AN EVALUATION OF THE RELATIVE SAFETY OF PEDESTRIAN INFRASTRUCTURE USING DRIVER BEHAVIOR AND CONFLICT AS SURROGATES FOR CRASHES

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ABSTRACT

AN EVALUATION OF THE RELATIVE SAFETY OF PEDESTRIAN INFRASTRUCTURE USING DRIVER BEHAVIOR AND CONFLICT AS SURROGATES FOR CRASHES

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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 signs (R1-6). 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 initial 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. Ultimately, only crash data and driver yielding compliance to pedestrians were included in the final analysis. 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. The primary limitation towards prediction of pedestrian crashes is the lack of a reliable exposure data to represent the amount of pedestrian activity on a given segment or intersection.

This thesis is dedicated to my late brother, Andrew Mark Stapleton,
who always encouraged me to do my best in all my endeavors.

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PREFACE

This thesis presents three methods of evaluating the relative safety of pedestrian infrastructure: crash analysis, conflict analysis, and yielding compliance. Crash and conflict analyses are presented to demonstrate the shortcomings of traditional crash analysis for pedestrian safety, as well as conflict, which is a common surrogate for crashes. While the utility of yielding compliance as a measure of effectiveness stands alone, crash and conflict analyses are included to establish the need for yielding compliance as a surrogate measure of effectiveness for crashes.

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KEY TO ABBREVIATIONS

HSM	Highway Safety Manual
AADT	Annual average daily traffic
ADT	Average daily traffic
SPF	Safety performance function
CMF	Crash modification factor
AASHTO	American Association of State Highway and Transportation Officials
FHWA	Federal Highway Administration
PHB	Pedestrian hybrid beacon
RRFB	Rectangular rapid flashing beacon
MOE	Measure of effectiveness

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 2012 and 2016, 11,395 pedestrian crashes occurred on roadways in Michigan, representing a 3.7 percent increase over the previous 5-year period of 2007 to 2011. Such crashes resulted in 761 fatal crashes involving pedestrians, representing an 18.9 percent increase over 2007 to 2011. During the same period, crashes not involving pedestrians decreased by 1.81 percent while fatal crashes not involving pedestrians decreased by 2.68 percent. While pedestrian-involved crashes comprised only a small portion (0.8 percent) of all crashes that occurred between 2012 and 2016, consider that fatal crashes involving pedestrians accounted for 17.2 percent of all fatal crashes in Michigan during that period. When considering the vulnerability and relative risk, pedestrians were 27 times more likely to be fatally injured when involved in a traffic crash compared to occupants of motor vehicles.

Crashes involving pedestrians 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 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 States, 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 engineering 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 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 Crashes by Location Type and Traffic Control, 2012-2016

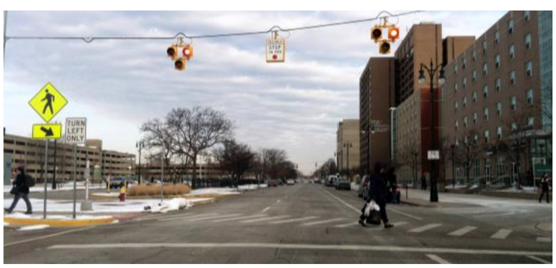
Road User Type	**Type of Location**	**Crash Statistics, 2012 - 2016**		
		Number of Crashes	**Number of Fatal Crashes**	**Fatal Crashes as Percent of All Crashes**
Pedestrian	Non Intersection – No Signal	5,794	548	9.5%
	Non Intersection - Signal	538	35	6.5%
	Intersection – No Control	1,443	82	5.7%
	Intersection – Stop or Yield	955	16	1.7%
	Intersection – Signal	2,387	68	2.8%

1.1 Problem Statement

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 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 SPF, which is based upon land use characteristics [2]. However, since pedestrian 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 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.

1.2 Research Approach

To address these issues, a field study was performed on low-speed roadways within three Michigan cities to determine factors related to pedestrian 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.

1.3 Objectives

This study sought to identify factors which contribute to pedestrian safety. Traditional crash-based modeling for evaluating pedestrian safety is challenging due to the small number of pedestrian crashes as well as the lack of reliable exposure data for pedestrians. This is reflected in the lack of pedestrian-specific safety performance functions (SPFs) at midblock areas in the Highway Safety Manual (HSM) as well as the lack of statistically significant crash modification factors (CMFs) for the RRFB and in-street R1-6 sign. To address these challenges, the following objectives were set:

- To evaluate the safety of pedestrian crossing treatments using a measure of effectiveness other than crashes
- To determine the safety impact of cross-sectional and site characteristics other than the pedestrian crossing treatment
- To use statistical analysis to directly compare different crossing treatments
- To provide for a methodology which states and local agencies can use to evaluate their own pedestrian infrastructure

1.4 Study Constraints

In order to meet study objectives, there were several constraints in site selection. Sites were limited to low speed locations on or near large public university campuses in Michigan during daytime hours (i.e., 9:00 AM to 4:00 PM) in the fall. This was done for several reasons:

- Pedestrian volume: This study sought to evaluate driver yielding compliance in areas where pedestrian activity already exists, and therefore, selecting sites with moderate-to-high pedestrian volume is imperative. College campuses and surrounding areas are reliable sources of pedestrian traffic. Times were selected during the mid-day to align with pedestrian travel behavior on university campuses. Lastly, observations took place in the fall to allow for observations when class is in session and pedestrian volumes are high, and to avoid the winter months where pedestrian activity would be expected to decrease

- Land-use and demographic characteristics: Utilizing sites located on university campuses allows for similar characteristics of land use, zoning, population density, as well as demographic characteristics of drivers and pedestrians, among sites
- Driver speed: It is expected that speed is a factor in pedestrian safety. However, the previously mentioned constraints limit the type of road which can be evaluated. On and surrounding the three university campuses studied, speed limits greater than 25 mph are rare, and have low pedestrian activity. Therefore, consistency was provided by only including sites with speed limits of 25 mph.

The following chapters describe the data collection and analytical methods along with results, conclusions and recommendations.

CHAPTER 2: LITERATURE REVIEW

To address pedestrian safety, a variety of pedestrian crossing safety treatments have been devised. The Manual of Uniform Traffic Control Devices (MUTCD) is a manual published by the Federal Highway Administration (FHWA) which lists and provides detail and guidance regarding the use of traffic control devices in the United States [3], and state design guides must be in substantial compliance with the MUTCD in order to provide nationwide consistency. To this end, the MUTCD includes several pedestrian crossing treatments, including crosswalk markings, in-street signs (R1-6), and the pedestrian hybrid beacon (PHB). In addition, FHWA has offered interim approval to the rectangular rapid-flashing beacon (RRFB).

In evaluating these treatments, a variety of methods have been explored. The Highway Safety Manual (HSM) provides a method for estimating the mean number of crashes at a site. However, various surrogates for crashes also exist in evaluating safety, such as conflicts (near crashes) as well as driver yielding compliance to pedestrians. These methods for evaluating pedestrian safety, as well as the safety performance of various pedestrian crossing treatments, are presented in the sections below.

2.1 Highway Safety Manual and the Predictive Method

The HSM was first published by the American Association of State Highway and Transportation Officials (AASHTO) in 2009. The HSM was created to provide tools to quantitatively measure safety performance with regards to frequency, severity, and type of crashes. The HSM uses two tools, safety performance functions (SPFs), which predict crashes at an intersection or segment under base conditions, and crash modification factors (CMFs), which describe the reduction in crashes when a countermeasure is installed. Although the use of regression modeling to predict crashes and assess safety existed prior to the HSM's publication, the HSM provided a standard, national reference for highway safety.

Part C of the HSM contains the predictive method, which estimates annual average crash frequency as a function of geometric design, the presence and type of traffic control devices, and traffic volume. There are three components to the predictive method: SPFs, CMFs, and calibration factors. SPFs provide an estimate of crashes for a roadway segment or intersection under base conditions as a function of average annual daily traffic (AADT) and segment length, while CMFs are used to take into account the impact of geometric design, traffic control, and any other factor present at an intersection or segment that has an impact on the total number of crashes. Calibration factors account for regional variation. The predictive method allows practitioners to estimate the total number of crashes annually at an intersection or road segment under current conditions, hypothetical or forecasted future conditions, and the total number of annual crashes using an alternative plan.

Crashes are countable events which are never negative, which therefore lends itself to using a Poisson distribution to estimate crashes. However, crash data are typically overdispersed, and therefore, a negative binomial distribution is used when developing SPFs. While SPFs in their most basic form take into account only segment length and AADT, CMFs adjust the total number of crashes based on the specific conditions at an intersection. There are CMFs for geometric design features, such as lane and shoulder width, as well as traffic control features such as a protected left turn lane. The CMF is multiplied by the SPF to determine the number of crashes: a CMF >1 indicates that crashes will be higher than base conditions, while a CMF <1 indicates the opposite.

The predictive method in the HSM covers rural two-lane two-way roads (Chapter 10), rural multilane highways (Chapter 11), and urban and suburban arterials (Chapter 12). The HSM only considers pedestrian crashes for urban and suburban arterials. Chapter 12 has separate methodologies for predicting vehicle-pedestrian crashes at segments, intersections with signals, and stop-controlled intersections (3-leg, where minor leg is stop controlled, and 4-leg, where two minor legs are stop controlled). The HSM does not provide SPFs for other intersection

For predicting crashes for pedestrians at segments, the HSM method takes the base SPF for road segments and multiplies it by an adjustment factor which takes into account the posted speed limit in relation to 30 mph and the type of road (2-lane undivided, 3-lane with two-way left-turn lane, 4-lane undivided, 4-lane divided, and 5-lane with two-way left-turn lane). For pedestrians at stop controlled intersections, the base SPF for intersections is multiplied by an adjustment factor which takes into account intersection type.

For predicting vehicle-pedestrian crashes at signalized intersections, the HSM provides a more sophisticated method than adjustment factors, and in fact has developed an SPF and CMFs unique to pedestrians. The formula for total crashes is as follows:

$$N_{pedi} = N_{pedbase} * CMF_{1p} * CMF_{2p} * CMF_{3p}, \tag{1}$$

Where,

- N_{pedi} = predicted average crash frequency of vehicle-pedestrian collisions
- $N_{pedbase}$ = predicted number of vehicle-pedestrian collisions per year for base conditions at signalized intersections
- CMF_{1p}, CMF_{2p}, CMF_{3p}, etc. = crash modification factors for vehicle-pedestrian collisions at signalized intersections

The base SPF is as follows:

$$N_{pedbase} = \exp(a + b * \ln(AADT_{tot}) + c * \ln(\frac{AADT_{min}}{AADT_{maj}}) + d * \ln(PedVol) + e * n_{lanesx}) \tag{2}$$

Where,

- a = intercept term
- b=coefficient for $AADT_{tot}$
- $AADT_{tot}$=AADT for major and minor legs
- c= coefficient for $\frac{AADT_{min}}{AADT_{maj}}$
- $AADT_{min}$=AADT for minor leg of intersection
- $AADT_{maj}$=AADT for major leg of intersection
- d=coefficient for *PedVol*
- *PedVol*=pedestrian volume at intersection
- e=coefficient for n_{lanesx}
- n_{lanesx}=number of lanes at intersection x

The HSM provides estimates for *PedVol* based on general levels of activity. The CMFs provided take into account the number of bus stops within 1000 ft of the intersection, the presence of schools within 1000 ft of the intersection, and the number of alcohol sales establishments within 1000 ft of the intersection [2].

The HSM provides additional CMFs in Part D. Those pertaining to vehicle-pedestrian crashes include:

- Permit right-turn-on-red [2]
- Convert minor-road stop control to all-way stop control [4]
- Remove unwarranted signal [5]
- Provide intersection illumination [6]

The HSM provides no predictive method for pedestrian crashes at midblock crossing locations or anywhere in rural locations, and no provides no CMFs beyond those already mentioned. In addition, the HSM does not provide a distinction between injury and fatal crashes, and assumes no vehicle-pedestrian crashes are property damage only [2].

There are additional CMFs describing vehicle-pedestrian crashes which have not been included in the HSM, but which can be found in the CMF Clearinghouse [cmfclearinghouse.org]. For vehicle-pedestrian crashes, these include:

- Install raised pedestrian crosswalks [6]
- Provide a raised median [7]
- Implement automated speed enforcement cameras [8]
- Install bicycle lanes [9]
- Install a traffic signal [10]
- Provide split phases [10]
- Increase cycle length for pedestrian crossing [10]
- Install high-visibility crosswalk [10]
- Convert from yield signal control to signalized control [11]
- Install lighting [12]
- Install flashing yellow arrow [13]
- Install pedestrian countdown timer [13]
- Implement a leading pedestrian interval [14]
- Installation of a High intensity Activated crosswalk (HAWK) pedestrian-activated beacon at an intersection [15]
- Raised median with marked or unmarked crosswalk at an uncontrolled intersection [16]

2.2 Using Conflict as a Surrogate Measure for Crashes

Vehicle conflict has been used as a surrogate for crashes as crashes are rare and unexpected events. In presenting the concept of surrogacy, a TRB white paper compares the use of surrogate measures within the field of traffic safety engineering with the use of the same in the medical field. They conclude that acceptable surrogates must be “fully correlated with the clinically meaningful outcome” of reducing or eliminating crashes, and they must “fully capture the effect of the treatment,” meaning the surrogate measure must be physically related to crashes [17]. Surrogates should go beyond mere near crashes, and instead be measures which take into account the mechanisms of crashes. In doing so, a hierarchical Bayesian approach can be adopted to take into account some surrogate measures being more strongly correlated with crashes than others [18]. In doing so, these surrogate measures will capture some, but not all of the factors that lead to crashes [17]. Additionally, just as crashes are rare events, severe conflicts are also rare, which may lead to an under-prediction of crashes when relying on conflict as a surrogate measure [19].

Researchers rarely observe crashes directly during their study period. One problem with validating the relationship between near crashes or conflict and crashes is the study’s duration: typically, the time period in which behavior and vehicle interaction is being studied is a much shorter time period than that in which crash reports are analyzed [19]. However, some studies have been able to collect sufficient data to correlate crashes with conflicts and near crashes. A 2006 study performed by researchers at the Virginia Tech Transportation Institute outfitted 100 vehicles with monitoring equipment which continuously recorded driving data for a period of 1 year, logging approximately 2 million vehicle miles, 43,000 hours of data, and utilizing 241 drivers in order to determine causal relationships between a host of safety related factors. The data collected included crashes and near-crashes, which were defined as rapid evasive maneuvers by the study vehicle. [20]. An evaluation of this data in 2010 looked at the use of conflict as a surrogate measure for motor vehicle crashes, and using Poisson regression found that there was a significant (p-value < 0.001) positive relationship between crashes and near crashes. In particular, the authors endorsed using near-crashes as a surrogate measure for crashes in small-scale studies with a low number of crashes [21], although the focus of these studies was not specific to vehicle-pedestrian crashes.

2.3 Using Staged Crossing to Evaluate Pedestrian Crossing Treatments

In evaluating the safety performance of pedestrian crosswalk treatments, driver yielding compliance to pedestrians been a primary performance measure [22]. Yielding performance can be measured by utilizing trained staged pedestrians who make street-crossing attempts using standardized procedures while recording driver yielding behavior associated with each attempt.

A study published in 2006 by researchers from the Texas A&M Transportation Institute (TTI) used trained staged pedestrians to evaluate yielding compliance of motorists to pedestrians at unsignalized intersections. The authors chose to measure yielding instead of crashes as the measure of effectiveness (MOE) as their review of the existing literature found that the most common MOE for pedestrian crossing treatments was yielding. Staged pedestrians were used to provide a consistent crossing procedure without regional variability, as well as to provide a sufficient sample size. The trained pedestrians approached the pedestrian crossing and indicated their intent to cross by facing the oncoming traffic without stepping into the crosswalk. The pedestrian would only enter into the crosswalk once motorists had yielded [22].

A 2013 study at Western Michigan University used a similar procedure to measure yielding compliance. In order to determine whether the motorists ought to be scored as “yielding” or “not yielding,” study authors applied the concept of the dilemma zone, which is commonly applied when determining the timing of the amber interval at a traffic signal. In order to provide enough time for a driver to react and comfortably decelerate to a stop, the common formula for amber interval timing [23], shown below, was utilized in the formula.

$$Y = t + \frac{1.47v}{2(a+Gg)} \tag{3}$$

The distance required was taken by multiplying the amber indication time by the posted speed limit. As such, vehicles were only scored as not yielding if the staged pedestrian approached the crosswalk prior to the motorist entering the dilemma zone and did not yield. Another deviation from the TTI procedure is that the staged pedestrians indicated their intent to cross by placing one foot in the crosswalk and the other on the curb [24], which more closely follows the typical crosswalk right-of-way laws followed by municipalities in Michigan and elsewhere [25]. The study also compared the yielding results for staged and unstaged pedestrian crossings, and found no significant difference in results, supporting the use of staged pedestrians to measure driver yielding compliance to pedestrians [24].

Later research by the previously mentioned TTI team incorporated these improvements in their staged pedestrian crossing procedures by using the AASHTO stopping sight distance formula to determine dilemma zone, and having staged pedestrians place one foot into the crosswalk to indicate intent to cross. The reason for placing one foot in the crossing to indicate intent is that in Texas, where the study took place, motorists are only compelled by law to yield to pedestrians already in the crosswalk. Additionally, all staged pedestrians wore similar clothing [26].

2.4 Predicting Pedestrian Crashes Using Behavioral Information

A recent study published in 2014 sought to use behavioral information to predict pedestrian crashes at signalized and midblock crossing locations. The research combined observed pedestrian conflicts with crossing distance and building setback. The authors studied 100 pedestrian crossing locations in Connecticut. Sites 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 observed using a variation of the Swedish Traffic Conflict Technique. Pedestrian crossings were categorized as undisturbed passages, potential conflicts, minor conflicts, or serious conflicts.

Vehicular volume was calculated using Department of Transportation (DOT) volume counts, which were adjusted for the time and day of the week that the observations occurred (traffic volume counts were not taken at the time of observation). Pedestrian counts taken during observations were converted to Annual Average Daily Pedestrian Volume (AADPV) using the following formula:

$$AADPV = AADT * P/V_o \tag{4}$$

Where,

P = Pedestrian volume during observation period, and

V_o = Calculated vehicular volume during observation period.

The researchers used negative binomial and ordered proportional odds to estimate crashes. The research found that minor conflicts have a p-value of 0.1628 for predicting KAB crashes, and serious conflicts have a p-value of 0.1318 for predicting KABCO crashes (significance level is 0.10). Greater crossing distance and small building setbacks were associated with larger numbers of pedestrian-vehicle crashes, while pedestrian volume was not significant [27].

2.5 Safety Performance of Midblock Pedestrian Crosswalk Treatments

Various forms of pedestrian crossing treatments have been devised, including crosswalk markings, as well as enhancement devices such as the in-street sign, RRFB, and PHB. The following subsections explore the known safety performance of these treatments in detail, which is summarized in Table 2.

2.5.1 Marked and Unmarked Crosswalks

Using pavement markings to indicate pedestrian crossing areas is the most basic pedestrian safety treatment. One of the first studies evaluating the safety of marked crosswalks, published in 1972, found that installing pavement markings at crosswalks resulted in an increase in pedestrian crashes at these locations, although the analysis did not consider pedestrian exposure but rather evaluated total crash numbers alone [28]. Since that was published, other studies have come to similar conclusions, including studies in Sweden [29] and Ontario [30], as well as a Swedish study which considered pedestrian exposure and found crash rates increase [31]. These studies evaluated before and after numbers without further statistical analysis to determine whether the change in crashes was significant, nor did they control for regression-toward-the-mean bias or take into account trends in crashes. The Ontario study, for instance, found that crashes were increasing year-over-year in the before period as well as the after period [30].

More recently, studies have analyzed the effects of marking crosswalks in a more comprehensive manner. An evaluation of 2,000 marked and unmarked crosswalks in 30 cities, representing all regions of the United States, found that among locations with marked crosswalks, two-lane roads and locations with raised medians are less crash-prone than marked crosswalks on multilane and undivided roads. However, the authors found that on two-lane roads and multilane roads at traffic volumes with average daily traffic (ADT) of less than 12,000 vehicles per day there was no significant difference in crashes between marked and unmarked crosswalks, even with pedestrian volume included as a factor. When traffic volumes were greater than 12,000 ADT marked crosswalks were associated with an increase in crashes relative to unmarked crosswalks [16].

While most studies evaluate the change in crashes when pavement markings are installed, a study in Israel looked pedestrian behavior when crosswalk markings were removed. They found that pedestrians are more likely to stop and look for traffic at sites where markings were removed, which led to fewer conflicts, but also led to longer waiting times at crossing locations and fewer vehicles yielding to pedestrians [32], indicating that pedestrians will likely choose a marked crosswalk over unmarked when given the choice. When included as a factor in studies of marked crosswalks, pedestrians express a clear preference for marked crosswalks [16]. Due to this preference, it may be safer at a network level to choose safe locations for marked crosswalks rather than eliminate them altogether in order to encourage users to use safe crossing locations.

2.5.2 In-Street Pedestrian Crossing Signs

Several studies have shown that treatments can be added to a marked crosswalk to improve pedestrian safety, such the addition of an in-street sign along a roadway centerline advising drivers to yield to pedestrians. This treatment is included in the MUTCD as the R1-6 sign [3]. A 2007 study evaluating four crosswalks in San Francisco found that driver yielding rates at crosswalks treated with the in-street pedestrian crossing signs (R1-6) ranged from 60 percent to 74 percent, while sites without any treatment had yielding rates ranging from 20 percent to 60 percent [33]. Another study conducted in Pennsylvania found this type of treatment to be effective in increasing driver yielding behavior with driver yielding increasing from 17 percent to 24 percent at midblock crossings [34]. A compendium of research on midblock crosswalk treatments found that in-street pedestrian crossing signs may be most effective on two lane roads, although this type of treatment has still been found to increase driver yielding in additional lane configuration situations [35].

Adding two additional R1-6 signs to both edgelines in addition to the centerline in the Gateway configuration (Figure 1) has been shown to increase yielding rates more than a single R1-6 sign. In one Michigan study, driver yielding compliance rates went from 25 percent with markings alone to 57 percent with a single R1-6, but increased to 82 percent when signs were installed in the Gateway configuration. Other sites in Michigan showed similarly dramatic increases in driver yielding compliance in spite of this treatment costing as low as $450 per sign [13]. Guidance from the Michigan Department of Transportation recommends the Gateway treatment when traffic volumes are less than 12,000 ADT in most cases, or 25,000 ADT on three-lane roads with pedestrian refuge islands based on prior research of the effectiveness of the Gateway treatment [36].

The R1-6 treatment also has a channelizing effect for pedestrians, with pedestrians choosing treated crosswalks over those which are unmarked or with markings alone [34] [37] [38].

2.5.3 Rectangular Rapid Flashing Beacon

The RRFB has been shown to increase driver yielding rates. A before and after analysis by Brewer found that yielding rates at sites with the RRFB treatment increased by a range of 35 percent to 79 percent. Pedestrian compliance with RRFB treatment was also strong, with 94 percent of non-staged pedestrians activating the treatment [39]. Similarly, at a high-volume shared-use trail crossing location in Florida, yielding by drivers increased from 2 percent to 35 percent after the treatment was installed. Looking exclusively at when the beacon was activated, driver yielding increased to 54 percent. However, unlike the study previously mentioned, user activation of the beacon was much lower, with 32 percent of users activating the beacon, and only 51 percent of users crossing when the beacon was activated [40]. However, it is important to note that this location is a shared-use path with large bicycle volumes [40], unlike the previous study which observed a pedestrian only facility [39]. In subsequent studies, a sign was added near the push button saying, “push button to activate beacons” to improve pedestrian compliance, but the low beacon activation rate persisted [40].

A 2010 paper published by FHWA observed a more geographically diverse set of sites, with locations in St. Petersburg, Florida, Washington, D.C., and Mundelein, Illinois, to note how the RRFB impacted driver yielding behavior. The research found that in St. Petersburg, using 4 RRFBs (89 percent average driver yielding rate) was more effective for driver yielding than the typical 2 RRFB (82 percent average driver yielding rate) setup, and both setups were more effective for driver yielding than no treatment at all (18 percent average driver yielding rate). Additionally, yielding drivers left more distance between their front bumper and the crosswalk when compared with the baseline treatment. However, the research did not find this type of treatment had a significant impact on evasive behavior by either pedestrians or motorists. Similarly, the research found that the RRFB treatment was also associated with increased driver yielding in Washington, D.C. (yielding was 1.7 percent with no treatment, and 85 percent with the RRFB treatment), and that yielding drivers left more room between their front bumper and the crosswalk when compared with the baseline treatment, as previous. The research also considered modifying the RRFB to flash its LED in the drivers’ eyes. FHWA found that yielding increased from 0 percent with no treatment to 80 percent with the typical RRFB treatment and to 89 percent with the beacon’s LED flashing in the drivers’ eyes. Lastly, the research also looked at combining the RRFB with advanced warning devices, which resulted in no change in driver yielding compared to a RRFB treatment with no advanced warning signs [41]. The RRFB has been shown to be more effective when mounted overhead than when mounted on either side of the road [42].

A study in Bend, Oregon found that in addition to increasing driver yielding from an average rate of 17.8 percent before treatment to 79.9 percent after treatment, the RRFB also significantly reduced pedestrian motorist conflicts from 4.4 per 100 crossings to 1.4 per 100 crossings. Motorist speeds were also reduced [43].

More recently, a CMF was developed for the RRFB, which found a 47 percent reduction in crashes [44]. However, the result was not statistically significant, and therefore questions remain as to the effect that this treatment has on crashes.

2.5.4 Pedestrian Hybrid Beacon

The PHB, also known as the High-intensity Activated crossWalK beacon (HAWK), is a crosswalk treatment that is effective in improving pedestrian safety. Shurbutt found a 69 percent reduction in pedestrian crashes, a 15 percent reduction in severe crashes, and a 29 percent reduction in total crashes when the PHB treatment was applied [41]. Similarly, another study found that the PHB was associated with a 28 percent reduction in total crashes and a 58 percent reduction in pedestrian crashes [42].

Additionally, research by Fitzpatrick (2016) found that pedestrian and motorist compliance with the PHB was strong: a study of 20 locations in Austin, Texas and Tucson, Arizona found that only 6 percent of pedestrians crossed during the beacon's dark indication and that driver yielding when the PHB was activated was 96 percent. The same study found that about half of vehicle-pedestrian conflicts, defined as events when a vehicle or pedestrian takes evasive action to avoid a collision, occurred when the beacon was dark. Furthermore, in one study, PHB installation was correlated significantly with an increase in pedestrian volume at the treatment location. Out-of-crosswalk pedestrian volume also increased, with anecdotal evidence showing that out-of-crosswalk pedestrians were typically following the PHB indications [45].

A summary of the safety performance of these treatments is presented in Table 2 below.

TABLE 2. Safety Performance of Crossing Treatments from Literature

Treatment	Typical Measure of Effectiveness	Safety Performance
Crosswalk markings	Crashes	• Crosswalk markings associated with an increase in both crashes [28] [30] and crash rate [29] compared to unmarked crosswalks • Crosswalk marking associated with no significant change in crashes at ADT<12,000 compared to unmarked crosswalks [16]
In-street signage	Driver yielding compliance	• Single in-street R1-6 sign associated with increases in driver yielding compliance to pedestrians [3] [33] [34] [35] • Multiple R1-6 signs in the “gateway” configuration have generated yielding compliance comparable to PHB [13]
RRFB	Driver yielding compliance	• Associated with yielding compliance improvements, including at high volume sites [40]
PHB	Crashes	• Associated with reductions in pedestrian crashes [41] [42]

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.

3.1 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. Sites were selected to provide a broad range of site and cross-sectional characteristics (i.e., lane width, presence of auxiliary lanes, type of crosswalk marking) with moderate to high pedestrian volume.

The sites were selected from three Michigan cities and all sites were on or near major university campuses, which provided for a degree of consistency in terms of land use characteristics in addition to having similar driver and pedestrian demographics among all sites. 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.

Tables 4 and 5 display the basic site characteristics for the 40 midblock crossing locations and 26 signalized intersections included in the study, respectively. Aerial photos of site locations are provided in the Appendix. 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. Furthermore, few sites with speed limits greater than 25 mph met site selection criteria (i.e., on or near a university campus, high pedestrian activity) and sites that did meet this criteria had distinguishing features which made direct comparison with other sites difficult. Thus, the results of this study are limited to low speed locations.

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

TABLE 4. Characteristics of Midblock Crosswalk Study Sites

Site No	City	Primary Street	Cross Street or Landmark	Total Street Crossing Dist. (ft.)	Crosswalk Type	Median Presence	GPS Coordinates (latitude, longitude)
1	Detroit	Anthony Wayne Dr.	Atchison Hall	61	Continental	Yes	42.355525, -83.071787
2	Detroit	Anthony Wayne Dr.	W. Palmer Ave.	102	Continental	Yes	42.359443, -83.073668
3	Detroit	Anthony Wayne Dr.	PS 5	94	Continental	Yes	42.358867, -83.073625
4	Detroit	Anthony Wayne Dr.	W. Hancock St.	65	Unmarked	Yes	42.353380, -83.070549
5	Detroit	Anthony Wayne Dr.	W. Ferry Ave.	94	Continental	Yes	42.359004, -83.073511
6	Detroit	W. Palmer Ave.	PS 1	58	Continental	Yes	42.361002, -83.071057
7	Detroit	Cass Ave.	W. Kirby St.	50	Unmarked	No	42.358933, -83.068318
8	Detroit	Cass Ave.	Kohn Building	48	Continental	No	42.360288 -83.069138
9	Detroit	Cass Ave.	Prentis St.	50	Unmarked	No	42.352980, -83.064925
10	Detroit	Cass Ave.	W. Ferry Ave.	46	Unmarked	No	42.360655, -83.069312
11	Detroit	Lodge Service Dr.	Matthaei Center	40	Continental	No	42.355802, -83.075208
12	Detroit	W. Palmer Ave.	Shapero Hall	69	Continental	Yes	42.360128, -83.072945
13	Detroit	John R St.	Garfield St.	52	Continental	No	42.354613, -83.060026
14	Detroit	Cass Ave.	W. Willis St.	46	Unmarked	No	42.350500, -83.063508
15	E. Lansing	Bogue St.	Snyder Hall	51	Continental	Yes	42.730708, -84.471992
16	E. Lansing	Chestnut Rd.	Wilson Hall	30	Continental	No	42.723477, -84.487475
17	E. Lansing	E. Circle Dr.	Olin Health Center	30	Continental	No	42.732702, -84.479157
18	E. Lansing	E. Grand River Ave.	Charles St.	53	Standard	Yes	42.734166, -84.479936
19	E. Lansing	Red Cedar Rd.	Eng. Building	54	Continental	No	42.724922 -84.482371
20	E. Lansing	Red Cedar Rd.	Spartan Stadium	26	Continental	No	42.730383, -84.485680
21	E. Lansing	S. Shaw Ln.	Anthony Hall	24	Continental	Yes	42.72522 -84.478992
22	E. Lansing	N. Shaw Ln.	Erickson Hall	24	Continental	Yes	42.725996, -84.478987
23	E. Lansing	N. Shaw Ln.	Intl Center	24	Continental	Yes	42.726024, -84.48091
24	E. Lansing	N. Shaw Ln.	Planetarium	22	Continental	Yes	42.726009, -84.476540

TABLE 4. (cont'd)

Site No	City	Primary Street	Cross Street or Landmark	Total Street Crossing Dist. (ft.)	Crosswalk Type	Median Presence	GPS Coordinates (latitude, longitude)
25*	E. Lansing	N. Shaw Ln.	Shaw Hall	24	Continental	Yes	42.726029, -84.475715
26	E. Lansing	N. Shaw Ln.	Holmes Hall	47	Continental	Yes	42.725352, -84.463949
27*	E. Lansing	N. Shaw Ln.	Holmes Hall	47	Continental	No	42.725444, -84.464775
28*	E. Lansing	N. Shaw Ln.	Holmes Hall	29	Continental	No	42.725350, -84.464765
29	E. Lansing	W. Circle Dr.	Gd River Ramp	25	Continental	No	42.732966, -84.481141
30	E. Lansing	Wilson Rd.	Wharton Center	50	Continental	Yes	42.723256, -84.469874
31	E. Lansing	Wilson Rd.	E. Wilson Hall	28	Continental	No	42.721974, -84.488592
32	E. Lansing	Wilson Rd.	W. Wilson Hall	28	Continental	No	42.72195, -84.489091
33*	Kalamazoo	W. Michigan Ave.	Student Rec	40	Standard	No	42.284981 -85.609556
34*	Kalamazoo	Dormitory Rd.	Univ Prog Bldg	22	Standard	No	42.285626 -85.610532
35*	Kalamazoo	W. Walnut St.	Health Plaza	73	Standard	No	42.286131, -85.580328
36	Kalamazoo	Knollwood Ave.	Western View	26	Continental	No	42.279918, -85.620105
37*	Kalamazoo	Rankin Ave.	Welborn Hall	40	Standard	No	42.28278, -85.61954
38	Kalamazoo	Gilkison Ave.	Western Heights	32	Standard	No	42.286838 -85.614961
39	Kalamazoo	Goldsworth Dr.	Valley Pond	38	Standard	No	42.288534 -85.615437
40*	Kalamazoo	Dormitory Rd.	PS 1	41	Continental	No	42.286639 -85.610737
Note: an asterisk indicates that staged crossing data were not collected at this location							

TABLE 5. Characteristics of Signalized Intersection Study Sites

Site No	City	Primary Street	Cross Street	Average Street Crossing Dist (ft)	Crosswalk Type	Right-Turn-on-Red Permitted	GPS Coordinates (latitude, longitude)
41	Detroit	2nd	Warren	71	Continental	Yes	42.35523, -83.06869
42	Detroit	Lodge Service Dr	Warren	59	Continental	No	42.353966, -83.073030
43	Detroit	Randolph	Jefferson	98.5	Continental	Yes	42.329755, -83.041970
44	Detroit	Cass	Palmer	61.5	Continental	No	42.361390, -83.069739
45	Detroit	Cass	Putnam	44	Continental	Yes	42.356984, -83.067176
46	Detroit	Cass	Library	49	Continental	No	42.358282, -83.067948
47	Detroit	2nd	Forest	53.5	Continental	No	42.353082, -83.067608
48	Detroit	Trumbull	Warren	54.5	Standard	No	42.352160, -83.078716
49	Detroit	Anthony Wayne Dr	Forest	57	Continental	No	42.352304, -83.069939
50	Detroit	Cass	Forest	45	Continental	No	42.353745, -83.065361
51	Detroit	Cass	Antoinette	43	Standard	No	42.363285, -83.070801
52	Detroit	Cass	Milwaukee	43.5	Standard	No	42.368564, -83.074049
53	Detroit	Shelby	Lafayette	38.5	Continental	No	42.33101, -83.04943
54	Detroit	Shelby	Fort	49.5	Continental	Yes	42.330134, -83.048774
55	Detroit	Cass	Fort	60	Continental	No	42.329286, -83.050711
56	Detroit	Washington	Congress	46	Continental	No	42.328742, -83.049213
57	Detroit	Washington	Larned	47	Continental	Yes	42.327990, -83.048613
58	Detroit	John R	Warren	69	Standard	No	42.357710, -83.062145
59	Detroit	Cass	Michigan	79	Continental	No	42.331683, -83.052623
60	Detroit	3rd	Michigan	86.5	Continental	No	42.331653, -83.057522
61	Detroit	Woodward	Jefferson	91	Continental	No	42.328695, -83.044569
62	E. Lansing	Farm Lane	River Trail	40	Continental	No	42.727240, -84.477869
63	E. Lansing	Red Cedar	South Shaw	40	Continental	Yes	42.725437, -84.482282
64	Kalamazoo	Dormitory	Michigan	49	Brick	No	42.284827, -85.610292
65	Kalamazoo	Howard	Michigan	83.5	Standard	No	42.281626, -85.621621
66	Kalamazoo	Howard	Valley	57	Standard	No	42.286532, -85.623164

3.2 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, which was chosen to provide for high pedestrian volume. 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 2 displays an example of the video camera setup and field-of-view.

Figure 2. Typical Video Camera Setup for Recording Motorist Yielding Behavior

3.2.1 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 [13] [35]:

- 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, provided earlier in equation 1. For 25 mph, this distance was calculated to be 104 ft, which was rounded to 110 ft in order to provide additional buffer space for the driver to make the yielding decision, reflecting the minimum value of 3.0 s for yellow light timing [23]. This distance was measured from the near edge of either the crosswalk, stop line, or pedestrian landing and was marked with a roadside object (Figure 3). 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.

An event was classified as a yielding event when a motorist that was initially positioned upstream of the 110 ft boundary point at the start of the staged crossing attempt slowed or stopped to allow the pedestrian to safely 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, in either the same or the opposite direction, this assessment was made once the pedestrian had crossed to within a half-lane distance of their position. Vehicles in lanes other than the near lane were evaluated irrespective of whether a vehicle in the near lane was present or yielded. 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 [25], including all three cities studied. Staged crossing events, used to evaluate driver yielding compliance at uncontrolled midblock crosswalks, were recorded on a per-event basis. An example of a staged pedestrian indicating intent to cross is shown in Figure 4.

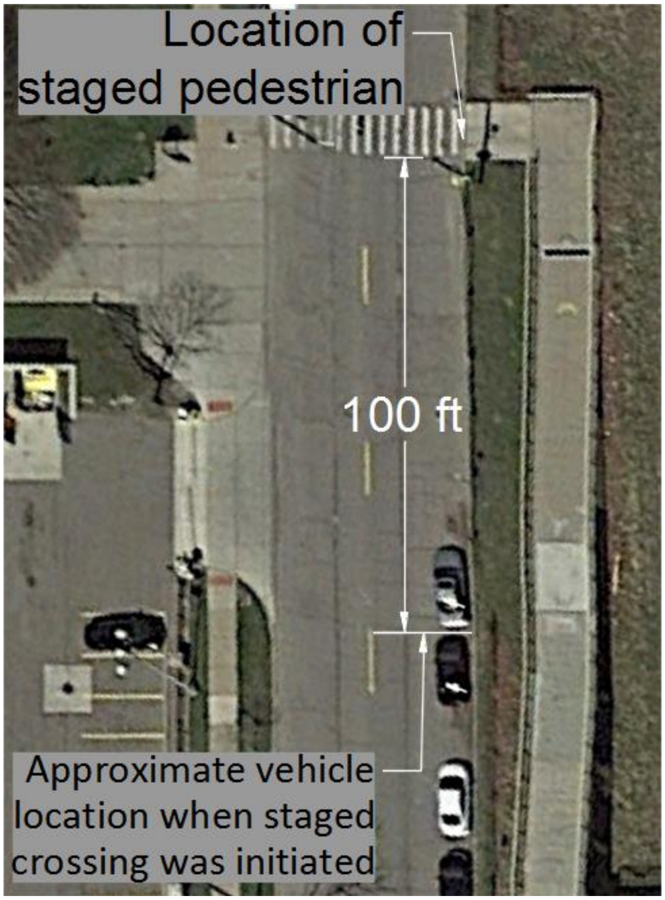


Figure 3. Location of Dilemma Zone Relative to Crosswalk

Figure 4. Screenshot of Staged Crossing Attempt

3.2.2 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 would must yield to pedestrians in this scenario [25]. Thus, driver yielding compliance was scored accordingly for each permissive turning event where pedestrians were present either at or within the crosswalk.

3.2.3 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.

3.2.4 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 for each crosswalk were averaged and converted to an hourly volume.

3.3 Pedestrian Crash Data Collection

In addition to evaluating driver yielding compliance, traffic crash data 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 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 location associated with 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 5 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 5, 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.

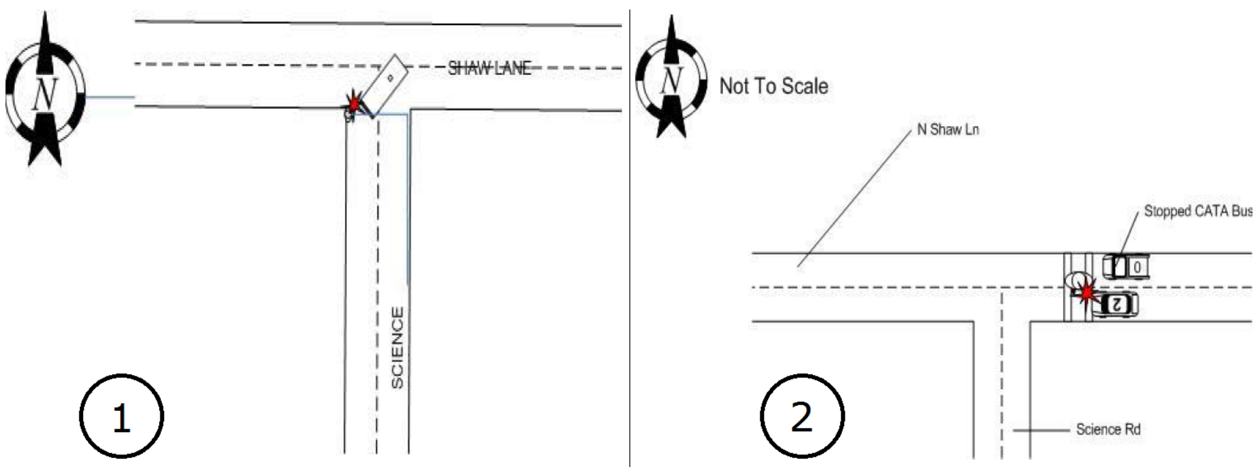


Figure 5. Distinction between Pedestrian Crashes at a Minor Street Intersection: (1) Stop Controlled Leg Crash vs. (2) Uncontrolled Midblock Crosswalk Crash

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 ft 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 29 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. Due to the lack of crashes over a 10 year period, crash analysis performed at the site level (i.e. at a particular midblock crossing location or crossings at signal or stop controlled intersections) was not included in the final analysis.

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.

CHAPTER 4: CRASH ANALYSIS

Pedestrian crash data for 25 homogeneous uncontrolled segments were utilized for the crash data analysis, as initial screening of the pedestrian crash data at 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. Segment endpoints, as well as the number of crosswalks and driveways within each segment, are shown in Table 6. The crash data included the most recent 10 years of data (2005 – 2014).

TABLE 6. Characteristics of Midblock Study Segments

Site ID	Node-To-Node Distance (ft)	Number of Crosswalks	Number of Driveways	Primary Street	Endpoints	
Cluster 5*	555	1	1	Palmer	Anthony Wayne	2nd
Cluster 6*	550	2	3	Anthony Wayne	Kirby	Palmer
17*	675	1	6	Palmer	2nd	Cass
22*	2870	1	6	Lodge Svc Dr	Trumbull	Warren
27*	775	2	3	John R	Forest	Canfield
102	1760	4	1	Bogue	Gd River	Lansing River Tr
103	1150	3	5	Chestnut	Shaw	Wilson
104	1350	7	4	E Circle	W Circle	Farm Ln
107	765	1	2	Gd River	M.A.C.	Division
109	705	1	5	Red Cedar	S Shaw	Wilson
110	2375	6	8	Red Cedar	N Shaw	Chestnut
114	1090	3	2	S Shaw	Red Cedar	Farm Ln
Cluster 3	1085	3	5	N Shaw	Red Cedar	Farm Ln
Cluster 4	1530	5	8	N Shaw	Farm Ln	Bogue
Cluster 1	1990	7	7	Shaw	Owen Entrance	Hagadorn
125	4305	16	7	W Circle	Beal	Kalamazoo
126	1975	2	6	Wilson	Bogue	Shaw
Cluster 2	795	3	6	Wilson	Birch	Chestnut
213^	690	3	9	Knollwood	Michigan	Auditorium
215^	845	1	1	Gilkison	Parking	Dormitory Rd
217^	2065	2	2	Rankin	Valley	Dormitory Rd
201^	605	1	2	Michigan	Western Ave	Dormitory Rd
Cluster 7^	885	2	2	Dormitory Rd	Michigan	Tennis Courts
208^	1020	2	7	Walnut	Burdick	Jasper
214^	580	2	3	Rankin	Michigan	Business Ct

Note: Detroit segments denoted by a (*), and Kalamazoo sites by a (^)

4.1 Data Summary

After compiling the crash data by segment, a series of basic graphical displays were generated and data screening measures were performed. Figures 6 and 7 depict the 10-year pedestrian crashes normalized per crosswalk (Figure 6) and per mile (Figure 7) 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.

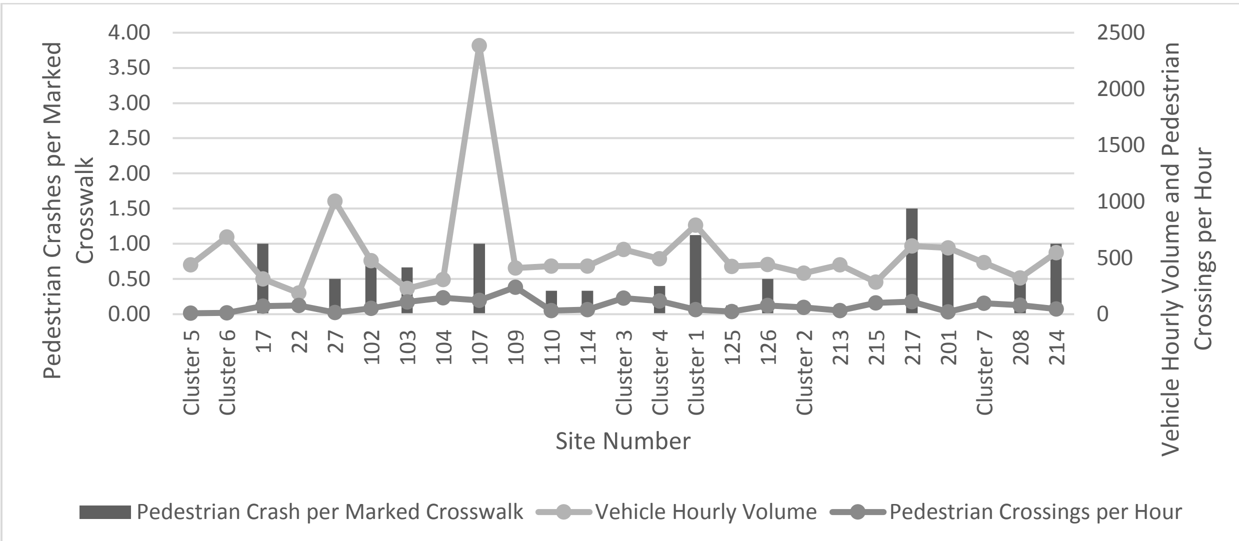


Figure 6. Pedestrian Crashes per Marked Crosswalk with Hourly Vehicular Traffic Volume and Hourly Pedestrian Crossings by Site

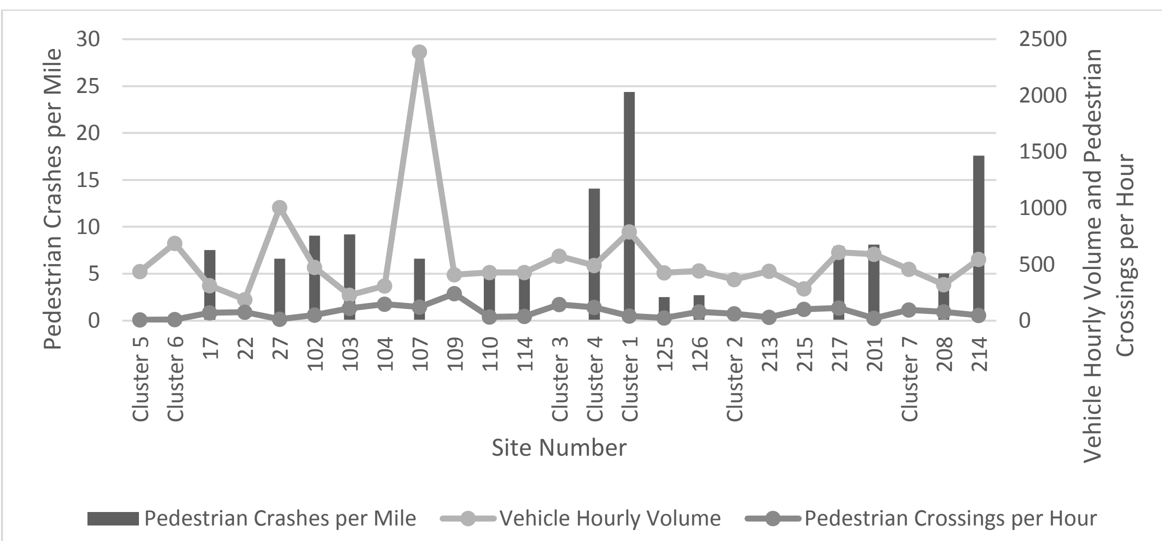


Figure 7. Pedestrian Crashes per Mile with Hourly Vehicular Traffic Volume and Hourly Pedestrian Crossings by Site

A summary of the traffic crash data and relevant site characteristics for the 25 midblock segments analyzed is provided in Table 7.

TABLE 7. 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 more than four-fifths of a mile. 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 27.4 per mile. The number of access points averaged 24.2 per mile across all study segments with a minimum density of 6.25 per mile and a maximum of 68.9 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.

4.2 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:

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

where $P(y_i)$ is probability of segment i experiencing y_i 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 λ_i = EXP(βX_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 λ_i = EXP(βX_i

+ ε_i), where EXP(ε_i) is a gamma-distributed error term with mean 1 and variance α. The addition of this term allows the variance to differ from the mean as $VAR[y_i] = E[y_i] + \alpha E[y_i]^2$. The 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).

One concern with using crash data from three different cities in Michigan is unobserved heterogeneity between cities, as each city and college campus has different characteristics which cannot be accounted for, such as driver and pedestrian demographics, land use characteristics, and policies for maintaining pavement markings and signs. In order to account for these differences, a city-specific random effect was incorporated into the model.

4.3 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. 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 8, 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, crosswalk length, 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:

$$E_{x_{ij}}^{\lambda_i} = \frac{EXP(\beta_j)-1}{EXP(\beta_j)}, \tag{6}$$

TABLE 8. Negative Binomial Results for Vehicle-Pedestrian Crashes on Uncontrolled Midblock Segments

Parameter	Estimate	Std. Error	z value	Pr(>|z|)	Odds Ratio
Intercept	-22.5	5.01	-4.49	<0.001	
Segment Length (ln ft)	1.64	0.426	3.85	<0.001	
Hourly pedestrian volume (ln)	0.774	0.255	3.04	0.00240	
Average crosswalk length (ln ft)	2.06	0.737	2.80	0.00507	
<13 Crosswalks per mile	*baseline*				
13-18 Crosswalks per mile	2.72	0.926	2.94	0.00331	15.2
>18 Crosswalks per mile	1.99	0.662	3.01	0.00263	7.34
Standard crosswalk	*baseline*				
Continental crosswalk	-1.58	0.717	-2.21	0.0273	0.206
No auxiliary lane present	*baseline*				
Auxiliary lane present	-0.787	0.499	-1.58	0.115	0.455
Overdispersion parameter	9.42E-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].

Initial models showed a positive correlation between driveway density and 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]. However, further analysis found a correlation between driveway density and crosswalk density (Figure 8), with one or the other being found significant but not both. Due to the manner in which pedestrian related crashes were collected (recall Chapter 3) whereby crashes were excluded if the pedestrian was hit while crossing a driveway, driveway density was removed from the model while marked crosswalk density remained.

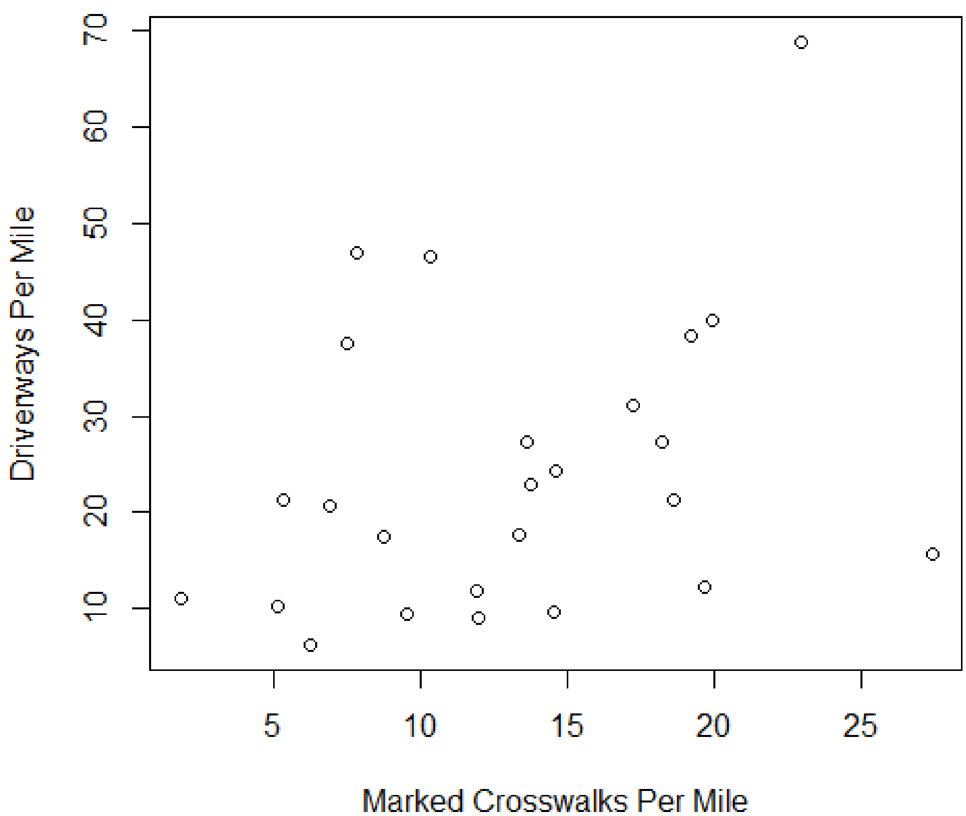


Figure 8. Relationship Between Driveway and Crosswalk Density

Greater crosswalk density along the segment was also associated with increased crash frequency. Segments with crosswalk densities of 13 crosswalks per mile or greater were found to predict significantly more crashes than those with fewer than 13 crosswalks per mile. This is consistent with prior research indicating that marked crosswalks are associated with higher crash rates than unmarked crosswalks [16] [46] due to the generally greater midblock pedestrian crossing activity along the segment. The tendency for pedestrians to select marked crosswalks over unmarked was reflected in pedestrian volumes: among the 40 midblock sites evaluated in this study, unmarked crosswalks had an average crossing volume of 14 pedestrians per hour, while marked crosswalks (with and without enhancement devices) had average crossing volumes of 102 pedestrians per hour. The channelizing effect which marked crosswalks have, in addition to the increased crash rates associated with marked crosswalks indicate that engineers should be conservative in their placement of midblock crosswalks, choosing locations with narrow crossing widths and low motorist speeds. Crosswalk marking pattern also had an effect on crashes, with segments utilizing continental crosswalks showing fewer pedestrian-vehicle crashes along the segment compared to those segments with standard crosswalks. This indicates that choosing a more visible crosswalk marking strategy may mitigate the increase in crashes associated with marked crosswalks. 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, as well as crashes being analyzed at a segment rather than node-level.

Furthermore, crosswalk length was positively correlated with pedestrian crashes. This is supported by previous research which found fewer pedestrian-involved crashes on narrower roads [47]. It should be noted that on median divided segments crosswalk length was the crossing distance for one direction of traffic. While the presence of an auxiliary lane (i.e. parking lane, bike lane, or shoulder) adds to crosswalk length, these lanes were found to reduce pedestrian crash occurrence. While the factor was not significant (p-value=0.115), the reduction in crashes could be due to the traffic calming effects and subsequent lower speeds associated with on-street parking [48].

The crash analysis performed had several limitations. Enhancement devices (i.e., R1-6, RRFB, and PHB) were not analyzed due crashes being analyzed at a segment rather than node-level, as enhancement devices treat a particular crosswalk rather than an entire segment. Likewise, segment analysis of crashes does not allow for analysis of treatments present at signalized intersections. Most importantly, 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, and therefore caution should be taken with interpretation of crash analysis results. Furthermore, no association between driver yielding compliance and pedestrian crash occurrence was found.

CHAPTER 5: DRIVER YIELDING BEHAVIOR AT SIGNALIZED INTERSECTIONS

Pedestrian crossings at signalized intersections are an important safety consideration for roadway agencies, and such crossings will continue to become more important as non-motorized safety programs further encourage travel via walking in the future. Twenty-six signalized intersections were identified across the three Michigan cities in order to further evaluate pedestrian crossing safety. Field observational data for driver yielding compliance as well as historical traffic crash data were collected and analyzed along with historical traffic crash data at each location in order to assess the selected safety performance measures. Due to the small sample size of pedestrian crashes at the intersections studied, only naturalistic driver yielding compliance is included in the final analysis.

5.1 Data Summary

Vehicle-pedestrian naturalistic yielding compliance data were collected at each of the 26 signalized intersections considered as a part of this study. Yielding in the context of this study was only assessed for cases where turning vehicles (right and left) encountered one or more pedestrians in the crosswalk. According to state law, during a permissive signal indication, the driver would must yield to pedestrians within the crosswalk in this scenario [25]. Figure 9 shows an example of a right-turning vehicle not yielding to pedestrians within the crosswalk who have the right-of-way. Thus, driver yielding compliance was scored accordingly for each crossing pedestrian's encounter with a turning vehicle. Videos at signalized intersections were positioned such that signal indication was visible, which allowed for consistent and accurate naturalistic observations of driver and pedestrian yielding behavior at these intersections. As vehicles must slow down to turn, dilemma zone was not a concern. These data were aggregated into 15-minute intervals for subsequent analysis to simplify the data collection process. Data from 104 unique 15-minute intervals were collected. However, only 84 unique 15-minute intervals had any turning vehicle-pedestrian interactions, and therefore 84 intervals were included in the final analysis. A summary of the naturalistic yielding compliance behavior collected at the 26 signalized intersections is presented in Table 9.

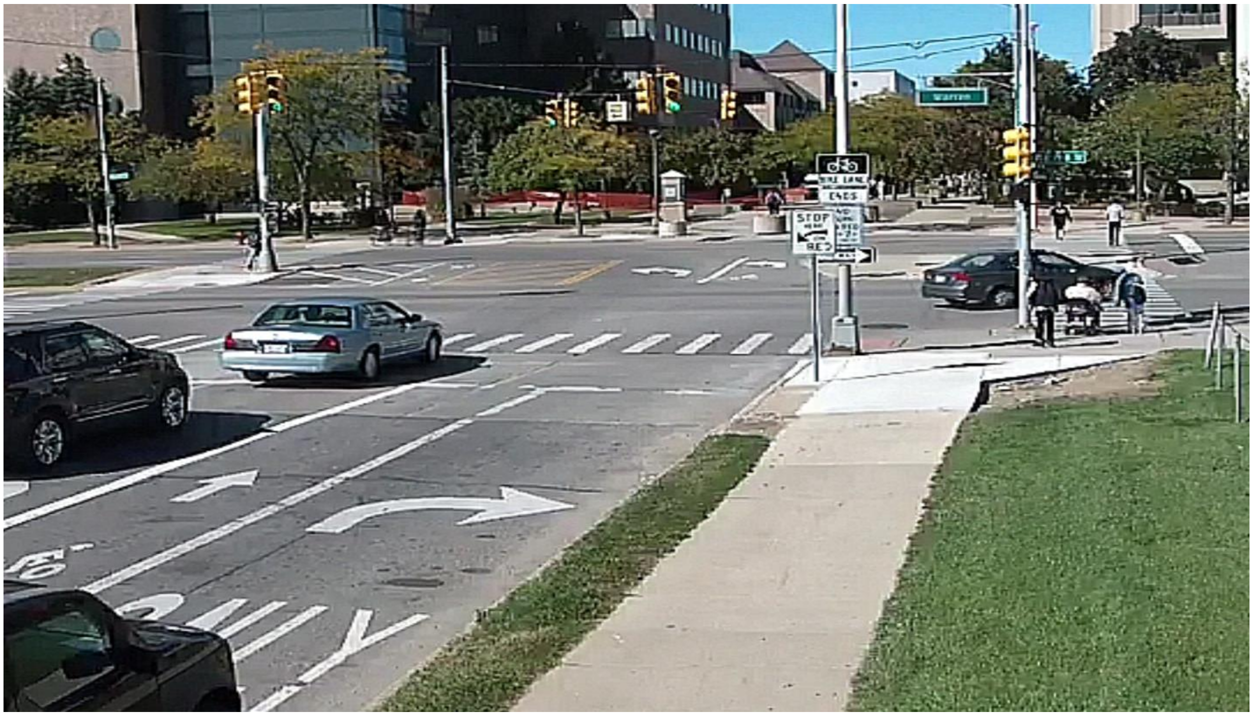


Figure 9. Screenshot of Noncompliant Turning Vehicle at Signalized Intersection

TABLE 9. Summary of Naturalistic Driver Yielding Behavior Data at Signalized Intersections

Continuous Factors					
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
Categorical Facotrs					
Factor	**Level or Unit**	**Proportion of Periods**	**Number of Sites**		
Geometry	signalized crosswalk	0.08	2		
	4-leg intersection	0.73	19		
	3-leg intersection	0.19	5		
Laneage	bike lanes present	0.31	7		
	parking lanes present	0.77	20		
	no additional lanes	0.08	3		
Crosswalk Treatment	standard crosswalk	0.25	6		
	continental crosswalk	0.72	19		
	brick paver	0.04	1		
Directionality	one-way	0.44	11		
	two-way	0.56	15		
Pedestrian signal	no countdown timer	0.24	5		
	countdown timer	0.76	21		
Right-turn-on-red	Permitted	0.72	20		
	Prohibited	0.28	6		
Median	Not present	0.72	19		
	Present	0.28	7		

5.2 Results and Discussion

The yielding compliance rates were disaggregated by intersection characteristics of interest and are presented in Table 10. Additionally, a statistical model was estimated based upon the negative binomial regression techniques outlined in Chapter 4. The final model results are presented in Table 11, which estimates driver yielding compliance at signalized intersections based upon several explanatory variables. It should be noted that Table 11 includes the coefficient estimate, standard error, odds ratio (for cases where binary indicator variables were utilized), and p-value for each variable.

TABLE 10. Naturalistic Driver Yielding Compliance Rates by Site Characteristics

Category	Parameter	Number of Locations	Number of Interactions	Interactions per location	Percent of Turning Vehicles Yielding
Intersection geometry	Three-leg	4	178	44.5	93.26%
	Four-leg	20	418	20.9	86.36%
	Signalized crosswalk	1	21	21.0	80.95%
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	7	247	35.3	92.71%
Median	Not present	18	428	23.8	88.08%
	Present	7	189	27.0	88.36%

TABLE 11. Negative Binomial Results for Naturalistic Driver Yielding Compliance at Signalized Intersections

Category	Parameter	Estimate	Std. Error	z value	Pr(>|z|)	Odds Ratio
	Intercept	-3.818	0.859	-4.443	8.860E-06	
Volume	15-min pedestrian-turning vehicle interactions	0.029	0.003	8.716	< 2e-16	
	15-min vehicle volume (ln)	0.568	0.115	4.950	7.420E-07	
	15-min pedestrian volume (ln)	0.458	0.092	4.972	6.610E-07	
Approach configuration	Signalized crosswalk	*baseline*				
	Three-leg	1.179	0.290	4.064	4.820E-05	3.25
	Four-leg	0.919	0.303	3.030	0.002	2.51
Crosswalk type	Brick paver	*baseline*				
	Standard	-0.586	0.270	-2.173	0.030	0.56
	Continental	-0.636	0.225	-2.821	0.005	0.53

A four-leg intersection is shown in the negative binomial model to result in fewer yielding events compared to a signalized pedestrian crosswalk with an adjacent driveway, while a three-leg intersection is more likely to result in yielding behavior. The relationship of yielding behavior between three- and four-leg intersections 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 [47]. It can also be seen in Table 10 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. The regression modeling shows that increasing volumes of pedestrians and vehicles was associated with increased yielding compliance for turning vehicles. 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 10. The improved yielding performance associated with increasing numbers of pedestrian-turning vehicle interactions could be due to driver familiarity. On intersections with high pedestrian and turning vehicle volume, the driver is more likely to expect pedestrians, and consequently yield to them.

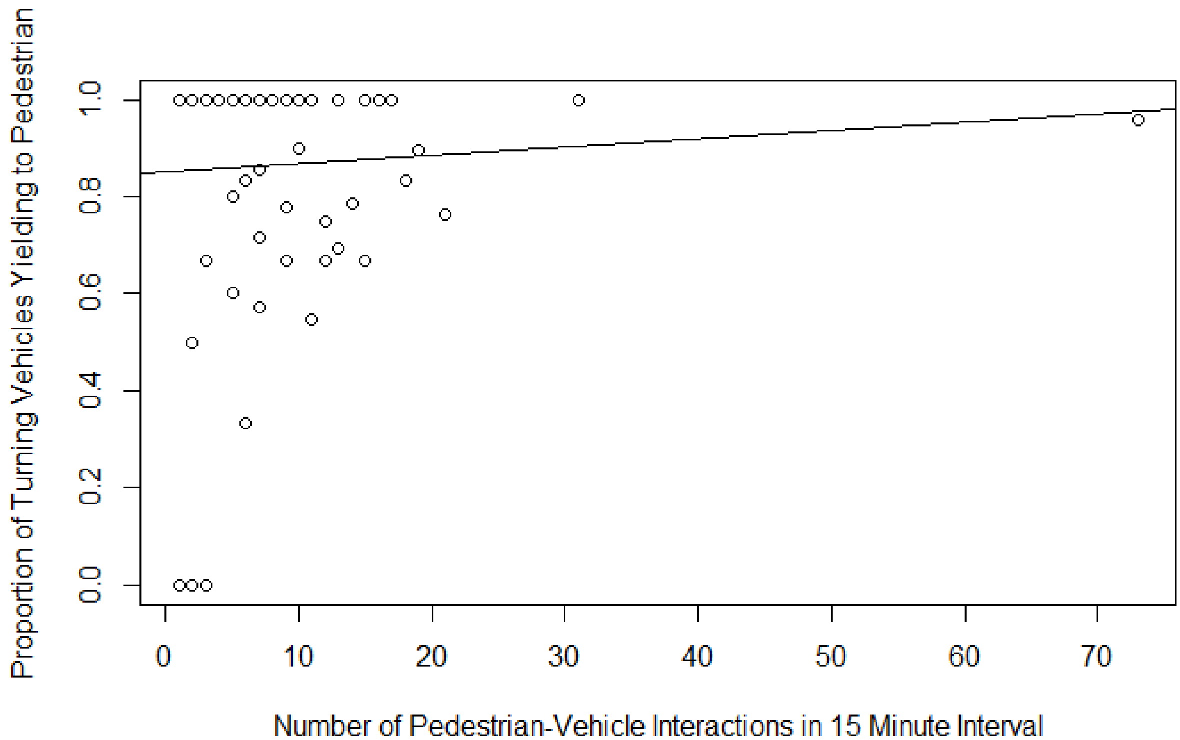


Figure 10. Yielding Rates vs. Pedestrian-Turning Vehicle Interactions per 15 Minute Interval

Looking at crosswalk type, the decorative brick paver crosswalk performed better than the more conventional standard and continental crosswalks. Caution should be taken in interpreting this result due to the small sample size (one site with 41 interactions). In spite of strong demand by local communities for these types of crosswalks due to aesthetics, research is currently limited in evaluating the safety impact of this crosswalk treatment. Guidance from FHWA indicates that textured crossings, such as non-slip brick pavers, can increase driver attention by means of noise, vibration, and contrasting colors [50].

While brick pavers performed the best out of the three crosswalk treatments evaluated, at first glance, the standard crosswalk markings performed better than the continental pattern. However, when looking at the standard error for these two crosswalk marking patterns, there is no significant difference between them in turning vehicle yielding compliance. This is a surprising result, as the continental crosswalk is more visually conspicuous and performed better than the standard crosswalk at mid-block intersections. This could be due to the nature of turning vehicles. Turning is a complex task, particularly turning right on red. As most pavement markings are white, the crosswalk patterns could be in the driver's periphery in contrast with the brick paver crosswalks which have both a contrasting color and texture, and therefore warn the driver in multiple ways. In addition, turning vehicles must slow down, and at lower speeds, they may be more aware of the pedestrian attempting to cross than the pavement markings themselves.

CHAPTER 6: DRIVER YIELDING COMPLIANCE AT MIDBLOCK CROSSINGS

In selecting an alternative measure of effectiveness for crashes at midblock crossings, two options were considered: vehicle-pedestrian near-crashes (conflicts) and driver yielding compliance to staged pedestrians. As previously described in Chapter 3, naturalistic driver and pedestrian behavior was evaluated, including vehicle-pedestrian conflicts, which were defined as evasive maneuvers by drivers (i.e., swerving or extreme braking to avoid collision) or pedestrians (i.e., hurried walking or stepping back to the curb to avoid collision). However, this method of evaluating safety had several challenges. Primarily, determining driver and pedestrian intent was difficult or impossible to determine from video review, particularly related to the pedestrian evasive actions, which made up a majority of the conflict data sample. Simply put, it was often impossible to discern whether the pedestrian was forced to make an evasive action, such as walking faster, running, or making a path change, or did so voluntarily.

As driver and pedestrian intent could not be ascertained from video review, all potential evasive actions by pedestrians or drivers were scored as conflicts. Ultimately, this resulted in 151 conflict events over a time period of 99.25 h, or more than 1.5 conflicts/h. Previous research correlating conflicts with motor vehicle crashes using specially equipped vehicles indicate that true conflicts, similar to crashes, are rare and random events [20]. Given the rarity of true conflicts, this large number of conflicts raised concerns, which were confirmed by the unusual results found in the preliminary negative binomial regression analysis. Ultimately, after further investigation of the data collection methods, evasive action event scoring, and modeling results, the vehicle-pedestrian conflict data collected as a part of this study were deemed invalid for further evaluation.

Driver yielding compliance to pedestrians, on the other hand, allowed for a consistent methodology from observation-to-observation, as all pedestrian crossing attempts which were evaluated were attempted by trained researchers, providing for consistency. Furthermore, the staged crossing procedure allowed for sample sizes sufficient for meaningful analysis. Lastly, the methodology reflects a performance measure which is meaningful to pedestrians and engineers alike (driver yielding compliance to pedestrians) as a safety as well as an operational metric.

6.1 Data Summary

Driver yielding compliance data were extracted from the 31 sites where staged pedestrians were utilized, resulting in a total of 1,281 observations, which were either scored as "yielded" or "did not yield." These data are summarized in Table 12. However, 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, which is a result incompatible with the statistical method utilized here. Thus, only 1,245 yielding compliance observations were included in the final analysis, although the RRFB compliance rate was included in subsequent discussions. Note that the summary statistics in Table 12 exclude the RRFB site, unless noted otherwise. Sites with in-street R1-6 signs, PHB, and RRFB treatments all utilized the continental style (i.e., markings parallel to the traffic direction) crosswalk. Utilization of R1-6 signs were limited to a single sign placed on the centerline within the crosswalk, and the three sign "gateway" application of this sign was not used in this study.

TABLE 12. Summary of Site Characteristics for Midblock Yielding Compliance Assessment

Categorical Factors

Factor	Level or Unit	Proportion of Observations	Number of Sites
Driver Action[a]	Yield	0.61	
	Did not yield	0.39	
Vehicle Lane Position	Near (curb) lane	0.70	
	Center or far lanes	0.30	
Position of Vehicle in Queue	Unqueued vehicle	0.66	
	Queue leader	0.21	
	Queue follower	0.13	
Crosswalk Treatment	Unmarked	0.20	5
	Standard only	0.07	3
	Continental only	0.58	17
	In-street R1-6 sign	0.08	3
	PHB	0.04	2
	RRFB (excl. from model)	0.03	1
Crossing Width (excludes median)	≤30 ft	0.54	15
	31-40 ft	0.11	4
	41-50 ft	0.31	9
	>50 ft	0.04	2
Traffic Direction at Crosswalk	One-Way	0.55	15
	Two-Way	0.45	15
Through Lanes at Crosswalk	2 lanes	0.85	24
	3 lanes	0.10	4
	4 lanes	0.04	2
Roadway Cross-Section	Two-lane	0.45	14
	Undivided multilane	0.05	3
	Divided multilane	0.50	13
Auxiliary Lane	None	0.37	12
	Bike, parking or shoulder	0.63	18
Pedestrian Crossing Volume	<50 pedestrians/h	0.54	15
	≥50 pedestrians/h	0.46	15

Continuous Factors

Factor	Level or Unit	Mean	SD	Min	Max
Crossing Width (excludes median)	ft	34.91	11.13	22	54
Through Lanes at Crosswalk	count	2.19	0.49	2	4
Vehicle Volume at Crosswalk	vehicles/h	439.30	200.20	218	1,204
Pedestrian Crossing Volume	pedestrians/h	85.95	101.36	5	662
Bicycle Volume	bicycles/h	9.16	7.93	0	31

Note: The RRFB site was excluded from the summary statistics, except where noted

[a]Dependent variable

6.2 Data Analysis

As driver yielding compliance is a binary (yes/no) outcome, 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:

$$\ln\left[\frac{p_i}{1-p_i}\right] = \alpha + \beta' X_i, \tag{7}$$

where p_i is the response probability of driver i yielding to a 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).

One concern that arises within the context of this study is the potential correlation in compliance rates within individual locations due to common, unobserved factors (i.e., unobserved heterogeneity). Failure to account for such correlation may lead to biased or inefficient parameter estimates. To account for this concern, a site-specific random effect is added for each location j, resulting in:

$$\ln\left[\frac{p_i}{1-p_i}\right] = \alpha_j + \beta X_i, \tag{8}$$

This approach allows for the constant term to vary across locations, but maintain the same value for all crossing events observed at an individual location. In addition to impacting the constant term, unobserved heterogeneity can also lead to explanatory parameters varying across locations. For example, various site characteristics may occur in combination with other factors (e.g., land use, local design practices) that are not directly accounted for as a part of the analysis. To address this issue, a series of site-specific random parameters can be similarly introduced as follows:

$$\beta_j = \beta + u_j, \tag{9}$$

where β is the vector of estimable parameters and u_j is a randomly distributed term for each location j with mean zero and variance σ^2. Parameters that are found to vary across study locations take this random parameter form while those parameters that are shown to have homogeneous impacts across locations are treated as traditional fixed parameters (i.e., u_j is equal to zero). Model estimation was done through simulated maximum likelihood using 10,000 Halton draws.

The variables from Table 12 were considered as potential predictors when estimating this mixed effects logistic regression model. Several preliminary versions of the models were estimated, and in many cases, categorical factors were utilized over the continuous analogs in order to improve model fit. The variables found to be statistically significant in the preliminary model were then each considered as normally distributed random parameters. Those parameters shown to vary across locations were retained as random parameters, with the remaining variables included as fixed parameters.

6.3 Results and Discussion

The final model results for driver yielding compliance are displayed in Table 13, which includes the coefficient estimate, standard error, t-statistic, and odds ratio for each variable included in the mixed effects logistic regression model. The base conditions for the model were included as follows: unmarked crosswalk, undivided roadway cross-section, subject vehicle in the lane nearest to the curb, and subject vehicle not queued.

TABLE 13. Logistic Regression Results for Driver Yielding Compliance

Variable	Level or Unit	Coefficient Estimate	Standard Error	t-stat	Odds Ratio
Fixed Parameters					
Constant		-3.416	1.217	0.005	N/A
Crosswalk Treatment	Unmarked	*baseline*			
	In-Street R1-6 Sign	2.83458	0.64039	<0.0001	17
	PHB	2.93714	0.66567	<0.0001	18.9
Crossing Width	ln ft	0.54656	0.31341	0.0822	1.7
Pedestrian Volume	ln ped/hr	0.18541	0.07108	0.0099	1.2
Vehicle Lane Position	Near (curb) lane	*baseline*			
	Other lane	0.83107	0.12889	<0.0001	2.3
Vehicle Position in Queue	Unqueued vehicle	*baseline*			
	Queue leader	0.45534	0.13549	0.0011	1.6
	Queue follower	-0.35329	0.17239	0.0411	0.7
Random Parameters					
Crosswalk Treatment	Unmarked	*baseline*			
	Standard only *mean*	1.01445	0.3484	0.0044	2.8
	Standard only *st. dev.*	2.01124	0.5202	<0.0001	N/A
	Continental only *mean*	1.24722	0.2022	<0.0001	3.5
	Continental only *st. dev.*	0.30001	0.0873	0.0011	N/A
Cross-Section	Undivided	*baseline*			
	Divided *mean*	-0.34902	0.1184	0.0032	0.7
	Divided *st. dev.*	0.38509	0.10342	0.001	1.5

N=1,245
Initial log-likelihood (constant only) = -833.24
Log-likelihood at convergence = -629.73
McFadden Pseudo R^2=0.244

The results of the mixed effects logistic regression model revealed several interesting findings. 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. Both the standard and continental crosswalks were shown to increase compliance over unmarked crosswalks. On average, compliance rates were 2.8 times higher for standard crosswalks and 3.5 times higher for continental crosswalks. These effects were shown to vary across sites and this variability was particularly pronounced for the standard crosswalks, which may be reflective of the settings under which either type of crosswalk was installed. The inclusion of an R1-6 in-street sign, PHB, or RRFB provided substantial improvements in yielding compliance over the standard and continental crosswalks. To further enhance discussion of the crosswalk treatment results, the raw yielding compliance summary statistics are displayed for each treatment type in Table 14.

TABLE 14. Driver Yielding Compliance by Crosswalk Treatment

Crosswalk Treatment	Number of Locations	Number of Observations	Percent of Drivers Yielding
Unmarked	5	261	28.70%
Standard only	3	88	50.00%
Continental only	17	744	66.30%
In-Street Sign (R1-6)	3	101	95.00%
PHB	2	51	98.00%
RRFB	1	36	100.00%
ALL	31	1,281	62.00%

The raw yielding compliance rates for each type of treatment revealed several interesting findings that generally followed the results of the mixed effect model. First, the PHB yielding compliance rate of 98 percent was in general agreement with PHB yielding compliance (85 to 97 percent) observed in other states [51]. The single RRFB location showed 100 percent yielding compliance, which was substantially higher than the 22 to 94 percent rates observed in other states [26] [41] [51] [52]. The PHB and RRFB locations also displayed higher yielding rates compared to rates observed at several Michigan PHB and RRFB locations in 2012 (77 percent, on average, for both devices) [16]. Considering that the current PHB and RRFB study sites were also included in the 2012 study suggests that yielding compliance may improve over time as drivers become more familiar with these devices. However, although prior studies have also shown improvements in driver compliance rates over time [13] [41], these results should be viewed with caution due to the small number of PHB and RRFB locations observed in the current study. The sites with an R1-6 sign positioned within the crosswalk showed a yielding compliance rate of 95 percent, which was similar to rates observed at the PHB and RRFB locations and substantially higher than crosswalks with no additional treatment. Although crosswalks with R1-6 signs have shown compliance rates of up to 87 percent in prior studies [51], such a high level of compliance was a surprising result given the substantially lower cost of the R1-6 sign compared to RRFBs and PHBs.

Turning to other variables of interest, there was significant variability in compliance based upon the lane where the subject vehicle encountered the pedestrian. Drivers traveling in the near (curb) lane were 2.3 times less likely to yield for a pedestrian compared to drivers traveling in any other lane. This effect may be reflective of differences in driver expectancy based upon pedestrian location and behavior. When crossing attempts were initiated at the near (curb) lane, approaching drivers may have either not been observed by the approaching driver or the driver may not have realized their intention to cross. In contrast, the pedestrians' intensions were likely clearer while attempting to cross the other lanes where the individual was completely within the roadway as the driver approached. The pedestrians were also likely more conspicuous to approaching drivers overall.

Regarding the roadway cross-section variables, drivers' likelihood to yield increased as the crossing distance increased. Interpretation of the parameter estimate suggests a crossing width of 48 ft (i.e., a four-lane street) would result in a 46 percent greater likelihood of driver yielding compared to a width of 24 ft (i.e., a two-lane street). This again may be due to the increased conspicuity of the pedestrian to approaching drivers. In contrast, drivers were, on average, 30 percent less likely to yield on divided roadways compared to undivided roadways. This effect was shown to vary across locations due to unobserved heterogeneity between sites, which suggests the presence of additional factors affecting yielding compliance.

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 15. 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.

TABLE 15. Interaction of Lane Position with Roadway Cross-Section and Crosswalk Treatment

	Number of Observations		Yielding Compliance	
Variable	**Near Lane**	**Other Lane**	**Near Lane**	**Other Lane**
2-Lane	390	170	55.60%	74.70%
Multilane - Undivided	36	23	80.60%	91.30%
Multilane - Divided	464	198	51.90%	79.80%
Unmarked	166	95	19.90%	44.20%
Standard only	66	22	34.80%	95.50%
Continental only	575	169	61.40%	82.80%
In-Street Sign (R1-6)	40	61	92.50%	96.70%
PHB	25	26	96.00%	100.00%
RRFB	18	18	100.00%	100.00%
TOTAL	890	391	54.80%	78.20%

Turning to the interaction between lane position and crosswalk treatment, the results for which are also displayed in Table 15, 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., R1-6 sign, PHB, RRFB) were utilized, further emphasizing the effectiveness of these treatments (Figure 11). Far lane yielding compliance was higher than near lane yielding compliance for sites without enhancement devices, likely due to the increased conspicuity of the pedestrian approaching lanes other than the curb lane.

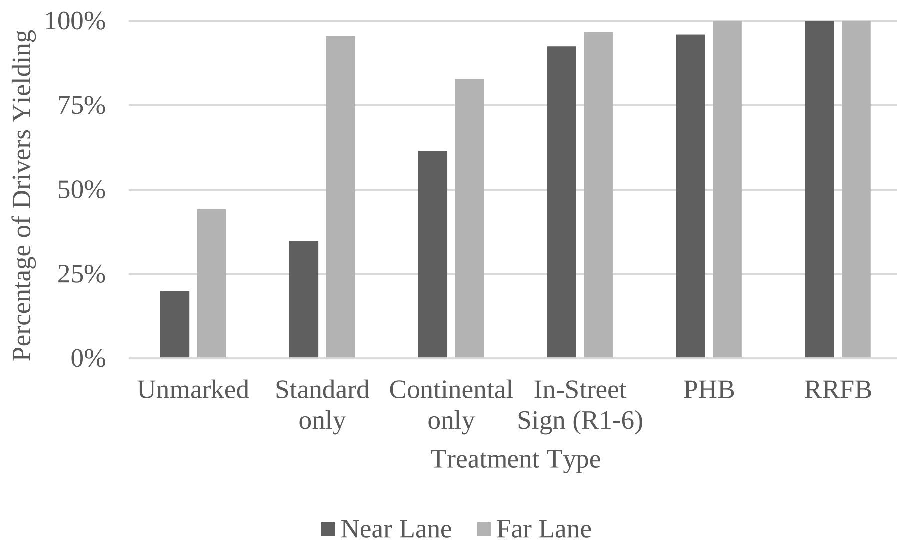


Figure 11. Yielding Compliance by Lane Position and Treatment

The vehicle's position within the queue also affected the likelihood of driver yielding. The logistic regression results displayed in Table 13 suggest that queue leaders were 1.6 times more likely to yield compared to unqueued drivers and were 2.3 times more likely to yield compared to queued drivers that were not in the lead position. These results are not surprising, as queued drivers in many cases are simply following the leading vehicle, who obviously also did not yield for the pedestrian. Past research on the PHB has shown that queued drivers will tend to follow the queue leader without first checking for pedestrians attempting to cross [42] [45].

Finally, greater pedestrian volumes were associated with an increase in yielding compliance. This was not a surprising result, as greater pedestrian activity would serve to raise driver awareness at the particular crosswalk. However, although preliminary analyses showed yielding rates to decrease with hourly traffic volume, this effect was not statistically significant in the final analysis when considering other pertinent factors.

6.4 Conclusions and Recommendations

The results of this study provide several important insights to inform subsequent decisions by road agencies as to the installation of pedestrian crosswalk treatments. A mixed effects logistic regression model was estimated to account for intra-site correlation in yielding rates, as well as for the effects of unobserved heterogeneity across study locations. The results demonstrate the importance of applying robust analytical methods to examine driver-pedestrian interactions.

Ultimately, the findings provide a clear indication 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. This is an important finding, which suggests that compliance improves as drivers become more familiar with a particular treatment.

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 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. Perhaps most importantly, however, yielding compliance showed little sensitivity to the particular travel lane of the subject vehicle at locations where additional treatments (i.e., in-street R1-6 sign, PHB, RRFB) were utilized, further validating the effectiveness of these devices.

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 may further increase compliance and provide subsequent safety benefits. 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.

While the results of this study provide important insights to guide subsequent investment strategies for mid-block crossings, there are some important limitations that must be stated. First, the results are limited to low-speed locations only. Yielding compliance is likely different on higher speed roadways, where 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, the samples of pedestrians and drivers included in this study are a non-random sample and it is unclear how these trends would extrapolate to a broader population.

CHAPTER 7: CONCLUSIONS

Ultimately, this thesis found driver yielding compliance to pedestrians to be an ideal surrogate for crashes in analyzing pedestrian safety. At midblock crossing areas, statistical analysis of yielding compliance found that enhancement devices were associated with increased propensity to yield on the part of drivers. Using yielding compliance as a measure of effectiveness in and of itself is not novel. Rather, the primary contribution this thesis makes is the analysis technique. Binary logistic regression with mixed effects was used to determine the probability of driver yielding based on not only crosswalk treatment, but also on site and cross-sectional characteristics. A cross-sectional study was ideal for these purposes, as driver familiarity with new devices was not a concern. Ultimately, the study design combined with the analysis technique found yielding performance for the PHB and in-street R1-6 sign to be similar to each other on low-speed roads based on odds ratio, which is an important finding considering the high cost of installing the PHB. This was an unexpected result, and direct comparison of these treatments was only possible because of the analysis method.

7.1 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 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. 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.

7.2 Recommendations

In evaluating the safety of existing pedestrian crossing sites, road agencies are advised to use yielding compliance as their performance measure. Crash analysis is typically infeasible due to the low number of pedestrian crashes at crossing locations, in addition to the lack of meaningful pedestrian exposure data. Meaningful pedestrian-vehicle conflicts (i.e. near crashes) are also extremely rare, and therefore the labor costs to collect enough data would also be infeasible. While there is no objective measure for what constitutes satisfactory yielding compliance at any given location, engineering judgement and public feedback can be useful in determining yielding compliance targets in locations with high pedestrian activity. When additional treatments are installed to improve pedestrian safety, agencies should conduct a yielding compliance study before and after the treatment is installed to determine its effectiveness.

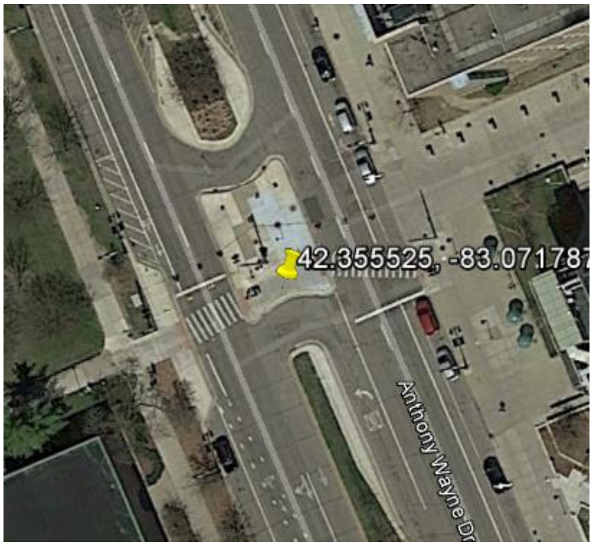
Road agencies are advised to place crosswalks in otherwise unmarked locations where pedestrians frequently cross and, when necessary, install additional treatment. Providing marked crosswalks at midblock locations on low speed roadways with light to moderate vehicle volumes will result in higher yielding compliance and will typically not require additional treatment unless special circumstances (i.e., school, hospital, etc.) exist. For midblock crosswalks on low speed roadways 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.

APPENDIX

APPENDIX

This appendix contains aerial imagery for study sites (Table 16). Refer to Tables 4 and 5 for site descriptions.

TABLE 16. Aerial Imagery for Study Sites

Site 1  Image Source: Google Earth	**Site 2**  Image Source: Google Earth
Site 3  Image Source: Google Earth	**Site 4**  Image Source: Google Earth

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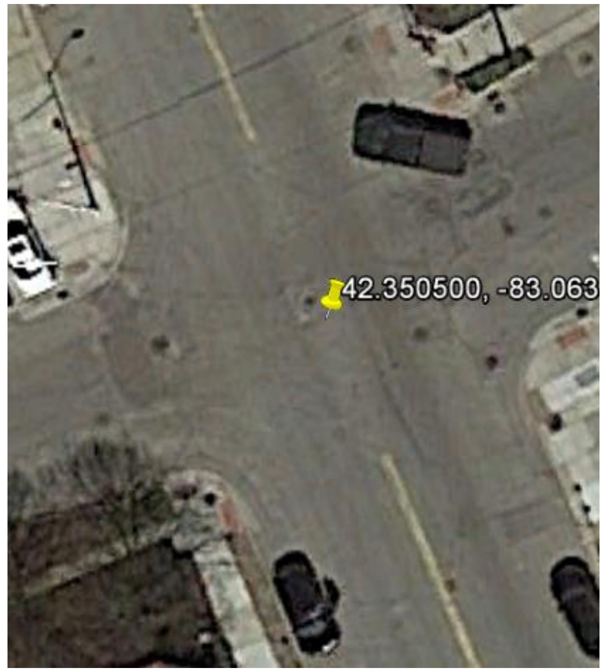
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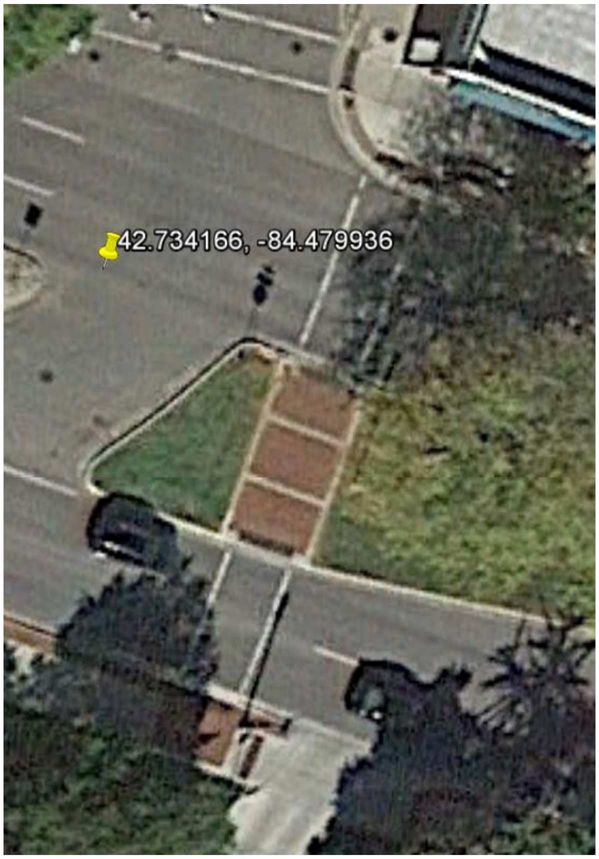
Site 17  Image Source: Google Earth	**Site 18**  Image Source: Google Earth
Site 19  Image Source: Google Earth	**Site 20**  Image Source: Google Earth

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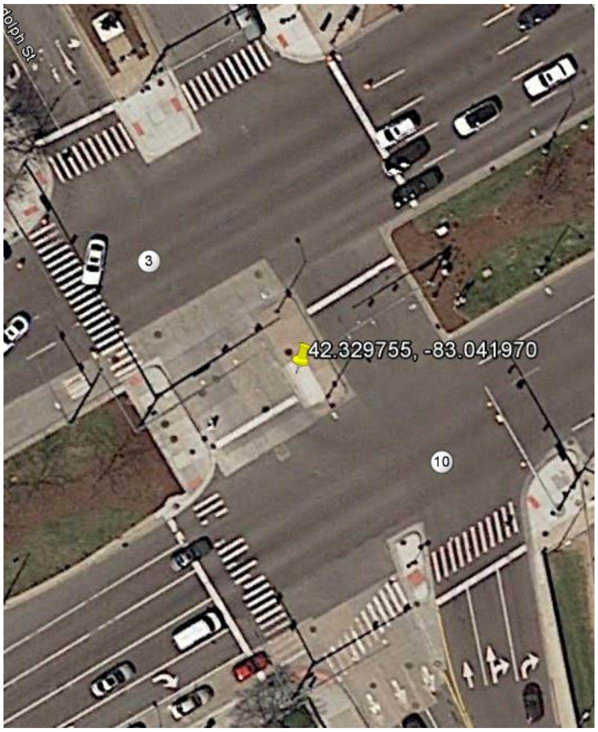

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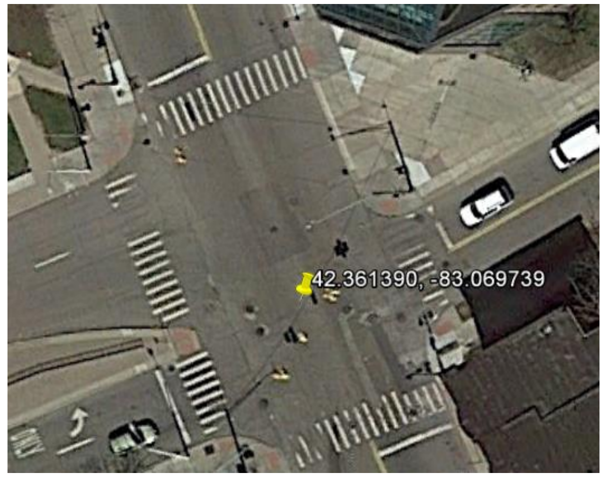

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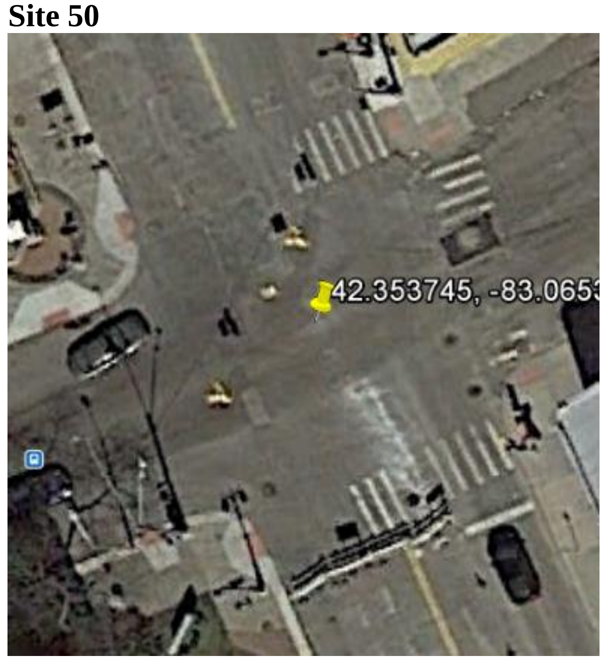

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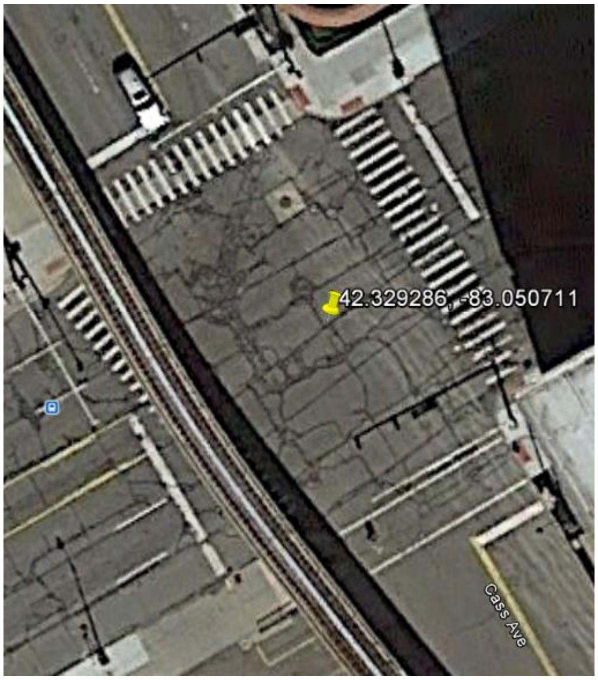

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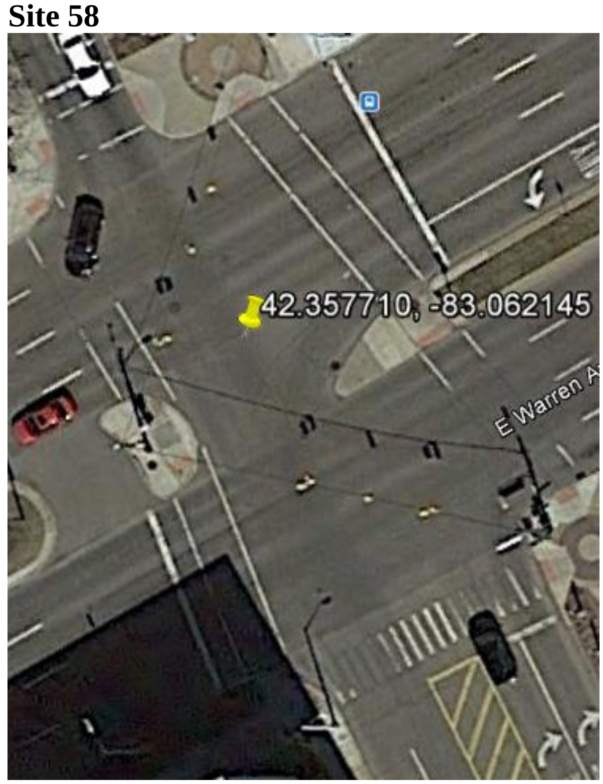

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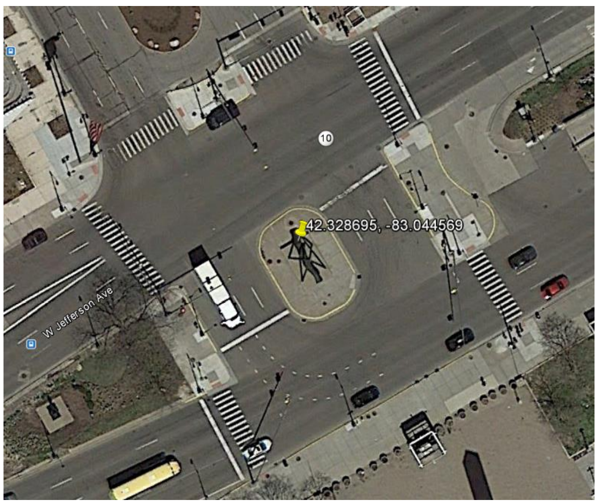

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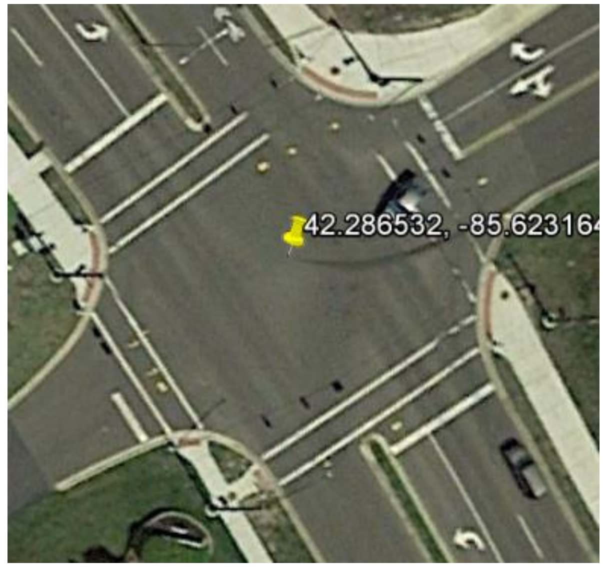
 Image Source: Google Earth	 Image Source: Google Earth

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