SAFETY EFFECTIVENESS OF PEDESTRIAN CROSSING ENHANCEMENTS

Final Report

SPR 778

RESEARCH

Oregon Department of Transportation

SAFETY EFFECTIVENESS OF PEDESTRIAN CROSSING ENHANCEMENTS

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16. Abstract - Over the last decade, the Oregon DOT and other agencies have systematically implemented many pedestrian crossing enhancements (PCEs) across the state. This study explored the safety performance of these enhanced crossing in Oregon. Detailed data were collected on 191 crossings. Supplemental data items included crossing location information, route characteristics, surrounding land use and crossing enhancement descriptions. Pedestrian volume at the crossing locations was a highly desirable but unavailable data element. To characterize pedestrian activity, a method was developed to estimate ranges for pedestrian crosswalk activity levels based on the land use classification at the census block level and the presence of pedestrian traffic generators such as bus stops, schools, shopping centers and hospitals within a 0.25-mile radius. Each crosswalk was categorized into one of six levels of activity – very low, low, medium-low, medium, medium-high and high. Crash data for the 2007-2014 period were assembled for the safety analysis. After filtering, 62 pedestrian crashes and 746 rear-end crashes were retained for further analysis. The crash data were merged and analyzed. Crash patterns and risk ratios were explored. The most important trend observed was a shift (reduction) in the pedestrian crash severity after the installation of the crosswalk treatments. This shift was from fatal and injury A crash type to lower severity crashes of injury B and injury C. For pedestrian crashes, increases in the risk ratio were observed for increases in the number of lanes, the posted speed, and estimated pedestrian activity level. Similar trends were observed for rear-end crashes. Due to data limitations, subsequent safety analysis focused on installations of RRFB crossing enhancements. A CMF for RRFB installations was estimated. The CMFS for pedestrian crashes are 0.64 +/- 0.26 using a simple before-after analysis; for rear-end crashes: 0.93 +/- 0.22 using an empirical Bayes analysis approach.

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APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in^2	square inches	645.2	millimeters squared	mm^2
ft^2	square feet	0.093	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	kilometers squared	km^2
VOLUME				
fl oz	fluid ounces	29.57	milliliters	ml
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3
NOTE: Volumes greater than 1000 L shall be shown in m^3.				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
TEMPERATURE (exact)				
°F	Fahrenheit	(F-32)/1.8	Celsius	°C

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
m^2	meters squared	1.196	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	kilometers squared	0.386	square miles	mi^2
VOLUME				
ml	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams	1.102	short tons (2000 lb)	T
TEMPERATURE (exact)				
°C	Celsius	1.8C+32	Fahrenheit	°F

*SI is the symbol for the International System of Measurement

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DISCLAIMER

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1.0 INTRODUCTION

Improving pedestrian safety is an important objective of many transportation agencies. Mid-block crossings of streets, particularly large busy arterials, can be challenging for many pedestrians to safely cross. Over the last decade, the Oregon DOT and local agencies in Oregon have systematically implemented many pedestrian crossing enhancements (PCEs) across the state at these mid-block locations. The most commonly deployed treatments include continental crosswalk markings, pedestrian median islands, curb bulb-outs, pedestrian-activated flashing beacons (rapid flashing and regular flash) and advanced stop bars.

Prioritization of locations for future enhancements requires data-driven safety decision-making. Use of the AASHTO Highway Safety Manual (HSM) methods requires the use of robust crash modification factors (CMFs). However, despite recent research efforts and the implementation of the crash modification factor clearinghouse, gaps remain regarding the quantification of PCEs on crash frequency. Only two of the countermeasures – raised medians and pedestrian hybrid beacons (HAWK signal) – have CMFs with a four or higher star rating in the FHWA's countermeasure clearinghouse.

The objective of this research was to estimate the safety effectiveness of PCEs and to derive, when there was enough data, CMFs calibrated to Oregon design contexts. This research analyzed pedestrian crashes and rear-end motor vehicle crashes in the vicinity of PCEs. The estimation of the safety effectiveness of pedestrian treatments was challenging due to the low frequency of pedestrian crashes, knowledge of the exact time of crossing improvements, and the general lack of reliable pedestrian counts. In addition, many mid-block crossings were incrementally improved so it was difficult to find consistent before-and-after conditions. Nonetheless, this research attempted to incorporate relevant factors such as roadway geometry, surrounding land use, and pedestrian activity levels in the analysis. The research includes three key efforts to accomplish these objectives:

- Identifying and collecting detailed data about pedestrian crossing enhancements in Oregon (see Chapter 3);
- Analysis of pedestrian and rear-end crash data at PCE locations (see Chapter 4); and
- Developing CMFs for Oregon pedestrian crossing enhancements (Chapter 5).

This *Final Report* summarizes the research and is organized into six chapters. Chapter 2 presents a brief literature review. Chapter 3 describes the process used to identify the crossing and the data collection methods used to assemble the data. Chapter 4 reviews the basic analysis of the crossing inventory data and the crash data. Chapter 5 presents the estimates of the effectiveness of the crossing enhancements. Chapter 6 summarizes the findings and presents recommendations. Finally, cited references are summarized in Chapter 7.

2.0 LITERATURE REVIEW

This chapter presents a literature review of PCEs and their safety effectiveness. The list of widespread PCEs employed by agencies to improve pedestrian safety includes: provision of sidewalks and walkways, improvements at crossing locations such as curb ramps and extensions, marked crosswalks, median islands, raised pedestrian crossings and lighting improvements, rectangular rapid flashing beacons, signal treatments such as leading pedestrian intervals, pedestrian hybrid beacons (HAWK) and provision of advance stop lines. A recent study by Mead et al. *(Mead et al. 2013)* provides a comprehensive review of multiple pedestrian measures that have been employed around the world. This review draws heavily from Mead et al. but also incorporates more recently published literature. Due to the challenges of using pedestrian crash data, many studies have used safety surrogates such as driver speeding and driver yielding rates as measures of effectiveness.

2.1 CROSSWALKS

This section reviews the safety effects of marked crosswalks and high-visibility crosswalks.

2.1.1 Marked Crosswalks

Marked crosswalks for pedestrian crossings are typically found at signalized intersections, unsignalized intersections, school zones, and mid-block locations *(Mead et al. 2013)*. The most common markings are standard parallel lines, ladder or continental stripes and diagonal stripes *(MUTCD 2009)*. Figure 2.1 shows the commonly used crosswalk markings. Prior to 2002, the literature on safety effects of marked and unmarked crosswalks suggested the treatments have mixed results. Some studies found higher pedestrian crash risk at marked crosswalks than at unmarked crosswalks *(Herms et al. 1972; Gurnett et al. 1974; Gibby et al. 1994; Jones et al. 2000; Koepsell et al. 2002)*; other studies found a lower pedestrian crash risk at marked crosswalks than at unmarked crosswalks *(Tobey et al. 1983)*. The results of these studies cannot be readily compared or transferred because most of these studies did not control for key factors such as roadway cross-sections or traffic volumes.

More recent research efforts have focused on the evaluation of the effects of crosswalk markings on driver and pedestrian behavior. Knoblauch et al. *(Knoblauch et al. 2000)* studied driver and pedestrian behavior at 11 unsignalized locations (two- or three-lane roads with low speeds limits (35-40 mph) and low volumes (< 12,000 vehicles per day)) in four U.S. cities and found no statistically significant differences in driver and pedestrian behavior when comparing marked crosswalks and unmarked crosswalks. Another study performed by Knoblauch *(Knoblauch 2011)* revealed slight reductions in speed that were statistically significant at some locations after marked crosswalks were installed.

Zegeer et al. *(Zegeer et al. 2002)* studied 1,000 marked and 1,000 unmarked crosswalks at unsignalized intersections and mid-block locations in 30 U.S. cities and found that at uncontrolled locations on two-lane roads and multilane roads with low average daily traffic

(ADT < 12,000), a marked crosswalk alone did not produce a statistically significant difference in the pedestrian crash rate. However, on multilane facilities with higher ADT (ADT > 12,000), a marked crosswalk alone without any other enhancements was associated with a statistically significant higher pedestrian crash rate than the pedestrian crash rates of unmarked crosswalks after controlling for site factors, including pedestrian exposure. Zegeer et al. *(Zegeer et al. 2002)* found that on multilane roads, a raised median in either a marked or unmarked crosswalk produced a statistically significant lower pedestrian crash rate compared to roads with no raised median. They also found that older pedestrians had higher crash rates relative to their crossing exposure *(Zegeer et al. 2002)*. Most recently, Mitman et al. *(Mitman et al. 2007)* found statistically significant higher driver yielding rates at marked crosswalks than at unmarked crosswalks. They also found that 17.6% of the pedestrian crashes in marked crosswalks were classified as multiple threat, whereas no crashes in unmarked crosswalks were coded as multiple threat crashes. This data seems to indicate that the yielding behavior was different at marked than unmarked crosswalks. No further information was available regarding whether yielding was same irrespective of speed or number of lanes *(Mitman et al. 2007; Zegeer et al. 2002)*

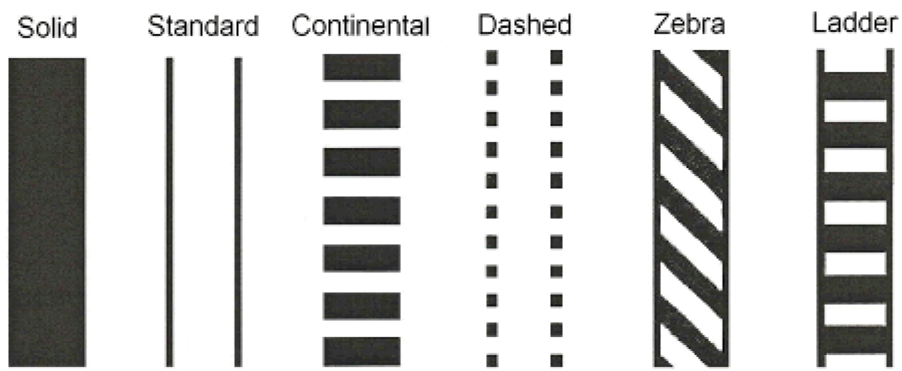


Figure 2.1: Common Crosswalk Markings *(Zegeer et al. 2001)*

2.1.2 High-Visibility Crosswalks

Several studies have evaluated the effect of high-visibility markings on driver and pedestrian behavior with mixed results. The high-visibility markings are typically either solid, continental, zebra, ladder or dashed, as shown in Figure 2.1. Nitzburg et al. *(Nitzburg et al. 2001)* studied two locations in Clearwater, FL, with high-visibility crosswalk markings and illuminated overhead crosswalk signs and found statistically significant higher driver yielding rates during the day; smaller statistically insignificant higher driver yielding rate at night; and statistically significant higher pedestrian crossings. Nitzburg et al. *(Nitzburg et al. 2000)* found a statistically significant increase in daytime driver yielding behavior and percentage of pedestrians using the crosswalk at locations with an illuminated crosswalk sign and high-visibility crosswalk on narrow low-speed roads. The Chicago Department of Transportation evaluated colored crosswalk markings at 100 elementary school zone crosswalks *(CDOT 2005)* and found no statistically significant reductions in the proportion of speeding drivers at the locations. Several studies found statistically significant reduction in pedestrian collisions at high-visibility crosswalk locations

(Feldman et al. 2010; Chen et al. 2012) as well as a statistically significant increase in the proportion of pedestrians who looked for vehicles before crossing *(Pulugurtha et al. 2012)*.

Some researchers have also studied the differences in the visibility of different types of markings during the day and night *(Fitzpatrick et al. 2011)*. Their results revealed that detection distances of markings for continental and bar pairs (crossings where ladder bars are spaced in pairs, so as to avoid the wheel path of automobiles) were similar and statistically different (longer) than transverse markings both during the day and night.

2.2 CROSS WALK ENHANCEMENTS

Some crosswalk enhancements are added to enhance the visibility of crosswalks to drivers, reduce pedestrian crossing distance, or physically separate pedestrians and vehicular traffic.

2.2.1 Pedestrian-Activated Flashing Yellow Beacons

Pedestrian-activated flashing beacons are devices that are used to increase the visibility of pedestrian crossings for motorists. Several studies have shown increased driver yielding rates at crossings where they have been installed *(Nitzburg et al. 2001; Huang et al. 2000; Van Houten et al. 1998; Pecheux et al. 2009; Hua et al. 2009)*. These beacons are often used with other treatments such as illuminated signs, high-visibility crosswalks and advanced yield markings.

2.2.2 In-Pavement Lighting

In-pavement lighting is often used to alert motorists to the presence of a crosswalk *(Mead et al. 2013)*. Results have been mixed, with one study reporting increased driver compliance and yielding rates *(Godfrey et al. 1999)* and others reporting a statistically significant increase in driver yielding behavior *(Karkee et al. 2006)*, reductions in vehicle speeds and collision rates *(Hakkert et al. 2002; Van Derlofske et al. 2003; Karkee et al. 2006)*. One study did not achieve positive results *(Huang et al. 2000)*. Researchers have documented several well-known drawbacks of this treatment including the necessity to replace the system when roads are resurfaced, visibility for the first car in the platoon only, and limited visibility during daylight hours *(Mead et al. 2013)*.

2.3 CURB EXTENSIONS

Curb extensions are designed to narrow the roadway by extending the curb, thus leading to reduced crossing distance for pedestrians. After this treatment some studies have documented safety benefits such as reduced overall severity rate *(King et al. 1999)* and a statistically significant increase in far-lane driver yielding rates *(Hengel et al. 2013)*. Other studies have found no significant improvements *(Huang et al. 2001; Johnson 2005)*.

2.4 MEDIAN REFUGE ISLANDS

Median refuge islands are raised areas that are typically found at the center of a roadway, and provide pedestrians with a safe place to wait for gaps in traffic and allow them to cross a wide road in two stages. They are used at intersections as well as mid-block locations. Figure 2.2 shows a median refuge island adjacent to a crosswalk.

Figure 2.2: Median Refuge Island, Credit: N. Foster (PSU)

Many studies showed positive safety benefits such as statistically significant lower pedestrian crash rates *(Bowman et al. 1994; Claessen et al. 1994; Bacquie et al. 2001; Zegeer et al. 2005)*; a statistically significant increase in pedestrians using the crosswalk *(Huang et al. 2001)*; a statistically significant increase in the proportion of drivers yielding to pedestrians and the distance at which drivers yielded to pedestrians *(Pulugurtha et al. 2012)*; a statistically significant reduction in mean speeds *(Kamyab et al. 2003; King et al. 2003)*; and an increase in speed limit compliance when used along with pedestrian crossing signs *(Kamyab et al. 2003)*. A study by Pecheux et al. *(Pecheux et al. 2009)* at two signalized intersections in San Francisco found no statistically significant improvements in driver yielding, the number of trapped pedestrians or pedestrian-vehicle conflicts at either of the sites, and a statistically significant increase in pedestrian delay at one of the sites. There are limited studies that have examined how the configuration of the median affects pedestrian behavior. However, Foster et al. *(Foster et al. 2014)* found that pedestrians did not use the staggered median crossing at a multilane RRFB location where drivers had already yielded for the second-stage crossing.

2.5 RAISED PEDESTRIAN CROSSINGS

Raised pedestrian crossings can be applied at both intersections and mid-block and are most commonly used in an urban, low-speed context, but there is limited research on the effects of this treatment. Huang et al. *(Huang et al. 2001)* studied the impacts of raised crosswalks on pedestrian and driver behavior at three sites, two in North Carolina and one in Maryland, and found a statistically significant reduction in speeds at two sites (North Carolina) and a statistically significant increase in drivers yielding behavior (one North Carolina site). In the same study, they also evaluated the impact of a raised intersection in Cambridge, MA *(Huang et al. 2001)*. Statistically significant increases were found in the number of pedestrians using the crosswalk.

2.6 ROADWAY LIGHTING IMPROVEMENTS

Gibbons et al. *(Gibbons et al. 2008)* conducted tests to determine the impact of lighting direction and levels on driver yielding behavior; results indicated that vertical illuminance provided the best detection distance in most cases. Vertical illuminance is the luminous intensity emitted by a luminaire in the direction of the pedestrian times the cosine of the angle between the direction of propagation and a horizontal line parallel to the road surface divided by the distance between the luminaire and the pedestrian *(Gibbons et al. 2008)*. Nambisan et al. *(Nambisan et al. 2009)* tested an automated, smart lighting system that increased the illumination of the mid-block crossing when pedestrians were detected; results from the test showed statistically significant increases in crosswalk utilization and yielding rates and a statistically significant decrease in the proportion of pedestrians trapped in the roadway. Bullough et al. *(Bullough et al. 2012)* tested four types of pedestrian crosswalk lighting configurations with low-beam vehicle headlamps at crosswalks: no fixed lighting, pole-mounted lighting directly over the crosswalk, pole-mounted lighting offset from the crosswalk, and a bollard lighting system. They concluded that bollard luminaires using linear florescent lamps were most effective at identification of silhouettes among the configurations that were tested.

2.7 PEDESTRIAN OVERPASSES/UNDERPASSES

Pedestrian overpasses and underpasses can provide significant safety benefits for pedestrians; however, due to their cost and users' perceived concerns about safety in a more confined space they are not used often. A research study in Tokyo, Japan, evaluated before-and-after crashes at 31 locations and found substantial reductions in pedestrian crossing collisions after the grade-separated facilities were installed, but an increase in non-related crashes *(Campbell et al. 2004)*.

An important consideration in the effectiveness of overpasses and underpasses is pedestrian utilization and perception of convenience and safety. Moore et al. *(Moore et al. 1965)* found that the additional amount of time it takes to cross the underpass or overpass compared to a regular crossing is significant, defined as convenience measure R. If R is close to 1, the study found greater utilization of the overpass by pedestrians. For similar values of R, usage of pedestrian underpasses was not as high as overpasses.

2.8 RECTANGULAR RAPID FLASHING BEACON (RRFB)

RRFBs are typically used at unsignalized intersections or mid-block crossings to enhance pedestrian safety. They incorporate a flash pattern to catch the attention of motorists to alert them to the pedestrians' presence. RRFBs were granted interim approval by FHWA in 2008 *(FHWA 2009)*. These beacons can be activated automatically or pedestrian activated via push buttons. Figure 2.3 shows a RRFB assembly on SW Barbur Boulevard in Portland, OR.

Figure 2.3: RRFB Assembly, SW Barbur Blvd. Credit: N. Foster (PSU)

Many research studies have demonstrated the effectiveness of RRFBs in statistically significant increases in driver yielding behavior *(Van Houten et al. 2008; Pecheux et al. 2009; Hua et al. 2009; Hunter et al. 2009; Shurbutt et al. 2010; Ross et al. 2011; Domarad et al. 2013;Foster et al. 2014)*. All these studies reported a statistically significant decrease in the number of pedestrian-vehicle conflicts and trapped pedestrians. One study also reported that enhanced crosswalks with RRFBs attracted more pedestrians even though other crossing options were present nearby *(Foster et al. 2014)*. Many studies have recommended that RRFBs should be considered as a "highly effective" countermeasure due to their proven safety benefits (yielding), but crash performance has not yet been measured.

2.9 IN-STREET PEDESTRIAN SIGNS

Studies that evaluated the effectiveness of these signs found that, in general, the signs showed statistically significant reductions in mean speeds and increases in compliance with the speed limit at the crosswalk location *(Madison 1999; Huang et al. 2000; IDOT 2003; Kamyab et al. 2003; Strong et al. 2006; Banerjee et al. 2007; Ellis et al. 2007; Hua et al. 2009; Pecheux et al. 2009; Bennett et al. 2014; Gedafa et al. 2014)*. Statistically significant increases in driver yielding behavior and the number of pedestrians diverted to use treated crosswalks were observed. Ellis et al., *(Ellis et al. 2007)* evaluated the impacts of placing an in-roadway "Yield to Pedestrians" sign at different distances (at the crosswalk, 20 feet and 40 feet) in advance of a crosswalk. They found that the signs were associated with greater driver yielding and lower vehicle speeds when used directly at the crosswalk. Bennett et al. *(Bennett et al. 2014)* studied the use of in-street pedestrian crossing signs in a gateway configuration in East Lansing, MI. The presence of multiple in-street signs led to increased motorist yielding. In the same study, they also compared the gateway in-street signs with the more expensive enhancements such as the pedestrian hybrid beacon and RRFB. In-street pedestrian signs installed in the gateway configuration proved to be a viable alternative to both the pedestrian hybrid beacon as well as the

RRFB due to high levels of driver yielding. Overall, in-street pedestrian signs were considered effective treatments to improve pedestrian safety at uncontrolled crosswalk locations.

2.10 ADVANCED STOPLINES/YIELD MARKINGS

These are a type of pavement markings that are placed in advance of the crosswalk to increase the distance at which drivers must stop or yield to allow pedestrians to cross *(Mead et al. 2013)*. Early studies in Nova Scotia by Van Houten indicated decreases in vehicle-pedestrian conflicts as well as increases in motorist yielding behavior *(Van Houten 1988; Malenfant et al. 1989; Van Houten et al. 1992; Van Houten et al. 2001; Van Houten et al. 2002)*. Figure 2.4 shows a picture of an advance stop line.

Figure 2.4: Advance Stop Line, Source: Pedestrian and Bicycle Information Center

Recent research by Nambisan et al. showed that yield markings were more successful when combined with other treatments such as refuge islands *(Nambisan et al. 2007)*. Pecheux et al. *(Pecheux et al. 2009)* found no change in driver behavior or pedestrian safety at one signalized and one unsignalized location in San Francisco with advance stop lines. Hengel observed a statistically significant increase in yielding for far-lane drivers at one location in Santa Barbara with a curb extension, median island and advance stop bar *(Hengel et al. 2013)*.

2.11 TRAFFIC SIGNAL-RELATED TREATMENTS

A number of traffic signal-related treatments have also been applied to improve pedestrian safety at crosswalks at intersections. Primary among them are automated pedestrian detection, leading pedestrian interval, exclusive pedestrian phase (Barnes Dance) and pedestrian hybrid beacon (also known as the HAWK).

2.11.1 Automated Pedestrian Detection

Automated pedestrian detection attempts to sense when a pedestrian is waiting at a crosswalk and will automatically activate the "Walk" signal without any pedestrian action. This technology has also been used to dynamically increase the clearance time for slower-moving pedestrians. Some studies demonstrated statistically significant reductions in pedestrian-vehicle conflicts and in the number of people entering the crosswalk during the "Don't Walk" phase *(Hughes et al. 2000)* and a non-statistically significant decrease in late crossings *(Lovejoy et al. 2012)*. Another study showed a statistically significant decrease in the percentage of pedestrians trapped in the roadway *(Pecheux et al. 2009)*. Nambisan et al. *(Nambisan et al. 2009)* evaluated a smart lighting system that automatically increased illumination when pedestrians were detected coupled with an automated pedestrian detection system at a mid-block crosswalk in Las Vegas. They found statistically significant increases in the percentage of diverted pedestrians, motorists yielding to pedestrians and yielding distance.

2.11.2 Leading Pedestrian Intervals

A leading pedestrian interval (LPI) is a type of signal treatment where the pedestrians are given a head start typically ranging between 2-5 seconds while all other traffic is held. This allows pedestrians to enter the crosswalk and establish their presence, thus increasing their visibility before the turning vehicles start their maneuvers. A number of studies have evaluated the effectiveness of LPIs to produce a statistically significant reduction in pedestrian-vehicle conflicts *(King et al. 1999; Van Houten et al. 2000; Hua et al. 2009; and Fayish et al. 2010)* and the severity of conflicts *(King et al. 1999)*. One study also demonstrated a statistically significant increase in the number of pedestrians who used the push button and the percentage of pedestrians who crossed during the first few seconds of the "Walk" phase *(Pecheux et al. 2009)*.

2.11.3 Pedestrian Countdown Timers

Countdown timers are used with pedestrian signal heads to provide information on how much time is left to safely cross the street before a change in the signal indication to "Don't Walk." Some studies showed positive safety benefits such as a statistically significant reduction in pedestrian-vehicle conflicts *(Markowitz et al. 2006; Van Houten et al. 2014)*; safer speed decisions when approaching intersections *(Schrock et al. 2008)*; a statistically significant increase in successful crossings *(Reddy et al. 2008)*; improved pedestrian crossing behavior *(Vasudevan et al. 2011)*; and faster walking speeds and an increase in pedestrian compliance *(Sharma et al. 2012).* Other studies showed mixed results *(Eccles et al. 2004; Levasseur et al. 2011; Camden et al. 2011)*. Schrock et al. *(Schrock et al. 2008)* found that drivers used countdown timers to drive less aggressively and make better decisions about their ability to reach the intersection prior to the red indication.

2.11.4 Pedestrian Scramble

The pedestrian scramble phasing (also known as Barnes Dance) offers pedestrians an exclusive phase in which they can cross the intersection laterally as well as diagonally, while all other conflicting vehicle traffic is stopped. One study found that when pedestrian volumes are more than 1,200 crossings per day, the pedestrian scramble phase led to statistically significant reductions in pedestrian-vehicle conflicts *(Zegeer et al. 1985)*. Later studies found safety benefits via statistically significant reductions in pedestrian-vehicle conflicts *(Bechtel et al. 2004; Kattan et al. 2009; Chen et al. 2012)*, but they also showed a decrease in pedestrian compliance.

2.11.5 Pedestrian Hybrid Beacon (HAWK Signal)

A pedestrian hybrid beacon (PHB) was first installed in 2000 in Tucson, AZ. A PHB is also known as a High-intensity Activated crossWalK beacon, or HAWK signal. Prior to 2009, HAWK beacons were considered an experimental treatment. After the inclusion of PHBs in the 2009 MUTCD, they are now one of the many treatment options available to increase pedestrian safety. Figure 2.5 shows a PHB assembly.

Figure 2.5: Pedestrian Hybrid Beacon (HAWK), Photo N. Foster

Studies of PHBs looked at pedestrian crosswalk compliance, pedestrian-vehicle compliance and driver yielding behavior, and results suggest very high levels of driver yielding rates which are comparable to other red signal and beacon treatments *(Fitzpatrick et al. 2006)*. Most studies were typically completed on arterials with high levels of traffic and high speeds. Statistically significant reductions in total crashes were observed, with even greater reductions in pedestrian crashes *(Fitzpatrick et al. 2010)*. Furthermore, the proportion of trapped pedestrians was statistically significantly reduced following the installation of a PHB *(Pulugurtha et al. 2014)*.

2.11.6 Half Signals

A half-signalized intersection has a standard red-amber-green traffic signal display for the major road, stop-sign control for the minor road, and a push-button actuation for pedestrians and bicyclists crossing the major road. While half signals were allowed in the 1970s, they are currently not permitted in the MUTCD due to concerns regarding minor-street vehicular movements and their conflicts with major-street vehicular movements. Johnson *(Johnson 2015)* found that half signals were effective in providing opportunities for pedestrians and did not find that crash rates at half-signalized intersections were statistically different from a comparison group of minor-stop controlled locations. In a video review, Johnson found evidence of motor vehicles departing the minor street and coming into minor conflict with pedestrians in the crosswalk but no major conflicts. This conflict was the primary concern expressed in the decision to remove half signals from the MUTCD *(Johnson 2015)*.

2.12 EXISTING CRASH MODIFICATION FACTORS (CMFS)

A CMF is a multiplicative factor that is used to estimate the expected number of crashes after a particular treatment is implemented relative to a base condition *(Gross et al. 2010)*. A CMF greater than 1.0 indicates an expected increase in the number of crashes after the treatment is implemented, whereas a CMF less than 1.0 indicates a decrease in the number of crashes. CMFs are often used to estimate the safety benefits of alternative treatments and/or identify cost-effective strategies *(Gross et al. 2010)*. The number of crashes before the treatment was implemented must be known before applying or analyzing the impact of alternative CMFs.

2.12.1 Review of Available CMFs for PCEs

A web-based repository (www.cmfclearinghouse.org) was developed and launched by the FHWA in 2009 to provide an online archive of CMFs as well as a forum to share data about the development of new CMFs. The online repository also provides a star quality rating system to assess the quality of the research endeavor that resulted in a new CMF. The criteria for the star rating include: study design, sample size, standard error, potential bias and data source quality. The scale of the rating ranges between 1-5, with 1 being the lowest rating and 5 the best rating possible. The star rating is based on study quality and sample size.

An extensive review of this database was undertaken by the research team to categorize pedestrian treatments with and without developed CMFs. Table 2.1 lists CMFs for pedestrian treatments along with their corresponding star ratings. Only two of the countermeasures – raised medians and pedestrian hybrid beacons (HAWK signal) – have CMFs with a four or higher star rating. Only raised medians have been extensively studied, with 126 documented studies; the remaining treatments have at most seven documented studies. Furthermore, as Table 2.2 shows, a large number of treatments do not have CMFs and for these treatments it is challenging to assess their safety benefits. Also, in practice multiple countermeasures are often applied at a single location, which adds to the challenge of isolating the safety effects of a single treatment. Currently, there is very limited research on the impacts of multiple countermeasures at one location. It is a common practice to multiply the CMFs for each treatment. However, the multiplication of CMFs can overestimate the benefits because it is unlikely that the full safety improvements of individual treatments will be obtained when multiple treatments are implemented concurrently *(Gross et al. 2010)*.

Table 2.1: CMFs for Pedestrian Treatments from Clearinghouse

Countermeasure Name	CMF Available	High CMF Value	Low CMF Value	Highest Star Rating	Highest Star Rating CMF Value	Total Number of CMF Studies Available
CROSSWALKS						
High-Visibility School (Yellow) Crosswalk	✓	0.63[1]		★★★	0.63[1]	1
High-Visibility Crosswalk	✓	0.81[2]	0.60[1]	★★	0.60[1]	2
RAISED MEDIANS						
Raised Median with Marked Crosswalk	✓	0.54[1]		★★★	0.54[1]	1
Raised Median with Unmarked Crosswalk	✓	0.61[1]		★★	0.61[1]	1
Raised Median	✓	2.28[5]	0.00[4]	★★★★★	0.78[5]	126
Replace TWLTL with Raised Median	✓	0.81[3]	0.53[4]	★★★	0.53[4]	7
RAISED PEDESTRIAN CROSSINGS						
Raised Pedestrian Crosswalks	✓	0.70[5]	0.55[1]	★	0.55[1]	3
SIGNAL-RELATED TREATMENTS						
Leading Pedestrian Interval	✓	0.71[6]	0.55[6]	★★★	0.55[6]	7
Scramble Phase (Barnes Dance)	✓	1.10[2]	0.49[1]	★★	0.49[1]	2
Pedestrian Hybrid Beacon (HAWK)	✓	0.85[5]	0.31[1]	★★★★	0.71[5]	3

[1] Vehicle/Pedestrian Crashes
[2] Angle, Head on, Left Turn, Rear End, Rear to Rear, Right Turn, Sideswipe Crashes
[3] Rear-End Crashes
[4] Head-on Crashes
[5] All Crashes
[6] Vehicle/Bicycle, Vehicle/Pedestrian Crashes

Table 2.2: Pedestrian Treatments Identified in Literature without CMFs

Countermeasure Name
CROSSWALKS
Strong Yellow/Green (SYG) Crosswalk Markings
CROSSWALK ENHANCEMENTS
Pedestrian-Activated Overhead Beacons
In-Pavement Flashing Beacons
CURB EXTENSIONS
Curb Extensions
ROADWAY LIGHTING IMPROVEMENTS
All Pedestrian Lighting Systems
PEDESTRIAN OVERPASSES/UNDERPASSES
Pedestrian Overpasses/Underpasses
RECTANGULAR RAPID FLASHING BEACON
Rectangular Rapid Flash Beacon (RRFB)
IN-STREET PEDESTRIAN SIGNS
In-Street Pedestrian Signs
ADVANCED STOP LINES
Advance Stop Lines
All Advanced Yield Treatments
SIGNAL-RELATED TREATMENTS
All Automated Pedestrian Detection Systems

2.13 METHODS FOR ESTIMATING PEDESTRIAN VOLUMES

Pedestrian activity or volumes are necessary to quantify pedestrian exposure before and after a treatment has been implemented. Although non-motorized travel has been increasing, the tools and methods available to model and estimate non-motorized demand have been lagging. The recent NCHRP Report 770 *(Kuzmyak et al. 2014)* cites several methods and tools for estimating bicycle and pedestrian volumes for a variety of different scenarios. Geographic scale is an important factor that needs to be considered prior to estimating pedestrian demand. Regional, corridor and facility scales are the common geographic scales that have been used. Table 2.3, Table 2.4 and Table 2.5 show examples of different scales of models, along with the typical variables that are commonly used in estimation. These tables have been adapted and modified from NCHRP Report 770.

To estimate demand on a regional scale, the most common approach is to use the traditional four-step forecasting models. However, improvements are needed because the size of travel analysis zones (TAZs) are too large and not sensitive enough for accurate predictions of non-motorized travel. Enhancements such as reducing the size of TAZs, taking into account land use, pushing bicycle and pedestrian trips into the destination and mode choice steps, using GIS-based methods to represent finer granularity of land use, and use of microsimulation models are emerging techniques to improve model accuracy at the regional level *(Kuzmyak et al. 2014)*. Examples of corridor planning tools are scenario planning tools such as Envision Plus, EPA's

Smart Growth Index and walk trip models such as PedContext *(Urbitran Associates 2004)* and MoPeD *(Clifton 2008)*. Demand estimation at a facility level is more common.

Table 2.3: Summary of Regional Planning Models

Application Category/Approach	Examples	Typical Variables Used
Trip generation: trip generation augmented by special models that estimate non-motorized productions based on density, land use mix, accessibility, and/or urban design	Atlanta (ARC), Austin (CAMPO), Portland (Metro), Durham, NC; Buffalo	Demographic profile, employment profile, household size, household income, household age, employment category, household behavior (from travel survey)
Auto ownership: context-enhanced auto ownership an input to non-motorized trip production	Atlanta (ARC), Austin (CAMPO), Los Angeles (SCAG)	Income distribution, land use, accessibility, fuel price, auto operating cost, transit capacity, transit frequency, telecommute, freeway capacity
Destination choice: separate models to forecast trip generation for inter and intrazonal trips based on land use/accessibility context factors	Buffalo, Durham	Highway distance, non-motorized distance, travel time, parking cost, transit cost, toll cost, etc.
Mode choice: special context-sensitive models to estimate non-motorized mode split for intrazonal trips	Buffalo, Durham	Parking cost, level of service, socio-economic characteristics, availability
Activity/Tour-based models: projected replacement to trip-based models, spatial resolution reduced to parcel level and individual travelers - remove TAZ aggregation bias in clarifying non-motorized mode use; travel treated as simple versus complex tours which impact mode choice	Edmonton Transport Analysis Model; San Francisco (SFCTA), Sacramento (SACOG), many under development	Pedestrian Environment: network continuity/integrity, ease of street crossing, perception of safety and personal security, topological barriers
		Parking: average parking cost for work trip, average parking cost for other trip
		Accessibility: auto travel time, transit travel time

Table 2.4: Summary of Corridor Models

Application Category/Approach	Examples	Typical Variables Used
Scenario Planning Tools: Estimation of non-motorized travel and VMT reduction in relation to alternative land use and transportation investment scenarios	US EPA Index 4D method (2001); Frank & Co. I-PLACES (2008); Ewing, et al.—MXD model (2010); Kuzmyak, et al.—Local Sustainability Planning Model (2010)	Land Use: residential density, intersection density, land use mix, retail floor area ratio, access to parks parks/retail/food/transit Accessibility: transit peak, transit off-peak Demographic: household workers, household children, income, car per household Built Environment: density, diversity, design, destination accessibility, distance to transit
Walk Trip Models: Models that resemble four step regional approach, but employ "pedestrian" zones instead of TAZs; create trip tables and assign to facilities	PedContext – Maryland State Highway Administration and Univ of MD Nat Center for Smart Growth (2004/08); Clifton—MoPeD Model (2008)	Demographic: own vehicle or not, income Accessibility: residential, total employment, retail employment Transport System: street connectivity Socio-economic: ethnicity Land Use: retail, service, other, commercial

Table 2.5: Summary of Facility Planning Models

Application Category/Approach	Examples	Typical Variables Used
Factoring and sketch planning methods: attempt to predict facility demand levels based on peer comparisons, application of trip generation rates to sociodemographic data, association with other related data/trends, proximity rules, etc.	Lewis & Kirk (1997); Wigan, et al. (1998); Goldsmit (1997); Ercolano et al., (1997); Clark (1997); Krizek et al., (2006)	Socio-demographic: sex, skill level Economic: income Transport System: peak vehicular volumes, vehicle occupancy, grid network Land Use: retail, office, food service, residential, parking
Direct Demand: Project bicycle or pedestrian volumes based on counts related to various context and facility factors through regression models	Ashley & Banister (1989); Parkin & Wardman (2008); U.C. Berkeley—Seamless Travel (2010); Schneider et al., —Alameda (2009); Liu & Griswold (2008); Fehr & Peers—Santa Monica (2010)	Socio-economic: sex, ethnicity, socio-economic classification, age, level of qualification Geographic: distance to work place, home location (urban versus rural), type of neighborhood (car oriented or not), weather, topography Transport System: roadway condition, type of provision for cycle traffic, transport demand intensity, speed, parking, other journey end facilities, public transport alternatives Transport System: roadway condition, type of provision for cycle traffic, transport demand intensity, speed, parking, other journey end facilities, public transport alternatives Built Environment: housing density, land use, employment density, total population, population density Travel Characteristics: mode split, total commuting population

Application Category/Approach	Examples	Typical Variables Used
Aggregate demand: Seek to quantify relationship between overall demand (e.g., annual regional bike trips) and underlying factors, often as a way of gauging importance of infrastructure types and extents	Baltes (1996); Dill & Carr (2003); Buehler and Pucher (2011); Nelson & Allen (1997)	Occupation/Employment: percen workers by industry category, pe category, percent armed forces, p percent male workers, percent ur
		Availability/Attractiveness of Mo household, percent households w availability, gasoline price, trans
		Built Environment: number of bi residents,
		Land Use: population density, pe 1950, percent housing units own
		Socio-economic: income, percen
		Weather: annual number of days precipitation in inches
		Public Support: per capita annua and pedestrian improvements
Route or path choice: Methods that try to account for the characteristics of a transportation network or its users in determining route choice, and for identifying network improvement priorities	Hunt & Abraham (2006); Krizek (2006); Menghini et al., (2009); Dill & Gliebe (2008); Hood et al., (2011); Space Syntax—Raford and Ragland, Oakland pedestrian master plan (2003); McCahill & Garrick—Cambridge MA bike network (2008)	Route Characteristics: length, av gradient, percent marked bike pa traffic lights, path size, path or tr traffic volume, surface construct
		Socio-economic: sex, children or crime
		Destination: shower availability,
		Land Use: residential density, em

2.14 SUMMARY

Across the United States, walking trips have increased over the last two decades *(Pucher et al. 2011)*. Despite the increase in walking trips, pedestrian safety still remains a significant concern. In 2012, pedestrian fatalities accounted for 14% of the total motor vehicle fatalities in the U.S. *(NHTSA 2014).* As a result, many jurisdictions have taken steps to enhance pedestrian safety by implementing PCEs. A review of the literature was undertaken to understand the safety effectiveness of the various PCEs. Key findings and data gaps are summarized below:

- A number of PCEs are associated with increases in driver yielding rates and decreases in pedestrian-vehicle crashes. These PCEs include: marked crosswalks, high-visibility markings, pedestrian-activated flashing beacons, illuminated crosswalks, in-pavement lighting, curb extensions, median refuge islands, raised pedestrian crossings, lighting improvements, pedestrian overpasses and underpasses, RRFBs, in-street pedestrian signs, advanced stop lines and yield markings, signal related enhancements such as LPI, Barnes Dance, countdown timers and pedestrian hybrid beacons.

- Only 10 PCEs have an associated CMF; there are 13 PCEs with no CMF. Only raised medians have been extensively studied and documented.

- There is a critical gap regarding the availability of high-quality CMFs. Currently, high star rating CMFs are only available for raised medians (five stars) and pedestrian hybrid beacons (four stars).

- CMFs are critical for understanding and improving multimodal safety and comparing alternative treatments. Methods for developing CMFs are well-documented but data availability for pedestrians, especially sufficient crash and exposure data, limits the number of feasible estimation methods.

- Methods and models to estimate pedestrian demand have not kept pace with the increase in pedestrian demand. New methods to quantify pedestrian exposure are emerging but their application to safety studies is challenging. Most methods are suitable for medium to large geographic scales – not at the block level. In addition, most of the variables are often not easily transferable between scales.

3.0 DATA COLLECTION

An extensive data collection effort was undertaken to both 1) identify crossing improvements across the state and 2) gather relevant information about the crossing location, including linking to the reported crash data. This section describes the methods used to accomplish these efforts.

3.1 IDENTIFICATION OF CROSSING LOCATIONS

The first step in the data collection process was to develop a list of pedestrian crossing enhancements in Oregon. ODOT, regional and local agencies were contacted by the research team and were requested to provide a list of pedestrian crossing enhancements in their jurisdictions. The initial sample provided to the research team consisted of the following enhancements: rectangular rapid flashing beacons (RRFBs); high-intensity activated crosswalk beacons (HAWK); flashing amber, high-visibility crosswalks; unmarked and marked crosswalks; standard parallel crosswalks; pedestrian signals; and half signals. The research team reviewed the listed locations one at a time.

Figure 3.1 shows a flowchart of the data collection methodology. In order to collect supplemental data elements, it was first necessary to determine whether the crossings were a part of the state system. If the crossing locations were on the state system, ODOT's digital video log (DVL) imagery was available for data collection in addition to Google Streetview. Pedestrian crossing enhancement installation date was an essential data field. An accurate installation date is necessary to compile and compare crash histories pre- and post-PCE installation. For locations on the state system, DVL photos for each year were available to determine the PCE installation year. For off-state system locations, a similar process was carried out using Google Streetview. However, in many locations the Google Streetview history is not complete (i.e., images for several years are missing). In these cases, the research team tried to obtain the installation date directly from the jurisdiction. If the installation date could not be determined, even after several requests and agency contacts, the pedestrian crossing enhancement with a missing installation data was discarded from the sample. Sample size was a major concern throughout this task. For PCE categories with a low number of records, repeated efforts were made to reach out to the relevant agency before discarding a PCE location.

Figure 3.2 shows the distribution of the 191 crossings in the final sample by type and region. Of these, 139 (72%) crossings were located on ODOT facilities. The majority of the RRFBs are present in ODOT Regions 1, 2 and 3. Nine of the 14 flashing amber enhancements in the sample are found in Region 2. High-visibility crosswalks were more evenly distributed across the regions, with the majority of them in Region 5. The vast majority of the standard parallel crosswalks in the sample were located in Region 5.

Ultimately, the research team decided to focus on four types of PCEs: RRFBs, flashing amber, high-visibility and standard parallel crossings. Figure 3.4 shows images of the typical type of crossing in each category. Other than location, detailed data collection was not undertaken for the standard parallel crossing locations. Pedestrian hybrid beacons (PHB) and pedestrian signal enhancements were excluded from the detailed data collection due to their small sample size. Half signals, which are used extensively in the city of Portland (but are not common in other cities in Oregon) were also excluded since they are not currently allowed in the MUTCD. A half-signalized intersection has the standard red-amber-green traffic signal display for the major road, stop-sign control for the minor road, and a push-button actuation for pedestrians and bicyclists. Figure 3.3 shows a map displaying the locations of the crossings (including the standard parallel locations). Appendix B contains the list of identified locations that are included in the study.

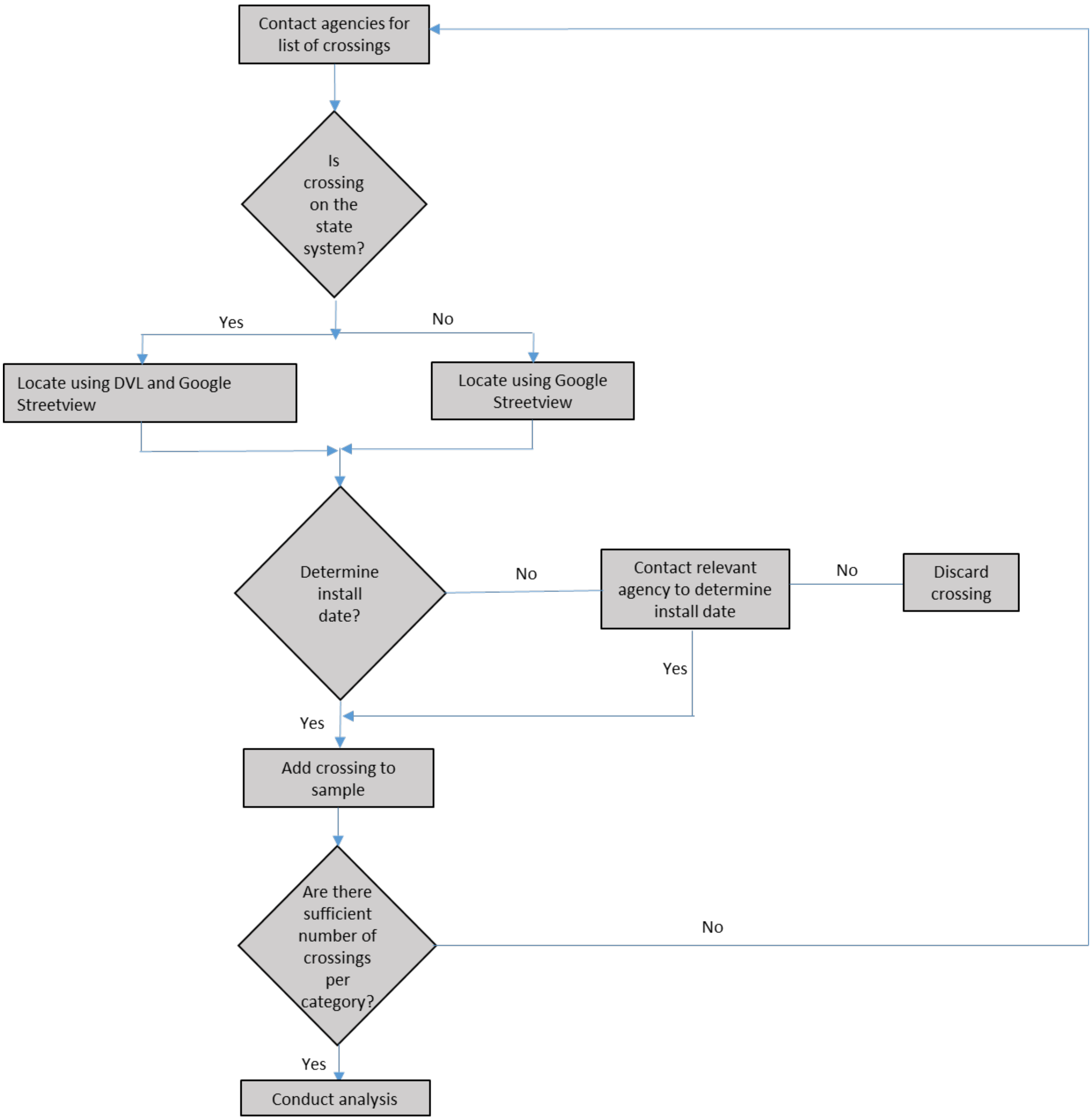


Figure 3.1: Data Collection Approach

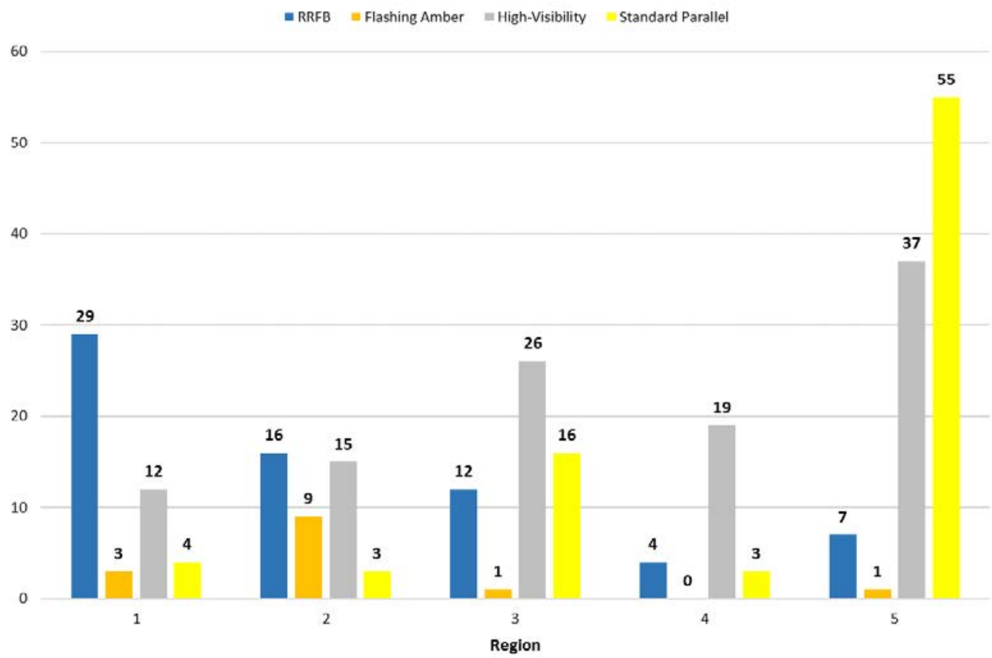


Figure 3.2: Distribution of Crossings by Type and Region

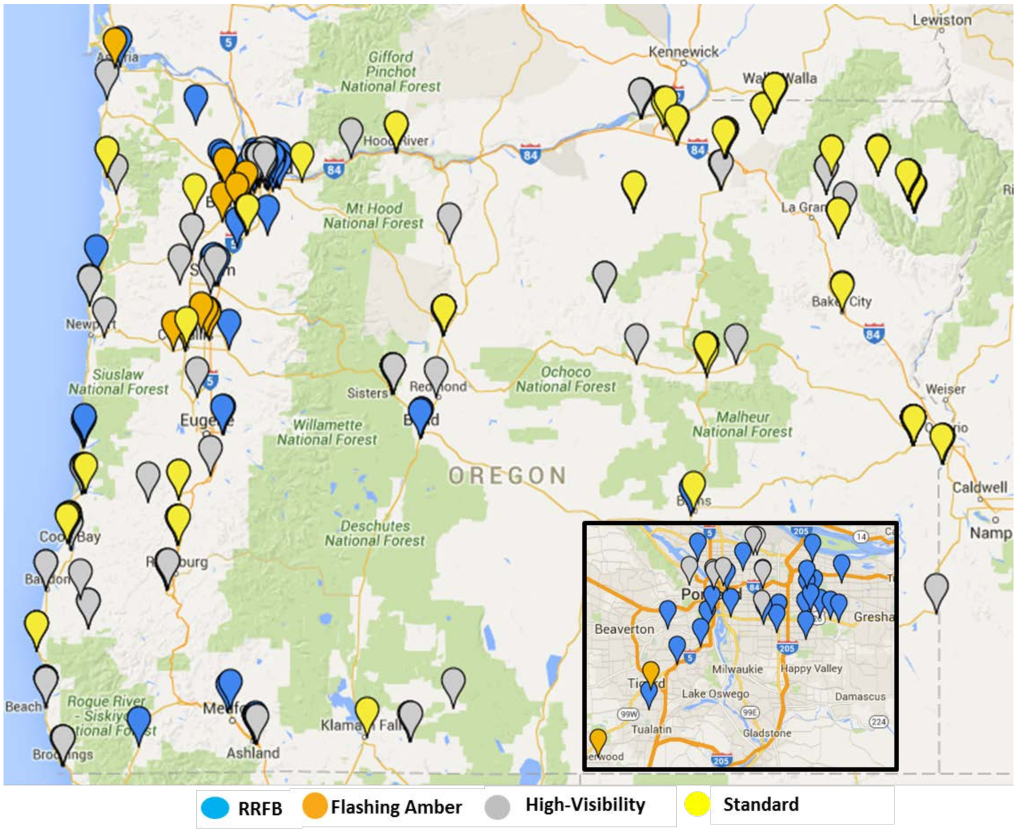


Figure 3.3: Crossing Enhancement Locations

Standard Parallel

High-Visibility

Flashing Amber

RRFB

Figure 3.4: Images of Crossing Types

3.2 DATA COLLECTION

With the crossing installation date determined, the team proceeded with supplemental data collection about each crossing. The 2005 study to determine the safety effects of marked versus unmarked crosswalks at uncontrolled locations *(Zegeer et al. 2005)* and the FHWA report on the safety effectiveness of HAWK pedestrian crossing treatment *(Fitzpatrick and Park 2010)* were studied as potential models for supplemental data collection. Zegeer et al. collected a number of data elements such as location description, number of lanes, median type, type of crosswalk, condition of crosswalk markings, speed limit, estimated pedestrian ADT and traffic ADT. Fitzpatrick and Park divided the intersections into reference groups based on major cross-section, major speed limit, refuge island on the major, intersection type, major- and minor-road ADT, and estimates of pedestrian ADT.

Data collection was undertaken for the following categories: RRFBs, flashing amber and high-visibility crosswalk markings. The supplemental data include crossing location information, route characteristics, surrounding land use and crossing enhancement descriptions. For locations on the state system, the research team obtained DVL photos for available travel directions and years (at some locations there is only one-way traffic). Due to ODOT protocols, video log images are not collected on minor highways every year. Figure 3.5 shows an example of the image sequence for data collection. For each year, the images were mined to collect data elements pertaining to route characteristics, surrounding land use and crossing enhancement descriptors.

3.2.1 Crossing Location

Crossing location data was collected for each record in the sample. Table 3.1 shows the data fields collected. A unique crossing ID was created and assigned for each crossing in the samples so that multiple datasets could be linked. Other data include the year the data was collected and the location of the crossing (i.e., ODOT region, route, city/town, milepost, latitude, longitude). Additionally, a description of the crossing location and a link to the image showing the crossing location were also collected. Most of this information was obtained from the agency contacts directly, from observation of the digital video log and/or Google Streetview. For each crossing, the research team collected data for each year the DVL or Google Streetview images were available, and noted any significant changes that occurred.

Table 3.1:Crossing Location Information

Data Element	Description
Crossing ID	Number assigned to each crossing in the sample
Year	Year the data was collected
Crossing Source	Source that provided the crossing data
ODOT Region	ODOT region the crossing is located in
Route	Roadway the crossing is installed on
Functional Class	Functional class of roadway
City/Town	City/town where the crossing is located
Crossing Location	Detailed description of the crossing location
Milepoint	Milepoint along the route where the crossing is located, if available
Latitude	Latitude of the crossing location
Longitude	Longitude of the crossing location
Image Link	Digital video log or Google Streetview link of the crossing location
Image Date	Date of the image used for data collection

Add Direction **Non-Add Direction**

2010

2011

2012

2013

2014

Figure 3.5: Sample Image Sequence for Data Collection (Crossing ID 172)

3.2.2 Route Characteristics

Roadway characteristics along with the crossing location were also gathered as part of the data collection process. These included whether the route was one way, posted speed, number of lanes, lane description, number of bike lanes, presence of sidewalks and AADT at the crossing location. Table 3.2 shows the various data elements collected as part of the route characteristics. Most of these data elements were collected using ODOT's digital video log images and/or Google Streetview. The AADT information was collected using ODOT's TransGIS viewer and/or obtained via agency contacts. As these data elements were collected for each year the DVL or Google Streetview images were available, changes in route characteristics over time were also documented.

Table 3.2: Route Characteristics

Data Element	Description
One Way	Whether the route is one way, (yes/no)
Posted Speed	Posted speed at the crossing location (mph)
Number of Lanes	Number of lanes crossed by pedestrians at the crossing location
Lane Description	Description of all lanes crossed; (THRU, TWLTL, LT, RT etc.)
Bike Lane(s)	Number of bike lanes at the crossing location; (0, 1 or 2)
Sidewalk(s)	Number of sidewalks at the crossing location; (0, 1 or 2)
AADT	Annual Average Daily Traffic

3.2.3 Surrounding Land Use

Pedestrian volume at the crossing locations is also an important part of the route characteristics, especially for estimating exposure. However, because of a general lack of pedestrian volumes, this information on land use was collected to characterize the level of pedestrian activity.

Detailed data on the land use surrounding the crossing locations was collected. The data elements in this category included information on presence of bus stops and bus shelters, and presence of and distance to major shopping centers, hospitals and schools. Table 3.3 shows the data elements that were collected as a part of the data collection for surrounding land use characteristics. These elements were obtained using ODOT's digital video log and/or Google Streetview. The distance to these bus stops and shelters, shopping centers, schools, hospitals and traffic signals was computed if they were within one mile of the crossing location and along or near the roadway on which the crossing was located. These elements were obtained using the measurement tool in Google Maps.

Table 3.3 Surrounding Land Use Characteristics

Data Element	Description
Bus Stop	Is a bus stop located near the crossing location; yes/no
Bus Stop Shelter	Is a bus stop shelter located near the crossing location; yes/no
Distance to Bus Stop/Shelter (ft)	Distance to nearest bus stop, measured from the edge of the crossing
Major Shopping Center	Is there a major shopping mall located near the crossing location; yes/no
Distance to Major Shopping Center (ft)	Distance to nearest shopping center, measured from the edge of the crossing
School	Is there a school near the crossing location; yes/no
Distance to School (ft)	Distance to nearest school, measured from the edge of the crossing
Hospital	Is there a hospital near the crossing location; yes/no
Distance to Hospital (ft)	Distance to the nearest hospital, measured from the edge of the crossing
Distance to Signal (N/W)	Distance to the nearest signal, measured from the center of the crossing
Distance to Signal (S/E)	Distance to the nearest signal, measured from the center of the crossing

Additionally, past literature and other sources were explored to identify any pedestrian-specific land use classifications that could be used to understand the level of pedestrian activity at the selected crosswalk location. Currans et al. *(Currans et al. 2014)* defined five neighborhood concepts (AB, C-F) on the urban-suburban spectrum using three measures of the built environment – density, diversity and design – and classified the census blocks in Oregon based on these categories. Figure 3.6 shows a map of the neighborhood concepts for Oregon with the crosswalk locations. Each crosswalk was assigned a neighborhood concept based on its location with respect to the census block group.

In another study, Chen et al. *(Chen et al. 2013)* developed five area types for classifying household locations within census blocks based on accessibility metrics. For each crosswalk location, these area types were determined and are listed below:

- Major urban center
- Urban near major city
- Rural near major city
- Isolated city
- Rural

"Walk Score" was another metric that was collected to determine the walkability of the crosswalk location to provide some guidance on expected pedestrian volumes. Walk score uses the distance from the location to surrounding amenities, population density, block length and intersection density to determine a score for each location. Walk scores range from 0-100, with 0 being least walkable and 100 being most walkable. For each crosswalk location, using the latitude and longitude, Walk scores were extracted.

Since pedestrian volumes were unavailable for most crosswalk locations, the research team decided to determine ranges for pedestrian activity levels in order to account for exposure. These ranges were based on the land use classification of the census block within which the crosswalk was situated and the presence of pedestrian traffic generators within 1,320 feet (0.25 mile) of the crosswalk. Bus stops, schools, shopping centers and hospitals were considered as the distances to these generators were collected as part of the data collection process. Six ranges of volumes were defined – very low, low, medium-low, medium, medium-high and high. These were determined based on the criteria below. The parameters to score the estimated levels of activity, which have not been validated, are shown in Table 3.4. To balance the land use and levels by urban and rural uses, separate categories were created.

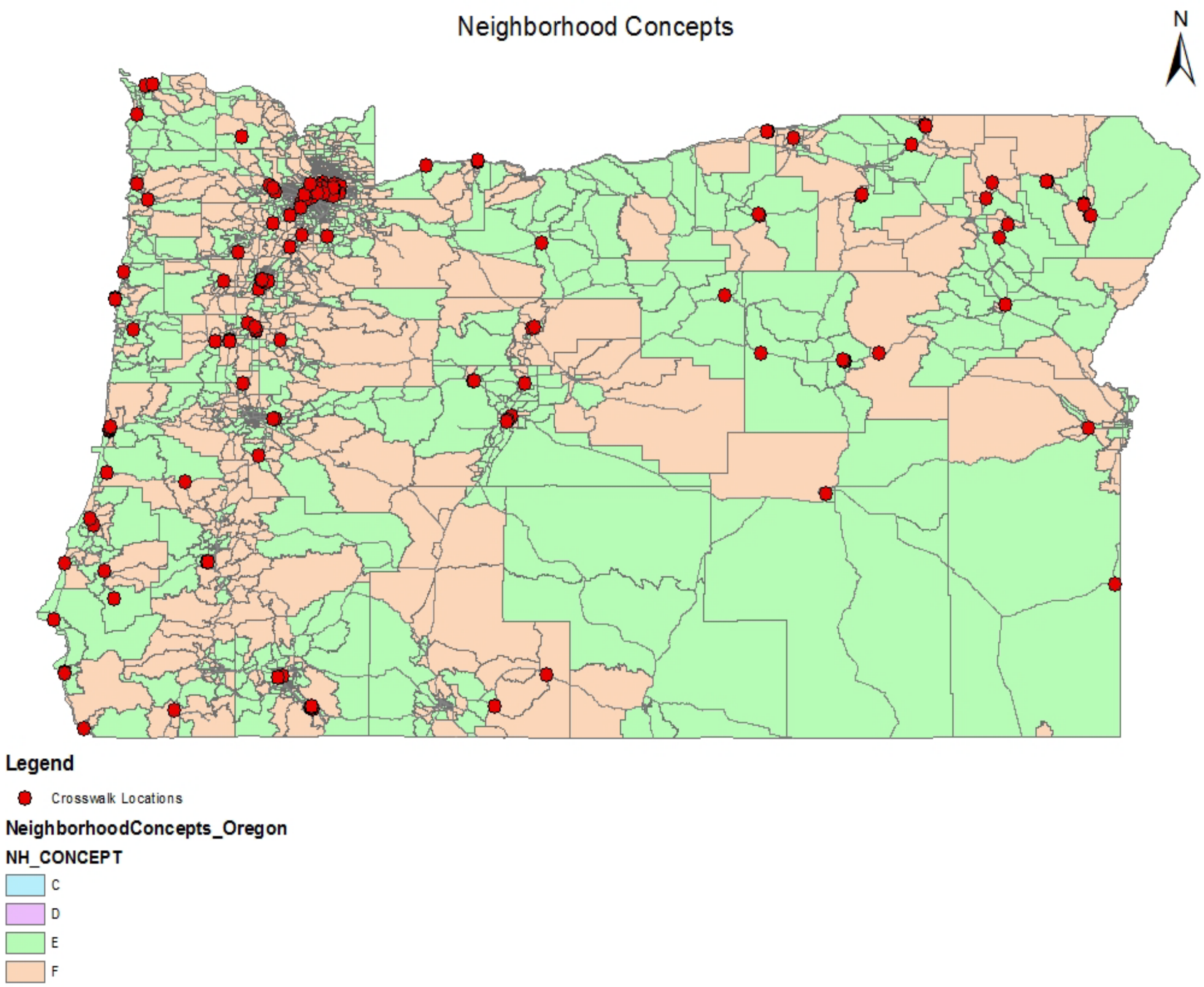


Figure 3.6: Neighborhood Concepts for Oregon

Table 3.4: Estimated Level of Pedestrian Activity

Estimated Pedestrian Activity Level	Isolated/Rural	Major Urban Center/Urban near Major City
Very low	Presence of any one – bus stop, school, shopping center or hospital within ¼ mile (1,320 ft)	NA
Low	Presence of any two – bus stop, school, shopping center or hospital within ¼ mile	Presence of any one – bus stop, school, shopping center or hospital within ¼ mile
Medium-Low	NA	Presence of any two – bus stop, school, shopping center or hospital within ¼ mile
Medium	Presence of any three – bus stop, school, shopping center or hospital within ¼ mile	NA
Medium-High	NA	Presence of any three – bus stop, school, shopping center or hospital within ¼ mile
High	Presence of all four – bus stop, school, shopping center, and hospital within ¼ mile	Presence of all four – bus stop, school, shopping center or hospital within ¼ mile

3.2.4 Crossing Enhancements

Data on additional signs and markings present at the crossing enhancements were also noted for each year. These elements were obtained using ODOT's digital video log and/or Google Streetview images. These included crosswalk markings, lighting at the crossing location, curb ramps and raised medians, data on various crossing signs and installation date. A significant change flag column was also created to note any important changes to the crossing location each year. Since all these data elements were collected for each year, the crossing category column was used to understand how each PCE evolved. Table 3.5 shows the data elements that were collected in this category.

Table 3.5 Crossing Enhancements

Data Element	Description
Installation Date	Installation date of the crossing enhancement (year)
Significant Change Flag	Flag to denote significant changes each year of operation; (yes/no)
Notes	Description of significant change, if any
Crossing Category	Crossing category (RRFB, HI-VIS, FLASH, STANDARD)
Crosswalk Markings	Is the crossing marked; (yes/no)
Crosswalk Marking Type	If yes, type of marking; (Continental, Ladder, Diagonal, Bar Pair)
High-Visibility Crosswalk	Are the markings high visibility; (yes/no)
Advance Stop Bar	Number of advance stop bars in travel lanes leading up to the crossing; (0, 1 or 2)
Pedestrian Warning Sign	Are pedestrian warning signs present at the crossing location; (yes/no)
School Warning Sign	Are school warning signs present at the crossing location; (yes/no)
Overhead Sign	Are overhead signs present at the crossing location; (yes/no)
Number of Light Poles	Number of light poles present at the crossing location; (0, 1 or 2)
Number of Curb Ramps	Number of curb ramps at the crossing location; (0, 1 or 2)
Number of Curb Extensions	Number of curb extensions at the crossing location; (0, 1 or 2)
TWLTL	Is a two-way, left-turn lane present at the crossing location; (yes/no)
Raised Median	Is a raised median present at the crossing location; (yes/no)
Pedestrian Refuge Island	Is a pedestrian refuge island present at the crossing location; (yes/no)
Raised Pedestrian Crossing	Is the crossing raised; (yes/no)
Yellow/Amber Flashing Beacons	Are flashing beacons present at the crossing location; (yes/no)
Number of Flashing Beacons	Number of beacons at the crossing location
Yield/Ped/X-ing Pavement Marking	Are there markings indicating a crossing ahead prior to the crossing location; (yes/no)
Yield Here to Peds Sign	Are there “Yield Here to Pedestrians” signs at the crossing location; (yes/no)
Crosswalk Stop on Red Sign	Are there “Crosswalk Stop on Red Signs” at the crossing location; (yes/no)
Number of RRFB Assemblies	Number of RRFB assemblies counted in both directions
Stop Here for Pedestrian Sign	Are there “Stop Here for Pedestrians” signs at the crossing location; (yes/no)
Pedestrian Advance Sign Assembly	Number of advance pedestrian crossing head assemblies prior to the crossing; (0, 1 or 2)
School Advance Crossing Assembly	Number of advance school crossing ahead assemblies prior to the crossing; (0, 1 or 2)

The significant change flag column is the most subjective of the data fields as it was primarily derived based on observation of the site images. As such, if the site image was unavailable for a particular year and there was no change in crossing category, this field could not be populated. For Figure 3.5, the year 2012 will be flagged as a “significant change,” as an RRFB was added at the crossing location.

3.3 CRASH DATA

Statewide geolocation of reported crashes in Oregon began in the 2007 data year. To merge and extract the crash data for safety analysis, locations of all the crossing enhancements were mapped in ArcGIS® using the latitude and longitude of the location at the center of the crossing. The crashes for each year were also imported into ArcGIS® using the latitude and longitude. A circular buffer of 300 feet was constructed around each crossing, as shown in Figure 3.7. The Oregon crash database was then queried to extract crashes that occurred at each crossing buffer during 2007-2014.

Only crashes contained within the 300-foot buffer and along the roadway that contains the PCE were extracted. All crashes in the buffer area were linked to the crossing location. Using the buffering process, pedestrian and rear-end motor vehicle crashes were collected at the crossings with RRFBs, flashing amber beacons and high-visibility crosswalk markings between 2007 and 2014 using a 300-foot buffer, along the major facility where the crossing location was situated. A total of 124 pedestrian and 1,043 rear-end crashes were gathered at the crosswalks in the sample using a 300-foot buffer around each crosswalk. These crashes were further filtered to identify only those crashes that could be attributed to the crosswalks. All pedestrian crashes that occurred between the crosswalk and the nearest intersection within the 300-foot buffer were retained and the rest were not included in the analysis. For rear-end crashes, a buffer of 150 feet was used. This distance was determined by calculating the distance from the center of the crosswalk to the rear-end crash location for all crashes in the 300-foot buffer, and then determining the 70th percentile distance. Using this process, 62 pedestrian crashes and 746 rear-end crashes were retained for further analysis.

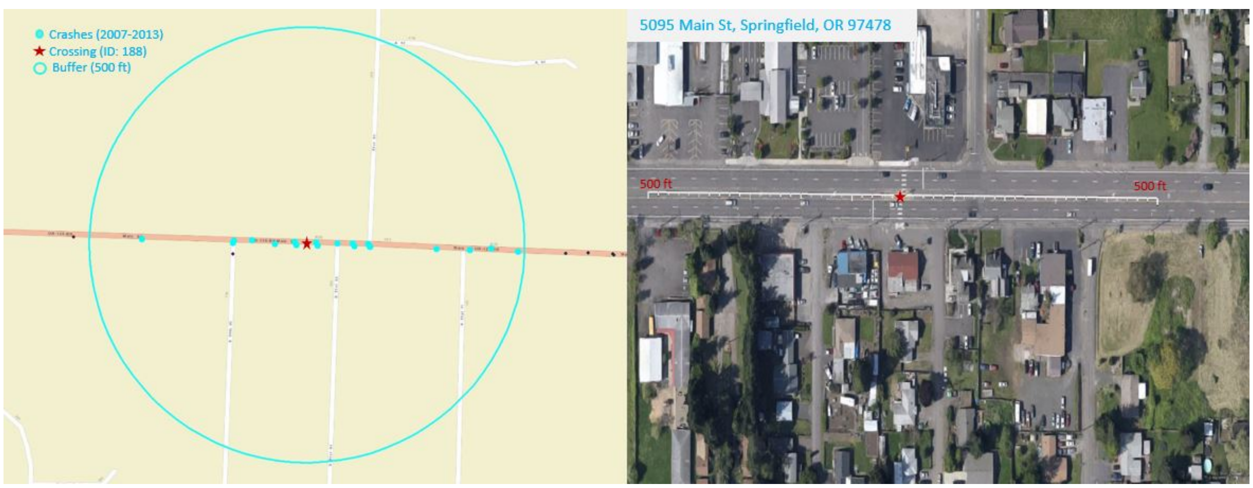


Figure 3.7: Example of Crash Merging Buffer

4.0 DESCRIPTIVE DATA ANALYSIS

This chapter presents first a descriptive analysis of crossing and crash data for the 191 crosswalk locations with pedestrian crossing enhancements. The chapter ends with an analysis of risk ratios for pedestrian and rear-end crashes and a chapter summary.

4.1 CROSSING DATA

4.1.1 Installation Year

Table 4.1 shows the distribution of 191 crossings by installation date based on the crossing configuration in 2014. More than 92% of the RRFBs, 63 out of 68 in the sample, were installed between 2011 and 2014. Only 21% of the high-visibility crosswalks, 23 out of 109 in the sample, were installed between 2011 and 2014. There are only 14 crosswalks with flashing amber beacons, most of them (71%) installed before 2011.

Table 4.1: Number of Enhanced Crossings by Install Year

Year	1997	2000	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	TOTAL
RRFB	-	-	-	-	-	-	-	-	1	4	14	17	19	13	68
FLASH	-	-	-	1	-	4	1	3	1	-	1	2	1	-	14
HI_VIS	1	2	9	9	1	24	18	8	13	1	11	5	3	4	109

Most crossings have been enhanced over the data collection period. Two figures were created to summarize the changes in crosswalk configuration over time. Figure 4.1 shows the frequency of each crossing type by year of all 191 crossings in the sample. In the figure, all unmarked crossings in the sample in 2007 have been marked by 2014. Similarly, all of the standard marked crossings have been enhanced. To further visualize the changes in each of the individual crossing treatments over time, the distribution of treatment types by year and by crossing are shown in Figure 4.2. This figure shows that RRFBs have been installed at locations that previously had seven standard markings, seven flashing amber treatments, and 22 high-visibility treatments. A total of 32 previously unmarked mid-block locations have been treated with RRFBs since 2009.

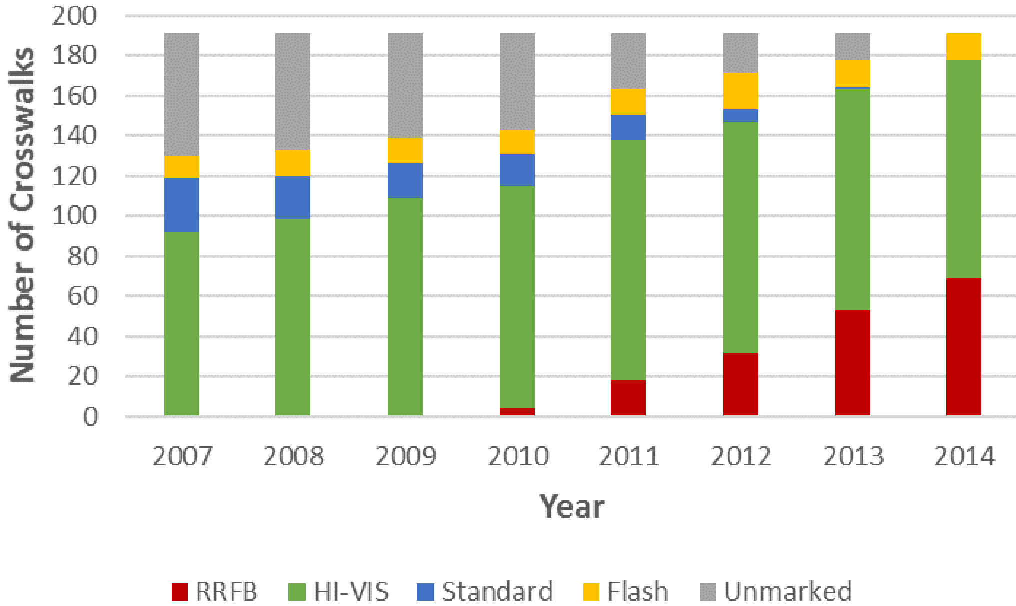


Figure 4.1: Number of Crossings in Each Category by Year

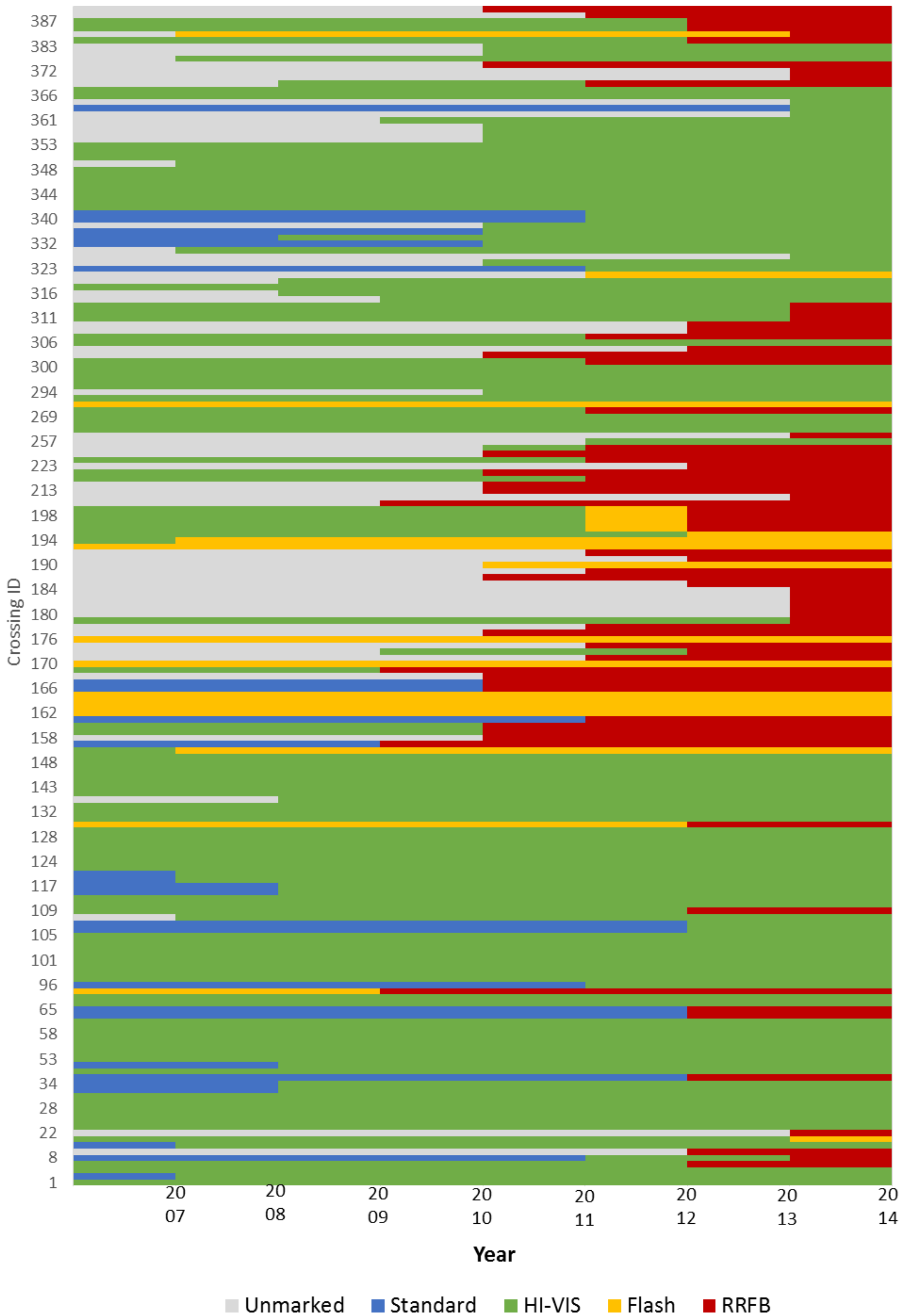


Figure 4.2: Crossing Treatments by Year and Location

4.1.2 Descriptive Summary

Table 4.2 presents the descriptive statistics for the continuous variables, and Table 4.3 shows the descriptive statistics for the categorical variables in the sample. These statistics are calculated only for the 191 crossings with RRFBs, flashing amber beacons and high-visibility markings. The number of lanes at the crosswalk locations varied between a minimum of two and a maximum of five, with a mean of 3.2 lanes. The maximum posted speed was 45 mph with a mean of 31 mph. Most locations have sidewalks on both sides (mean 1.78, median 2) with curb ramps (mean=1.80, median 2). Histograms are provided for a selected number of variables in Figure 4.3.

Table 4.2: Descriptive Statistics - Numerical Variables (n=191)

Data Element	Number of Obs.	Mean	Median	Standard Deviation	Max	Min
Number of Lanes	191	3.21	3	1.13	5	2
Posted Speed (mph)	190	30.76	30	6.49	45	20
AADT (2014)	160	10,302	9,100	7,286	37,244	480
Number of Bike Lanes	191	1.16	2	0.97	2	0
Number of Sidewalks	190	1.78	2	0.56	2	0
Distance to Bus Stop Shelter (ft)	113	376.89	220	457.54	2,697	5
Distance to School (ft)	142	1,278.37	956	1235	5,913	5
Distance to Hospital (ft)	21	2,193.71	2048	1,506.99	6,336	50
Distance to Shopping Center (ft)	27	1046.67	536	1367.72	5650	21
Distance to Signal (N,W) (ft)	119	1,614.76	1,277	1,657.06	11,880	238
Distance to Signal (S,E) (ft)	105	1,549.77	1,083	1,317.21	8078	251
Number of Light Poles	191	0.81	1	0.71	2	0
Number of Curb Ramps	191	1.80	2	0.56	2	0
Number of Curb Extension	190	0.41	0	0.79	2	0
Number of Ped Advance Sign Assemblies	191	0.55	0	0.88	2	0
Number of School Advance Sign Crossing Assembly	189	0.64	0	0.92	2	0

Most of the crossings are located near a facility or land use type that may attract pedestrian traffic (school, bus stop, hospital, or commercial center). On average, the mid-block crossings in the sample were within 1,500 feet of a school or traffic signal. Similarly, the mean distance to the nearest school was 1278.37 feet.

About 72% of the crossing locations were located on a state highway. At the crossing locations, the majority of the roads have two-way traffic (95.8%). Similarly, most of the crossing locations did not have school signs (68.06%) or overhead signs (90.58%). There is only one location with a raised crossing, whereas 66.49% had a pedestrian refuge island. About 59% of the crossings had a bus stop present at or close to the crossing, while 86.38% of these locations did not have a bus stop shelter. About 56% of the crossing locations did not have a two-way, left-turn lane. (Table 4.3 presents the descriptive statistics in categorical variables.)

Table 4.4 presents the distribution of crossings by estimated pedestrian activity level. A total of 84% of the crossings were in land use areas considered to generate very low or low levels of pedestrian activity. Table 4.5 shows the distribution of the crossings by functional class. Most crossings are on arterial level roadways.

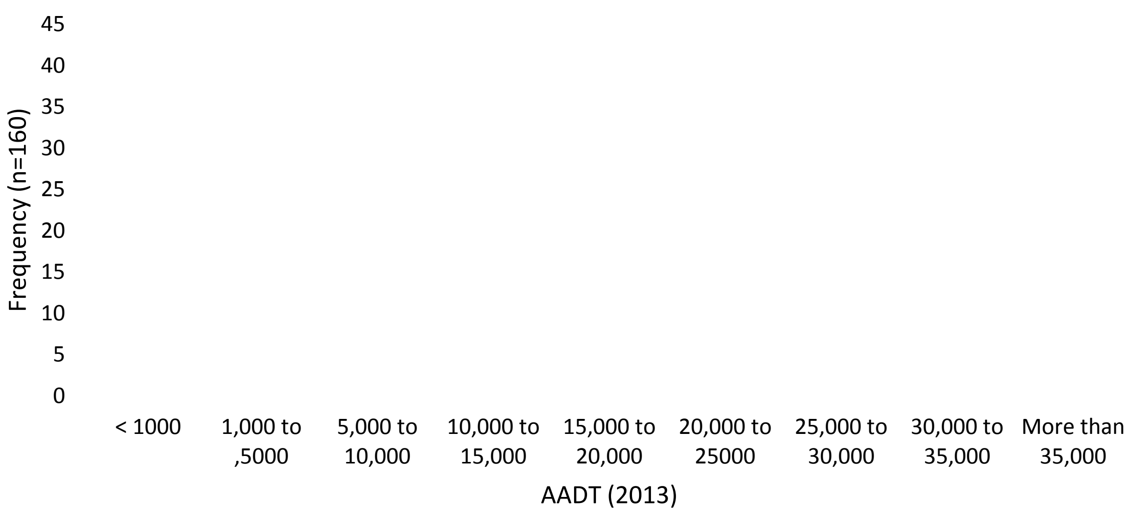


Figure 4.3: Histograms of Selected Continuous Variables

Table 4.3: Descriptive Statistics - Categorical Variables (n = 191)

Data Element	Yes	No
State Highway	139 (72%)	52 (28%)
One Way	9 (4.71%)	183 (95.81%)
Bus Stop at Crossing	113 (59.16%)	78 (40.84%)
Bus Stop Shelter	26 (13.61%)	165 (86.38%)
Major Shopping Center	27 (14.13%)	164 (85.86%)
Hospital	19 (9.9%)	172 (90.1%)
School	143 (74.86%)	48 (25.13%)
Pedestrian Signs	93 (48.69%)	98 (51.31%)
School Signs	61 (31.93%)	130 (68.06%)
Overhead Signs	18 (9.42%)	173 (90.57%)
Two-Way, Left-Turn Lane	84 (43.97%)	107 (56.02%)
Raised Median	20 (10.47%)	171 (89.53%)
Pedestrian Refuge Island	64 (33.51%)	127 (66.49%)
Raised Pedestrian Crossing	1 (0.00%)	189 (98.95%)
Yield Pavement Marking	15 (7.85%)	176 (92.15%)
Stop on Red Sign	0 (0.00%)	191 (100%)
Stop Here for Ped Sign	68 (35.60%)	123 (64.39%)

Table 4.4: Crossings by Estimated Level of Pedestrian Activity (n = 191)

Pedestrian Land Use	Percent of Crossings
Very low	45
Low	39
Med- low	14
Medium	0
Med - high	2

Table 4.5: Functional Class of Crossing (n = 191)

Functional Classification	Number	Percent
Other Urban Principal Arterial	64	33.51
Urban Minor Arterial	29	15.18
Urban Collector	12	6.28
Rural Other Principal Arterial	59	30.89
Rural Minor Arterial	14	7.33
Rural Major Collector	13	6.81
Total	191	100.00

4.2 CRASH DATA

This subsection presents pedestrian and rear-end crash data descriptive statistics. The final category of crossing was used to determine the before-and-after time windows.

4.2.1 Pedestrian Crashes

For background, Table 4.6 provides a summary of pedestrian crashes and injuries reported in Oregon between 2004 and 2011. A total of 540 persons were fatally injured and another 1,142 persons sustained major injuries. A further 3,893 sustained moderate injuries and 2,657 had minor injuries. Note that reported property damage only (PDO) crashes are relatively low (59) since most reported vehicle pedestrian crashes result in an injury.

Table 4.6: Summary of Oregon Pedestrian Crashes and Injuries, 2004-2014

Year	Crashes						Injuries (Persons)				
	Fatal	Major Injury	Mod. Injury	Minor Injury	PDO	Total	Fatal	Major Injury	Mod. Injury	Minor Injury	Total
2004	44	73	278	156	0	551	45	75	296	168	584
2005	47	119	286	155	2	609	48	125	315	173	661
2006	47	126	313	168	3	657	47	131	333	195	706
2007	49	100	259	146	4	558	49	104	277	159	589
2008	48	90	237	200	4	579	50	91	254	220	615
2009	38	86	294	209	11	638	38	89	313	234	674
2010	58	93	377	237	1	766	59	102	404	263	828
2011	45	111	368	289	6	819	45	115	387	323	870
2012	60	102	420	299	6	887	60	106	451	337	954
2013	47	91	401	252	15	806	49	96	426	276	847
2014	50	104	418	274	7	853	50	108	437	309	904
Total	533	1095	3651	2385	59	7723	540	1142	3893	2657	8232

Descriptive statistics for pedestrian crashes at crossing locations with pedestrian enhancements (RRFBs, flashing amber beacons and high-visibility crosswalk markings) are presented in this section. Figure 4.4 shows the distribution of pedestrian crashes before and after enhancements were deployed. A total of 30 and 26 pedestrian crashes were observed at crosswalks before and after the installation of pedestrian enhancements, after excluding the crashes that occurred during the installation years. It is important to highlight that the time durations for the before-and-after periods are not the same in terms of treatment years.

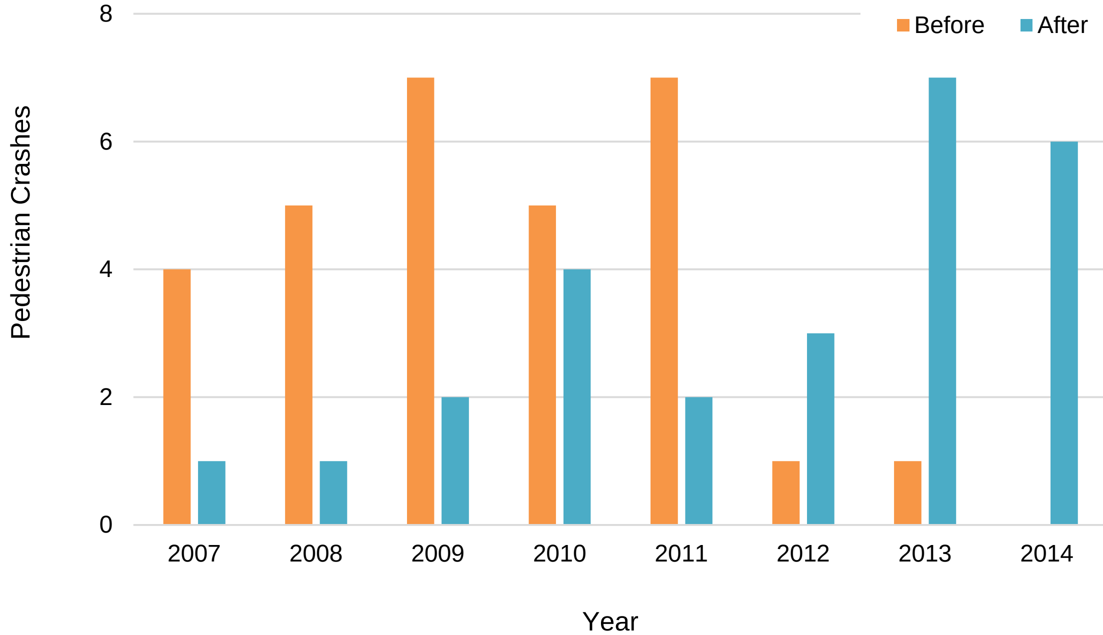


Figure 4.4: Pedestrian Crashes Before and After a Pedestrian Crossing Enhancement Installation

Table 4.7 shows the distribution of pedestrian crashes before and after enhancement installations by crash cause. Due to different before-and-after treatment durations, Table 4.7 shows crash percentages by cause. The majority of the crashes, before and after, were reported as caused by drivers' "no-yield" behavior. Other reported crash causes included pedestrians in roadway, inattention, carelessness, recklessness, and excessive speed.

Table 4.7: Distribution of Pedestrian Crashes by Crash Cause

Crash Cause	Before Crashes (%) n=30	After Crashes (%) n=26
Careless	--	3.8
In Roadway	30.0	7.7
Inattention	10.0	--
No Yield	50.0	73.1
Not Visible	--	7.7
Other	3.3	--
Recklessness	--	7.7
Speed	3.3	--
Too Fast	3.3	--

Note: "--" is zero percent in the category.

Figure 4.5 shows the distribution of pedestrian crashes before and after the installation of an enhancement by level of severity. Due to different before-and-after treatment durations, Figure 4.5 shows crash percentages by severity. Before enhancement, 13% of pedestrian crashes were fatal, 23% were categorized as injury A, 43% as injury B and 20% as injury C crashes. After the enhancements were installed, the level of severity decreased with a clear reduction in fatal and injury A crash percentage. The severity trend is an important shift to present by crossing type.

For each of the three crossing types, the severity distribution is shown for RRFB in Figure 4.6, Flash in Figure 4.7, and Hi-Vis in Figure 4.8. The severity shifts are reflective of the overall trend. Some of the shift in severity may be regression-to-the-mean effects since the locations were most likely selected for treatment based on crash history.

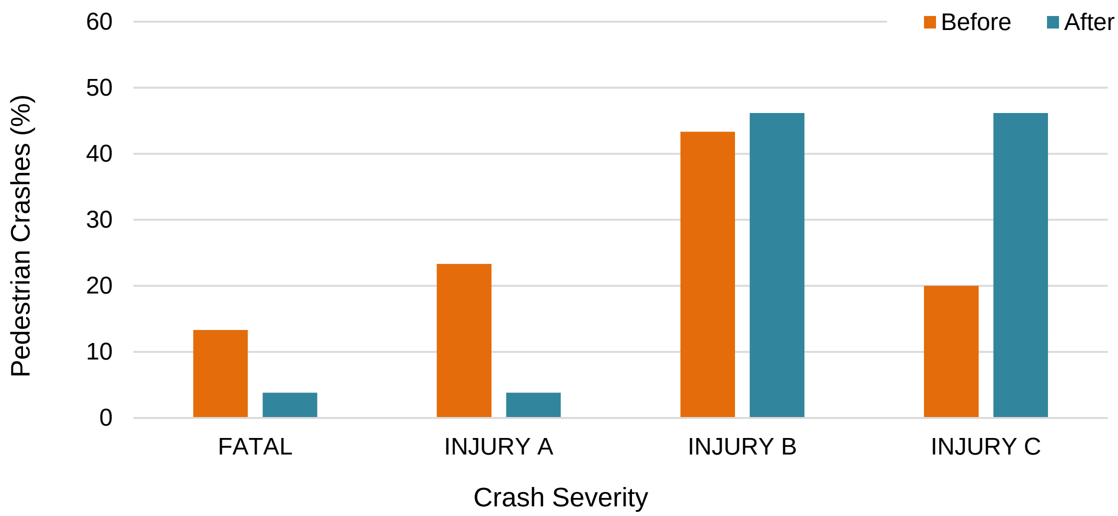


Figure 4.5: Distribution of Before-and-After Pedestrian Crashes by Level of Severity

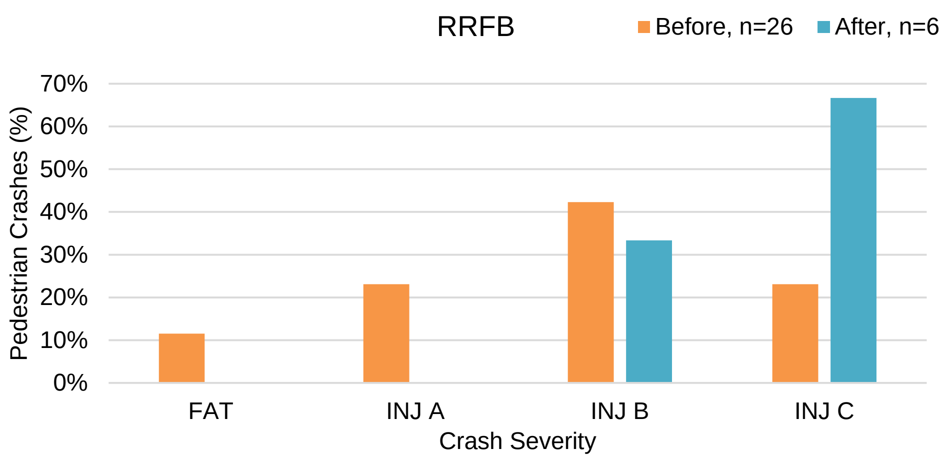


Figure 4.6: Distribution of Before-and-After Pedestrian Crashes by Level of Severity, RRFB

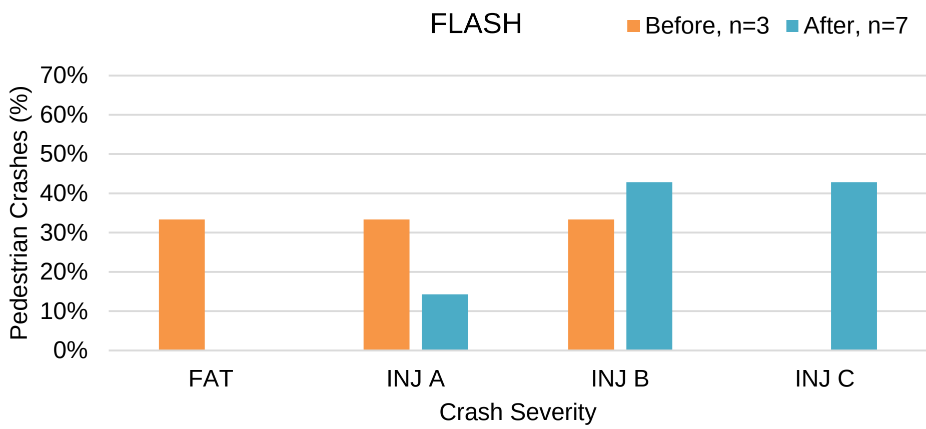


Figure 4.7: Distribution of Before-and-After Pedestrian Crashes by Level of Severity, FLASH

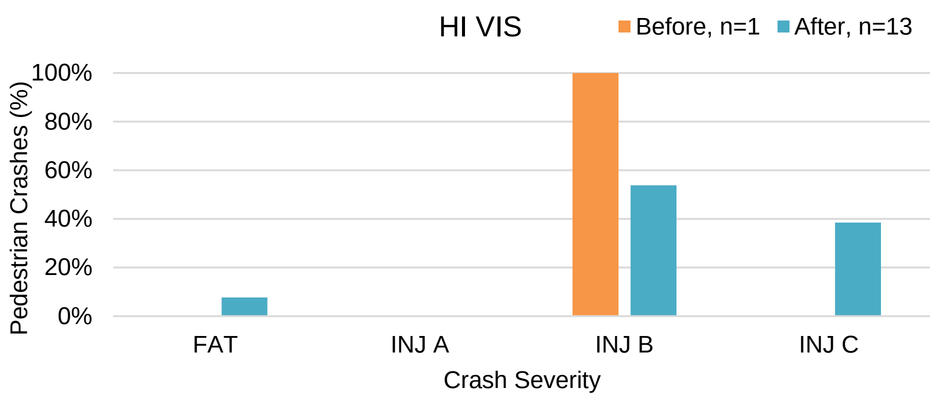


Figure 4.8: Distribution of Before-and-After Pedestrian Crashes by Level of Severity, HIVIS

Figure 4.9 shows the distribution of pedestrian crashes by month of year. Before the enhancement was installed, higher proportions of crashes were seen in fall and winter months (Nov-Jan). After the enhancement installation, the crashes were lower during the winter months, perhaps due to increased visibility provided at the crosswalks due to the crossing enhancements. It is also possible that pedestrian activity and exposure increased in the spring and summer months after the installation of the treatments.

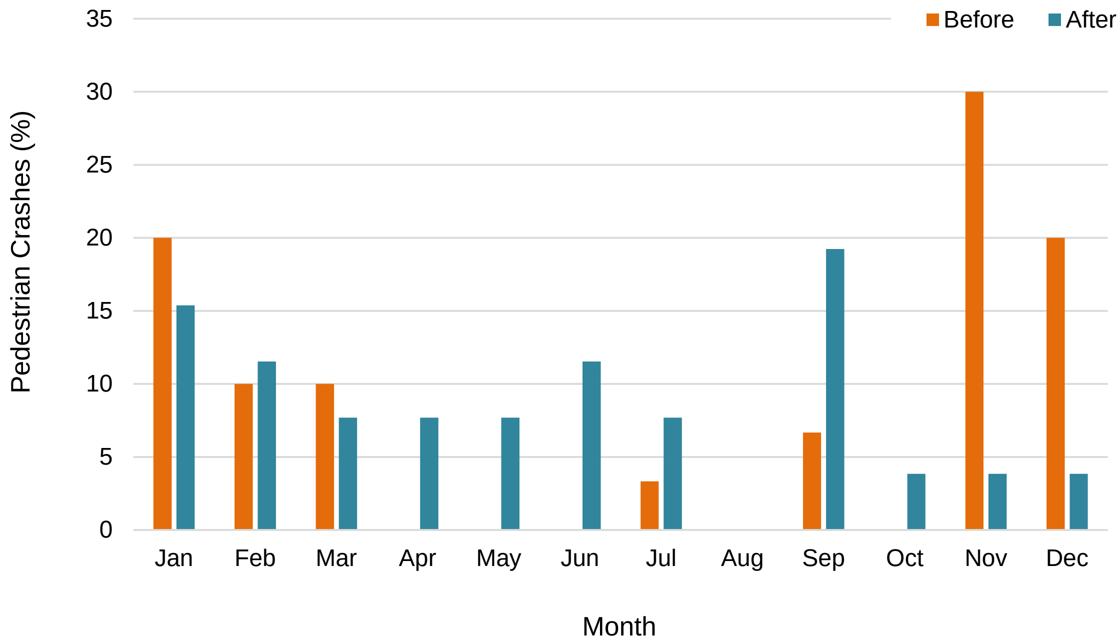


Figure 4.9: Distribution of Pedestrian Crashes by Month

Table 4.8 shows the pedestrian crash distribution by weather conditions. Though most crashes occurred during clear weather, a higher/lower proportion of crashes occurred with clear/rainy weather conditions, respectively, in the after period. This is consistent with a shift of crashes from the fall and winter months to the spring and summer months (Figure 4.4).

Table 4.8: Distribution of Pedestrian Crashes by Weather

Weather	Before (%)	After (%)
Cold	13.3	15.4
Clear	46.7	65.4
Fog	6.7	--
Rain	26.7	19.2
Snow	3.3	--
Unknown	3.3	--

Note: "--" is zero percent in the category.

Table 4.9 shows the pedestrian crash distribution by light conditions. The amount of ambient light available at the time of crash is represented by the light condition variable. In the before condition, the highest proportion of crashes occurred during darkness, with street lights present (50%). However, in the after period, a reduction was observed in the proportion of crashes that occurred during darkness with street lights. While the proportion of crashes occurring during darkness with no street lights increased slightly during the after period, the total proportion of crashes occurring during darkness (with and without street lights) decreased in the after period as compared to the before period (56.7% vs. 34.6%).

Table 4.9: Distribution of Pedestrian Crashes by Light Condition

Light Condition	Before (%)	After (%)
Dark – no street lights	6.7	11.5
Dark – with street lights	50.0	23.1
Daylight	33.3	53.8
Dusk	10.0	11.5

Note: "--" is zero percent in the category.

4.2.2 Rear-End Crashes

Descriptive statistics for rear-end crashes at crosswalks before and after pedestrian crossing enhancements are presented in this section. Figure 4.10 shows the distribution of rear-end crashes at crosswalks before and after pedestrian crossing enhancements were installed. Until 2011, rear-end crashes were higher in the before period; however, between 2012-2014, rear-end crashes in the after period are noticeably higher. It is important to highlight that the time durations for the before and after periods are not the same in terms of treatment years.

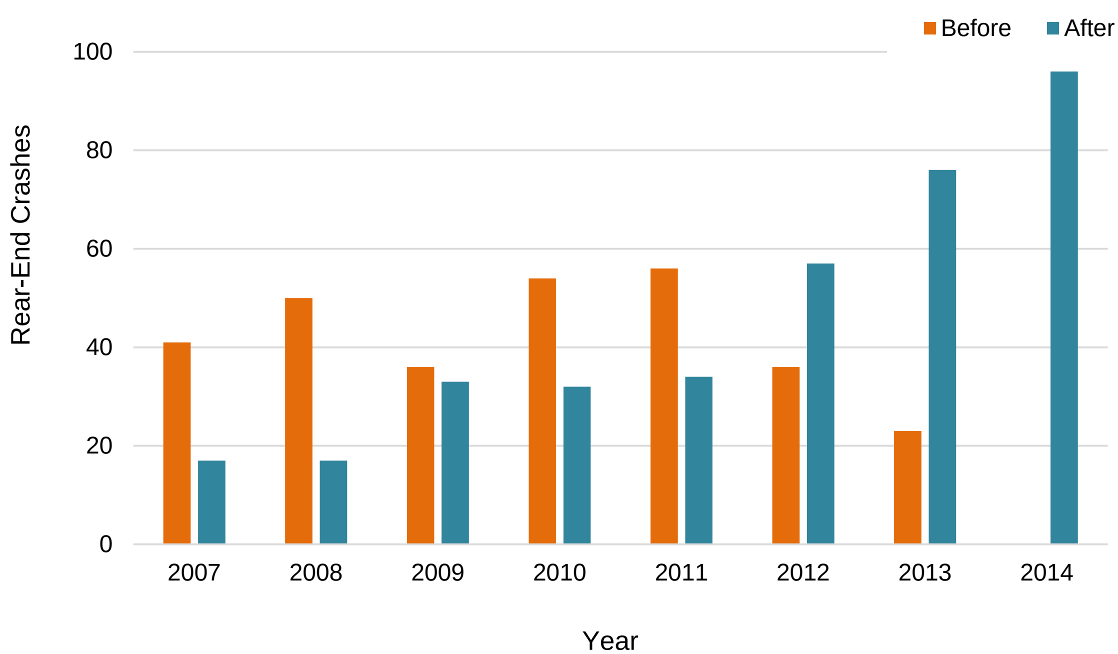


Figure 4.10: Distribution of Rear-End Motor Vehicle Crashes Before and After Pedestrian Crossing Enhancement Installation

Table 4.10 compares the distribution of crash causes for rear-end crashes before and after treatment installations (this is only the primary cause). The vast majority (over 80%) of the reported rear-end crashes were caused by short gaps between vehicles. Inattention and high speeds, which are somewhat related to short gaps, were also reported as causes of rear-end crashes as well as careless driving.

Table 4.10: Rear-End Crash Cause

Crash Cause	Before Crashes (%) n=296	After Crashes (%) n=362
Careless	2.4	4.7
Inadequate or no brakes	--	0.3
Disregarded traffic control device	0.3	1.1
Failure to avoid vehicle ahead	--	2.8
Fatigue	0.3	0.6
Illness	--	0.3
Improper overtaking	0.3	0.3
Improper change of traffic lanes	1.0	1.4
Inattention	3.0	3.9
Drove left of center	0.3	--
Mechanical defect	--	0.3
Did not yield right-of-way	0.7	--
Other improper driving	2.0	0.6
Reckless driving	0.3	0.3
Speed racing	0.3	0.6
Followed too closely	85.8	80.1
Speed too fast for conditions	3.0	3.0

Note: “--“ is zero percent in the category.

Figure 4.11 shows the distribution of rear-end crashes by level of severity. The majority of the rear-end crashes have low severity in both the before and after periods.

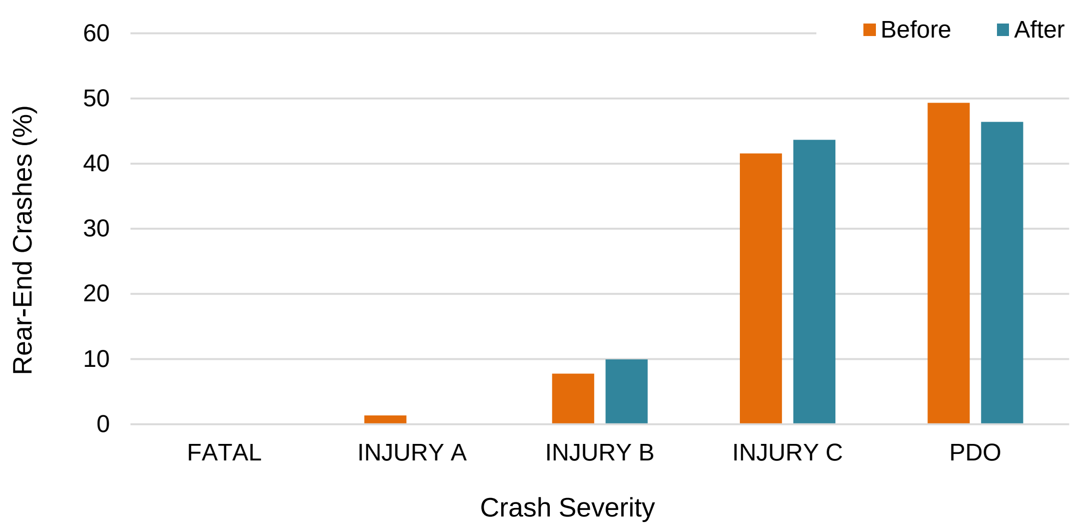


Figure 4.11: Distribution of Rear-End Crashes Before and After Enhancement by Level of Severity

Figure 4.12 shows the distribution of the rear-end crashes by month. Overall, the percentage of rear-end crashes is somewhat higher during the summer months and similarly distributed during the other months. The trend shown in Figure 4.12 may be caused by a combination of higher auto traffic and higher pedestrian traffic during the summer or nice weather months.

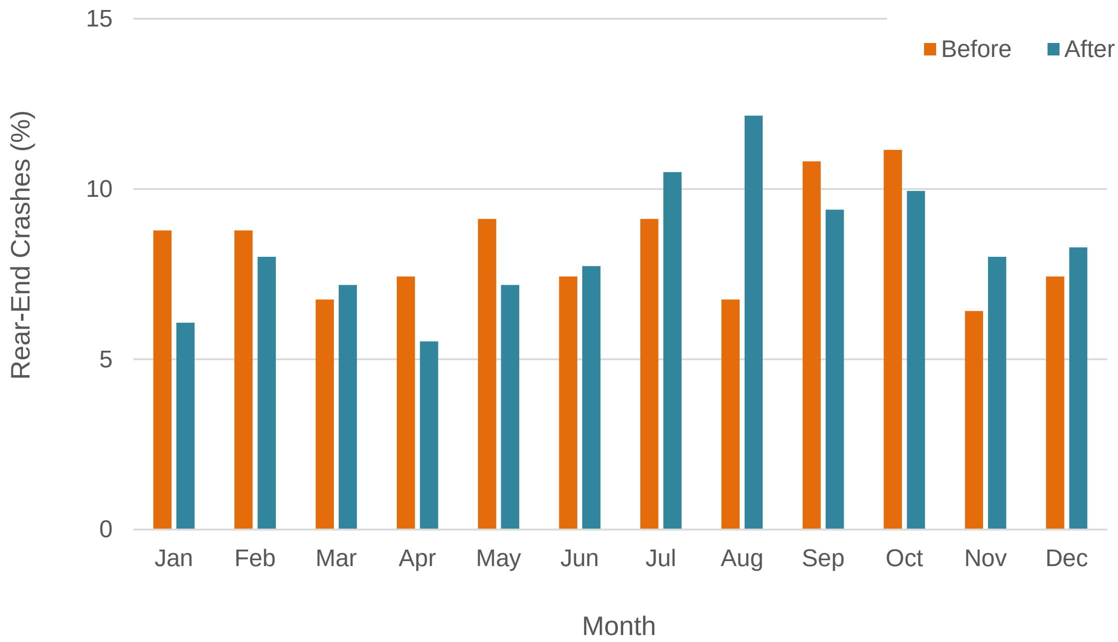


Figure 4.12: Distribution of Rear-End Crashes by Month

Table 4.11 shows the rear-end crash distribution by weather conditions. The majority of the crashes occurred when weather conditions were clear. No major differences can be observed when comparing crash percentages in the before and after periods. Rainy conditions were present in 13.5% and 11% of the before and after crashes, respectively; for pedestrian crashes (Table 4.7), rainy conditions were present in 27% and 19% of the before and after crashes, respectively.

Table 4.11: Rear-End Crash Distribution by Weather Conditions

Weather	Before Crashes (%)	After Crashes (%)
Cold	6.8	9.4
Clear	76.0	76.0
Fog	0.4	--
Rain	13.5	11.3
Snow	2.0	1.4
Unknown	1.4	1.4
Sleet	--	0.3
Smoke	--	0.3

Note: “--“ is zero percent in the category.

Table 4.12 shows the rear-end crash distribution by light condition. Similar to pedestrian crashes, a reduction in total proportion of crashes during darkness (with and without street lights) was observed in the after condition compared to the before condition (14.1% vs. 6.7%). An increase in the proportion of rear-end crashes during daylight was also observed in the after period compared to the before period.

Table 4.12: Distribution of Rear-End Crashes by Light Condition

Light Condition	Before (%)	After (%)
Dark – no street lights	3.0	0.6
Dark – with street lights	11.1	6.1
Daylight	82.4	88.1
Dusk	2.4	3.0
Dawn	1.0	2.2

Note: "--" is zero percent in the category.

4.3 RISK RATIOS

Risk ratios were calculated to further explore how the relative crash frequency changes across well-known risk factors for pedestrians, such as the number of roadway lanes, posted speed and pedestrian activity. Risk ratios were calculated utilizing the following formula:

$$Risk\ Ratio = \frac{Crash\ Frequency\ Ratio_{i=level,\ \ j=crossing\ type}}{Crossing\ Years\ Ratio_{i=level,\ \ j=crossing\ type}}$$

When interpreting risk-ratio trends, the reader should note that the number of observations is low or very low for most bins (less than five crash counts). Hence, caution should be exercised when interpreting some risk-ratio trends. Note that the values of the risk ratios can be compared vertically but should not be compared horizontally (across crossing types) because they are calculated for a specific crossing type.

4.3.1 Pedestrian Crashes

Table 4.13 shows the cross tabulation of crosswalk and pedestrian crashes as well as the estimated risk ratios by number of lanes between 2007 and 2014. For example, in Table 4.13 two-lane RRFB configurations represent 19 of the 176 data years (~0.10) while one out of 12 crashes (~0.08%) were observed at two-lane RRFB locations. The RRFB two-lane risk ratio is 0.77 or 0.77 = (1*176)/(12*19). Ratios greater than 1.0 show an over-representation of a roadway characteristic in the crash performance (uncontrolled by the effect of other variables). In Table 4.13, the crossing type included "unmarked" since many of the crossings were originally unmarked in their configuration (see Figure 4.2).

In Table 4.13 there is a trend showing that the risk ratio increases when the number of lanes increases. This is consistent with the literature that suggests that multilane crossings are riskier for pedestrians. Figure 4.13 shows this graphically.

Table 4.14 shows the risk ratios based on posted speed limit at the crosswalk location. The trend is again consistent with the literature; as the posted speed increases the relative risk tends to increase. This trend is clearer for speeds up to 35 or 40 mph. For higher speeds the low number of observations may be affecting the trend. Figure 4.14 shows this graphically.

Table 4.15 shows the risk ratio based on pedestrian activity levels. Most of the crossing locations have low levels of estimated pedestrian activity. However, for the first three levels of estimated pedestrian activity, the trend shows that risk ratios increase with estimated pedestrian activity. As there were no observed crashes for the medium and medium-high categories, the risk ratios for those categories could not be estimated.

Table 4.13: Risk Ratio for Pedestrian Crashes by Crossing Type and Number of Lanes

Data Type	No. of Lanes	RRFB	HI-VIS	Standard	Flash	Unmarked
Number of Crossing-Years (ratio of sub-column total)	2	19 (0.10)	408 (0.47)	48 (0.48)	23 (0.21)	78 (0.27)
	3	55 (0.31)	179 (0.21)	19 (0.19)	14 (0.13)	102 (0.36)
	4	39 (0.22)	162 (0.19)	23 (0.23)	22 (0.20)	36 (0.13)
	5	63 (0.36)	116 (0.13)	10 (0.10)	48 (0.44)	64 (0.23)
	Total	**176**	**865**	**100**	**107**	**280**
Number of Crashes (ratio of sub-column total)	2	1 (0.08)	4 (0.14)	0 (0)	1 (0.11)	1 (0.09)
	3	1 (0.08)	4 (0.14)	0 (0)	0 (0)	3 (0.27)
	4	3 (0.25)	11 (0.39)	2 (1)	3 (0.33)	3 (0.27)
	5	7 (0.58)	9 (0.12)	0 (0)	5 (0.55)	4 (0.36)
	Total	**12**	**28**	**2**	**9**	**11**
Risk Ratio	2	0.77	0.30	-	0.52	0.33
	3	0.27	0.69	-	-	0.75
	4	1.13	2.10	4.35	1.62	2.12
	5	1.63	2.40	-	1.24	1.59

Note: "-" is either zero in the either the numerator or denominator of the calculation.

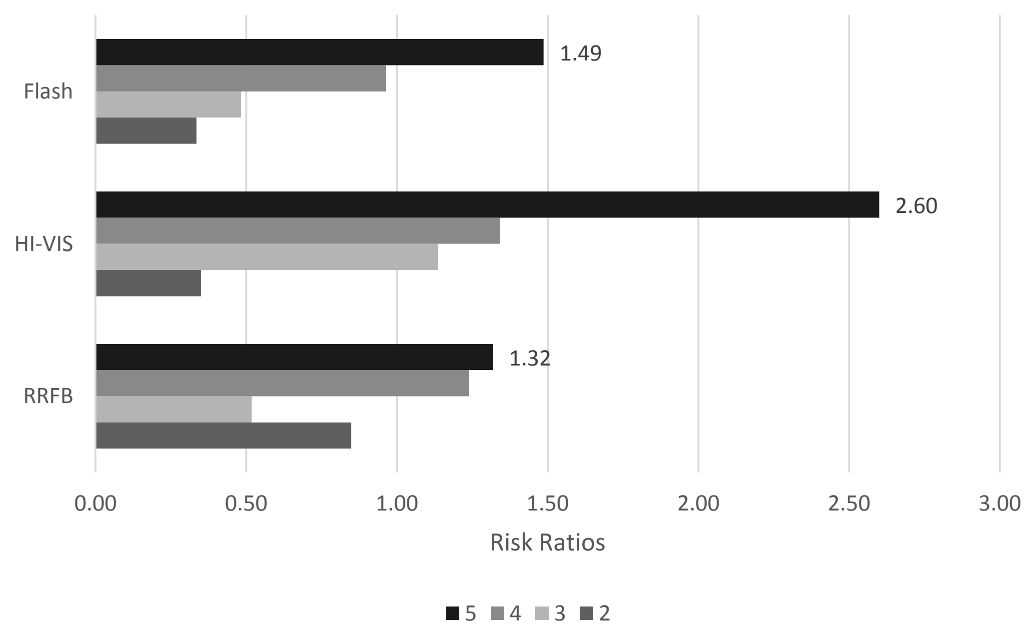


Figure 4.13: Risk Ratio Crossing Type and Number of Lanes (Pedestrian Crashes)

Table 4.14: Risk Ratios for Pedestrian Crashes by Crossing Type and Posted Speed

Data Type	Speed Limit (mph)	RRFB	HI-VIS	Standard	Flash	Unmarked
Number of Crossing-Years (ratio of sub-column total)	20	4 (0.22)	7 (0.09)	5 (0.05)	0 (0)	1 (0)
	25	33 (0.19)	321 (0.37)	45 (0.45)	35 (0.32)	50 (0.17)
	30	35 (0.19)	240 (0.27)	35 (0.35)	7 (0.06)	55 (0.19)
	35	50 (0.28)	160 (0.18)	15 (0.15)	38 (0.35)	74 (0.26)
	40	32 (0.18)	38 (0.04)	0 (0)	11 (0.10)	71 (0.25)
	45	22 (0.12)	28 (0.03)	0 (0)	16 (0.14)	29 (0.10)
	Total	**176**	**865**	**100**	**107**	**280**
Number of Crashes (ratio of sub-column total)	20	0 (0)	1 (0.03)	0 (0)	0 (0)	0 (0)
	25	1 (0.08)	7 (0.25)	0 (0)	4 (0.44)	1 (0.09)
	30	2 (0.16)	7 (0.25)	2 (1)	1 (0.11)	1 (0.09)
	35	5 (0.41)	9 (0.32)	0 (0)	3 (0.33)	5 (0.45)
	40	3 (0.25)	3 (0.10)	0 (0)	0 (0)	4 (0.36)
	45	1 (0.08)	1 (0.03)	0 (0)	1 (0.11)	0 (0)
	Total	**12**	**28**	**2**	**9**	**11**
Risk Ratio	20	—	0.40	—	—	—
	25	044	0.67	—	1.36	0.51
	30	0.84	0.90	2.86	1.70	0.46
	35	1.47	1.74	—	0.94	1.72
	40	1.38	2.44	—	—	1.43
	45	0.67	1.10	—	0.74	—

Note: "-" is either zero in the either the numerator or denominator of the calculation.

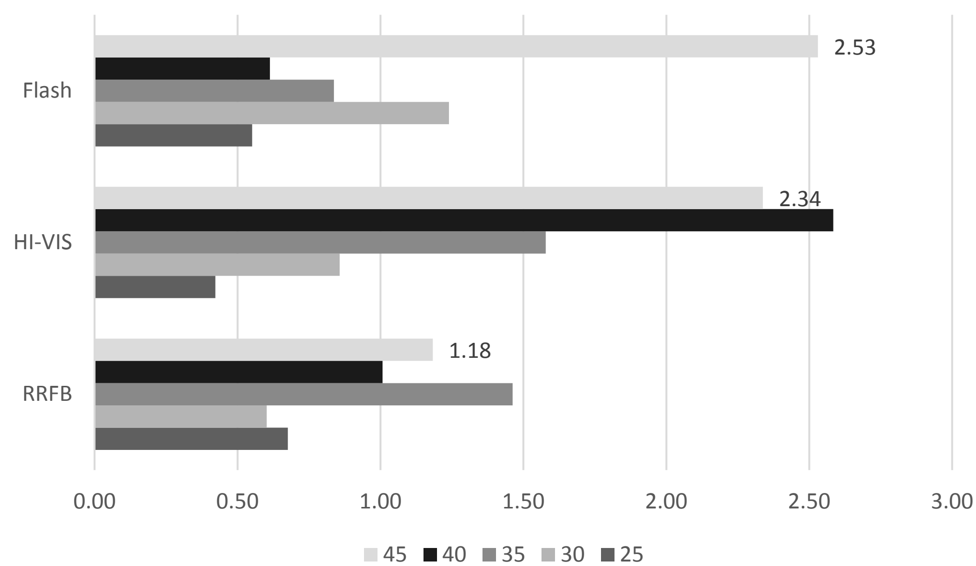


Figure 4.14: Risk Ratio Crossing Type and Posted Speed (Pedestrian Crashes)

Table 4.15: Risk Ratios for Pedestrian Crashes by Crossing Type and Pedestrian Activity Levels

Data Type	Estimated Ped Activity	RRFB	HI-VIS	Standard	Flash	Unmarked
Number of Crossing-Years (ratio of sub-column total)	Very low	44 (0.25)	479 (0.55)	63 (0.63)	17 (0.16)	65 (0.24)
	Low	99 (0.56)	275 (0.32)	37 (0.37)	32 (0.3)	157 (0.59)
	Med-low	25 (0.14)	91 (0.11)	0 (0)	58 (0.54)	41 (0.15)
	Medium	0 (0)	8 (0.01)	0 (0)	0 (0)	0 (0)
	Med--high	8 (0.05)	12 (0.01)	0 (0)	0 (0)	4 (0.01)
	Total	**176**	**865**	**100**	**107**	**267**
Number of Crashes (ratio of sub-column total)	Very low	0 (0)	6 (0.21)	2 (1)	1 (0.11)	0 (0)
	Low	8 (0.67)	14 (0.5)	0 (0)	1 (0.11)	9 (0.82)
	Med-low	4 (0.33)	8(0.29)	0 (0)	7 (0.78)	2 (0.18)
	Medium	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Med-high	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Sum	**12**	**28**	**2**	**9**	**11**
Risk Ratio	Very low	—	0.39	1.59	0.70	—
	Low	1.19	1.57	—	0.37	—
	Med-low	2.35	2.72	—	1.43	2.36
	Medium	—	—	—	—	—
	Med-high	—	—	—	—	—

Note: "—" is either zero in the either the numerator or denominator of the calculation.

4.3.2 Rear-end Crashes

Table 4.16 and Table 4.17 show rear-end crash risk ratios by number of lanes and posted speed. Both tables show trends already observed with pedestrian data, increased risk with a higher number of lanes and posted speed. Figure 4.15 shows this graphically. Table 4.18 shows rear-end crash risk ratios by pedestrian activity levels. An increasing trend in risk was observed from very low to medium-low activity levels. However, a decrease in risk was calculated for the medium-high category, though there are few crossings in these categories. Figure 4.16 shows this graphically.

Table 4.16: Risk Ratio for Rear-End Crashes by Crossing Type and Number of Lanes

Data Type	No. of Lanes	RRFB	HI-VIS	Standard	Flash	Unmarked
Number of Crossing-Years (ratio of sub-column total)	2	19 (0.10)	408 (0.47)	48 (0.48)	23 (0.21)	78 (0.27)
	3	55 (0.31)	179 (0.21)	19 (0.19)	14 (0.13)	102 (0.36)
	4	39 (0.22)	162 (0.19)	23 (0.23)	22 (0.20)	36 (0.13)
	5	63 (0.36)	116 (0.13)	10 (0.10)	48 (0.44)	64 (0.23)
	Total	**176**	**865**	**100**	**107**	**280**
Number of Crashes (ratio of sub-column total)	2	13 (0.09)	61 (0.16)	3 (0.18)	8 (0.07)	33 (0.30)
	3	23 (0.16)	87(0.23)	8 (0.5)	7 (0.06)	22 (0.20)
	4	39 (0.27)	93 (0.25)	3 (0.18)	22 (0.19)	19 (0.17)
	5	67 (0.47)	129 (0.34)	2 (0.12)	74 (0.66)	33 (0.30)
	Total	**142**	**370**	**16**	**111**	**107**
Risk Ratios	2	0.85	0.35	0.39	0.34	1.11
	3	0.52	1.14	2.63	0.48	0.56
	4	1.24	1.34	0.82	0.96	1.38
	5	1.32	2.60	1.25	1.49	1.35

Note: "—" is either zero in the either the numerator or denominator of the calculation.

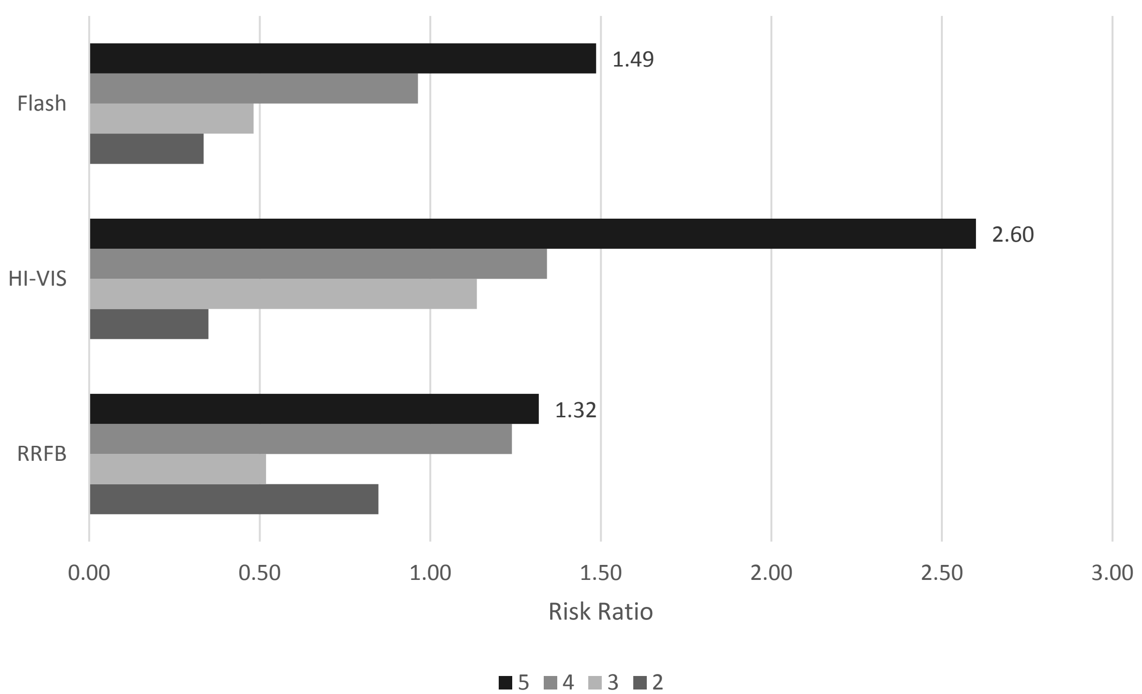


Figure 4.15: Risk Ratio Crossing Type and Number of Lanes (Rear-End Crashes)

Table 4.17: Risk Ratio for Rear-End Crashes by Crossing Type and Posted Speed

Data Type	Speed (mph)	RRFB	HI-VIS	Standard	Flash	Unmarked
Number of Crossing-Years (ratio of sub-column total)	20	4 (0.22)	7 (0.09)	5 (0.05)	0 (0)	1 (0)
	25	33 (0.19)	321 (0.37)	45 (0.45)	35 (0.32)	50 (0.17)
	30	35 (0.19)	240 (0.27)	35 (0.35)	7 (0.06)	55 (0.19)
	35	50 (0.28)	160 (0.18)	15 (0.15)	38 (0.35)	74 (0.26)
	40	32 (0.18)	38 (0.04)	0 (0)	11 (0.10)	71 (0.25)
	45	22 (0.12)	28 (0.03)	0 (0)	16 (0.14)	29 (0.10)
	Total	**176**	**865**	**100**	**107**	**280**
Number of Crashes (ratio of sub-column total)	20	1 (0)	46 (0.12)	0 (0)	0 (0)	2 (0.01)
	25	18 (0.12)	58 (0.15)	8 (0.5)	20 (0.18)	5 (0.04)
	30	17 (0.11)	88 (0.23)	7 (0.43)	9 (0.08)	12 (0.11)
	35	59 (0.41)	108 (0.29)	1 (0.06)	33 (0.29)	53 (0.49)
	40	26 (0.18)	42 (0.11)	0 (0)	7 (0.06)	31 (0.28)
	45	21 (0.14)	28 (0.07)	0 (0)	42 (0.37)	4 (0.03)
	Total	**142**	**370**	**16**	**111**	**107**
Risk Ratios	20	0.31	1.38	0.00	—	5.23
	25	0.68	0.42	1.11	0.55	0.26
	30	0.60	0.86	1.25	1.24	0.57
	35	1.46	1.58	0.42	0.84	1.87
	40	1.01	2.58	—	0.61	1.14
	45	1.18	2.34	—	2.53	0.36

Note: "—" is either zero in the either the numerator or denominator of the calculation.

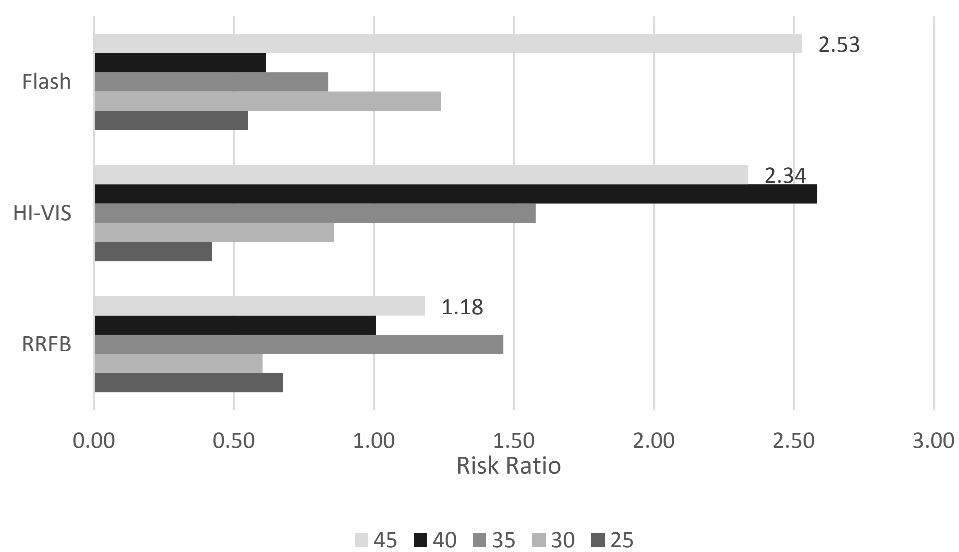


Figure 4.16: Risk Ratio Crossing Type and Posted Speed (Rear-End Crashes)

Table 4.18: Risk Ratio for Rear-End Crashes by Crossing Type and Pedestrian Activity Level

Data Type	Ped Activity	RRFB	HI-VIS	Standard	Flash	Unmarked
Number of Crossing-Years (ratio of sub-column total)	Very low	44 (0.25)	479 (0.55)	63 (0.63)	17 (0.16)	65 (0.24)
	Low	99 (0.56)	275 (0.32)	37 (0.37)	32 (0.3)	157 (0.59)
	Med-low	25 (0.14)	91 (0.11)	0 (0)	58 (0.54)	41 (0.15)
	Medium	0 (0)	8 (0.01)	0 (0)	0 (0)	0 (0)
	Med-high	8 (0.05)	12 (0.01)	0 (0)	0 (0)	4 (0.01)
	Total	**176**	**865**	**100**	**107**	**267**
Number of Crashes (ratio of sub-column total)	Very low	13 (0.09)	113 (0.31)	10 (0.63)	12 (0.11)	14 (0.13)
	Low	80 (0.56)	154 (0.42)	6 (0.38)	24 (0.22)	68 (0.64)
	Med-low	48 (0.34)	97 (0.26)	0 (0)	75 (0.68)	24 (0.22)
	Medium	0 (0)	0 (0)	0 (0)	0 (0)	0 (0)
	Med-high	1 (0.01)	6 (0.02)	0 (0)	0 (0)	1 (0.01)
	Total	**142**	**370**	**16**	**111**	**107**
Risk Ratios	Very low	0.37	0.55	0.99	0.68	0.14
	Low	1.00	1.31	1.01	0.72	—
	Med-low	2.38	2.49	—	1.25	2.92
	Medium	—	—	—	—	—
	Med-high	0.15	1.17	—	—	—

Note: "—" is either zero in the either the numerator or denominator of the calculation.

4.4 SUMMARY

This chapter presented and analyzed both crossing and crash data descriptive statistics. Most crossings in the sample have been enhanced over the data collection period. In particular, RRFBs have been installed at locations that previously had standard markings, flashing amber treatments, and high-visibility markings. In recent installations, RRFBs have also been installed at crossings that were previously unmarked. RRFBs have been installed mostly after 2010 (more than 92% of the RRFBs, 63 out of 68 in the sample, were installed between 2011 and 2014).

Due to the differing durations of the before and after periods of the crosswalk enhancements, the distribution of the total crashes in each time period was tabulated. The following trends were observed for pedestrian crashes:

- There was a reduction in the percentage of crashes coded as "no yield" and "in roadway" for the primary crash cause. In the before time period, 50% of crash causes were coded as "no yield" and 30% were coded as "in roadway." After, these percentages were 73% and 8%, respectively. This primarily reflects that with a crosswalk marking present the cause of the crash would be more likely coded as "driver's not yielding." This is likely related to the presence of additional enhancements making it more likely that this is coded as the primary error code.

- There was a shift in the pedestrian crash severity after the installation of the crosswalk treatments. This shift was from fatal and injury type A crash types to lower severity crashes of injury B and injury C. This trend was also observed for the RRFB and Flash crossing enhancement types (though the numbers in each category are small).

- There was a shift in the percentage of total crashes reported in November, December and January from the before to after periods. A smaller percentage of these crashes occurred during these months in the after periods. More of the crashes in the after period occurred in the May to September window.

- There was a shift in the percentage of total crashes reported in rainy or foggy weather. In the before time period, 33% of the total crashes occurred in rain and fog; in the after period, only 19% of the crashes occurred in these weather conditions.

- There was a shift in the lighting conditions coded for the crashes. In the before time period, 56.7% of the crashes occurred during dark hours (with and without street lights). In the after time period, there were 34.6% of the total crashes.

Some of the shift in these trends may be regression-to-the-mean effects since the locations were most likely selected for treatment based on crash history. It is difficult to speculate based on the crash trends independently; many of these trends could be related to the enhanced visibility of the pedestrians to drivers at the enhanced locations.

The following trends were observed for rear-end crashes:

- For both time periods, the primary crash cause was “following too closely.” In the before time period 85% and in the after period 80% of the crash causes were coded.

- There was not a significant change in the percentage distribution by severity type. Most of the crashes – 80 to 90% – were either injury C or PDO crash severity.

- There was not an obvious shift for rear-end crashes by month of the year.

- There was not an obvious shift for rear-end crashes by weather. In the before time period, 76% of the total crashes occurred in clear weather; in the after period, 76% of the crashes occurred in these weather conditions.

- There was a shift in the lighting conditions coded for the crashes. In the before time period, 14% of the crashes occurred during dark hours (with and without street lights). In the after time period, these were 7% of the total crashes.

For rear-end crashes, there are not any notable shifts in the crash severity, causes or month of the year. Since these trends are excluding pedestrian crashes at the crosswalk and only related to motor vehicles, small or no changes might be expected. The only noted shift was in crashes by lighting condition. Again, it is difficult to speculate based on the crash trends independently, but this could be related to the enhanced visibility of the crosswalk location to drivers at the enhanced locations.

The data were also analyzed by calculating the risk ratio based on observation years and crash counts. Ratios greater than 1.0 show an over-representation of a roadway characteristic in the crash performance (uncontrolled by the effect of other variables). For pedestrian crashes, the following trends were observed:

- Number of lanes: With an increase in the number of lanes and posted speed, the risk ratio generally increased in each crossing category.

- Posted speed: With an increase in the number of lanes and posted speed, the risk ratio generally increased (with the exception of 45 mph posted locations). There were few locations or crashes observed at locations with 45 mph speed limits.

- Estimated pedestrian activity level: Most of the crossing locations have low levels of estimated pedestrian activity. However, for the first three levels of estimated pedestrian activity, the trend shows that risk ratios increase with estimated pedestrian activity. Note that these risk ratios are not for individuals so would not reflect the "safety in numbers" hypothesis that with growing pedestrian activity levels the individual risk decreases.

For rear-end crashes, the following trends were observed:

- Number of lanes: With an increase in the number of lanes and posted speed, the risk ratio generally increased in each crossing category.

- Posted speed: With an increase in the number of lanes and posted speed, the risk ratio generally increased.

- Estimated pedestrian activity level: An increasing trend in risk was observed from very low to medium-low activity levels. However, a decrease in risk was calculated for the medium-high category, though there are few crossings in these categories.

5.0 SAFETY PERFORMANCE

This chapter presents the analysis of the data to develop crash modification factors (CMFs). Four approaches were utilized to develop CMFs – simple or naïve analysis, before-after comparison group study, cross-sectional study, and empirical Bayes before-after. The chapter begins with a description of the methodology for each technique, then is followed by a summary of the analysis for pedestrian crashes and rear-end crashes.

5.1 METHODOLOGY

When evaluating the effect of an engineering treatment for safety, the key question is "*What would the safety (crash performance) of the treated location have been without any treatment at all?* To answer this question, the observed crash rate in the before period can be compared to the observed and/or estimated number of crashes in the after period. The difference in crash performance can be used to estimate the CMF. However, this seemingly simple procedure usually produces biased estimates because, in addition to the treatment, there are other changes in before and after conditions that must be controlled for in the estimation procedure. These changes include:

- Changes in traffic conditions, weather, land use and traffic control;
- Changes in crash reporting levels;
- Installation of the other treatments; and
- Regression-to-the-mean bias (e.g., a site was selected for an improvement due to a recent high-crash record).

The random assignment of control and treatment groups, common in medical research, are typically not feasible in road safety research; more specifically, CMF research is limited to observed data. There are a number of methodological approaches utilized in CMF research which are generally broken down into before-after and cross-sectional approaches *(Carter et al., 2012)*. The most common approaches under each category are listed below:

- Before-after methods

➢ Simple approach (naïve before-after)

➢ Before-after with comparison group

➢ Empirical-Bayes before-after study

➢ Full or hierarchical Bayes before-after study

➢ Intervention and time series analysis methods

- Cross-sectional methods
  - ➢ Cross-sectional modeling
  - ➢ Case control
  - ➢ Cohort studies

More generally, Hauer defines before-after studies as “all techniques by which one may study the safety effect of some change that has been implemented on a group of entities (road sections, intersections, drivers, vehicles, neighborhoods, etc.)” *(Hauer 1997, p. 2),* whereas cross-sectional studies compare “the safety of one group of entities having some common feature (say, stop-controlled intersections) to the safety of a different group of entities not having that feature (say, yield-controlled intersections) in order to assess the safety effect of that feature (stop vs. yield signs)” *(Hauer 1997, pp. 2-3).*

The before-after methods are generally preferred and the empirical Bayes before-after study is considered the state of the practice and preferred approach for developing CMFs. This approach controls for selection bias and minimizes some of the problems associated with cross-sectional approaches. The quality of CMFs estimated utilizing cross-sectional approaches is an open research question. However, cross-sectional approaches may be the only approach available for certain treatments. For example, the estimation of the safety effects of median width is difficult to quantify with a before-after approach since there are few (if any) projects that change the median width *(Carter et al. 2012).*

To some extent, the selection of the best CMF estimation approach is constrained by the intervention being studied and the available data. For example, Fayish and Gross *(Fayish and Gross 2010)* used a comparison group approach to estimate the effect of leading pedestrian intervals (LPIs) installed in intersections in State College, PA. The more robust empirical Bayes approach was not used because it was not possible to develop safety performance functions due to the inadequate size of the reference sample. Zeeger et al. *(Zeeger et al. 2008)* used a time-series approach to estimate area-wide effects of pedestrian safety campaigns since the “treatment” was area-wide and over a long temporal period.

Two recent publications provide robust guidance on the selection of the appropriate method. These documents, which can be considered companion documents, are: 1) FHWA’s “Guide for Developing Quality Crash Modification Factors” and 2) “Recommended Protocols for Developing Crash Modification Factors” *(Carter et al. 2012).* Chapter 9 in the Highway Safety Manual also provides guidance on the safety effectiveness evaluation and provides sample problems. Figure 5.1 taken from FHWA’s “Guide for Developing Quality Modification Factors” *(Gross et al. 2010)* provides a framework for identifying the most appropriate analysis methodology given the conditions available to the researcher.

The first step in the flowchart is to assess the number of sites and the availability of data. This is a critical step that has a large impact on the number and type of feasible study designs; many of the subsequent steps require information that can only be gained after preliminary data collection. At the time of the before-after analysis, the researcher can explore the suitability of the identified sample in more detail. Determination of an adequate sample size a priori is difficult because it depends on a number of factors including average crash frequencies, the level of statistical significance desired in the model, and the expected effect of the treatment. In general, quantification of statistically significant effects that are small require larger samples. Methods presented in Hauer *(Hauer 1997)* and Gross et al. *(Gross et al. 2010)* provide recommendations for the estimation of sample sizes in before-after studies. Once the data requirements and crash experience are known for the treated sites, the researchers can explore how well the available data and questions can be answered by the various methods.

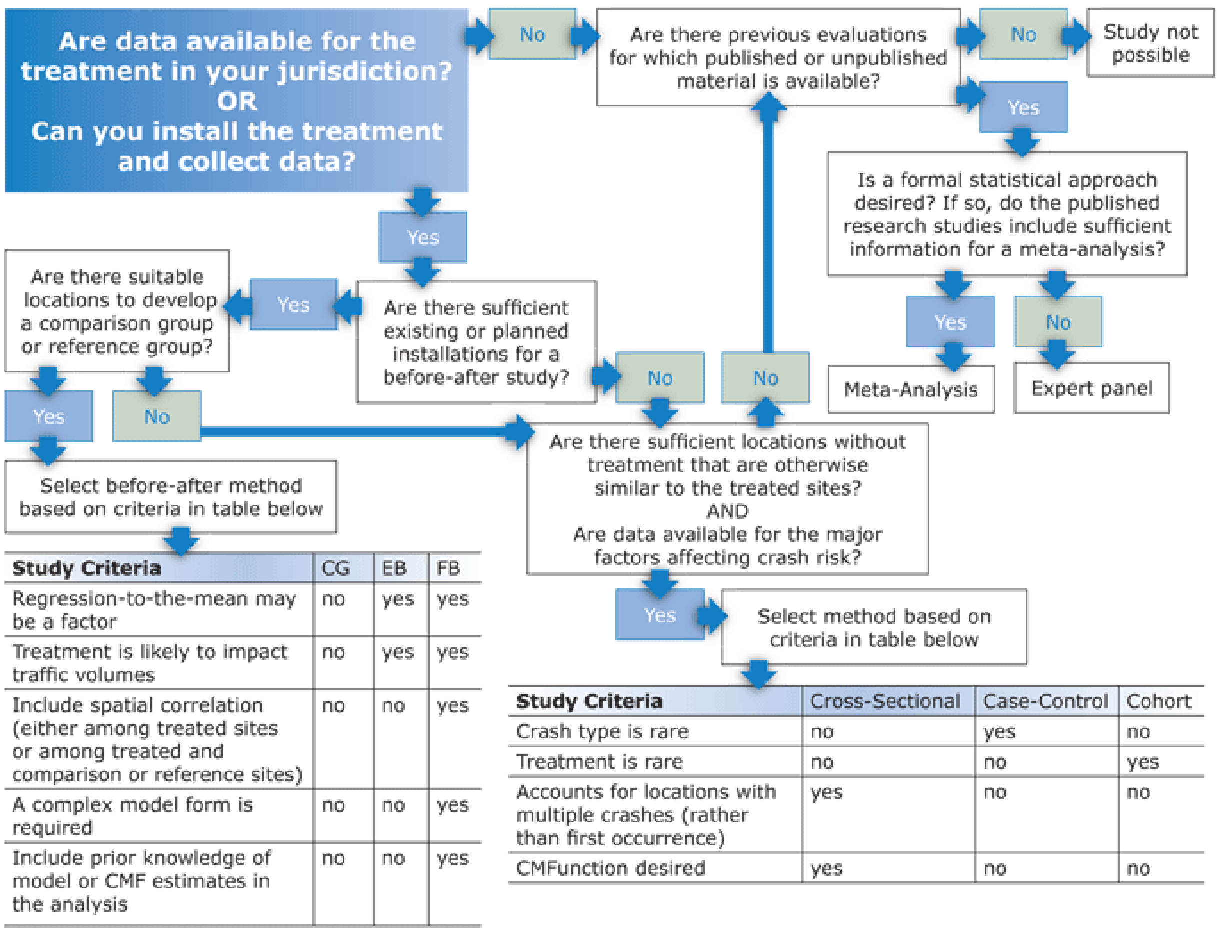


Figure 5.1: Flowchart for Study Design Selection *(Gross 2010)*

As mentioned in the literature review, a CMF is a multiplicative factor that is used to estimate the expected number of crashes after a particular treatment is implemented relative to a base condition *(Gross et al. 2010).* A CMF greater than 1.0 indicates an expected increase in the number of crashes after the treatment is implemented, whereas a CMF less than 1.0 indicates a decrease in the number of crashes.

There are two current repositories of CMFs:1) the Highway Safety Manual (HSM) Part D and 2) Crash Modification Factors Clearinghouse (www.cmfclearinghouse.org). All the CMFs in the current HSM Part D are also in the clearinghouse. For CMFs to be included in the HSM, the adjusted standard error was required to be 0.1 or less. If a study produced a CMF with this standard error, other CMFs from the same study with adjusted standard errors up to 0.3 were included. The HSM inclusion process adjusted the standard error to account for method, sample size and failure to account for regression to the mean *(Bahar 2010).* The CMF clearinghouse assigns a 1-5-star rating to CMFs. Five categories (study design type, sample size, standard error, potential bias and source of the data) are scored either excellent, fair, or poor to combined by means of a weighted equation *(Carter et al. 2012).*

5.1.1 Simple Before-After Analysis

The simple before-after approach assumes that past trends will predict future crash counts. Hauer *(Hauer 1997)* notes that several problems arise when the simple before-after study is used. The factors that make any conclusive results about a treatment questionable fall into six groups:

- In addition to the change due to treatment, other factors change over time such as traffic, weather, road use behavior, vehicle fleet, and land use.

- Various other programs and treatments may have affected the changes at various times during the before or after period.

- The cost of repairs, which change gradually over time, will affect the count of property damage only (PDO) crashes. The reporting limit will occasionally cause the crash count to suddenly change (one change in reporting occurred in the analysis period).

- The probability of reportable crashes being reported may be changing with time.

- The results of the crash history may be affected by regression-to-the-mean bias. Accounting or adjusting for this regression-to-the-mean bias is important whenever the crash history of an entity is related in some way to the reason why its safety is estimated. In traditional safety evaluations, entities are often treated because they have experienced some unusual or high crash pattern. If an entity is chosen on the basis of unusually high crash counts, then this “unusual” crash history is not a good basis for predicting what would be expected in the future if treatment were not applied. In the case of this analysis, the selection bias is present – locations were chosen for illumination reductions because, in part, they did not experience a safety problem.

- It is also assumed that crash counts follow a Poisson distribution.

Hauer states that the main deficiency of the simple before-after study is that the statistical analysis can only determine the estimated size of the mix of effects; it cannot determine how much of it is due to the treatment and how much of it is due to other influences. Although statistical precision may be high, the estimate may not tell researchers what they want to know. Other drawbacks include the fact that reductions in crashes tend to be overestimated and large sample sizes are needed to detect small changes in safety.

The methodology used in this analysis procedure for a composite entity is similar. In the procedure, modified locations are identified by entity number (*j*) and year (*y*). Crash counts for the before period at the before sites are designated K(1), K(2), . . . , K(j). Note that K is the sum of crash counts for all before *y* years. For example, if the yearly before counts for three years were 2, 3 and 5 at entity (*j*), K(*j*) would be 10. Likewise, the after-period crash counts are designated with L(1), L(2), . . . , L(j) and L is the sum of crashes in the after period. The duration period for each entity for the before and after period may be different for each entity. The ratio of durations is defined as:

$$r_d(j) = \frac{Duration\ of\ after\ period\ for\ entity\ j}{Duration\ of\ before\ period\ for\ entity\ j} \quad \textbf{(5.1)}$$

In this analysis, the unit of time measurement is one year. As is the case for both analysis methods, the best estimate for what the crash performance in the after period is simply the count of crashes in the after period as shown in equation (5.2) and the variance is shown in equation (5.3). Note that since a Poisson counting process is assumed, the variance is equal to the mean.

$$\boldsymbol{\lambda = \sum_{i=j}^{n} L(j)} \quad \textbf{(5.2)}$$

$$var\,\{\lambda\} = \sum_{i=j}^{n} L(j) \quad \textbf{(5.3)}$$

The estimate of what the crash performance would have been without the treatment is the extension of the before crash counts by the ratio of the duration periods. For example, if five crashes were observed in three before years and the after period was also three years, π would also be five crashes. The following equation is used:

$$\pi = \sum_{i=j}^{n} r_d(j)K(j) \quad \textbf{(5.4)}$$

$$var\,\{\pi\} = \sum_{i=j}^{n} r_d(j)K(j) \quad \textbf{(5.5)}$$

Finally, the estimated change in the total number of crashes is

$$\delta = \pi - \lambda \quad \textbf{(5.6)}$$

With the estimated variance of δ is then given by

$$\mathrm{VAR}\{\delta\} = \mathrm{VAR}\{\pi\} + \mathrm{VAR}\{\lambda\} \quad \textbf{(5.7)}$$

To estimate the index of effectiveness, θ, the unbiased estimator of θ is calculated with

$$\theta = \frac{\lambda/\pi}{1 + \mathrm{VAR}\{\pi\}/\pi^2} \quad \textbf{(5.8)}$$

The correction factor (he denominator) is usually only slightly larger than 1. Assuming the correction factor in equation (5.9) is constant the estimate of the variance of θ is

$$\mathrm{VAR}\{\theta\} = \frac{\theta^2\left[\left(\mathrm{VAR}\{\lambda\}/\lambda^2\right) + \left(\mathrm{VAR}\{\pi\}/\pi^2\right)\right]}{\left[1 + \mathrm{VAR}\{\pi\}/\pi^2\right]^2} \quad \textbf{(5.9)}$$

With these parameters estimated the standard deviations can be estimated with equations

$$\sigma(\delta) = \sqrt{\mathrm{VAR}\{\delta\}} \quad \textbf{(5.10)}$$

and

$$\sigma(\theta) = \sqrt{\mathrm{VAR}\{\theta\}} \quad \textbf{(5.11)}$$

Finally, the percent reduction is estimated as 100(1- θ). The analysis can be completed for individual entities as well as pooled for a composite estimate.

5.1.2 Before-After Comparison Group Study

A before-after comparison group study compares an untreated comparison group of sites with the treated sites. The method does not directly account for changes in traffic volume or time *(Gross et al. 2010)*. The ratio of the observed crashes in the after period to those in the before period is computed for the comparison group. The observed crash frequency in the before period at the treatment site is multiplied by this ratio to obtain an estimate for the crash frequency if no treatment had been applied. Thus, the modified observed crash frequency in the before period is then compared with the observed crashes in the after period at the treatment sites to estimate the safety impacts of the treatment.

There are a few considerations that need to be taken into account before using this method. It is recommended that the comparison sites be drawn from the same jurisdictions as the treatment sites *(Gross et al. 2010).* In practice, this is difficult because of jurisdictional policies of applying treatments area-wide or due to spillover effects of treatment sites on untreated sites *(Gross et al. 2010)*. Additionally, this method does not account for regression to the mean unless treatment and comparison sites are carefully selected and matched on the basis of the observed crash frequency in the before period, which is difficult *(FHWA 2010)*. This method is applicable when regression to the mean does not exist and a suitable comparison group is available.

Hauer *(Hauer 1997)* recommends performing a test of comparability for the treatment and potential comparison groups. The test of comparability compares a time series of target crashes for a treatment group and a candidate comparison group during a period before the treatment is implemented *(Gross et al. 2010).* The comparison group is considered good if the annual trend in its crash frequencies is similar to the treatment group (before treatment). The comparability test can be performed by visual inspection or using a sample odds ratio, which is calculated using the equation below.

$$Sample\ odds\ ratio = \frac{Treatment_{before}Comparison_{after}\ /\ Treatment_{after}Comparison_{before}}{1+\frac{1}{Treatment_{after}}+\frac{1}{Comparison_{before}}}$$

Where,

$Treatment_{before}$ = total crashes for the treatment group in year i

$Treatment_{after}$ = total crashes for treatment group in year j
$Comparison_{before}$ = total crashes for comparison group in year i
$Comparison_{after}$ = total crashes for comparison group in year j

The sample odds ratio is computed for each before-after pair in the time series before the treatment is implemented and sample mean and standard error are determined. If the sample mean is close to 1.0 and the confidence interval is narrow and includes 1.0 then the candidate reference group is suitable. Additionally, the before and after periods for the treatment and comparison groups should be the same as other factors that potentially influence safety (such as traffic volumes) and crash counts must be sufficiently large.

The CMF for a given crash type at the treatment site is estimated by summing the observed crashes for both treatment and comparison groups for the two time periods, which are assumed equal. Table 5.1 shows the summary of the notation for the comparison group method.

Table 5.1: Summary of Notation for Comparison Group Method

Time Period	Treatment Group	Comparison Group
Before	$N_{observed,T,B}$	$N_{observed,C,B}$
After	$N_{observed,T,A}$	$N_{observed,C,A}$

Where,

$N_{observed,T,B}$ = the observed number of crashes in the before period for the treatment group
$N_{observed,T,A}$ = the observed number of crashes in the after period for the treatment group
$N_{observed,C,B}$ = the observed number of crashes in the before period in the comparison group
$N_{observed,C,A}$ = the observed number of crashes in the after period in the comparison group

The comparison ratio ($N_{observed,C,A}$/ $N_{observed,C,B}$) indicates how crash counts are expected to change in the absence of the treatment *(FHWA 2010).* The expected number of crashes for the treatment group that would have occurred in the after period without treatment ($N_{expected,T,A}$) is estimated using the following equation.

$$N_{expected,T,A} = N_{observedT,B}\left(\frac{N_{observed,C,A}}{N_{observed,C,B}}\right)$$

If the comparison group is deemed suitable, after determining that the crash trends in the comparison and treatment group are similar, the variance of $N_{expected,T,A}$ is estimated as

$$Var\left(N_{expected,T,A}\right) = N_{expected,T,A}^2\left(1/N_{observed,T,B} + 1/N_{observed,C,B} + 1/N_{observed,C,A}\right)$$

This estimate is considered an approximation since it applies to an ideal comparison group with yearly trends identical to the treatment group, which is impossible. A more precise estimate can be obtained by applying a modification which is minor *(Hauer 1997).* Estimating the modification may not be a trivial task, hence Hauer suggests estimating the variance assuming an ideal comparison group and recognizing that the estimate is a conservatively low approximation. In the ideal case, the CMF and its variance are estimated using the following equations.

$$CMF = ({N_{observed,T,A}}/{N_{expected,T,A}})/(1 + \frac{Var(N_{expected,T,A})}{N^2_{expected,T,A}})$$

$$Variance\ (CMF) = \frac{CMF^2[\left({1}/{N_{observed,T,A}}\right) + \left(\frac{Var(N_{expected,T,A})}{N^2_{expected,T,A}}\right)]}{1 + Var(N_{expected,T,A})/N^2_{expected,T,A}]^2}$$

5.1.3 Cross-Sectional Approach

In cross-sectional studies, CMF is estimated as the ratio of the average crash frequency for sites with and without treatment. These studies are useful particularly when enough treatment locations are not available to conduct a before-after study *(Gross et al. 2010).* For achieving reliable results, it is recommended that all locations are similar to each other in all factors affecting crash risk. However, in practice this requirement is difficult to achieve. Hence, cross-sectional analyses are conducted using multiple variable regression models. The regression models typically include all variables that impact safety, and these models are used to study the change in crashes that result from a unit change in a variable *(Gross et al. 2010).* Subsequently, once the model is estimated, the CMF is derived from the model parameters.

An important consideration while developing CMFs from a cross-sectional study is the comparison between two distinct groups of sites *(Gross et al. 2010).* The observed difference in crashes may be due to factors that are unaccounted for in the regression models. These factors may be unknown or known but unmeasured and thus unaccounted for in the models. Therefore, CMFs derived from cross-sectional studies should be applied with caution. The FHWA guide suggests that if sufficient treatment locations are available, a before-after study is preferred. The FHWA guide also suggests that CMFs from multivariate regression models are still evolving and validation of CMFs from cross-sectional studies is important. Inaccuracies in CMFs estimated using regression models may arise from using inappropriate functional form, omitted variable bias, or correlation of variables. Errors may also result due to small sample size and little to no variation in the elements used to develop the model *(Gross et al. 2010).*

5.1.4 Empirical Bayes Before-After

The objective of the empirical Bayes method is to estimate the number of crashes that would have occurred at an individual treatment site in the after period, in the absence of a treatment. The methodology involves comparing the sum of estimates of the expected crashes from all the treatment sites with the actual number of crashes that were observed after the treatment. The advantage of the Bayes method over the comparison group is that it accounts for the effects of regression to the mean *(Gross et al. 2010).*

To correctly account for the regression   the- mean, the number of crashes in the before period is a weighted average of the number of crashes observed in the before period at the treated sites and the number of predicted crashes at the treated sites based on reference sites with similar traffic and physical characteristics. A reference group is established first and used to estimate weights and number of crashes at sites with similar traffic and physical characteristics. However, unlike the comparison group method, a safety performance function (SPF) is estimated first to predict the average crash frequency for similar locations with similar characteristics. The SPF is then used to predict the estimated number of crashes at treated sites based on similar operational and geometric characteristics *(Gross et al. 2010).*

The expected number of crashes without treatment is computed using the following equation.

$$N_{expected,T,B} = SPF\ weight\ \left(N_{predicted,T,B}\right) + (1 - SPF\ weight)(N_{observed,T,B})$$

The SPF weight is derived using the over-dispersion parameter from the SPF calibration process and also depends on the number of years of crash data in the period before treatment *(Gross et al. 2010)*. The over-dispersion parameter has an inverse relationship with SPF weight. If little over-dispersion is observed, more weight is placed on the predicted crashes and less weight on the observed crashes.

The adjusted value of the empirical Bayes estimate, $N_{expected,T,A}$, is the expected number of crashes in the after period without treatment and is calculated using the equation below.

$$N_{expected,T,A} = N_{expected,T,B}\ (N_{predicted,T,A} / N_{predicted,T,B})$$

Where,

$N_{expected,T,B} =$ the unadjusted empirical Bayes estimate

$N_{predicted,T,B} =$ the predicted number of crashes estimated by the SPF in the before period

$N_{predicted,T,A} =$ the predicted number of crashes estimated by the SPF in the after period

The variance of $N_{expected,T,A}$ is estimated from $N_{expected,T,A}$, the before and after SPF estimates and the SPF weight, using the following equation.

$$Var(N_{expected,T,A}) = N_{expected,T,A}\ (N_{predicted,T,A} / N_{predicted,T,B})(1 - SPF\ weight)$$

5.2 RESULTS—PEDESTRIAN CRASHES

This section presents the results for CMFs estimated by the methods described in the methodology section for pedestrian-only crashes. As the final report was being finalized, the 2015 crash data for injury and fatal crashes became available. For the simple before-and-after analysis and the comparison group analysis, the 2015 data was included. For all other analysis, the 2015 data are not included.

5.2.1 Simple Before-After Analysis (All PCEs)

This analysis was conducted for the three categories of PCE (RRFB, flashing amber, and high-visibility) and a pooled data set of RRFB and flashing amber. Table 5.2 shows the results of the simple before-after analysis. At the pooled locations with RRFB and flashing amber beacons a CMF of 0.30 was estimated with a standard deviation of 0.15. For the RRFB-only locations, a CMF of 0.78 was estimated with a standard deviation of 0.35. An estimate of the 95% confidence interval does include 1.0 and the standard deviation is greater than 0.30. At the flashing amber-only locations, the CMF is estimated at 0.06. The high-visibility locations were estimated to have a CMF of 1.20 with a high standard deviation of 0.65 (95% confidence interval includes 1.0).

All of the estimates are limited by the low crash counts (primarily from the short duration of the after periods). Estimates of CMF from low crash counts can be very sensitive to small changes in counts in future years. The flashing amber locations have very few sites (n=3). All of the locations were likely selected for treatment due to pedestrian crash history. As the simple before-after approach cannot account for the regression to the mean, some bias is likely present. Due to the low number of sites and low crash counts, the CMF estimated for the flashing amber locations is not considered reliable. Prior to the actual analysis, it was thought that pooling the RRFB and flashing amber locations made sense (both have warning lights visible to the driver). However, it was clear that the low crash counts at the flashing amber crossings had a significant influence on the CMF estimated if all PCEs were pooled. The CMF estimated for the RRFB crossing locations appears reasonable for both the data through 2014 and including 2015. The CMF using the 2007-2014 data is 0.78 and with the addition of an additional year of data, the CMF is 0.64. The standard deviations are 0.35 and 0.26, respectively. There are a larger number of sites (19) but the crash counts are low.

The high-visibility locations have an estimated CMF greater than 1.0 (an increase in crashes). However, the standard deviation is large (0.65 or 0.63) and there are few crashes estimated in the after period. The addition of the 2015 data did not improve the high-visibility location estimates.

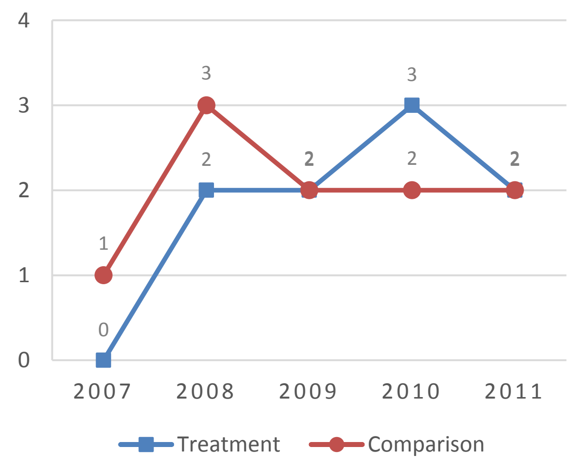
For the remainder of the analysis, the safety effectiveness is focused on RRFB locations.

Table 5.2: Simple Before-After Analysis for Pedestrian Crashes

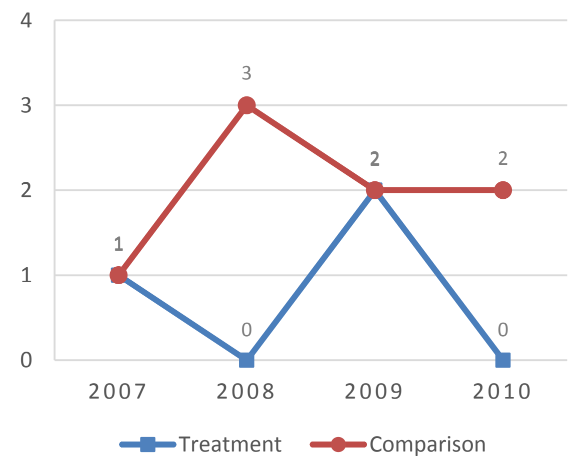
Parameter	RRFB (2007-14)	RRFB (2007-2015)	FLASH (2007-14)	HI-VIS (2007-14)	HI-VIS (2007-15)
Number of crosswalks	19	19	3	5	5
Crashes in the after period (λ)	6	8	1	6	7
Crashes in the before period w/o treatment (π)	7.20	11.94	12.40	2.50	3.00
Estimated change in total number of crashes (δ)	1.20	3.94	11.40	-3.50	-4.00
CMF=Index of effectiveness (θ)	0.78	0.64	0.06	1.20	1.17
Standard deviation (δ)	3.11	3.96	8.55	3.50	4.00
Standard deviation (θ)	0.35	0.26	0.05	0.65	0.63
CMF (+/- 1 std. dev)	0.42 to 1.13	0.38 to 0.89	0.01 to 0.10	0.55 to 1.85	0.54 to 1.79
CMF (95% C.I.)	0.08 to 1.47	0.14 to 1.14	-0.03 to 0.14	-0.07 to 2.47	-0.06 to 2.39

5.2.2 Before-After Comparison Group (RRFB)

A comparison group analysis was performed for pedestrian crashes. For the comparison analysis, the treatment years of 2011 and 2012 were analyzed. Unfortunately, due to the later installation dates of many of the RRFBs, the number of sites meeting the criteria for inclusion was substantially reduced. To ensure whether the comparison group is adequate, Hauer *(Hauer 1997)* recommends estimating the sample odds ratio and conducting a visual inspection of crashes in the treatment and comparison groups before the treatment was installed. If the trend between the treatment and comparison group is similar, then the comparison group can be used to forecast crashes at the treatment sites after treatment. Figure 5.2 shows the trends in pedestrian crash frequency for the treatment and comparison group sites in the before period. The figure shows that treatment and comparison are not very similar (annual changes are not in the same directions except for the 2007-2008 time period).



Installation Year = 2011 (±4 Years of data)



Installation Year = 2012 (±3 Years of data)

Figure 5.2: Trends in Pedestrian Crash Frequency for Treatment and Comparison Groups Prior to Treatment Installation

To make a more rigorous comparison, the sample ratio is estimated for each before-after pair in the time series and sample mean and standard error are determined. Table 5.3 shows the sample odds ratio estimation results. The sample mean is estimated as 0.41, which is not close to 1.0 as Hauer recommends. The confidence interval does not include 1.0; however, the confidence interval is large, indicating that the CMF may not be suitable for estimating the crashes at the after location. For the 2012 installation, zero crashes in the treatment series do not allow a pair ratio to be calculated.

Table 5.3: Sample Odds Estimation

Installation Year = 2011		Installation Year = 2012	
Parameter	**Sample Odds Ratio**	**Parameter**	**Sample Odds Ratio**
Pair 1 (2007-2008)	0.00	Pair 1 (2007-2008)	NA
Pair 2 (2008-2009)	0.36	Pair 2 (2008-2009)	0
Pair 3 (2009-2010)	0.36	Pair 3 (2009-2010)	NA
Pair 4 (2010-2011)	0.75		
Mean	0.36	Mean	Not calculable since ratio of two pairs is NA
Std. Dev	0.31	Std. Dev	
95% CI -	0.96	95% CI -	
95% CI+	-0.23	95% CI+	

To perform the comparison group calculations, the sites of locations with RRFBs were selected as the treatment group and sites consisting of crosswalk locations with high-visibility crosswalk marking and standard parallel crosswalks were chosen as the comparison group. Table 5.4 shows the crash comparison for the treatment and comparison groups in the before-after period and the number of sites in each period. For the 2012 install sites, the crash frequency dropped from 7 to 1 at the eight locations while the comparison group counts were unchanged at 6. For the 2011 installation group, the crashes were unchanged in the two groups.

Table 5.4: Treatment and Comparison Group Crashes

Install 2012 (±3 Years of data)	Treatment Group (n=8)	Comparison Group (n=13)
Before (2009-2011)	7	6
After (2013-2015)	1	6
Install 2011 (±4 Years of data)	**Treatment Group (n=5)**	**Comparison Group (n=13)**
Before (2007-2010)	3	8
After (2012-2015)	3	8

Table 5.5 shows the CMF estimation for pedestrian crashes using the comparison group method. For the 2012 installed locations, the CMF is estimated as 0.10, implying that a 90% reduction in pedestrian crashes is estimated at crosswalk locations with RRFB. For the 2011 installations sample the CMF is estimated at 0.63 with a large standard error at 0.38. This CMF is closer to the As the 95% confidence interval does not include 1.0, the estimated CMF is statistically significant. There are two issues with the comparison group method with these data: 1) the number of sites eligible is very small, 5 and 8) the identified comparison group did not meet the criteria as being suitable. As such, the estimated CMFs for the comparison group approach are not recommended.

Table 5.5: CMF Estimation for Pedestrian Crashes

Parameter	Install 2012 (±3 Years of data)	Install 2011 (±4 Years of data)
($N_{expected,T,A}$)	7.00	3.00
Variance ($N_{expected,T,A}$)	23.33	5.25
CMF	0.10	0.63
Standard Error	0.08	0.38
95% CI-	-0.06	-0.12
95% CI+	0.25	1.38

5.2.3 Cross-Sectional analysis (RRFB and Flash)

To prepare the data set for a cross-sectional analysis, a time window had to be identified where crossings were only of one category (i.e., for the time window a crossing was always a RRFB crossing). The analysis was focused on RRFB as the treatment of interest and it was difficult to find a time period where the crossing type was consistent (as shown in Figure 4.2); the windows where crossings are consistent is very small. To develop the regression models a window of two years was used. After cleaning and preparing the data to match this criteria, a Poisson regression model was estimated with pedestrian crashes as the dependent variables and the geometric and crossing data that were collected as independent variables. Table 5.6 shows the results of the estimated regression model for pedestrian crashes. Many models were explored, including an automated step-wise search for significant variables. However, other than AADT, no other variables were found to be significant predictors of pedestrian crashes. In order to estimate a

CMF, the categorical variable related to the presence of treatment (flashing amber or RRFB) would need to be significant in the estimated model. A CMF from the cross-sectional model cannot be estimated.

$$Number\ of\ pedestrian\ crashes = \mathrm{e}^{-19.41+1.82*\log(\mathrm{AADT})}$$

Table 5.6: Final Poisson Regression Model for Estimating Pedestrian Crashes

Variable	Coefficient	Standard Error
Ln(AADT)	1.82**	0.636
Constant	-19.41	6.161
Observations	124	
Log likelihood	-31.37	
Akaike Inf. Criteria	66.75	

Note: *p<0.1; **p<0.05; ***p<0.01

5.2.4 Empirical Bayes Before-After Analysis

As mentioned in the methods section, the empirical Bayes before-after analysis requires a SPF for prediction of after-crash frequency at the treatment sites. An SPF must be developed from a reference group of non-treated locations. Initially in the research design, the use of standard parallel crossings was considered as a reference group. However, after further review it was determined that these crossings were not a suitable reference group for the enhanced crossings. The standard parallel crossings are primarily in Region 5 and have low estimated levels of pedestrian activity. Since many RRFBs started as high-visibility crosswalks, we tried estimating models using these crosswalks as the reference group. However, those locations had so few crashes, the crash frequency models were not estimable.

Given the lack of pedestrian volumes for exposure, it is not surprising that a SPF could not be estimated from the available data. From prior research, a clear contributor to pedestrian crashes is exposure (the number of pedestrians crossing). The models included the categorical variables of the estimated pedestrian activity levels and combinations of these with motor vehicle volumes. None of these model attempts yielded a useable SPF.

5.3 RESULTS – REAR-END CRASHES

This section presents the results for CMFs estimated by the four approaches described in the methodology section for rear-end crashes.

5.3.1 Simple Before-After (All PCEs)

Similar to the pedestrian crashes, this analysis was conducted for rear-end crashes at the three categories of PCE (RRFB, flashing amber, and high-visibility) and a pooled data set of RRFB and flashing amber. Table 5.7 shows the parameters estimated from the simple before-after analysis. All of the crossing categories estimated an increase in rear-end crashes at the enhanced crossing. At the pooled locations with RRFB and flashing amber beacons a CMF of 1.56 was estimated with a standard deviation of 0.21. For the RRFB-only locations, a CMF of 1.30 was estimated with a standard deviation of 0.19. An estimate of the 95% confidence interval does include 1.0. For the flashing amber-only locations, the CMF is estimated at 6.47 with a very high standard deviation of 2.16. The high-visibility locations were estimated to have a CMF of 1.76 with a high standard deviation of 0.61.

If the enhancements increase yielding to pedestrians in the crosswalk, then the opportunities for rear-end crashes also would increase. It is plausible that the enhanced crossing locations might see an increase in rear-end crashes. However, the simple before-after study does not control for exposure changes. While pedestrian volumes are unavailable, vehicle volumes are available and there have been changes in vehicle volumes. The locations were not likely selected for rear-end crash history so while the regression-to-the-mean bias is present, it is not much of a concern as for the pedestrian crossings. Similar to the limitations of the pedestrian analysis, the flashing amber locations are small (n=3). The research team has concerns that the CMF estimated for the flashing amber locations is not reliable. For the remainder of the analysis, the safety effectiveness is focused on RRFB locations.

Table 5.7: Simple Before-After Analysis for Rear-End Crashes

Parameter	RRFB	FLASH	HI-VIS
Number of crosswalks	19	3	5
Crashes in the after period (λ)	86	21	60
Crashes in the before period without treatment (π)	65.45	2.75	29.85
Estimated change in total number of crashes (δ)	-20.55	-18.25	-30.15
CMF=Index of effectiveness (θ)	1.30	6.47	1.76
Standard deviation (δ)	11.14	4.73	13.60
Standard deviation (θ)	0.185	2.16	0.61
CMF (+/- 1 std. dev)	1.12 to 1.49	4.31 to 8.63	1.15 to 2.37
CMF (95% C.I.)	0.94 to 1.66	2.24 to 10.7	0.56 to 2.96

5.3.2 Comparison Group Analysis (RRFB)

Similar to the pedestrian crash analysis, comparison group analysis was also undertaken for rear-end crashes at crosswalks. An analysis was conducted for treatments installed in 2012. Figure 5.3 shows the trends in rear-end crash frequencies for the treatment and comparison groups in the before period (2007-2011) for crosswalks where the pedestrian crossing treatment were installed in 2012. Visual inspection of the rear-end crash frequencies of the treatment and comparison groups show that the trends are dissimilar year to year and overall. The sample ratio is estimated for each before-after pair in the time series before the treatment is implemented, and sample mean and standard error are determined. Table 5.8 shows the sample odds ratio estimation. The sample mean is estimated as 1.03, which is close to 1.0 as Hauer recommends. The confidence interval includes 1.0; however, there is a large interval (-0.91 to 2.97) indicating that the comparison group is not the most suitable for this analysis.

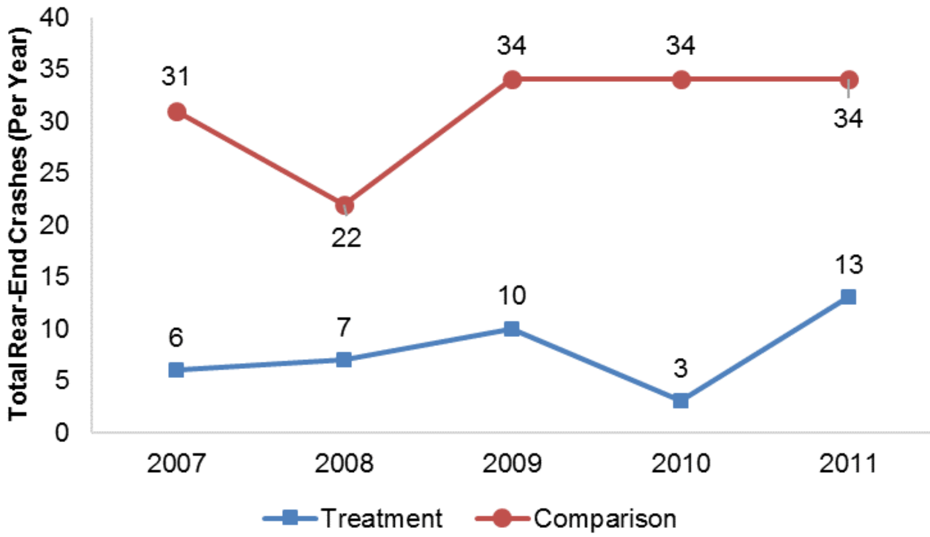


Figure 5.3: Trends in Rear-End Crash Frequencies for Treatment and Comparison Groups Prior to Treatment Installation (2007-2011)

Table 5.8: Sample Odds Ratio for Rear-End Crashes (2007-2011)

Parameter	Sample Odds Ratio
Pair 1 (2007-2008)	0.52
Pair 2 (2008-2009)	0.94
Pair 3 (2009-2010)	2.45
Pair 4 (2010-2011)	0.21
Mean	1.03
Std. Dev	0.99
95% CI -	2.97
95% CI+	-0.91

A total of 15 sites comprised of crosswalk locations with RRFBs were chosen for the treatment group, and 65 sites consisting of locations with high-visibility crosswalk markings and standard parallel crosswalks were chosen as the comparison group. Table 5.9 shows the crash comparison for the treatment and comparison groups in the before-after period. While 18 crashes were observed in the before period and 26 crashes were observed in the after period for the treatment group, 58 crashes were observed in the before period and 74 crashes were observed in the after period for the comparison group.

Table 5.9: Treatment and Comparison Group Rear-End Crashes (two years, 2012 treatment year)

Time Period	Treatment Group (n=15)	Comparison Group (n=65)
Before (2010-2011)	16	68
After (2013-2014)	19	74

Table 5.10 shows the CMF estimation for rear-end crashes using the comparison group analysis. The expected number of crashes for the treatment group that would have occurred in the after period without treatment ($N_{expected,T,A}$) is estimated as 17.41. The variance of the expected number of crashes in the treatment group Var ($N_{expected,T,A}$) is estimated as 27.50. The CMF is estimated as 1.00, implying no increase in rear-end crashes at crosswalk locations with RRFB and flashing amber beacons. However, as the 95% confidence interval includes 1.0, the estimated CMF is not statistically significant.

Table 5.10: CMF Estimation for Rear-End Crashes

Parameter	Estimate
($N_{expected,T,A}$)	17.41
Variance ($N_{expected,T,A}$)	27.50
CMF	1.00
Std Error (CMF)	0.34
95% CI-	0.31
95% CI+	1.68

5.3.3 Cross-Sectional Analysis (RRFB and Flash)

To prepare the data set for a cross-sectional analysis, a time window needed to be identified where crossings were only of one category (i.e., for the time window a crossing was always an RRFB crossing). As shown in Figure 4.2, the windows where crossings are consistent is very small. To develop the regression models, a window of two years was used. After cleaning and preparing the data to match this criteria, a Poisson count regression model estimated rear-end crashes as the dependent variable. (Table 5.11) After a series of model fitting exercises, the variables of AADT, presence of bus stops and treatment (RRFB, flashing amber beacons) were significant predictors.

$$Number\ of\ rear-end\ crashes = \mathrm{e}^{-11.35+1.14*log(AADT)+0.66*BusStop+0.56*Treatment}$$

All the coefficients of the above variables were positive. In the model, the presence of a RRFB or a flashing amber beacon estimates an increase in rear-end crashes. To estimate the CMF from the log-linear model, the estimated coefficient for the treatment can be used. The estimated CMF is $e^{0.56}$ = 1.75 (standard error = 0.33, 95% confidence interval 1.14 to 2.67).

Table 5.11: Poisson Regression Model for Rear-End Crashes

Variable	Coefficient	Standard Error
Ln (AADT)	1.14***	0.196
Presence of Bus Stops	0.66**	0.258
Treatment	0.56***	0.216
Constant	-11.35***	1.776
Observations	124	
Log likelihood	-151.26	
Akaike Inf. Criteria	310.52	

Note: *p<0.1; **p<0.05; ***p<0.01

5.3.4 Empirical Bayes Before-After Analysis (RRFB)

The most reliable of the proposed methods for estimating CMFs is the EB method. The primary exposure variable (AADT) for vehicles was available in the data set. To develop a SPF, a treatment group data set was first developed. Using these data, a negative binomial count regression model was developed to estimate SPF for the frequency of rear-end crashes for two years. Many versions of the model were attempted; however, the only significant predictor for rear-end crashes was AADT. The results of the model estimation process are shown in Table 5.12.

Table 5.12: Final Negative Binomial Regression Model for Estimating Rear-End Crashes

Variable	Coefficient	Standard Error
Ln(AADT)	1.706***	0.379
Constant	-15.962***	3.476
Observations	85	
Log likelihood	-69.03	
Akaike Inf. Criteria	66.75	
theta	1.137	0.699

Note: *p<0.1; **p<0.05; ***p<0.01

As suggested by Hauer, a CUmulative REsidual (CURE) plots was constructed for diagnostic purposes. The plot is shown below in Figure 5.4. The plot can be used to visually assess how well the model fits across the fitted value. If the walk of the plotted cumulative residuals stays within the fitted bounds (the red lines) and oscillates around the value of zero, the SPF has good fit over the range of the model. As the figure shows, the residual plot lines are within the bounds.

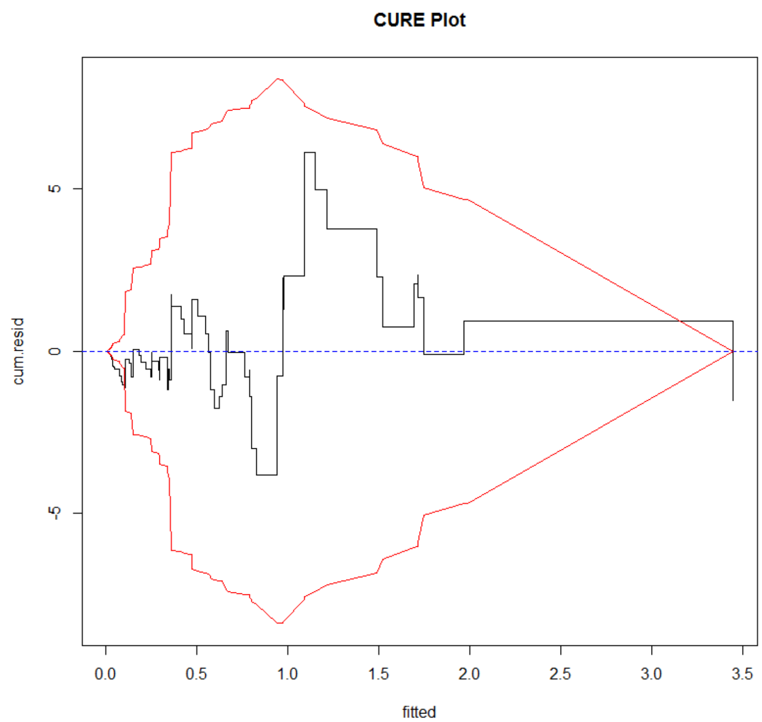


Figure 5.4: CURE Plot for SPF Model for Rear-End Crashes at Mid-Block Crosswalks

Thus, the results of the SPF estimation model were used in the empirical Bayes procedure. The SPF for rear-end crashes can be rewritten as:

$$SPF_{rear\ end\ crash,\ 2\ year} = 1.17 * 10\text{-}7 * AADT^{1.705}$$

Rear-end crashes were predicted as the sum of the SPF estimates for the before and after period and are shown in Table 5.13. Table 5.14 shows the parameters estimated using the empirical Bayes approach. The empirical Bayes estimate, $N_{expected,T,B}$, is estimated as 20.24. The expected number of crashes in the after period in the treatment group that would have occurred without treatment ($N_{expected,T,A}$) is estimated as 19.71. The CMF is estimated as the after-period crash count divided by the expected number without treatment, which results in a value of 0.93. The standard error of the CMF is 0.22, respectively, and the 95% confidence interval (0.49 to 1.37) still includes 1.0.

Table 5.13: Empirical Bayes Method Summary, Rear-End Crashes RRFB Only

Treatment Year	Treatment Group Observed Crashes (15 sites)	SPF Estimates for Treatment Group (85 sites)
Before	16	20.21
After	29	20.76

Table 5.14: Estimated Parameters Empirical Bayes, Rear-End Crashes, RRFB

Parameter	Estimate
N expected, T, B	19.71
N expected, T, A	20.24
Var (N expected, T, A)	2.49
CMF	0.93
Variance	0.05
SE (CMF)	0.22
95% CI-	0.49
95% CI+	1.37

5.4 SUMMARY

Using the crossing inventory and crash data, three analyses were conducted to estimate the safety impacts of pedestrian enhancements at mid-block locations. First, a simple before-and-after analysis of the pedestrian and rear-end crash data revealed that the flashing beacon amber results were not reliable. Following these analyses, the research elected to focus on only the RRFB locations. For pedestrian crashes, a CMF was only estimated using the simple before-after approach and a comparison group. Insufficient data were available for either the cross-sectional or empirical Bayes approach. For rear-end crashes, CMFs were estimated using all four methods. However, these CMFs were not statistically significant due to the size of the standard errors. In summary, estimated CMFs and standard errors for the RRFB locations are listed below:

- Pedestrian crashes (CMF +/- standard error):
  - 0.78 $^{+}/_{-}$ 0.35 Simple before-after (with 2007-2014 data)
  - 0.64 $^{+}/_{-}$ 0.26 Simple before-after (with 2007-2015 data)
  - 0.10 $^{+}/_{-}$ 0.07 Comparison group (with 2009-2015 data)
  - 0.63 $^{+}/_{-}$ 0.38 Comparison group (with 2007-2015 data)
- Rear-end crashes (CMF +/- standard error):
  - 1.30 $^{+}/_{-}$ 0.19 Simple before-after
  - $^{+}/_{-}$ 0.34 Comparison group
  - 1.75 $^{+}/_{-}$ 0.33 Cross-sectional
  - 0.93 $^{+}/_{-}$ 0.22 Empirical Bayes analysis before-after

While these analyses revealed important trends with respect to a decrease in pedestrian crashes and an increase in rear-end crashes following installation of pedestrian enhancements at crosswalk locations, these results must be interpreted with caution. Most of the RRFBs were installed in the last couple of years, which resulted in a small sample of crashes for analysis. The unavailability of pedestrian volumes at the crosswalk locations also created issues while estimating pedestrian exposure. Repeating these analyses when more data is available would provide more confidence in the obtained results. The Highway Safety Manual recommends using data from 10 to 20 treatment sites and comparable non-treatment sites, along with three to five years of crash and volume data from before and after treatment for EB analysis *(HSM 2009)*. The recommended CMF for RRFB installations from this research are from the simple before-after analyses for the pedestrian crashes and for the EB analysis for the rear-end crashes.

- Pedestrian crashes:
    - 0.64 $^{+}/_{-}$ 0.26 Simple before-after
- Rear-end crashes:

    0.93 $^{+}/_{-}$ 0.22 Empirical Bayes before-after

Detailed documentation as required by the FHWA CMF clearinghouse for the CMF is included in Chapter 6.

6.0 CONCLUSIONS AND RECOMMENDATIONS

This final report documents the research performed to estimate the safety effectiveness of mid-block pedestrian crossing enhancements installed on Oregon roadways. The report also summarizes the literature in a comprehensive review, documents site selection and data collection, and describes the analysis methods and results. The research effort collected detailed geometric, operational, land use and crash data on 191 pedestrian crossing enhancements (RRFBs, flashing amber, high-visibility markings) in Oregon. Due to data limitations and TAC priorities, the focus of the research was on locations with RRFB installations. Using a variety of estimation methods, the research established a crash modification factor for RRFB installations from the available data.

Chapter 2 presented a comprehensive literature review on the safety effects of PCEs such as marked crosswalks, high-visibility markings, pedestrian-activated flashing amber beacons, illuminated crosswalks, in-pavement lighting, curb extensions, median refuge islands, raised pedestrian crossings, lighting improvements, pedestrian overpasses and underpasses, RRFBs, in-street pedestrian signs, advanced stop lines and yield markings. The review found that a number of PCEs are associated with increases in driver yielding rates and decreases in pedestrian-vehicle crashes. The literature review highlighted a critical gap regarding the availability of high-quality CMFs in the FHWA Crash Modification Factors Clearinghouse. CMFs' quality are rated on 1 to 5 star rating system and currently high-quality CMFs are only available for raised medians (five stars) and pedestrian hybrid beacons (four stars).

Chapter 3 documented the data collection process. It included the process for creating the inventory and establishing the locations for four types of PCEs: RRFBs, flashing amber, high-visibility and standard parallel crossings. The chapter describes each of the supplemental data items, including crossing location information, route characteristics, surrounding land use and crossing enhancement descriptions. Pedestrian volume at the crossing locations was a highly desirable, but unavailable data element. To characterize pedestrian activity, a method was developed to estimate ranges for pedestrian crosswalk activity levels based on the land use classification at the census block level and the presence of pedestrian traffic generators such as bus stops, schools, shopping centers and hospitals within a 0.25-mile radius. Each crosswalk was categorized into one of six levels of activity – very low, low, medium-low, medium, medium-high and high. Finally, crash data for the 2007-2014 period were assembled for the safety analysis. A total of 124 pedestrian crashes and 1,043 rear-end crashes were gathered at the crosswalks in the sample using a 300-foot-diameter buffer around each crosswalk. Further analysis indicated that only rear-end crashes within 75 feet of the marked crosswalk (a 150-foot-diameter buffer) could be attributed, with high probability, to the enhanced crosswalk. Using this buffer 62 pedestrian crashes and 746 rear-end crashes were retained for further analysis.

Chapter 4 included two key components: (1) descriptive analysis of crossing and crash data for each PCE analyzed, and (2) exploration of risk ratios for pedestrian and rear-end crashes by the number of lanes, posted speed limit, and estimated level of pedestrian activity. A temporal graph of each crossing was created and from its examination it is clear that most crossings have undergone significant changes over the study period. For the crash analysis, the differing durations of the before and after periods of the crosswalk enhancements required a careful analysis of the distribution of crashes in each time period. The most important trend observed was a shift (reduction) in the pedestrian crash severity after the installation of the crosswalk treatments. This shift was from fatal and injury A crash types to lower severity crashes of injury B and injury C. Some of the shift in the severity trends may be regression-to-the-mean effects since the locations were most likely selected for treatment based on crash history. There was some evidence of crash trend changes possibly related to the higher visibility of pedestrians at the enhanced locations. Changes were observed in crashes by month of the year, weather condition, and lighting condition. For rear-end crashes, there were no notable shifts by crash severity, causes, or month of the year; the only observed shift was in crashes by lighting condition. It is difficult to speculate based on the crash trends independently, but this could be related to higher braking frequency due to higher yielding for pedestrians at the enhanced locations.

Crash and geometric data were tabulated based on the number of observation-years for each PCE category and the frequency of crashes and a risk ratio were calculated. In this way, over-representation of a roadway characteristic in the crash performance (uncontrolled by the effect of other variables) could be explored. For pedestrian crashes, increases in the risk ratio were observed for increases in the number of lanes, the posted speed, and estimated pedestrian activity level. Similar trends were observed for rear-end crashes. The data showed that risk ratios for rear-end crashes increased with the number of lanes, posted speed, and estimated pedestrian activity level. It should be noted that none of these variables were significant predictors in the multi-variate modeling efforts that were conducted in Chapter 5.

Chapter 5 presented the safety effectiveness analysis. Using the crossing inventory and crash data, three analyses were conducted to estimate the safety impacts of pedestrian enhancements at mid-block locations. First, a simple before-and-after analysis of the pedestrian and rear-end crash data revealed that flashing amber beacon results were not reliable for CMF purposes. Based on these results, the research team elected to focus only on the RRFB locations. Late in the preparation of the final report, the 2015 fatal and injury crash data became available. The 2015 data were included only for the pedestrian crash analysis (since all of the pedestrian crashes include have reported injuries. For pedestrian crashes, a CMF was only estimated using a simple before after and comparison group analysis. Insufficient data were available for either the cross-sectional or empirical Bayes approach. For rear-end crashes, CMFs were estimated using all four methods. These CMFs were not statistically significant due to the size of the standard errors and the small effect on crashes expected. The next section documents the recommended CMFs and standard errors estimated for the RRFB locations

6.1 RECOMMENDED CMF

In order to facilitate the consideration of a new CMF for inclusion in the CMF Clearinghouse, Gross et al. *(Gross et al. 2010)* suggest that the documentation of the new CMF should include sufficient detail for the elements used for evaluating its quality. The FHWA guidance document recommends the information in Table 6.1 be prepared for each CMF study. The table provides the documentation for the RRFB installations analyzed in Oregon.

Table 6.1: Required Documentation for the Countermeasure Clearinghouse, RRFB

Countermeasure Name and Description	Install enhanced RRFB pedestrian crossing at mid-block crossing location.	
Crash Type	Pedestrian	Rear-end
Crash Severity	All (KABCO)	
Time of Day	All hours	
Crash Modification Factor	0.64	0.93
Measures of Precision for the CMF (standard error/deviation)	0.26	0.22
Prior Conditions	Previously unmarked or at a location with prior high-visibility markings. The data set pooled these locations in the estimation of CMFs.	
Roadway Class	Principal arterial, minor arterial, major collector, minor collector	
Road Division Type	Undivided	
State	Oregon	
Area Type	Rural; Urban; Suburban	
Number of Through Lanes	Two to five lanes (includes TWLTL)	
Speed Limit	20 mph to 45 mph	
Traffic Volume Range	Average = 13,000	
Traffic Control	No control	
Intersection Type	Roadway to pedestrian crossing (i.e., mid-block crossing).	
Years of Data	Nine	Four
Type of Methodology	Simple Before-After	EB Before-After
Site Selection Criteria	Sites for inclusion in the study were identified from a list of enhanced crossing locations from state and local inventories. Sites were excluded primarily due to undetermined installation date of treatment.	
Sample Size Used (Crashes)	26 before, eight after	18 before, 26 after
Sample Size Used (Sites)	19	15
Biases Documentation	Sites likely selected for pedestrian crash experience. Regression-to-the-mean bias present and not accounted for in simple before-after analysis. Changes in pedestrian volume also not accounted for in method.	Sites not likely selected based on rear-end crash history. EB analysis approach includes adjustment for traffic volumes. Changes in pedestrian volume also not accounted for in method.

6.2 LIMITATIONS

There are several limitations of this research:

- Most of the RRFBs were installed in the last couple of years, which resulted in a small sample of crashes for analysis. Most RRFB installations have taken place between 2011 and 2014, which limits the length of the post-installation crash data. Unfortunately, in order to have sufficient data to estimate CMFs all RRFB enhanced crossing had to be pooled together.

- The unavailability of pedestrian volumes at the crosswalk locations also created issues for the analysis. Without a way to capture changes in pedestrian volumes over time, the analysis may underestimate the effectiveness of the treatment, especially if the enhanced treatment encourages more pedestrian activity.

- The estimated CMF for pedestrian crashes does not account for regression to the mean, hence, it may overestimate the effectiveness of the treatment.

- One of the key challenges in the data analysis is that many locations have had staged enhancements at the locations. For most safety analysis, detecting small changes in safety performance is difficult. The combination of low crash numbers and incremental changes precluded the estimation of statistically significant CMFs for individual enhancements.

6.3 RECOMMENDATIONS FOR IMPROVED DATA INVENTORIES

- Data inventories on pedestrian crossing enhancements were generally inadequate, especially off the state highway system which lacks the annual video recording. The project would have benefited from more systematic record keeping.

- When a pedestrian crossing enhancement is installed, the minimum information needed to be recorded includes:
    - Date of installation
    - Type of enhancements made (striping, signs, beacons)
    - Pedestrian crossing counts both before and after installation (about 3-5 months after):
        - Desirable: multiday counts 24-hour counts
        - Preferable: 24-hour counts
        - Minimum: Four-hour counts during peak periods

6.4 FURTHER RESEARCH

There are a number of obvious areas for further research following this research. Some of these are:

- Re-estimation of the RRFB locations with more crash data. There are at least three situations for which it would be desirable to have suitable samples to estimate individual CMFs: 1) installation of a RRFB-enhanced crossing at a location with no previous marking; 2) installation of a RRFB-enhanced crossing at a location with existing flashing amber beacons and 3) installation of a RRFB-enhanced crossing at a location with high visibility or standard mid-block crosswalk markings.

- Establishing methods to count pedestrians to better estimate pedestrian crash SPFs. The lack of pedestrian volumes, which are critical for exposure and estimating pedestrian risk, preclude the estimation of robust SPFs and CMFs. At crossings, it is likely that there is also a temporal trend of increased pedestrian volumes (i.e., more pedestrians and/or housing or commercial activities are attracted to the new facilities).

- Characterization or research that accounts for the effect of the idea that corridor treatments may have more safety benefits than isolated areas (if those “isolated” areas are still part of a pedestrian network).

- Extension and validation of the pedestrian-activity characterization developed in this research.

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APPENDIX A

Table A1: Descriptive Statistics for Numerical Variables for Crossings with RRFBs

Data Element	Number of Observations	Mean	Median	Standard Deviation	Max	Min
Number of Lanes	68	3.76	4.00	1.05	5.00	2.00
Posted Speed (mph)	68	33.46	35.00	6.71	45.00	20.00
Number of Bike Lanes	68	1.40	2.00	0.90	2.00	0.00
Number of Sidewalks	67	1.84	2.00	0.45	2.00	0.00
Distance to Bus Stop Shelter (ft)	48	216.52	106.00	259.06	1087.00	0.00
Distance to School (ft)	44	1357.95	911.00	1420.64	5280.00	0.00
Distance to Hospital (ft)	7	3.86	4.00	1.95	6.00	1.00
Distance to Signal (N, W) (ft)	61	1693.03	1367.00	1628.22	339.00	11510.00
Distance to Signal (S, E) (ft)	56	1690.29	1196.00	1485.72	328.00	8078.00
Lighting	68	0.79	1.00	0.76	2.00	0.00
Curb Ramps	68	1.87	2.00	0.45	2.00	0.00
Curb Extension	68	0.44	0.00	0.82	2.00	0.00
Number of Ped Advance Sign Assemblies	68	1.01	1.00	0.97	2.00	0.00
Number of School Advance Sign Crossing Assembly	68	0.29	0.00	0.71	2.00	0.00

Table A2: Descriptive Variables for Categorical Variables in the RRFB Sample

Data Element	Yes	No
One-Way	4 (5.88%)	64 (94.11%)
Bus Stop at Crossing	48 (70.58%)	20 (29.41%)
Bus Stop Shelter	17 (25%)	51 (75%)
Major Shopping Center	11 (16.17%)	57 (83.82%)
School	43 (63.23%)	25 (36.76%)
Pedestrian Signs	58 (85.29%)	10 (14.71%)
School Signs	8 (11.76%)	60 (88.23%)
Overhead Signs	7 (10.29%)	61 (89.70%)
Two-Way Left-Turn Lane	39 (57.35%)	29 (42.64%)
Raised Median	14 (20.58%)	54 (79.41%)
Pedestrian Refuge Island	39 (57.35%)	29 (42.65%)
Raised Pedestrian Crossing	1 (1.47%	66 (97.05%)
Yield Pavement Marking	4 (5.88%)	64 (94.11%)
Stop on Red Sign	0 (0.00%)	68 (100.00%)
Stop Here for Ped Sign	40 (58.82%)	28 (41.17%)

Table A3: Descriptive Statistics for Numerical Variables at Crossings with Flashing Amber Beacons

Data Element	Number of Observations	Mean	Median	Standard Deviation	Max	Min
Number of Lanes	14	3.50	3.00	1.29	5.00	2.00
Posted Speed (mph)	14	33.93	35.00	7.12	45.00	25.00
Number of Bike Lanes	14	1.57	2.00	0.85	2.00	0.00
Number of Sidewalks	14	1.79	2.00	0.58	2.00	0.00
Distance to Bus Stop Shelter (ft)	12	244.92	171.50	247.58	818.00	26.00
Distance to School (ft)	8	1367.62	726.50	1901.86	5913.00	59.00
Distance to Hospital (ft)	1	4459.00	4459.00	NA	4459.00	4459.00
Distance to Signal (N, W) (ft)	11	1570.00	1277.00	1137.92	4605.00	614.00
Distance to Signal (S, E) (ft)	9	1451.00	947.00	1213.95	4316.00	481.00
Lighting	14	0.79	1.00	0.58	2.00	0.00
Curb Ramps	14	1.71	2.00	0.73	2.00	0.00
Curb Extension	14	0.14	0.00	0.53	2.00	0.00
Number of Ped Advance Sign Assemblies	14	0.43	0.00	0.85	2.00	0.00
Number of School Advance Sign Crossing Assembly	14	0.29	0.00	0.73	2.00	0.00

Table A4: Descriptive Variables for Numerical Variables at Crossings with Flashing Amber Beacons

Data Element	Yes	No
One-Way	0 (0.00%)	14 (100.00%)
Bus Stop at Crossing	12 (85.71%)	2 (14.28%)
Bus Stop Shelter	4 (28.57%)	10 (71.42%)
Major Shopping Center	3 (21.42%)	11 (78.57%)
School	9 (64.28%)	5 (35.71%)
Pedestrian Signs	10 (71.42%)	4 (28.57%)
School Signs	2 (14.29%)	12 (85.71%)
Overhead Signs	4 (28.57%)	10 (71.42%)
Two-Way Left-Turn Lane	9 (64.28%)	5 (35.71%)
Raised Median	1 (7.14%)	13 (92.85%)
Pedestrian Refuge Island	5 (35.71%)	9 (64.28%)
Raised Pedestrian Crossing	0 (0.00%)	14 (100.00%)
Yield Pavement Marking	0 (0.00%)	14 (100.00%)
Stop on Red Sign	0 (0.00%)	14 (100.00%)
Stop Here for Ped Sign	7 (50.00%)	7 (50.00%)

Table A5: Descriptive Statistics for Numerical Variables at Crossings with High-Visibility Crosswalk Markings

Data Element	Number of Observations	Mean	Median	Standard Deviation	Max	Min
Number of Lanes	109	2.81	2.00	1.00	5.00	2.00
Posted Speed (mph)	109	28.76	30.00	5.41	45.00	20.00
Number of Bike Lanes	109	0.80	0.00	0.97	2.00	0.00
Number of Sidewalks	109	1.67	2.00	0.68	2.00	0.00
Distance to Bus Stop Shelter (ft)	54	541.80	348.00	563.81	2697.00	39.00
Distance to School (ft)	90	1238.79	990.00	1079.38	4528.00	5.00
Distance to Hospital (ft)	15	2473.20	2317.00	1380.01	6336.00	584.00
Distance to Signal (N, W) (ft)	47	1523.66	1041.00	1813.06	11880.00	238.00
Distance to Signal (S, E) (ft)	40	1375.28	913.00	1072.25	4536.00	251.00
Lighting	109	0.76	1.00	0.71	2.00	0.00
Curb Ramps	109	1.68	2.00	0.69	2.00	0.00
Curb Extension	108	0.33	0.00	0.74	2.00	0.00
Number of Ped Advance Sign Assemblies	109	0.28	0.00	0.69	2.00	0.00
Number of School Advance Sign Crossing Assembly	107	0.91	0.00	0.98	2.00	0.00

Table A6: Descriptive Variables for Categorical Variables at Crossings with High-Visibility Crosswalk Markings

Data Element	Yes	No
One-Way	4 (3.67%)	105 (96.33%)
Bus Stop at Crossing	53 (48.62%)	56 (51.37%)
Bus Stop Shelter	5 (4.58%)	104 (95.41%)
Major Shopping Center	13 (11.92%)	96 (88.07%)
School	91 (83.48%)	18 (16.51%)
Pedestrian Signs	25 (22.93%)	84 (77.06%)
School Signs	51 (46.78%)	58 (53.21%)
Overhead Signs	7 (6.42%)	102 (93.57%)
Two-Way Left-Turn Lane	36 (33.02%)	73 (66.97%)
Raised Median	5 (4.58%)	104 (95.41%)
Pedestrian Refuge Island	20 (18.34%)	89 (81.65%)
Raised Pedestrian Crossing	0 (0.00%)	109 (100.00%)
Yield Pavement Marking	11 (10.09%)	98 (89.91%)
Stop on Red Sign	0 (0.00%)	109 (100.00%)
Stop Here for Ped Sign	21 (19.27%)	88 (80.73%)

APPENDIX B

Table B1: Location of Crosswalks

Crossing ID	Year	ODOT Region	Route	City/Town	Crossing Location (Description)	Milepoint	Latitude	Longitude
0001	2007	5	US 95 (456)	Jordan Valley	Northside of Oregon Avenue	20.3	42.975767	-117.053126
0004	2007	5	OR 351 (351)	Joseph	Both sides of McCully Avenue	0.13	45.35243	-117.229886
0006	2007	5	OR 350 (350)	Joseph	Westside of N. East Street	0.2	45.354391	-117.225975
0007	2007	5	OR 237 (342)	Cove	Eastside of French Street	13.52	45.296731	-117.809291
0008	2003	5	OR 334 (334)	Athena	Westside of 5th Street	17.49	45.811687	-118.487651
0012	2001	5	OR 207 (333)	Hermiston	Midblock, west side of hospital entrance	7.93	45.849635	-119.308072
0014	2008	5	OR 204 (330)	Elgin	Westside of 11th Avenue	40.68	45.564828	-117.920768
0015	2008	5	OR 204 (330)	Elgin	Eastside of 12th Avenue	40.63	45.564847	-117.921517
0022	2007	2	12th	Salem	Southside of Mill Street		44.933956	-123.028602
0024	2007	5	OR 237 (066)	Union	Both sides of Fulton Street	16.71	45.205679	-117.865511
0025	2007	5	OR 237 (066)	Union	Both sides of Dearborn Street	16.61	45.207098	-117.865481
0027	2007	5	OR 74 (052)	Heppner	Both sides of Barratt Street	46.18	45.355694	-119.55053
0028	2007	5	OR 74 (052)	Heppner	Southside of Court Street	46.02	45.353473	-119.55103
0030	2007	5	OR 74 (052)	Heppner	Southside of Hinton Street	45.38	45.360397	-119.555108
0032	2007	5	US 395 (048)	John Day	Northside of 1st Avenue	0.07	44.415138	-118.952715
0033	2008	5	US 395 (028)	Pilot Rock	Northside of 3rd Street	15.48	45.480895	-118.835184
0034	2008	5	US 395 (028)	Pilot Rock	Southside of Alder Drive	15.21	45.483631	-118.833289
0035	2001	5	OR 7 (012)	Baker City	Midblock, west end of P.R. Bridge	0.32	44.781669	-117.828145
0039	2009	5	OR 82 (010)	Enterprise	Westside of School Street	65.74	45.420051	-117.272188
0042	2009	5	OR 82 (010)	Enterprise	Southside of Greenwood Street	65.21	45.424487	-117.277578
0053	2009	5	OR 82 (010)	Wallowa	Eastside of Whipple Street	47.01	45.570194	-117.531501
0054	2009	5	OR 82 (010)	Wallowa	Eastside of Clairmont Street	46.93	45.570209	-117.533351
0055	2009	5	OR 82 (010)	Wallowa	Eastside of Douglas Street	46.89	45.570227	-117.534595
0056	2009	5	OR 82 (010)	Wallowa	Southside of Fifth Street	46.59	45.573791	-117.536279
0058	2009	5	OR 82 (010)	Imbler	Southside of 6th Street	12.34	45.461777	-117.96266

0059	2009	5	OR 82 (010)	Imbler	Northside of 5th Street	12.27	45.460913	-117.962648
0060	2009	5	OR 82 (010)	Imbler	Southside of Main Street	12.2	45.459639	-117.962627
0061	2002	5	OR 11 (008)	Milton-Freewater	Northside of 4th Avenue	30.55	45.931795	-118.387298
0065	2002	5	OR 11 (008)	Milton-Freewater	Northside of 12th Avenue	30.01	45.924693	-118.382606
0081	2007	5	US 20 (007)	Vale	Both sides of Holland Street	246.15	43.982665	-117.243113
0082	2007	5	US 20 (007)	Vale	Both sides of Holland Street	246.15	43.981898	-117.243114
0093	2002	5	US 20 (007)	Hines	Southside of Barnes Ave	129.12	43.561565	-119.083083
0096	2007	5	US 26 (005)	Prairie City	Eastside of Bridge Street	175.17	44.462481	-118.711249
0097	2007	5	US 26 (005)	John Day	Both sides of Dayton Street	162.36	44.416061	-118.951202
0098	2007	5	US 26 (005)	John Day	Eastside of Brent Street	162.22	44.416237	-118.953599
0099	2007	5	US 26 (005)	John Day	Eastside of Bridge Street	162.18	44.416325	-118.954253
0101	2007	5	US 26 (005)	John Day	Mid-block @ MP 161.73	161.73	44.419816	-118.961776
0102	2007	5	US 26 (005)	John Day	Mid-block @ MP 161.65	161.65	44.419768	-118.963354
0103	2007	5	US 26 (005)	Dayville	Southside of Schoolhouse Drive	131.01	44.468173	-119.535287
0104	2007	5	OR 19 (005)	Spray	Northside of Park Street	92.41	44.83371	-119.793756
0105	2007	5	OR 19 (005)	Spray	Northside of Cox Street	92.35	44.834846	-119.793915
0106	2007	5	US 730 (002)	Irrigon	Westside of 12th Street	175.97	45.896594	-119.48675
0107	2007	5	US 730 (002)	Irrigon	Eastside of 10th Street	175.87	45.896316	-119.488614
0108	2007	5	US 730 (002)	Irrigon	Westside of Division Street	175.57	45.895207	-119.494823
0109	2001	5	US 730 (002)	Irrigon	Eastside of First Street	175.31	45.894293	-119.49966
0110	2007	3	US 101 (009)	Reedsport	Both sides of 20th Street	212.53	43.695795	-124.120073
0111	2007	3	US 101 (009)	Reedsport	Both sides of 21st Street	212.61	43.695474	-124.121552
0116	2007	3	US 101 (009)	Coos Bay	Both sides of Golden Avenue	238.61	43.362715	-124.213232
0117	2007	3	US 101 (009)	Coos Bay	Both sides of Ingersoll Avenue	238.84	43.359563	-124.213257
0118	2007	3	US 101 (009)	Bandon	Southside 9th Avenue	274.36	43.115055	-124.414997
0119	2007	3	US 101 (009)	Bandon	Southside of 10th Avenue	274.42	43.114152	-124.41501
0120	2007	3	US 101 (009)	Port Orford	Northside of 12th Street	300.82	42.74819	-124.497404
0124	2007	3	US 101 (009)	Gold Beach	Southside of Gauntlett Street	328.52	42.416709	-124.419864
0125	2007	3	US 101 (009)	Gold Beach	Northside of Caughell Street	328.6	42.415807	-124.420344
0126	2007	3	US 101 (009)	Gold Beach	Mid-block @ MP 328.85	328.85	42.41237	-124.420611

0127	2007	3	US 101 (009)	Gold Beach	Mid-block @ Gold Beach HS	329.09	42.40852	-124.420775
0128	2007	3	US 101 (009)	Gold Beach	Southside of 10th Street	329.34	42.405112	-124.4213
0129	2007	3	US 101 (009)	Brookings	Southside of Pacific Avenue	357.08	42.053062	-124.285667
0130	2001	3	US 101 (009)	Brookings	Mid-block @ MP 357.26	357.26	42.052388	-124.282221
0131	2007	3	US 101 (009)	Brookings	Westside of Fern Avenue	357.33	42.052635	-124.281196
0132	2007	3	US 101 (009)	Brookings	Westside of Willow Street	357.41	42.053066	-124.279793
0134	2008	3	OR 540 (240)	North Bend	Both sides of 14th Street	1.13	43.401341	-124.23928
0139	2009	3	OR 38 (045)	Elkton	Northside of Binder Road	35.62	43.641681	-123.577627
0142	2007	3	OR 542 (242)	Powers	North end of Coquille River Bridge	18.21	42.885258	-124.073068
0143	2007	3	OR 542 (242)	Powers	South end of Coquille River Bridge	18.31	42.883755	-124.073042
0144	2007	3	OR 42 (035)	Myrtle Point	Southside of Maple Street	20.63	43.063935	-124.139186
0146	2007	3	OR 42 (035)	Winston	Westside of Cary Street	72.94	43.11998	-123.420613
0147	2007	3	OR 42 (035)	Winston	Westside of Civil Bend Avenue	73.08	43.120627	-123.41838
0148	2007	3	OR 42 (035)	Winston	Mid-block @ MP 73.25	73.25	43.121566	-123.415095
0149	2007	3	OR 42 (035)	Winston	Southside of Baker Street	73.47	43.123506	-123.412418
0156	2001	2	US 30 (092)	Astoria	Northside of Bay Street	99.13	46.189257	-123.849161
0157	2001	2	US 30 (092)	Astoria	Westside of 37th Street	96.7	46.193523	-123.80134
0158	2002	4	US 20 (007)	Bend	Eastside of 12th Street	1.16	44.059895	-121.289402
0159	2002	4	US 97 (004)	Bend	Southside of Reed Lane	139.68	44.032377	-121.313172
0160	2002	4	US 97 (004)	Bend	Southside of Badger Road	140.3	44.024503	-121.318583
0161	2001	3	US 199 (025)	Cave Junction	Midblock @ MP 28.77	28.77	42.165607	-123.646524
0162	2001	2	OR 99W (091)	Corvallis	South of Chapman Place	84.33	44.553833	-123.264929
0163	2001	2	OR 99W (091)	Corvallis	North of Lilly Avenue	84.77	44.548425	-123.26553
0164	2001	2	OR 99W (091)	Corvallis	South of Mayberry Avenue	84.83	44.546851	-123.265704
0165	2001	2	OR 99W (091)	Corvallis	North of Richland Avenue	85.15	44.542905	-123.266119
0166	2001	2	US 101 (009)	Florence	Southside of 2nd Street	190.72	43.968457	-124.107638
0167	2001	2	US 101 (009)	Florence	North of 7th Street	190.33	43.973171	-124.104225
0168	2001	2	US 101 (009)	Florence	Between 18th and 19th Street	189.64	43.982969	-124.101272
0169	2001	2	US 101 (009)	Florence	Northside of 30th Street	188.97	43.992794	-124.101395
0170	2002	1	OR 8 (029)	Hillsboro	East of 44th Avenue	10.08	45.501212	-122.938165

0172	2002	2	US 20 (016)	Lebanon	Southside of Hospital Entrance	12.47	44.551144	-122.908669
0173	2001	2	US 101 (009)	Lincoln City	Between 33rd and 34th Street	113.23	44.989416	-124.005674
0175	2001	1	OR 213 (160)	Mulino	Southside of Passmore Road	11.06	45.220016	-122.581556
0176	2002	2	US 20 (033)	Philomath	Westside of 17th Street	50.88	44.540014	-123.362037
0177	2002	1	OR 213 (068)	Portland	South of Fancis Street	5	45.493699	-122.578757
0178	2001	1	OR 99W (091)	Portland	South of Rasmussen Apartments	2.69	45.487258	-122.682653
0179	2001	1	OR 99W (091)	Portland	Eastside of 13th Avenue	4.45	45.469007	-122.691887
0180	2001	1	OR 99W (091)	Portland	South of Luradel Street	6.6	45.450739	-122.727466
0181	2001	1	US 26 (026)	Portland	South of Water Avenue	0.08	45.50274	-122.67635
0182	2001	1	US 26 (026)	Portland	Westside of 119th Avenue	7.06	45.496976	-122.540726
0183	2001	1	US 26 (026)	Portland	Eastside of 141st Street	8.16	45.498743	-122.518325
0184	2001	1	US 26 (026)	Portland	Eastside of 156th Avenue	8.89	45.496278	-122.503726
0186	2001	1	US 30 BY (123)	Portland	Westside of 131th Place	12.89	45.555641	-122.528741
0188	2001	2	OR 126B (015)	Springfield	Westside of 51st Street	5.6	44.045711	-122.943161
0189	2001	2	OR 126B (015)	Springfield	East of 44th Avenue	4.93	44.045757	-122.957332
0190	2002	1	OR 141 (141)	Tigard	OR 141 and Fanno Creek Trail	5.69	45.42418	-122.765719
0191	2002	2	OR 47 (102)	Vernonia	Eastside of Missouri Avenue	61.6	45.85763	-123.179761
0192	2002	2	OR 214 (140)	Woodburn	Westside of Park Avenue	38.82	45.151548	-122.841228
0193	2008	2	Gilbson Hill	Albany	Eastside of Pulver Lane		44.656825	-123.135602
0194	2007	2	Waverly	Albany	Southside of 36th Avenue		44.608739	-123.073251
0195	2007	2	Oak	Albany	Oak at Periwinkle Creek Bike Trail		44.630606	-123.088359
0196	2008	3	Siskiyou	Ashland	Soutside of Bridge Steet	20.47	42.186472	-122.693861
0197	2008	3	Siskiyou	Ashland	North of Avery Street	20.41	42.187057	-122.695026
0198	2008	3	Siskiyou	Ashland	Southside of Garfield Street	20.33	42.187658	-122.696246
0199	2008	3	Siskiyou	Ashland	Southside of Palm Avenue	20.25	42.188295	-122.697534
0201		3	Hamrick	Central Point	Northside of New Haven Road		42.387746	-122.891815
0202	2002	3	OR 99 (063)	Central Point	Maple Street	2.52	42.376405	-122.920376
0213	2007	1	Halsey	Gresham	Westside of 172nd Avenue		45.534689	-122.486609
0215	2012	4	B	Madras	Eastside of 10th Street		44.635938	-121.124341
0217	2011	1	33rd	Portland	Northside of Klickitat Street		45.546792	-122.630686
0219	2007	1	Foster	Portland	East of 80th Avenue		45.483519	-122.580737

0223	2007	2	Commercial	Salem	Southside of Bellevue Street		44.936343	-123.042495
0224	2007	2	Court	Salem	Both sides of Capitol Bldg		44.938879	-123.029521
0229	2008	2	State	Salem	Mid-block at Roberts H.S.		44.92793	-122.989533
0230	2007	2	State	Salem	Mid-block at Capitol Bldg		44.937927	-123.030686
0257	2001	1	US 26 (026)	Portland	Westside of 58th Avenue	3.83	45.497428	-122.603867
0259	2001	1	US 26 (026)	Portland	Westside of 168th Avenue	9.58	45.493442	-122.490196
0267	2002	1	US 30 (100)	Cascade Locks	Southside of Cascade Ave	31.19	45.670357	-121.889153
0268	2002	1	OR 281 (281)	Hood River	South of Pacific Avenue	1.02	45.694989	-121.523643
0269	2002	1	OR 30 (100)	Hood River	Westside of 9th Street	50.36	45.70875	-121.520163
0272	2007	1	Jackson School	Hillsboro	Jackson School and Estate Drive		45.542948	-122.979711
0285	2007	1	Main	Sherwood	Main and Railroad Street		45.35545	-122.841924
0293	2007	1	Killingsworth	Portland	Killingsworth and 52nd Avenue		45.562754	-122.6096
0294	2007	1	Killingsworth	Portland	Killingsworth and 46th Place		45.562788	-122.6152
0295	2007	1	Cornell	Portland	Cornell and Summit Avenue		45.532541	-122.708493
0296	2007	1	Naito Parkway	Portland	Natio Parkway and Union Station		45.529049	-122.674201
0297	2007	1	Naito Parkway	Portland	Natio Parkway and Mid-Block		45.527746	-122.672705
0300	2007	1	Multnomah	Portland	Multnomah and 6th Avenue		45.531505	-122.659696
0303	2007	1	Beaverton Hillsdale	Portland	Beaverton Hillsdale and 62nd Avenue		45.48707	-122.740154
0304	2007	1	Stark	Portland	Stark and 126th Avenue		45.5190443	-122.5334646
0305	2007	1	Stark	Portland	Stark and 133rd Avenue		45.5190843	-122.5260904
0306	2007	1	60th	Portland	60th and Oregon Street		45.528219	-122.602254
0307	2007	1	60th	Portland	60th and Willow Street		45.529066	-122.602219
0308	2007	1	12th	Portland	12th and Glisan Street		45.526888	-122.653582
0309	2007	1	122nd	Portland	122nd and Morrison Street		45.516757	-122.537744
0311	2007	1	Division	Portland	Division and 128th Avenue		45.504072	-122.532364
0313	2007	1	Foster	Portland	Foster and 120th Avenue		45.4765	-122.539434
0314	2007	1	122nd	Portland	122nd and Oregon Street		45.528233	-122.537716
0315	2001	2	US 101 (009)	Seaside	Southside of 17th Avenue	20.21	46.005098	-123.915828
0316	2001	2	US 101 (009)	Depoe Bay	Both sides of Clarke Street	127.4	44.812885	-124.062417
0317	2001	2	US 101 (009)	Depoe Bay	North of Vista Drive	127.06	44.817884	-124.06306
0318	2001	2	US 101 (009)	Depoe Bay	Both side of Collins Street	127.48	44.811706	-124.062331

0319	2002	2	OR 219 (140)	Newberg	Westside of Everest Road	20.78	45.300373	-122.960881
0323	2009	2	Butler Bridge	Toledo	Butler Bridge and Main Street		44.618855	-123.937528
0326	2001	1	OR 99E	Aurora	Northside of Ottaway Avenue	25.55	45.223478	-122.758591
0330	2001	4	OR 361 (361)	Madras	OR 361 and Trail Crossing	0.69	44.627515	-121.139383
0331	2001	2	US 6 (037)	Tillamook	US 6 and Goodspeed Place	0.33	45.456822	-123.837352
0332	2001	2	US 101 (009)	Garibaldi	US 101 and 4th Street	55.69	45.559198	-123.911935
0334	2002	4	US 197 (004)	Maupin	US 197 and 4th Street	45.24	45.175867	-121.079444
0337	2001	2	OR 99E (058)	Harrisburg	Southside of Smith Street	28.58	44.27224	-123.170959
0339	2001	5	OR 99 (226)	Cottage Grove	Northside of Geer Avenue	14.15	43.804983	-123.055699
0340	2001	2	OR 99W (091)	Amity	Both sides of 6th Street	44.76	45.114564	-123.2062
0341	2001	2	OR 99W (091)	Amity	Northside of Chruch Street	44.82	45.113885	-123.206206
0342	2001	4	US 20 (015)	Sisters	Both sides of Pine Street	92.27	44.291336	-121.553823
0343	2001	4	US 20 (015)	Sisters	Both sides of Oak Street	92.35	44.29133	-121.552406
0344	2001	4	US 20 (015)	Sisters	Mid-Block	92.42	44.29133	-121.551188
0345	2001	4	US 20 (015)	Sisters	Both sides of Elm Street	92.48	44.291315	-121.54997
0346	2001	4	US 20 (015)	Sisters	Both sides of Fir Street	92.54	44.291338	-121.548743
0347	2001	4	US 20 (015)	Sisters	Both sides of Spruce Street	92.6	44.29133	-121.547517
0348	2001	4	US 20 (015)	Sisters	Both sides of Larch Street	92.65	44.291275	-121.546313
0349	2001	4	US 20 (015)	Sisters	Both sides of Hood Street	92.74	44.290689	-121.544838
0350	2001	4	US 20 (015)	Sisters	Westside of Locus Street	92.8	44.29027	-121.544029
0351	2002	2	OR 223 (189)	Dallas	Westside of Uglow Street	0.2	44.929979	-123.307634
0353	2012	4	B	Madras	Both sides of 6th Street		44.635963	-121.128539
0354	2012	4	B	Madras	Both sides of 7th Street		44.635953	-121.127512
0355	2012	4	B	Madras	Westside of 8th Street		44.635955	-121.126593
0357	2001	4	OR 126 (015)	Redmond	Eastside of 23rd Street	110.9	44.269253	-121.194196
0361	2002	4	OR 140 (020)	Bly	Eastside of Main Avenue	53.87	42.398067	-121.043033
0362	2001	4	OR 70 (023)	Bonanza	Both sides of 5th Avenue	6.6	42.198727	-121.406431
0363	2001	4	OR 70 (023)	Bonanza	Both sides of 4th Avenue	6.65	42.198706	-121.405275
0364	2001	4	OR 70 (023)	Bonanza	Both sides of 3rd Avenue	6.72	42.198629	-121.40396
0366	2002	3	OR 99 (063)	Ashland	Westside of Harmony Street	21.01	42.182255	-122.685425
0367	2002	3	OR 99 (063)	Ashland	Southside of Clay Street	21.57	42.177752	-122.67643
0370	2007	1	Foster	Portland	Westside of Cora Street		45.491724	-122.601112
0371	2007	1	Powell	Portland	North of Pershing Street		45.499177	-122.648533

0372	2011	1	28th	Hillsboro	Southside of Veterans Drive	45.527845	-122.9541
0374	2007	1	Durham	Tigard	Westside of 88th Avenue	45.404304	-122.768077
0381	2007	2	Waverly	Albany	Southside of 22nd Avenue	44.620456	-123.072794
0382	2007	2	Liberty	Salem	Southside of Holder Lane	44.875784	-123.061434
0383	2007	2	25th	Salem	Southside of Claude Street	44.925426	-123.010703
0384	2007	1	Basin	Portland	Going and Basin Avenue	45.556182	-122.697122
0385	2008	3	Siskiyou	Ashland	Midblock @ Ashland H.S.	42.189744	-122.700468
0386	2008	3	Siskiyou	Ashland	Southside of Frances Lane	42.184348	-122.689596
0387	2012	3	Ashland	Ashland	Eastside of Stadium Street	42.185456	-122.689458
0388	2008	3	Main	Ashland	Eastside of Campus Way	42.194915	-122.689731
0389	2007	2	Geary	Albany	South of 12th Avenue	44.630557	-123.083421