety and horizontal curvature (*36*, *76*, *77*). In general, these studies have consistently shown negative associations between curve radii and predicted crash frequency.

Zegeer et al. (1992) estimated the safety performance of horizontal curves along two-lane highways. The findings suggested that crash rates on horizontal curves were 1.5 to 4 times more than those on tangent sections. Also, 500 feet and 1,000 feet radii curves were more likely to experience crashes than equivalent tangent sections by 200 percent and 50 percent respectively

(*77*). Hauer (1999) investigated the correlation of safety with the characteristics of horizontal curves, such as degree of curve, superelevation, lane width, density of curves upstream, length of connecting tangent sections, and sight distance. One observation made by this study was that the change in crash frequency is proportional to the change in radius length, and all else being equal, greater the horizontal curve radii, fewer the crashes (*78*). Harwood et al. (2000) determined that when both length and radius of the horizontal curves were 100 feet, the crash rate was more than 28 times as high as on tangent sections on two-lane rural roadways (*36*). Elvik (2013) in a study on horizontal curve safety from North America, Europe, and Australia revealed a consistent inverse relationship between the radius of curve and safety. Mostly in these studies, the crash rate on curves increased rapidly as the curve radius decreased below 656 feet (~200 m) (*50*).

A recent study of rural two-lane state highways in Pennsylvania found that the locations with a curve radius for 55 mph design speed (radius < 1,008 feet) with superelevation of 7 percent have 43 percent and 48 percent higher total and injury crashes, respectively, compared to the tangent sections (*79*). Bonneson and Pratt (2009) showed that the crash frequency increased significantly, especially when the radius was less than 2,000 feet. Also, the curve radius was associated with a larger increase in crashes if vehicle speeds were higher (*80*). Saleem and Persaud (2017) estimated CMFs for rural two-lane highways for flattening a horizontal curve from the minimum radius by factors of 1.10, 1.25, 1.50, and 2.00. Their results indicated the greater the curve-flattening factor, the higher the reduction in crashes (*81*).

Recently, Hamilton et al. (2019) explored the relationship between horizontal curves and the roadway departure crash frequency along rural two-lane roads in Indiana and Pennsylvania. The data analyzed in this study was obtained from the SHRP 2 Roadway Information Database. Results indicate that the curve's radius, the radii on the upstream and downstream curves, and the ratio of the length of upstream and downstream tangents relative to a curve radius significantly impacted the crash frequency. Interestingly, flatter and longer upstream and downstream radii resulted in a higher number of roadway departure crashes on the subject curve and vice versa (*82*).

Fitzpatrick et al. (2010) developed CMFs for horizontal curves on rural four-lane highways and compared with the tangent sections. Crash data from 1997 to 2001 were analyzed with negative binomial models for approximately 121 miles (194.8 km) of roadways. Results show that the effect of driveway density was different for horizontal curves and tangents; although the differences were relatively minor. When both driveway and segment crashes were considered, factors including driveway density, and degree of curvature were statistically significant (*76*).

Results of another study from Pennsylvania indicated that both the presence of a horizontal curve and its degree of curvature must be considered when predicting the crash frequency on horizontal curves and both were positively associated with crashes. Also, the degree of curvature of adjacent curves in close proximity (within 0.75 mile/1.21 km) was statistically significant and negatively correlated with crash frequency (*83*). They further determined that overall, the safety performance on horizontal curves differed significantly from that on tangent sections with respect to traffic volumes, segment length and other roadway features (*84*).

While most evaluations of curvature have focused on rural roadways, urban residential collector road segments have been found to possess a significant positive relationship between the presence of a horizontal curve and crash occurrence (*85*). A study by Hauer et al. (2004) shows the effects of degree of horizontal curvature was the strongest for the injury crashes followed by total, and property damage only (PDO) crashes on urban four-lane roadways (Figure 4) (*69*).

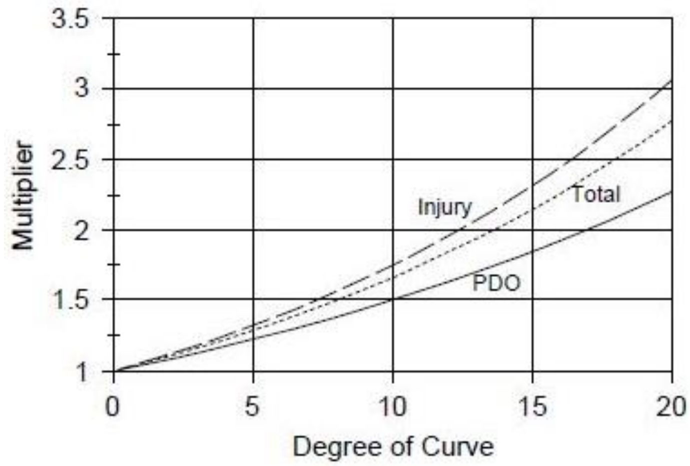


Figure 4: Relationship between the degree of curve and crash multiplier.

Crash prediction models for total, and fatal and injury crashes on horizontal curves along Wisconsin state highways were developed by Khan et al. (2013). Analysis results identified that there was a significant increase in the average number of crashes on horizontal curves with radius less than 2,500 feet and AADT greater than approximately 1,300 vehicles per day (*86*).

Lord et al. (2011) determined that the crash frequency increased with increases in curve densities as well as degree of curvatures. Also, crash rates on rural highways were influenced by both presence and sharpness of horizontal curves, and that curve-related crashes were more frequent on higher-speed roadways. Moreover, there was a positive association between speed limit and curve density, such that the expected increase in crash rate due to curve density was more pronounced on roadways with higher speed limits (*87*).

Donnell et al. (2014) identified horizontal curve density as one of the factors that significantly affect crash frequency on rural two-lane road segments (*88*). In a subsequent study, Donnell et al. (2016) used both horizontal curve density and total degree of curvature per mile in their SPFs with the tangent sections as the baseline condition. The results indicated that 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. However, the superelevation or any other indicator of whether the characteristics of the curves are appropriate for the operational speed of the roadway, was not considered in this study (*89*).

Using the data from rural interstate highways, Strathman et al. (2001) found that on urban roads, the maximum horizontal curve angle, and maximum curve length, did not have a significant effect on crash rates. However, number of horizontal curvature had a positive and statically significant association with crash rates (*90*). Shankar et al. (1995) estimated a series of negative binomial regression models with the data from Washington State and found that when the horizontal curves are spaced further apart (i.e., fewer curves per mile) more severe overturn crashes increase. This same study also found that highway segments that have curves with lower design speeds result in fewer crashes relative to those with higher design speeds; though the presence of snowfall tended to increase crashes on those segments with curves of lower design speeds. However, crashes attributable to curves of lower design speeds tended to be less severe than those associated with curves of higher design speeds (*52*).

Gabauer and Li (2015) found that isolated curves, decreases in curve radius, and increases in curve length would increase the risk of motorcycle-to-barrier crashes (*91*). Another study assesses the effectiveness of several different countermeasures on urban collectors and arterials with speed limits less than 45 mph and found that the highest decrease in the crash rate occurred after the improvement in the horizontal and vertical alignments followed by the increase in lane width (*92*). Recent studies also showed that densities of curves corresponding to design speed lower than the speed limit were associated with increased crash likelihood (*34*, *35*).

2.3 Posted Speed Limit

Literature identified speed limit to be an important predictor in traffic safety (*43*, *93*). An early study that analyzed crashes from 21 countries for both rural and urban regions showed that particularly urban speed limits have a considerable effect on safety (*94*). Several other early studies estimated the impacts of increased speed limits on safety when the National Maximum Speed Law (NMSL) was relaxed in 1987 allowing for maximum speed limits of 65 mph, or repealed in 1995 when states were granted autonomy to set their speed limits, resulting states to raise interstate speed limits.

Baum et al. (1989, 1990) found 15 and 26 percent increases in fatalities in the first (*95*) and second year (*96*), respectively, on the rural interstates in states with 65 mph speed limit compared to the states with speed limit of 55 mph. Farmer et al. (1997) compared changes in fatalities on freeways for 12 states that raised speed limits with those in 18 states that did not raise limits or that did so on fewer than 10 percent of urban interstate mileage. Results show that interstate fatalities increased by 12 percent in the states where speed limits were raised (*97*).

Another earlier study assessed the effects of speed limit increase from 55 mph to 65 mph on rural interstates in Arizona in 1987. Results of this study show that the number of crashes increased for total, and fatal, and injury crashes in the after period on rural interstates where speed limit increased. However, crash count did not vary significantly on urban interstates, where the speed limits remained the same (*98*). Using a time series model, Garber and Graham (1990) estimated an increase of 15 percent in fatalities on rural interstate highways and an increase of 5 percent on non-interstate roads where speed limits were raised. Findings of this study showed increased fatalities in some states, reduced fatalities in others, and no discernible change in the rest of the states (*99*).

The effect of different factors including speed limit change on number of fatalities for forty-seven states was assessed by Zlatoper (1991). Results of linear regression model found that among other factors, speed limit was significantly related to fatality rates (*100*). Parker (1997) examined the effects of both raising and lowering posted speed limits on driver behavior for urban and rural non-limited access highways from a total of twenty-two states. The study was conducted during the period from 1985 to 1992, when the maximum speed limit was 55 mph on non-limited access highways. Although driver violations of the speed limits increased when posted speed limits were lowered, the author argued that there was not sufficient evidence to reject the hypothesis that crash experience changed when posted speed limits were either lowered or raised. In fact, where the speed limits were raised, both the total and injury crashes increased significantly (*101*).

McKnight and Klein (1990) found a 27 percent increase in fatal crashes on 65 mph highways, but also reported a 10 percent increase in fatal crashes on 55 mph highways in states that did not raise the speed limit (*102*). Ossiander and Cummings (2002) study assessed the impact of the increased speed limits from 55 to 65 mph in 1987 on rural freeways in Washington State on safety using the crash data from 1974 through 1994. Results of this study indicated that the incidence of fatal crashes more than doubled after 1987, compared with what would have been expected if there had been no speed limit increase. The total crash rate did not change substantially, although an increase of 10 percent was reported (*103*).

In another study for urban state-owned road segments, models were calibrated with speed limits ranging from 25 mph to 70 mph. Findings indicate that the likelihood of a fatal crash increases from 0.7 percent at 25 mph to 3.7 percent at 70 mph. Fewer crashes were observed at locations where two or more schools were located nearby, despite the speed limit (*104*).

Friedman et al. (2007) evaluated the effect of raised speed limit from 90 kilometer per hour (kph) to 100 kph on safety using ARIMA time series with data from 1988 to 1999. Results showed that, due to the increase in speed limit, the largest increase in fatality occurred on interurban roads but a spillover effect was observed on urban roads as well. Overall, the raise in speed limit resulted in an additional 4.7 more fatalities per month (*105*).

A longitudinal study by Davis et al. (2015) analyzed the relationship between speeds and safety associated with the speed limits and fatal crashes on rural interstate with data from 1999 through 2011, using random parameter negative binomial models. The results reveal that the increase in speed limits increased traffic fatalities, but, states with 60 or 65 mph and higher than 70 mph speed limits had less increase in fatal crashes than that with 70 mph (*106*). A few other studies that focused on safety impacts of speed limits and average speed on non-interstate roadways confirmed that the increase in crashes is more pronounced in urban areas, where the traffic congestion is much higher (*107*).

In contrast to the extensive analysis of the safety impacts of speed limit increase, relatively fewer studies have examined the effects of lowering speed limits, especially on urban roadways in the U.S. Taylor et al. (2000) reported that reducing the speed of the fastest drivers brings greater safety benefits than reducing the overall average speed of all drivers, especially on urban roads (*108*). A recent study in Belgium valuated the impacts of reduction in speed limit from 90 to 70 kph on a number of highways in Flanders, occurred during 2001-2002. The study determined approximately a 5 percent decrease in the total crash rates after the speed limit restriction. Moreover, the lowering of speed limit resulted a decrease by a greater margin, approximately 33 percent, in case of fatal and severe injury crashes, and occurred at 67 percent of the locations. When compared the safety effectiveness of the reduced speed limit, decrease in crashes were by a larger magnitude along the road segments (70 percent reduction) compared to intersections (43 percent reduction). Overall, the speed limit restrictions indicated to have a favorable effect on traffic safety, especially on severe crashes (*109*). Similar reduction is speed limit, from 90 to 70 kph on major arterial roads in Oslo, Norway was studies by Elvik (2013) in a before-and-after study with a comparison group. The study showed an 11 percent decrease in interurban injury crashes and a 36 percent decrease in severe injury crashes (*110*).

A more recent study analyzed the long-term traffic safety effect of both increased, as well as reduced speed limits. The results of this study demonstrated that the number of fatalities decreased by 14 per year on rural roads where the speed limit reduced from 90 kph to 80 kph. However, this reduction in speed limit showed no significant changes in case of serious injuries. This estimate is similar to the cases where speed limit decreased from 110 kph to 100 kph, resulting in a reduction for the seriously injured by approximately 16 annually. On the other hand, on roadways where the speed limit increased from 110 kph to 120 kph, the number of seriously injured increased by about 15 per year, whereas the number of deaths did not experience any significant change. Also, the greater increase in the number of seriously injured were on narrower roadways (*111*). Similar conclusions were drawn by a some other studies pertaining the safety effectiveness of lowering speed limits (*112–114*).

Some studies, however, presented confounding effects of speed limits on safety, and in certain cases, higher speed limits may actually save lives. This is supported by the arguments that the 85th percentile of vehicle speeds is a good speed at which to set the speed limit, that speed variance is more important than speed limits in determining crash rates, and that speed variance may decrease if speed limits are raised to the 85th percentile (*115*, *116*). This also implies that if raising the speed limit causes speed variance to decrease, then the higher speed limit may actually reduce the number of crashes and fatalities (*117*).

Lave and Elias (1994) argued that previous research has ignored system-wide effects of speed limit changes by measuring only localized effects and found that states that increased rural interstate speeds achieved an overall 3.62 percent reduction in fatalities compared with states that did not (*118*). A study on the safety of urban and suburban arterials in Minnesota considered three speed categories based on speed limit: low (30 mph or less); intermediate (35 to 45 mph); and high (50 mph or more). There was a statistically significant relationship between these speed limit categories and safety, but in almost all cases, higher crashes were observed on arterials with lower speed limits. Researchers hypothesized that driveways on segments might create turbulence in traffic flow to affect non-driveway crashes (*119*).

Hauer et al. (2004) that predicted the non-intersection crash frequency on urban four-lane undivided roads in Washington State and reported that the fit depends mostly on AADT, the number of commercial driveways, and speed limit. The posted speed limit variable was proved to have a complex and noisy relationship with off-the-road crashes. All other factors remaining the same, four-lane undivided roads with speed limits up to 30 mph and 45 mph or more experience more crashes than that with 35 mph and 40 mph speed limits (*69*).

A unique example of the effect of speed limits on driver behavior and fatal crash rates can be seen in Montana when speed limits were instituted in a previously "no daytime speed limits" environment. When speed limits were re-introduced, Montana roads were "never safer", a situation coined as the "Montana Paradox"—the desired safety effect from posting speed limits was achieved by removing them (*120*). Najjar et al. (2000) evaluated speed limit increases from 55 mph to 65 mph on most urban interstates and two-lane rural highways, and 55 mph to 70 mph on most rural multilane highways in Kansas found no statistically significant increase in fatal crashes on rural and urban interstates (*121*).

Garber and Gadiraju (1988) reported that crash rates increased with increasing variance on all types of roadways and that speeds were higher on roads with higher design speeds, irrespective of posted speed limits (*122*). While analysis of traffic and crash data from urban arterials in North Carolina with speed limits not exceeding 45 mph showed a negative correlation of crashes with posted speed limits and operating speeds (*123*), posted speed limit variable was not found to be not significant in influencing midblock crashes on urban arterials in Florida (*124*). Similarly, Kopelias et al. (2007) determined that speed limit on toll highways in metropolitan Athens, Greece had negative correlation with crashes implying sections with lower speed limits have more severe crashes (*125*).

2.4 Roadway Cross-Sectional Features

The results of past studies to determine the traffic safety effects of lane width are varied. Concerns have been raised that the use of narrower lanes could increase crash frequencies, but there are no definitive studies that address the relationship between lane width and safety for urban and suburban arterials. If narrower lanes can be used on urban and suburban arterials without affecting safety negatively, there may be many other benefits to highway agencies and highway users. The use of narrower lanes may have advantages in some situations on arterials by reducing pedestrian crossing distances or providing space for additional through lanes, auxiliary lanes, bicycle lanes, buffer areas between travel lanes and sidewalks etc.

Narrow travel lanes on rural two-lane highways have been associated with increases in single-vehicle run-off-the-road, head-on, and sideswipe type crashes (*26*, *126*), and the effect is most pronounced at lane widths of nine feet or less as shown in Figure 5.

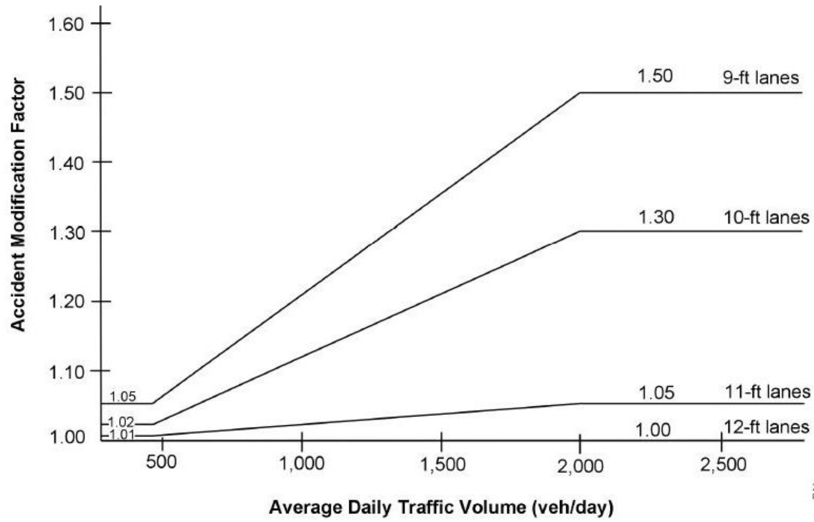


Figure 5: Lane width AMF for two-lane highways.

However, a recent study in rural Pennsylvania found a lower occurrence of total crashes and fatal and injury crashes on segments with narrower lanes (*83*). Yet another study found that narrower lane widths were associated with reductions in same-direction crashes, and fatal and incapacitating injury crashes, but an increase in single-vehicle crashes as well as total crashes, non-incapacitating injury, and non-injury crashes (*79*). Vogt and Bared (1998) determined that increasing lane widths and reducing horizontal curvature decreases total crashes (*37*).

Hauer et al. (2007) authors concluded that for off-road crashes, if crash frequency is influenced by lane width, it is not discernable. For on-road crashes, lane width was found to be associated with PDO crashes but not injury crashes. For the PDO model, wider lanes were associated with higher crash frequencies (*127*). Hadi et al. (1995) indicated that increasing lane widths up to 12 ft (3.6 m) and 13 ft (4.0 m) would be expected to decrease crash rates for urban two-lane and four-lane undivided roadways, respectively (*128*). Noland and Oh (2004) analyzed the data from the Highway Safety Information System (HSIS) for the State of Illinois with fixed-effect negative binomial models for total crashes and total fatalities. Increases in the number of lanes and lane widths appear to increase traffic-related fatalities but did not have any statistically significant effect on total crashes (*129*). An earlier study on four-lane undivided urban arterial segments with curb-and-gutter, no on-street parking, and speed limits not exceeding 72 kph (45 mph) showed that as traffic lane width decreased, speeds decreased, and crashes increased (*123*).

A study by Milton and Mannering (1998) on principal arterials concluded that narrower "substandard" lane widths (less than 11.5 ft/3.5 meters) reduce crash frequency (*130*). Potts et al. (2007) did not find a general indication that the use of lanes narrower than 3.6 m (12 ft) on urban and suburban arterials increases crash frequencies. This finding suggests that geometric design policies should provide substantial flexibility for use of lane widths narrower than 3.6 m (12 ft) (*127*). Collectively, the prior literature suggests that the relationship between crash occurrence and lane width is difficult to estimate, and likely does not follow a monotonic relationship.

Turning to other roadway cross-sectional features, a study by Fitzpatrick (2003) suggested that several factors other than posted speed limit influence safety and operating speed on tangent roadway sections, including access density, median type, and parking along the streets, among others (*131*). Hauer et al. (2004) determined that on-street parking results in slightly fewer crashes compared to roadways where parking is prohibited (*69*). Conversely, Greibe (2003) found roads with on-street parking have greater crash risk, particularly for crashes involving pedestrians and parked vehicles, and involving motor vehicles from minor roads (*132*). Zegeer et al. (2001) suggested that on two-lane roads and lower volume multilane roads, crosswalks alone, without other traffic calming treatments, are not recommended to be installed at uncontrolled locations or locations that may pose unusual safety risks to pedestrians (*133*). A study in Canada used generalized linear models to analyze the safety performance on urban arterial roadways in the Greater Vancouver Regional District, British Columbia, Canada. The results showed that variables having significant effect on crash occurrence included section length, traffic volume, unsignalized intersection density, driveway density, pedestrian crosswalk density, and type of land-use, among others (*134*).

Additionally, a few studies indicate pavement surface to influence crash occurrence as well (*135*). Rural unpaved roads include a wide variety of design standards, design speeds, and surface characteristics, which can be greatly affected by the effects of weather and heavy traffic loads. The safety of these roads may also be affected by a lack of pavement markings and insufficient signage, narrow road widths, and the absence of shoulders. Differing design standards between primary and local roadways make it difficult to compare safety performance between paved and unpaved roadways without constraining such analyses to roadways with lower traffic volumes and lower functional classes. Nevertheless, research has found that at the lowest of volumes (e.g., less than 250 vehicles per day), little to no difference in crash occurrence between paved and unpaved roads is seen. However, at higher volumes, paved roads were found to have lower crash occurrence than unpaved roads (*135*).

2.5 Review Summary

To summarize the literature findings, while driveway density has been explored with respect to their impacts on highway safety, little is known about the safety performance across various classifications of driveway land-use, especially for rural county roads. For states with a highly rural road network, including Michigan, it is imperative to understand how the development type of driveways impacts highway safety across roadway jurisdictions and functional classifications.

Also, several previous studies analyzed the association between crash occurrence and certain horizontal curve characteristics including curve radius, and length of curve, and number of curves at an aggregated level. However, little is known about several other important alignment-related factors, particularly on rural highways. For states with a highly rural road network, including Michigan, understanding the underlying influence of these factors on safety becomes even more crucial.

Posted speed limit is another factor which is consistently associated with increase in crash frequency, although there have been some contradicting findings by a few studies. In terms of lane width, and other roadway cross-sectional elements including on-street parking, and midblock crosswalk, among others, confounding results were found in the literature.

Lastly, considerable research has been conducted to understand the safety performance of rural and urban higher functional roadways including principal arterials, in general, but little research has explored minor arterial or collector road segments with lower speed limits, particularly for urban roadways. Also, roadways that are owned by non-state agencies are often designed and maintained to lower standards and include different driver populations and trip characteristics compared to freeways and interstates, but have received limited attention in previous research.

2.6 Safety Performance Functions (SPFs)

Transportation and safety researchers have adopted various methodological approaches to model crash frequency. A seminal study by Lord and Mannering (2010) (*136*) provide detailed review of different methodological approaches for crash frequency analysis. Following sub-sections present a detailed literature review on crash frequency analysis.

The analysis of crash frequency has evolved over decades and the modeling techniques have been improvised since years. As explained in the predictive methods in Part C consisting of Chapters 10, 11, and 12 of the *HSM*, the crash prediction models, also known as safety performance functions (SPFs), can be used to estimate the total number of crashes expected on rural two-way two-lane, rural multilane, and urban and suburban arterials, respectively, during a given period under base conditions (*26*). However, *HSM* does not include a safety prediction methodology for urban and suburban arterials with six or more lanes and one-way segments.

The SPFs as described in *HSM* are the building blocks for more advanced analytical tools, such as the empirical Bayes (EB) method. They were developed based upon the results of empirical studies (*36*, *54*, *119*, *137–139*). The main purpose of an SPF is to estimate the expected frequency of crashes given various traffic and site characteristics, such as traffic volume, segment length, and lane width. Transportation agencies and practitioners typically apply SPFs in their processes to select safety projects for funding.

2.6.1 Studies on the Development of SPFs

A number of states have conducted research that has shown the accuracy of the SPFs from the *HSM* to vary considerably from state to state as a result of differences in geography, design practices, driver behavior, differences in crash reporting requirements, among other factors (*140–*

143) and that the direct application of the SPFs from the *HSM* or other non-local sources may not provide accurate results without any calibration using local data (*36*, *137*, *140*, *144*).

Brimley et al. (2012) calibrated *HSM* SPFs for rural two-lane two-way roadway segments in Utah using negative binomial regression. The significant variables included traffic volume (AADT), segment length, speed limit, and the percentage of AADT made up of multiple-unit trucks. The new specific models show that the relationships between crashes and roadway characteristics in Utah may be different from those presented in the *HSM*. The calibration factor of the SPF for rural two-lane two-way roads in Utah was found to be 1.16. This indicates that more crashes occur on rural two-lane two-way roads in Utah than those predicted by *HSM* models where the calibration factor is 1.10 (*143*). The SPFs in Part C of the *HSM* were calibrated using data from North Carolina by Srinivasan and Carter (2011) (*140*).

An alternative approach to calibrate prediction models on segments for a rural secondary road network in Italy by Martinelli et al. (2000) developed the predictive models by using the full model with variables such as AADT, segment length, lane width, shoulder width, horizontal curvature, and driveway density, among others. The method calibrated all variables except for AADT and segment length to obtain the SPF. This study argued 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 (*145*). For rural two-lane highways, Najjar and Mandavilli (2009) identified that eight different explanatory variables influenced crashes including AADT, section length, functional class, segment width, shoulder width, shoulder type, average speed limit, and average percent of heavy vehicles (*146*).

Lord et al. (2016) developed methodologies suitable for inclusion in the *HSM* (*26*). To accomplish this objective, SPFs with negative binomial regression were estimated using data from California, Illinois, Michigan, Oregon, and Texas for crashes on two-way urban and suburban arterials with six or more lanes, one-way urban and suburban arterials, and intersections located on these facilities (*147*). Recently, another study on the impact of driveways on rural two-lane and four-lane highway crashes, suggested 3 driveways per mile as the assumed base condition instead of 5 driveways per mile. Negative binomial regression models were used to determine the effects of multiple factors including driveway density ranging between 0 to 30 driveways per mile on crashes (*148*).

Dixon et al. (2012) developed SPFs to evaluate the safety impacts of various driveway configurations on rural and urban arterial state highways in Oregon. The proposed models exhibited different effects for urban and rural conditions, but land-use type was proved to be a key factor for both the urban and the rural models. Results indicated that roadside safety is influenced primarily by commercial and industrial driveways in the urban environment, but the same is true for industrial driveways in rural environments. In addition, the rural model found to have fewer crashes with clustered driveways compared to isolated driveways (*22*).

Collectively, from these studies, the variables most commonly used in crash prediction model development included traffic volume, segment length, speed limit, driveway/access density or count, horizontal curve radius, lane and shoulder widths, and surface type, among other factors. Generally, AADT and segment length were found to have the greatest predictive powers similar to that explained in *HSM*.

In the crash frequency analysis, negative binomial regression models have been widely used (*36*, *149–152*) and accepted as the current practice for modeling crashes, as such models account for overdispersion, which is common with crash data. Shively et al. (2010) implemented a semi-parametric Poisson-gamma model to estimate the relationships between crash counts and various roadway characteristics, including curvature, traffic levels, speed limit and surface width. A Bayesian nonparametric estimation procedure was employed for the model's link function. Results suggest that the key factors explaining crash rate variability across roadways included the amount and density of traffic, the presence and degree of a horizontal curve, and road classifications (*153*).

Recent research advocates the use of count models with random parameters as an alternative method for analyzing crash frequencies to address unobserved heterogeneity in the observations, as ignoring the same might produce biased and inefficient estimated parameters, leading to erroneous inferences and predictions (*136*, *154–159*). Especially, for the data where one entity has multiple observations, such as panel data, group-specific random parameters models may be adopted to account for heterogeneity among groups (*160*, *161*). Garber et al. (2010) developed SPFs for two-lane roads in Virginia and AADT was identified as the most significant causal factor for crashes. Separate SPFs were developed for urban and rural roads as well as total, and fatal and injury crashes utilizing generalized linear modeling with negative binomial regression (*142*). Shankar et al. (2016) documents a comprehensive set of safety performance functions developed using random parameter negative binomial models for the entire urban-suburban arterial road segment system on the state highway system in Washington. Several variables including roadway and shoulder widths, horizontal curve radius and maximum super elevation, and functional class, among others, were treated as random parameters (*162*).

A recent study analyzed crashes on urban segments using multivariate random parameters zero-inflated negative binomial model to account for unobserved heterogeneity produced by correlations across segments, correlations across crash types, excessive zero crashes, and over dispersion. The results indicated that the multivariate random parameters zero-inflated negative binomial model was superior to other common crash frequency models in terms of both goodness of fit and prediction accuracy. (*163*). El-Basyouny and Sayed (2009) assessed factors influencing crash frequencies on urban arterials in Vancouver, British Columbia. The study identified several covariates to significantly impact crashes, however, they resulted in random parameters and thereby their effects on crash frequency were found to vary significantly across corridors. Ultimately, a Poisson-lognormal model with random parameters for each corridor provided the best fit (*164*).

3. METHODOLOGY

Relevant details pertaining to the collection and compilation process of the data as well as the analytical method utilized in this research are provided in the sections that follow.

3.1 Data Collection – Rural Roadway Analysis

To accomplish the objectives of this research as stated earlier in this document, it was first necessary to collect and integrate data on roadway characteristics, and traffic crashes. For the first two objectives, i.e., analysis of driveway land-use type and horizontal curve characteristics, the data were obtained from selected rural roadway segments and corresponding horizontal curves across all regions of Michigan. To provide adequate representation across all rural roadway jurisdictions and functional classes, data were collected for state and county road segments and curves, including both paved and unpaved. The analysis period was for eight years from 2011 through 2018; and the roadway segment, horizontal curve, and crash data were obtained from a variety of sources for this analysis period. The geospatial analysis was performed in the Environmental Systems Research Institute's (ESRI) ArcGIS platform. Existing shapefiles were utilized, where available, while a significant effort was employed to collect additional data manually.

As part of the safety performance analysis of driveway land-use type and horizontal curve characteristics, the data were obtained and analyzed for the following facilities.

1. Rural state-owned two-lane two-way roadway segments,
2. Rural county-owned two-lane two-way paved roadway segments,
3. Rural county-owned unpaved/gravel roadway segments,

4. Horizontal curves on rural two-lane state highway segments,
5. Horizontal curves on rural two-lane two-way county highway segments, both paved and unpaved.

Figure 6 displays the two-lane two-way road segments (facilities# 1, 2, and 3 as stated above) included in this study.

MDOT 2-lane undivided segments

County 2-lane paved segments

County 2-lane gravel segments

Figure 6: Rural highway segment jurisdictions considered for SPF development.

Similarly, Figure 7 displays the two-lane two-way curve segments (facilities# 4, and 5 as stated above) included in this study.

MDOT 2-lane horizontal curve County 2-lane horizontal curve

Figure 7: Rural horizontal curve jurisdictions considered for SPF development.

3.1.1 Rural Roadway Segments Data

The data for state highways were primarily collected from the Michigan Department of Transportation's (MDOT) sufficiency file, a database that maintains an annual roadway inventory for the state-owned roads in Michigan. The annual MDOT sufficiency files for the period of 2011 to 2018 were utilized to populate the geometric and cross-sectional characteristics of the segments utilized in this study.

For county roads, initially roadway data for all public two-lane roadways in Michigan was collected via the Michigan Geographic Framework "All Roads" (MGF-AR) from the Michigan Center for Geographic Information (MCGI) open data portal (*165*). The MGF "All Roads" file consists of all public road segments along with the census boundaries and other spatial characteristics across the state. This dataset provided information on the physical road (PR) reference number, the begin milepoints (BMP), end milepoints (EMP), and jurisdictional ownership of each road segment, among others. Typically, segments' BMPs and EMPs are determined based on a change in various factors including annual average daily traffic (AADT), surface type, and jurisdictional boundary, thereby splitting roadways into unique homogeneous segments.

For county roads, all non-state highway rural segments were identified out of the "All Roads" shapefile. The selection criteria for this pool excluded all state highways 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 (possessing a minimum population of 5,000), had a left-right rural designation, and were categorized as principal arterial, minor arterial, and general non-certified segments. The PRs, BMPs, and EMPs are used in identifying and locating events including crashes, AADT, and roadway characteristics along Michigan's transportation network. The U.S. Census boundaries were used to isolate rural segments located beyond the urban boundaries. Additionally, for the county roads, segments within any incorporated census area boundary were excluded to isolate county highways with speed limits of 55 mph, which was the statutory speed limit on rural non-freeway roadways before the speed limit increase in 2017. After that, the speed limit on several study segments became 65 mph. A minimum segment length of 0.1 miles was selected for this analysis as recommended by *HSM* (*26*).

3.1.2 Horizontal Curvature Data

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 radius and length of all horizontal curves with radii up to 0.75 miles (3,960 feet) were extracted from the MGF-AR shapefile.

For the segment level analysis, the curve data were aggregated for each segment for the count of curves on each segment, length of the curved portion of the segment, the proportion of the segment on a curve, and the average radius of curves on the segment, organized in cumulative categories, decreasing in order of radii, from 0.5 mile (2,640 feet) radii to 0.088 mile (465 feet) radii.

Ultimately, all curves were represented as a binary variable where the curves with radii corresponding to design speeds lower than the speed limits along the road segments, i.e., a maximum of 55 mph (0.191 mi/1,008 ft) (assuming a superelevation of 7 percent, the maximum superelevation used by MDOT) were treated as a curved segment and curves with radii corresponding to design speeds more than 55 mph were treated as a tangent section (*166*). It is important to note that the statutory speed limit for rural highways in Michigan until 2017 was 55 mph and curves designed below this speed would typically possess curve warning signage as per the Manual on Uniform Traffic Control Devices (MUTCD) (*167*). The maximum speed limit increased for non-freeway segments in Michigan to 65 mph in 2017 for approximately 938 miles of segments, but the speed limit for the remaining 12,483 miles of rural highway segments were unaltered at 55 mph. While it was not possible to verify the presence of a curve warning sign at each location, 55 mph was a reasonable upper threshold as curves with design speeds falling below the statutory speed limit were deemed underdesigned or substandard as per the MUTCD.

For curve level analysis to evaluate the horizontal curve characteristics, the curve data were then merged with the roadway data for the respective segment. A significant manual effort was carried out to collect additional data. First the dataset comprising all horizontal curves with radii up to 0.75 miles (3,960 feet) were extracted from the MGF-AR shapefile. Thus, this extracted dataset included information including curve radius, and curve length of the horizontal curve segments owned by both state- and non-state agencies from across the state. Thereafter, the curve PRs, BMPs, and EMPs were matched with the previously identified PR and milepoint values of the segments of interest to identify the study curves on both state and county highways. The curved segments that fall within the previously identified study segments for both state and county highways were finally chosen for the subsequent analysis.

Next, each curve was spatially analyzed on ArcGIS to obtain additional curve related data. This includes curve type (i.e., simple, compound, or reverse as shown in Figure 8), the curve-approaching, curve-following, and inner-curve tangent distances, direction of a curve (left or right), and cardinal direction of curve (e.g., N, S, E, W, NE, NW, SE, and SW).

To obtain other cross-sectional and traffic characteristics, segment-specific traffic volume, lane width, surface width, and surface type were merged with the study curves based on the curve PRs and milepoint values. Finally, each curved segment was split into two observations to account for the effect of roadway characteristics preceding a curve with respect to specific lane direction.

Simple horizontal curve

Compound horizontal curve

Reverse horizontal curve

Figure 8: Rural horizontal curve types considered for SPF development.

3.1.3 Driveway Data

The classification of driveway types may largely vary across transportation agencies. For the state-owned roads, MDOT maintains a 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 state highway system. These driveway counts were joined to the appropriate segments based on the driveway coordinates and BMPs and EMPs of each segment.

A similar driveway count strategy was replicated for the county highway segments while manually collecting this information from Google Earth aerial view. For the county road segments, driveways were classified as residential or commercial/industrial. Figure 9 displays the examples of the different driveway types along the county road segments that were manually reviewed on Google Earth.

To account for the overabundance and relatively low utilization of field access points, driveways were only counted if connected to a structure. For purposes of this study, these structures have building footprint the size of a house or larger, and may include barns, electrical stations, or utility structures, in addition to homes, businesses, and industrial buildings. The driveway density was calculated for each land-use type category on each segment by dividing the number of driveways by the segment length.

Residential driveways on county roads

Commercial/Industrial driveways on county roads

Field Driveways on County Roads

Figure 9: Examples of driveway land-use types on county roads.

3.1.4 Traffic Volumes

Traffic volume estimates for rural highways were obtained from the three primary sources, described as follows. AADTs for the state highways were obtained directly from the MDOT sufficiency file for each respective year from 2011 to 2018. AADTs for the county federal-aid roadways were collected from the GIS shapefile for non-state-owned federal aid (NTFA) roadways, titled "NTFA_Segment.shp" GIS shapefile maintained by MDOT for 2014 or 2015 across all counties statewide.

Traffic volume estimates for the county non-federal aid roadways were obtained directly from the county road commissions or the corresponding regional planning commission, where available. Because the AADTs for non-federal aid county roadways were obtained directly from the county or regional planning entity, the years for which traffic volumes were available varied from county to county. Annual traffic growth factors were obtained from MDOT's Highway Performance Monitoring System (HPMS) database and applied to the traffic volumes to adjust to the appropriate analysis year, where necessary. 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. These AADTs were then spatially matched to the appropriate segment based on PR and milepoint values.

For the county segments, 30 counties were identified for which the annual traffic volume estimates were available for all classes of roadways analyzed in this study, including both federal aid and non-federal aid roads. These counties were: 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. The following figure (Figure 10) represents the map of two-lane two-way undivided state and county road segments and curves used in this study.

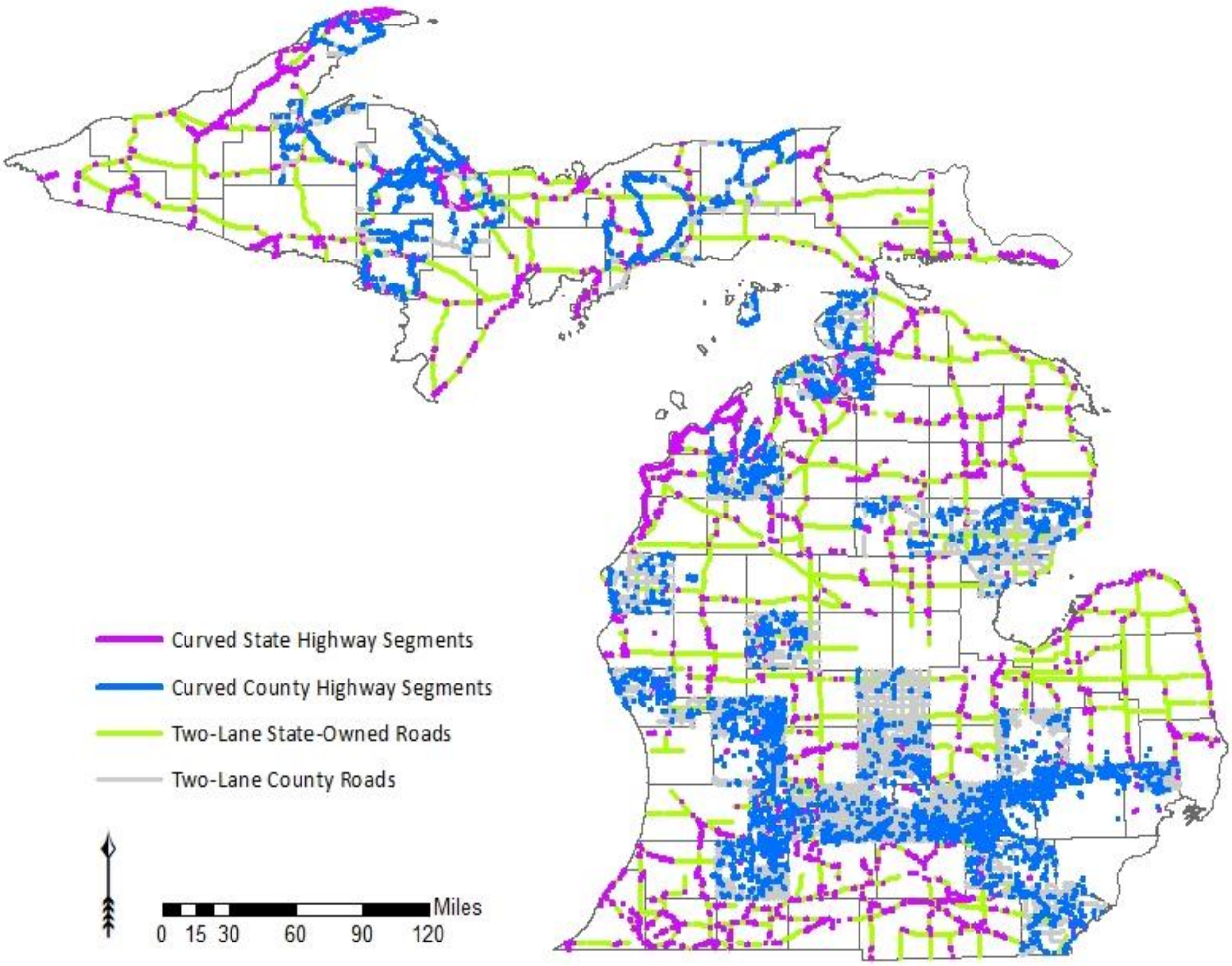


Figure 10: Map of study segments and horizontal curves, by jurisdiction.

3.1.5 Crash Data

The data on traffic crashes were collected from the annual statewide crash database Traffic Crash Reporting System (TCRS), maintained by MDOT (*168*), which is originally obtained from the Michigan State Police (MSP). The MSP crash database contains information of all reported public roadway crash records in the state of Michigan. Records in this database are maintained at the crash-, unit or vehicle-, and person or occupant-levels. Injury severity was defined for each crash based on the most significant injury sustained by anyone involved in the incident.

The *HSM* recommends using three to five years of crash data for safety analyses (*26*). Periods shorter than three years are subject to high variability due to the randomness of crashes. For this study, crash data for the most recent eight-year period was collected from 2011 to 2018. Only crashes with a roadway area type coded as "midblock" ("mdot_area_type_cd" = 3), which includes driveway crashes but excludes crashes occurring at public road intersections, were utilized. The PRs, BMPs, and EMPs of the segments were used in locating crashes, along with obtaining the segment length and roadway characteristics along the study segments. The crash data, along with all relevant information including crash severity and type, were aggregated annually and merged with the roadway inventory data for each segment. Animal crashes, which represented more than 64 percent of all crashes occurring on the study segments, were excluded from this analysis so as to better isolate the effects of geometry and other relevant roadway characteristics. Furthermore, contrasting with prior analyses of driveway density, the analysis of driveway land-use type in this study was not limited to multi-vehicle crashes only, and single-vehicle run-off-road crashes were included primarily due to small crash sample sizes and the potential for run-off-road crashes on higher speed roadways to occur because of the influence of other vehicles entering the roadway.

However, for investigating the horizontal curve characteristics, only single-vehicle crashes were included, as that represented over 92 percent of all non-animal crashes on rural highway curved segments. Hence, for curve-level analysis, single-vehicle crash data, along with all relevant information including crash severity and type, and direction of vehicle prior to a crash, were aggregated annually and merged with the curved segments inventory data based on the PRs, BMPs, and EMPs for each curve.

3.1.6 Other Data

Additional roadway data, which were already present in the state highway inventory unlike the county roads, were manually reviewed for county curved highway segments on Google Earth aerial and street view (where available) based on the PRs and milepoint values, and subsequently joined with each segment and curve. For this effort, the Google Earth ruler tool was used to make measurements from the aerial imagery and these measurements were recorded to the nearest 0.5 ft. This additional data included surface type, and surface width and lane widths, among others. Surface width (in feet) was measured for paved roadways from paved edge to paved edge. For gravel roadways, the surface width was taken as the predominant extent of width. Lane width (in feet) was calculated as the traveled way width (i.e., width between edgelines (if present) on paved surfaces only) divided by the number of lanes.

3.2 Data Collection – Urban Roadway Analysis

Prior to developing the safety performance functions, it was first necessary to collect and integrate data on traffic crashes, traffic volumes, and roadway characteristics from multiple sources, including the Michigan Department of Transportation (MDOT), Michigan State Police, the Southeast Michigan Council of Governments (SEMCOG), and Google Earth, among others. The geospatial analysis was performed in the ESRI's ArcGIS platform using existing shapefiles, where available, while additional data were added manually. The geographic boundary for the data analyzed was Washtenaw County, which is located in the Southeast Michigan. Washtenaw County is the sixth largest county in the State of Michigan with a population of 344,791, as per the latest available census data (*169*). Within Washtenaw County's 721 square miles are 29 local units of government including seven cities, six charter townships, fourteen civil townships, and two villages, thereby providing a diverse collection of urban and suburban roadway networks and land-use contexts. The County comprises the Ann Arbor Metropolitan Statistical Area and is included in the Detroit-Warren-Ann Arbor Combined Statistical Area. Other major urban areas in Washtenaw County include the cities of Ypsilanti, Saline, Chelsea, Dexter, and Milan. For this analysis, the data were obtained and analyzed for the following facilities, as shown in Figure 11.

1. Urban/suburban county- or city-owned two-lane two-way minor arterial segments, and
2. Urban/suburban county- or city-owned two-lane two-way collector segments.

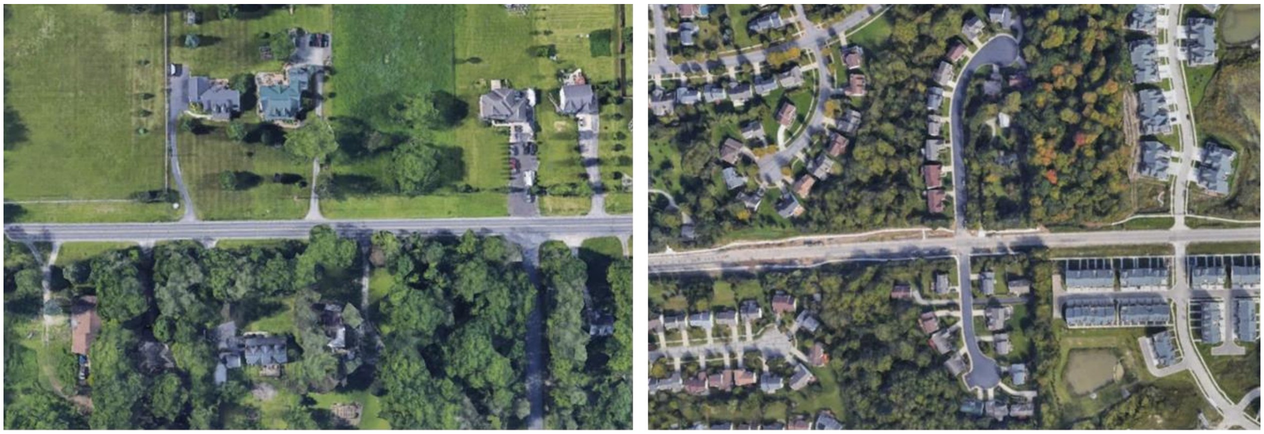


Figure 11: Urban roadway classes considered for SPF development.

3.2.1 Urban Roadway Segments Data

Initially, the roadway inventory data for all public highways in Washtenaw County was collected via the Michigan Geographic Framework (MGF) "All Roads" shapefile from the Michigan Center for Geographic Information (MCGI) open data portal (*170*). Additionally, posted speed limits from the SEMCOG database were also joined with the roadway data. This data was integrated based on the physical road (PR) reference number (based on a statewide linear referencing system), begin milepoints (BMP), end milepoints (EMP) of the segments.

Typically, segments' begin and end milepoints are determined based on a change in various factors including AADT, surface type, and jurisdictional boundary, thereby splitting roadways into unique homogeneous segments. However, an alternate segmentation process was adopted in this analysis. The candidate roadways in this study were segmented in a way such that each roadway segment's endpoints were intersections controlled via either signalization, stop control (on the subject roadway), a roundabout, or the route otherwise ending (such as the county line). A spatial analysis was performed on ArcGIS to identify the location of all public roadway intersections along these roadways. A manual review of satellite imagery was undertaken to determine the traffic control for each intersection. This ensures that there is no traffic control along the major route within the bounds of each segment.

This data was further reduced to only include urban and suburban roadways that had posted speed limits ranging from 25 mph to 50 mph. Ultimately, the study segments included two-lane undivided roadways that were classified as minor arterial or collector, while excluding freeways, major arterials, and local roads. A minimum segment length of 0.1 miles was selected for this analysis as recommended by *HSM* (*26*). Figure 12 shows the two-lane undivided segments included in this analysis.

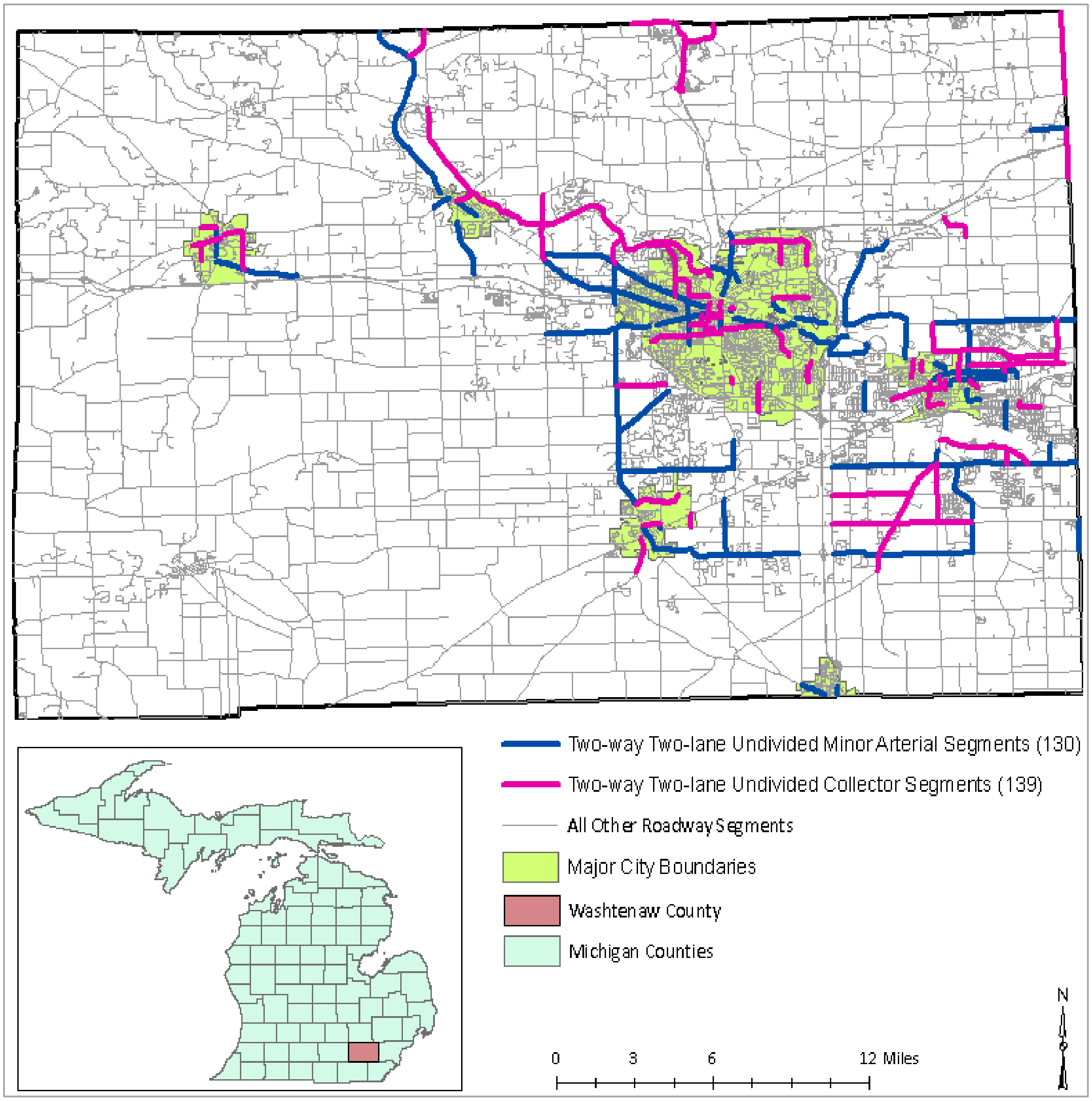


Figure 12: Two-lane two-way undivided minor arterial and collector roadway study segments in Washtenaw County, Michigan.

3.2.2 Traffic Volumes

AADT volume estimates were obtained from the Federal Highway Administration's (FHWA) Highway Performance Monitoring System (HPMS) (*171*) shapefile and the Southeast Michigan Council of Governments (SEMCOG) (*172*) open-source database for all analysis years from

2011 to 2018. These AADTs were then spatially matched to the appropriate segment in the roadway data based on PR and milepoint values. In all cases, these traffic volume data represent actual observed counts along the road segments. Annual traffic growth factors were obtained from Washtenaw County and applied to the traffic volumes to adjust to the appropriate analysis year, where necessary.

3.2.3 Crash Data

The historical traffic crash data were collected from the annual statewide crash database Traffic Crash Reporting System (TCRS), maintained by MDOT. For this study, crash data for an eight-year period from 2011 to 2018 were utilized. Crashes on each segment were included, excluding those occurring within 250 ft of the terminal intersections on either end. The crash data, along with all relevant information including crash severity and type, were aggregated annually and merged with the roadway data for each segment. Furthermore, contrasting with prior analyses in urban areas, the analysis was not limited to multi-vehicle crashes only, and single-vehicle run-off-road crashes were included. This is primarily due to small crash sample sizes and the potential for run-off-road crashes on higher speed roadways to occur because of the influence of other vehicles entering the roadway. Lastly, animal crashes were not excluded included in the analysis because of its small proportion (less than 8 percent) of total midblock crashes.

3.2.4 Other Data

Additional data were manually reviewed in Google Earth and subsequently joined with the roadway data for each segment. This additional data included:

- count and classification of access points (residential driveway, commercial driveway, public intersections;)
- presence of bus stops, school zones, sidewalks, crosswalks, bike lanes, on-street parking, and midblock crosswalks;
- widths of travel lanes, shoulders, bike lanes, parking lanes, and the space between sidewalks and traffic lanes.

3.3 Quality Control/Quality Assurance Verification

In order to ensure accuracy in the data, the research team performed thorough quality assurance/quality control (QA/QC) checks for both rural and urban roadway datasets. The same resources used to create the initial dataset, primarily Google Earth, were utilized to perform the QA/QC review. This entailed a different observer reviewing traffic and roadway geometric characteristics analyzed in this research. Evidence of systematic errors caused by any particular observer were repeated by a more experienced observer.

3.4 Analytical Method for the Development of SPFs

Traditional linear regression techniques are generally not appropriate as crash data are comprised of non-negative integers. As an alternative, the Poisson distribution provides a starting point for the analyses. In the Poisson model, the probability of segment *i* experiencing y_i crashes in a one-year period can be expressed as

$$P(y_i) = \frac{EXP(-\lambda_i)\lambda_i^{y_i}}{y_i!} \qquad (1)$$

where $P(y_i)$ is the probability of segment *i* experiencing y_i crashes, and λ_i is the Poisson parameter or the expected number of crashes per year for segment i, E[y_i].

The Poisson regression model relates the expected number of crashes on a segment, λ_i, to a function of explanatory variables, expressed as

$$\lambda_i = exp(\beta X_i) \qquad (2)$$

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

A limitation with the Poisson distribution is the assumption that the mean and variance are equal, which often is not the case with the crash data. Commonly with crashes, variance exceeds mean, leading to an overdispersion. The negative binomial model addresses this overdispersion by adding an error term as,

$$\lambda_i = exp(\beta X_i + \varepsilon_i) \qquad (3)$$

where $EXP(\varepsilon_i)$ is a gamma-distributed error term with mean 1 and variance α. The inclusion of this term essentially allows the variance to differ from mean as

$$Var[y_i] = E[y_i] + \alpha E[y_i]^2 \qquad (4)$$

This α is termed as the overdispersion parameter. In the safety analysis, negative binomial regression models have been widely used (*149*, *151*, *152*) and accepted as the current practice for modeling crashes, essentially developing safety performance functions (SPFs), as such models account for overdispersion.

In this analysis, AADT is included in natural log form and, its parameter estimate reflects elasticity. The coefficients for the natural log of the segment length for the analysis of driveway land-use type and urban roadways were set to 1 by treating as an offset to normalize the crash counts per unit length, as the crash frequency on a segment is generally considered to be proportional to the segment length. Similarly, in lieu of segment length, for horizontal curve analysis, the natural log of curve length was treated as an offset.

The negative binomial models in this analysis are used to develop crash modification factors (CMFs). CMFs represent the change in crashes associated with a unit change in a predictor variable. These factors are typically the ratio of the expected values of crashes with and without the change. The CMFs can be expressed as

$$CMF = \exp(\beta_j) \tag{5}$$

where β_j is the regression coefficient associated with the variable j.

CMF values less than 1.0 indicate that alternative treatment reduces the estimated average crash frequency compared to the base condition and vice versa.

Recently, mixed-effect negative binomial models have become popular due to the capability of accounting for spatial effects and heterogeneity across observations (*173*, *174*). Unobserved heterogeneity can be defined as unknown variability in the effect of variables across the sample population. It is imperative to address this issue of unobserved heterogeneity to avoid erroneous predictions resulting from the biased estimated parameters (*154*).

In this context, unobserved heterogeneity may be introduced when collecting data from across various counties and regions of the state, due to the inability to measure or otherwise quantify all data necessary to account for this variability. For example, design standards and maintenance practices, along with other factors, including weather, topography, land-use, and driver behavior are known to vary from county to county. Also, each site is replicated as many times as the number of analysis years in this study. Hence, the issue with non-random sampling and unobserved heterogeneity in the data is addressed by including county- and site-specific random parameters for the rural roadways and site-specific random parameter for urban and suburban roadways in the negative binomial models, whereby the intercept terms are allowed to vary across the random parameters, effectively developing mixed-effects models. In a mixed-effects model, each intercept is drawn at random from the intercept distribution and is independent of the error term for any particular observation and uncorrelated with the independent variables. The mixed-effect negative binomial model with random parameters (intercept) by adding an unobserved heterogeneity term takes the following general form;

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

where $EXP(\eta_i)$ is random effect on the intercept for observation groups with mean 1 and variance α. The mixed-effects negative binomial regression analyses in this study were conducted using R statistical software version 4.1.2.

4. ANALYSIS AND RESULTS: SAFETY PERORMANCE OF DRIVEWAY LAND-USE CLASSIFICATIONS ON RURAL HIGHWAYS

4.1 Preliminary Analysis

The safety performance of driveway land-use categories for rural two-way two-lane undivided highway segments were analyzed using the data from across Michigan, as described in Chapter 3. Due to the differences in design characteristics, maintenance standards, traffic volumes, trip distances, and driver characteristics, among other factors, separate datasets were created for state- and county-owned highways. After the data were assembled for rural highway segments, a series of preliminary analyses were conducted to examine general trends across all locations for each facility type as below.

1. Rural two-lane two-way undivided state highway segments
2. Rural two-lane two-way undivided paved county segments
3. Rural two-lane two-way undivided unpaved/gravel county segments

4.1.1 Descriptive Statistics, Rural Highway Segments

A total of 1,660 state highway segments, totaling 5,520 miles of length were included in this analysis. The summary statistics of road segments and crashes including minimum, maximum, mean, and standard deviation are presented in

Table 1. Similarly, approximately a total of 5,894 miles (12,814 segments) of paved county highways were investigated in this analysis and the summary statistics pertaining to the roadway attributes for this segment type is presented in Table 2. Finally, the summary statistics for unpaved roads totaling 2,007 miles (3,983 segments) are shown in Table 3.

When compared between the different rural segment types, traffic volume is observed to be the highest on the state highway segments, followed by paved county roads, and lastly the unpaved road segments. While on average, segment length is much higher on state highways compared to county roads.

Total driveway count per mile is observably greater on county road segments, particularly on paved county roads. However, when field driveways are excluded, the total driveway density is comparable between state and paved county highway segments, indicating an overabundance of field driveways on county roads. In terms of individual land-use type, while the state highway data contain a separate category for industrial driveways, manually collected commercial and industrial driveway data were combined into a single category for the county segments. Also, residential and commercial/industrial driveway densities are higher on the state highways with respect to the county roads, both paved and unpaved.

Moreover, the presence of horizontal curves with radii corresponding to 55 mph or lower design speed is higher on county road segments compared to state highways. Average lane widths are comparable between the state and paved county highways, with slightly higher on the state roads. While almost all state highway segments have paved shoulders, approximately 44 percent county road segments have paved shoulder present along the segments.

Average crash frequencies are substantially higher on state highways than any type of county highways for all crashes including both midblock and non-animal midblock crashes. In general, in all years, the proportions of crashes increase as the severity of crashes decreases for all segment types. Overall, PDO crashes are the most frequent type.

Table 1: Summary Statistics for Rural Two-lane Undivided State Highway Segments (*n* = *1,660*)

Factor	Min	Max	Mean	Std. Dev
Traffic volume (AADT) (vehicles per day)	23	30,976	4,713	3,328
Segment length (mi)	0.11	21.7	3.30	2.75
Total driveway density (including field) (count/mi)	0	146.8	14.50	11.03
Total driveway density excluding field) (count/mi)	0	143.7	14.30	10.91
Residential driveway density (count/mi)	0	94.8	8.51	36.85
Commercial driveway density (count/mi)	0	54.1	2.15	13.32
Industrial driveway density (count/mi)	0	79.3	0.90	12.74
Horizontal curve presence (< 55 mph design speed)	0	1	0.06	0.26
Lane width (ft)	10	12	11.60	0.50
Presence of paved shoulder	0	1	0.96	0.19
Midblock crashes (count/segment-year)	0	75	8.60	8.92
Midblock non-animal total crashes (count/segment-year)	0	34	2.80	3.40
Midblock non-animal fatal and injury crashes (FI) (count/segment-year)	0	11	0.76	1.20
Midblock non-animal fatal crashes (K) (count/segment-year)	0	2	0.04	0.20
Midblock non-animal incapacitating injury crashes (A) (count/segment-year)	0	4	0.12	0.37
Midblock non-animal non-incapacitating injury crashes (B) (count/segment-year)	0	7	0.23	0.55
Midblock non-animal possible injury crashes (C) (count/segment-year)	0	6	0.38	0.74
Midblock non-animal property damage only crashes (O) (count/segment-year)	0	26	2.10	2.59

Table 2: Summary Statistics for Rural Two-lane Undivided Paved County Segments (*n = 12,814*)

Factor	Min	Max	Mean	Std. Dev
Traffic volume (AADT) (vehicles per day)	3	12,781	1,491	1,611
Segment length (mi)	0.1	8.2	0.46	0.32
Total driveway density (including field) (count/mi)	0	138.7	16.86	13.93
Total driveway density excluding field) (count/mi)	0	138.7	14.29	13.61
Residential driveway density (count/mi)	0	69	6.71	6.97
Commercial/Industrial driveway density (count/mi)	0	77.7	1.24	3.29
Horizontal curve presence (< 55 mph design speed)	0	1	0.08	0.24
Lane width (ft)	9	21	10.96	0.78
Presence of paved shoulder	0	1	0.44	0.50
Midblock crashes (count/segment-year)	0	23	0.60	1.06
Midblock non-animal total crashes (count/segment-year)	0	12	0.23	0.59
Midblock non-animal fatal and injury crashes (FI) (count/segment-year)	0	7	0.07	0.27
Midblock non-animal fatal crashes (K) (count/segment-year)	0	1	0.003	0.05
Midblock non-animal incapacitating injury crashes (A) (count/segment-year)	0	2	0.009	0.09
Midblock non-animal non-incapacitating injury crashes (B) (count/segment-year)	0	3	0.02	0.15
Midblock non-animal possible injury crashes (C) (count/segment-year)	0	4	0.03	0.19
Midblock non-animal property damage only crashes (O) (count/segment-year)	0	9	0.17	0.48

Table 3: Summary Statistics for Rural Two-lane Undivided Unpaved Road Segments (*n = 3,983*)

Factor	Min	Max	Mean	Std. Dev
Traffic volume (AADT) (vehicles per day)	4	6,298	246	430
Segment length (mi)	0.1	4.6	0.50	0.37
Total driveway density (including field) (count/mi)	0	93.0	13.53	10.84
Total driveway density excluding field) (count/mi)	0	93.0	11.75	10.77
Residential driveway density (count/mi)	0	50.0	5.87	5.95
Commercial/Industrial driveway density (count/mi)	0	37.7	0.70	2.08
Horizontal curve presence (< 55 mph design speed)	0	1	0.09	0.27
Surface width (ft)	12	40	21.28	3.85
Midblock crashes (count/segment-year)	0	5	0.12	0.37
Midblock non-animal total crashes (count/segment-year)	0	5	0.08	0.30
Midblock non-animal fatal and injury crashes (FI) (count/segment-year)	0	3	0.02	0.15
Midblock non-animal fatal crashes (K) (count/segment-year)	0	1	0.0003	0.02
Midblock non-animal incapacitating injury crashes (A) (count/segment-year)	0	1	0.003	0.05
Midblock non-animal non-incapacitating injury crashes (B) (count/segment-year)	0	2	0.008	0.09
Midblock non-animal possible injury crashes (C) (count/segment-year)	0	2	0.010	0.10
Midblock non-animal property damage only crashes (O) (count/segment-year)	0	5	0.06	0.25

The crash data and driveway land-use categories as the primary independent variable of interest of this study were further explored with the help of graphical representations to examine general trends of them for each facility type as shown in Figure 13, Figure 14, and Figure 15. For both annual crash frequency and driveway density normalized on a per-mile basis, the observed data were plotted against traffic volumes.

From these figures, the crash frequency per mile is observably greater particularly on paved county roads compared to that on state highways. Also, the residential driveways are much more frequent on paved county roads, compared to other two facilities.

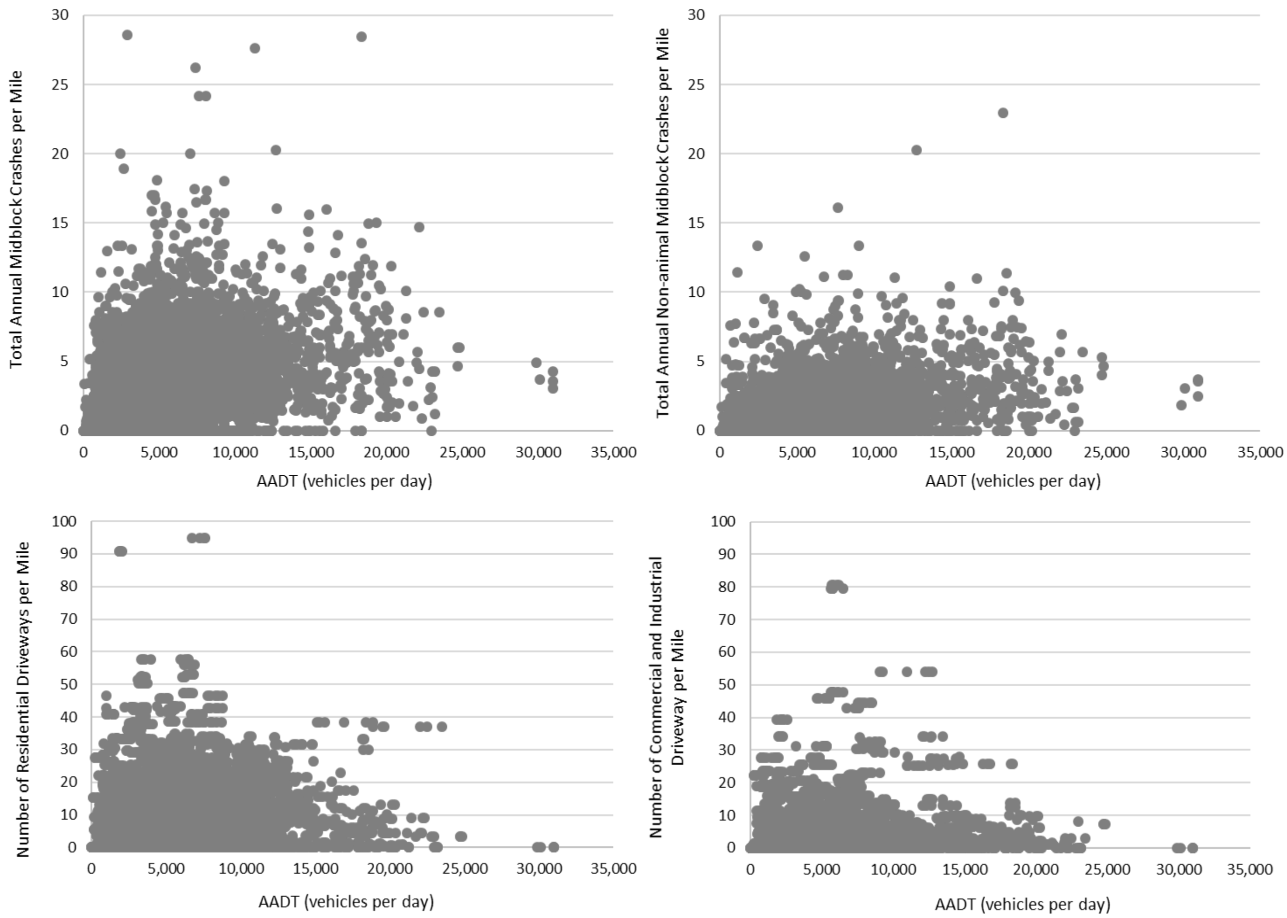


Figure 13: Annual midblock crashes per mile and number of driveways per mile for various land-use categories vs AADT on state highways.

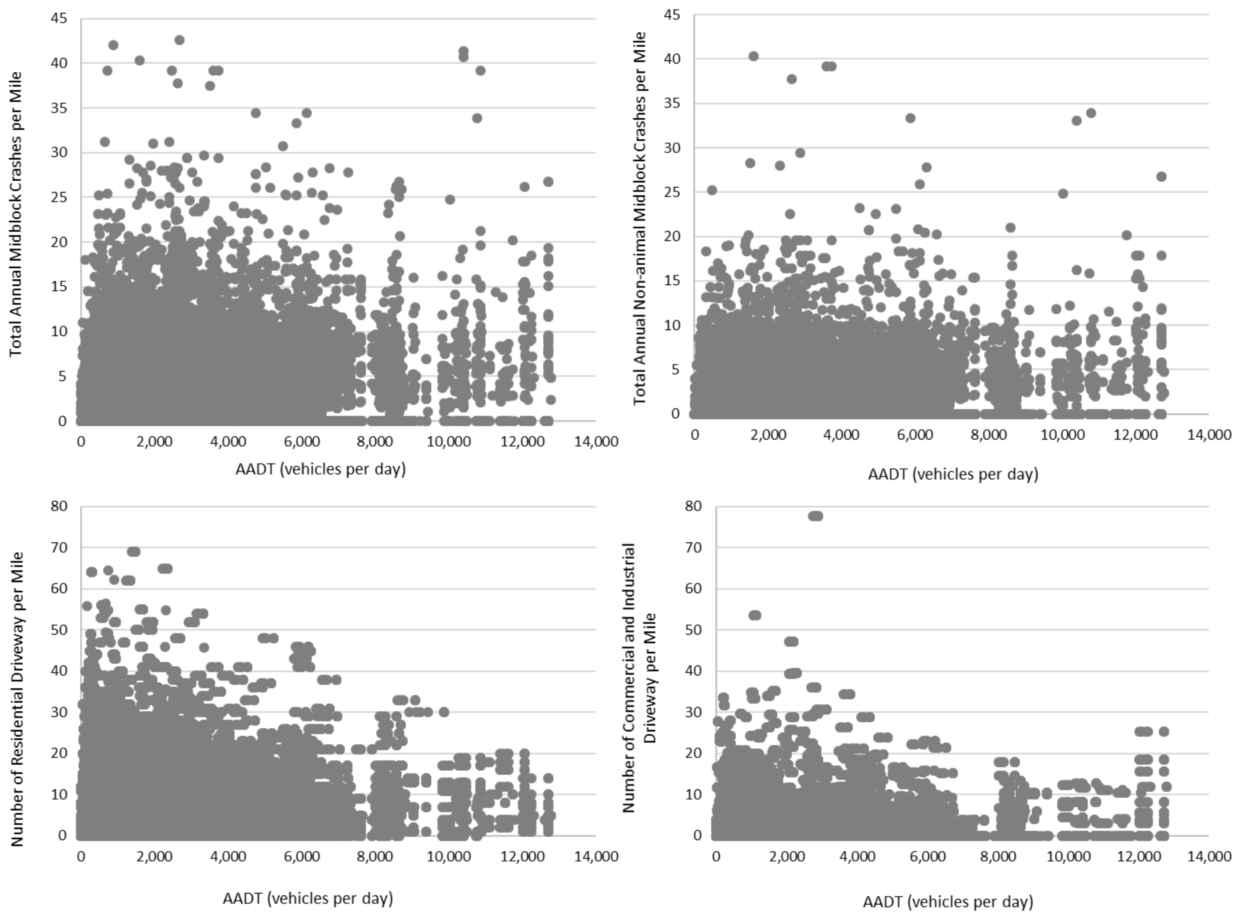


Figure 14: Annual midblock crashes per mile and number of driveways per mile for various land-use categories vs AADT on paved county roads.

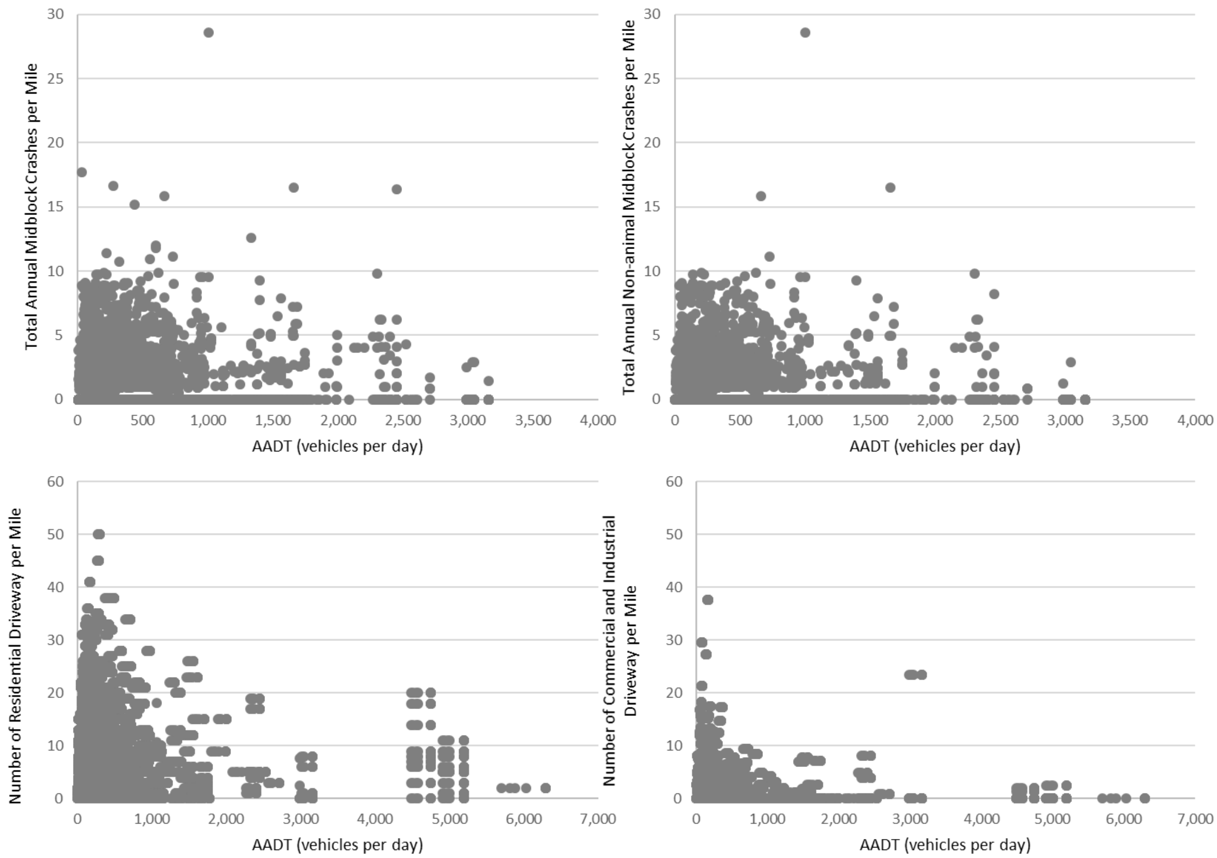


Figure 15: Annual midblock crashes per mile and number of driveways per mile for various land-use categories vs AADT on unpaved county roads.

Additionally, Table 4, Table 5, and Table 6 show the crash distributions for individual crash severity and different collision types on state highway, paved county highways, and unpaved roads, respectively.

Table 4: Crash Severity and Collision Type Distributions for Midblock Crashes on Rural Two-lane Undivided State Highway Segments

Crash severities and collision types	Midblock crashes		Non-animal midblock crashes		Percent of non-animal midblock crashes w.r.t. all midblock crashes
	Count	Percent of midblock crashes	Count	Percent of non-animal midblock crashes	
Total	114,466	100.0%	37,642	100.0%	32.9%
Fatal and injury (FI)	11,654	10.2%	10,144	26.9%	87.0%
Fatal (K)	490	0.4%	479	1.3%	97.8%
Incapacitating injury (A)	1,735	1.5%	1,618	4.3%	93.3%
Non-incapacitating injury (B)	3,479	3.0%	3,052	8.1%	87.7%
Possible injury (C)	5,950	5.2%	4,995	13.3%	83.9%
Property damage only (PDO)	102,812	89.8%	27,498	73.1%	26.7%
Single-vehicle	99,632	87.0%	23,249	61.8%	23.3%
Multi-vehicle	14,834	13.0%	14,393	38.2%	97.0%
Head-on	1,169	1.0%	1,151	3.1%	98.5%
Head-on left turn	313	0.3%	313	0.8%	100.0%
Angle	1,247	1.1%	1,240	3.3%	99.4%
Rear end	6,745	5.9%	6,688	17.8%	99.2%
Sideswipe same	1,976	1.7%	1,966	5.2%	99.5%
Sideswipe opposite	1,252	1.1%	1,246	3.3%	99.5%
In dry road	78,133	68.3%	18,367	48.8%	23.5%
Alcohol/Drug involved	2,912	2.6%	2,782	7.3%	95.5%
Truck/bus related	3,069	2.7%	2,224	5.9%	72.5%
Pedestrian/Bike related	303	0.3%	300	0.8%	99.0%
Motorcycle related	1,044	0.9%	679	1.8%	65.0%
In Daylight	39,680	34.7%	22,591	60.0%	56.9%

Table 5: Crash Severity and Collision Type Distributions for Midblock Crashes on Rural Two-lane Undivided Paved County Highway Segments

Crash severities and collision types	Midblock crashes		Non-animal midblock crashes		Percent of non-animal midblock crashes w.r.t. all midblock crashes
	Count	Percent of midblock crashes	Count	Percent of non-animal midblock crashes	
Total	61,646	100.0%	23,739	100.0%	38.5%
Fatal and injury (FI)	7,446	12.1%	6,681	28.1%	89.7%
Fatal (K)	300	0.5%	287	1.2%	95.7%
Incapacitating injury (A)	954	1.5%	896	3.8%	93.9%
Non-incapacitating injury (B)	2,447	4.0%	2,201	9.3%	89.9%
Possible injury (C)	3,745	6.1%	3,297	13.9%	88.0%
Property damage only (PDO)	54,200	87.9%	17,058	71.9%	31.5%
Single-vehicle	55,463	90.0%	17,775	74.9%	32.0%
Multi-vehicle	6,183	10.0%	5,964	25.1%	96.5%
Head-on	594	1.0%	582	2.5%	98.0%
Head-on left turn	135	0.2%	135	0.6%	100.0%
Angle	723	1.2%	718	3.0%	99.3%
Rear end	2,219	3.6%	2,193	9.2%	98.8%
Sideswipe same	776	1.3%	775	3.3%	99.9%
Sideswipe opposite	833	1.4%	827	3.5%	99.3%
In dry road	39,880	64.7%	11,174	47.1%	28.0%
Alcohol/Drug involved	2,569	4.2%	2,472	10.4%	96.2%
Truck/bus related	701	1.1%	591	2.5%	84.3%
Pedestrian/Bike related	190	0.3%	190	0.8%	100.0%
Motorcycle related	767	1.2%	540	2.3%	70.4%
In Daylight	21,507	34.9%	13,137	55.3%	61.1%

Table 6: Crash Severity and Collision Type Distributions for Midblock Crashes on Rural Two-lane Undivided Unpaved County Segments

Crash severities and collision types	Midblock crashes		Non-animal midblock crashes		Percent of non-animal midblock crashes w.r.t. all midblock crashes
	Count	Percent of midblock crashes	Count	Percent of non-animal midblock crashes	
Total	3,740	100.0%	2,436	100.0%	65.1%
Fatal and injury (FI)	707	18.9%	669	27.5%	94.6%
Fatal (K)	10	0.3%	10	0.4%	100.0%
Incapacitating injury (A)	93	2.5%	88	3.6%	94.6%
Non-incapacitating injury (B)	269	7.2%	256	10.5%	95.2%
Possible injury (C)	335	9.0%	315	12.9%	94.0%
Property damage only (PDO)	3033	81.1%	1,767	72.5%	58.3%
Single-vehicle	3,278	87.6%	1,984	81.4%	60.5%
Multi-vehicle	462	12.4%	452	18.6%	97.8%
Head-on	41	1.1%	41	1.7%	100.0%
Head-on left turn	2	0.1%	2	0.1%	100.0%
Angle	87	2.3%	87	3.6%	100.0%
Rear end	89	2.4%	88	3.6%	98.9%
Sideswipe same	70	1.9%	70	2.9%	100.0%
Sideswipe opposite	94	2.5%	94	3.9%	100.0%
In dry road	1,837	49.1%	1,043	42.8%	56.8%
Alcohol/Drug involved	302	8.1%	299	12.3%	99.0%
Truck/bus related	68	1.8%	64	2.6%	94.1%
Pedestrian/Bike related	14	0.4%	14	0.5%	100.0%
Motorcycle related	28	0.7%	23	0.9%	82.1%
In Daylight	1,691	45.2%	1,399	57.4%	82.7%

4.2 SPF Development

The analysis involved the development of the several mixed-effects negative binomial models separately for state and county highway segments. Also, separate models were estimated for total, fatal and injury (FI), and property damage only (PDO) crashes. The independent variables included traffic volume, driveway density based on different land-use categories, lane width (state highways and paved county roads), surface width (unpaved roads only), and paved shoulder presence (state highways and paved county roads). The driveway density was calculated for each land-use classification on each segment by dividing the number of driveways by the segment length.

A recent study from Michigan indicated that the horizontal curves with a radius corresponding to a design speed less than the posted speed limit along the segments has a significant impact on crash frequency (*175*). Therefore, along with all other variables, the presence of horizontal curves with a radius less than 0.191 miles/1,008 feet (corresponding to design speed 55 mph which was the speed limit for the majority of the study segments) was also added as a binary variable in the SPF models.

Additionally, the models included binary variables for lane widths (less than or equal to 11 feet vs greater than 11 feet), and the presence of a paved shoulders for state and paved county highways. For unpaved roads, in lieu of lane width and shoulder width, a binary indicator was added for the overall surface width (less than or equal to 22 feet vs greater than 22 feet). In all models, segment length was treated as an offset with its parameter estimate fixed at 1 thereby normalizing the results to homogenous one-mile segments, as the crash frequency on a segment is generally considered to be proportional to the segment length. Several combinations of independent variables were tested to develop the full models and based on the p-values of the parameter estimates, AIC, and log-likelihood information, best fit models were chosen. A significance level of 0.1 ($\alpha = 0.1$) was used in this analysis. Table 7, Table 8, and Table 9, and Table 10, Table 11, and Table 12, and Table 22, Table 23, and Table 24 display the results of mixed-effect negative binomial models including parameter estimates, elasticity, standard errors (S.E.), z-statistics, and p-values for the state highway segments, paved county highway segments, and unpaved road segments, respectively. The following subsections present the discussion of the model results for all facilities analyzed in this study.

4.3 Results and Discussion

4.3.1 State Highway Segments

The results of the analysis of state highway segments, as shown in Table 7, Table 8, and Table 9, revealed several interesting findings. First, with regard to the safety effects of driveway density across the various driveway land-use categories on state highway segments, the results show that densities for all driveway types are positively associated with crash frequency (i.e., greater driveway densities result in higher crash occurrence), and this association is statistically significant for each driveway type. Specifically, the parameter estimates indicate that the crash occurrences increase by up to 2.1 percent, 2.3 percent, and up to 2.0 percent for total, fatal and injury, and PDO crashes, respectively, with every additional driveway per mile segment, considering all land-use types. Among all driveway types, commercial driveways have the strongest effect on crashes for all crash severities. The effect of industrial driveway density is slightly greater than that of residential driveway density for total, and PDO crashes on state highways, with a lower impact for FI crashes. The residential and commercial driveway densities exhibited a stronger effect on FI crashes than that on total and PDO crashes. Overall, these results are aligned with prior research that found crash frequency to be influenced by various driveway configurations and their land-uses (*22*, *33*, *68*).

Turning to the safety effects of horizontal curvature, horizontal curve presence was positively correlated with crash frequency, and this relationship was consistent and statistically significant for total, FI, and PDO crashes on state highways. The horizontal curve presence exhibited a stronger impact on FI crashes than that on total and PDO crashes. This is expected and supported by previous research that the association between horizontal curvature and FI are the strongest among all severities (*28*, *82*). Specifically, the parameter estimates indicate 24.1 percent, 33.5 percent, and 20.2 percent greater total, FI, and PDO crashes, respectively, when horizontal curves (with design speeds <55 mph) are present on the segment. Overall, these findings agree with expectations, as the driving maneuvers become more complicated along the horizontal curves compared to tangent sections, increasing the risk of crashes.

Additionally, the relationship between the number of traffic crashes and AADT is non-linear and inelastic, with parameter estimates ranging between 0.73 and 0.82 depending on crash severity, a finding consistent with other studies (*44*). Among different crash severities, the association between traffic volume and crash frequency is the strongest for fatal and injury crashes, while this association for total and PDO crashes are mostly comparable, with a slightly stronger association with PDO crashes.

Moreover, a lane width greater than 11 feet has no significant impact on crashes. Furthermore, the presence of a paved shoulder shows a negative association with crash frequency for only total, and PDO crashes. Particularly, the presence of a paved shoulder decreases the crash frequency by up to 11.8 percent, and 16.5 percent for total, and PDO crashes, respectively. Finally, the variances of the site- and county-specific random effects indicate that there is more variation between sites in general than there is variation in sites between counties on state highway segments.

Table 7: Mixed-Effects Negative Binomial Model Results for Total Non-animal Midblock Crashes on Rural State Highway Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.297		0.178	-35.29	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.726	0.726	0.019	37.52	<0.001
Residential Driveway Density	Continuous variable	0.010	0.010	0.001	7.17	<0.001
Commercial Driveway Density	Continuous variable	0.021	0.021	0.003	6.79	<0.001
Industrial Driveway Density	Continuous variable	0.011	0.011	0.003	3.32	0.001
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.216	0.241	0.044	4.91	<0.001
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	0.031	0.031	0.025	1.22	0.223
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	-0.126	-0.118	0.064	-1.98	0.048
Variance of site-specific random effect	0.1213					
Variance of county-specific random effect	0.0297					
Overdispersion	0.0551					
Log-likelihood	-23403					
AIC (Akaike information criterion)	46827.2					

Table 8: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Non-animal Midblock Crashes on Rural State Highway Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-8.633		0.248	-34.84	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.821	0.821	0.026	31.01	<0.001
Residential Driveway Density	Continuous variable	0.013	0.013	0.002	7.10	<0.001
Commercial Driveway Density	Continuous variable	0.023	0.023	0.004	5.44	<0.001
Industrial Driveway Density	Continuous variable	0.010	0.010	0.004	2.79	0.005
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.289	0.335	0.056	5.20	<0.001
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	-0.020	-0.020	0.033	-0.59	0.553
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	0.108	0.114	0.093	1.16	0.246
Variance of site-specific random effect	0.1077					
Variance of county-specific random effect	0.0255					
Overdispersion	0.0769					
Log-likelihood	-13463					
AIC (Akaike information criterion)	26947.2					

Table 9: Mixed-Effects Negative Binomial Model Results for Property Damage Only Non-Animal Midblock Crashes on Rural State Highway Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.618		0.190	-34.82	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.734	0.734	0.021	35.63	<0.001
Residential Driveway Density	Continuous variable	0.010	0.010	0.002	6.42	<0.001
Commercial Driveway Density	Continuous variable	0.020	0.020	0.003	5.86	<0.001
Industrial Driveway Density	Continuous variable	0.011	0.011	0.004	3.15	0.002
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.184	0.202	0.047	3.92	<0.001
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	0.037	0.038	0.027	1.37	0.171
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	-0.181	-0.165	0.068	-2.66	0.008
Variance of site-specific random effect	0.1262					
Variance of county-specific random effect	0.0323					
Overdispersion	0.0522					
Log-likelihood	-20810					
AIC (Akaike information criterion)	41642.7					

4.3.2 Paved County Highway Segments

This section present the analysis for paved county segments as shown in Table 10, Table 11, and Table 12. The results indicate that, in terms of the safety effects of driveway density across the various driveway land-use categories on paved county road segments, similar to the state highways, both residential and commercial/industrial driveway densities show positive associations with crashes for all crash severities, and this association is statistically significant for each driveway type, except for commercial and industrial driveways for PDO crashes. This could be due to the fact that a large proportion (more than 83 percent) of the paved county road segments that experience PDO crashes do not have any commercial or industrial driveways along the segments. The increase in crashes with the increase in driveway density is much smaller for all driveway types along this facility compared to the state highway segments. Specifically, the parameter estimates indicate that the crash occurrences increase by up to 0.9 percent, 1.1 percent, and 0.5 percent for total, fatal and injury, and PDO crashes, respectively, with every additional driveway per mile segment, considering all land-use types. Among all driveway types, the density for commercial/industrial driveways has a greater impact on crash frequency than that for residential driveways for all crash types, except for PDO crashes on paved county roads.

Similar to the state highway models, the presence of horizontal curves with a radius less than 0.191miles on paved county roads was associated with higher crash occurrence for total, FI, and PDO crashes. Also, like the state highways, among different crash severities, the impact of the horizontal curve presence showed the strongest association with FI crashes. Specifically, the parameter estimates indicate that the total, FI, and PDO crash frequencies are greater by 55.5 percent, 68.5percent, and 50.6 percent, respectively, when horizontal curves (with design speeds <55 mph) are present on the segment. It is important to note that, the effect of the presence of horizontal curves with radius corresponding to design speed lower than the speed limit of the segments is much more pronounced on paved county roads compared to that on state highways.

Similar to the state highway segments, the relationship between the number of traffic crashes and AADT is also non-linear and inelastic for paved county roadways. However, it is less elastic (β_0 ranging between 0.72 and 0.74) than the state highway segments for all crashes. Moreover, among the different crash severities, the association between traffic volume and crash frequency is the strongest for fatal and injury crashes, while this association for total and PDO crashes are mostly comparable.

Moreover, as also found for the state highways, a lane width greater than 11 feet has no significant impact on crashes for any crash severity. Furthermore, the presence of paved shoulder exhibits an unexpected positive association with crashes. This may also be attributable to the considerably higher, approximately twice as much average traffic volume (2,005 vpd) on segments with paved shoulder present as that on road segments without any presence of paved shoulders (1,090 vpd). Finally, the variances of the site- and county-specific random effects indicate that there is more variation between sites in general than there is variation in sites between counties on paved county roadway segments.

Table 10: Mixed-Effects Negative Binomial Model Results for Total Non-animal Midblock Crashes on Rural Paved County Highway Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.203		0.099	-62.85	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.718	0.718	0.013	55.75	<0.001
Residential Driveway Density	Continuous variable	0.005	0.005	0.001	6.031	<0.001
Commercial/Industrial Driveway Density	Continuous variable	0.009	0.009	0.003	0.70	0.049
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.442	0.555	0.039	11.41	<0.001
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	0.053	0.055	0.024	2.26	0.124
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	0.123	0.130	0.024	5.21	<0.001
Variance of site-specific random effect	0.3257					
Variance of county-specific random effect	0.0629					
Overdispersion	0.1197					
Log-likelihood	-52311					
AIC (Akaike information criterion)	104621					

Table 11: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Non-animal Midblock Crashes on Rural Paved County Highway Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-7.613		0.147	51.76	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.744	0.744	0.021	35.72	<0.001
Residential Driveway Density	Continuous variable	0.007	0.007	0.001	2.32	0.020
Commercial/Industrial Driveway Density	Continuous variable	0.011	0.011	0.005	0.546	0.058
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.522	0.685	0.057	9.14	<0.001
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	0.029	0.029	0.035	0.815	0.415
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	0.116	0.123	0.035	3.29	0.001
Variance of site-specific random effect	0.3462					
Variance of county-specific random effect	0.0259					
Overdispersion	0.0555					
Log-likelihood	-22244					
AIC (Akaike information criterion)	44508.5					

Table 12: Mixed-Effects Negative Binomial Model Results for Property Damage Only Non-Animal Midblock Crashes on Rural Paved County Highway Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.537		0.110	59.21	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.716	0.716	0.014	50.09	<0.001
Residential Driveway Density	Continuous variable	0.005	0.005	0.001	6.30	<0.001
Commercial/Industrial Driveway Density	Continuous variable	0.007	0.007	0.003	0.47	0.638
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.409	0.506	0.043	9.54	<0.001
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	0.051	0.051	0.026	1.93	0.534
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	0.112	0.119	0.026	4.32	<0.001
Variance of site-specific random effect	0.3276					
Variance of county-specific random effect	0.0808					
Overdispersion	0.1437					
Log-likelihood	-42572					
AIC (Akaike information criterion)	85162.9					

A subsequent analysis was carried out controlling for traffic volumes on segments with paved shoulders to understand the confounding results of the association between paved shoulder presence and crash frequency in the previous model results, and the results of this subsequent analysis are presented in Table 13, Table 14, and Table 15. For these models, an overlapping range of traffic volume between 300 and 5,000 vehicles per day was considered for both segments with and without paved shoulder. As the subsequent analysis indicate, when the crash frequency is estimated controlling for traffic volume on paved county road segments with paved shoulder presence, the effect of the presence of paved shoulder becomes insignificant.

Table 13: Mixed-Effects Negative Binomial Model Results for Total Non-animal Midblock Crashes on Rural Paved County Highway Segments (AADT Range: 300-5,000 vpd)

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.152		0.128	-48.09	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.710	0.710	0.017	41.58	<0.001
Residential Driveway Density	Continuous variable	0.006	0.006	0.001	6.54	<0.001
Commercial/Industrial Driveway Density	Continuous variable	0.010	0.010	0.003	1.00	0.032
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.488	0.630	0.042	11.66	<0.001
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	0.044	0.045	0.026	1.69	0.901
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	0.119	0.127	0.025	4.73	0.228
Variance of site-specific random effect	0.3197					
Variance of county-specific random effect	0.0761					
Overdispersion	0.1181					
Log-likelihood	-44620.2					
AIC (Akaike information criterion)	89260.4					

Table 14: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Non-animal Midblock Crashes on Rural Paved County Highway Segments (AADT Range: 300-5,000 vpd)

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-7.559		0.192	-39.46	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.734	0.734	0.027	27.22	<0.001
Residential Driveway Density	Continuous variable	0.007	0.007	0.001	2.78	0.005
Commercial/Industrial Driveway Density	Continuous variable	0.010	0.010	0.005	0.95	0.034
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.571	0.770	0.061	9.31	<0.001
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	0.036	0.037	0.039	0.93	0.352
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	0.107	0.113	0.038	3.11	0.186
Variance of site-specific random effect	0.3349					
Variance of county-specific random effect	0.0334					
Overdispersion	0.1234					
Log-likelihood	-18680.1					
AIC (Akaike information criterion)	37380.2					

Table 15: Mixed-Effects Negative Binomial Model Results for Property Damage Only Non-Animal Midblock Crashes on Rural Paved County Highway Segments (AADT Range: 300-5,000 vpd)

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.478		0.142	-45.58	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.707	0.707	0.019	37.41	<0.001
Residential Driveway Density	Continuous variable	0.005	0.005	0.001	6.80	<0.001
Commercial/Industrial Driveway Density	Continuous variable	0.008	0.008	0.004	0.63	0.530
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.455	0.576	0.046	9.83	<0.001
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	0.040	0.041	0.029	1.39	0.166
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	0.110	0.117	0.028	3.95	0.773
Variance of site-specific random effect	0.3233					
Variance of county-specific random effect	0.0958					
Overdispersion	0.1382					
Log-likelihood	-36390.6					
AIC (Akaike information criterion)	72801.2					

Additionally, to understand the differences in the safety performance of driveway land-use categories between paved federal aid county roads and paved non-federal aid county roads, separate models were developed for these two facilities, as shown in Table 16, Table 17, and Table 18, and Table 19, Table 20, and Table 21, respectively.

Table 16: Mixed-Effects Negative Binomial Model Results for Total Non-animal Midblock Crashes on Rural Paved Federal Aid County Highway Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-5.756		0.121	-47.64	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.663	0.663	0.015	43.16	<0.001
Residential Driveway Density	Continuous variable	0.005	0.005	0.001	3.32	0.001
Commercial/Industrial Driveway Density	Continuous variable	0.010	0.010	0.003	0.62	0.053
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.464	0.591	0.042	10.93	<0.001
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	0.054	0.055	0.025	2.16	0.309
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	0.108	0.114	0.025	4.27	<0.001
Variance of site-specific random effect	0.3189					
Variance of county-specific random effect	0.0948					
Overdispersion	0.1163					
Log-likelihood	-44706.1					
AIC (Akaike information criterion)	89432.1					

Table 17: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Non-animal Midblock Crashes on Rural Paved Federal Aid County Highway Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-7.151		0.177	-40.51	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.685	0.685	0.024	28.21	<0.001
Residential Driveway Density	Continuous variable	0.009	0.009	0.002	2.27	0.023
Commercial/Industrial Driveway Density	Continuous variable	0.012	0.013	0.005	0.49	0.062
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.517	0.677	0.062	8.33	<0.001
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	0.028	0.029	0.037	0.76	0.446
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	0.095	0.100	0.038	2.54	0.011
Variance of site-specific random effect	0.3283					
Variance of county-specific random effect	0.0546					
Overdispersion	0.0575					
Log-likelihood	-19215.7					
AIC (Akaike information criterion)	38451.4					

Table 18: Mixed-Effects Negative Binomial Model Results for Property Damage Only Non-Animal Midblock Crashes on Rural Paved Federal Aid County Highway Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.128		0.134	-45.89	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.669	0.669	0.017	39.38	<0.001
Residential Driveway Density	Continuous variable	0.004	0.004	0.002	2.73	0.006
Commercial/Industrial Driveway Density	Continuous variable	0.006	0.006	0.004	0.43	0.067
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.444	0.558	0.047	9.49	<0.001
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	0.051	0.052	0.027	1.86	0.628
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	0.101	0.106	0.028	3.63	<0.001
Variance of site-specific random effect	0.3170					
Variance of county-specific random effect	0.1139					
Overdispersion	0.1431					
Log-likelihood	-36530.1					
AIC (Akaike information criterion)	73080.2					

Table 19: Mixed-Effects Negative Binomial Model Results for Total Non-animal Midblock Crashes on Rural Paved Non-Federal Aid County Highway Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.783		0.204	-33.25	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.799	0.799	0.032	25.15	<0.001
Residential Driveway Density	Continuous variable	0.008	0.008	0.003	2.88	0.004
Commercial/Industrial Driveway Density	Continuous variable	0.007	0.007	0.011	0.66	0.512
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.361	0.435	0.096	3.75	<0.001
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	-0.036	-0.036	0.082	-0.44	0.659
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	0.029	0.029	0.063	0.46	0.648
Variance of site-specific random effect	0.3865					
Variance of county-specific random effect	0.0390					
Overdispersion	0.1381					
Log-likelihood	-7552.6					
AIC (Akaike information criterion)	15125.1					

Table 20: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Non-animal Midblock Crashes on Rural Paved Non-Federal Aid County Highway Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-8.189		0.348	-23.56	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.805	0.805	0.053	15.10	<0.001
Residential Driveway Density	Continuous variable	0.009	0.009	0.005	1.33	0.018
Commercial/Industrial Driveway Density	Continuous variable	0.014	0.014	0.019	0.74	0.457
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.528	0.696	0.152	3.47	0.001
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	0.048	0.050	0.135	0.36	0.719
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	0.051	0.052	0.106	0.48	0.629
Variance of site-specific random effect	0.6115					
Variance of county-specific random effect	0.0813					
Overdispersion	0.007					
Log-likelihood	-3000.9					
AIC (Akaike information criterion)	6021.9					

Table 21: Mixed-Effects Negative Binomial Model Results for Property Damage Only Non-Animal Midblock Crashes on Rural Paved Non-Federal Aid County Highway Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-7.132		0.238	-29.99	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.795	0.795	0.037	21.58	<0.001
Residential Driveway Density	Continuous variable	0.005	0.005	0.003	2.79	0.005
Commercial/Industrial Driveway Density	Continuous variable	0.003	0.003	0.012	0.45	0.651
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.285	0.330	0.114	2.51	0.012
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	-0.084	-0.080	0.096	-0.87	0.385
No Paved Shoulder	Baseline					
Paved Shoulder Presence	Binary indicator variable	0.023	0.023	0.073	0.31	0.756
Variance of site-specific random effect	0.4775					
Variance of county-specific random effect	0.0449					
Overdispersion	0.1019					
Log-likelihood	-6004.7					
AIC (Akaike information criterion)	12029.4					

From the above results (Table 16, Table 17, and Table 18, and Table 19, Table 20, and Table 21), it can be clearly seen that, for federal aid county roads, both residential and commercial/industrial driveways are significantly and positively associated with crash occurrence, similar to the models results of all paved county road segments. However, for non-federal aid county roads, only the residential driveways seemed to have an effect on crash frequency, but unlike federal roads, commercial/industrial driveways did not have any discernable impact on crashes. This could be due to the overabundance of residential driveways on non-federal aid county roads where more than 92 percent of segments have residential driveways, and less than 20 percent of segments have any commercial or industrial driveways on them.

Additionally, while the effects of traffic volumes for all crash severities and horizontal curve presence for total and PDO crashes are higher on non-federal aid county roads, the association between horizontal curve presence and crash occurrence is stronger on federal aid county roads. Lastly, the confounding effect of paved shoulder presence on increased crash likelihood, similar to the paved county road segment model results, were also found on federal aid county road segments, but not on non-federal aid roads. This again validates that the counterintuitive effect of paved shoulder is not discernable on non-federal aid roads where the difference in traffic volume between the segments with and without paved shoulder is small, unlike the federal aid roads.

4.3.3 Unpaved County Road Segments

The regression models for unpaved roads show slightly different results, as displayed in Table 22, Table 23, and Table 24. With regard to the safety effects of driveway density across the various land-use categories on unpaved road segments, the results showed that driveway density did not have a significant impact on crash frequency across all driveway land-use types. This supports the findings in an earlier study that driveway density may not be a significant factor influencing crash likelihood when the traffic volume is low (<2,000) (*148*).

Turning to the safety effects of horizontal curvature, similar to other facilities, statistically significant positive associations were found between crash occurrence and horizontal curve presence for all crash severities. In fact, the effect of horizontal curve presence is the strongest on unpaved roads, compared to that on both state highway and paved county highway segments. This supports expectations and previous research (*33*), as such curves are more often present on the low-volume non-federal aid county segments compared to the other roadway classes and the reduced surface friction provided by unpaved or gravel roads is particularly problematic along curves. However, unlike state and paved county highways, the effect of horizontal curves is stronger on total and PDO crashes compared to FI crashes. Specifically, the parameter estimates indicate up to 112.5 percent, 82.6 percent, and 112.9 percent greater total, FI, and PDO crashes, respectively, with the presence of horizontal curves on the segment, compared to the tangent segments.

The relationship between traffic crash frequency and AADT for unpaved roads is the least elastic among all roadway types included in this analysis, likely due to the less frequent (spatially and/or temporally) collection of traffic volume data on gravel roadways. Among all crashes, the association between AADT and crash occurrence is the strongest for PDO crashes and the weakest for fatal and injury crashes.

Moreover, a surface width greater than 22 feet was found to increase crash frequency for only total and PDO crashes. This may be attributable to the three times average traffic volume (594 vpd) on segments with surface width greater than 22 feet experiencing PDO crashes compared to that on the road segments with surface width up to 22 feet (198 vpd). Finally, unlike state and paved county highways, the variances of the site- and county-specific random effects indicate that there is more variation in sites between counties than there is variation between sites in general, on unpaved county roads.

Table 22: Mixed-Effects Negative Binomial Model Results for Total Non-animal Midblock Crashes on Rural Unpaved County Road Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-5.345		0.257	-20.79	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.509	0.509	0.032	16.02	<0.001
Residential Driveway Density	Continuous variable	0.005	0.005	0.004	0.135	0.893
Commercial/Industrial Driveway Density	Continuous variable	0.010	0.011	0.015	0.703	0.482
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.754	1.125	0.074	10.19	<0.001
Surface Width <= 22 feet	Baseline					
Surface Width >22 feet	Binary indicator variable	0.148	0.160	0.063	2.34	0.020
Variance of site-specific random effect	0.3340					
Variance of county-specific random effect	0.9035					
Overdispersion	0.0225					
Log-likelihood	-7848.3					
AIC (Akaike information criterion)	15714.6					

Table 23: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Non-animal Midblock Crashes on Rural Unpaved County Road Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-5.972		0.318	18.79	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.415	0.415	0.052	8.02	<0.001
Residential Driveway Density	Continuous variable	0.008	0.008	0.006	1.35	0.176
Commercial/Industrial Driveway Density	Continuous variable	0.012	0.012	0.026	0.585	0.558
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.602	0.826	0.122	4.93	<0.001
Surface Width <= 22 feet	Baseline					
Surface Width >22 feet	Binary indicator variable	0.056	0.057	0.106	0.523	0.601
Variance of site-specific random effect	0.2975					
Variance of county-specific random effect	0.4841					
Overdispersion	0.0010					
Log-likelihood	-3026.6					
AIC (Akaike information criterion)	6071.2					

Table 24: Mixed-Effects Negative Binomial Model Results for Property Damage Only Non-Animal Midblock Crashes on Rural Unpaved County Road Segments

Parameter	**Description**	**Estimate**	**Elasticity**	**S.E.**	**z-stat**	**p-value**
Intercept		-5.933		0.291	-20.38	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.538	0.538	0.036	14.80	<0.001
Residential Driveway Density	Continuous variable	0.003	0.003	0.004	0.28	0.780
Commercial/Industrial Driveway Density	Continuous variable	0.005	0.005	0.017	0.316	0.752
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.802	1.229	0.083	9.65	<0.001
Surface Width <= 22 feet	Baseline					
Surface Width >22 feet	Binary indicator variable	0.178	0.195	0.072	2.47	0.014
Variance of site-specific random effect	0.3575					
Variance of county-specific random effect	1.0997					
Overdispersion	0.0253					
Log-likelihood	-6204					
AIC (Akaike information criterion)	12426					

In order to further understand the confounding results of the association between surface width and total and PDO crashes on unpaved road segments in the previous model results, a subsequent analysis was carried out controlling for traffic volumes on segments with surface width greater than 22 feet, and the results of this subsequent analysis are presented in Table 25, Table 26, and Table 27. In these models, an overlapping range of traffic volume between 80 and 400 vehicles per day was considered. As the subsequent analysis indicate, when the crash frequency is estimated controlling for traffic volume on unpaved county road segments with surface width greater than 22 feet, the effect of surface width becomes insignificant.

Table 25: Mixed-Effects Negative Binomial Model Results for Total Non-animal Midblock Crashes on Rural Unpaved County Road Segments (AADT Range: 80-400 vpd)

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-5.683		0.516	-11.00	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.612	0.612	0.094	6.52	<0.001
Residential Driveway Density	Continuous variable	0.005	0.005	0.005	0.93	0.352
Commercial/Industrial Driveway Density	Continuous variable	0.011	0.011	0.022	1.81	0.708
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.622	0.863	0.094	6.64	<0.001
Surface Width <= 22 feet	Baseline					
Surface Width >22 feet	Binary indicator variable	0.057	0.059	0.080	0.71	0.477
Variance of site-specific random effect	0.2748					
Variance of county-specific random effect	0.9766					
Overdispersion	0.0463					
Log-likelihood	-4284					
AIC (Akaike information criterion)	8585.9					

Table 26: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Non-animal Midblock Crashes on Rural Unpaved County Road Segments (AADT Range: 80-400 vpd)

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.617		0.922	-7.180	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.477	0.477	0.184	2.598	0.009
Residential Driveway Density	Continuous variable	0.008	0.008	0.009	1.842	0.654
Commercial/Industrial Driveway Density	Continuous variable	0.013	0.013	0.042	0.856	0.392
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.343	0.409	0.197	1.742	0.081
Surface Width <= 22 feet	Baseline					
Surface Width >22 feet	Binary indicator variable	0.032	0.032	0.151	0.021	0.983
Variance of site-specific random effect	0.1920					
Variance of county-specific random effect	0.3010					
Overdispersion	0.0004					
Log-likelihood	-1678					
AIC (Akaike information criterion)	3374.1					

Table 27: Mixed-Effects Negative Binomial Model Results for Property Damage Only Non-Animal Midblock Crashes on Rural Unpaved County Road Segments (AADT Range: 80-400 vpd)

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.556		0.577	-11.36	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.711	0.711	0.106	6.72	<0.001
Residential Driveway Density	Continuous variable	0.003	0.003	0.005	0.90	0.370
Commercial/Industrial Driveway Density	Continuous variable	0.004	0.004	0.026	1.63	0.104
No Horizontal Curves	Baseline					
Horizontal Curve Presence (design speed <55 mph)	Binary indicator variable	0.665	0.944	0.101	6.59	<0.001
Surface Width <= 22 feet	Baseline					
Surface Width >22 feet	Binary indicator variable	0.043	0.044	0.088	0.48	0.628
Variance of site-specific random effect	0.1902					
Variance of county-specific random effect	1.0418					
Overdispersion	0.0667					
Log-likelihood	-3331.3					
AIC (Akaike information criterion)	6680.7					

4.3.4 Model Comparisons

For the purpose of comparing the model results between three segment types, comparative graphical representations of predicted total annual crash frequencies per mile as developed in the SPF models for rural two-lane roads with respect to traffic volume are presented in Figure 16. In all these graphics, crash estimates are plotted separately for the base condition of no driveways compared to 13 driveways per mile that includes 10 residential and 3 commercial/industrial driveways per mile. The driveway count per mile chosen here for each land-use category roughly represented the average driveway density values for rural roadways in Michigan.

Moreover, the other variables included in the SPFs were fixed to the most common values for each variable, as follows: lane width greater than 11 feet (state highways and paved county roads) or surface width greater than 22 feet (unpaved roads only), paved shoulder present (state highways and paved county roads), and no horizontal curves below 55 mph design speeds. Additionally, for comparison purposes, two-lane rural highway *HSM* SPF was calibrated for non-animal crashes (excluding 12.1 percent of animal crashes) using a total driveway density of 13 per mile and lane width of 12 feet and shown in the figure.

Figure 16 clearly depicts the effects of driveway density on total (non-animal) midblock crashes for all facilities. Even when set to typical values for driveway density, the estimated crash frequency for a given AADT is clearly greater than when no driveways are present, particularly for state highways at higher AADTs. Figure 16 also displays that the predicted total crash frequencies are consistently higher on paved county roadways compared to the state highways and unpaved roads. Moreover, for AADTs below approximately 3,000 vehicles per day, paved county roads show a slightly greater crash occurrence for total crashes than the *HSM* model. However, for AADTs greater than approximately 3,000 vehicles per day, the *HSM* model shows a much higher crash occurrence than that all three facilities.

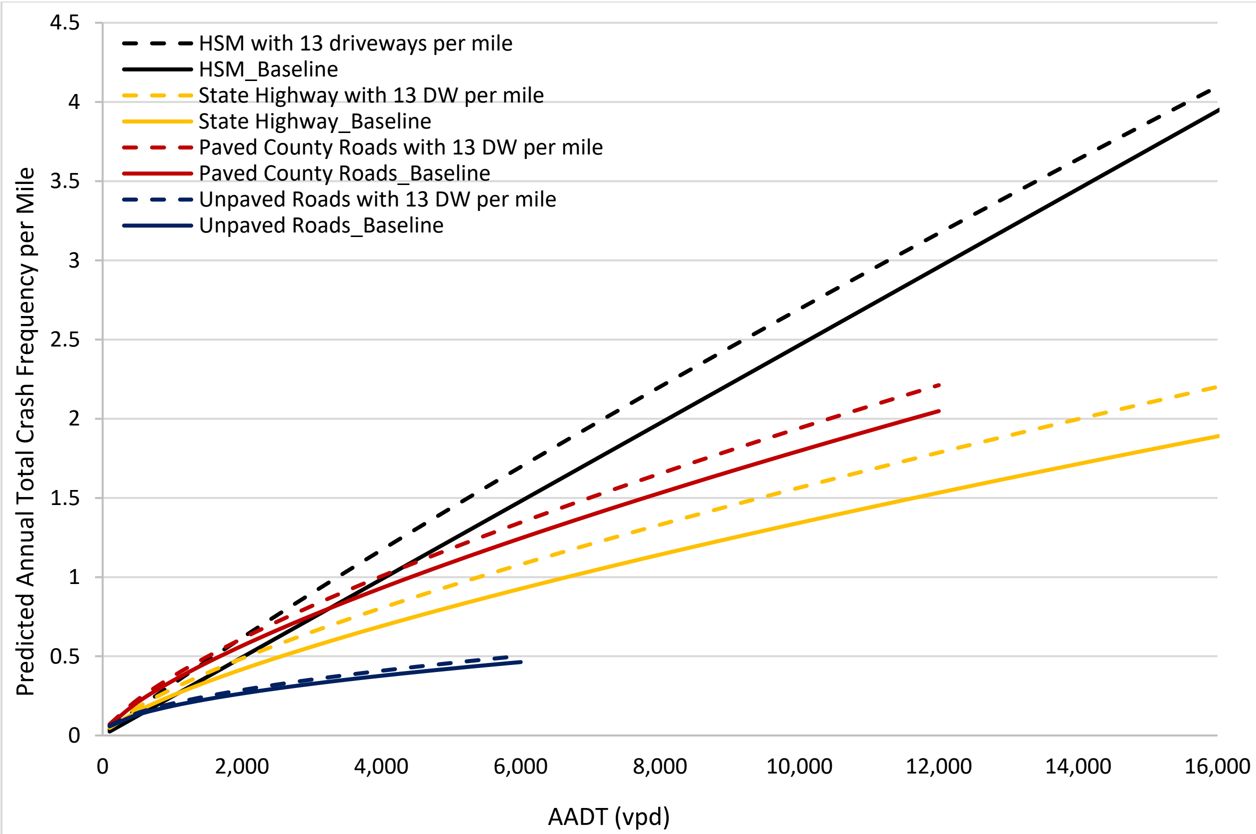


Figure 16: Estimates of predicted total annual crashes for two-lane rural highway segments.

4.4 Summary of Findings

This study involves the assessment of the safety impacts of various classifications of driveway land utilization, including residential, commercial, and industrial on rural two-lane state and county (paved and unpaved) road segments in Michigan. Non-animal road segment crashes from 2011 to 2018 were analyzed along with roadway geometry data for greater than 5,520 miles of state highways, 5,894 miles of paved county road segments, and 2,007 miles of unpaved road segments from across Michigan. To account for the unobserved heterogeneity associated with varied county design standards and site characteristics, mixed-effects negative binomial regression models with county- and site-specific random effects were utilized. Separate models were developed for state highways, paved county highways, and unpaved county roads. Also, the models were estimated separately for total, fatal and injury, property damage only crashes.

The results indicate that driveway land-use has a significant effect on safety performance along the road segments. Specifically, the density of commercial driveways was shown to have a stronger effect on crash frequency than other driveway land-use classes, although residential and industrial driveways also affected crash occurrence. The effect of driveway density on crash frequency was also found to be stronger on state highways compared to the paved county roads. However, driveway density does not have any significant impact on safety performance for unpaved road segments regardless of the land-use classification.

Additionally, the presence of horizontal curves with design speeds less than 55 mph was found to adversely impact safety on all segment types. Particularly, the effect of horizontal curve presence is the stronger on county roads, compared to the state highways. Considering all crash severities, the effect of horizontal curve presence was stronger for fatal and injury crashes on state and paved county highways, and for PDO crashes on unpaved county roads.

While the presence of a paved shoulder was associated with a decrease in crash occurrence for total and PDO crashes on state highways only, lane width did not have any significant impact on crash frequency for all segment types.

In general, the results of this study support the previous research findings related to the effect of driveway density on traffic safety and provide further evidence that various driveway land-use types affect safety to different extents on rural road segments. This study contributes to the limited body of knowledge regarding the relationship between traffic safety and driveway land-use for rural roadway segments, particularly for county roads, which typically possess design and travel characteristics that are considerably different from those of state highways.

5. ANALYSIS AND RESULTS: SAFETY PERORMANCE OF HORIZONTAL CURVE CHARACTERISTICS ON RURAL HIGHWAYS

5.1 Preliminary Analysis

The safety performance of horizontal curve characteristics for rural two-way two-lane undivided highway segments were analyzed using the data from across Michigan, as described in Chapter 3. Similar to the previous analysis, due to the differences in design characteristics, maintenance standards, traffic volumes, trip distances, and driver characteristics, among other factors, separate datasets were created for state- and county-owned highway curves. It is to note that, this analysis includes only single-vehicle crashes due to the overrepresentation (greater than 92 percent of all curve crashes) of such vehicle crashes on rural horizontal curves, and multi-vehicle crashes were excluded from this analysis. Also, minimum curve length analyzed was 0.1 mile. After the data were assembled for the horizontal curves on rural two-lane highways, a series of preliminary analyses were conducted to explore general trends for each facility type as below.

1. Horizontal curves on rural two-lane state highway segments
2. Horizontal curves on rural two-lane two-way county highway segments

5.1.1 Descriptive Statistics, Rural Highway Segments

A total of 1,324 horizontal curves on state highways, totaling 277 miles of length and 3,599 horizontal curves on county highways amounting to 557 miles of length were included in this analysis. It is important to note that, unlike the previous analysis, both paved and unpaved county highway curves are analyzed together. This is because, among all county highway curves, only less than 20 percent were gravel or otherwise unpaved. The summary statistics of horizontal curve characteristics for each variable associated with the curves along state and county highways are presented in Table 28 and Table 29.

As can be seen from Table 28 and Table 29, the prevalence of horizontal curves with design speed less than 55 mph is considerably more on county highways compared to the state highways. The tangent distances preceding and following a curve as well as inner-curve distance are much shorter on county roads indicating a more frequent presence of curved alignment compared to state highways. Moreover, the reverse curves are more prevalent on county roads compared to the state road segments, while the isolated curves are more common on state highways. Expectedly, the traffic volumes, curve length, and average crash frequencies for all crash severities for horizontal curves analyzed in this study were higher along the state highways. Also, wider lanes (lane width >11 feet) were more common along the curves on state highways, an observation consistent with higher design standards compared to county roads.

When these summary statistics of the geometric characteristics of horizontal curves are compared those on the road segments including both curved and tangent sections for the respective facilities from the previous analysis, it can be clearly seen that, overall, the results are consistent. Particularly, average traffic volume, lane width, and average crash frequency for all severities are consistently higher on state highway segments (including both curved and tangent sections) as well only horizontal curves.

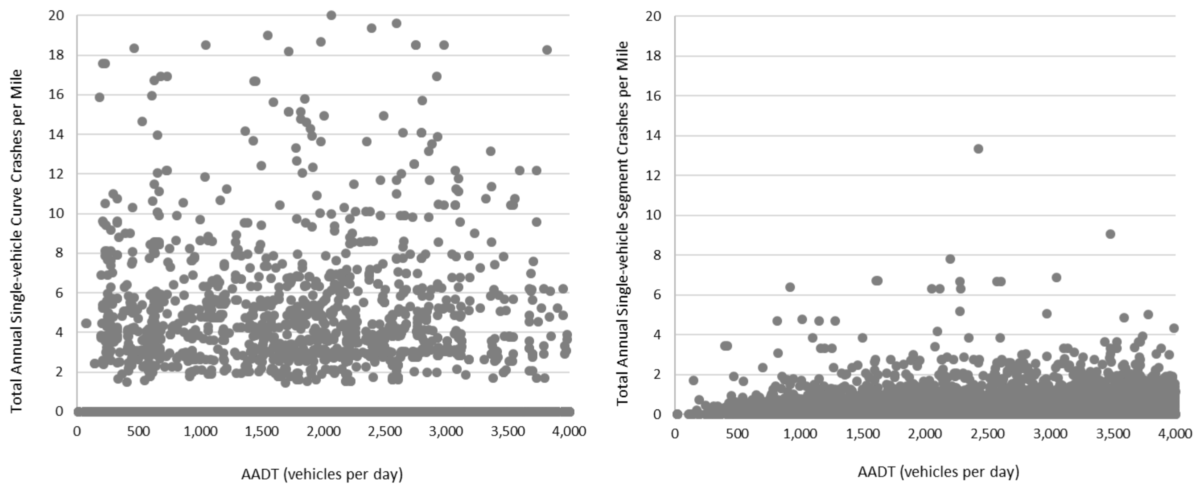
Table 28: Summary Statistics for Horizontal Curve Characteristics on Rural Two-lane Undivided State Highway Segments (*n = 1,324*)

Factor	Min	Max	Mean	Std. Dev
Traffic volume (AADT) (vehicles per day)	23	22,154	3.315	2,777
Curve length (mi)	0.11	0.76	0.21	0.12
Curve design speed < 55 mph	0	1	0.06	0.29
Approaching tangent distance for a simple curve or the first of the series of a compound or reverse curve (mi)	0	33.60	1.79	2.73
Following tangent distance for a simple curve or the last of the series of a compound or reverse curve (mi)	0	21.92	1.88	2.67
Inner-curve distance for compound or reverse curves (mi)	0	17.77	0.58	1.81
Simple curve	0	1	0.35	0.48
Compound curve	0	1	0.47	0.50
Reverse curve	0	1	0.18	0.38
Left turning curve	0	1	0.51	0.50
Lane width > 11 feet	0	1	0.47	0.50
Non-animal total single-vehicle curve crashes (count/segment-year)	0	5	0.07	0.29
Non-animal fatal-injury (FI) single-vehicle curve crashes (count/segment-year)	0	3	0.02	0.15
Non-animal property damage only (PDO) single-vehicle curve crashes (count/segment-year)	0	4	0.05	0.24

Table 29: Summary Statistics for Horizontal Curve Characteristics on Rural Two-lane Undivided County Highway Segments (*n = 3,599*)

Factor	Min	Max	Mean	Std. Dev
Traffic volume (AADT) (vehicles per day)	5	8.810	787	1,088
Curve length (mi)	0.10	0.74	0.16	0.08
Curve design speed < 55 mph	0	1	0.45	0.50
Approaching tangent distance for a simple curve or the first of the series of a compound or reverse curve (mi)	0	13.57	0.80	1.23
Following tangent distance for a simple curve or the last of the series of a compound or reverse curve (mi)	0	12.51	0.57	1.07
Inner-curve distance for compound or reverse curves (mi)	0	10.87	0.21	0.68
Simple curve	0	1	0.27	0.44
Compound curve	0	1	0.48	0.50
Reverse curve	0	1	0.25	0.44
Left turning curve	0	1	0.52	0.50
Lane width > 11 feet	0	1	0.28	0.45
Non-animal total single-vehicle curve crashes (count/segment-year)	0	6	0.03	0.22
Non-animal fatal-injury (FI) single-vehicle curve crashes (count/segment-year)	0	3	0.01	0.10
Non-animal property damage only (PDO) single-vehicle curve crashes (count/segment-year)	0	4	0.02	0.16

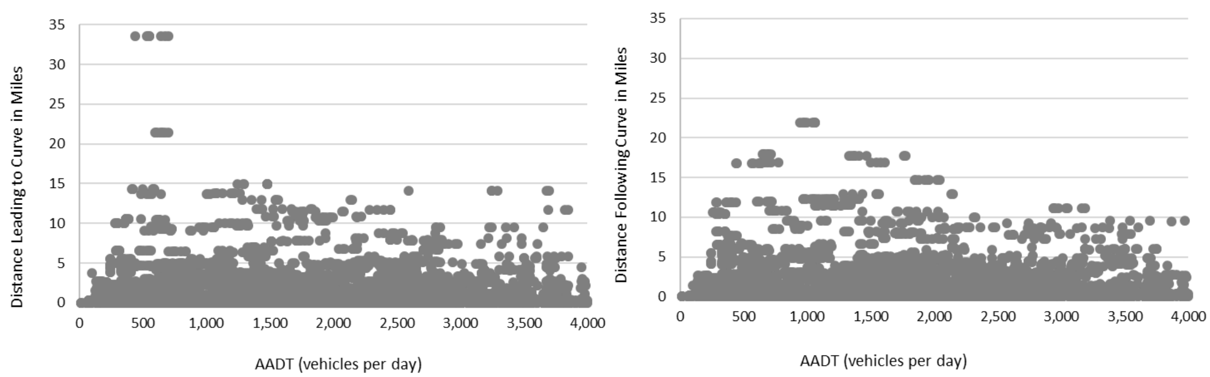
The crash data and horizontal curve characteristics being the primary variables of interest of this study, were further explored with the help of graphical representations to examine general trends of them for each facility type as shown in Figure 17 and Figure 18, and Figure 19 and Figure 20, respectively, for state and county highways. For annual crash frequency normalized on a per-mile basis, the observed data were plotted against traffic volumes. Also, the total crash frequency on horizontal curves is compared with that on roadway segments previously analyzed in Chapter 4, for single-vehicle crashes. This gives us a comparative understanding of crash occurrence between only the horizontal curves and the roadway segments comprising both curved and tangent sections. Additionally, tangent distances leading to and following a curve, and curve radius, all represented in miles, are plotted against AADT.



Annual single-vehicle crash frequency on state highway curves

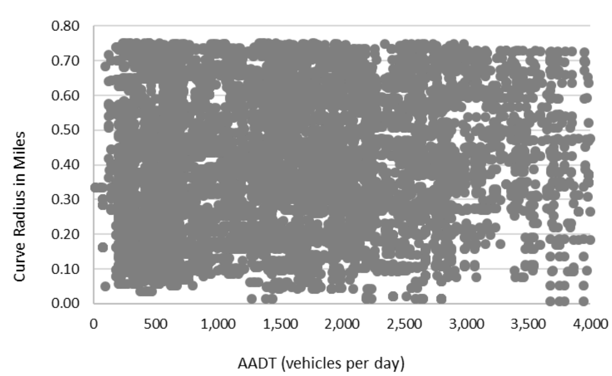
Annual single-vehicle crash frequency on state highway segments

Figure 17: Annual single-vehicle crashes per mile on horizontal curves and road segments vs AADT, state highways.



Distance leading to a curve in miles

Distance following a curve in miles



Curve radius in miles

Figure 18: Tangent distance leading to a horizontal curve, tangent distance following a horizontal curve, and horizontal curve radius vs. AADT on state highways.

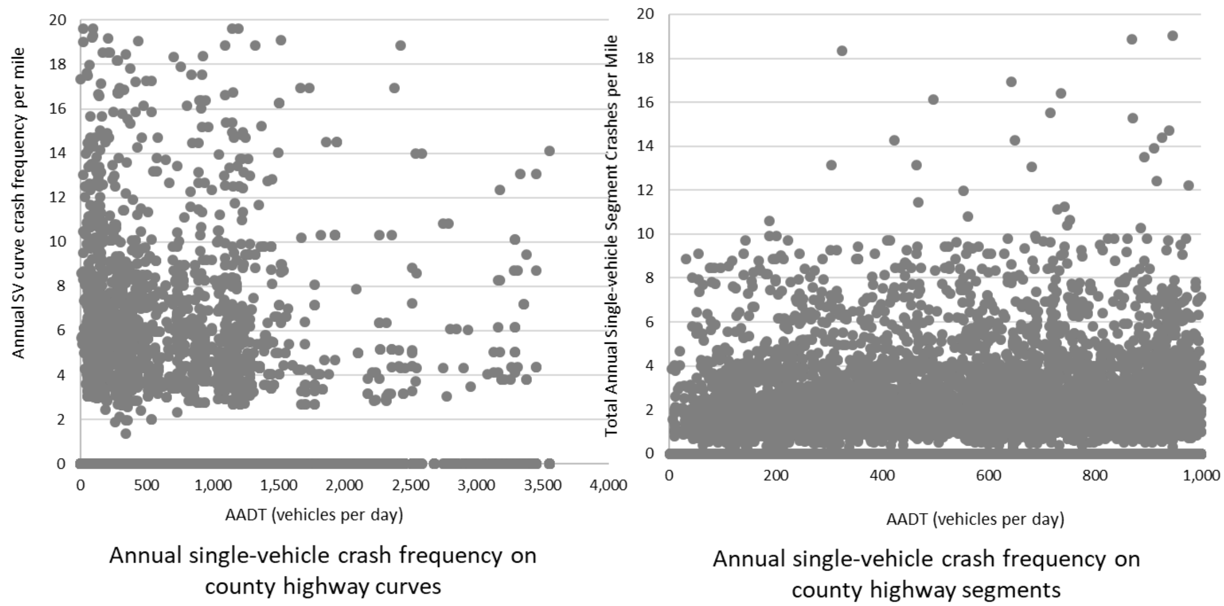


Figure 19: Annual single-vehicle crashes per mile on horizontal curves and road segments vs AADT, county highways.

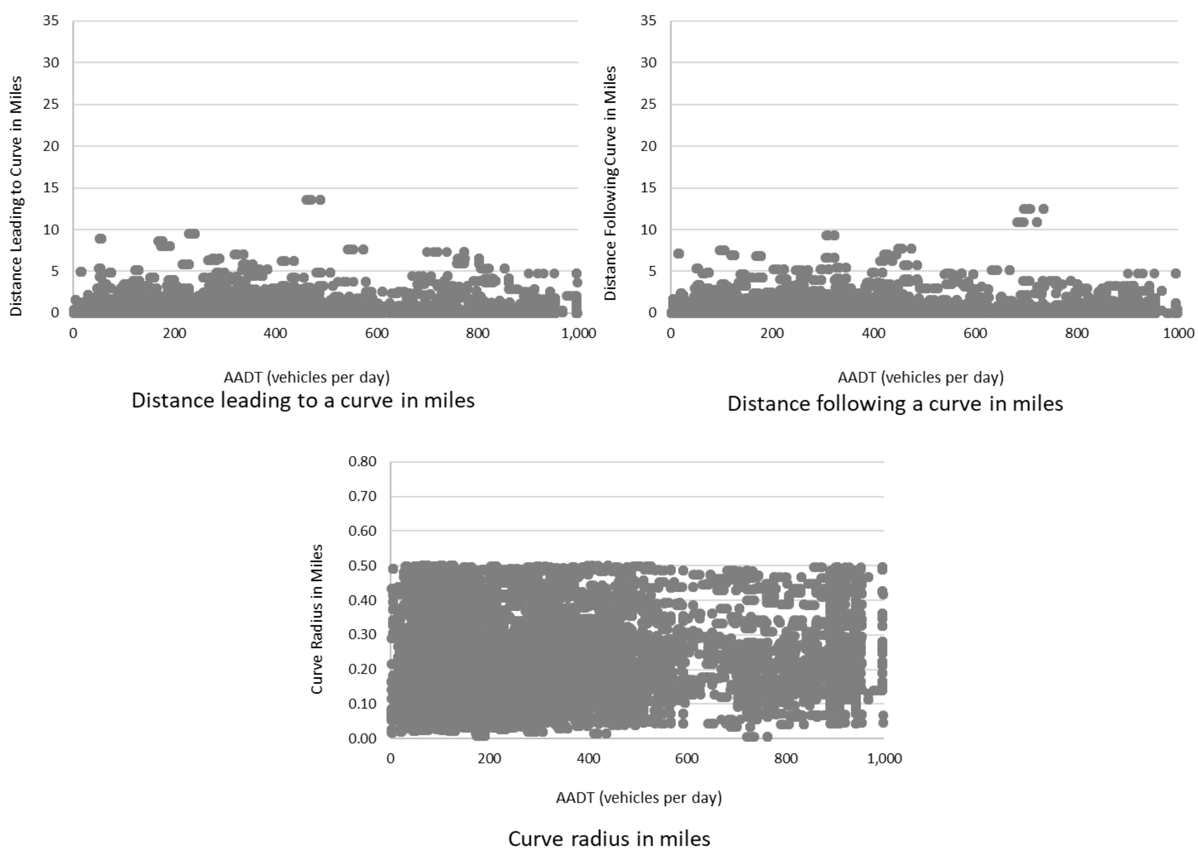


Figure 20: Tangent distance leading to a horizontal curve, tangent distance following a horizontal curve, and horizontal curve radius vs. AADT on county highways.

Figure 17 and Figure 19 clearly show that, when comparing between horizontal curves and road segments (including both curved and tangent sections), the total single-vehicle crash frequency per mile on horizontal curves is consistently greater than that on road segments for same range of AADT and this is true for both state and county highways. Also, crash frequency per mile is higher on county highway curves compared to state highway curves.

Additionally, Figure 18 and Figure 20 show that the tangent distances leading to and following a curve as well as inner-curve distances are much smaller on county road curves than the state highway curves indicating a more frequent presence of horizontal curves along the county highways. Similarly, the average curve radius is observably smaller on county road curves compared to that on state highways, indicating an overabundance of underdesigned curves along the county roads.

Additionally, Table 30 shows the crash distributions for individual crash severity and different collision types for single-vehicle crashes on horizontal curves along the state highway and county roads.

Table 30: Crash Severity and Collision Type Distributions for Non-animal Single-vehicle Midblock Crashes on Horizontal Curves along Rural Two-lane Undivided State and County Highways

Crash severities and types	Horizontal Curves on State Highways		Horizontal Curves on County Highways	
	Count	**Percent of non-animal midblock crashes**	**Count**	**Percent of non-animal midblock crashes**
Total Crashes	1,550	100.0%	1,846	100.0%
Fatal and injury (FI)	441	28.5%	555	30.1%
Fatal (K)	19	1.2%	17	0.9%
Incapacitating injury (A)	81	5.2%	73	4.0%
Non-incapacitating injury (B)	145	9.4%	207	11.2%
Possible injury (C)	196	12.7%	258	14.0%
Property damage only (PDO)	1,109	71.5%	1,291	69.9%
In dry road	706	38.3%	762	41.4%
Alcohol/Drug involved	193	10.5%	321	17.4%
Pedestrian/Bike related	13	0.7%	4	0.2%
In Daylight	797	43.2%	991	53.7%

5.2 SPF Development

The analysis involved the development of the several mixed-effects negative binomial models separately for curves on different jurisdictions (state and county highway curves) and different crash severities of single-vehicle crashes. The models included curve types with the baseline condition of simple curves.

A recent study from Michigan indicated that the horizontal curves with a radius corresponding to a design speed less than the posted speed limit along the segments has a significant impact on crash frequency (*175*). Therefore, along with all other variables, the curve design speed (less than 55 mph vs more than or equal to 55 mph) was also added as a binary variable. The radii of curves were utilized to compute the corresponding design speeds, assuming a superelevation of 7 percent, the maximum superelevation used by MDOT (*166*) and a curve radius threshold of 0.191 miles or 1,008 feet corresponded to a design speed of 55 mph or lower. This design speed was chosen as the statutory speed limit for rural county highways in Michigan during the analysis period was 55 mph and curves designed below this speed would typically possess curve warning signage.

Additionally, the approaching, following, and inner-curve tangent distances were treated as continuous variables and were added in their natural log forms in the models. Moreover, a binary variable indicating the direction of curve (left vs right) were also included in the models. Lastly, the models included binary variables for lane widths (less than or equal to 11 feet vs greater than 11 feet) for paved horizontal curves and surface widths (less than or equal to 22 feet vs greater than 22 feet) for unpaved horizontal curves in lieu of lane width and shoulder width, respectively.

Separate models were estimated for total, fatal and injury (FI), and property damage only (PDO) single-vehicle crashes, although the applicability of the FI crashes is diminished for the county-curves models, due to the generally low occurrence of such crashes.

Moreover, due to the confounding effects of the tangent distances between simple, and compound or reverse curves on crash likelihood, separate models were developed including all curve types (Table 34, Table 35, and Table 36, and Table 43, Table 44, and Table 45), excluding curve type and including approaching/following tangent distance for a simple curve or the first/last curve of a series of compound or reverse curves (Table 37, Table 38, and Table 39, and Table 46, Table 47, and Table 48), and excluding curve type and including inner-curve distance of compound or reverse curves (Table 31, Table 32, and Table 33, and Table 40, Table 41, and Table 42), respectively.

In all models, curve length was treated as an offset with its parameter estimate fixed at 1 thereby normalizing the results to homogenous one-mile curves, as the crash frequency on a road segment is generally considered to be proportional to the segment length. Initial models included various combinations of independent variables and based on the p-values of the parameter estimates, AIC, and log-likelihood information, the best fit models were chosen. A significance level of 0.1 ($\alpha = 0.1$) was used in this analysis. Table 31 to Table 48 display the results of mixed-effect negative binomial models including parameter estimates, elasticity, standard errors (S.E.), z-statistics, and p-values for single-vehicle crashes on the horizontal curves along the state and county highways. The following subsections present the discussion of the model results for both facilities analyzed in this study.

5.3 Results and Discussion

5.3.1 Horizontal Curves on State Highway Segments

The results of the analysis of horizontal curves along state highway segments yielded several interesting findings. First, in terms of the type of curve, significant adverse safety impacts on single-vehicle crashes were associated with compound and reverse curves compared to simple curves for all crash severities. Moreover, among all curve types, the safety impacts of curves on single-vehicle crash occurrence were the greatest for reverse curves. Also, the effect of curve type is the most pronounced on fatal and injury (FI) crashes. Specifically, the parameter estimates (Table 31, Table 32, and Table 33) indicate greater crash occurrences on compound curves by 17.6 percent, 19.2 percent, and 15.8 percent for total, FI, and PDO crashes, respectively, compared to that on simple curves. Similarly, the results showed greater crash occurrences on reverse curves by 21.8 percent, 23.4 percent, and 20.3 percent for total, FI, and

PDO crashes, respectively, compared to that on simple curves. Overall, these findings agree with expectations and compare favorably with prior works that the driving maneuvers become more complicated along the reverse or compound curves, increasing the risk of crash, particularly for fatal and severe injury crashes (*176*).

Additionally, curve design speed lower than the posted speed limit, which is 55 mph in this analysis, were found to be associated with higher single-vehicle crash frequency on state highway curves, a finding supported by previous research (*33*). This factor, as well, had a more pronounced effect on FI crashes. Particularly, the model results indicate (Table 31, Table 32, and Table 33) increased crash occurrence by 20.0 percent, 21.7 percent, and 17.2 percent for total, FI, and PDO crashes, respectively, on curves with radius corresponding to design speed lower than 55 mph, compared to curves with design speeds of 55 mph or higher.

In terms of the distance between two consecutive curves, the approaching tangent distance for a simple curve or the first curve of a series of compound or reverse curves was associated positively with crash occurrence, meaning greater the distance higher the crash occurrence (Table 34, Table 35, and Table 36). This could perhaps be due to the lack of driver expectancy for such curvature as the distance from the prior curve or other geometric feature increases. Particularly, the model results indicate that crash occurrence increased by 4.1 percent, 5.4 percent, and 3.8 percent for total, FI, and PDO crashes, respectively, for one mile increase of the approaching tangent distance for a simple curve or the first curve of a series of compound or reverse curves. However, when only the inner-curve distance is analyzed for the compound and reverse curves, this factor is negatively associated with crash likelihood, implying the smaller the inner-curve distance, the greater the crash occurrence (Table 37, Table 38, and Table 39). The parameter estimates indicate that the crash frequency decreases by 8.3 percent, 9.1 percent, and

7.6 percent, for total, FI, and PDO crashes, respectively, for one mile increase in the inner-curve distance for the compound and reverse curves. Interestingly, when all curve types are included in the models, this variable is shown to be negatively associated with a crash occurrence due to the overrepresentation of the compound or reverse curves (Table 31, Table 32, and Table 33) in the data. Moreover, the tangent distance following a simple curve or the last curve of a series of compound or reverse curves did not have any significant impact on crash occurrence.

Furthermore, a left-turning curve was found to experience significantly higher single-vehicle crashes compared to that on a right-turning curves. This can be partially due to the fact that the left-turning curves position vehicles towards the roadside, thereby increasing the likelihood of roadway departure crashes. The increase in crash frequency (Table 31, Table 32, and Table 33) was shown to be by 11.4 percent, 13.1 percent, and 7.9 percent, for total, FI, and PDO crashes, respectively, on a left-turning curve compared to that on a right-turning curve. This also supports the findings from a previous study that indicate left-turning curves pose more challenge on driving task while negotiating the curves compared to right-turning curves (*177*). For all these factors stated above, the extent of influence was greater for fatal and injury crashes, compared to the property damage only crash types, a finding consistent with previous studies (*28*, *34*, *35*).

Turning to the safety effects of other roadway factors, the association between single-vehicle crash frequency and AADT was inelastic with the strongest effect on FI crashes. Furthermore, lane width greater than 11 feet did not impact crash frequency for all crash severities on horizontal curves along state highways, a finding consistent with a previous research from Michigan on state highway segments (including both curved and tangent sections) that indicated no significant impact of lane widths on total or fatal and injury crashes (*34*).

Finally, the variances of the curve- and county-specific random effects indicate that there is more variation between curves in general than there is variation in curves between counties on state highways.

Table 31: Mixed-Effects Negative Binomial Model Results for Total Non-animal Single-vehicle Crashes on Horizontal Curves along Rural State Highways

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.198		0.393	-17.15	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.763	0.763	0.055	13.93	<0.001
Simple Curve	Baseline					
Compound Curve	Binary indicator variable	0.162	0.176	0.121	1.92	0.055
Reverse Curve	Binary indicator variable	0.197	0.218	0.094	2.70	0.022
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.182	0.200	0.093	3.04	<0.001
Tangent distance leading to a curve	Natural log of, miles	-0.056	-0.056	0.015	-0.65	0.027
Tangent distance following a curve	Natural log of, miles	0.015	0.015	0.013	0.17	0.243
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.108	0.114	0.042	0.35	0.020
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	-0.032	-0.031	0.090	-0.58	0.348
Variance of site-specific random effect	0.6567					
Variance of county-specific random effect	0.0477					
Overdispersion	0.1304					
Log-likelihood	-7295.1					
AIC (Akaike information criterion)	14614.3					

Table 32: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Non-animal Single-vehicle Crashes on Horizontal Curves along Rural State Highways

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-8.268		0.577	-15.45	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.880	0.880	0.079	11.10	<0.001
Simple Curve	Baseline					
Compound Curve	Binary indicator variable	0.176	0.192	0.081	3.05	0.023
Reverse Curve	Binary indicator variable	0.210	0.234	0.143	3.59	0.010
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.196	0.217	0.134	4.37	<0.001
Tangent distance leading to a curve	Natural log of, miles	-0.062	-0.062	0.026	-0.61	0.009
Tangent distance following a curve	Natural log of, miles	0.016	0.016	0.020	0.43	0.407
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.123	0.131	0.074	0.78	0.053
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	-0.054	-0.053	0.129	-0.59	0.544
Variance of site-specific random effect	0.9556					
Variance of county-specific random effect	0.0352					
Overdispersion	0.0951					
Log-likelihood	-3151.8					
AIC (Akaike information criterion)	6327.5					

Table 33: Mixed-Effects Negative Binomial Model Results for Property Damage Only Non-Animal Single-vehicle Crashes on Horizontal Curves along Rural State Highways

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.746		0.423	-15.94	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.723	0.723	0.059	12.23	<0.001
Simple Curve	Baseline					
Compound Curve	Binary indicator variable	0.147	0.158	0.086	2.54	0.011
Reverse Curve	Binary indicator variable	0.185	0.203	0.102	2.80	0.005
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.159	0.172	0.101	3.30	0.003
Tangent distance leading to a curve	Natural log of, miles	-0.055	-0.055	0.017	-0.69	0.010
Tangent distance following a curve	Natural log of, miles	0.010	0.010	0.014	0.25	0.452
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.076	0.079	0.049	0.67	0.022
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	-0.022	-0.022	0.096	-0.43	0.827
Variance of site-specific random effect	0.5984					
Variance of county-specific random effect	0.0528					
Overdispersion	0.1030					
Log-likelihood	-5623.2					
AIC (Akaike information criterion)	11270.4					

Table 34: Mixed-Effects Negative Binomial Model Results for Total Non-animal Single-vehicle Crashes on Horizontal Curves along Rural State Highways Considering Approaching and Following Curve Distances

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.347		0.493	-19.39	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.797	0.797	0.083	12.76	<0.001
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.176	0.192	0.170	2.66	0.008
Approaching tangent distance for a simple curve or first of a series of compound / reverse curve	Natural log of, miles	0.041	0.041	0.015	0.05	0.065
Following tangent distance for a simple curve or the last of a series of compound / reverse curve	Natural log of, miles	0.034	0.034	0.015	0.14	0.696
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.094	0.099	0.049	0.07	0.039
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	-0.019	-0.019	0.122	-0.02	0.307
Variance of site-specific random effect	0.4538					
Variance of county-specific random effect	0.0464					
Overdispersion	0.1333					
Log-likelihood	-3114.3					
AIC (Akaike information criterion)	6248.6					

Table 35: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Non-animal Single-vehicle Crashes on Horizontal Curves along Rural State Highways Considering Approaching and Following Curve Distances

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-9.167		0.891	-11.41	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.913	0.913	0.122	11.15	<0.001
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.191	0.210	0.171	4.90	0.057
Approaching tangent distance for a simple curve or first of a series of compound / reverse curve	Natural log of, miles	0.054	0.054	0.045	0.82	0.075
Following tangent distance for a simple curve or the last of a series of compound / reverse curve	Natural log of, miles	0.029	0.029	0.025	0.42	0.903
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.110	0.116	0.053	0.67	0.008
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	0.038	0.039	0.191	0.50	0.452
Variance of site-specific random effect	0.6970					
Variance of county-specific random effect	0.0554					
Overdispersion	0.0853					
Log-likelihood	-1333.1					
AIC (Akaike information criterion)	2686.2					

Table 36: Mixed-Effects Negative Binomial Model Results for Property Damage Only Non-Animal Single-vehicle Crashes on Horizontal Curves along Rural State Highways Considering Approaching and Following Curve Distances

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-7.517		0.674	-11.16	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.770	0.770	0.094	13.22	<0.001
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.155	0.168	0.193	2.15	0.003
Approaching tangent distance for a simple curve or first of a series of compound / reverse curve	Natural log of, miles	0.038	0.038	0.018	0.91	0.027
Following tangent distance for a simple curve or the last of a series of compound / reverse curve	Natural log of, miles	0.033	0.033	0.018	0.23	0.407
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.069	0.071	0.035	0.71	0.048
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	-0.032	-0.031	0.132	-0.24	0.811
Variance of site-specific random effect	0.5019					
Variance of county-specific random effect	0.0232					
Overdispersion	0.0579					
Log-likelihood	-2464.3					
AIC (Akaike information criterion)	4948.7					

Table 37: Mixed-Effects Negative Binomial Model Results for Total Non-animal Single-vehicle Crashes on Horizontal Curves along Rural State Highways Considering Inner-Curve Distance for Compound / Reverse Curves

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.363		0.546	-11.67	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.744	0.744	0.078	9.56	<0.001
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.188	0.207	0.124	1.68	0.007
Inner-curve tangent distance for compound / reverse curves	Natural log of, miles	-0.083	-0.083	0.016	-1.02	0.044
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.121	0.129	0.028	1.67	0.008
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	-0.017	-0.017	0.126	-1.37	0.171
Variance of site-specific random effect	0.6459					
Variance of county-specific random effect	0.1295					
Overdispersion	0.1862					
Log-likelihood	-3981.6					
AIC (Akaike information criterion)	7981.2					

Table 38: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Non-animal Single-vehicle Crashes on Horizontal Curves along Rural State Highways Considering Inner-Curve Distance for Compound / Reverse Curves

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-8.557		0.791	-10.81	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.848	0.848	0.115	7.39	<0.001
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.208	0.231	0.206	1.10	0.027
Inner-curve tangent distance for compound / reverse curves	Natural log of, miles	-0.091	-0.091	0.027	-1.31	0.019
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.137	0.147	0.050	2.95	0.023
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	-0.031	-0.031	0.190	-0.61	0.540
Variance of site-specific random effect	1.41661					
Variance of county-specific random effect	0.02595					
Overdispersion	0.0302					
Log-likelihood	-1734.7					
AIC (Akaike information criterion)	3487.3					

Table 39: Mixed-Effects Negative Binomial Model Results for Property Damage Only Non-Animal Single-vehicle Crashes on Horizontal Curves along Rural State Highways Considering Inner-Curve Distance for Compound / Reverse Curves

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.591		0.604	-10.92	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.722	0.722	0.086	8.39	<0.001
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.169	0.184	0.135	2.95	0.003
Inner-curve tangent distance for compound / reverse curves	Natural log of, miles	-0.076	-0.076	0.018	-1.80	0.073
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.102	0.107	0.034	1.21	0.003
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	0.009	0.009	0.137	1.41	0.159
Variance of site-specific random effect	0.6102					
Variance of county-specific random effect	0.1587					
Overdispersion	0.0981					
Log-likelihood	-3025.7					
AIC (Akaike information criterion)	6069.5					

5.3.2 Horizontal Curves on County Highway Segments

As can be seen from Table 40 to Table 48, similar to curves on state highways, both compound and reverse curves resulted in greater single-vehicle crash occurrence compared to simple curves for all crash severities. Also, the effect of reverse curves was more pronounced relative to simple and compound curves. Additionally, the effect of curve type is the most pronounced on fatal and injury (FI) crashes, similar to curves on state highways. Specifically, the parameter estimates (Table 40, Table 41, and Table 42) indicate greater crash occurrences on compound horizontal curves by 22.3 percent, 23.6 percent, and 19.6 percent for total, FI, and PDO crashes, respectively, compared to that on simple curves. Similarly, the results showed greater crash occurrences on reverse horizontal curves by 25.0 percent, 28.3 percent, and 23.9 percent for total, FI, and PDO crashes, respectively, compared to that on simple curves. It is important to note that the effect of different curve types is stronger on county highway curves compared to the curves along state highways.

Moreover, radius of curvatures corresponding to design speed lower than the posted speed limit were associated with higher single-vehicle crash frequency on county highway curves, and to a greater extent compared to curves on state highways. This factor, as well, had a more pronounced effect on FI crashes. Particularly, the model results indicate (Table 40, Table 41, and Table 42), increased crash occurrence by 23.2 percent, 23.7 percent, and 20.2 percent for total, FI, and PDO crashes, respectively, on curves design speed lower than 55 mph, compared to curves with design speeds of 55 mph or higher.

In terms of the distance between two consecutive curves, similar to the state highway curves, the approaching tangent distance for a simple curve or the first curve of a series of compound or reverse curves was associated increased crash occurrence and to a greater extent on county highway curves (Table 43, Table 44, Table 45). Particularly, the model results indicate that crash occurrence increased by 5.5 percent, 6.8 percent, and 4.1 percent for total, FI, and PDO crashes, respectively, for one mile increase of the approaching tangent distance for a simple curve or the first curve of a series of compound or reverse curves. However, when only the inner-curve distance is analyzed for the compound and reverse curves, this factor is negatively associated with crash likelihood, and to a smaller extent on county highway curves (Table 46, Table 47, and Table 48). The parameter estimates indicate that the crash frequency decreases by

6.8 percent, 7.4 percent, and 5.7 percent, for total, FI, and PDO crashes, respectively, for one mile increase in the inner-curve distance for the compound and reverse curves. Interestingly, when all curve types are included in the models, this variable is shown to be negatively associated with a crash occurrence due to the overrepresentation of the compound or reverse curves (Table 40, Table 41, and Table 42) in the data. Moreover, the tangent distance following a simple curve or the last curve of a series of compound or reverse curves did not have any significant impact on crash occurrence, similar to the curves on state highways.

Furthermore, a left-turning curve was found to experience higher single-vehicle crashes compared to that on a right-turning curves, similar to that on state highways but to a smaller extent. The increase in crash frequency (Table 40, Table 41, and Table 42), was found to be by 9.1 percent, 10.6 percent, and 7.1 percent, for total, FI, and PDO crashes, respectively, on a left-turning curve compared to that on a right-turning curve. Also, similar to other factors, the extent of influence by this variable on crash occurrence was greater for FI crashes, compared to the total and PDO crashes.

In terms of the safety effects of other roadway characteristics, the relationship between single-vehicle crash frequency and AADT for county curves is less elastic than that for state highway curves across all crash severities with a stronger effect on FI crashes. Furthermore, similar to the results for the state highway models, lane width (for paved curves only) and surface width (for unpaved curves only) did not have a significant effect on crashes, comparing favorably with previous research (*34*, *35*). Finally, the variances of the curve- and county-specific random effects indicate that there is more variation between curves in general than there is variation in curves between counties on county highways.

Table 40: Mixed-Effects Negative Binomial Model Results for Total Non-animal Single-vehicle Crashes on Horizontal Curves along Rural County Highways

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-4.234		0.171	-24.75	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.549	0.549	0.026	13.61	<0.001
Simple Curve	Baseline					
Compound Curve	Binary indicator variable	0.201	0.223	0.071	3.77	0.019
Reverse Curve	Binary indicator variable	0.223	0.250	0.074	4.78	0.002
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.209	0.232	0.054	5.52	0.020
Tangent distance leading to a curve	Natural log of, miles	-0.037	-0.037	0.036	-0.87	0.011
Tangent distance following a curve	Natural log of, miles	0.017	0.017	0.025	0.17	0.383
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.087	0.091	0.041	0.40	0.033
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	0.008	0.008	0.062	0.12	0.703
Variance of site-specific random effect	0.5994					
Variance of county-specific random effect	0.0593					
Overdispersion	0.0272					
Log-likelihood	-10015					
AIC (Akaike information criterion)	20053					

Table 41: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Non-animal Single-vehicle Crashes on Horizontal Curves along Rural County Highways

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-5.392		0.284	-18.96	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.647	0.647	0.042	5.81	<0.001
Simple Curve	Baseline					
Compound Curve	Binary indicator variable	0.212	0.236	0.131	3.54	0.055
Reverse Curve	Binary indicator variable	0.249	0.283	0.136	4.42	0.012
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.213	0.237	0.096	5.15	0.076
Tangent distance leading to a curve	Natural log of, miles	-0.043	-0.043	0.065	-0.21	0.027
Tangent distance following a curve	Natural log of, miles	0.012	0.012	0.045	0.18	0.114
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.101	0.106	0.071	0.47	0.089
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	-0.024	-0.024	0.107	-0.24	0.252
Variance of site-specific random effect	1.817					
Variance of county-specific random effect	0.0361					
Overdispersion	0.0176					
Log-likelihood	-4192.8					
AIC (Akaike information criterion)	8409.6					

Table 42: Mixed-Effects Negative Binomial Model Results for Property Damage Only Non-Animal Single-vehicle Crashes on Horizontal Curves along Rural County Highways

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-4.967		0.197	-25.24	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.518	0.518	0.029	14.24	<0.001
Simple Curve	Baseline					
Compound Curve	Binary indicator variable	0.179	0.196	0.081	2.66	0.078
Reverse Curve	Binary indicator variable	0.214	0.239	0.083	3.21	0.002
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.184	0.202	0.061	3.19	0.027
Tangent distance leading to a curve	Natural log of, miles	-0.033	-0.033	0.043	-0.49	0.070
Tangent distance following a curve	Natural log of, miles	0.014	0.014	0.029	0.21	0.130
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.069	0.071	0.049	0.35	0.040
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	0.042	0.043	0.069	0.20	0.546
Variance of site-specific random effect	0.5634					
Variance of county-specific random effect	0.0576					
Overdispersion	0.0857					
Log-likelihood	-7364.6					
AIC (Akaike information criterion)	14753.2					

Table 43: Mixed-Effects Negative Binomial Model Results for Total Non-animal Single-vehicle Crashes on Horizontal Curves along Rural County Highways Considering Approaching and Following Curve Distances

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.052		0.304	-19.88	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.705	0.705	0.048	14.66	<0.001
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.195	0.215	0.099	1.89	0.059
Approaching tangent distance for a simple curve or first of a series of compound / reverse curve	Natural log of, miles	0.055	0.055	0.030	0.64	0.008
Following tangent distance for a simple curve or the last of a series of compound / reverse curve	Natural log of, miles	0.038	0.038	0.032	0.71	0.475
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.085	0.089	0.029	0.94	0.030
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	0.017	0.017	0.111	0.17	0.333
Variance of site-specific random effect	0.9159					
Variance of county-specific random effect	0.1562					
Overdispersion	0.1349					
Log-likelihood	-4105					
AIC (Akaike information criterion)	8229.7					

Table 44: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Non-animal Single-vehicle Crashes on Horizontal Curves along Rural County Highways Considering Approaching and Following Curve Distances

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-7.840		0.489	-16.05	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.756	0.756	0.074	10.16	<0.001
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.206	0.229	0.166	1.44	0.015
Approaching tangent distance for a simple curve or first of a series of compound / reverse curve	Natural log of, miles	0.068	0.068	0.048	0.37	0.018
Following tangent distance for a simple curve or the last of a series of compound / reverse curve	Natural log of, miles	0.035	0.035	0.056	0.49	0.624
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.097	0.102	0.051	0.48	0.013
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	-0.012	-0.012	0.174	-0.28	0.495
Variance of site-specific random effect	0.2080					
Variance of county-specific random effect	0.0230					
Overdispersion	0.0902					
Log-likelihood	-1721.3					
AIC (Akaike information criterion)	3462.7					

Table 45: Mixed-Effects Negative Binomial Model Results for Property Damage Only Non-Animal Single-vehicle Crashes on Horizontal Curves along Rural County Highways Considering Approaching and Following Curve Distances

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.475		0.343	-18.86	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.701	0.701	0.054	13.10	<0.001
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.171	0.186	0.111	1.91	0.056
Approaching tangent distance for a simple curve or first of a series of compound / reverse curve	Natural log of, miles	0.041	0.041	0.035	0.71	0.007
Following tangent distance for a simple curve or the last of a series of compound / reverse curve	Natural log of, miles	0.037	0.037	0.036	0.34	0.257
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.060	0.062	0.035	0.92	0.055
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	0.020	0.020	0.123	0.19	0.276
Variance of site-specific random effect	0.9155					
Variance of county-specific random effect	0.1848					
Overdispersion	0.2455					
Log-likelihood	-3140					
AIC (Akaike information criterion)	6300.2					

Table 46: Mixed-Effects Negative Binomial Model Results for Total Non-animal Single-vehicle Crashes on Horizontal Curves along Rural County Highways Considering Inner-Curve Distance for Compound / Reverse Curves

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-5.940		0.255	-23.34	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.699	0.699	0.038	18.20	<0.001
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.211	0.235	0.075	1.30	0.020
Inner-curve tangent distance for compound / reverse curves	Natural log of, miles	-0.068	-0.068	0.031	-1.78	0.075
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.098	0.103	0.025	3.18	0.020
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	0.015	0.015	0.086	1.81	0.700
Variance of site-specific random effect	0.7726					
Variance of county-specific random effect	0.2619					
Overdispersion	0.1475					
Log-likelihood	-5845.3					
AIC (Akaike information criterion)	11708.6					

Table 47: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Non-animal Single-vehicle Crashes on Horizontal Curves along Rural County Highways Considering Inner-Curve Distance for Compound / Reverse Curves

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-8.015		0.438	-18.32	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.768	0.768	0.068	11.32	<0.001
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.225	0.252	0.141	0.04	0.020
Inner-curve tangent distance for compound / reverse curves	Natural log of, miles	-0.074	-0.074	0.053	-1.39	0.016
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.107	0.113	0.046	2.18	0.029
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	-0.012	-0.012	0.150	-0.08	0.938
Variance of site-specific random effect	0.2570					
Variance of county-specific random effect	0.0277					
Overdispersion	0.0558					
Log-likelihood	-2300.5					
AIC (Akaike information criterion)	4618.9					

Table 48: Mixed-Effects Negative Binomial Model Results for Property Damage Only Non-Animal Single-vehicle Crashes on Horizontal Curves along Rural County Highways Considering Inner-Curve Distance for Compound / Reverse Curves

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.521		0.287	-22.70	<0.001
Curve Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.682	0.682	0.044	16.56	<0.001
Curve Design Speed ≥ 55 mph	Baseline					
Curve Design Speed <55 mph	Binary indicator variable	0.206	0.229	0.085	1.95	0.051
Inner-curve tangent distance for compound / reverse curves	Natural log of, miles	-0.057	-0.057	0.038	-1.07	0.028
Right Turning Curve	Baseline					
Left Turning Curve	Binary indicator variable	0.087	0.091	0.031	2.39	0.017
Lane Width ≤ 11 feet	Baseline					
Lane Width > 11 feet	Binary indicator variable	0.016	0.016	0.097	1.61	0.107
Variance of site-specific random effect	0.8111					
Variance of county-specific random effect	0.2571					
Overdispersion	0.1235					
Log-likelihood	-4485.2					
AIC (Akaike information criterion)	8988.5					

5.3.3 Model Comparisons

Figure 21, Figure 22, and Figure 23, display comparative graphical representations of the Michigan-specific SPFs for total annual single-vehicle curve crashes on rural two-lane state and county highway segments with respect to horizontal curve characteristics and traffic volumes. In all these plots, lane width is fixed at less than 11 feet (for paved curves only) or surface width less than 22 feet (for unpaved curves only).

Figure 21 compares the predicted single-vehicle crash frequency between right and left turning curves, keeping baseline as highway segments consisting of both curved and tangent sections. In this figure, it can be clearly seen that the crash occurrence on curves, regardless its direction, is higher than that on the whole segment. This compares favorably with prior research that showed the average crash rate for horizontal curves is about three times that of other locations of highway segments (5). Between left- and right- turning curves, a much greater crash occurrence on the left turning curves was found, for all ranges of traffic volumes. Also, in all cases, crash frequency is higher on the county road curves than those on the state highways.

In Figure 22, the SPFs were plotted separately for the different curve types. Here also the crash occurrence is higher on both compound and reverse curves compared to the simple curves, with the greatest impact by the reverse curves. The effect of curve type is also more pronounced on the county curves.

Lastly, in Figure 23, the effect of curve design speed lower than the posted speed limit compared to those with greater or equal to the speed limit is presented. This figure clearly depicts that the under-designed or substandard curves are predicted to have a much greater crash occurrence and they are more problematic along the curves on county roads.

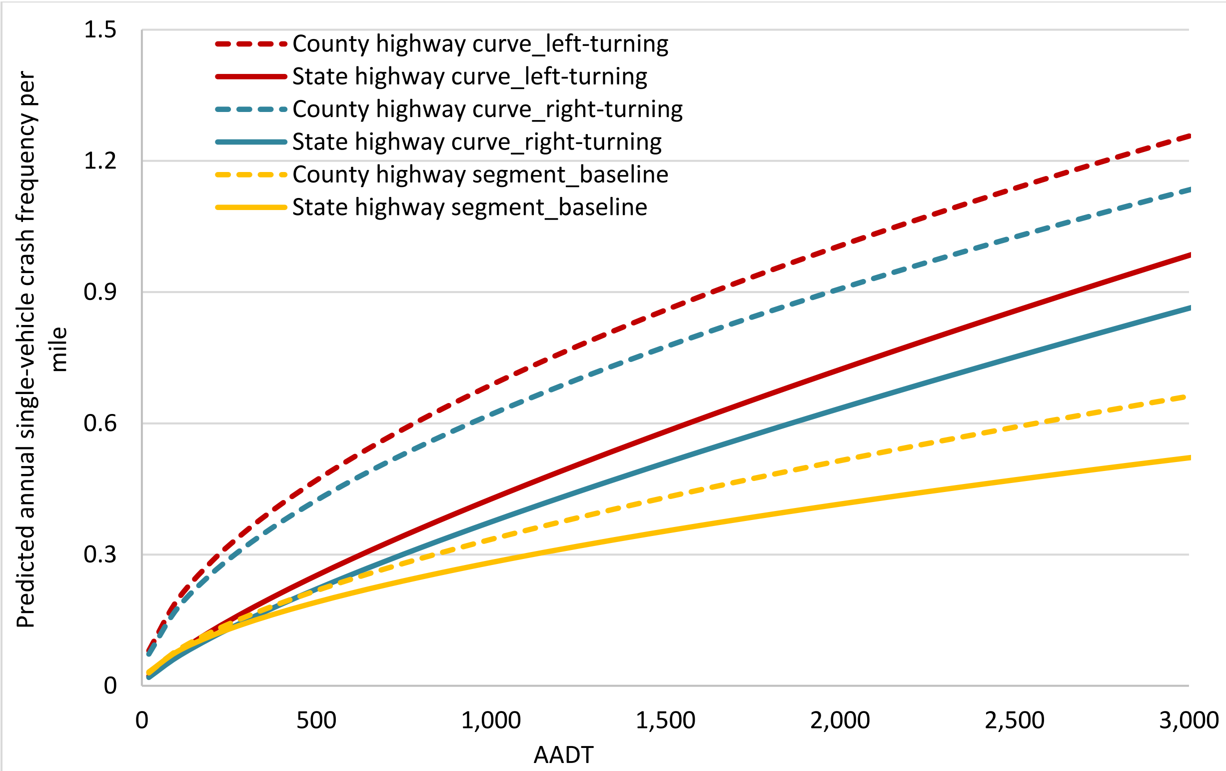


Figure 21: Model estimates for total annual single-vehicle crashes on horizontal curves and road segments on state and county highways

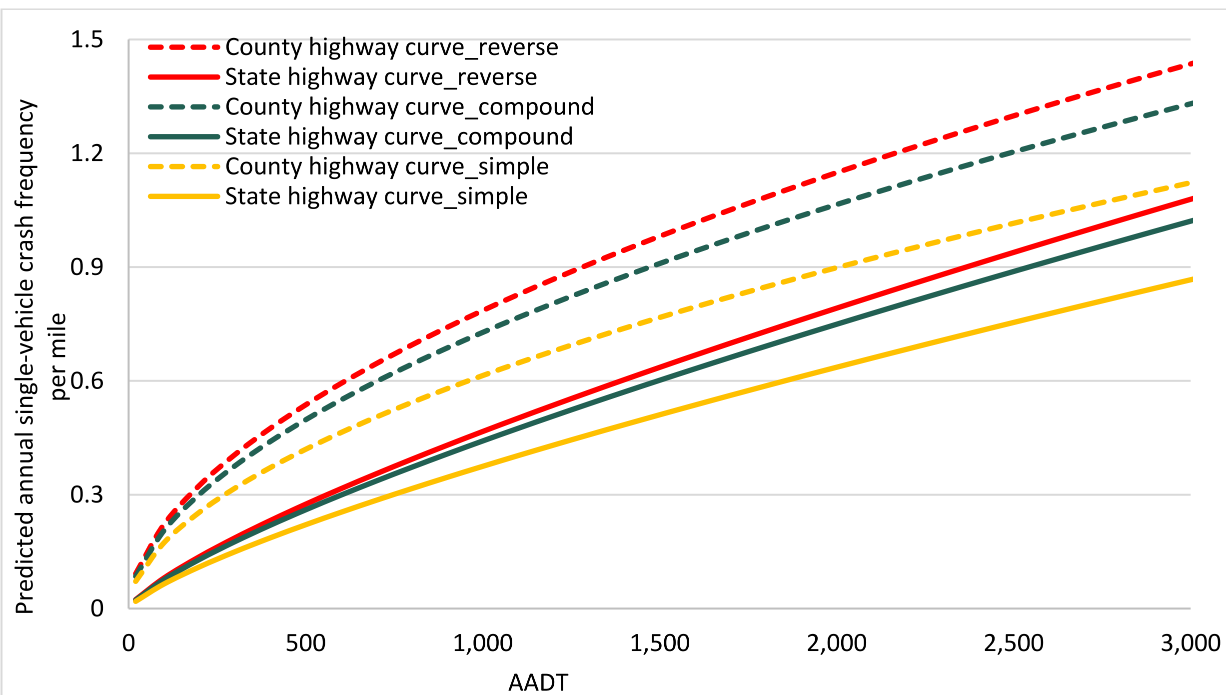


Figure 22: Model estimates for total annual single-vehicle crashes on various types of horizontal curves along state and county highways

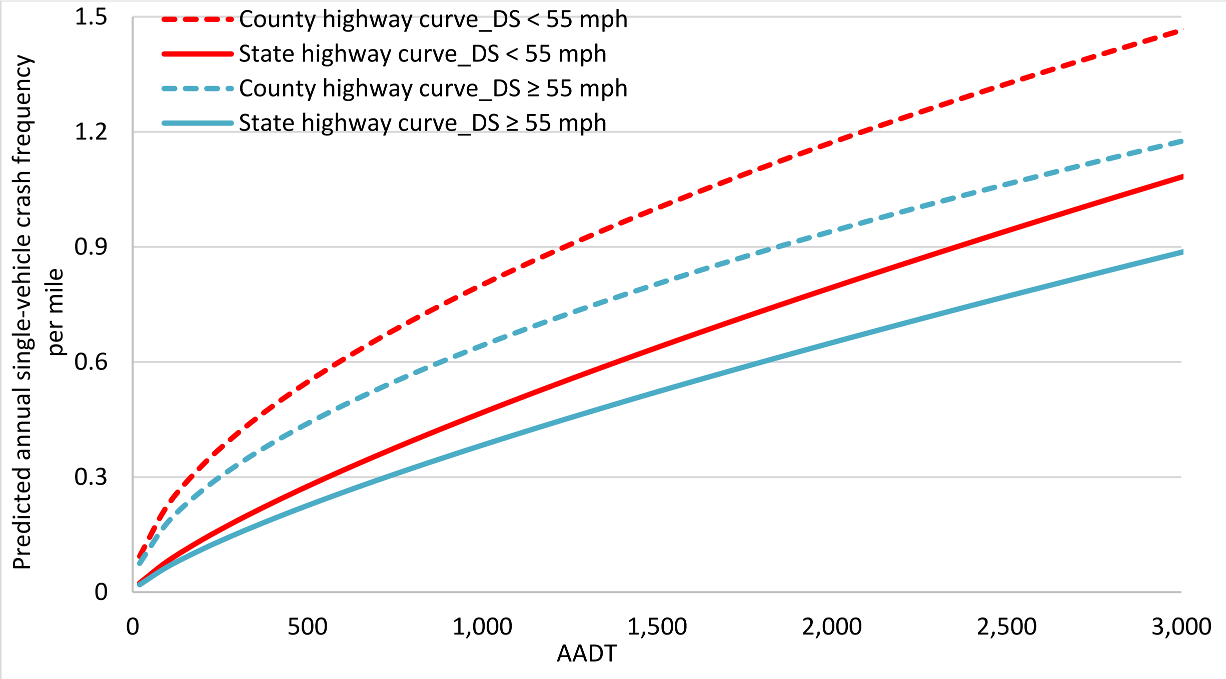


Figure 23: Model estimates for total annual single-vehicle crashes on horizontal curves with design speed lower than vs greater than or equal to speed limit on state and county highways

5.4 Summary of Findings

This study involved the assessment of the safety impacts of horizontal curve characteristics including curve type, curve direction, curve-approaching, curve-following and inner-curve tangent distances, and curve design speed associated with single-vehicle crashes on rural two-lane undivided state and county highways. Non-animal single-vehicle curve crashes occurring between 2011 and 2018 from across Michigan were analyzed along with curve geometry data for greater than 277 miles of state highway curves, and over 557 miles of county highway curves, respectively. To account for the unobserved heterogeneity associated with varied county design standards and site characteristics, several mixed-effects negative binomial regression models with a combination of county- and site-specific random effects were utilized. Separate models were developed for state and county highway curves, for total, fatal and injury, and property damage only crashes.

The results of this study indicated significant adverse safety impacts of curve type on single-vehicle curve crashes on rural two-lane highways. Among all curve types, compound and reverse curves were found to result in greater crash occurrence with a more pronounced effect by reverse curves on both state and county highways. Also, between the two facilities, curve type had a stronger effect on county curves.

Additionally, curve design speed lower than the posted speed limit was found to be associated with considerably higher crash frequency compared to that on the curve design speed greater than or equal to the posted speed limit on both state and county-owned roadways, with a greater effect on county curves.

Moreover, the approaching tangent distance for a simple curve or the first curve of a series of compound or reverse curves was positively associated with crash likelihood with a stronger association on county curves. Conversely, the inner-curve distance of compound or reverse curves was found to be negatively associated with crash occurrence, and this association is more pronounced on state highway curves. However, no discernable impact of tangent distance following a simple curve or the last curve of a series of compound or reverse curves on crashes was found.

Furthermore, a left-turning curve was found to experience significantly higher single-vehicle crashes compared to that on a right-turning curves, although this impact was higher on state highway curves. For all curve characteristics analyzed, the effects were consistently greater for fatal and injury crashes, a finding consistent with prior research that indicated horizontal alignments along the roadways were particularly risky for severe injury crashes. Also, most of the factors analyzed had greater effects for county curves, which might be partially attributed to the lower design and maintenance standards of county highway segments, in general.

Regarding other roadway characteristics, traffic volume was positively associated with crash frequency and its effect was higher on state highway curves and also for fatal and injury crashes. Lane width (for paved curves only) and surface width (for unpaved curves only) did not have any influence on curve crash occurrence on either jurisdiction.

Overall, the results of this study support the previous research findings in general related to the safety concerns along horizontal roadway alignments and provide further evidence that horizontal curve characteristics at a disaggregate level significantly influence crash likelihood, particularly for rural two-lane undivided roadways. This study also further contributes to the limited body of knowledge regarding the safety performance of horizontal curve characteristics on rural secondary highways, including roads under county jurisdictions.

6. ANALYSIS AND RESULTS: SAFETY PERORMANCE ON URBAN/SUBURBAN MINOR ARTERIALS AND COLLECTOR ROADS

6.1 Preliminary Analysis

The safety performance of roadway characteristics for urban two-way two-lane undivided minor arterial and collector road segments were analyzed using the data from Washtenaw County in Southeast Michigan, as described in Chapter 3. Due to the differences in design characteristics, maintenance standards, traffic volumes, trip distances, and driver characteristics, among other factors, separate datasets were created for minor arterial and collector roads. After the data were assembled for urban lower functional class road segments, a series of preliminary analyses were conducted to examine general trends for each facility type as below.

1. Urban/suburban county- or city-owned two-lane two-way minor arterial segments, and
2. Urban/suburban county- or city-owned two-lane two-way collector segments.

6.1.1 Descriptive Statistics, Urban Road Segments

In total, approximately 189 miles of two-lane undivided urban/suburban roadways, consisting of 269 segments were included in this study. Approximately, 48 percent of these study segments were minor arterials totaling about 100 miles, while with the remaining 52 percent were collector road segments including both major and minor collectors amounting to almost 89 miles. The segment summary statistics associated with the variables considered for the analysis including minimum, maximum, mean, and standard deviations are presented in Table 49 and Table 50.

As can be seen from Table 49 and Table 50, not surprisingly, traffic volume is considerably higher on minor arterials compared to that on collector roads, while the average segment length is also slightly greater on minor arterials. Consistent with the higher functional classification, minor arterials have a higher average posted speed limit with respect to the collector roadway counterparts. Also, as expected, the average driveway density is greater on collectors for all land-use types. The average lane width is comparable between minor arterial and collector road segments. Also, on-street parking, midblock crosswalks, horizontal curvatures, bus stops, and sidewalks are more prevalent on collector road segments, consistent with the urban nature of lower class of road segments. Lastly, for all severities of midblock crashes analyzed, average annual crash frequency is consistently higher on minor arterials compared to that on collector road segments.

Table 49: Summary Statistics for Urban Two-lane Undivided Minor Arterial Segments (*n = 130*)

Factor	Min	Max	Mean	Std. Dev
Traffic volume (AADT) (vehicles per day)	856	20,710	8,352.1	3,898.3
Segment length (mi)	0.1	3.58	0.77	0.7
Posted Speed Limit (mph)	25	50	37.92	9.30
Total Driveway Density (count/mi)	0	107.28	36.04	29.68
Residential Driveway Density (count/mi)	0	107.28	29.68	28.95
Commercial Driveway Density (count/mi)	0	46.88	6.36	8.39
Lane Width (ft)	10	14	11.13	0.65
On-street Parking Presence	0	1	0.15	0.36
Crosswalk Presence	0	1	0.16	0.42
Horizontal Curve Presence	0	1	0.15	0.35
Sidewalk Presence	0	1	0.65	0.48
Bus Stop Presence	0	1	0.22	0.41
School Zone Presence	0	1	0.06	0.24
Midblock total crashes (count/segment-year)	0	29	4.24	4.98
Midblock fatal and injury crashes (FI) (count/segment-year)	0	9	0.92	1.42
Midblock fatal crashes (K) (count/segment-year)	0	2	0.02	0.16
Midblock incapacitating injury crashes (A) (count/segment-year)	0	2	0.08	0.30
Midblock non-incapacitating injury crashes (B) (count/segment-year)	0	4	0.27	0.59
Midblock possible injury crashes (C) (count/segment-year)	0	6	0.55	0.98
Midblock property damage only crashes (O) (count/segment-year)	0	25	3.32	4.03

Table 50: Summary Statistics for Urban Two-lane Undivided Collector Segments (*n = 139*)

Factor	Min	Max	Mean	Std. Dev
Traffic volume (AADT) (vehicles per day)	380	13,395	5,041.7	3,128.1
Segment length (mi)	0.1	6.84	0.65	0.86
Posted Speed Limit (mph)	25	50	30.94	7.72
Total Driveway Density (count/mi)	0	123.02	40.82	32.27
Residential Driveway Density (count/mi)	0	123.02	32.41	32.53
Commercial Driveway Density (count/mi)	0	60.98	8.41	10.96
Lane Width (ft)	10	15	11.40	1.13
On-street Parking Presence	0	1	0.34	0.47
Crosswalk Presence	0	1	0.19	0.39
Horizontal Curve Presence	0	1	0.22	0.42
Sidewalk Presence	0	1	0.79	0.41
Bus Stop Presence	0	1	0.30	0.46
School Zone Presence	0	1	0.05	0.22
Midblock total crashes (count/segment-year)	0	26	1.91	3.24
Midblock fatal and injury crashes (FI) (count/segment-year)	0	10	0.41	1.02
Midblock fatal crashes (K) (count/segment-year)	0	1	0.01	0.07
Midblock incapacitating injury crashes (A) (count/segment-year)	0	2	0.05	0.23
Midblock non-incapacitating injury crashes (B) (count/segment-year)	0	4	0.14	0.46
Midblock possible injury crashes (C) (count/segment-year)	0	7	0.22	0.62
Midblock property damage only crashes (O) (count/segment-year)	0	16	1.51	2.51

The crash data, posted speed limit, and driveway density for various land-use were further explored with the help of graphical representations to examine general trends of them for each facility type as shown in Figure 24 and Figure 25. For both annual crash frequency and driveway density normalized on a per-mile basis, and posted speed limit, the observed data were plotted against traffic volumes.

From these figures, the crash frequency per mile is observably greater on minor arterial roads compared to that on collector roads. Similarly, the posted speed limits on minor arterials are relatively higher on minor arterials compared to that on collectors. However, the driveway density, particularly, the commercial/industrial driveway density is substantially greater on collector road segments compared to minor arterials.

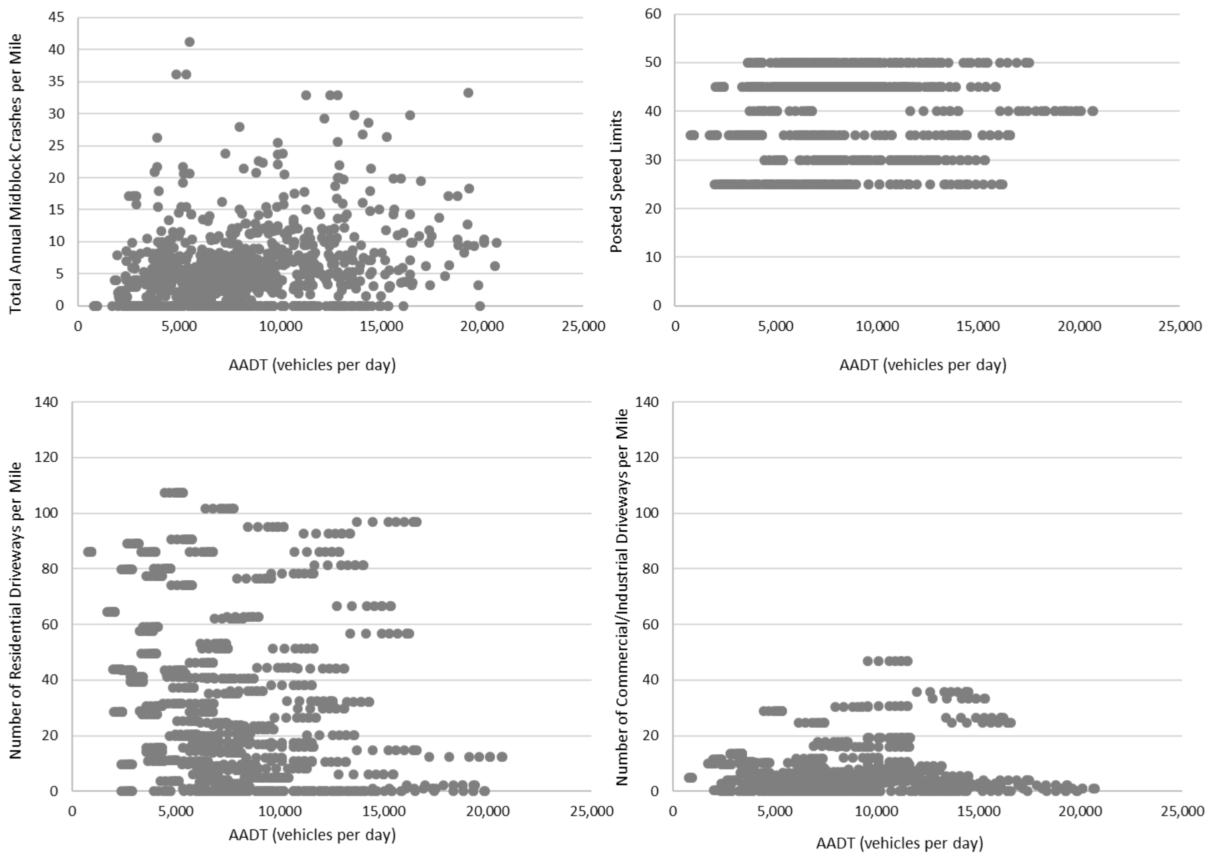


Figure 24: Annual midblock crashes per mile and number of driveways per mile for various land-use categories vs AADT on minor arterials.

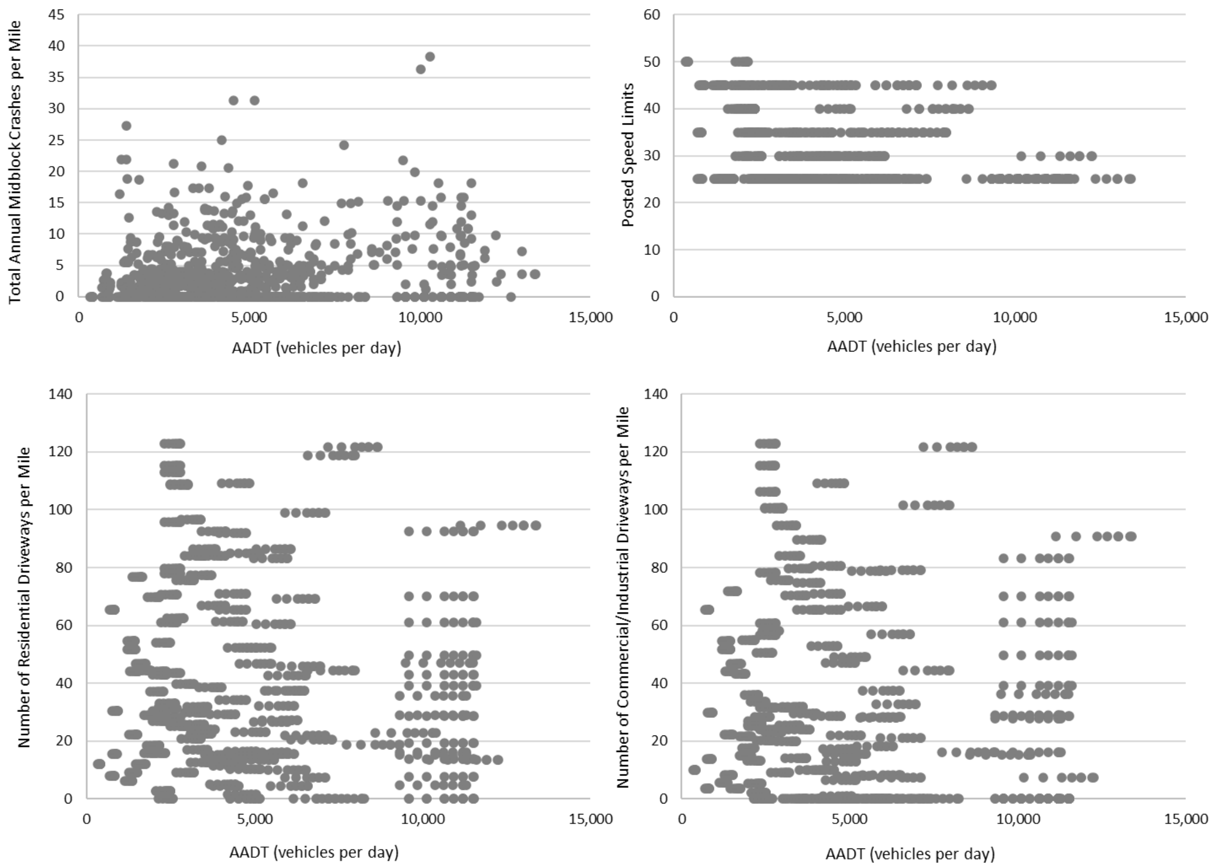


Figure 25: Annual midblock crashes per mile and number of driveways per mile for various land-use categories vs AADT on collectors.

Additionally, Table 51 shows the crash distributions for individual crash severity and different collision types on minor arterial and collector roads.

Table 51: Crash Severity and Collision Type Distributions for Midblock Crashes between 2011 and 2018 on Urban Two-lane Undivided Minor Arterial and Collector Road Segments

Crash severities and types	Minor Arterial Road Segments		Collector Road Segments	
	Count	Percent of midblock crashes	Count	Percent of midblock crashes
Total Crashes	4,412	100.0%	2,126	100.0%
Fatal and injury (FI)	958	21.7%	455	10.3%
Fatal (K)	22	0.5%	6	0.1%
Incapacitating injury (A)	81	1.8%	51	1.2%
Non-incapacitating injury (B)	284	6.4%	154	3.5%
Possible injury (C)	571	12.9%	244	5.5%
Property damage only (PDO)	3,454	78.3%	1,671	37.9%
Single-vehicle	1,840	41.7%	851	19.3%
Multi-vehicle	2,572	58.3%	1,275	28.9%
Head-on	89	2.0%	46	1.0%
Head-on left turn	64	1.5%	40	0.9%
Angle	567	12.9%	379	8.6%
Rear end	1,391	31.5%	466	10.6%
Sideswipe same	199	4.5%	153	3.5%
Sideswipe opposite	117	2.7%	74	1.7%
In dry road	3,021	68.5%	1,386	31.4%
Alcohol/Drug involved	228	5.2%	126	2.9%
Truck/bus related	105	2.4%	63	1.4%
Pedestrian/Bike related	88	2.0%	66	1.5%
Motorcycle related	46	1.0%	46	1.0%
In Daylight	2,658	60.2%	1,345	30.5%

6.2 SPF Development

The analysis involved the development of the several mixed-effects negative binomial models separately for minor arterials and collector road segments. Also, separate models were estimated for total, fatal and injury (FI), and property damage only (PDO) crashes. The independent variables included traffic volume, posted speed limit, driveway density based on different land-use categories, lane width, and presence of various factors including horizontal curve, on-street parking, bus stop, crosswalk, school zone, and sidewalk. While traffic volume and driveway density are treated as continuous variables, the other factors added as binary indicators into the models. The driveway density was calculated for each land-use classification on each segment by dividing the number of driveways by the segment length. In all models, AADT is included in natural log form and the elasticity of the parameter estimate can, thus, be interpreted directly. Also, the coefficient for the natural log of the segment length was set to 1 (i.e., the length is treated as an offset), which normalizes the crash counts per unit length as the crash frequency on a segment is generally considered to be proportional to the segment length.

Several combinations of independent variables were tested to develop the full models and based on the p-values of the parameter estimates, AIC, and log-likelihood information, best fit models were chosen. A significance level of 0.1 ($\alpha = 0.1$) was used in this analysis. Table 52, Table 53, and Table 54, and Table 55, Table 56, and Table 57 display the results of mixed-effect negative binomial models including parameter estimates, elasticity, standard errors (S.E.), z-statistics, and p-values for the minor arterial and collector road segments, respectively. The following subsections present the discussion of the model results for both the facilities analyzed in this study.

6.3 Results and Discussion

6.3.1 Minor Arterial Road Segments

The results of the analysis of minor arterial segments revealed several interesting findings. As it can be seen from Table 52, Table 53, and Table 54, the relationship between traffic crash frequency and AADT is non-linear and inelastic and varies between crash severities, with parameter estimates ranging from 0.59 to 0.61 having the greatest effect on fatal and injury (FI) crashes, a finding consistent with prior research (*44*, *47*).

With regard to the effects of posted speed limits, crash occurrence consistently increased with increasing speed limit, which is consistent with previous research on urban road segments (*47*, *108*). While this trend was observed for both PDO and FI crashes, the effect was larger for FI crashes. Specifically, the parameter estimates indicate 5.4 percent, 8.9 percent, and 3.6 percent greater total, FI, and PDO crashes, respectively, on segments with posted speed limit of 35 to 40 mph, compared to segments with 25 to 30 mph speed limit. The parameter estimates increase further when the speed limit is greater than 40 mph, indicating 7.4 percent, 12.0 percent, and 7.6 percent greater crash occurrence for total, FI, and PDO crashes, respectively, compared to segments with 25 to 30 mph speed limit.

Turning to the safety effects of driveway density across the various driveway land-use categories on minor arterial road segments, the results show that the density of both residential and commercial/industrial driveway types was found to be positively associated with crash frequency (i.e., greater driveway density results in higher crash occurrence), and this association is statistically significant for each driveway type. Also, the effect of driveway density is greater for FI crashes compared to that on PDO crashes. Considering driveway land-use type, commercial/industrial driveways were found to have a stronger effect on crashes than residential driveways across all severity levels, likely due to greater utilization. The parameter estimates indicate that crash occurrence increases by 1.5 percent1.6 percent, and 0.9 percent for total, FI, and PDO crashes, respectively, with every additional residential driveway per mile segment. Similarly, the crash occurrence increases by 5.2 percent, 5.5 percent, and 4.7 percent for total, FI, and PDO crashes, respectively, with every additional commercial or industrial driveway per mile segment. These results suggest that commercial/industrial driveways increase crash occurrence at rates that are more than 3.4 times and 5.2 times greater than residential driveways for FI and

PDO crashes, respectively. Overall, these results are aligned with prior research that found crash frequency on urban roads to increase with increasing driveway density, and that commercial driveways have more pronounced effect on crash occurrence compared to residential driveways (*22, 35, 69*). Furthermore, the finding that factors such as traffic volume, driveway density, and posted speed limit influence safety significantly on urban roadways compares favorably with a prior study by Hauer et al. (2004), where the model fits depended mostly on the independent predictors including AADT, number of commercial driveways, and speed limit (*69*).

Turning to the effects of other roadway factors, on-street parking is found to increase crash likelihood for total and PDO crashes, and reduce crash frequency for FI crashes on minor arterial segments. This is not a surprising result, as on-street parking, while introducing additional vehicle-to-vehicle conflicts, also tends to reduce operating speeds, thereby reducing the likelihood of FI crashes. Additionally, while the presence of a horizontal curvature, midblock crosswalks, and bus stops are associated with increased crash occurrence; school zone presence, and lane width greater than 11 feet are found to decrease crash likelihood on minor arterial roadways. Presence of school zones show a stronger negative association with FI crashes, perhaps due to drivers traversing school zones more cautiously and at lower rates of speed than along comparable segments in other areas. Interestingly, presence of sidewalks demonstrates a counterintuitive positive association with PDO crashes only, perhaps due to the increased parking and/or pedestrian activity on these.

Table 52: Mixed-Effects Negative Binomial Model Results for Total Midblock Crashes on Urban/Suburban Minor Arterial Road Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-4.564		1.034	-3.83	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.604	0.604	0.114	5.276	<0.001
Posted Speed Limit 25-30 mph	Baseline					
Posted Speed Limit 35-40 mph	Binary indicator variable	0.053	0.054	0.191	0.46	0.065
Posted Speed Limit > 40 mph	Binary indicator variable	0.071	0.074	0.188	0.47	0.064
Residential Driveway Density	Continuous variable	0.015	0.016	0.002	0.67	0.050
Commercial/Industrial Driveway Density	Continuous variable	0.050	0.052	0.010	0.95	0.034
No Midblock Crosswalk	Baseline					
Midblock Crosswalk Presence	Binary indicator variable	0.233	0.263	0.169	1.38	0.017
No On-street Parking	Baseline					
On-street Parking Presence	Binary indicator variable	0.029	0.029	0.198	0.01	0.091
No Bus-stop	Baseline					
Bus-stop Presence	Binary indicator variable	0.018	0.018	0.156	0.12	0.026
No School-zone	Baseline					
School-zone Presence	Binary indicator variable	-0.008	-0.008	0.224	-0.03	0.097
No Horizontal Curve	Baseline					
Horizontal Curve Presence	Binary indicator variable	0.208	0.231	0.160	1.31	0.019
No Sidewalk	Baseline					
Sidewalk Presence	Binary indicator variable	0.119	0.127	0.114	0.83	0.408
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	-0.071	-0.068	0.181	-1.50	0.013
Variance of site-specific random effect	0.3226					
Overdispersion	0.0315					
Log-likelihood	-1995.2					
AIC (Akaike information criterion)	4020.4					

Table 53: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Midblock Crashes on Urban/Suburban Minor Arterial Road Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-6.115		1.240	-4.45	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.595	0.595	0.137	4.35	<0.001
Posted Speed Limit 25-30 mph	Baseline					
Posted Speed Limit 35-40 mph	Binary indicator variable	0.086	0.089	0.221	0.68	0.050
Posted Speed Limit > 40 mph	Binary indicator variable	0.114	0.120	0.229	0.70	0.048
Residential Driveway Density	Continuous variable	0.016	0.016	0.003	0.050	0.062
Commercial/Industrial Driveway Density	Continuous variable	0.053	0.055	0.013	0.040	0.069
No Midblock Crosswalk	Baseline					
Midblock Crosswalk Presence	Binary indicator variable	0.256	0.291	0.172	1.48	0.014
No On-street Parking	Baseline					
On-street Parking Presence	Binary indicator variable	-0.039	-0.039	0.255	-1.55	0.012
No Bus-stop	Baseline					
Bus-stop Presence	Binary indicator variable	0.012	0.012	0.177	0.07	0.049
No School-zone	Baseline					
School-zone Presence	Binary indicator variable	-0.049	-0.048	0.232	-0.21	0.083
No Horizontal Curve	Baseline					
Horizontal Curve Presence	Binary indicator variable	0.216	0.241	0.167	0.98	0.033
No Sidewalk	Baseline					
Sidewalk Presence	Binary indicator variable	0.254	0.290	0.151	1.68	0.929
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	-0.056	-0.055	0.213	-0.10	0.034
Variance of site-specific random effect	0.2376					
Overdispersion	0.0794					
Log-likelihood	-1111.2					
AIC (Akaike information criterion)	2252.2					

Table 54: Mixed-Effects Negative Binomial Model Results for Property Damage Only Midblock Crashes on Urban/Suburban Minor Arterial Road Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-4.674		1.065	-3.82	<0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.590	0.590	0.118	5.01	<0.001
Posted Speed Limit 25-30 mph	Baseline					
Posted Speed Limit 35-40 mph	Binary indicator variable	0.035	0.036	0.194	0.44	0.066
Posted Speed Limit > 40 mph	Binary indicator variable	0.074	0.076	0.192	0.32	0.075
Residential Driveway Density	Continuous variable	0.009	0.009	0.003	0.67	0.050
Commercial/Industrial Driveway Density	Continuous variable	0.046	0.047	0.010	0.09	0.037
No Midblock Crosswalk	Baseline					
Midblock Crosswalk Presence	Binary indicator variable	0.159	0.173	0.190	0.31	0.076
No On-street Parking	Baseline					
On-street Parking Presence	Binary indicator variable	0.010	0.010	0.202	0.49	0.062
No Bus-stop	Baseline					
Bus-stop Presence	Binary indicator variable	0.020	0.021	0.159	0.03	0.020
No School-zone	Baseline					
School-zone Presence	Binary indicator variable	-0.026	-0.025	0.226	-0.11	0.091
No Horizontal Curve	Baseline					
Horizontal Curve Presence	Binary indicator variable	0.164	0.178	0.161	1.34	0.018
No Sidewalk	Baseline					
Sidewalk Presence	Binary indicator variable	0.091	0.096	0.146	0.63	0.053
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	-0.069	-0.066	0.185	-0.45	0.015
Variance of site-specific random effect	0.3184					
Overdispersion	0.0322					
Log-likelihood	-1846.4					
AIC (Akaike information criterion)	3722.8					

6.3.2 *Collector Road Segments*

As can be seen from Table 55, Table 56, and Table 57, the relationship between traffic crash frequency and AADT for collector roadways is less elastic than that for minor arterials with parameter estimates ranging between 0.42 and 0.53 and the greater effect on PDO crashes than FI crashes, unlike minor arterials.

Similar to the minor arterial road segments, significant adverse safety impacts were associated with an increasing speed limit with greater effect on FI crashes. However, the relationship between posted speed limit and crash occurrence was weaker for collector roads compared to minor arterials. Specifically, the parameter estimates indicate 3.9 percent, 4.1 percent, and 2.6 percent greater total, FI, and PDO crashes, respectively, on segments with posted speed limit of 35 to 40 mph, compared to segments with 25 to 30 mph speed limit. Similar to the minor arterials, the parameter estimates increased incrementally when the speed limit is greater than 40 mph, indicating 5.0 percent, 7.3 percent, and 4.0 percent greater crash occurrence for total, FI, and PDO crashes, respectively, compared to segments with 25 to 30 mph speed limit.

Both residential and commercial/industrial driveway densities were associated with increased crash occurrence, and the effect of this factor was stronger on collector roads compared to minor arterials, especially when considering residential driveways. Similar to minor arterials, commercial/industrial driveways have stronger effect on crashes for all crash severities than do residential driveways. Further, unlike minor arterials, the effect of residential driveway density is greater for PDO crashes, although, the commercial/industrial driveway density effect is greater for FI crashes than PDO crashes. Particularly, the parameter estimates indicate that crash occurrence increases by 3.7 percent, 2.4 percent, and 3.4 percent for total, FI, and PDO crashes, respectively, with every additional residential driveway per mile segment. Similarly, crash occurrence increases by 5.4 percent, 6.6 percent, and 5.5 percent for total, FI, and PDO crashes, respectively, with every additional commercial/industrial driveway per mile segment. These results suggest that commercial/industrial driveways increase crash occurrence at rates that are 2.8 times and 1.6 times greater than residential driveways for FI and PDO crashes, respectively.

Additionally, unlike minor arterials, on-street parking is found to decrease crash likelihood on collector roads across all severity levels, which was consistent with prior research (*69*). Midblock crosswalks were found to be associated with increased crash likelihood, and this effect is stronger on collector roads compared to minor arterials. Bus stop presence is associated with greater crash frequency for total and FI crashes only, and unlike minor arterials, the presence of a horizontal curvature and school zones did not have any significant impact on crashes. For horizontal curves, this result is likely due to underdesigned horizontal curves being relatively uncommon on urban/suburban collector segments (i.e., curves that are designed below the speed limits). Lane width greater than 11 feet on collector roads was associated with a decreased occurrence of total and PDO crashes only and to a greater extent compared to minor arterials. Unlike minor arterials, presence of sidewalks on collector segments was found to be negatively associated with FI crash occurrence, but with no discernable impact on PDO crashes.

Table 55: Mixed-Effects Negative Binomial Model Results for Total Midblock Crashes on Urban/Suburban Collector Road Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-4.397		1.276	-2.98	0.003
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.510	0.510	0.143	3.56	<0.001
Posted Speed Limit 25-30 mph	Baseline					
Posted Speed Limit 35-40 mph	Binary indicator variable	0.039	0.039	0.271	1.18	0.024
Posted Speed Limit > 40 mph	Binary indicator variable	0.049	0.050	0.338	0.40	0.069
Residential Driveway Density	Continuous variable	0.036	0.037	0.003	1.51	0.013
Commercial/Industrial Driveway Density	Continuous variable	0.053	0.054	0.012	0.95	0.034
No Midblock Crosswalk	Baseline					
Midblock Crosswalk Presence	Binary indicator variable	0.301	0.351	0.253	1.98	0.048
No On-street Parking	Baseline					
On-street Parking Presence	Binary indicator variable	-0.060	-0.059	0.244	-2.48	0.013
No Bus-stop	Baseline					
Bus-stop Presence	Binary indicator variable	0.012	0.012	0.227	0.08	0.094
No School-zone	Baseline					
School-zone Presence	Binary indicator variable	0.152	0.164	0.402	0.38	0.705
No Horizontal Curve	Baseline					
Horizontal Curve Presence	Binary indicator variable	0.101	0.106	0.228	0.44	0.658
No Sidewalk	Baseline					
Sidewalk Presence	Binary indicator variable	0.335	0.398	0.286	1.18	0.240
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	-0.090	-0.086	0.226	-0.28	0.020
Variance of site-specific random effect	0.8907					
Overdispersion	0.0164					
Log-likelihood	-1481.1					
AIC (Akaike information criterion)	2992.3					

Table 56: Mixed-Effects Negative Binomial Model Results for Fatal-Injury Midblock Crashes on Urban/Suburban Collector Road Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-5.074		1.340	-3.34	0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.415	0.415	0.154	2.70	0.007
Posted Speed Limit 25-30 mph	Baseline					
Posted Speed Limit 35-40 mph	Binary indicator variable	0.040	0.041	0.264	2.24	0.025
Posted Speed Limit > 40 mph	Binary indicator variable	0.070	0.073	0.314	0.67	0.050
Residential Driveway Density	Continuous variable	0.024	0.024	0.004	0.04	0.097
Commercial/Industrial Driveway Density	Continuous variable	0.064	0.066	0.016	0.73	0.047
No Midblock Crosswalk	Baseline					
Midblock Crosswalk Presence	Binary indicator variable	0.311	0.365	0.253	2.42	0.016
No On-street Parking	Baseline					
On-street Parking Presence	Binary indicator variable	-0.065	-0.063	0.297	-0.78	0.029
No Bus-stop	Baseline					
Bus-stop Presence	Binary indicator variable	0.015	0.015	0.234	0.18	0.028
No School-zone	Baseline					
School-zone Presence	Binary indicator variable	0.104	0.110	0.355	0.29	0.769
No Horizontal Curve	Baseline					
Horizontal Curve Presence	Binary indicator variable	0.131	0.140	0.219	0.14	0.888
No Sidewalk	Baseline					
Sidewalk Presence	Binary indicator variable	-0.011	-0.011	0.273	-0.04	0.097
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	0.051	0.053	0.236	0.22	0.828
Variance of site-specific random effect	0.4780					
Overdispersion	0.0428					
Log-likelihood	-699.4					
AIC (Akaike information criterion)	1406.7					

Table 57: Mixed-Effects Negative Binomial Model Results for Property Damage Only Midblock Crashes on Urban/Suburban Collector Road Segments

Parameter	Description	Estimate	Elasticity	S.E.	z-stat	p-value
Intercept		-4.801		1.308	-3.21	0.001
Segment Length	Offset, natural log of, miles					
AADT	Natural log of, vehicles per day	0.531	0.531	0.147	3.61	<0.001
Posted Speed Limit 25-30 mph	Baseline					
Posted Speed Limit 35-40 mph	Binary indicator variable	0.026	0.026	0.276	0.78	0.043
Posted Speed Limit > 40 mph	Binary indicator variable	0.040	0.040	0.342	0.49	0.063
Residential Driveway Density	Continuous variable	0.034	0.034	0.003	1.68	0.094
Commercial/Industrial Driveway Density	Continuous variable	0.054	0.055	0.013	0.92	0.036
No Midblock Crosswalk	Baseline					
Midblock Crosswalk Presence	Binary indicator variable	0.159	0.172	0.256	1.79	0.073
No On-street Parking	Baseline					
On-street Parking Presence	Binary indicator variable	-0.055	-0.053	0.248	-2.20	0.028
No Bus-stop	Baseline					
Bus-stop Presence	Binary indicator variable	-0.037	-0.037	0.232	-0.16	0.872
No School-zone	Baseline					
School-zone Presence	Binary indicator variable	0.103	0.108	0.406	0.25	0.800
No Horizontal Curve	Baseline					
Horizontal Curve Presence	Binary indicator variable	-0.120	-0.113	0.232	-0.52	0.604
No Sidewalk	Baseline					
Sidewalk Presence	Binary indicator variable	0.396	0.485	0.290	1.36	0.172
Lane Width <= 11 feet	Baseline					
Lane Width >11 feet	Binary indicator variable	-0.107	-0.102	0.231	-1.56	0.012
Variance of site-specific random effect	0.8895					
Overdispersion	0.0315					
Log-likelihood	-1361.5					
AIC (Akaike information criterion)	2753.1					

6.3.3 Model Comparisons

Figure 26 displays a comparative graphical representation of the developed SPFs for total annual segment crashes on urban two-lane minor arterials and collectors with respect to traffic volumes. For these graphics, the SPFs were plotted for the base condition of 30 residential and 5 commercial/industrial driveways per mile, which roughly represented the average driveway density values for the two segment types analyzed. Also, the speed limit for the base condition was considered as 25 to 30 mph for both minor arterials and collectors. In addition, the other variables included in the SPFs were fixed to the most common values for each variable, as follows: no on street parking, no midblock crosswalk or sidewalk, no bus stop or horizontal curve, no school zones, and lane width greater than 11 feet.

As can be seen from Figure 26, the predicted total crash frequencies are slightly higher on collectors compared to the minor arterials for AADTs below approximately 3,000 vehicles per day. However, for AADTs greater than approximately 3,000 vehicles per day, the crash occurrence on minor arterials is consistently higher than that for collector roadways.

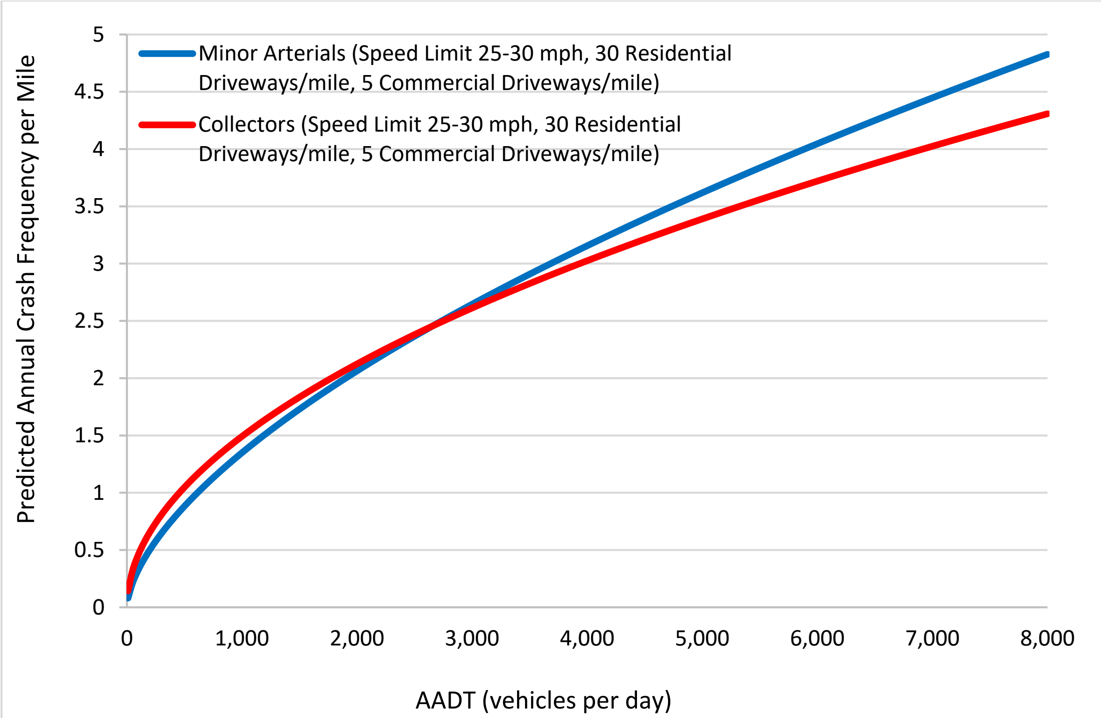


Figure 26: Model estimates for total annual crash frequency per mile on minor arterial and collector roadways.

6.4 Summary of Findings

This study involved a safety performance evaluation of roadway characteristics along urban/suburban minor arterial and collector roadway segments. A series of safety performance functions were developed utilizing eight years of crash data (2011-2018), roadway characteristics, and traffic volume data, for approximately 189 miles of two-lane undivided urban and suburban roadways with speed limits between 25 mph to 50 mph from Washtenaw County (i.e., greater Ann Arbor), Michigan. Mixed-effect negative binomial models with site-specific random intercept were developed separately for minor arterial and collector road segments, and for total, FI, and PDO crashes.

In general, minor arterial roadways showed greater crash occurrence compared to collector roads. Posted speed limit was found to have a significant positive association with crash frequency, and this effect increased when the speed limit exceeds 40 mph. This effect was stronger on minor arterial segments and was also stronger when considering FI crashes compared to PDO crashes.

Additionally, driveway density was found to have significant effect on safety performance across all driveway land-use types both for minor arterials and collectors. Not surprisingly, commercial/industrial driveways were found to have a stronger effect on crash frequency than residential driveways, likely due to greater utilization. Moreover, the impact of driveway density was stronger on collector roads compared to minor arterials, particularly when considering the effect of residential driveways. In general, driveways posed a greater effect on FI crashes than PDO crashes, although when considering residential driveways on collector segments, the effect was stronger for PDO crashes.

Lane width greater than 11 feet generally showed reduced crash occurrence across both segment types. Midblock crosswalks and bus stops were associated with increased crash occurrence. On-street parking was generally associated with lower crash occurrence, with a stronger effect occurring on collectors compared to minor arterials, likely due to greater turnover. Lastly, on minor arterials, school zone presence was associated with lower crash occurrence, while horizontal curves were associated with elevated crash occurrence.

Overall, the results of this study support the previous research findings and provides further evidence that roadway characteristics impact safety to different extents across different functional classifications. Most importantly, this study contributes to the limited body of knowledge regarding the safety performance characteristics observed on lower functional classes of urban/suburban roads, specifically minor arterials and collectors, which typically possess design and travel characteristics that are considerably different from those of primary arterials.

7. CONCLUSIONS AND CONTRIBUTIONS

Evaluating the safety performance of roadway segments and intersections typically involves associating traffic crashes, injuries, and fatalities to various roadway and traffic characteristics, which typically vary broadly between rural and urban contexts. In rural areas, where fatal crash rates are higher than those in urban areas, high speeds, adverse geometry, and unlighted conditions, often play a critical role in the safety performance of a given roadway. In urban areas, myriad other characteristics, including speed limits, land access, pedestrian/bicyclist activity, transit activity, and parking, lead to complex interactions between road users and greatly influence roadway safety. While the safety performance effects of many roadway geometric, cross-sectional, and land-use characteristics have been explored in prior research, certain aspects, such as specific alignment-related characteristics of the horizontal curvature and the impact of driveway land-use type have not been well-explored in prior roadway safety research.

Furthermore, previous research of roadway safety performance has generally focused on higher functional class roadways, both in rural and urban areas. However, roadways with lower functional classifications typically possess traffic, driver, design, and maintenance characteristics that considerably differ from those of higher classes. Therefore, assumptions made on the general effect of the predictor variables from typical safety performance functions, such as traffic volume or roadway characteristics, may not apply to lower roadway classes such as minor arterials and collectors. Such roadways are often owned by local agencies and comprise a substantial portion of the nationwide roadway network. This research sought to explore those gaps in the roadway safety research domain.

An extensive literature review found that while the safety impacts of driveway density have been explored extensively in prior research, little has been done to capture the effects of various driveway land-use categories on rural roadway safety performance, particularly for county roadways. Furthermore, while prior work has investigated the relationship between crash occurrence and aggregated horizontal curve characteristics, including number of curves, curve radius, and length of curve, several important alignment-related aspects including curve type, curve direction, tangent distances leading into and following the curve, and curve design speed have been minimally explored. Finally, in the context of both urban and rural roadways, prior research has largely focused on higher functional class roads, which are typically owned by the state DOTs. However, little is known in terms of the safety performance of roadway geometric characteristics on minor arterial or collector roads owned by local agencies (e.g., city or county), even though these lower-class roadways constitute a substantial portion of the overall roadway mileage in many states. Therefore, assumptions made on the general effect of the predictor variables from typical safety performance functions may not apply to lower roadway classes.

This research attempted to address these aforementioned knowledge gaps pertaining to the safety performance on rural and urban roadways. Consequently, three principal research objectives were formulated as follows:

Objective 1: Determine the association between driveway land-use and safety performance on rural two-lane two-way undivided state and county highways,

Objective 2: Determine the association between horizontal curve characteristics and safety performance on rural two-lane two-way undivided state and county highways, and

Objective 3: Determine the association between roadway characteristics and safety performance on urban and suburban lower functional class (minor arterials and collectors) two-lane two-way undivided county and city roadways.

To accomplish these objectives, roadway characteristics were collected along with traffic volume and crash data for greater than 13,000 miles of two-lane roadways in rural, urban, and suburban areas from across the state of Michigan for the period of 2011 through 2018. The data for this research were separately obtained for rural and urban roadways. For the first and second objectives, the data were obtained from selected rural roadway segments and corresponding horizontal curves owned by state and county agencies, including both paved and unpaved, across all regions of Michigan for the period of eight years from 2011 through 2018. A series of safety performance functions were developed using mixed-effects negative binomial modeling structure, which included fixed-effects and random-effects to account for the unobserved heterogeneity associated with varying design standards and site characteristics. Ultimately, the safety performance analysis of driveway land-use type and horizontal curve characteristics was carried out for the following facilities:

1. Rural state-owned two-lane two-way roadway segments (5,520 miles),
2. Rural county-owned two-lane two-way paved roadway segments (5,894 miles),
3. Rural county-owned unpaved/gravel roadway segments (2,007 miles),
4. Horizontal curves on rural two-lane state highway segments (277 miles),
5. Horizontal curves on rural two-lane two-way county highway segments, both paved and unpaved (557 miles).

For the third objective, data for roadway segments and crashes were obtained from Washtenaw County, Michigan for the same analysis period for the following facilities:

6. Urban/suburban county- or city-owned two-lane two-way minor arterial segments (100 miles), and
7. Urban/suburban county- or city-owned two-lane two-way collector segments (89 miles).

A series of safety performance functions were developed using mixed-effects negative binomial modeling structure, which included fixed-effects and random-effects to account for the unobserved heterogeneity associated with varying design standards and site characteristics. The following sub-sections outline the key findings from this research, its contributions, implications, and recommendations, and future research directions.

7.1 Safety Performance of Driveway Land-Use Classifications on Rural Highways

Previous research has investigated the safety impacts of driveway density, but little has been done to capture the effects of the various driveway land-use categories on rural roadway safety performance, particularly for county roadways. To address this gap, the safety impacts of various classifications of driveway land utilization, including residential, commercial, and industrial were analyzed using a sample of greater than 11,400 miles of rural two-lane state and county road segments in Michigan.

First, there was an association between driveway density and crash occurrence across all driveway types and roadway surface types. The association between driveway density and crash occurrence was strongest on state highways compared to paved county roads. Further, driveway density showed a more pronounced effect on fatal and injury crashes, compared to PDO crashes.

Most notably, driveway land-use had a significant effect on roadway safety performance for both rural state and paved county highways. Specifically, for paved rural highways, the density of commercial driveways was shown to have a stronger effect on crash frequency than other driveway land-use classes, although residential and industrial driveways also affected crash occurrence. No discernable impact of driveway land-use type was observed on rural unpaved roads.

Overall, the results of this study confirm previous research findings related to the influence of driveway density on crash occurrence and provide further evidence that various driveway land-use types affect safety to different extents on rural roads. Thus, this research contributed to the limited body of knowledge regarding the relationship between crash frequency and driveway land-use for rural roadway segments, particularly for county roads that, most commonly, have design and travel characteristics that are different from their state highway counterparts. These findings also confirms that driveway land-use classification provides additional insights into the safety performance on rural roads that may not be necessarily captured with the total driveway count combining all land-uses.

It is worth noting that, although driveway land-use classifications were the key variable of interest for this analysis, the presence of horizontal curves with radius corresponding to the posted speed limit or lower along the segments (i.e., underdesigned curves) were also included. The results of this analysis revealed that the presence of underdesigned horizontal curves was one of the greatest predictors (i.e., one of the strongest associations), other than traffic volumes, among all the factors analyzed. In fact, the effect of horizontal curves is even stronger on county roads compared to the state highways. This finding is important and forms the basis of the following objective, where instead of only a curve presence, several horizontal curve characteristics including the curve type, curve radius, curve direction, tangent distance preceding and following a curve is explored.

7.2 Safety Performance of Horizontal Curve Characteristics on Rural Highways

This research also assessed the safety impacts associated with horizontal curve characteristics on rural highway segments, including curve type, curve direction, curve-approaching, curve-following, and inner-curve tangent distances, and curve design speed on rural two-lane undivided highways. Similar to prior research, curves with design speeds lower than the posted speed limit showed elevated crash occurrence compared to curves with design speeds greater than the posted speed limits. This is important as more and more states are increasing their statutory maximum speed limits on rural highways, the selection of rural two-lane highway segments for speed limit increases should pay attention to existing roadway geometry, particularly with respect to horizontal curve radius. Consistent with the finding from the previous analysis (Objective 1), the effect of horizontal curves on crash likelihood was greater on county roads compared to state highways, which may be partially attributed to the lower design and maintenance standards of county highways.

Mostly notably, compound, and reverse curves were associated with greater crash occurrence compared to simple curves. While increased curve-approaching distance for simple curves, or the first of a series of reverse or compound curves was found to increase crash occurrence, the inner-curve distance for the reverse or compound curves was found to be negatively associated with crash frequency. Not surprisingly, the curve-following tangent distance did not have any impact on crashes for any of the models.

Lastly, the left-turning curves were found to be associated with greater crash occurrence than that on the right-turning curves, and this effect was stronger on state highway curves. This may be due to the fact that a left-turning curve positions the vehicle closer to the roadside, increasing the likelihood of a single vehicle run-off-road collision. As shown in previous research, the effect of horizontal curves was consistently stronger on fatal and injury crashes, compared to PDO crashes.

Overall, the results of this study support the previous research findings in general related to the safety concerns along horizontal curves and further contributes to the limited body of knowledge regarding the safety performance of horizontal curve characteristics at a disaggregate level on rural secondary highways, including roads under county jurisdictions. The findings from this study would be of particular interest to transportation researchers and highway design engineers, as they explore several geometric characteristics beyond only curve radius and length critical to understand the safety performance on horizontal roadway alignment.

7.3 Safety Performance on Urban/Suburban Minor Arterial and Collector Roads

Previous research of roadway safety performance has generally focused on higher functional class roadways, both in rural and urban areas. To address this knowledge gap, a safety performance evaluation was performed using a sample of two-lane undivided urban and suburban roadways with speed limits between 25 mph to 50 mph from Washtenaw County (i.e., greater Ann Arbor), Michigan.

In general, minor arterial roadways showed greater crash occurrence compared to collector roads. Posted speed limit was found to have a significant positive association with crash frequency, and this effect increased when the speed limit exceeds 40 mph. This effect was stronger on minor arterial segments and was also stronger when considering FI crashes compared to PDO crashes.

Additionally, driveway density was found to have significant effect on safety performance across all driveway land-use types both for minor arterials and collectors. Not surprisingly, commercial/industrial driveways were found to have a stronger effect on crash frequency than residential driveways, likely due to greater utilization. Moreover, the impact of driveway density was stronger on collector roads compared to minor arterials, particularly when considering the effect of residential driveways. In general, driveways possessed a greater effect on PDO crashes than FI crashes, although when considering commercial/industrial driveways on collector segments, the effect was stronger for FI crashes.

Lane width greater than 11 feet generally showed reduced crash occurrence across both segment types. Midblock crosswalks and bus stops were associated with increased crash occurrence. On-street parking was generally associated with lower crash occurrence, with a stronger effect occurring on collectors compared to minor arterials, likely due to greater turnover. Lastly, on minor arterials, school zone presence was associated with lower crash occurrence, while horizontal curves were associated with elevated crash occurrence.

Overall, the results of this study support the previous research findings and provides further evidence that roadway characteristics impact safety to different extents across different functional classifications. Most importantly, this study contributes to the limited body of knowledge regarding the safety performance characteristics observed on lower functional classes of urban/suburban roads, specifically minor arterials and collectors, which typically possess design and travel characteristics that are considerably different from those of primary arterials. However, in order to achieve a more comprehensive understanding on the difference of safety performance of roadway geometry between various functional classes, major arterial roadways should be investigated and compared with the results from this analysis.

Considering all three research objectives, to summarize, this study contributes to the limited body of knowledge of safety performance on lower class and lower speed roads, particularly those owned by non-state agencies. These roads typically possess design and travel characteristics considerably different from those of state highways. Also unpaved roads previously were not adequately explored which were evaluated in this research. This study also provided a novel specification of select roadways attributes such as driveway density by land-use type or specific horizontal curve characteristics at a more disaggregated level, which was really not explored well in the prior research. And overall, the study provides a comparative understanding between state highways and county roads in rural context and between minor arterials and collectors in the urban context.

7.4 Implications and Recommendations

The findings from these analyses may help identify policy implications and/or provide recommendations design interventions. However, they should be suggested with caution as the viability of these implications would depend on various other factors that need to be taken into account.

7.4.1 Rural two-lane highways

For driveway density on rural roads, land-use, and spacing of driveways should be taken into account and given a consideration to reduce the density, especially for commercial/industrial driveways. Prior research has suggested that clustering multiple, closely-spaced driveways instead of isolated driveways can be beneficial (*68*), so that can also be given a consideration, if possible.

In terms of horizontal curves on rural roads, compound or reverse curves should be minimized where a simple curve will do. But in most cases, they are a necessary component in roadway design, so it would be a trade-off. Reducing substandard curves can be given a consideration, or otherwise enhanced warning signage like flashing signs, beacons, or speed feedback signs should be considered.

7.4.2 Lower class urban/suburban roadways

On lower class urban roads, reducing speed limit could be given attention. It is noteworthy that, following the Third Global Ministerial Conference on Road Safety in February 2020 (*178*), continent-wide major European cities have started reducing their speed limits to 30 kilometers per hour (kph) (or 20 mph) from the typical urban speed limit of 50 kph (31 mph) to diminish pedestrian fatalities and carbon emissions. The focus of this conference, as noted in the Stockholm Declaration (*179*), has been on the strengthening of law enforcement to prevent speeding and decreasing the speed limit in areas with prevalence of vulnerable road users and vehicles mix. Reportedly, cities have already started to experience a decline in crashes involving vulnerable road users since the introduction of reduced speed limit on urban streets (*180*). The results in this study support this consensus revealing greater crash frequency due to speed limits more than 30 mph, and allude to the potential of safety benefits in adopting a lower speed limits along the urban roads of lower functional class including minor arterials and collectors. Also, Similar recommendations to that for rural roads can also be provided for the driveway density on urban roads where land-use, and spacing of driveways should be taken into account and given a consideration to reduce the density, especially for commercial/industrial driveways.

7.5 Limitations and Future Research

The research in this dissertation also identifies the scope for future research. For rural highway segments, field driveways should also be explored, as they are overabundant especially on the county non-federal aid and unpaved roads and possess different traffic, driver, and vehicle characteristics, presenting a different roadway environment than the other driveway land-uses that have been investigated in this research. Also, research can be carried out to identify the threshold of driveway density base condition for each land-use type. While *HSM* suggests a baseline of 0-5 driveway per mile for total driveways, a prior study recommended a baseline of 0-3 driveways per mile beyond which the safety performance of total driveways significantly worsened. However, with regard to various land-use types, the understanding of a baseline driveway density range has not been adequately studied.

This research also explored several important geometric characteristics of horizontal curves on rural roads. Nevertheless, to understand the difference in safety performance of horizontal curves and tangent sections, a comparative assessment will be insightful evaluating crashes on comparable and/or adjacent tangent sections on the road segments. Also, it would be insightful to investigate the effects of curve warning technologies on driver behavior approaching significant horizontal curves. Additionally, on two-lane undivided highways, head-on or head-on left turn should be of significant interest. Due to the overabundance of single-vehicle crashes, and a very small sample size of multi-vehicle crashes, these crash types could not be explored. Hence, a future study should include multi-vehicle crashes that are typically more severe on horizontal curves.

Another important question pertaining to horizontal curves is to identify the radius threshold at which a horizontal curve possesses safety performance similar to a tangent segment or in other words determine the minimum radius at which a horizontal curve shows no impacts on safety performance. Moreover, while this research compared the safety performance of curves having radius corresponding to design speeds below 55 mph with those having radius with corresponding to design speeds of 55 mph or greater, future research should explore curves belonging to different design speed ranges separately. Additionally, this research evaluated the horizontal curves along all county highway segments, as sample sizes separately for curves along paved federal aid, paved non-federal aid, and unpaved roads were sufficiently small. A future study should consider different functional classes and roadway jurisdictions while examining the safety performance of horizontal curves.

The research scope of the safety performance on urban/suburban minor arterial and collector roads can further be refined and broadened by including local roads into the analysis. Additionally, future research comparing the results of this study with safety performance of primary arterials will be insightful. Also, to account for regional diversity across larger geographic boundaries and validation of model results, this study should further be expanded by including additional data from other urban/suburban regions. Moreover, exploring the types of crashes occurring on these urban/urban roadway classes, particularly those involving vulnerable road users would provide additional understanding, which was not performed herein due to the very small sample sizes.

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