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14-06 Development of Safety Performance Functions and Other Decision Support Tools to Assess Pedestrian and Bicycle Safety

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Development of Safety Performance Functions and Other Decision Support Tools to Assess Pedestrian and Bicycle Safety

FINAL REPORT

By

Timothy J. Gates, Peter T. Savolainen, Steven Stapleton, Trevor Kirsch, and Santosh Miraskar

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16. Abstract

A field study was performed at 40 uncontrolled midblock crosswalks and 26 signalized intersections on low-speed roadways selected from the areas surrounding three major urban college campuses across lower Michigan. An array of existing traffic control devices existed at the study sites, including various crosswalk marking strategies, along with additional treatments, such as pedestrian hybrid beacons (PHBs), rectangular rapid-flashing beacons (RRFBs) and single in-street R1-6 signs. The sites also collectively included a diverse set of roadway and traffic characteristics, including crossing widths, number of lanes, and median presence, along with vehicular, pedestrian, and bicyclist volumes. Three primary evaluations were performed for the midblock segments and signalized intersection study sites, including: driver yielding compliance, vehicle-pedestrian conflicts, and non-motorized traffic crash data. The yielding compliance study found that the type of crosswalk treatment has a strong influence over driver yielding compliance. While yielding compliance improves substantially when crosswalk markings are utilized, the highest compliance rates are achieved when an additional enhancement device (i.e., RRFB, PHB, or R1-6 sign), is also provided. To supplement small crash sample sizes at the study sites, Michigan statewide pedestrian and bicyclist crash data were collected and utilized to develop safety performance functions (SPFs) and other methods for predicting pedestrian and bicyclist crashes at road segments and intersections. Because pedestrian and bicyclist volumes were not available statewide, each model was developed for pedestrian and bicycle crashes based solely on vehicular AADT. In general, the models showed that pedestrian and bicycle crashes tend to increase with increasing traffic volumes. However, even in the highest volume cases, only a fraction of crashes involved a pedestrian or bicyclist. Pedestrian and bicycle crashes were further estimated based on the respective proportion of the Michigan specific SPF models for total crashes. The primary limitation towards prediction of pedestrian and bicycle crashes is the lack of a reliable exposure data to represent the amount of pedestrian or bicyclist activity on a given segment or intersection.

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EXECUTIVE SUMMARY

INTRODUCTION AND OBJECTIVES

Safety performance functions (SPFs) provide a promising approach for quantifying the level for pedestrian crashes at specific intersections or road segments. The Highway Safety Manual (HSM) currently provides an aggregate pedestrian/bicycle SPF, which is based upon land use characteristics. However, since pedestrian and especially bicycle crashes are particularly rare, such an approach limits the ability to proactively identify sites with the potential for crashes that are not reflected by recent crash data. As a result, research is limited in terms of disaggregate-level studies considering the effects of motor vehicle/bicycle/pedestrian volumes, roadway geometry, and other factors on pedestrian and bicycle crashes. Furthermore, research has also been limited with respect to how these factors influence the underlying behaviors of both motorized and non-motorized road users. Therefore, alternative surrogate measures for identification of locations possessing comparatively high safety risks were investigated here.

METHODS

To address these issues, a field study was performed on low-speed roadways within Detroit, East Lansing, and Kalamazoo, Michigan to determine factors related to pedestrian and bicyclist safety risk. A variety of existing traffic control devices were considered, including various crosswalk marking strategies, along with additional treatments, including pedestrian hybrid beacons (PHBs), rectangular rapid-flashing beacons (RRFBs) and single in-street R1-6 signs. A diverse set of roadway and traffic characteristics were also considered, including crossing width, number of lanes, and median presence, along with vehicular, pedestrian, and bicyclist volumes collected during the study period. A total of 66 sites were selected, including 40 uncontrolled midblock locations and 26 signalized intersections, which were selected to provide diversity among existing crosswalk treatments and roadway characteristics, along with a range of vehicular and pedestrian volumes. To ensure adequate pedestrian activity, all locations were selected on or near college campuses or commercial business districts.

Driver and pedestrian behavioral observations were collected at each of the study sites using an elevated high-definition video camera, while historical crash data were collected for the most recent 10-year period from the Michigan State Police annual crash databases. Using these data, three primary evaluations were performed for both segments and signalized intersections, which included: driver yielding compliance, vehicle-pedestrian conflicts, and non-motorized traffic crash data, and attempts were made to examine the relationships between the behavioral measures and the crash data. Unfortunately, small sample sizes of vehicle-pedestrian conflicts and especially pedestrian/bicycle crashes limited the ability to draw meaningful conclusions from these data. Thus, to supplement small crash sample sizes at the study sites, statewide pedestrian and bicyclist crash data were collected and utilized to develop safety performance functions and other methods for predicting pedestrian and bicyclist crashes on road segments and intersections. The following sections describe the data collection and analytical methods along with results, conclusions and recommendations.

RESULTS

Driver Behavior During Pedestrian Crossing Attempts

The driver yielding compliance results at midblock crosswalks indicated that the type of crosswalk treatment has a strong influence over driver behavior when encountering a pedestrian in the crosswalk. While both yielding compliance and vehicle-pedestrian conflicts improve substantially when crosswalk markings are utilized, much greater compliance is obtained when additional enhancement devices, such as RRFBs, PHBs, or in-street R1-6 signs, are also provided. Yielding compliance rates for the various crosswalk treatments were shown to be in agreement with previous research performed outside of Michigan, and also showed improvements across all treatment types compared to prior studies performed within Michigan. This is an important finding, which suggests that compliance may improve as drivers become more familiar with a particular treatment.

Driver yielding compliance at midblock crosswalks was shown to increase as the pedestrian crossing volumes increased, but decrease as the vehicular volume increased. It was also found that yielding compliance is highly sensitive to both the roadway cross-section and lane position of the vehicle relative to the location of the crossing pedestrian. Drivers were much less likely to yield when the driver encountered the staged pedestrian at the nearside curb lane compared to any other lane. This is not a surprising result, as the pedestrian is in a less conspicuous and less vulnerable position when waiting near the curb, compared to encounters that occurred while the pedestrian was approaching a driver in any other lane. While this result is reflective of the interaction between motorists and pedestrians attempting to cross, it does indicate the necessity for yielding compliance studies to control for the driver lane position. And while low curb-lane compliance persisted across each of the observed types of roadway cross sections (two-lane, multilane undivided, and multilane divided), it was particularly low on median divided roadways. This may be indicative of potential obstructions within the median that reduce the visibility of pedestrians waiting to cross. Interestingly, vehicle-pedestrian conflicts were found to be lower at midblock crosswalks on divided roadways compared to undivided roadways. Perhaps most importantly, however, yielding compliance showed little sensitivity to driver lane position at locations where additional treatments (i.e., in-street R1-6 sign, PHB, RRFB) were utilized, providing further evidence of the effectiveness of these treatments.

Considering signalized intersections, yielding compliance was greater at 3-leg intersections compared to 4-leg intersections. Additionally, yielding compliance for turning vehicles at signalized intersections actually improved as the turning vehicle and pedestrian crossing volumes increased (and subsequent number of pedestrian-vehicle interactions increased). This effect was particularly strong when considering only right-turning vehicles.

Readers should also be aware of the limitations of the field study. First, the results are limited to low speed locations only. Driver and pedestrian behavior is likely different on higher speed roadways and pedestrian activity is typically less frequent. Furthermore, all sites selected in this study were on or near public universities in the Midwest during the early fall when school was in session. Therefore, both the pedestrians and drivers on which this model is based on may be more likely to fit a younger demographic than the pedestrian population at large.

Finally, and most importantly, although the investigation of pedestrian crashes at the study sites provided some indication of relationships between the various site, traffic, and behavioral factors, the small sample size of crashes across the study sites did not provide definitive results nor did it allow for formal SPF development. To help counter the small sample of pedestrian crashes, additional investigation into pedestrian-vehicle crashes statewide was performed.

Pedestrian and Bicycle SPFs

The lack of pedestrian and bicycle crash data at the study sites precipitated the need to perform a broader statewide assessment of pedestrian and bicycle crashes. Two parallel SPF development projects for the Michigan Department of Transportation (MDOT) led by the authors of this report allowed for development of pedestrian and bicyclist crash SPFs for various types of urban roadway segments and urban intersections based on traffic volumes, traffic control (intersections), speed limits, roadway cross section characteristics, driveway counts, lighting, and a number of roadway geometric variables. These data were aggregated into comprehensive databases along with historical traffic crashes from 2008 to 2012 for a representative statewide sample of urban segments and urban intersections.

Michigan-specific SPFs were developed for pedestrian and bicycle crashes separately for eight different types of urban segments (2-lane, 3-lane, and 4-lane undivided; 4-lane, 5-lane, 6-lane, and 8-lane divided; and one-way) along with four different types of urban intersections (3-leg and 4-leg stop control; and 3-leg and 4-leg signal control) for total, fatal and injury, and property damage only crashes. Because pedestrian and bicyclist volumes were not available statewide, each model was developed for pedestrian and bicycle crashes based solely on vehicular annual average daily traffic (AADT). In general, the models showed that pedestrian and bicycle crashes tend to increase with increasing traffic volumes. However, even in the highest volume cases, only a fraction of crashes involved a pedestrian or bicyclist. Furthermore, in most cases, the property damage only (PDO) models were not statistically significant. This is reflective, at least in part, of the fact that pedestrian- or bicycle-involved crashes that result in no injury are very rare and most crashes of this type tend to go unreported.

Relative Proportions of Pedestrian and Bicycle Crashes by Roadway Type

After development of the simple pedestrian and bicycle specific SPFs, pedestrian and bicycle crashes were further estimated based on the respective proportion of the SPF models for total crashes developed for each of the aforementioned urban facility types using a representative statewide sample of MDOT roadway segments and intersections. Several variables were incorporated in the development of the SPFs and crash modification factors (CMFs) including AADT, MDOT region, speed limits, functional class, and numerous roadway geometric variables such as shoulder and median width, driveway density, intersection and crossover density, and horizontal curvature.

The pedestrian crash proportion results suggested that one-way urban segments, two-lane 55 mph undivided urban segments and 4-lane divided urban segments possessed the lowest proportions of pedestrian crashes on MDOT urban roadway segments in Michigan. These results are not surprising, as urban one-way segments typically possess very low speed limits, pedestrian volumes on 55 mph segments are likely very low, and 4-lane divided segments offer refuge for pedestrians. The greatest proportion of pedestrian crashes occurred on 8-lane divided segments, which likely indicates the high level of pedestrian activity coupled with high levels of exposure when crossing the roadway. When compared to segments, intersections displayed greater proportions of pedestrian crashes across all facility types. Considering the various intersection types, pedestrian crashes represented lower proportions at 3-leg intersections compared to 4-leg intersections. Stop-controlled intersections showed greater pedestrian crash proportions compared to signalized intersections.

Similar to the pedestrian crash proportions, two-lane 55 mph undivided urban segments and 4-lane divided urban segments were found to possess the lowest proportion of bicyclist crashes on MDOT urban roadway segments in Michigan. These results are not surprising, as bicyclist volumes on 55 mph segments are likely lower than on lower speed segments, although it should be noted that 100 percent of the bicycle crashes on this segment type resulted in an injury or fatality, likely a result of the high vehicular speeds on such roadways. The greatest proportion of crashes occurred on one-way segments, although it should be noted that the overall crash samples were considerably lower than the other segment types. When compared to segments, intersections displayed greater proportions of bicycle crashes across all facility types, with the exception of one-way segments, which showed comparable bicycle crash proportions to those of intersections. Considering the various intersection types, bicycle crashes represented lower proportions at 3-leg intersections compared to 4-leg intersections. Stop-controlled intersections showed greater pedestrian crash proportions compared to signalized intersections, especially for 4-leg stop intersections.

RECOMMENDATIONS

Road agencies are advised to place crosswalks in otherwise unmarked locations where pedestrians frequently cross and, when necessary, install additional treatment. Providing marked crosswalks in locations with light to moderate vehicle volumes will result in higher yielding compliance and will typically not require additional treatment unless special circumstances (i.e., school, hospital, etc.) exist. For midblock crosswalks in locations with high vehicle and/or high pedestrian volumes, particularly at multilane locations, additional low-cost treatments such as in-street pedestrian crossing signs (R1-6) may further increase compliance and provide subsequent safety benefits, whether used in a single installation on the centerline (studied here) or in a gateway configuration on both the centerline and at the edges of the roadway. Due to high costs, RRFBs and especially PHBs, should only be installed at select locations displaying high pedestrian and vehicular volumes, particularly where other treatments have proven to be ineffective.

The SPF models provided here give a general starting point for pedestrian and bicycle safety analyses. Perhaps the greatest limitation to prediction of pedestrian and bicyclist crashes, including those developed here, is the lack of reliable exposure data to represent the amount of pedestrian or bicyclist activity on a given segment or intersection. Future programs by transportation agencies or researchers should be aimed at collecting such exposure data for non-motorized users, in addition to motor vehicle traffic volumes.

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CHAPTER 1:
INTRODUCTION

The safety of pedestrians continues to be a critical transportation issue, both nationally and throughout Michigan. Approximately 65,000 pedestrians are injured in traffic crashes in the United States annually, including approximately 5,000 fatalities [1]. A query of the Michigan Traffic Crash Database via the Michigan Traffic Crash Facts Website [michigantrafficcrashfacts.org] showed that between 2011 and 2015, 11,442 pedestrian crashes occurred on roadways in Michigan, representing a 2.1 percent increase over the previous 5-year period of 2006 to 2010. Such crashes resulted in 729 pedestrian fatalities, representing a 15.7 percent increase over 2006 to 2010. While pedestrian-involved crashes comprised only a small portion (0.8 percent) of all crashes that occurred between 2011 and 2015, consider that pedestrians accounted for 17.0 percent of all fatalities in Michigan during that period. When considering the vulnerability and relative risk, pedestrians were 32 times more likely to be fatally injured when involved in a traffic crash compared to drivers of motor vehicles.

The frequency of bicyclist involved traffic crashes is very similar to that of pedestrians, although the number of fatalities is much smaller. Consider that between 2011 and 2015, 9,353 bicyclist involved traffic crashes occurred. However, bicyclists displayed a much lower fatal crash vulnerability compared to pedestrians, with only 125 bicyclist fatalities occurring, meaning that bicyclists were 4.8 times less likely to be killed during a collision than pedestrians.

Crashes involving pedestrians and bicyclists occur most frequently within urban and suburban areas, particularly on or near college campuses, since these areas experience the highest levels of pedestrian activity and traffic volumes. Further, there is considerably greater distraction present for both motorists and pedestrians in such areas, and the focus of motorists is often drawn away from the roadway. As a result, pedestrians and bicyclists are often put into situations where approaching motorists do not see them or are surprised by their presence, which may lead to conflicts and traffic crashes. Unfamiliar drivers, which are particularly common on college campuses, further exacerbate these safety issues.

Various efforts have been implemented to address pedestrian safety issues throughout the United State, including “Complete Streets” policies, “Safe Routes to School” programs, and other initiatives. However, while these efforts have improved safety and connectivity for non-motorized road users, they have also facilitated increases in pedestrian and bicyclist travel, thereby leading to an increased exposure and subsequent crash risk. Such risks may be mitigated by the application of appropriate engineering treatments to enhance motorists' awareness of crossing pedestrians, while also encouraging pedestrians to cross at these treated crossing areas. However, given limited financial resources, adequate guidance is necessary to assist agencies in determining when and where to implement pedestrian safety treatments in the most cost effective manner possible.

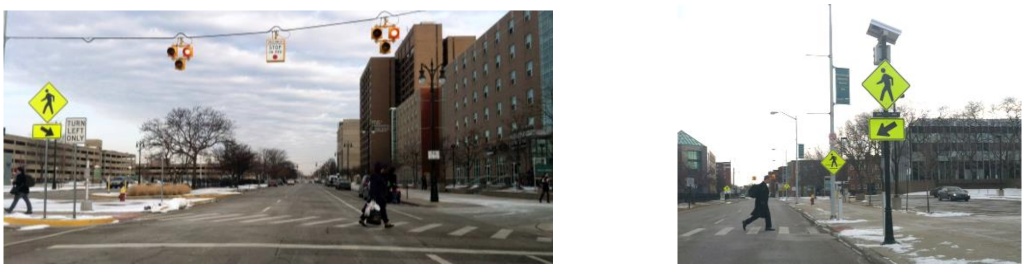
As can be observed in Table 1, the need for effective pedestrian and bicyclist safety countermeasures is particularly important at non-intersection (i.e., midblock) locations, especially at such locations where no signal exists (i.e., uncontrolled). Also problematic for pedestrian safety are intersections with no traffic control, including uncontrolled legs of stop controlled intersections, as vehicular operations are similar to that experienced at midblock areas but with the additional risk of turning traffic.

Table 1. Michigan Pedestrian and Bicyclist Crashes by Location Type and Traffic Control, 2011-2015 [Michigan Traffic Crash Facts Website]

		Crash Statistics, 2011 - 2015		
Road User Type	**Type of Location**	**Number of Crashes**	**Number of Fatalities**	**Fatalities as Percent of All Crashes**
Pedestrian	Non Intersection – No Signal	4,998	484	9.7%
	Non Intersection - Signal	540	32	5.9%
	Intersection – No Control	1,237	71	5.7%
	Intersection – Stop or Yield	872	13	1.5%
	Intersection – Signal	2,291	66	2.9%
Bicyclist	Non Intersection – No Signal	2,903	77	2.7%
	Non Intersection - Signal	366	3	0.8%
	Intersection – No Control	949	10	1.1%
	Intersection – Stop or Yield	1,986	12	0.6%
	Intersection – Signal	2,482	20	0.8%

A variety of pedestrian safety treatments are available for implementation at such locations, including pedestrian hybrid beacons (PHBs), rectangular rapid flashing beacons (RRFBs), and in-street pedestrian signs (R1-6), examples of which are displayed in Figure 1. Resource constraints make it imperative that agencies are able to identify those locations that are at the highest risk for pedestrian-involved (and bicyclist-involved) crashes so that appropriate countermeasures may be implemented. As such, there is a clear need for well-supported guidelines to assist in determining appropriate locations for specific pedestrian safety treatments.

Single R1-6 **R1-6 Gateway Configuration**



Pedestrian Hybrid Beacon **Rectangular Rapid Flashing Beacon**

Figure 1. Typical Pedestrian Crosswalk Enhancements in Michigan

Typically, these types of network screening activities have been done on the basis of historical crash data. More recently, development of safety performance functions (SPFs) has provided a promising approach for quantifying the level for pedestrian crashes at specific intersections or road segments. The Highway Safety Manual (HSM) currently provides an aggregate pedestrian/bicycle SPF, which is based upon land use characteristics [2]. However, since pedestrian and especially bicycle crashes are particularly rare, such an approach limits the ability to proactively identify sites with the potential for crashes that are not reflected by recent crash data. As a result, research is limited in terms of disaggregate-level studies considering the effects of motor vehicle/bicycle/pedestrian volumes, roadway geometry, and other factors on pedestrian and bicycle crashes. Furthermore, research has also been limited with respect to how these factors influence the underlying behaviors of both motorized and non-motorized road users. Therefore, alternative surrogate measures for the identification of roadway locations which possess comparatively high safety risks should be investigated.

To address these issues, a field study was performed on low-speed roadways within three Michigan cities to determine factors related to pedestrian and bicyclist safety risk. A variety of existing traffic control devices were considered, including various crosswalk marking strategies, along with additional treatments, including PHBs, RRFBs and single in-street R1-6 signs. A diverse set of roadway and traffic characteristics were also considered, including crossing width, number of lanes, and median presence, along with vehicular, pedestrian, and bicyclist volumes collected during the study period. Three primary evaluations were performed for both segments and signalized intersections, which included: driver yielding compliance, vehicle-pedestrian conflicts, and non-motorized traffic crash data, and attempts were made to examine the relationships between the behavioral measures and the crash data. To supplement small crash sample sizes at the study sites, statewide pedestrian and bicyclist crash data were collected and utilized to develop safety performance functions and other methods for predicting pedestrian and bicyclist crashes on road segments and intersections. The following chapters describe the data collection and analytical methods along with results, conclusions and recommendations.

CHAPTER 2:

LITERATURE REVIEW

Given that pedestrian and bicycle safety has been a key area of concern for many safety stakeholders throughout the United States, there have been a variety of efforts aimed to provide better guidance and tools for engineers and planners to improve safety and connectivity for such non-motorized users. Specifically, previous research has focused on methods for predicting vehicle-pedestrian and vehicle-bicycle crashes along highway facilities based upon a diverse set of roadway conditions. Additionally, work has also been performed to evaluate the impacts on non-motorized safety performance subsequent to the implementation of pedestrian or bicycle safety treatments. Other work has examined potential surrogate measures for non-motorized safety given the relative infrequency of vehicle-pedestrian and vehicle-bicycle crashes. Finally, there have also been several studies evaluating the impacts of implementing several midblock crosswalk treatments along roadways with varying geometric, operational and other highway characteristics. A summary of the prior work related to pedestrian and bicycle safety with a specific focus on the aforementioned topics is provided in the following subsections.

PREDICTING VEHICLE-PEDESTRIAN AND VEHICLE-BICYCLE CRASHES

The HSM includes methods for estimating pedestrian crashes for urban and suburban arterials, with separate methods provided for segments, signalized intersections, and stop-controlled intersections [2]. For signalized intersections, the predictive method in the HSM is based on a pedestrian-specific safety performance function (SPF) that is estimated based on the number of intersection legs, major and minor traffic volumes, and pedestrian volumes. A series of CMFs are then applied to the base SPF to account for bus stops, schools, and the number of alcohol establishments nearby. Additional CMFs can be found in the research literature, and include: increasing the cycle length for pedestrian crossing [3], installing a pedestrian countdown timer [4], and implementing a leading pedestrian interval [5].

In contrast, the method for predicting pedestrian crashes along segments is rather simplistic in nature, utilizing the base condition for segments multiplied by an adjustment factor to predict pedestrian crashes. Unfortunately, the HSM provides no predictive method for pedestrians at midblock crossing locations. However, CMFs for various pedestrian crossing treatments are found in the research literature, including: raised pedestrian crosswalks [6]; raised medians [7] [8]; high-visibility crosswalks [3]; and pedestrian hybrid beacons [9]. The lack of available pedestrian crash prediction models has prompted the use of surrogate measures, including driver yielding compliance and conflicts, as alternative methods for assessing pedestrian safety at midblock crossing areas. Predicted pedestrian crashes at stop controlled intersections are calculated in a similar manner.

The HSM's method for predicting vehicle-bicycle crashes along both segments and at intersections involves using the base SPF and multiplying that by an adjustment factor, in the same manner as vehicle-pedestrian crashes are calculated at segments [2]. Similar to vehicle-pedestrian crashes, CMFs for various treatments pertaining to vehicle-bicycle crashes are found in the research literature, including: bike lanes [10], colored bike lanes at signalized intersections [11], and moving midblock bicycle crossings to intersections [12]. Additionally, treatments pertaining to vehicle or pedestrian infrastructure also have CMFs specific to vehicle-bicycle crashes, such as: implementing a leading pedestrian interval [5], presence of parking entrances [13], and the presence of driveways for parking [13].

SURROGATE SAFETY MEASURES

Due to the rarity and randomness of pedestrian crashes, various surrogate measures, including conflicts and yielding compliance, are often utilized to assess pedestrian safety. To be effective, surrogates should be correlated with crash occurrence and fully capture the effect of the treatment [14]. A recent naturalistic driving study by Virginia Tech Transportation Institute, provided the most extensive investigation into the relationship between crashes and near-crashes (i.e., conflicts), which were defined as rapid evasive maneuvers by the study vehicle [15]. Analysis of these data found a positive relationship between crashes and near crashes, suggesting that near-crashes are an acceptable surrogate measure for crashes at locations where crash occurrence is rare [16].

However, just as crashes are rare events, vehicle-pedestrian conflicts are also rare, which may lead to an under-prediction of crashes when relying on conflict as a surrogate measure [17]. To overcome this lack of data, driver yielding compliance has often been utilized as a surrogate measure for crashes [18] [19] [20]. In order to reduce bias, staged crossing attempts are performed in a uniform and consistent manner by a trained observer. During each staged crossing event, the observer indicates the desire to cross by placing one foot in the crosswalk when the vehicle has reached a pre-defined upstream location, typically determined based on the signal dilemma zone or stopping sight distance equations. This method is consistent with right-of-way laws in most states. Driver yielding or non-yielding behavior is assessed during each crossing attempt. A comparison of the yielding results for staged and unstaged crossings found no significant difference in results, supporting the use of staged pedestrians for assessment of yielding compliance [19].

A study published in 2014 investigated using behavioral information to predict pedestrian crashes at signalized and midblock crossing locations. The research combined observed pedestrian conflicts with crossing distance and building setback using 100 pedestrian crossing locations in Connecticut, which included signalized and unsignalized mid-block crossings, 3-leg intersections, and 4-leg intersections. The research considered crossing type, traffic control, speed limit, presence of median or pedestrian refuge island, crossing distance, number of lanes, on-street parking, and building setback. Conflicts were classified using a variation of the Swedish Traffic Conflict Technique, which categorized pedestrian crossings as undisturbed passages, potential conflicts, minor conflicts, or serious conflicts as defined in Table 2.

Negative binomial and ordered proportional odds were used to estimate crashes. The research found that minor conflicts were somewhat useful for predicting KAB crashes (p-value of 0.1628), and serious conflicts were also somewhat useful for predicting KABCO crashes (p-value of 0.1318). Greater crossing distance and minimal building setbacks were associated with larger numbers of pedestrian-vehicle crashes, while pedestrian volume was not significant [39].

Table 2. Definitions of Conflicts used to Predict Pedestrian-Vehicle Crashes

Undisturbed Passage	Pedestrian crosses with no possibility of a collision with vehicles. At a signal-controlled intersection, this usually means vehicles are stopped at a red light. At a midblock crossing location, there are no vehicles in the vicinity.
Potential Conflict	Low-level interaction between pedestrian and vehicle. A vehicle slowing to a stop as the pedestrian is crossing is an example.
Minor Conflict	Chance of collision. Driver takes evasive action to avoid pedestrian, either by swerving out of the pedestrian's way or by extreme braking. Vehicle is traveling slowly enough that the pedestrian could take evasive action to avoid collision.
Serious Conflict	Evasive action is taken late to avoid collision. Examples would be a pedestrian jumping out of the way of the vehicle's path or the vehicle itself taking extreme evasive action to avoid collision.

MIDBLOCK CROSSWALK TREATMENTS

Prior research has indicated that simply converting an unmarked midblock crossing area to a marked crosswalk with no additional treatment will not improve safety [8]. Furthermore, marked crosswalks are specifically not recommended when the speed limit is greater than 40 mph or on a high volume multilane roadway without a refuge island or median [8]. Over the past decade, innovative pedestrian safety treatments, including PHBs, RRFBs, and in-street pedestrian signage have been implemented nationwide, and numerous evaluations of these treatments have been performed [9] [4] [21] [22] [23] [24] [25]. The prior research has generally focused on evaluating the effectiveness of such treatments with respect to a baseline condition (i.e., marked crosswalk-only), typically utilizing yielding compliance rates as the primary performance measure.

Pedestrian hybrid beacons have been utilized in the United States since the early 2000's and were first included in the 2009 edition of the federal Manual on Uniform Traffic Control Devices (MUTCD) [26]. Driver yielding compliance with the PHB is varied and is largely related to the level of driver familiarity with the devices within the specific area of use [4] [21] [22]. For example, a sample of PHB installations in Tucson, where PHBs had been in place for multiple years, showed a driver compliance rate of 97 percent [21]. Driver compliance at three PHB installations in Florida, where the devices are less common, increased from 80 percent one week after installation to 85 percent after one year [4]. Yielding compliance at PHBs in Michigan, where such devices are relatively uncommon, was much lower, averaging only 77 percent at four non-intersection locations [4]. These findings are substantiated by an Oregon study that found drivers to be confused as to the meaning of the alternating flashing red indication [22]. Nevertheless, an empirical Bayes analysis of crash data at 21 PHB installations in Tucson found a nearly 70 percent reduction in pedestrian-involved crashes [9].

RRFBs are often considered as a lower cost alternative to PHBs, though the RRFB serves as a warning indication, as opposed to the regulatory indication of the PHB. However, motorist yielding compliance rates for RRFBs have shown to be similar to that of PHBs [21] [23] [24] [25]. A recent Florida evaluation at 22 locations where RRFBs were installed showed average compliance rates of 78 percent one-week after installation and 82 percent after one month [23]. Similarly, an evaluation at two crosswalks in Oregon showed average compliance rates of 83 percent [24]. RRFBs have also shown promise towards improving yielding compliance near schools as a Texas study found driver compliance during non-school hours increased from a baseline of less than 1 percent to approximately 80 percent after RRFB installation [25]. Similar to the PHBs, lower compliance was observed at RRFB locations in Michigan, with an average compliance rate of 77 percent at three uncontrolled crossing locations and 72 percent at two roundabout locations [4].

With installation costs of approximately $100,000 and $20,000 for PHBs and RRFBs, respectively, the application of these devices has been limited. Conversely, the in-street pedestrian sign (R1-6) is a very low cost pedestrian safety treatment that has shown favorable motorist compliance rates when used in certain configurations. A single R1-6 sign placed on the centerline within an uncontrolled crosswalk at three low-speed two-lane roadways in Washington produced average compliance rates of 87 percent [21]. Lower yielding compliance rates of 57 percent were observed with a single R1-6 in place on two low-speed multilane roadways in Michigan [4]. However, upgrading to a series of three R1-6 signs in the “gateway” configuration at these same Michigan locations improved motorist compliance to 81 percent, likely due to a combination of the message and the lane narrowing effect provided by the signs. Furthermore, the addition of a single R1-6 to the center of a crosswalk at two Michigan locations with an existing PHB increased motorist compliance from 77 percent to 90 percent [4].

CHAPTER 3:

DATA COLLECTION

In order to assess the safety performance of various pedestrian crossing treatments, it was initially necessary to collect data specific to existing locations in the field where such treatments have been implemented. First, this involved the identification of sites which possess varying geometric, operational, and other highway characteristics in addition to the pedestrian crossing treatment of interest. After the selection of appropriate field locations, behavioral data was collected in the field at each site, including data for both staged and naturalistic crossing events, in order to assess driver compliance to traffic control as well as quantify the occurrence of conflicts. Historical traffic crash data were also collected for each site from the annual databases maintained by the Michigan State Police. The data collection activities for this study are detailed in the subsections that follow.

SITE SELECTION

The study locations were selected to provide diversity among existing crosswalk treatments and roadway characteristics, along with a range of vehicular and pedestrian volumes. This included the identification of both midblock crossings (including uncontrolled legs at two-way stop-controlled intersections) as well as signalized intersections. To ensure adequate pedestrian activity, the locations were selected on or near college campuses or commercial business districts. A total of 66 sites were selected, including 40 uncontrolled midblock locations and 26 signalized intersections. The sites were selected from three Michigan cities and all sites were on or near major university campuses. This included 35 sites from the midtown area of Detroit (Wayne State University), 20 sites from East Lansing (Michigan State University), and 11 sites from Kalamazoo (Western Michigan University). Relevant site characteristics, including crosswalk treatment, crossing distance, median presence, pedestrian signage, lighting, speed limit, and access point density, as well as other highway features, were initially collected using Google Earth satellite imagery and were later validated in the field. Table 3 shows the distribution of the study sites by crossing type and city for both the midblock crossing locations and signalized intersections.

Table 3. Number of Study Sites by Crossing Type and City

Type of Crossing	Detroit	East Lansing	Kalamazoo	TOTAL
Uncontrolled Midblock	14	18	8	40
Signal Controlled	21	2	3	26

Tables 4 and 5 display the basic site characteristics for the 40 midblock crossing locations and 26 signalized intersections included in the study, respectively. As it was not possible to obtain speed data during the field data collection, in order to control for operating speeds, only sites with posted speed limits of 25 mph were selected at uncontrolled midblock locations, and with posted speed limits of 25 mph and 30 mph at signalized intersection locations. Thus, the results of this study are limited to low speed locations.

FIELD DATA COLLECTION

After the selection of sites was completed, observational field data related to the behavior of motorists and pedestrians during crossing events were collected during August, September, and October of 2015. The data were collected during daytime periods and under fair weather conditions for two to four hours per site. Covertly positioned elevated high-definition video cameras were temporarily installed at each location to record the staged pedestrian crossing attempts along with vehicle and pedestrian volumes. The videos were later reviewed to extract volume and behavioral information. Using video recordings provided two primary advantages over using on-site human observers: 1) the number of necessary field personnel at each site was reduced and 2) permanent record of the interactions was provided, which improved training and quality assurance procedures. Figure 1 displays an example of the video camera setup and field-of-view.

Figure 1. Typical Video Camera Setup for Recording Motorist Yielding Behavior

Table 4. Characteristics of Midblock Study Sites

City	Primary Street	Cross Street or Landmark	Total Street Crossing Dist. (ft.)	Crosswalk Type	Median Presence	Staged Crossing Data Collection
Detroit	Anthony Wayne Dr.	Atchison Hall	61	Continental	Yes	Yes
Detroit	Anthony Wayne Dr.	W. Palmer Ave.	102	Continental	Yes	Yes
Detroit	Anthony Wayne Dr.	Parking Structure 5	94	Continental	Yes	Yes
Detroit	Anthony Wayne Dr.	W. Hancock St.	65	Unmarked	Yes	Yes
Detroit	Anthony Wayne Dr.	W. Ferry Ave.	94	Continental	Yes	Yes
Detroit	W. Palmer Ave.	Parking Structure 1	58	Continental	Yes	Yes
Detroit	Cass Ave.	W. Kirby St.	50	Unmarked	No	Yes
Detroit	Cass Ave.	Kohn Building	48	Continental	No	Yes
Detroit	Cass Ave.	Prentis St.	50	Unmarked	No	Yes
Detroit	Cass Ave.	W. Ferry Ave.	46	Unmarked	No	Yes
Detroit	Lodge Service Dr.	Matthaei Center	40	Continental	No	Yes
Detroit	W. Palmer Ave.	Shapero Hall	69	Continental	Yes	Yes
Detroit	John R St.	Garfield St.	52	Continental	No	Yes
Detroit	Cass Ave.	W. Willis St.	46	Unmarked	No	Yes
E. Lansing	Bogue St.	Snyder Hall	51	Continental	Yes	Yes
E. Lansing	Chestnut Rd.	Wilson Hall	30	Continental	No	Yes
E. Lansing	E. Circle Dr.	Olin Health	30	Continental	No	Yes
E. Lansing	E. Grand River Ave.	Charles St.	53	Standard	Yes	Yes
E. Lansing	Red Cedar Rd.	Eng. Building	54	Continental	No	Yes
E. Lansing	Red Cedar Rd.	Spartan Stadium	26	Continental	No	Yes
E. Lansing	S. Shaw Ln.	Anthony Hall	24	Continental	Yes	Yes
E. Lansing	N. Shaw Ln.	Erickson Hall	24	Continental	Yes	No
E. Lansing	N. Shaw Ln.	International Center	24	Continental	Yes	Yes
E. Lansing	N. Shaw Ln.	Planetarium	22	Continental	Yes	Yes
E. Lansing	N. Shaw Ln.	Shaw Hall	24	Continental	Yes	No
E. Lansing	N. Shaw Ln.	Holmes Hall	47	Continental	Yes	Yes
E. Lansing	N. Shaw Ln.	Holmes Hall	47	Continental	No	No
E. Lansing	N. Shaw Ln.	Holmes Hall	29	Continental	No	No
E. Lansing	W. Circle Dr.	Grand River Ramp	25	Continental	No	Yes
E. Lansing	Wilson Rd.	Wharton Center	50	Continental	Yes	Yes
E. Lansing	Wilson Rd.	E. Wilson Hall	28	Continental	No	Yes
E. Lansing	Wilson Rd.	W. Wilson Hall	28	Continental	No	Yes
Kalamazoo	W. Michigan Ave.	Student Rec Center	40	Standard	No	No
Kalamazoo	Dormitory Rd.	Extended Univ Programs Bldg	22	Standard	No	No
Kalamazoo	W. Walnut St.	Health Care Plaza	73	Standard	No	No
Kalamazoo	Knollwood Ave.	Western View Apt Complex	26	Continental	No	Yes
Kalamazoo	Rankin Ave.	Welborn Hall	40	Standard	No	No
Kalamazoo	Gilkison Ave.	Western Heights	32	Standard	No	Yes
Kalamazoo	Goldsworth Dr.	Goldsworth Valley Pond	38	Standard	No	Yes
Kalamazoo	Dormitory Rd.	Parking Structure 1	41	Continental	No	No

Table 5. Characteristics of Signalized Intersection Study Sites

City	Primary Street	Cross Street	Average Street Crossing Dist (ft)	Crosswalk Type	Right-Turn-on-Red Permitted
Detroit	2nd	Warren	71	Continental	Yes
Detroit	Lodge Service Dr	Warren	59	Continental	No
Detroit	Randolph	Jefferson	98.5	Continental	Yes
Detroit	Cass	Palmer	61.5	Continental	No
Detroit	Cass	Putnam	44	Continental	Yes
Detroit	Cass	Library	49	Continental	No
Detroit	2nd	Forest	53.5	Continental	No
Detroit	Trumbull	Warren	54.5	Standard	No
Detroit	Anthony Wayne Dr	Forest	57	Continental	No
Detroit	Cass	Forest	45	Continental	No
Detroit	Cass	Antoinette	43	Standard	No
Detroit	Cass	Milwaukee	43.5	Standard	No
Detroit	Shelby	Lafayette	38.5	Continental	No
Detroit	Shelby	Fort	49.5	Continental	Yes
Detroit	Cass	Fort	60	Continental	No
Detroit	Washington	Congress	46	Continental	No
Detroit	Washington	Larned	47	Continental	Yes
Detroit	John R	Warren	69	Standard	No
Detroit	Cass	Michigan	79	Continental	No
Detroit	3rd	Michigan	86.5	Continental	No
Detroit	Woodward	Jefferson	91	Continental	No
East Lansing	Farm Lane	River Trail	40	Continental	No
East Lansing	Red Cedar	South Shaw	40	Continental	Yes
Kalamazoo	Dormitory	Michigan	49	Brick Paver	No
Kalamazoo	Howard	Michigan	83.5	Standard	No
Kalamazoo	Howard	Valley	57	Standard	No

Staged Pedestrian Crossing Events

Staged pedestrian crossing events were utilized for the assessment of driver yielding compliance, and took place at 31 midblock crossing locations. The staged crossing events utilized observers trained to follow a uniform crossing protocol for each approaching driver, thereby reducing external bias. Consistency was provided among the positioning, stance, gesture, eye contact, and aggressiveness used by the pedestrian while entering the crosswalk, in addition to control over external features such as the style and conspicuity of clothing. The staged crossing events also ensured a sufficient sample size at each location, which improved data collection efficiency at locations with low pedestrian crossing volumes. The staged crossing events followed protocols established in prior research [4] [21]:

- The staged pedestrian approached the crossing at any time when approaching vehicles were within sight of the crossing. Where present, active devices (PHB, RRFB) were activated at this time. Staged crossing attempts were avoided while other pedestrians were attempting to cross the same crosswalk.
- The staged pedestrian indicated an intention to cross by standing at the curb or roadway edge with one foot in the crosswalk and facing oncoming traffic. This action occurred when the vehicle approached a predetermined location upstream of the crosswalk, which was determined using the standard kinematic equation for the timing of an amber interval at a traffic signal based on the default reaction time (1.0 s) and deceleration rate (10 ft./s^2) parameters. The resulting distance was measured from the near edge of either the crosswalk, stop line, or pedestrian landing and was marked with a roadside object. In this manner, motorists were afforded ample distance to comfortably stop for the staged pedestrian. Vehicles already beyond this boundary point when the crossing was initiated were considered too close to comfortably stop and were not considered.
- The staged pedestrian began to cross when the motorist in the nearest lane had begun to yield and maintained eye contact with the motorist at all times.
- If additional vehicles were approaching from other lanes, the staged pedestrian crossed halfway into the lane where a motorist had already stopped or yielded and waited until the intention of the approaching motorist was determined. This process was completed as many times as necessary to cross the entire roadway or reach a median.
- After concluding the midblock crossing, the procedure was then repeated from the opposite direction at the same crosswalk.

A yielding event was classified as a motorist that was initially positioned upstream of the boundary point at the start of the staged crossing event that slowed or stopped to allow the pedestrian to safety cross. For motorists in the nearest lane to the pedestrian, the yielding assessment was made on the basis of the initial intention to cross the roadway. For motorists in the additional lanes, if present, this assessment was made once the pedestrian had crossed to within a half-lane distance of their position. Opposing directions of traffic on divided roadways were considered separately. These procedures are consistent with the crosswalk right-of-way requirements included within the *Uniform Traffic Code for Cities, Townships, and Villages* that has been adopted as a local ordinance by many Michigan municipalities [27]. Staged crossing events were recorded on a per-event basis.

Naturalistic Pedestrian Crossing Events

Naturalistic driver yielding compliance for vehicles turning on permissive signal indications was also recorded during naturalistic pedestrian crossing events at signalized intersections. According to state law, during a permissive signal indication, the driver must yield to pedestrians in this scenario. Thus, driver yielding compliance was scored accordingly for each permissive turning event where pedestrians were present either at or within the crosswalk.

Pedestrian-Vehicle Conflicts

In addition to the staged crossing events, the data related to pedestrian-vehicle conflicts were also collected. The pedestrian conflict data were collected from the aforementioned high-definition videos. Each video was manually reviewed to classify the types and frequency of evasive maneuvers taken by either party at each of the midblock and signalized intersection locations. The purpose of recording the naturalistic (i.e., not staged) events was to gather ancillary data on evasive maneuvers taken by motorists or pedestrians when the driver (or pedestrian in some cases) did not properly yield the right-of-way.

Conflicts were defined as cases where the driver or pedestrian took evasive action to avoid a collision. A vehicular evasive maneuver was recorded if the driver had to take evasive action such as swerving or extreme braking to avoid striking a crossing pedestrian. Alternatively, a pedestrian evasive maneuver was recorded if the pedestrian had to take evasive action such as hurried walking or stepping back to the curb to avoid a collision with a motorist.

Road User Volumes

Volumes of vehicles, bicycles, and naturalistic (i.e., non-staged) pedestrian crossings were collected from the videos at each study location during the study period. Pedestrians that crossed within 10 ft of the crosswalk were included in the pedestrian crossing volume for the particular crosswalk. Bicyclists were only counted if using the bike lane or traffic lane. Bicyclists utilizing the sidewalk were not counted as a part of this study, but were included as pedestrians if crossing at the crosswalk. All volume data were tallied in 15-minute intervals and were subsequently converted to hourly volumes. Where multiple crosswalks existed at a single location, the pedestrian volumes were aggregated together and normalized on a per-crosswalk, per-hour basis.

PEDESTRIAN AND BICYCLIST CRASH DATA COLLECTION

In addition to evaluating driver yielding compliance, the research team also collected historical crash data at the midblock crossing locations. Due to the fact that crashes involving pedestrians are rare events, especially at midblock crossing locations, ten years (including the period from 2005 to 2014) of crash data were collected and evaluated.

Traffic crash data for each site were obtained from queries of the annual traffic crash databases maintained by the Michigan State Police for the period of 2005 – 2014 for each study location. This period was utilized due the relative infrequency of vehicle-pedestrian and vehicle-bicycle crashes, although it is acknowledged that uncontrolled changes will have occurred at each site during this time period. Historical traffic crashes were selected from each of the ten annual databases by comparing the linear reference points for each crash to the particular study location.

After the initial query of crashes from the annual statewide databases was completed, a secondary screening was performed in order to ensure crashes were selected which were truly occurring at the specified locations. This involved obtaining the Michigan UD-10 crash report form associated with each crash from the Michigan Traffic Crash Report System, also maintained by the Michigan State Police. After each crash report form was collected, the responding officer's narrative and description of the crash was reviewed in order to determine the precise location of the crash. A key component of this manual review was to identify pedestrian and bicycle crashes which truly occurred along the segment or specific crossing location of interest.

Figure shows the diagram included in a typical UD-10 crash report form for two different crash events occurring at the same site. Science Road (running North-South) is stop controlled, while Shaw Lane (running East-West) is uncontrolled. Crash 1, shown on the left in Figure 3, which occurred in the crosswalk crossing Science Road would be categorized as having occurred at the stop-controlled leg of the, and therefore would not be included as a crash for the midblock crosswalk analysis. Crash 2, on the other hand, occurred on the crosswalk crossing Shaw Lane, which is uncontrolled, and therefore was included in the midblock crosswalk crash analysis.

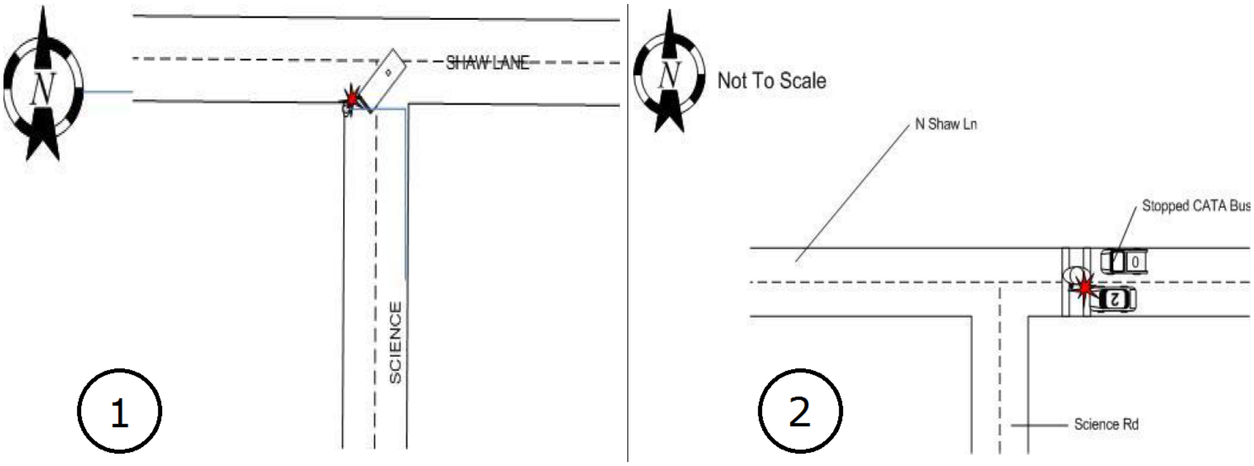


Figure 3. Distinction between Pedestrian Crashes at a Minor Street Intersection: (1) Stop Controlled Leg Crash vs. (2) Uncontrolled Midblock Crosswalk Crash

The pedestrian crashes were initially investigated on a per-crosswalk basis. In order to reduce the impact of crash coding inaccuracies and to capture a slightly broader area of influence of the subject crosswalk, rather than simply within the crosswalk itself, a 150 buffer distance on either side of the crosswalk along the subject roadway was utilized for the crash query. This distance was truncated to exclude the influence area of any nearby traffic signals or stop controlled intersections.

Upon completion of the crash data review for each crosswalk, it was determined that only 14 pedestrian crashes occurred within 150 feet of the 40 midblock crosswalks during the entire 10-

year period of investigation. These 14 crashes occurred at 11 crosswalks, while 30 of the crosswalks did not experience a single pedestrian crash during the 10-year period. The maximum number of pedestrian crashes at any given crosswalk during the 10-year period was two.

Thus, to expand the sample of crashes for analysis, it was decided to expand the query to include crashes that occurred along the entire homogeneous uncontrolled segment of roadway adjacent to the subject crosswalk. A segment was considered homogeneous if it maintained the same cross-sectional features (i.e., laneage, roadway width, and median presence/absence) and no stop, yield, or signal control for vehicles along the subject roadway. Segment endpoints were thus defined by the first stop sign, yield sign, traffic signal, or change in cross-section encountered along the subject roadway. This process yielded a total of 25 unique uncontrolled midblock segments, as several segments included two or more of the individual study crosswalks. In such cases, the site data collected at the individual crosswalks were aggregated across the entire segment.

Additionally, pedestrian crashes which occurred within 150 feet of each signalized intersection included in the study were identified and screened. Pedestrian crashes were included for further analysis only if it was determined that the crash occurred within the general vicinity of the crosswalk or the intersection itself. Note that the intersection pedestrian crash analysis was performed separately from the segment crash analysis.

It should be noted that only 11 bicycle-involved crashes were identified on the 25 segments during the 10-year analysis period. Thus, bicyclist crashes at the study sites were not analyzed further due to the small sample size.

CHAPTER 4:
EVALUTION OF PEDESTRIAN SAFETY AT UNCONTROLLED MIDBLOCK CROSSWALKS

Improving driver and pedestrian behavior as it relates to street crossing at uncontrolled midblock crosswalks is a key component of reducing non-motorized crashes. Therefore, to investigate the safety performance of various midblock crossing treatments, the data pertaining to driver yielding compliance, traffic conflicts, and historical traffic crash data were analyzed using data collected at the 40 uncontrolled midblock crossing locations selected from the three aforementioned Michigan cities.

Appropriate statistical methodologies were identified to evaluate the three safety performance measures utilized in this study, which included driver yielding compliance, traffic conflict analysis, and traffic crash occurrence. A case-control study design was utilized in each case as there was no provision for modification of the pedestrian crosswalk treatments during this study. Although a case-control study creates challenges with isolating the effects of specific treatments, data were collected for numerous roadway and traffic related factors at each study location, which were included as variables in the analyses. Furthermore, compared to a before-after study, the case-control study design provides a distinct advantage because the treatments had existed at each location for several years, allowing for the dissipation of any novelty effects associated with any particular treatment. The statistical methodology used to evaluate the selected safety performance measures are detailed within the appropriate subsections that follow.

DRIVER YIELDING COMPLIANCE DURING STAGED MIDBLOCK CROSSINGS

Analytical Procedures

As driver yielding compliance is a binary (yes/no) outcome, binary logistic regression provides an appropriate framework for determining those vehicle, pedestrian, and roadway factors associated with driver yielding behavior. Within the context of this study, the logistic regression model takes the general form:

$$\ln\left[\frac{p_i}{1-p_i}\right] = \alpha + \beta' X_i, \qquad (1)$$

where p_i is the response probability of a driver yielding to the pedestrian, α is an intercept term, β' is a vector of estimable parameters, and X_i is a vector of predictor variables (e.g., crosswalk treatment, pedestrian/vehicular volumes, etc.).

Data Summary

Driver yielding compliance data were extracted from the 31 sites where staged pedestrians were utilized, resulting in a total of 1,281 driver yielding compliance observations. These data are summarized below in Table 6. Although 1,281 data points were extracted for this study, data for the site with the RRFB could not be included in the model, as that site showed a 100 percent yielding compliance rate. Thus, only 1,245 yielding compliance observations could be included in the final analysis. However, the RRFB compliance rate was included in subsequent discussions. Note that the summary statistics in Table 6 exclude the RRFB site, unless noted otherwise.

Results and Discussion

The variables from Table 6 were considered as potential predictors when estimating the logistic regression model. Several preliminary versions of the models were estimated, with several continuous variables grouped into the categorical equivalent. In many cases, the categorical factors were utilized over the continuous analogs in order to improve model fit. The final model only included those factors that were significant at a p-value of 0.10 or better.

The final model results for driver yielding compliance are displayed in Table 7, which includes the coefficient estimate, standard error, Wald score, p-value, and odds ratio for each variable included in the logistic regression model. The base conditions for the model were: unmarked crosswalk, undivided cross-section, hourly pedestrian volume of less than 50, subject vehicle in the lane nearest to the curb, and subject vehicle not queued.

Table 6. Summary of Site Characteristics for Midblock Yielding Compliance Assessment

Factor	Level or Unit	Mean or Proportion	SD	Min.	Max	Number of Sites
Driver Action[a]	yield	0.61		0	1	
	did not yield	0.39		0	1	
Vehicle Lane Position	Near (curb) lane	0.70		0	1	
	Center or far lanes	0.30		0	1	
Position of Vehicle in Queue	Unqueued vehicle	0.66		0	1	
	Queue leader	0.21		0	1	
	Queued vehicle	0.13		0	1	
Crossing Width	ft	34.91	11.13	22	54	
Through Lanes at Crosswalk	count	2.19	0.49	2	4	
Vehicle Volume at Crosswalk	veh/hr	439.3	200.2	218	2408	
Pedestrian Crossing Volume	pedestrians/hr	85.95	101.36	5	662	
Bicycle Volume	bicycles/hr	9.16	7.93	0	31	
Crosswalk Treatment	Unmarked	0.20		0	1	5
	Standard	0.07		0	1	3
	Continental	0.58		0	1	17
	In-street R1-6 sign	0.08		0	1	3
	PHB	0.04		0	1	2
	RRFB (excl. from model)	0.03		0	1	1
Crossing Width	≤30 ft	0.54		0	1	15
	31-40 ft	0.11		0	1	4
	41-50 ft	0.31		0	1	9
	>50 ft	0.04		0	1	2
Traffic Direction at Crosswalk	One-Way	0.55		0	1	15
	Two-Way	0.45		0	1	15
Through Lanes at Crosswalk	2 lanes	0.85		0	1	24
	3 lanes	0.10		0	1	4
	4 lanes	0.04		0	1	2
Roadway Cross-Section	Two-lane	0.45		0	1	14
	Undivided multilane	0.05		0	1	3
	Divided multilane	0.50		0	1	13
Auxiliary Lane	None	0.37		0	1	12
	Bike, parking, or shoulder	0.63		0	1	18
Pedestrian Crossing Volume	<50 pedestrians/hr	0.54		0	1	15
	≥50 pedestrians/hr	0.46		0	1	15

Note: The RRFB site was excluded from the summary statistics, except where noted
[a]Dependent variable

Table 7. Logistic Regression Results for Driver Yielding Compliance at Midblock Crosswalks

Variable	Level or Unit	β	Standard Error	Wald Score	p-Value	Odds Ratio [Exp(β)]
Crosswalk Treatment*	Unmarked	baseline				
	Standard	1.316	0.386	11.631	0.001	3.728
	Continental	1.790	0.240	55.562	<0.001	5.987
	In-Street R1-6 Sign	3.864	0.515	56.333	<0.001	47.678
	PHB	4.156	1.045	15.820	<0.001	63.802
Crossing Width	ft	0.021	0.009	5.371	0.020	1.022
Cross-Section	Undivided	baseline				
	Divided	-0.608	0.156	15.154	<0.001	0.545
Vehicle Volume	veh/hr	-0.001	0.000	8.442	0.004	0.999
Pedestrian Volume	<50 ped/hr	baseline				
	≥50 ped/hr	0.545	0.165	10.872	0.001	1.724
Vehicle Lane Position	Near (curb) lane	baseline				
	Other lane	1.213	0.174	48.371	<0.001	3.363
Vehicle Position Queue	Unqueued vehicle	baseline				
	Queue leader	0.673	0.177	14.473	<0.001	1.960
	Queued vehicle	-0.421	0.239	3.122	0.077	0.656
	Constant	-1.566	0.483	10.524	0.001	0.209

N = 1,245; Nagelkerke $R^2 = 0.348$
*RRFB showed 100% yielding compliance, which necessitated removal from logistic regression model

The logistic regression results revealed several interesting findings. First, based on examination of the Wald scores, the type of crosswalk treatment had the strongest association with driver yielding compliance of any variables included in the model. Compared to unmarked crossing areas, each of the crosswalk treatments provided significant improvements in driver yielding compliance during the staged pedestrian crossing attempts. While standard and continental crosswalks increased yielding compliance over the unmarked condition, the inclusion of an R1-6 in-street sign, PHB, or RRFB provided substantial improvements in yielding compliance over the standard and continental crosswalks. The raw yielding compliance summary statistics are displayed for each treatment type in Table 8, and will be used for further description of the results.

Table 8. Driver Yielding Compliance by Midblock Crosswalk Treatment

Crosswalk Treatment	Number of Locations	Number of Observations	Percent of Drivers Yielding
Unmarked	5	261	28.7%
Standard	3	88	50.0%
Continental	11	744	66.3%
In-Street Sign (R1-6)	3	101	95.0%
PHB	2	51	98.0%
RRFB	1	36	100.0%
ALL	31	1,281	62.0%

The PHB yielding compliance rate of 98 percent was in general agreement with results found in other states, where driver yielding compliance with PHBs ranged from 85 to 97 percent [4] [21]. This was also a substantial improvement over the 77 percent yielding compliance rate observed at these and other PHBs in Michigan in 2012 [4]. RRFBs showed a perfect yielding compliance rate of 100 percent, which was substantially higher than the 80 to 82 percent observed in prior studies in other states [23] [25]. This was also a significant improvement over the 77 percent yielding compliance rates observed at several Michigan RRFB locations in 2012 [4], This, along with the improved PHB compliance rates in Michigan, suggest that yielding compliance improves with driver familiarity of a new traffic control device. However, caution should be taken due to the small sample sizes observed, as only two PHB sites and one RRFB site were utilized in this study. Furthermore, a single R1-6 in-street sign positioned on the centerline showed yielding compliance rates of 95 percent, which was similar to the PHB and RRFB locations. Although R1-6 signs have produced compliance rates of up to 87 percent in prior studies [21], this was still a surprising result given the substantially lower cost of the R1-6 sign compared to an RRFB and especially a PHB.

Turning to the effects of other variables, the lane position of the vehicle relative to the location of the pedestrian also had a strong effect on yielding behavior. Drivers in the near (i.e., curb) lane when the staged crossing attempt began were 3.4 times less likely to yield when the pedestrian was approaching a driver in any lane other than that nearest to the curb. This effect is likely influenced by the staged crossing protocol. Whereas staged crossing attempts made from the curbside involve only placing a single foot into the crosswalk, a pedestrian approaching subsequent lanes was fully within the travel lanes, thereby increasing the conspicuity of the pedestrian to an approaching motorist. Furthermore, drivers likely sense the vulnerability of pedestrians in these situations, thereby contributing to a greater willingness to yield.

Regarding the roadway cross-section variables, drivers' likelihood to yield increased by approximately 30 percent for each additional 12-ft (i.e., one lane) of crossing width. Similar to the effects of lane position, this suggests that because multilane roadways increase the amount of time that pedestrians are in the roadway without refuge, thereby increasing the pedestrian's conspicuity and exposure to traffic, drivers are more likely to yield. In contrast, drivers were 1.8 times less likely to yield on divided roadways compared to undivided roadways. It is possible that the refuge provided by divided roadways lessens both drivers' willingness to yield, and more importantly, may reduce the visibility of pedestrians due to obstructions within the median.

Further investigation of the interaction effects of lane position and roadway cross-section on yielding compliance was performed, with the raw yielding compliance rates displayed in Table 9. Near-lane yielding compliance was lower across all roadway cross-section types. Near-lane compliance rates were substantially lower for multilane divided roadways, suggesting potential issues with visual occlusion of the pedestrian in the median. Similarly, compliance in lanes other than the near lane was considerably higher on multilane undivided roadways than for two-lane or divided roadways, further confirming that drivers were more aware of crossing pedestrians as the exposure time was increased.

Turning to the interaction between lane position and crosswalk treatment, yielding compliance was again lower in the near lane across all crosswalk treatments. Near-lane yielding compliance was especially poor for unmarked crosswalks (19.9 percent), improving to 34.8 percent and 61.4 percent where standard crosswalks and continental crosswalks were used, respectively. Yielding compliance at standard crosswalks was particularly sensitive to lane position, increasing from 34.8 percent for drivers in the near lane to 95.5 percent for drivers in any other lane. Yielding compliance was far less sensitive to driver lane position at locations where additional treatments (i.e., in-street sign, PHB, RRFB) were utilized, further emphasizing the effectiveness of these treatments. These findings are also provided in Table 9.

Table 9. Interaction of Lane Position with Roadway Cross-Section and Crosswalk Treatment on Driver Yielding Compliance

	Number of Observations		Driver Yielding Compliance	
Variable	**Near Lane**	**Other Lane**	**Near Lane**	**Other Lane**
2-Lane	390	170	55.6%	74.7%
Multilane - Undivided	36	23	80.6%	91.3%
Multilane - Divided	464	198	51.9%	79.8%
Unmarked	166	95	19.9%	44.2%
Standard	66	22	34.8%	95.5%
Continental	575	169	61.4%	82.8%
In-Street Sign (R1-6)	40	61	92.5%	96.7%
PHB	25	26	96.0%	100.0%
RRFB	18	18	100.0%	100.0%
TOTAL	890	391	54.8%	78.2%

The vehicle's position within the queue also affected the likelihood of driver yielding. Drivers that were leading a queue were nearly twice as likely to yield compared to unqueued drivers and were nearly three times as likely to yield compared to queued drivers that were not in the lead position. This result is not surprising, as queued drivers in many cases are simply following the leading vehicles, who obviously also did not yield for the pedestrian.

Finally, while greater vehicular traffic volumes reduced driver yielding compliance, pedestrian crossing volumes of greater than 50 per hour significantly improved yielding compliance. This was not a surprising result, as greater pedestrian activity would serve to raise driver awareness at the particular crosswalk. Nor was the negative effect of vehicular volume surprising, as greater volumes would indicate greater congestion, thereby diminishing the willingness of drivers to yield and wait for pedestrians.

The logistic regression modeling results indicate that the type of crosswalk treatment has a strong influence over driver yielding compliance. While yielding compliance improves substantially when crosswalk markings are utilized, much greater compliance is obtained when additional enhancement devices, such as RRFBs, PHBs, or in-street R1-6 signs, are also provided. Yielding compliance rates for the various crosswalk treatments were shown to be in agreement with previous research performed outside of Michigan, and also showed improvements across all treatment types compared to prior studies performed within Michigan. And while yielding compliance was found to be highly sensitive to both the roadway cross-section and lane position of the vehicle, this effect was not observed when additional treatments (i.e., in-street sign, PHB, RRFB) were utilized. To further assess the safety effectiveness of these treatments, an investigation of pedestrian involved traffic conflicts and crashes were performed, which is described in the following subsections.

PEDESTRIAN CRASHES

Pedestrian crash data for 25 homogeneous uncontrolled segments were utilized for the crash data analysis, as initial screening of the pedestrian crash data at the individual crosswalk level yielded impractically small samples for analysis. It is again noted that the segments were defined as homogenous roadway sections which maintain the same cross-sectional features (e.g., roadway width, laneage, median presence, etc.) with no stop signs, yield signs, or traffic signals along the subject roadway (stop or yield signs may have existed on the cross-streets or driveways). The segment start and end points were defined by a traffic control signal, stop sign, yield sign, or change in primary cross-sectional characteristics. For segments which contained multiple crosswalks from which volume and behavioral information were extracted, values were averaged to in order to conduct the analysis of historical crash data. The crash data included the most recent 10 years of data (2005 – 2014).

Preliminary Data Review

After compiling the crash data by segment, a series of basic graphical displays were generated and data screening measures were performed. Figures 4 and 5 depict the 10-year pedestrian crashes normalized per crosswalk (Figure 4) and per mile (Figure 5) for each observed segment along with hourly vehicular and pedestrian crossing volumes. From these figures it appears that very little, if any, trends can be observed between pedestrian crashes and vehicular volumes and especially between pedestrian crashes and pedestrian crossing volumes. The relationship between pedestrian crashes and volumes was further investigated using negative binomial modeling techniques, as described in the following subsection.

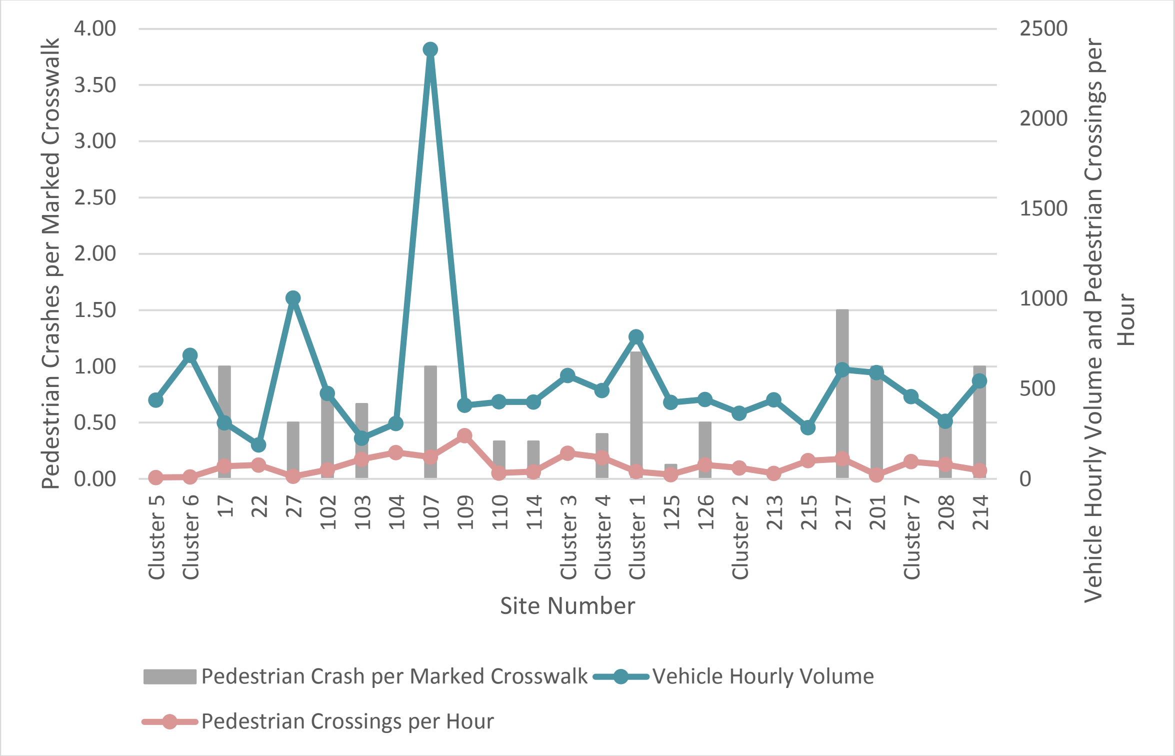


Figure 4. Pedestrian Crashes per Marked Crosswalk with Hourly Vehicular Traffic Volume and Hourly Pedestrian Crossings by Site

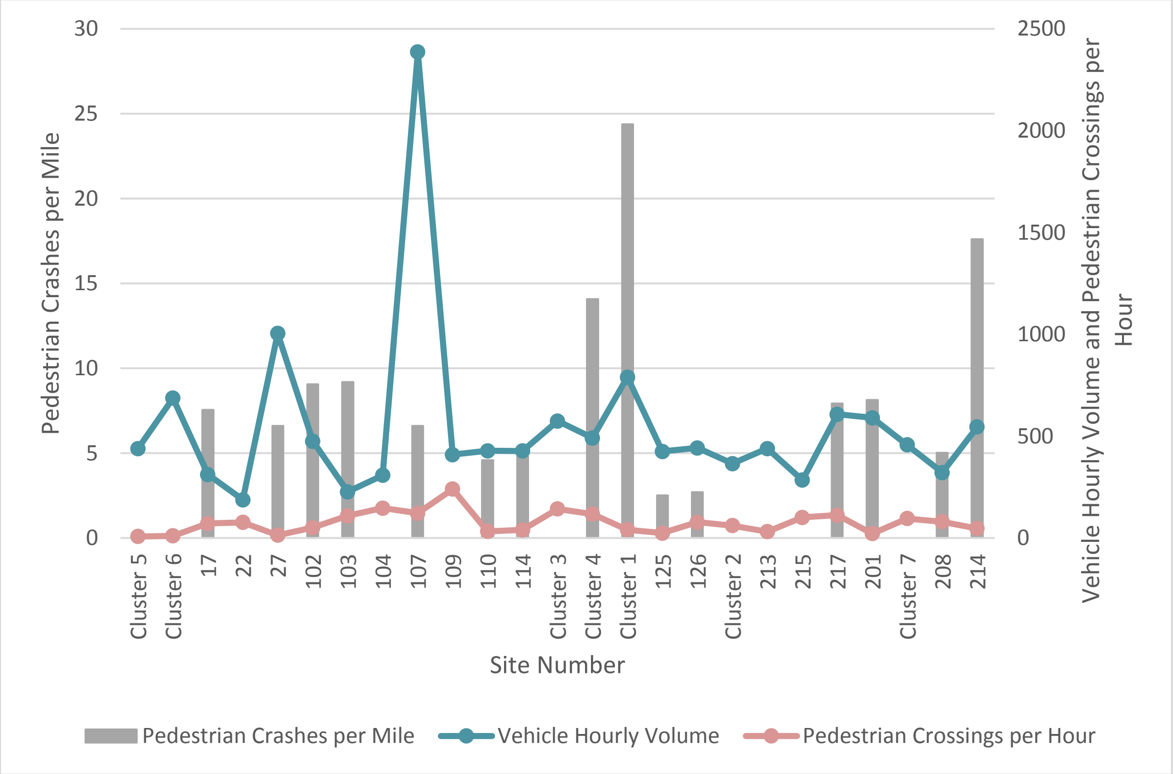


Figure 5. Pedestrian Crashes per Mile with Hourly Vehicular Traffic Volume and Hourly Pedestrian Crossings by Site

Analytical Procedures

For estimating a number of expected events given random data, the Poisson distribution is usually the most appropriate model. However, one of the underlying assumptions of the Poisson distribution is that the variance is equal to the mean, which is oftentimes not the case in the analysis of traffic safety data. In this case, the negative binomial distribution was used to address the dispersion of the pedestrian crash data between the segments. In fact, the HSM encourages using the negative binomial distribution for estimating or predicting crashes [2].

The negative binomial is a generalized form of the Poisson model. In the Poisson regression model, the probability of road segment *i* experiencing y_i events during a specific period is given by:

$$\mathbf{P(y_i) = \frac{EXP(-\lambda_i)\lambda_i^{y_i}}{y_i!}} \quad \textbf{(2)}$$

where $P(y_i)$ is probability of segment *i* experiencing y_i events during the period and λ_i is equal to the expected number of events for the segment, $E[y_i]$. Poisson regression models are estimated by specifying this Poisson parameter λ_i as a function of explanatory variables. The most common functional form of this equation is $\lambda_i = \mathrm{EXP}(\beta X_i)$, where X_i is a vector of explanatory variables (e.g., AADT, segment length, etc.) and β is a vector of estimable parameters. The negative binomial model is derived by rewriting the Poisson parameter for each segment *i* as $\lambda_i = \mathrm{EXP}(\beta X_i + \varepsilon_i)$, where $\mathrm{EXP}(\varepsilon_i)$ is a gamma-distributed error term with mean 1 and variance α. The addition of this term allows the variance to differ from the mean as $\mathrm{VAR}[y_i] = E[y_i] + \alpha E[y_i]^2$. The α term is also known as the over-dispersion parameter, which is reflective of the additional variation in event counts beyond the Poisson model (where α is assumed to equal zero, i.e., the mean and variance are assumed to be equal).

Data Summary

A summary of the traffic crash data and relevant site characteristics for the 25 midblock segments analyzed is provided in Table 10.

Table 10. Descriptive Statistics for Analysis of Pedestrian Crashes on Midblock Segments

Factor	Level or Unit	Mean	Std. Dev.	Min	Max
Pedestrian Crashes	Ten year total	1.2	1.98	0	8
Segment Length	Miles	0.25	0.17	0.1	0.82
Hourly Pedestrian Vol.	Pedestrians/hour	85.82	72.03	10.5	282.14
Hourly Bicycle Vol.	Bicycles/hour	6.73	8.25	0	30.67
Hourly Vehicular Vol.	Vehicles/hour	459.8	441.81	74.8	2,329.20
Uncontrolled Marked Crosswalk Density	Per mile	13.05	6.27	1.84	27.38
Driveway Density	Per mile	24.21	15.18	6.25	68.87
Cross-section	Two-Way Two-Lane (Baseline)	0.64	-	0	1
	Multilane Undivided	0.08	-	0	1
	Multilane Divided	0.28	-	0	1
Auxiliary Laneage	No Additional Lanes (Baseline)	0.56	-	0	1
	Bicycle Lane*	0.32	-	0	1
	Shoulder	0.04	-	0	1
	Parking Lane*	0.12	-	0	1
Crosswalk treatment	Standard Crosswalk (Baseline)	0.28	-	0	1
	Continental Crosswalk	0.72	-	0	1

*Certain segments had both a bike lane and a parking lane

Overall, the segments evaluated as a part of this study averaged approximately one quarter mile in length, with the shortest segment measuring a tenth of mile and the longest homogenous segment measuring 0.82 miles. Additionally, the study segments experienced 1.2 pedestrian crashes on average over the 10-year analysis period, with several segments experiencing zero pedestrian crashes and one segment experiencing eight crashes. With respect to the number of marked crosswalks, on average the study segments contained approximately 13 crosswalks per mile, with a minimum crosswalk density of 1.84 per mile and a maximum of 27.38 per mile. The number of access points averaged 24.205 per mile across all study segments with a minimum density of 6.25 per mile and a maximum of 68.87 per mile. Approximately 28 percent of the study segments were multilane divided highways, eight percent multilane undivided highways, and 64 percent two-lane two-way highways. Approximately 12 percent of the study sample included segments which included parking lanes.

Results and Discussion

Several versions of the pedestrian crash model were estimated. Variables were removed (and in some cases re-added) in a stepwise manner until only those variables that were found to be significant at a 90 percent level of confidence were included. Most significantly, it was found that neither hourly vehicular traffic volumes, nor yielding compliance, nor vehicle-pedestrian conflicts were significant predictors for pedestrian crash occurrence. The final negative binomial model results for estimating pedestrian-vehicle crashes at midblock segments are shown in Table 11, which includes the parameter estimate, standard error, and the exponential of the parameter estimate (for cases where the natural logarithm of the factor was not taken), and p-value for each. It should be noted that the natural logarithms were taken of segment length, crosswalks per mile, driveways per mile, and the hourly pedestrian volume. This conversion allows for the associated parameter estimates (β) to be more easily interpreted when determining the elasticity of the parameter with respect to traffic crash occurrence. Specifically, the parameter estimates for the log transformed variables represent the percent increase in crashes associated with a one-percent increase in the specific variable. For the binary variables, the pseudo-elasticity (shown as follows) represents the percent change in crashes when the binary variable is changed from zero to one:

$$E_{x_{ij}}^{\lambda_i} = \frac{EXP(\beta_j)-1}{EXP(\beta_j)},$$

Table 11. Negative Binomial Results for Vehicle-Pedestrian Crashes on Uncontrolled Midblock Segments

Parameter	β	Std Error	exp(β)	p-Value
Intercept	-25.224	6.645		<0.001
Segment length [ln(feet)]	2.314	0.644		<0.001
Uncontrolled marked crosswalks per mile (ln)	0.888	0.484		0.068
Driveways per mile (ln)	1.648	0.770		0.032
Hourly pedestrian volume (ln)	0.685	0.268		0.011
Multilane divided	0.777	0.400	2.175	0.052
Parking lane present	-2.167	1.315	0.115	0.099
Continental crosswalk	-2.174	0.788	0.114	0.006
Overdispersion parameter	4.611E-08	8.051E-05	-	-

Note: response variable is 10-year pedestrian crash frequency

Not surprisingly, the results show that an increase in segment length is associated with a corresponding increase in vehicle-pedestrian crashes. This is consistent with prior research, for which the primary factors in predicting crashes at segments are segment length and vehicular volume [2], although a relationship between crashes and vehicular volumes was not found here, likely due to the small crash sample size. The number of vehicle-pedestrian crashes also increased as hourly pedestrian volumes increased, which is in general agreement with the models presented in the HSM [2].

Greater driveway density was associated with an increased number of pedestrian crashes. Although no existing studies linking driveway density with pedestrian crashes in particular could be found, the result is consistent with existing research showing a positive relationship between driveway density and total crashes [2]. As the number of driveways along a segment increases, the number of potential vehicle-pedestrian conflict points also increases, which leads to an increasing likelihood of a vehicle-pedestrian crash along the segment. Furthermore, as these observations occurred on college campuses or in locations adjacent to a college campus, it is likely that driver unfamiliarity was a causal factor for many of the pedestrian crashes.

Greater crosswalk density along the segment also increased the crash frequency. This is consistent with prior research indicating that marked crosswalks are associated with higher crash rates than unmarked crosswalks [8] [34], due to the generally greater midblock pedestrian crossing activity along the segment. However, segments utilizing continental crosswalks showed fewer pedestrian-vehicle crashes along the segment compared to those segments with standard crosswalks. This suggests that the higher visibility continental type crosswalks are related to a lower crash occurrence. Special treatments like the R1-6, RRFB, and PHB were not specifically analyzed due to the treatment not being in effect for the entire 10 year study period.

Lastly, a multilane cross-section with a divided median was associated with a higher crash occurrence than either the two-lane two-way or multilane undivided segments, a finding which was consistent with the yielding compliance analysis and also supported by the literature. A before-after study conducted in Florida found that while the vehicle-pedestrian crash rate decreased after the installation of raised medians, this relationship was not significant, some sites saw increases in pedestrian crash rates, and the overall pedestrian fatality crash rate increased [7].

The greater frequency of crashes on divided roadways may be explained by sight issues inherent to multilane roads: when the vehicle in the lane closest to the curb yields, in many cases the view of the pedestrian to a vehicle approaching in the same direction in an adjacent lane is obstructed [8]. Presence of a median exacerbates this problem by introducing an additional approach with problematic sight distance. Parking lanes were also found to reduce pedestrian crash occurrence, perhaps due to the traffic calming effects and subsequent lower speeds associated with on-street parking [30].

In light of the crash findings, it must be noted that the small total 10-year sample size of 30 pedestrian crashes across the 25 segments is relatively small and clearly a limitation of this study. Furthermore, no association between driver yielding compliance and pedestrian crash occurrence was found. Thus, additional investigation into pedestrian-vehicle crashes was performed, which is described in Chapter 6.

VEHICLE-PEDESTRIAN CONFLICTS

Data Summary

The research team also evaluated vehicle-pedestrian conflicts at midblock crosswalks at all 40 midblock crossing locations. Vehicle-pedestrian conflicts were analyzed by binning conflict data into 15 minute intervals at each of the 40 locations, resulting in 401 unique 15 minute intervals. It should be noted that out of the 401 unique intervals, four were excluded due to a pedestrian volume of zero during those intervals. Thus, 397 unique 15-minute intervals were utilized for further analysis. Further, conflicts were defined as a pedestrian or a vehicle taking evasive action to avoid collision. A summary of the pedestrian-vehicle conflict data is provided in Table 12.

Table 12. Descriptive Statistics for Pedestrian Conflicts at Midblock Crosswalks

Factor	Level or Unit	Mean	SD	Min	Max
Conflict	Number of events per 15-min interval	1.87	5.94	0	47
Pedestrian Volume	Pedestrians per 15-min interval	25.64	40.1	1	318
Bicycle Volume	Bicycles per 15-min interval	1.84	2.796	0	22
Vehicular Volume	Vehicles per 15-min interval	133.16	94.44	18	650
Traffic Direction	One-Way	0.21	-	0	1
	Two-Way (Baseline)	0.79	-	0	1
Laneage	Bike Lane Present*	0.36	-	0	1
	Shoulder Present*	0.07	-	0	1
	Parking Lane Present	0.25	-	0	1
	No Additional Lanes (Baseline)	0.44	-	0	1
Cross-section	Two-Lane (Baseline)	0.58	-	0	1
	Multilane Undivided	0.10	-	0	1
	Multilane Divided	0.32	-	0	1
Distance to nearest marked crosswalk	Feet	277.04	184.97	75	1,139.00
Crosswalk treatment	Unmarked (Baseline)	0.12	-	0	1
	Standard Crosswalk	0.11	-	0	1
	Continental Crosswalk	0.58	-	0	1
	In-street R1-6 Sign	0.09	-	0	1
	RHB	0.06	-	0	1
	RRFB	0.04	-	0	1
Pedestrian crossing sign (W11-2) at crosswalk	Not Present (Baseline)	0.36	-	0	1
	Present	0.64	-	0	1

*Certain segments had both a bike lane and a parking lane

Analysis, Results, and Discussion

A negative binomial model was also utilized for the conflict analysis at midblock crosswalks. The model results are shown in Table 13, including the parameter estimate, standard error, odds ratio (for cases where the natural logarithm of the variable was not taken), and p-value for each variable.

Table 13. Model Results for Vehicle-Pedestrian Conflicts at Midblock Crosswalks

Parameter	β	Std Error	exp(β)	p-Value
Intercept	4.255	1.781		0.017
15-min ped volume (ln)	0.608	0.120		<0.001
15-min vehicle volume (ln)	0.799	0.250		0.001
Distance to nearest adjacent crosswalk (ln)	-1.562	0.279		<0.001
One-way	-1.416	0.348	0.243	<0.001
Shoulder present	1.879	0.480	6.547	<0.001
Multilane divided	-0.912	0.318	0.402	0.004
Standard crosswalk	-2.247	0.440	0.106	<0.001
Pedestrian crossing sign at crosswalk	-0.924	0.286	0.397	<0.001
Overdispersion parameter	3.183	0.415		

As expected, the frequency of pedestrian-vehicle conflicts was sensitive to pedestrian and vehicular volume, although this relationship was slightly inelastic, as evidenced by the coefficients of 0.608 and 0.799. This is intuitive because as volumes increase, the interactions between pedestrians and vehicles also increase, which create more opportunities for conflicts to occur. This result is similar to the crash analysis, where pedestrian-vehicle crashes were found to be positively correlated with pedestrian volume, although vehicular volume was not found to be a significant factor. Furthermore, the literature also suggests that vehicle-pedestrian conflicts increase with increasing traffic volume [31].

With regards to roadway cross-section, a multilane divided roadway was associated with fewer conflicts than a two-lane or multilane undivided road. This result contradicts the results with crash and yielding compliance analyses which found multilane divided roads more likely to result in crash or a driver not yielding to the pedestrian, although the small sample of crashes is a known limitation to the crash evaluation. The presence of shoulders was associated with higher numbers of conflicts. This is supported by prior research that found an increase in pedestrian crashes with increasing shoulder width [33], perhaps due to the increased crossing distance.

Standard crosswalk markings and side-mounted pedestrian signs were also associated with fewer conflicts. Although the other crosswalk treatments were not found to have a significant impact on conflict occurrence compared to unmarked crosswalks, this was likely due to the relatively small sample of pedestrian observations at locations with PHBs, RRFBs, and R1-6 signs.

CHAPTER 5:

EVALUTION OF PEDESTRIAN SAFETY AT SIGNALIZED INTERSECTIONS

Pedestrian crossings at signalized intersections are an important safety consideration for roadway agencies, and such crossings will continue to increase in importance as non-motorized safety programs further encourage travel via walking and bicycling in the future. The research team identified 26 signalized intersections across the three Michigan cities in order to further evaluate pedestrian crossing safety. Field observational data as well as historical traffic crash data were collected and analyzed at each location in order to assess the three selected safety performance measures. The findings specific to pedestrian crossings at signalized intersections are presented in the subsequent subsections.

YIELDING BEHAVIOR OF TURNING DRIVERS

Vehicle-pedestrian naturalistic yielding compliance data were collected at each of the 26 signalized intersections considered as a part of this study. These data were aggregated into 15-minute intervals for subsequent analysis by the research team to simplify the data collection process. Ultimately, 104 unique 15-minute intervals were collected for subsequent statistical analysis. Yielding in the context of this study was only assessed for cases where turning vehicles encountered one or more pedestrians in the crosswalk. According to state law, during a permissive signal indication, the driver must yield to pedestrians in this scenario. Thus, driver yielding compliance was scored accordingly for each observation. A summary of the naturalistic yielding compliance behavior collected at the 26 signalized intersections is presented in Table 14.

Table 14. Summary of Naturalistic Driver Yielding Behavior Data at Signalized Intersections

Factor	Level or Unit	Mean	SD	Min	Max
Driver yielding	number of events in a 15-min period	5.23	8.18	0	70
Pedestrian-turning vehicle interactions	number of events in a 15-min period	5.93	8.64	0	73
Vehicle volume	veh/15-min interval	259.58	144.3	56	679
Bicycle volume	bicycles/15-min interval	1.48	1.99	0	12
Pedestrian volume	peds/15-min interval	58.2	66.29	2	415
Right-turn	percent of total vehicles	0.17	0.1	0	0.46
Left-turn	percent of total vehicles	0.14	0.09	0	0.45
Geometry	4-leg intersection	0.73	-	0	1
	3-leg intersection	0.27	-	0	1
Laneage	bike lanes present	0.31	-	0	1
	parking lanes present	0.77	-	0	1
	shoulders present	0	-	0	0
	no additional lanes	0.08	-	0	1
Crosswalk Treatment	standard crosswalk	0.25	-	0	1
	continental crosswalk	0.72	-	0	1
	brick paver	0.04	-	0	1
Directionality	One-way	0.44	-	0	1
	Two-way	0.56	-	0	1
Pedestrian signal	No countdown timer	0.24	-	0	1
	Countdown timer	0.76	-	0	1
Right-turn-on-red	Permitted	0.72	-	0	1
	Prohibited	0.28	-	0	1
Median	Not present	0.72	-	0	1
	Present	0.28	-	0	1

The yielding compliance rates were disaggregated by intersection characteristics of interest and are presented in Table 15. Additionally, a statistical model was estimated based upon the binary logistic regression techniques outlined in Chapter 4. The final model results are presented in Table 16, which estimates driver yielding compliance at signalized intersections based upon several explanatory variables. It should be noted that Table 16 includes the coefficient estimate, standard error, odds ratio (for cases where the natural logarithm of the factor was not taken), and p-value for each variable.

Table 15. Naturalistic Driver Yielding Compliance Rates by Site Characteristics

Category	Parameter	Number of Locations	Number of Observations	Observations per location	Pct. of Turning Vehicles that Yielded To Ped
Intersection geometry	Three-leg	4	178	44.5	93.26%
	Four-leg	20	418	20.9	86.36%
Directionality	One-way	11	253	23.0	90.91%
	Two-way	14	364	26.0	86.26%
Crosswalk treatment	Standard	6	101	16.8	84.16%
	Continental	18	475	26.4	89.05%
	Brick paver	1	41	41.0	87.80%
Pedestrian signal	No countdown timer	6	110	18.3	88.18%
	Countdown timer	19	507	26.7	88.17%
Right-turn-on-red	Permitted	18	370	20.6	85.14%
	Prohibited	6	226	37.7	93.81%
Median	Not present	18	428	23.8	88.08%
	Present	7	189	27.0	88.36%

Table 16. Negative Binomial Results for Naturalistic Driver Yielding Compliance at Signalized Intersections

Category	Parameter	β	Std Error	exp(β)	p-Value
	Intercept	-5.906	0.863		<0.001
Volume	Total pedestrian-turning vehicle interactions	0.041	0.007	1.042	<0.001
	15-min vehicle volume (ln)	0.767	0.121		<0.001
	15-min pedestrian volume (ln)	0.636	0.092		<0.001
	Percent right turners	3.37	0.649	29.079	<0.001
Approach configuration	3-leg	Baseline			
	4-leg intersection	-0.433	0.135	0.649	0.001
Bicycle lanes	present	-0.547	0.144	0.579	<0.001
Parking lanes	present	0.327	0.157	1.387	0.037

A four-leg intersection is shown in the negative binomial model to result in fewer yielding events compared to a three-leg intersection. This is also shown in raw yielding rates, for which a three leg intersection has a yielding rate almost 7 percentage points higher than a four-leg intersection. Previous research has shown three-leg intersections to be associated with reduced numbers of pedestrian crashes [35]. It can also be seen in Table 15 that the three-leg intersection has more than double the observed number of pedestrian-turning vehicle interactions per location compared with four-leg intersections, due to the necessity of vehicles turning at the dead-end leg. Increasing volumes of pedestrian and turning vehicles increased yielding compliance. More importantly, an increasing number of pedestrian-vehicle interactions (i.e., yielding opportunities), was also associated with improved driver yielding compliance, which is shown in Figure . When limiting the turning vehicles to right-turners, the relationship between vehicle-pedestrian interaction and yielding compliance was even stronger.

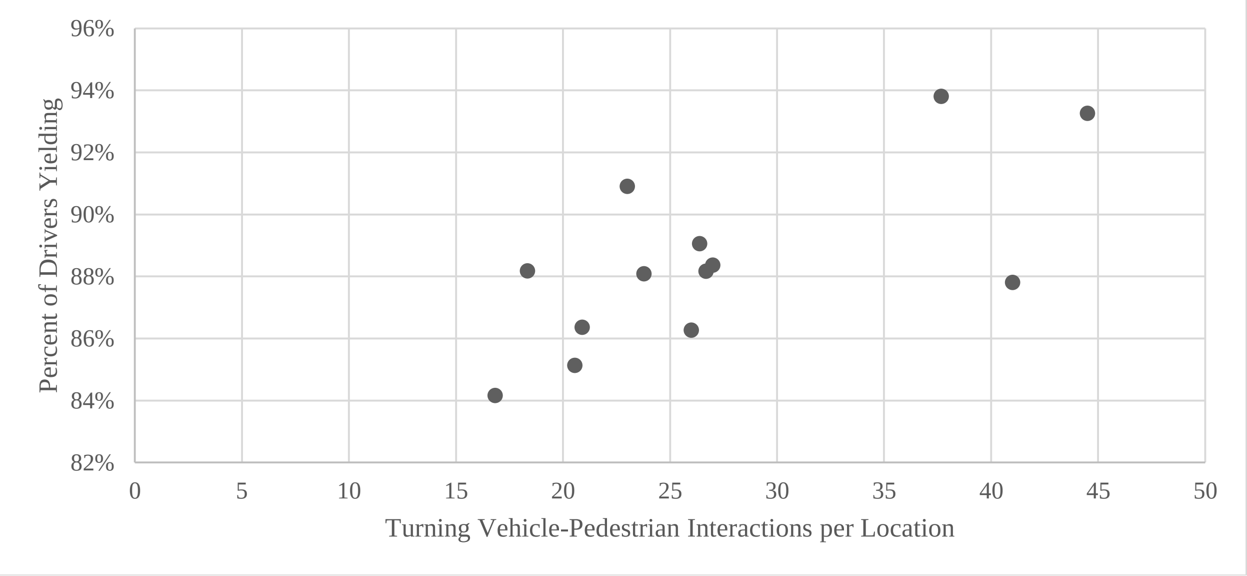


Figure 6. Yielding Rates vs. Pedestrian-Vehicle Interactions per Location

Bike lanes and parking lanes had minor effects on the number of yielding events, with bike lanes relating to lower yielding and parking lanes relating to greater yielding. It is plausible that because bike lanes increased the distance between the turning vehicle and the curb, the pedestrian is less visible, which leads to reducing yielding compliance. Parking lanes also increase the distance between the turning vehicle and the curb; however, as previously mentioned, parking lanes are associated with an increase in pedestrian volumes [31]. It is possible that the presence of parking lanes either increased pedestrian activity or increased the perception of pedestrian activity, which may have counteracted the increased distance between the vehicle and curb.

One-way streets had a higher yielding rate than two-way streets. This is in line with the results of conflict analysis at midblock crossings, where one-way streets were associated with fewer instances of evasive maneuvers. Sites with continental crosswalks displayed a higher rate of yielding than the standard crosswalk, which was also observed at midblock crosswalks, which may be a result of greater conspicuity. Sites where right-turn-on-red was prohibited had a higher rate of yielding than sites where it was permitted. Right-turn-on-red will be more thoroughly discussed in the discussion section pertaining to vehicle-pedestrian crashes at signalized intersections. There was no difference in yielding rates based on whether or not there was a countdown timer on the pedestrian signal, or whether or not a median was present.

PEDESTRIAN CRASHES AT SIGNALIZED INTERSECTIONS

Historical crash data were also collected for each of the 26 signalized intersections evaluated as a part of this study. Two specific analyses were conducted; first, all 26 signalized intersections were analyzed, and another that looked exclusively at the 24 sites which had right-turning traffic to further investigate the effect that turning vehicles have on crashes at signalized intersections. A summary of the historical traffic crash data is provided in Table 17 for all sites and Table 18 for the sites which included right-turning vehicles.

Table 17. Summary of Pedestrian Crashes at Signalized Intersections, All Sites

Factor	Level or Unit	Mean	SD	Min	Max
Ped crashes	number of	2.08	3.05	0	15
Vehicle volume	veh/h	1,038.31	578.84	240	2,423.00
Bicycle volume	bikes/h	5.92	6.94	0	35
Pedestrian volume	peds/h	232.81	243.52	16	1,194 .00
Did not clear int. by end of clearance interval	pct. of pedestrians	0.06	0.04	0	0.16
Entered on red	pct. of pedestrians	0.278	0.13	0	0.54
Right-turn	pct. of total veh.	0.17	-	0	0.41
Left-turn	pct. of total veh.	0.14	-	0	0.38
Geometry	3-leg	0.27	-	0	1
	4-leg	0.73	-	0	1
Crosswalk type	standard	0.27	-	0	1
	continental	0.73	-	0	1
Countdown pedestrian signal	present	0.88	-	0	1
	not present	0.12	-	0	1
Bicycle lanes	present	0.31	-	0	1
Parking lanes	present	0.77	-	0	1

Table 18. Summary of Pedestrian Crashes at Signalized Intersections, Excluding Sites with no Right Turns

Factor	Level or Unit	Mean	SD	Min	Max
Ped crashes	number of	2.25	3.11	0	15
Vehicle volume	veh/h	1,060.50	594.52	240	2,423.00
Bicycle volume	bikes/h	4.71	3.75	0	12
Pedestrian volume	peds/h	200.29	147.5	16	560
Did not clear intersection by end of clearance interval	pct, of pedestrians	0.061	0.04	0.01	0.16
Entered on red	pct. of pedestrians	0.27	0.11	0	0.5
Right-turn	pct. of total vehicles	0.19	0.09	0.03	0.41
Left-turn	pct. of total vehicles	0.15	0.09	0.01	0.38
Geometry	3-leg	0.21	-	0	1
	4-leg	0.79	-	0	1
Crosswalk type	standard	0.29	-	0	1
	continental	0.71	-	0	1
Countdown pedestrian signal	present	0.87	-	0	1
	not present	0.13	-	0	1
Bicycle lanes	present	0.29	-	0	1
Parking lanes	present	0.79	-	0	1

In both cases, the number of crashes ranged from 0 to 15. For all sites, the average number of crashes was 2.08, with a standard deviation of 3.05. When excluding sites with no right turns, the average number of crashes was 2.25 with a standard deviation of 3.11. Hourly vehicle volumes ranged from 240 to 2,323 vehicles per hour, with an average of 1038 at all sites, and 1061 at sites with right turning vehicles, with standard deviations of 578.8 for all sites and 594.5 at sites with right turning vehicles.

A negative binomial regression model was developed for the two scenarios based upon the techniques outlined in Chapter 4. The final model results for estimating pedestrian-vehicle crashes at signalized intersections are presented in Table 19 and Table 20, which include the coefficient estimate, standard error, p-value, and the odds ratio for each variable included in the negative binomial model. It should be noted that the natural logarithm was taken of vehicle and pedestrian volumes.

Table 19. Negative Binomial Results for Vehicle-Pedestrian Crashes at Signalized Intersections, All Sites

Parameter	β	Std Error	exp(β)	p-Value
Intercept	-10.019	2.298		<0.001
Hourly vehicle volume (ln)	0.477	0.226		0.001
Hourly pedestrian volume (ln)	0.477	0.226		0.035
Percent of pedestrians not clearing intersection by end of clearance interval	6.928	3.570	1,020.5	0.052
Percent of pedestrians entering on red	5.524	1.510	250.6	<0.001
Overdispersion parameter	8.598E-08	8.538E-05		

Table 20. Negative Binomial Results for Vehicle-Pedestrian Crashes at Signalized Intersections, Excluding Sites with No Right Turns

Parameter	β	Std Error	exp(β)	p-Value
Intercept	-9.804	2.460		<0.001
Parking lanes present	1.539	0.846	4.660	0.069
Hourly vehicle volume (ln)	1.257	0.317		<0.001
Percent left turners	6.826	3.765	921.497	0.070
Percent right turners	-6.777	2.356	0.001	0.004
Percent right-turns occurring on red	-2.856	1.639	0.057	0.081
Percent of pedestrians entering on red	4.830	1.604	125.211	0.003
Overdispersion parameter	1.335E-08	7.268E-06		

For both models, increasing vehicle volume was associated with increasing crashes, which is consistent with results from midblock analysis as well as the literature [2]. Both models also saw increasing numbers of crashes as the percentage of pedestrians entering on red increased. This is not surprising, as when pedestrians enter on red, pedestrians and through vehicles are in direct conflict. Through vehicles travel at significantly faster speeds than turning vehicles do, and therefore, when pedestrians and vehicles interact, the likelihood for an injury or fatal crash is higher, and the crash is more likely to be reported.

With regards to the all-site model, increasing pedestrian volume was associated with a higher number of crashes while bike volumes were associated with fewer vehicle-pedestrian crashes. Lastly, the percentage of pedestrians not clearing the intersection by the end of the clearance interval (also known as the “flashing don’t walk” indication) was also correlated with higher numbers of crashes.

With regards to the model that excluded sites with no right turns, as the percentage of left turning vehicles increased, crashes did as well. Conversely, as the percentage of right turns, and right-turning vehicles on red given right turns were associated with decreasing numbers of crashes. This is surprising, as the permissibility of right-turn-on-red is associated with an increase in total and pedestrian crashes [36]. However, in this study, right-turn-on-red prohibition was found to *increase* the number of estimated crashes. The reason for this relationship is unclear: one reason could be because of how few sites prohibited such turns (6 sites out of 26) and/or because of drivers disregarding such prohibitions (among sites where right-turn-on-red is prohibited, right-turn-on-red as a percentage of right-turning vehicles range from 1.02% to 21.8% compared with 6.25% to 50% among sites where right-turn-on-red is permitted). Another possibility could be that right-turn-on-red prohibition was introduced to these sites by roadway agencies specifically because of safety hazards, that those hazards are still present with this prohibition, and that the data has been biased as a result. In the final model, percent right-turn-on-red given right-turning vehicles was selected instead to address this bias, and found that as this percentage increases, estimated crashes decrease.

VEHICLE-PEDESTRIAN CONFLICTS AT SIGNALIZED INTERSECTIONS

Vehicle-pedestrian conflicts at signalized intersections were analyzed at the 15-minute interval level and included all 26 signalized intersection locations, with 104 unique 15-minute intervals. Conflicts were defined as a pedestrian or vehicle taking evasive action to avoid collision. Pedestrian-turning vehicle interactions were not categorized as conflicts unless evasive action was taken by either the turning vehicle or the pedestrian. The number of conflict events in a 15-minute period ranged from 0 to 9. Full descriptive statistics can be found in Table 21.

Table 21. Descriptive Statistics for Vehicle-Pedestrian Conflicts at Signalized Intersections

Factor	Level or Unit	Mean	SD	Min	Max
Conflict	number of events in a 15-min period	0.42	1.2	0	9
Left turns	percent of total vehicles	0.14	0.1	0	0.45
Right turns	percent of total vehicle	0.17	0.1	0	0.46
Right-turn-on-red	percent of right-turns occurring on red	0.23	0.18	0	0.56
Pedestrian volume	peds/15-min interval	58.2	66.29	2	415
Bicycle volume	bicycles/15-min interval	1.48	1.99	0	12
Vehicle volume	vehicles/15-min interval	259.6	144.3	56	679
Did not clear int. by end of clearance interval	percent of pedestrians	0.06	0.07	0	0.31
Entered on red	percent of pedestrians	0.28	0.17	0	0.91
Approach configuration	4-leg	0.27	-	0	1
	3-leg	0.73	-	0	1
Crosswalk type	Standard	0.27	-	0	1
	Continental	0.73	-	0	1
Pedestrian countdown timer	Present	0.88	-	0	1
	Not present	0.12	-	0	1
Right-turn-on-red	Permitted	0.85	-	0	1
	Prohibited	0.15	-	0	1
Bicycle lanes	Present	0.31	-	0	1
Shoulders	Present	0	-	0	0
Parking lanes	Present	0.77	-	0	1

Model results for estimating vehicle-pedestrian conflicts at signalized intersections are shown in Table 22, which includes the coefficient estimate, standard error, odds ratio (for cases where the natural logarithm of the factor was not taken), and p-value for each variable.

Table 22. Negative Binomial Results for Vehicle-Pedestrian Conflict at Signalized Intersections

Category	Parameter	β	Std Error	exp(β)	p-Value
	Intercept	-7.062	1.836		<0.001
Behavior	Pct left turning vehicles	-9.610	3.883	6.705E-05	0.013
	Pct right turning vehicles	5.984	3.221	397.025	0.063
	Pct right-turns occurring on red	4.742	1.702	114.663	0.005
Volume	15-min pedestrian volume (ln)	1.270	0.345		<0.001
Overdispersion parameter		1.369	0.807		

Similar to with crashes, expected conflicts increase with increasing numbers of pedestrians, which is consistent with expectations and the literature [31]. On the other hand, the remaining parameters displayed results inconsistent with crash analysis. As left turners as a percentage of total vehicles increases, the number of expected conflicts decreases. Right turns, on the other hand, are associated with more conflict events, for both right turners as a percentage of total vehicles as well as for right-turns-on-red as a percentage of right turning vehicles. This is a result more in line with what is known about the right-turn-on-red being associated with increased crashes and conflict [36].

While it is unusual for conflict and crash analysis to product opposing results in such a consistent manner, there are some potential explanations for this, such as the fact that percentage of turning vehicles may not be consistent throughout the entire ten-year crash data period. Even seasonally, traffic patterns on college campus will be drastically different during the period when school is in session compared to the summer or winter breaks.

However, similar to the midblock safety evaluation, the small total 10-year sample size of 54 pedestrian crashes across the 24 sites used in the crash analysis is relatively small and clearly a limitation of this study. To help counter the small sample of pedestrian crashes at both intersections and segments, additional investigation into pedestrian-vehicle crashes statewide was performed, which is described in Chapter 6.

CHAPTER 6:

PREDICTING PEDESTRIAN AND BICYCLE CRASHES USING MICHIGAN STATEWIDE DATA

The lack of pedestrian and bicycle crash data at the study sites precipitated the need to perform a broader statewide assessment of pedestrian and bicycle crashes. Two parallel SPF development projects for the Michigan Department of Transportation [40,41] led by the authors of this report allowed for development of pedestrian and bicyclist crash SPFs for various types of urban roadway segments and urban intersections. Sites were identified for the following facility types for MDOT trunkline roadways:

- Urban Trunkline Segments
    - Two-Lane Undivided
    - Three-Lane Undivided
    - Four-Lane Undivided
    - Four-Lane Divided
    - Five-Lane Undivided
    - Six-Lane Divided
    - Eight-Lane Divided
    - One-Way
- Urban Trunkline Intersections
    - Three-Leg Minor Road Stop Control
    - Three-Leg Signalized
    - Four-Leg Minor Road Stop Control
    - Four-Leg Signalized

DATA COLLECTION

In order to develop SPFs that will provide an accurate prediction of the safety performance of urban trunkline segments, it was imperative to develop a robust, high-quality database, which includes traffic crash information, traffic volumes, and roadway geometry. These data were obtained from a variety of sources, including the Michigan State Police Statewide Crash Database, MDOT Sufficiency File, Michigan Geographic Data Library (MiGDL) All Roads File, and Google Earth. In addition to traffic volume, crash data, and a number of roadway geometric variables, median crossover tallies, and traffic control information were collected using aerial imagery. A threshold value of 0.04 miles (211 ft) was established as the maximum distance from an intersection node that a crash would be considered an "intersection" crash. Segment crashes were those that fell outside of this boundary. The types of data compiled for each of the respective facility types are displayed in the following Table 23.

Table 23. Data Collected for Statewide Sample of Segments and Intersections

Segments	Intersections
AADT Speed limit MDOT region Number of lanes One-way or two-way traffic Presence of median Curvature Terrain type Lane width Paved shoulder presence and width Presence of lighting Presence of two-way left-turn lane (TWLTL) Presence of on-street parking Number of driveways Number of median crossovers Number of schools	Number of intersection legs Type of traffic control AADT for major and minor road Number of approaches with left-turn lanes Number of approaches with right-turn lanes Presence of lighting One-way or two-way traffic Intersection skew angle Presence/type of left-turn phasing Presence of sidewalks and ADA ramps Presence of bus stops Presence of on-street parking Presence of median

These data were aggregated to develop comprehensive databases for urban segments and intersections over the five-year study period from 2008 to 2012. The final sample was comprised of the following number of locations by facility type:

- MDOT Urban Trunkline Segments
  - 489 two-lane undivided (2U) segments (these segments were split into subcategories based on speed limit equal to 55 mph (55E) or less than 55 mph (55L) during SPF development);
  - 236 three-lane (3T) segments;
  - 373 four-lane undivided (4U) segments;

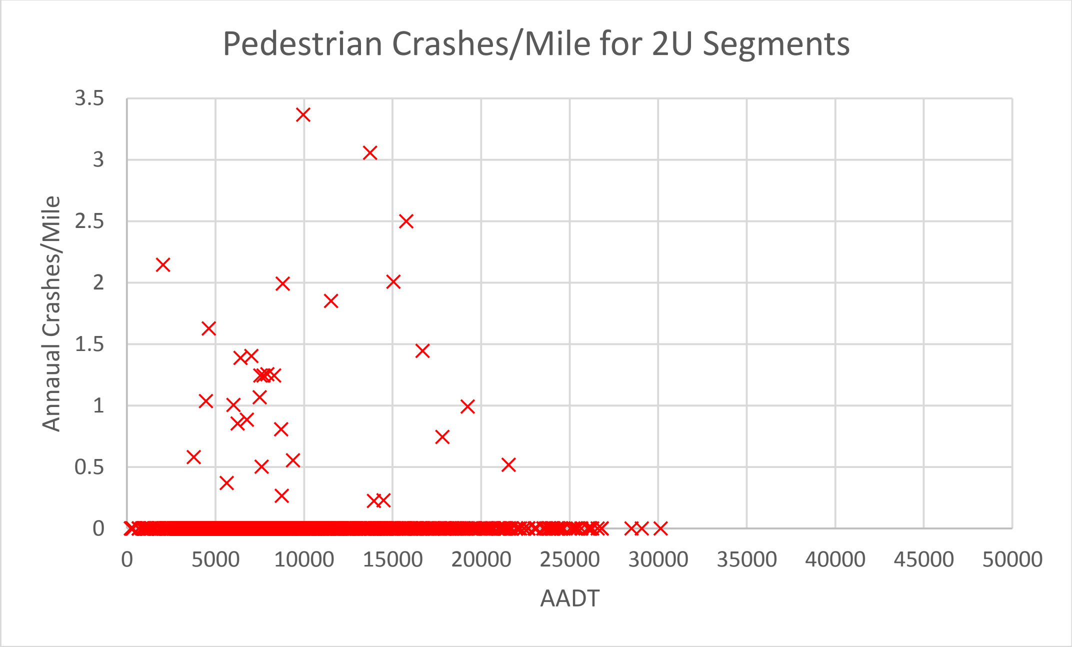
  - 439 four-lane divided (4D) segments;
  - 239 five-lane (5T) segments;
  - 119 six-lane divided (6D) segments;
  - 166 eight-lane divided (8D) segments;
  - 189 One-Way (OW) segments.(these segments were split into 2-lane (2O), 3-lane (3O) and 4-lane (4O) subcategories during SPF development).
- MDOT Urban Trunkline Intersections
  - 353 three-legged stop-controlled (3ST) intersections;
  - 350 four-legged stop-controlled (4ST) intersections;
  - 210 three-legged signalized (3SG) intersections; and
  - 349 four-legged signalized (4SG) intersections.

PRELIMINARY DATA INVESTIGATION

After the data were assembled, an exploratory analysis of the data was conducted separately for each segment type to identify general crash trends using Michigan-specific data.

Urban Segments

Figures 7 through 10 show the relationship between the rate of pedestrian crashes/mile and AADT, while Figures 11 through 14 show the relationship between the rate of bicycle crashes/mile and AADT. With respect to both pedestrian and bicycle crashes, it was found that more crashes involving pedestrians or bicyclists occur along segments with lower AADT volumes. This could reflect the fact that pedestrians and bicyclists prefer to travel on roads with less traffic, thus making these types of facilities more prone to experiencing non-motorized crashes.



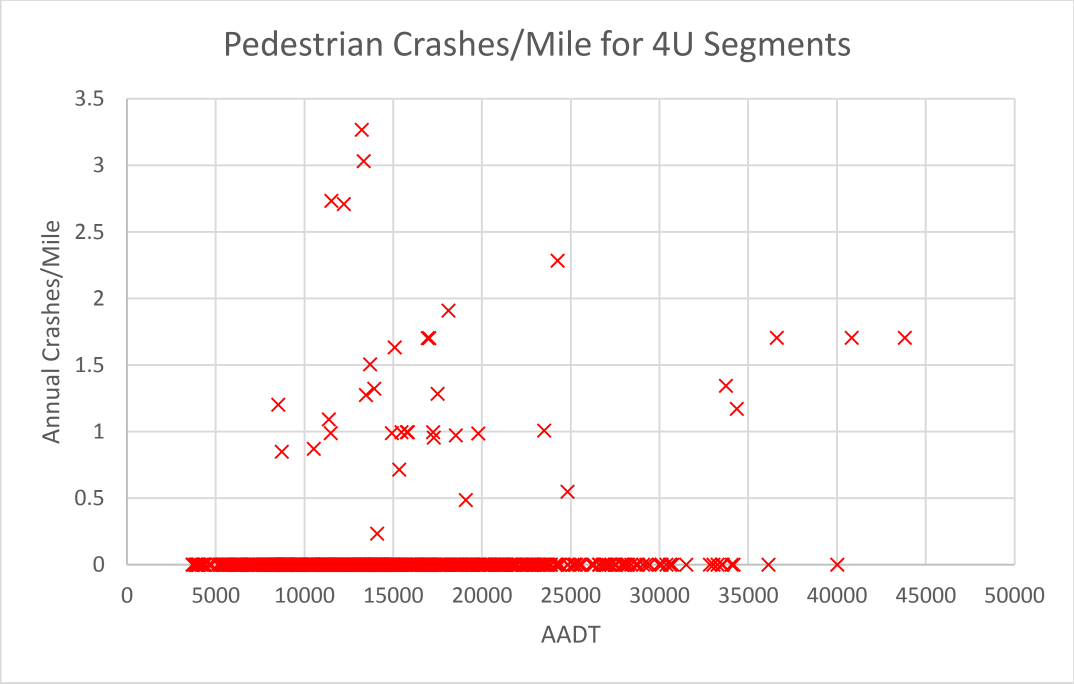
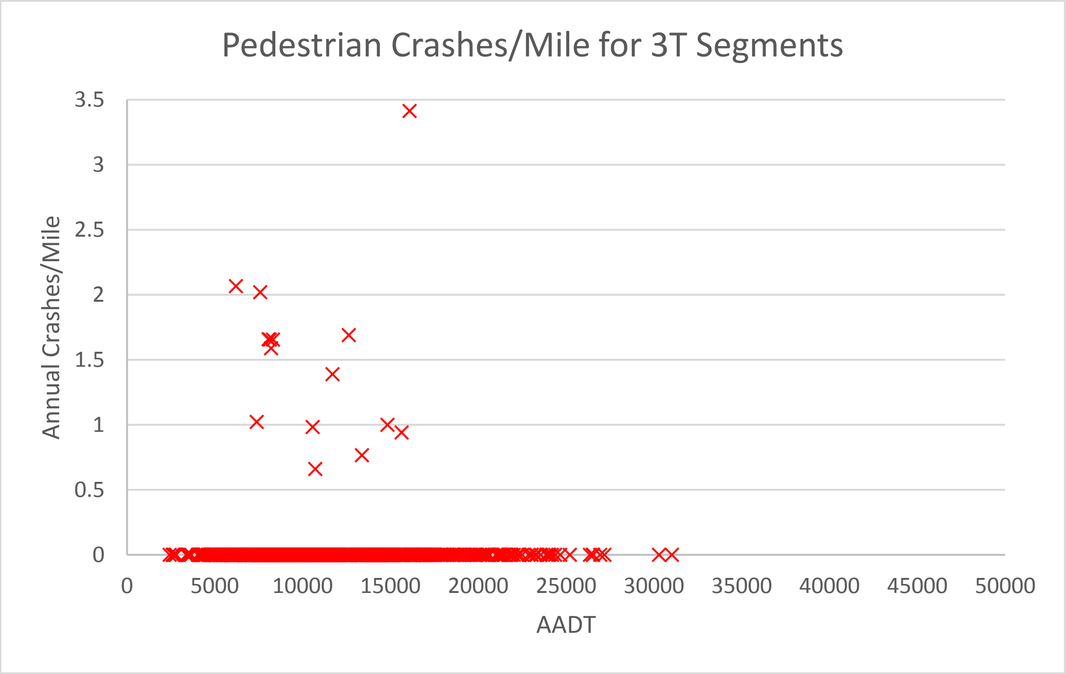


Figure 7. Relationship between Pedestrian Crashes/Mile and AADT for 2U and 4U Segments



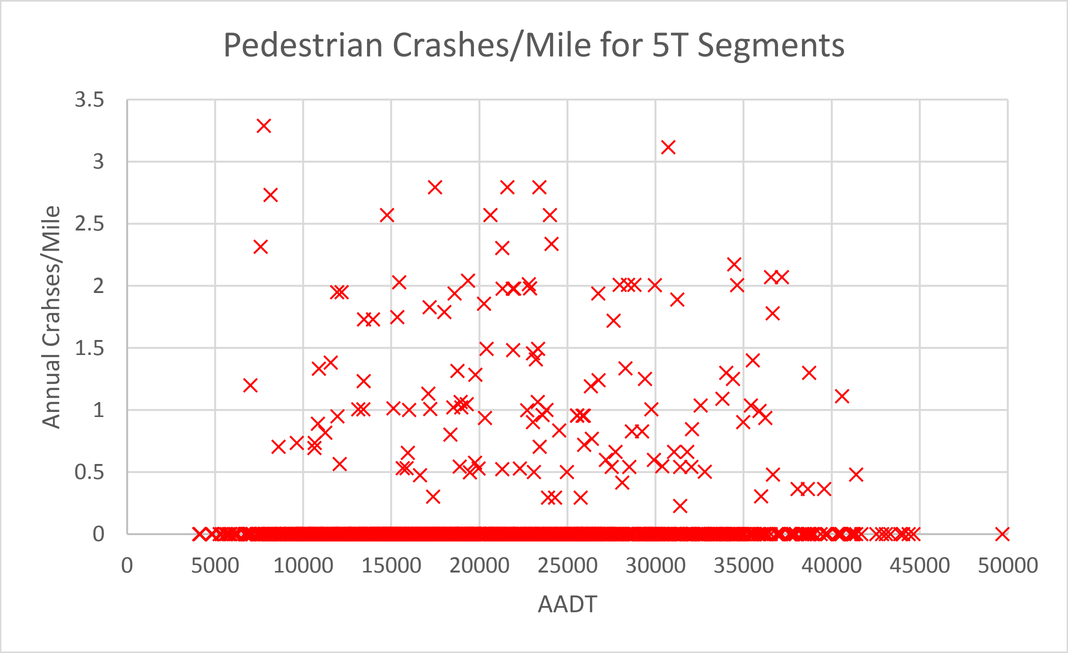


Figure 8. Relationship between Pedestrian Crashes/Mile and AADT for 3T and 5T Segments

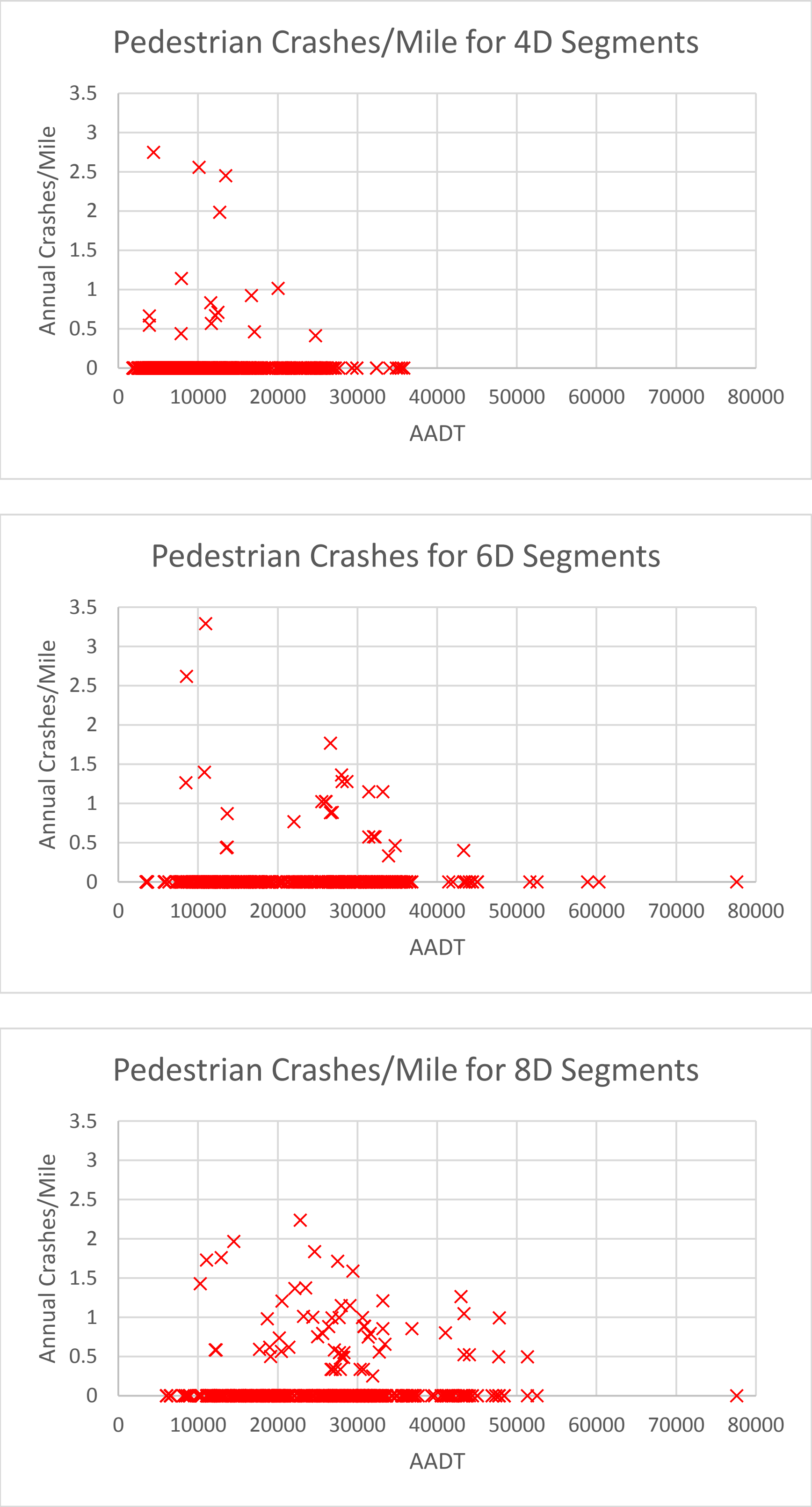


Figure 9. Relationship between Pedestrian Crashes/Mile and AADT for 4D, 6D, and 8D Segments

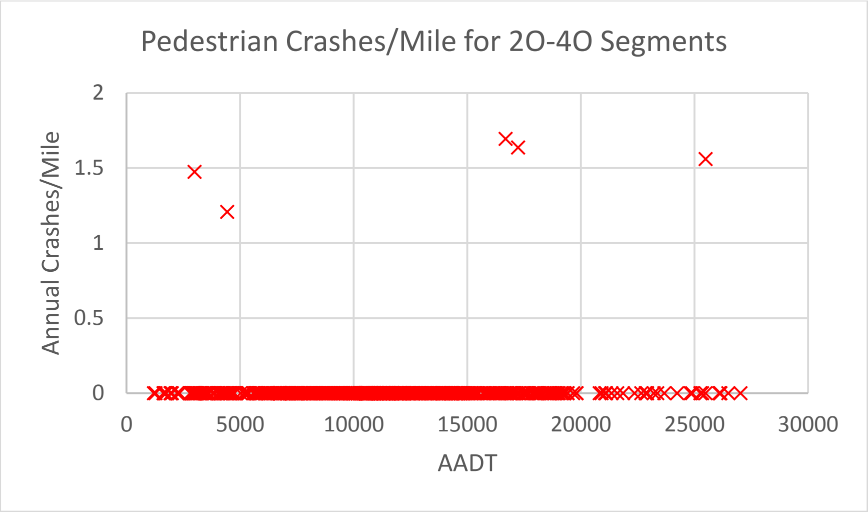
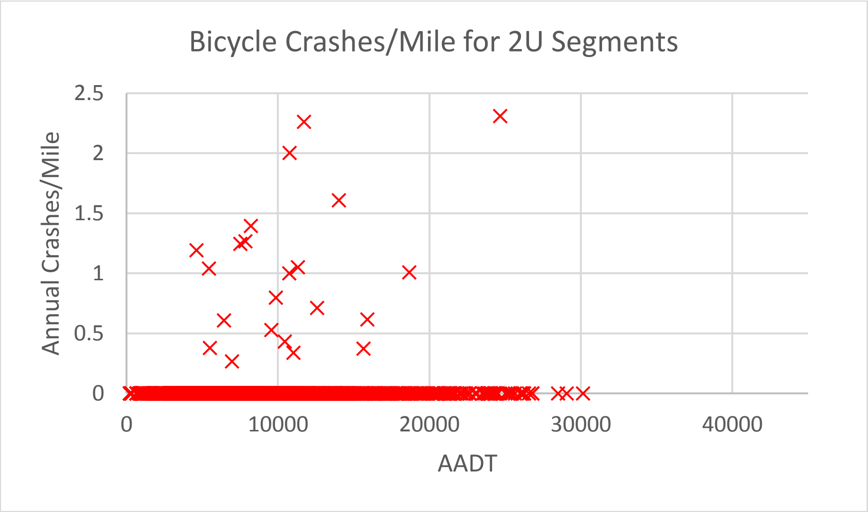


Figure 10. Relationship between Pedestrian Crashes/Mile and AADT for 2O-4O Segments



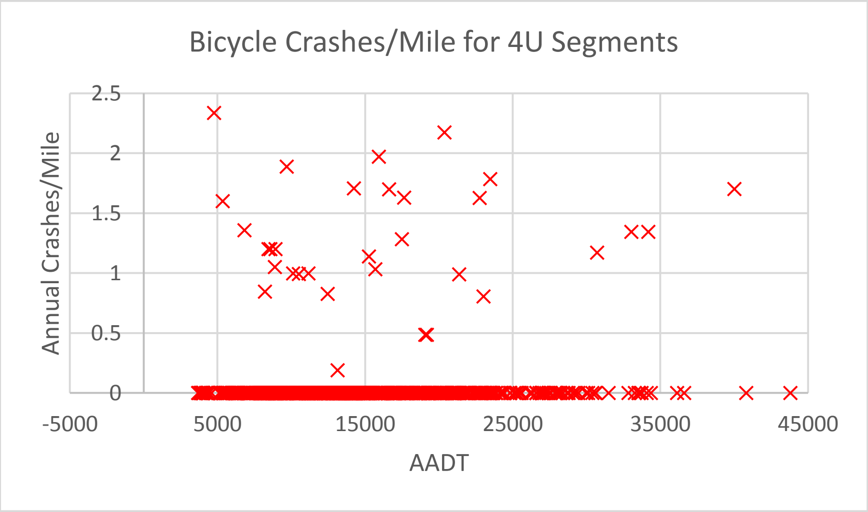
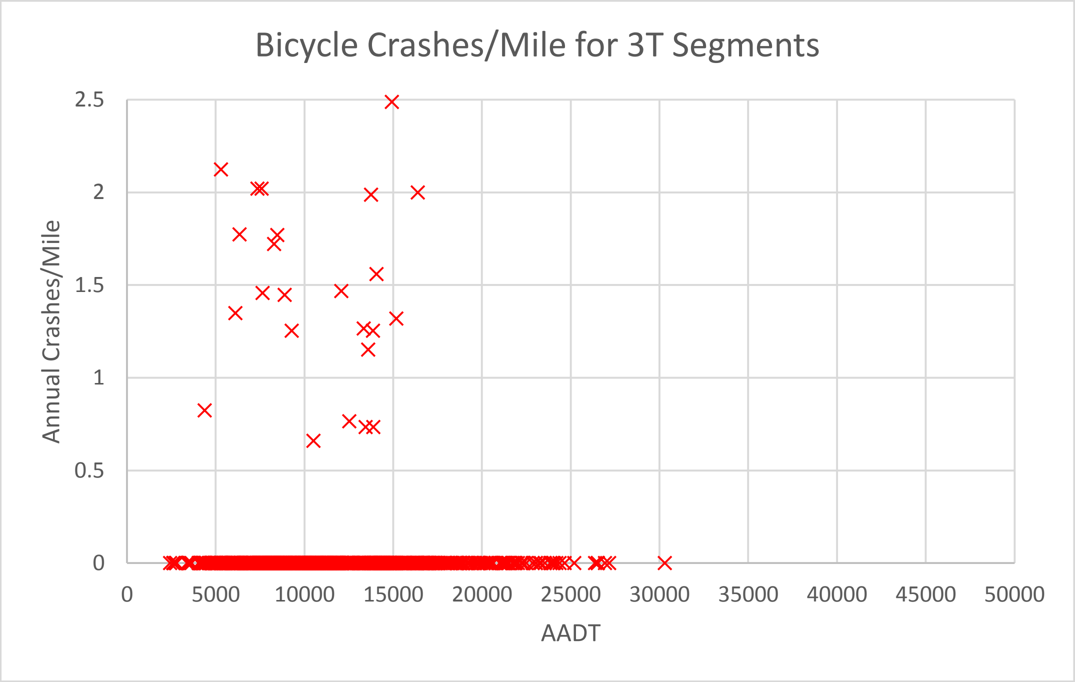


Figure 11. Relationship between Bicycle Crashes/Mile and AADT for 2U and 4U Segments



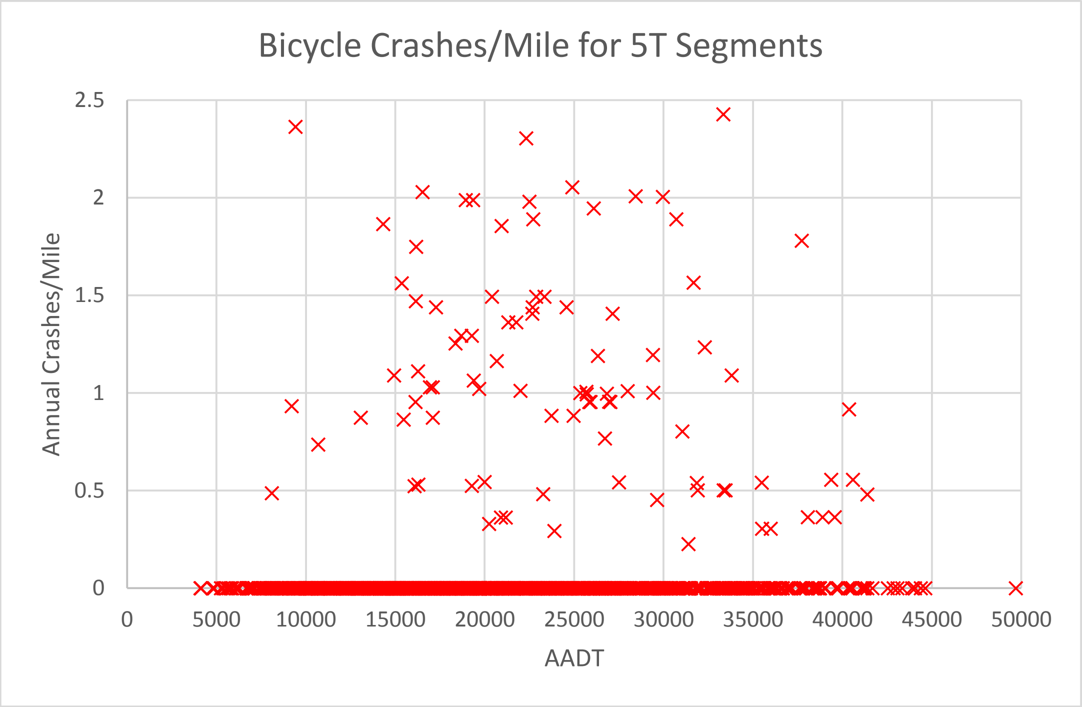


Figure 12. Relationship between Bicycle Crashes/Mile and AADT for 3T and 5T Segments

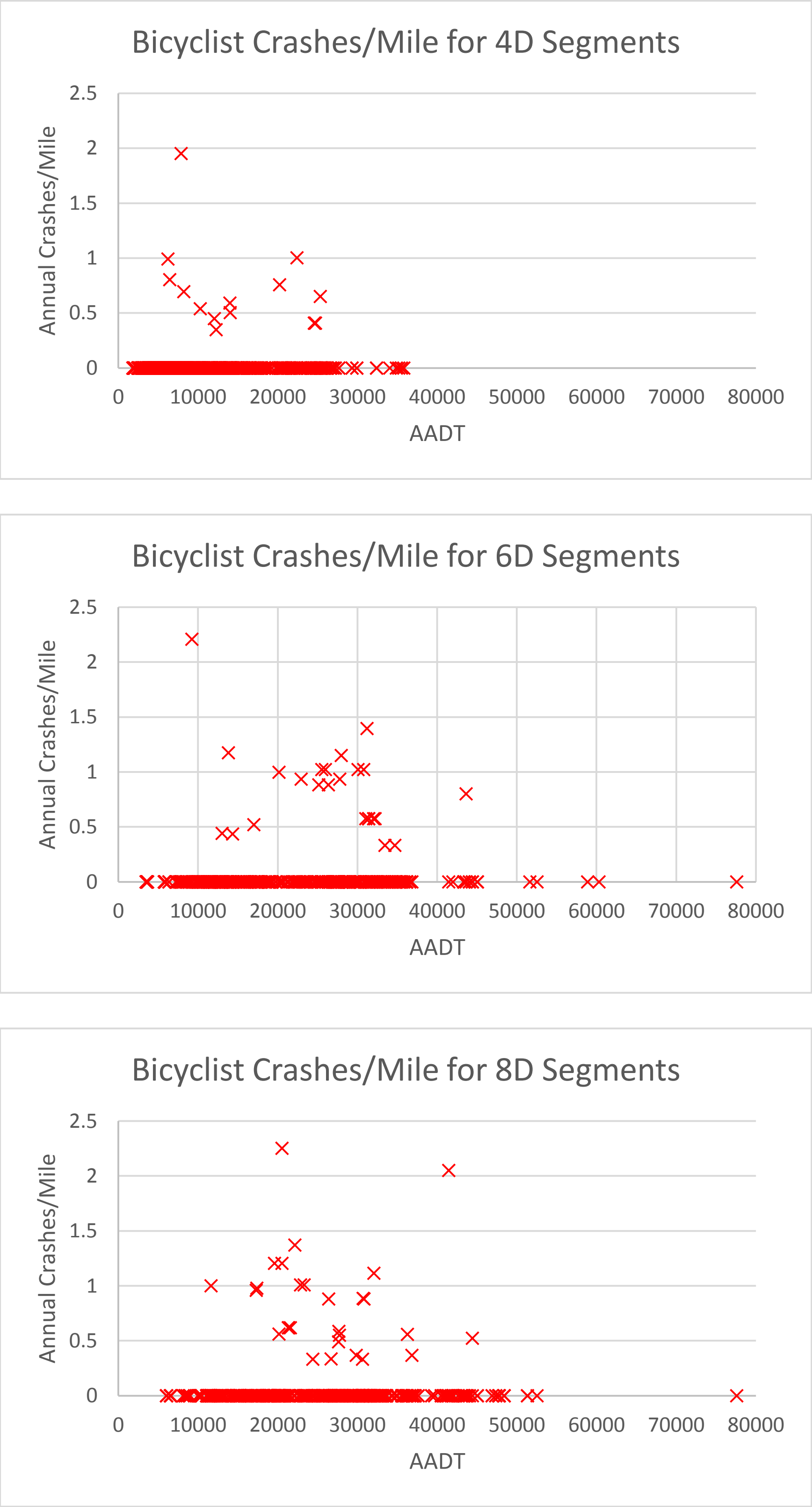


Figure 13. Relationship between Bicycle Crashes/Mile and AADT for 4D, 6D, and 8D Segments

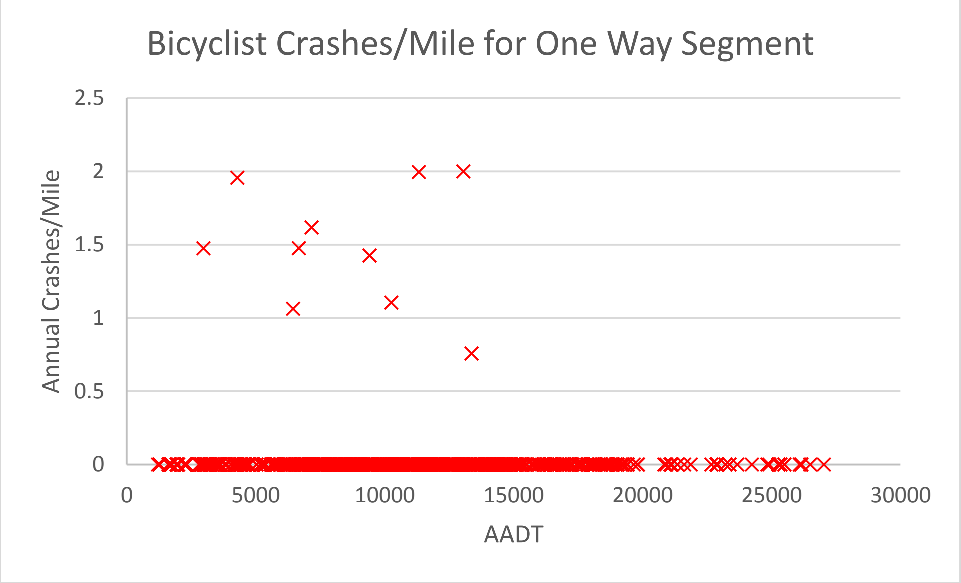
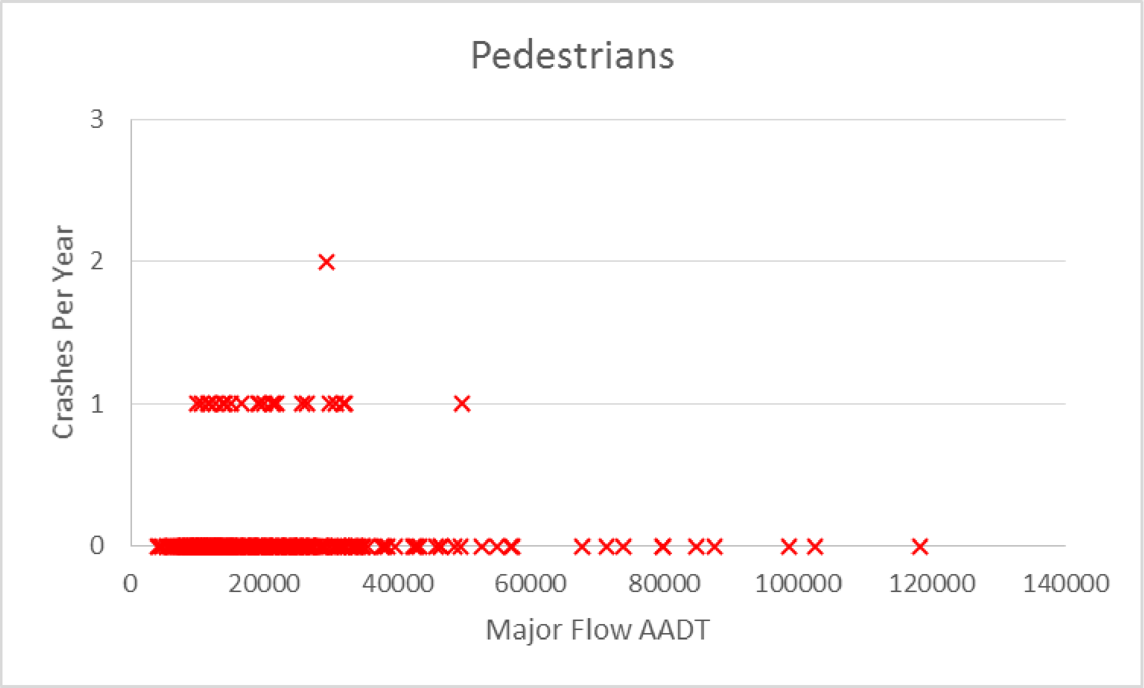


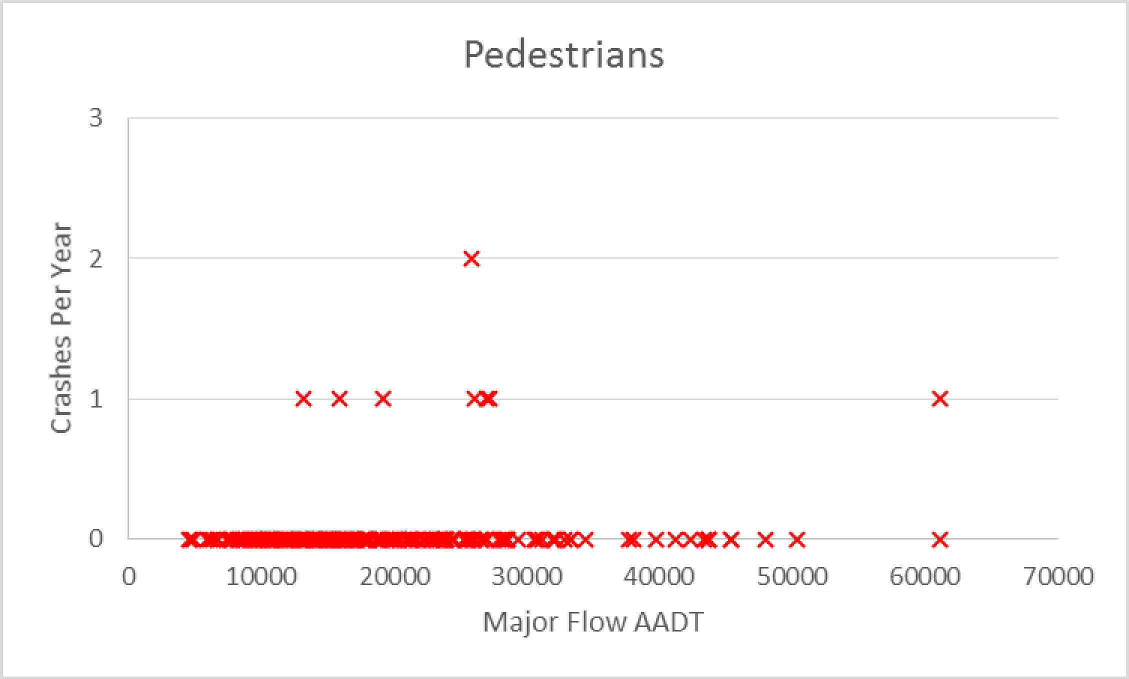
Figure 14. Relationship between Bicycle Crashes/Mile and AADT for One-way Segments

Urban Intersections

Figure 15 and Figure 16 show the relationship between the number of pedestrian crashes and major flow AADT. The relationship shows that more crashes involving pedestrians at intersections occur at lower major AADT volumes.

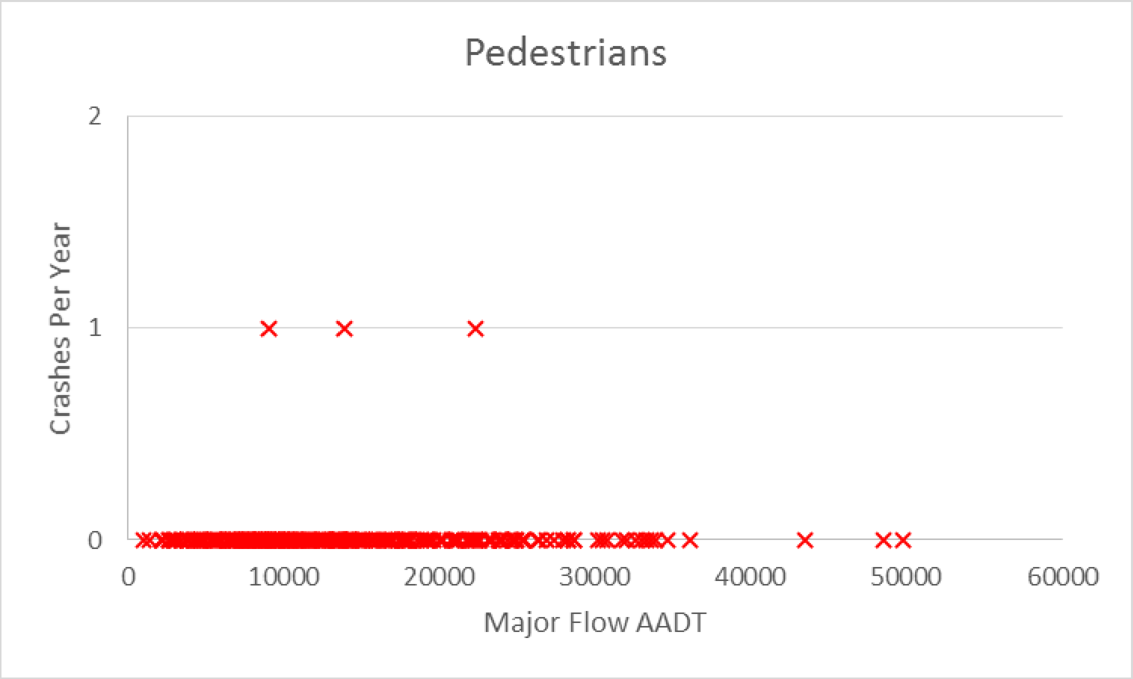


Four-Leg Intersections

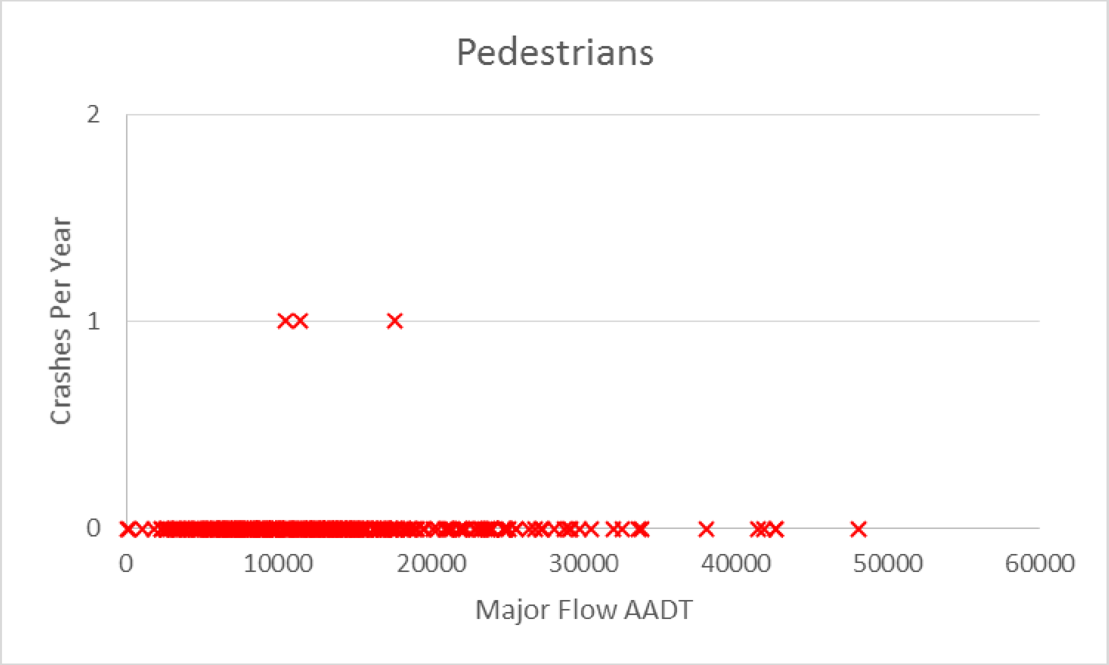


Three-Leg Intersections

Figure 15. Relationship Between the Number of Pedestrian Crashes and Major flow AADT for Signalized Intersections.



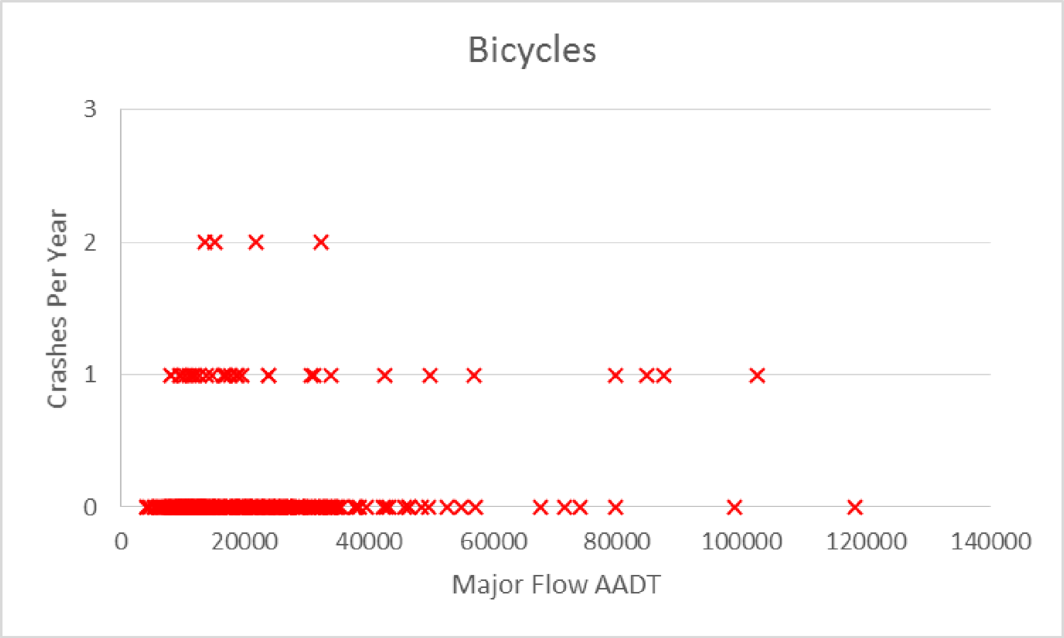
Four-Leg Intersections



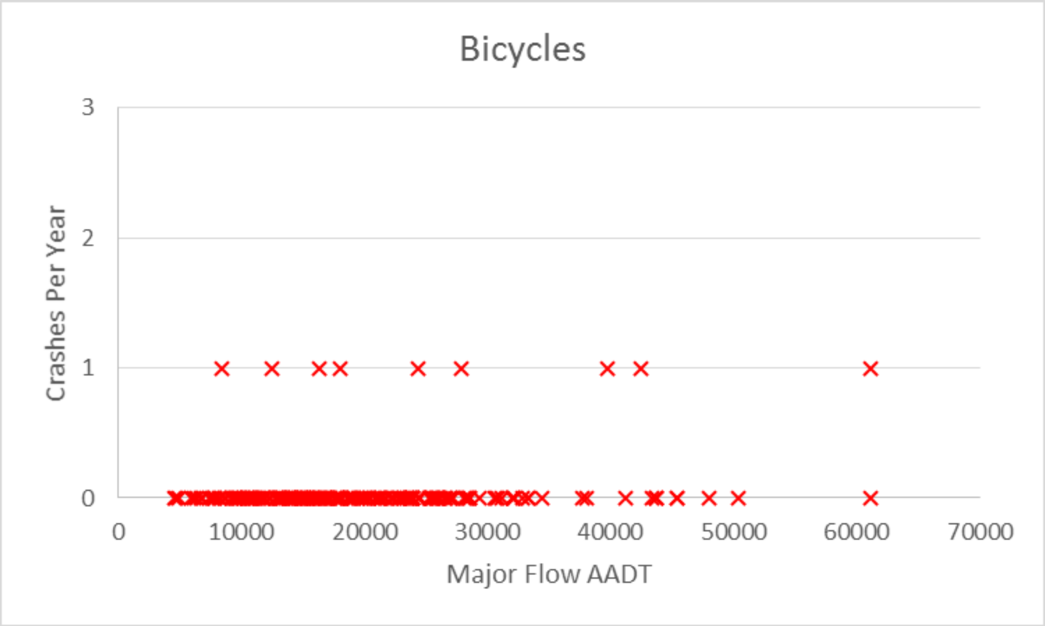
Three-Leg Intersections

Figure 16. Relationship Between the Number of Pedestrian Crashes and Major flow AADT for Stop-Controlled Intersections.

Figure 17 and Figure 18 show the relationship between the number of bicycle crashes and major flow AADT. The relationship shows that crashes involving bicycles at intersections occur at similar levels as a function of major AADT volumes.

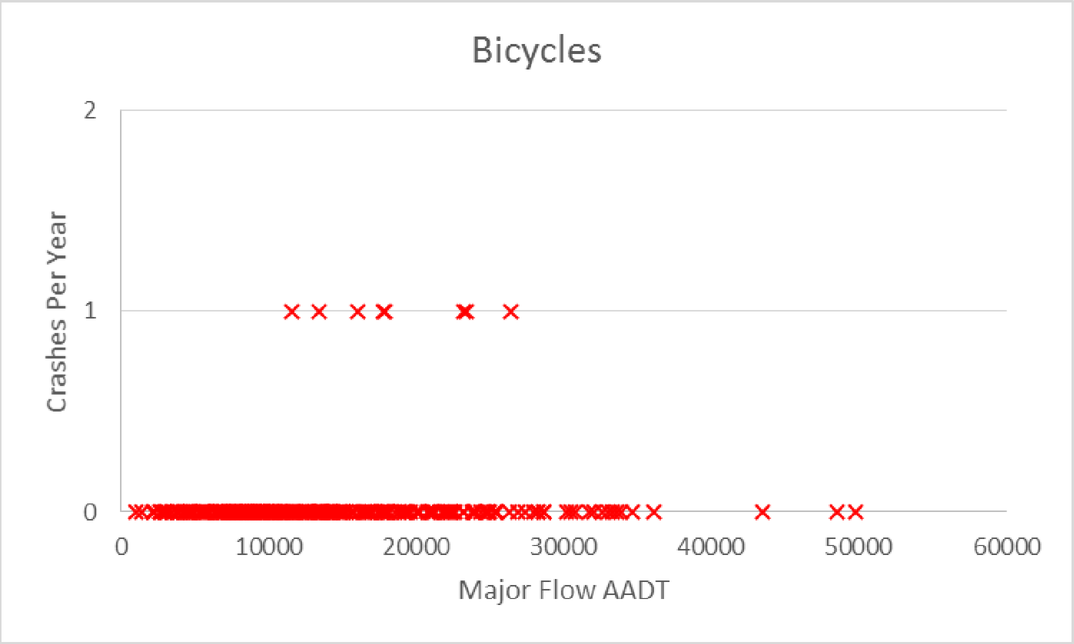


Four-Leg Intersections

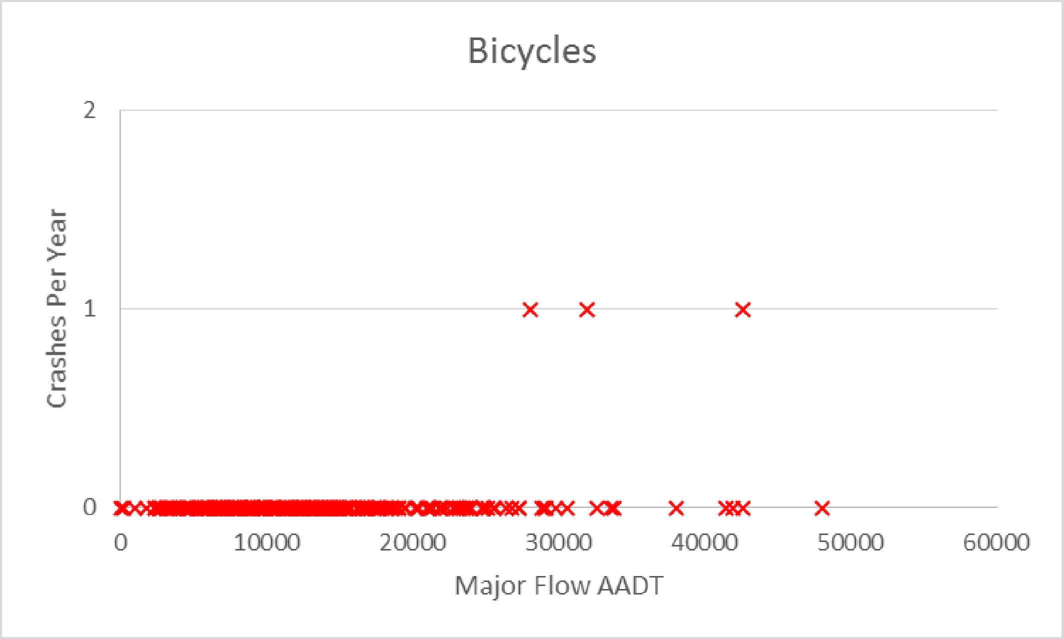


Three-Leg Intersections

Figure 17. Relationship Between the Number of Bicycle Crashes and Major flow AADT for Signalized Intersections.



Four-Leg Intersections



Three-Leg Intersections

Figure 18. Relationship Between the Number of Bicycle Crashes and Major flow AADT for Stop-Controlled Intersections.

PEDESTRIAN AND BICYCLE SAFETY PERFORMANCE FUNCTIONS

The Michigan-specific SPFs included a series of simple statewide models for total, FI, and PDO crashes. Because pedestrian and bicyclist volumes were not available statewide, the models were developed for pedestrian and bicycle crashes based on vehicular annual average daily traffic (AADT) volumes. The model results for MDOT urban segments are shown in Tables 24 and 25, while the model results for MDOT urban intersections are shown in Tables 26 and 27.

Table 24. Michigan Specific AADT Only Pedestrian Urban Segment Crash Models

	Segment Type	Intercept (a)	AADT (b)	Overdispersion Factor (k)
Total	**2U**	-19.53	0.38*	1.86E-14
	3T	-3.48*	-0.03*	7.16E-08
	4U	-21.04	1.87	2.00E-03
	5T	-9.28	0.69	0.12
	4D	-8.558	0.42*	1.03E-16
	6D	-5.52*	0.27*	1.58
	8D	-8.957	0.63*	1.04
	OneWay	-7.42*	0.36*	0.00
FI	**2U**	-21.05	0.54*	2.46E-15
	3T	-3.48*	-0.03*	7.16E-08
	4U	-22.49	2.00	0.00
	5T	-10.65	0.81	0.03
	4D	-8.15*	0.37*	9.92E-11
	6D	-4.60*	0.17*	0.87
	8D	-10.81	0.81	0.81
	OneWay	-0.90*	-0.37*	0.00
PDO	**2U**	-12.78	-0.65*	1.00
	3T	-	-	-
	4U	-14.64*	1.00*	0.00
	5T	-1.38*	-0.34*	2.96E-07
	4D	-20.04*	1.34*	1.00
	6D	-	-	-
	8D	1.68*	-0.65*	0.00
	OneWay	-178.87*	17.48*	0.00

*The variable was not significant at 95% confidence interval

Table 25. Michigan Specific AADT Only Bicycle Urban Segment Crash Models

	Segment Type	Intercept (a)	AADT (b)	Overdispersion Factor (k)
Total	**2U**	-25.17	0.96	0.00
	3T	-4.11*	0.09*	0.00
	4U	-6.51*	0.36*	0.64
	5T	-13.34	1.05	0.00
	4D	-17.722	1.381	0.00
	6D	-11.325	0.83*	0.00
	8D	-3.16*	-0.02*	0.04
	OneWay	-0.24*	-0.32*	1.00
FI	**2U**	-26.88	1.13	0.00
	3T	-5.47*	0.22*	0.00
	4U	-5.61*	0.24*	2.62
	5T	-14.45	1.15	0.00
	4D	-20.046	1.610	0.00
	6D	-11.672	0.85*	0.06
	8D	-4.05*	0.06*	0.62
	OneWay	-3.92*	0.07*	1.00
PDO	**2U**	-15.58*	-0.38*	0.00
	3T	0.08*	-0.57*	0.00
	4U	-10.98*	0.69*	0.00
	5T	-9.67*	0.49*	0.00
	4D	-8.44*	0.18*	0.00
	6D	-11.06*	0.55*	0.00
	8D	1.51*	-0.71*	0.00
	OneWay	12.79*	-2.04*	0.00

*The variable was not significant at 95% confidence interval

Table 26. Michigan Specific AADT Only Pedestrian Urban Intersection Crash Models

Severity	Intersection Type	Intercept (a)	AADTmaj (b)	AADTmin (c)	Overdispersion Factor (k)
Total	**3ST**	-15.512	0.765	0.385	2.143
	3SG	-9.044	0.402*	0.187	1.057
	4ST	-11.613	0.547	0.269	2.254
	4SG	-7.578	0.364	0.173	0.959
FI	**3ST**	-15.099	0.742	0.338	1.000
	3SG	-9.223	0.418*	0.182*	1.354
	4ST	-11.52	0.529	0.271	2.712
	4SG	-7.583	0.366	0.157	0.779
PDO	**3ST**	-20.711	0.886	0.661	1.168E-13
	3SG	-10.221	0.158*	0.283*	1.431E-16
	4ST	-16.547	0.793*	0.247*	0.000
	4SG	-10.535	0.316	0.311	0.977

*The variable was not significant at 95% confidence interval

Table 27. Michigan Specific AADT Only Bicycle Urban Intersection Crash Models

	Intersection Type	**Intercept (a)**	**AADTmaj (b)**	**AADTmin (c)**	**Overdispersion factor (k)**
Total	**3ST**	-14.744	0.778	0.394	1.214
	3SG	-11.092	0.575	0.232	1.000
	4ST	-11.173	0.618	0.188	1.184
	4SG	-6.958	0.256	0.227	0.884
FI	**3ST**	-15.567	0.873	0.353	0.939
	3SG	-10.889	0.551	0.204	1.000
	4ST	-11.555	0.659	0.157	0.083
	4SG	-7.834	0.340	0.203	0.702
PDO	**3ST**	-13.646	0.340*	0.591	1.648E-07
	3SG	-14.18	0.654*	0.331*	7.56E-11
	4ST	-11.718	0.408*	0.313	1.000
	4SG	-6.087	-0.072*	0.323	0.749

*The variable was not significant at 95% confidence interval

Each of the models show that pedestrian and bicycle crashes generally increase with respect to traffic volumes (major and minor volumes for intersections). However, even in the highest volume cases, the facilities were generally expected to experience only a fraction of a pedestrian or bicycle crash per year. In any case, these models provide a general starting point for pedestrian and bicycle safety analyses. The lack of a reliable exposure measure to represent the amount of pedestrian or bicyclist activity on a given segment or intersection is also a limitation which may be addressed through future programs aimed at collecting data for non-motorized users.

Another point worth noting is that most of the parameters in the property damage only (PDO) models are not statistically significant. This is reflective, at least in part, of the fact that pedestrian- or bicycle-involved crashes that result in no injury are very rare and most crashes of this type tend to go unreported.

ESTIMATING PEDESTRIAN AND BICYCLE CRASHES AS A PROPORTION OF TOTAL CRASHES

After development of the simple pedestrian and bicycle specific SPFs, pedestrian and bicycle crashes were further estimated based on respective proportions of the SPF models for total crashes developed for each of the aforementioned urban facility types using a representative statewide sample of MDOT roadway segments and intersections. Several variables were incorporated in the development of the SPFs and CMFs including AADT, MDOT region, speed limits, functional class, and numerous roadway geometric variables such as shoulder and median width, driveway density, intersection and crossover density, and horizontal curvature. Because these detailed statistical models account for the effects of a wide range of factors, they provide the greatest degree of accuracy. Please see references 40 and 41 for additional details pertaining to development and results of the fully specified SPFs for Michigan urban segments and intersections.

Pedestrian Crashes

Using the aforementioned procedure, the number of vehicle-pedestrian collisions per year for a segment or intersection was estimated as:

$$N_{ped} = N_b \times f_{ped}$$

$N_b =$ predicted average crash frequency of an individual urban segment or intersection (excluding vehicle-pedestrian and vehicle-bicycle collisions);

$N_{ped} =$ predicted average crash frequency of vehicle-pedestrian collisions for an urban segment or intersection;

$f_{ped} =$ pedestrian crash adjustment factor for the specific type of urban segment or intersection.

The pedestrian crash adjustment factor was estimated by dividing the vehicle-pedestrian crashes by the sum of single-vehicle and multiple-vehicle crashes for each facility type, based on the representative sample of locations within each of the categories. Table 28 presents the values of f_{ped}. All vehicle-pedestrian collisions are considered to be fatal-and-injury crashes.

Table 28. Pedestrian Crash Adjustment Factors for Use with Fully-Specified Models

Facility Category	Facility Type	Total Pedestrian Crashes	Total Single and Multi Vehicle Crashes*	f_{ped}
Segments	2U55E (55 mph)	8	5611	0.0014
	2U55L (<55 mph)	25	3695	0.0068
	3T	16	2812	0.0057
	4U	38	3004	0.0095
	4D	17	6925	0.0025
	5T	151	17703	0.0085
	6D	29	3810	0.0076
	8D	70	6731	0.0104
	2O	0	204	0.0000
	3O	4	676	0.0060
	4O	2	368	0.0005
Intersections	3SG	6	471	0.0127
	3ST	2	138	0.0145
	4SG	33	1937	0.0170
	4ST	6	313	0.0192

*Excludes pedestrian and bicycle crashes

Regarding the various segment types, the results displayed in Table 28 suggest that one-way urban segments, two-lane 55 mph undivided urban segments and 4-lane divided urban segments possess the lowest proportions of pedestrian crashes on MDOT urban roadway segments in Michigan. These results are not surprising, as urban one-way segments typically possess very low speed limits, pedestrian volumes on 55 mph segments are likely very low, and 4-lane divided segments offer refuge for pedestrians. However, the 4-lane divided result does contradict the yielding compliance and crash findings at the midblock study sites discussed earlier, which found yielding compliance to be lower and crash occurrence higher on divided roadway segments, although vehicle-pedestrian conflicts were lower at midblock crosswalks on divided segments. The greatest proportion of pedestrian crashes occurred on 8-lane divided segments, which likely indicates the high level of pedestrian activity coupled with high levels of exposure when crossing the roadway.

When compared to segments, intersections displayed greater proportions of pedestrian crashes across all facility types. Considering the various intersection types, pedestrian crashes represented lower proportions at 3-leg intersections compared to 4-leg intersections. Stop-controlled intersections showed greater pedestrian crash proportions compared to signalized intersections.

Bicycle Crashes

The number of vehicle-bicycle collisions per year for a segment or intersection was estimated as:

$$N_{bike} = N_b \times f_{bike}$$

$N_b =$ predicted average crash frequency of an individual urban segment or intersection (excluding vehicle-pedestrian and vehicle-bicycle collisions);
$N_{bike} =$ predicted average crash frequency of vehicle-bicycle collision for an urban segment or intersection;
$f_{bike} =$ bicycle crash adjustment factor for the specific type of urban segment or intersection.

The bicycle crash adjustment factor is estimated by dividing the vehicle-bicycle crashes by the sum of single-vehicle and multiple-vehicle crashes for each facility type, based on the representative sample of locations within each of the respective segment or intersection categories.

Table29 presents the values of f_{bike}. The vehicle-bicycle collisions by severity are estimated using the following equation.

$$N_{bikes,fi} = N_{bike} \times P_f$$
$$N_{bikes,pdo} = N_{bike} \times (1 - P_{fi})$$

$N_{bike,fi} =$ predicted average fatal and injury crash frequency of vehicle-bicycle collisions for a segment or intersection;

$N_{bike,pdo} =$ predicted average property damage only crash frequency of vehicle-bicycle collisions for a segment or intersection;

$P_{fi} =$ proportion of fatal and injury vehicle-bicycle crashes for the specific type of urban segment or intersection.

Table 29. Bicycle Crash Adjustment Factors

Facility Category	Facility Type	Bicycle Crashes			Total MV and SV Crashes*	f_{bike}
		Total	FI only	P_{fi}		
Segments	2U55E	9	9	1.00	5611	0.0016
	2U55L	14	12	0.86	3695	0.0038
	3T	26	22	0.85	2812	0.0092
	4U	38	28	0.74	3004	0.0095
	4D	15	13	0.87	6925	0.0022
	5T	103	89	0.86	17703	0.0058
	6D	25	23	0.92	3810	0.0066
	8D	31	28	0.90	6731	0.0046
	2O	5	4	0.80	204	0.0245
	3O	7	6	0.88	676	0.0104
	4O	3	3	1.00	368	0.0082
Intersections	3SG	8	6	0.75	471	0.0170
	3ST	3	1	--	138	0.0217
	4SG	25	18	0.72	1937	0.0129
	4ST	9	6	0.67	313	0.0288

*Excludes pedestrian and bicycle crashes

Similar to the pedestrian crash proportions, the results displayed in Table 29 suggest that two-lane 55 mph undivided urban segments and 4-lane divided urban segments possess the lowest proportions of bicyclist crashes on MDOT urban roadway segments in Michigan. These results are not surprising, as bicyclist volumes on 55 mph segments are likely lower than on lower speed segments, although it should be noted that 100 percent of the bicycle crashes on this segment type resulted in an injury or fatality, likely a result of the high vehicular speeds on such roadways. Four-lane divided urban segments possess a variety of speed limits and cross-sectional features (shoulders, bike-lanes, parking, curb-and-gutter, etc.), although it is plausible that bicycle volumes are also lower on such segments. The greatest proportion of crashes occurred on one-way segments, although it should be noted that the overall crash samples were considerably lower than the other segment types.

When compared to segments, intersections displayed greater proportions of bicycle crashes across all facility types, with the exception of one-way segments, which showed comparable bicycle crash proportions to those of intersections. Considering the various intersection types, bicycle crashes represented lower proportions at 3-leg intersections compared to 4-leg intersections. Stop-controlled intersections showed greater pedestrian crash proportions compared to signalized intersections, especially for 4-leg stop intersections.

CHAPTER 7:
CONCLUSIONS AND RECOMENDATIONS

SUMMARY

Safety performance functions (SPFs) provide a promising approach for quantifying the level for pedestrian crashes at specific intersections or road segments. The Highway Safety Manual currently provides an aggregate pedestrian/bicycle SPF, which is based upon land use characteristics [2]. However, since pedestrian and especially bicycle crashes are particularly rare, such an approach limits the ability to proactively identify sites with the potential for crashes that are not reflected by recent crash data. As a result, research is limited in terms of disaggregate-level studies considering the effects of motor vehicle/bicycle/pedestrian volumes, roadway geometry, and other factors on pedestrian and bicycle crashes. Furthermore, research has also been limited with respect to how these factors influence the underlying behaviors of both motorized and non-motorized road users. Therefore, alternative surrogate measures for identification of locations possessing comparatively high safety risks should be investigated.

To address these issues, a field study was performed on low-speed roadways within Detroit, East Lansing, and Kalamazoo, Michigan to determine factors related to pedestrian and bicyclist safety risk. A variety of existing traffic control devices were considered, including various crosswalk marking strategies, along with additional treatments, including PHBs, RRFBs and single in-street R1-6 signs. A diverse set of roadway and traffic characteristics were also considered, including crossing width, number of lanes, and median presence, along with vehicular, pedestrian, and bicyclist volumes collected during the study period. A total of 66 sites were selected, including 40 uncontrolled midblock locations and 26 signalized intersections, which were selected to provide diversity among existing crosswalk treatments and roadway characteristics, along with a range of vehicular and pedestrian volumes. To ensure adequate pedestrian activity, all locations were selected on or near college campuses or commercial business districts.

Driver and pedestrian behavioral observations were collected at each of the study sites using an elevated high-definition video camera, while historical crash data were collected for the most recent 10-year period from the Michigan State Police annual crash databases. Using these data, three primary evaluations were performed for both segments and signalized intersections, which included: driver yielding compliance, vehicle-pedestrian conflicts, and non-motorized traffic crash data, and attempts were made to examine the relationships between the behavioral measures and the crash data. Unfortunately, small sample sizes of vehicle-pedestrian conflicts and especially pedestrian/bicycle crashes limited the ability to draw meaningful conclusions from these data. Thus, to supplement small crash sample sizes at the study sites, statewide pedestrian and bicyclist crash data were collected and utilized to develop safety performance functions and other methods for predicting pedestrian and bicyclist crashes on road segments and intersections.

CONCLUSIONS

Driver Behavior During Pedestrian Crossing Attempts

The driver yielding compliance results at midblock crosswalks indicated that the type of crosswalk treatment has a strong influence over driver behavior when encountering a pedestrian in the crosswalk. While both yielding compliance and vehicle-pedestrian conflicts improve substantially when crosswalk markings are utilized, much greater compliance is obtained when additional enhancement devices, such as RRFBs, PHBs, or in-street R1-6 signs, are also provided. Yielding compliance rates for the various crosswalk treatments were shown to be in agreement with previous research performed outside of Michigan, and also showed improvements across all treatment types compared to prior studies performed within Michigan. This is an important finding, which suggests that compliance may improve as drivers become more familiar with a particular treatment.

Driver yielding compliance at midblock crosswalks was shown to increase as the pedestrian crossing volumes increased, but decrease as the vehicular volume increased. It was also found that yielding compliance is highly sensitive to both the roadway cross-section and lane position of the vehicle relative to the location of the crossing pedestrian. Drivers were much less likely to yield when the driver encountered the staged pedestrian at the nearside curb lane compared to any other lane. This is not a surprising result, as the pedestrian is in a less conspicuous and less vulnerable position when waiting near the curb, compared to encounters that occurred while the pedestrian was approaching a driver in any other lane. While this result is reflective of the interaction between motorists and pedestrians attempting to cross, it does indicate the necessity for yielding compliance studies to control for the driver lane position. And while low curb-lane compliance persisted across each of the observed types of roadway cross sections (two-lane, multilane undivided, and multilane divided), it was particularly low on median divided roadways. This may be indicative of potential obstructions within the median that reduce the visibility of pedestrians waiting to cross. Interestingly, vehicle-pedestrian conflicts were found to be lower at midblock crosswalks on divided roadways compared to undivided roadways. Perhaps most importantly, however, yielding compliance showed little sensitivity to driver lane position at locations where additional treatments (i.e., in-street sign, PHB, RRFB) were utilized, providing further evidence of the effectiveness of these treatments.

Considering signalized intersections, yielding compliance was greater at 3-leg intersections compared to 4-leg intersections. Additionally, yielding compliance for turning vehicles at signalized intersections actually improved as the turning vehicle and pedestrian crossing volumes increased (and subsequent number of pedestrian-vehicle interactions increased). This effect was particularly strong when considering only right-turning vehicles.

Readers should also be aware of the limitations of the field study. First, the results are limited to low speed locations only. Driver and pedestrian behavior is likely different on higher speed roadways and pedestrian activity is typically less frequent. Furthermore, all sites selected in this study were on or near public universities in the Midwest during the early fall when school was in session. Therefore, both the pedestrians and drivers on which this model is based on may be more likely to fit a younger demographic than the pedestrian population at large.

Finally, and most importantly, although the investigation of pedestrian crashes at the study sites provided some indication of relationships between the various site, traffic, and behavioral factors, the small sample size of crashes across the study sites did not provide definitive results nor did it allow for formal SPF development. To help counter the small sample of pedestrian crashes, additional investigation into pedestrian-vehicle crashes statewide was performed.

Pedestrian and Bicycle SPFs

The lack of pedestrian and bicycle crash data at the study sites precipitated the need to perform a broader statewide assessment of pedestrian and bicycle crashes. Two parallel SPF development projects for the Michigan Department of Transportation [40,41] led by the authors of this report allowed for development of pedestrian and bicyclist crash SPFs for various types of urban roadway segments and urban intersections based on traffic volumes, traffic control (intersections), speed limits, roadway cross section characteristics, driveway counts, lighting, and a number of roadway geometric variables. These data were aggregated into comprehensive databases along with historical traffic crashes from 2008 to 2012 for a representative statewide sample of urban segments and urban intersections.

Michigan-specific SPFs were developed for pedestrian and bicycle crashes separately for eight different types of urban segments (2-lane, 3-lane, and 4-lane undivided; 4-lane, 5-lane, 6-lane, and 8-lane divided; and one-way) along with four different types of urban intersections (3-leg and 4-leg stop control; and 3-leg and 4-leg signal control) for total, fatal and injury, and property damage only crashes. Because pedestrian and bicyclist volumes were not available statewide, each model was developed for pedestrian and bicycle crashes based solely on vehicular AADT. In general, the models showed that pedestrian and bicycle crashes tend to increase with increasing traffic volumes. However, even in the highest volume cases, only a fraction of crashes involved a pedestrian or bicyclist. Furthermore, in most cases, the property damage only (PDO) models were not statistically significant. This is reflective, at least in part, of the fact that pedestrian- or bicycle-involved crashes that result in no injury are very rare and most crashes of this type tend to go unreported.

Relative Proportions of Pedestrian and Bicycle Crashes by Roadway Type

After development of the simple pedestrian and bicycle specific SPFs, pedestrian and bicycle crashes were further estimated based on the respective proportion of the SPF models for total crashes developed for each of the aforementioned urban facility types using a representative statewide sample of MDOT roadway segments and intersections. Several variables were incorporated in the development of the SPFs and CMFs including AADT, MDOT region, speed limits, functional class, and numerous roadway geometric variables such as shoulder and median width, driveway density, intersection and crossover density, and horizontal curvature.

The pedestrian crash proportion results suggested that one-way urban segments, two-lane 55 mph undivided urban segments and 4-lane divided urban segments possessed the lowest proportions of pedestrian crashes on MDOT urban roadway segments in Michigan. These results are not surprising, as urban one-way segments typically possess very low speed limits, pedestrian volumes on 55 mph segments are likely very low, and 4-lane divided segments offer refuge for pedestrians. The greatest proportion of pedestrian crashes occurred on 8-lane divided segments, which likely indicates the high level of pedestrian activity coupled with high levels of exposure when crossing the roadway. When compared to segments, intersections displayed greater proportions of pedestrian crashes across all facility types. Considering the various intersection types, pedestrian crashes represented lower proportions at 3-leg intersections compared to 4-leg intersections. Stop-controlled intersections showed greater pedestrian crash proportions compared to signalized intersections.

Similar to the pedestrian crash proportions, two-lane 55 mph undivided urban segments and 4-lane divided urban segments were found to possess the lowest proportion of bicyclist crashes on MDOT urban roadway segments in Michigan. These results are not surprising, as bicyclist volumes on 55 mph segments are likely lower than on lower speed segments, although it should be noted that 100 percent of the bicycle crashes on this segment type resulted in an injury or fatality, likely a result of the high vehicular speeds on such roadways. The greatest proportion of crashes occurred on one-way segments, although it should be noted that the overall crash samples were considerably lower than the other segment types. When compared to segments, intersections displayed greater proportions of bicycle crashes across all facility types, with the exception of one-way segments, which showed comparable bicycle crash proportions to those of intersections. Considering the various intersection types, bicycle crashes represented lower proportions at 3-leg intersections compared to 4-leg intersections. Stop-controlled intersections showed greater pedestrian crash proportions compared to signalized intersections, especially for 4-leg stop intersections.

RECOMMENDATIONS

Road agencies are advised to place crosswalks in otherwise unmarked locations where pedestrians frequently cross and, when necessary, install additional treatment. Providing marked crosswalks in locations with light to moderate vehicle volumes will result in higher yielding compliance and will typically not require additional treatment unless special circumstances (i.e., school, hospital, etc.) exist. For midblock crosswalks in locations with high vehicle and/or high pedestrian volumes, particularly at multilane locations, additional low-cost treatments such as in-street pedestrian crossing signs (R1-6) may further increase compliance and provide subsequent safety benefits, whether used in a single installation on the centerline (studied here) or in a gateway configuration on both the centerline and at the edges of the roadway. Due to high costs, RRFBs and especially PHBs, should only be installed at select locations displaying high pedestrian and vehicular volumes, particularly where other treatments have proven to be ineffective.

The SPF models provided here give a general starting point for pedestrian and bicycle safety analyses. Perhaps the greatest limitation to prediction of pedestrian and bicyclist crashes, including those developed here, is the lack of reliable exposure data to represent the amount of pedestrian or bicyclist activity on a given segment or intersection. Future programs by transportation agencies or researchers should be aimed at collecting such exposure data for non-motorized users, in addition to motor vehicle traffic volumes.

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