Leading Pedestrian Intervals at Intersections in Proximity to Schools: An Evaluation of Safety and Effectiveness

by

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

I understand that my thesis may be made electronically available to the public.

Abstract

Pedestrians encounter substantial risks on roadways, particularly at signalized intersections where their exposure to traffic is unavoidable. A predominant cause of pedestrian crashes at these intersections is drivers' failure to yield while making turning manoeuvres. One effective countermeasure proposed to mitigate this issue is Leading Pedestrian Interval (LPI), which provides pedestrians with a walk signal during the 'all red' phase, preceding the green signal for parallel vehicular traffic. This timing allows pedestrians to establish themselves in the crosswalk, thereby enhancing their visibility to drivers. Despite extensive research demonstrating the effectiveness of LPIs, there is a lack of research regarding their safety effect when implemented at signalized intersections near schools and the factors influencing their effectiveness. Many existing guidelines and safety programs recommend LPI implementation near schools as part of comprehensive pedestrian safety strategies, highlighting the need to evaluate these proposed guidelines.

The main goal of this research is to assess the effectiveness of implementing LPIs at signalized intersections near schools. Additionally, the study aims to analyse in detail the factors that influence pedestrian crash risk in this context. The case study was conducted using ten-year crash data from thirty-three signalized intersections in the Region of Waterloo. An Empirical Bayesian (EB) before-and-after analysis was utilized to evaluate the impact of LPIs on pedestrian safety. Comprehensive data collection efforts were made to gather the necessary information for developing the Safety Performance Function (SPF) model. The collected data comprised detailed records of traffic volumes, pedestrian counts, roadway and intersection characteristics, and historical crash data.

In this study, two SPF models were selected using different traffic exposure variables. One model used Estimated Daily Traffic (EDT), while the other employed surrogate exposure measure - the number of legs with commercial entries/exits or residential driveways within 50 meters of the intersection (NCE). Several key factors were identified that increase pedestrian crash risks at intersections, including residential and commercial areas, the presence of commercial entries/exits or residential driveways, longer crosswalks, non-conventional crosswalk markings, and higher pedestrian and vehicular volumes. In contrast, certain factors were found to decrease pedestrian crashes at intersections, such as the presence of slip lanes and missing sidewalks.

The effectiveness of LPIs was evaluated using Crash Modification Factors (CMFs). The results suggest a 26.8% reduction in pedestrian–vehicle crashes at treated intersections. The effectiveness of

LPIs is significantly improved under certain conditions. LPIs are more effective at intersections with high pedestrian and vehicle volumes and those with complete pedestrian infrastructure, such as all sidewalks and non-conventional crosswalk markings. Conversely, LPIs are less effective at intersections with slip lanes. Calibrating the model significantly enhanced estimate accuracy and further reduced the CMF to 0.65, underscoring the importance of proper calibration to accurately measure the true impact of pedestrian safety measures.

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This journey has been truly extraordinary, and as I approach its culmination, I am filled with immense gratitude for those who have supported me throughout this remarkable experience.

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Dedication

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To my Amli



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Chapter 1
Introduction

1.1 Background

Pedestrians, often referred to as Vulnerable Road Users (VRUs), face disproportionate risks on roadways, with their likelihood of being killed or injured in traffic incidents far exceeding that of motorists by 284 times (Canadian Council of Motor Transport Administrators, 2013). In Canada, the past decade has seen an alarming trend, with over 300 pedestrian fatalities and more than 1500 injuries recorded annually from 2009 to 2019 (Transport Canada, 2023). Despite a slight decrease in the average number of pedestrian fatalities during this period, the share of pedestrian fatalities among total traffic-related fatalities has surged, peaking at 18.7% in 2016, as shown in Figure 1-1.

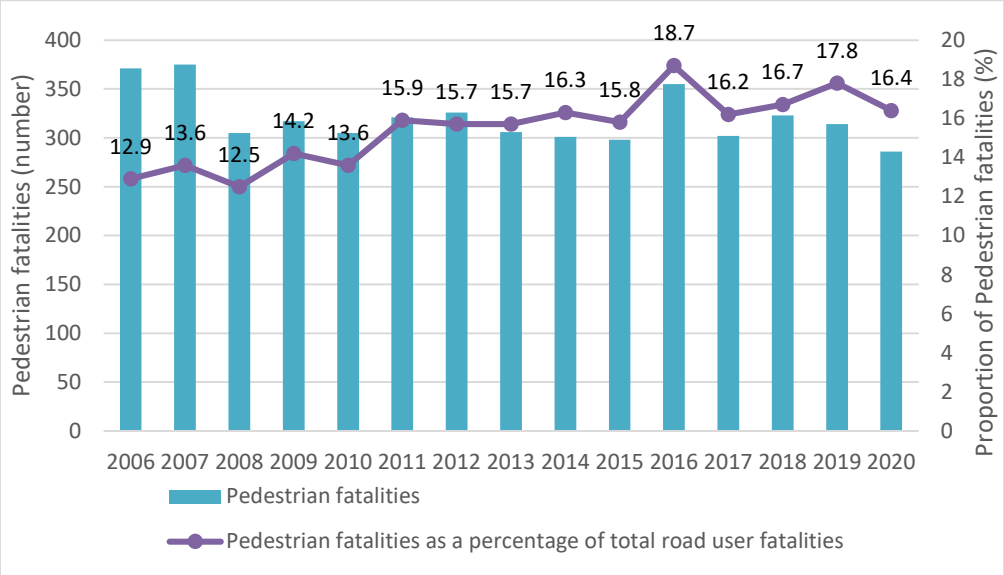


Figure 1-1 Pedestrian Fatalities in Canada (2006-2020)

Central to pedestrian safety is the intersections, where the paths of pedestrians and motor vehicles converge, creating potential conflict zones. Within the Region of Waterloo, a substantial 70% of pedestrian collisions occur at intersections. While there is a prevailing belief that signalizing intersections enhances safety by regulating traffic flow, safety at these intersections remains to be a significant concern due to high traffic exposure at these locations. Past reports have shown that 50% of all pedestrian-vehicle collisions occurred at signalized intersections, primarily due to drivers' failure to

yield right-of-way to pedestrians during turning movements (Regional Municipality of Waterloo, 2023). Recognizing the need for targeted interventions, transportation agencies have advocated for a suite of measures aimed at enhancing pedestrian visibility and reducing crash incidents. These measures include traditional methods such as signing and marking treatments, geometric modifications like curb extensions, and more innovative approaches such as LPIs (Federal Highway Administration (FHWA), 2022).

LPIs offer pedestrians a temporal advantage by displaying a brief advance WALK indication before the traffic light turns green. This strategic timing allows pedestrians to establish themselves in the crosswalk before parallel traffic receives a green signal, thereby increasing their visibility and prompting drivers to yield right-of-way (California Department of Transportation, 2021). Unlike other treatments that require extensive infrastructure changes, LPI implementation typically involves reprogramming existing traffic signals, making it a cost-effective and expeditious solution (Shangguan et al., 2023). This thesis research concerns with investigating the effectiveness of LPI for improving intersection safety and the potential contributing factors.

1.2 Problem Statement

The need to assess the effectiveness of LPIs for safety improvement has attracted several significant past efforts on the problem. While varying in study location and sample size, most of these studies had confirmed LPI's benefit in enhancing pedestrian safety, particularly in mitigating collisions between pedestrians and turning vehicles (King, 2000). These studies have reported significant decreases in pedestrian collisions, albeit with varying levels of reduction magnitude and statistical significance. For instance, a comprehensive study conducted across multiple cities consistently documented reductions in both total and pedestrian crashes following LPI implementation (Goughnour et al., 2021). Similarly, research focusing on LPI adoption indicated notable declines in collision rates and pedestrian injuries (King, 2000; Sze, 2019). Furthermore, several conflict-based studies have provided evidence of marked decreases in conflicts between pedestrians and turning vehicles across diverse locations (Arun et al., 2023; Guo et al., 2020; Osama et al., 2015). However, there have also been studies showing conflicting results, especially in suburban areas and intersections with skewness, where studies indicated an increase in non-yielding behaviour by vehicles. Consequently, this prompted the removal of LPI at the skewed intersection (Hubbard et al., 2008; Saneinejad & Lo, 2015). This raises the important question on the dependency of the effectiveness of LPI on the specific intersection and traffic

conditions such as traffic exposure, intersection layout and geometry, the built environment (e.g., school zone, residential and commercial setting).

In conclusion, despite the extensive past research on the effectiveness of LPI through both crash and conflict-based analyses in various settings, a significant research gap still exists. For example, many existing guidelines and safety programs on LPI implementation recommend LPIs for intersections near schools as part of broader pedestrian safety strategies (Lin et al., 2017; Saneinejad & Lo, 2015); empirical evidence specific to this context remains scarce. Implementing LPIs is generally considered as a low-cost solution, primarily involving adjustments to signal timing; however, it would still result in noticeable reduction of effective green time or capacity for vehicular traffic at the intersection. Furthermore, complexities may arise if new signal installations or additional infrastructure modifications, such as retrofitting an intersection, are required. Therefore, LPI implementation is essentially a resource allocation and prioritization problem, requiring optimal trade-off between intersection efficiency and safety.

1.3 Research Objectives

The primary objective of this research study is to evaluate the effectiveness of implementing LPIs at signalized intersections near schools. This evaluation aims to assess the impact of LPIs on overall pedestrian safety, particularly in reducing the risk of crashes involving pedestrians during peak school-related activity times.

Concurrently, the secondary objective is to conduct an in-depth analysis of the factors that influence pedestrian crash risk in this context. This analysis will involve examining various factors such as traffic volume, road infrastructure characteristics and built environment to better understand the complex dynamics contributing to the effect of LPI on pedestrian safety at signalized intersections.

The research objectives will be achieved through a case study using data from the Region of Waterloo, which had initiated a pilot project in 2017 with a deployment of LPIs at over 60 signalized intersections out of which 54 are near elementary schools, as of year 2024. Through a systematic analysis of crash data before and after implementing LPI, this research seeks to contribute robust empirical evidence on the effectiveness of LPI as related to various influencing factors. By informing evidence-based decision-making and optimizing pedestrian safety interventions in school zones, this study seeks to enhance the overall safety and well-being of vulnerable road users, particularly children, within the community.

1.4 Thesis Structure

This thesis is organized into five chapters. Chapter 1 introduced the research context, outlined the problem statement, and specified the research objectives.

Chapter 2 presents a comprehensive literature review, examining the factors influencing pedestrian crashes, the effectiveness of Leading Pedestrian Intervals (LPI), and methods used in safety effectiveness evaluations.

Chapter 3 details the research methodology, focusing on the Empirical Bayesian (EB) before-and-after analysis, calibration of Safety Performance Functions (SPFs), and data preparation.

Chapter 4 discusses the results of the analysis, highlighting factors influencing pedestrian crash risk, the overall effectiveness of LPIs.

Chapter 5 concludes the thesis by summarizing the main findings and offering recommendations for future research.

Chapter 2
Literature Review

This chapter provides a comprehensive review of the existing literature on factors influencing pedestrian crashes, the implementation and impact of LPI, and the methodologies employed to evaluate the effectiveness of various countermeasures. Section 2.1 delves into the key factors that impact pedestrian crash risk, including roadway and geometric features, traffic conditions, and built environment attributes. Section 2.2 explores the existing research on LPIs, detailing their usage and impact on pedestrian safety. Finally, Section 2.3 reviews the main methods used to assess the effectiveness of countermeasures, highlighting their respective strengths and limitations.

2.1 Factors Influencing Pedestrian Safety

The objective of this section is to review the factors found in existing literature that impact the risk of pedestrian accidents. These factors include roadway and geometric features, traffic conditions, and attributes related to the built environment and land use, as detailed in the following discussion.

2.1.1 Traffic Characteristics

Empirical evidence consistently demonstrates that increases in traffic volume of vehicles, pedestrian presence, and vehicular speed significantly elevate the likelihood of vehicle-pedestrian conflicts. Numerous studies have shown that higher traffic volumes correlate with a higher pedestrian crashes occurrence (Fernandes, 2013; Miranda-Moreno et al., 2011; Pulugurtha & Sambhara, 2011; Schneider et al., 2010; Wier et al., 2009), with some highlighting the importance of traffic volumes on both major and minor roads in predicting pedestrian crashes at intersections (Torbic et al., 2010). Increased pedestrian volume similarly leads to a higher probability of pedestrian crashes due to greater exposure. Additionally, pedestrian volumes significantly contribute to collision frequency, exhibiting a direct relationship with crash occurrences (Fernandes, 2013; Shankar et al., 2003). Previous research also indicates that individual pedestrian risk changes non-linearly with respect to pedestrian volumes, a phenomenon known as the "safety in numbers" effect. As pedestrian volume increases, it influences driver behaviour, thereby reducing the risk of pedestrian-vehicular accidents for each pedestrian (Fernandes, 2013; Turner et al., 2012). Furthermore, high vehicle speed has been consistently found to increase both the frequency and severity of collisions involving vehicles and pedestrians (Chimba et al., 2014; Gårder, 2004), with some noting that the 85th percentile speed provides a more accurate

reflection of actual traffic conditions (Zegeer et al., 2006). One-way roads are associated with higher crashes at intersections; however, their effect on intersections is not statistically significant (Zuniga-Garcia et al., 2022).

2.1.2 Roadway and Geometric Characteristics

Roadway and geometric characteristics play a crucial role in determining pedestrian crash occurrences. The number of approaches and lanes significantly impacts crash rates, with studies showing that intersections with four approaches experience more collisions and injuries than intersections with three approaches (Lyon & Persaud, 2002; Miranda-Moreno et al., 2011). This is corroborated by findings that the existence of combined left-through lanes and exclusive left-turn lanes correlates with higher accident frequencies due to increased left-turn volumes and associated sight distance issues (Poch & Mannering, 1996). Additionally, intersections with higher number of dedicated right turn lanes and higher number of commercial entry-exits within 50 feet tend to have significantly higher pedestrian crash rates (Schneider et al., 2010). Furthermore, pedestrian crossings with higher number of lanes and longer crossing distances inherently pose greater risks, further emphasizing the critical influence of roadway and geometric design on pedestrian safety (Chris Monsere et al., 2017).

The presence and design of crosswalks significantly impact pedestrian safety and crash rates. Studies have indicated that marked crosswalks generally enhance safety by making drivers more cautious and channelling pedestrian flow, thereby reducing crash rates (Diogenes & Lindau, 2010). Diogenes & Lindau (2010) found that crosswalks lead to slower driving speeds and safer pedestrian crossing behaviour at midblock crossings as well as intersections. Additionally, the presence of sidewalks, particularly in residential and mixed residential areas, has been shown to increase pedestrian safety, as noted by Schneider et al. (2010) and McMahon et al. (1999). However, research on the overall benefits of crosswalks for pedestrian safety presents mixed findings. Some studies, such as those by Zegeer et al. (2005) and Koepsell et al. (2002), suggest that crosswalks may sometimes be linked to increased crash rates. Crosswalks at signalized intersections, particularly on minor approaches, may increase the frequency of vehicle-pedestrian interactions, thereby elevating crash risk (Khattak et al., 2021). Moreover, longer crossing distances have been significantly linked to higher crash frequencies, with pedestrian crashes increasing by about 5% for every additional 3.7 meters of crossing distance (Islam et al., 2022). The impact of crosswalk markings also remains debated. While intersections with unconventional markings (such as zebra, ladder, or continental) have shown increased pedestrian

collisions in some models, the most thorough study by Zegeer et al. (2005) observed no significant correlation between crosswalk marking patterns and crash rates. This inconsistency suggests that the relationship between crosswalk markings and pedestrian safety may vary depending on specific study contexts and data (Islam et al., 2022).

Road classification, including the distinctions between arterial, collector, and local roads, significantly influences pedestrian safety. Researchers have highlighted the importance of road classification in pedestrian safety models, demonstrating that the functional class of roads is a significant variable affecting pedestrian crash frequencies (Kay Fitzpatrick et al., 2014; Miranda-Moreno et al., 2011; Wier et al., 2009). Notably, their effect on pedestrian safety has primarily been studied at the area-wide level and often used as a surrogate for pedestrian volumes when direct pedestrian volume data is unavailable.

The geometric design of roadways, including the presence of medians, bike lanes, and the skewness of intersections, plays a crucial role in influencing pedestrian safety and crash rates. Studies have shown that intersections with raised medians and narrower lanes tend to exhibit lower pedestrian crash frequencies (Schneider et al., 2010; Zegeer et al., 2006). Additionally, median islands at intersections and along multilane roads are associated with significantly lower pedestrian crash risks, as they assist in reducing crash risks at midblock and signalized intersections (Schneider et al., 2010; Torbic et al., 2010; Zegeer et al., 2006).

The presence of bicycle lanes also positively impacts pedestrian safety. Incorporating bike lanes on road approaches can reduce pedestrian collisions by 14%, as bike lanes could shorten the “effective” distance pedestrians need to cross or could reduce the distance and duration of exposure to motor vehicles. This reduction in crossing distance aligns with findings related to crosswalk length, further emphasizing the safety benefits of bike lanes (Islam et al., 2022).

Conversely, high skewness levels in intersections are linked to higher crash frequencies. Skewed intersections, particularly those with angles less than 75 degrees, can obscure sightlines and confuse drivers, increasing the risk of vehicle-pedestrian conflicts. However, the most dangerous angles are typically between 50 and 70 degrees, while angles below 50 degrees might pose a slightly lesser risk (Khattak et al., 2021). Overall, careful consideration of these geometric design elements is crucial for improving pedestrian safety and minimising crash occurrences.

2.1.3 Land Use & Built Environment Characteristics

The built environment of a road network, notably the presence of residential and commercial areas, has been found to be linked to vehicle-pedestrian collisions. Wier et al. (2009) discovered that higher proportions of neighbourhood commercial and residential-commercial areas correlate with increased vehicle-pedestrian collisions. Similarly, Loukaitou et al. (2007) highlighted the positive effect of commercial and high-density residential areas on pedestrian crashes, contrasting with the negative impact of vacant, industrial, and office land use. In contrast, Pulugurtha & Sambhara (2011) observed that certain land-use predictors, such as urban residential-commercial areas, tend to decrease pedestrian crashes, likely due to heightened pedestrian activity prompting more vigilant motorist behaviour. Moreover, intersections with numerous commercial retail properties nearby are associated with higher pedestrian collision rates, indicating elevated risk in commercial corridors due to intricate interactions between vehicles and pedestrians (Schneider et al., 2010). In these areas, drivers may become distracted while searching for parking or specific destinations, while pedestrians frequently opt to cross streets outside designated crosswalks for more direct access (Schneider et al., 2010). These findings underscore the critical role of considering land-use types in pedestrian safety models.

The occurrence of pedestrian crashes is consistently associated with the proximity of schools and presence of bus stops. Chimba et al. (2014) incorporated schools into their model and found a positive association with pedestrian crashes, likely due to increased exposure during school hours. This finding was echoed by Miranda-Moreno et al. (2011) using data from Montreal, where the number of schools positively impacted pedestrian crash frequencies. Schneider et al. (2004) identified higher crash risks near libraries, stadiums, and academic buildings. Similarly, intersections with more bus stops tend to experience higher pedestrian activity, increasing the likelihood of crashes if not properly managed (Fernandes, 2013). Public transportation stops or amenities frequently indicate increased pedestrian traffic and a higher likelihood of pedestrian-related crashes, as evidenced by studies conducted on intersection models using Canadian data (Miranda-Moreno et al., 2011; Torbic et al., 2010). However, researchers have also observed that this factor holds significance only in intersections with low pedestrian volumes, suggesting nuanced interactions between bus stop presence and pedestrian crash frequencies (Pulugurtha & Sambhara, 2011).

Understanding the complex factors that contribute to pedestrian crashes is crucial for developing robust Safety Performance Functions (SPFs) required to assess LPIs. These factors encompass a range of elements, from traffic characteristics—including volumes, pedestrian presence, and vehicle speeds

that influence crash likelihood—to roadway and geometric features like crosswalk design, lane configurations, medians, and bike lanes, all of which directly impact safety outcomes. Additionally, considerations of land use and built environment attributes, such as residential and commercial densities, school proximity, and the presence of bus stops, play significant roles in shaping pedestrian collision rates within these critical environments.

2.2 Leading Pedestrian Interval and Its Safety Benefit

Leading Pedestrian Interval (LPI), also referred to as Pedestrian Head Start or Delayed Vehicle Green, grants pedestrians a walk signal during the 'all red' phase before the signal turns green for parallel vehicle traffic. Although the concept of adjusting signal timing to provide pedestrians with a head start existed in the Manual of Uniform Traffic Control Devices (MUTCD) 1961 edition, the term "Leading Pedestrian Interval" gained prominence later (Fayish & Gross, 2010). The primary objective of LPI is to enable pedestrians to initiate crossing before adjacent through-traffic vehicles, allowing them to establish themselves in the crosswalk and enhance their visibility to drivers, thereby decreasing potential conflicts with turning vehicles. This adjustment involves modifying signal timings and pedestrian intervals to activate the pedestrian signal approximately 5 seconds prior to the corresponding green signal for vehicles.

Children, elderly, individuals with visible impairments, and those with physical limitations, stand to benefit significantly from LPI implementation by improving their visibility and safety in crosswalks (Saneinejad & Lo, 2015). The advantages of LPI include reduced pedestrian delay, improved compliance with signals among pedestrians, timely clearance of crosswalks by pedestrians, increased driver compliance with yielding to pedestrians, and enhanced visibility of pedestrians crossing the street, thus contributing to increased pedestrian safety.

However, implementing LPIs can lead to reduced intersection capacity and increased delays for motorists due to shortened time available for vehicles to clear intersections during each signal cycle, especially during peak traffic periods. A study from South Korea observed that the average overall delays for vehicles ranged from 1.5 seconds to 6.0 seconds after LPI implementation (Kim & Park, 2019). However, these delays, usually only a few seconds, could be mitigated by adjusting signal timing parameters, such as slightly extending cycle lengths. For example, a microsimulation study of 15 intersections found that, although LPI installation caused noticeable delays for vehicles, the post-LPI level of service remained acceptable (Hasanpour & Persaud, 2022). It is essential to adopt a holistic

perspective when managing the needs of all road users, especially vulnerable road users such as pedestrians and cyclists.

The cost of implementing LPIs varies significantly depending on the existing infrastructure (Oregon Department of Transportation, 2022). Bower et al. (2021) reported that costs can range from negligible amounts for minor timing adjustments to over $100,000 per intersection when new pedestrian signals and additional components, such as countdown timers and pushbuttons, are required. Fayish & Gross (2010) found that in State College, PA, the cost was $1,000 for each intersection, covering programming and wiring of the controller. If LPIs were integrated into new controllers prior to installation, the cost would be minimal. Further, older signal controllers might need new or additional phases for LPI implementation, as noted by Lin et al. (2017).

There are several existing studies on LPI program. Most of these studies were conducted for evaluating the safety benefit of LPI, including estimation of Crash Modification Factors (CMFs) (Fayish & Gross, 2010; Goughnour et al., 2021), proposal of LPI implementation guidelines (California Department of Transportation, 2021; Chris Bower et al., 2021; Lin et al., 2017; Saneinejad & Lo, 2015), and comparison to similar countermeasures such as Leading Through Interval (LTI) (Furth & Saeidi Razavi, 2019).

2.2.1 Evaluation of Safety Benefit of LPI

In the past, safety assessments of road improvements relied primarily on adherence to engineering-based standards, set forth by national or state guidelines. These standards aimed to meet the minimum safety requirements. However, contemporary safety evaluations in transportation have transitioned towards a more data-driven and evidence-based approach. Presently, transportation professionals rely on actual safety measures, such as crash data, to assess road safety performance. The same is true for assessing the safety benefits of LPI implementation, as discussed in the following section.

2.2.1.1 Crash Based Studies

Crash data stands as the cornerstone of road safety analysis due to its widespread utilization and perceived objectivity and reliability. Despite its prominence, challenges exist with crash data, including underreporting of crashes, rarity of crash occurrence, and years of data required for effectiveness evaluation (Shangguan et al., 2023). Nonetheless, crash data remains paramount in evaluating safety treatments, aiming to reduce both the frequency and severity of crashes. By integrating crash data with

additional datasets such as road characteristics and traffic volume data, it becomes possible to identify elements contributing to heightened crash risks and develop systemic safety approaches (Fernandes, 2013; Goughnour et al., 2021; Gross & Donnell, 2011; Xaykongsa, 2021).

In the past, several researchers have used crash data in evaluating the safety effect of LPI. King (2000) examined 26 signalized intersections with LPI implementation in New York City and compared crash rates of these sites with control sites without LPI. The study utilized 10 years of pedestrian-vehicle crash data, analysing eight different crash rates for each intersection, both absolute and severity factored, at both treated and controlled locations. The analysis indicated that LPIs improved pedestrian safety, especially in crashes involving turning vehicles, resulting in a 28% reduction compared to control location and a 64% decrease when factored for severity. However, the study did not report the statistical significance of the findings. Additionally, a rise in all injury crashes was observed at the treated intersections, but the significance of these findings was also not documented (King, 2000).

Another crash-based study was performed on 10 signalised intersections in the downtown of State College, Pennsylvania. Due to unavailability of enough reference sites, Before-After EB method, which accounts for RTM (Regression to mean), could not be used. Therefore, the simplified Before-after method with comparison groups was employed, using 14 intersections, which were stop-controlled. The results showed a significant reduction of 58% in pedestrian collision with a standard error of 6.4 pedestrian-vehicle collisions for the after period of 3 years at all the 10 sites. Insufficient sample size of comparison group, which could not account for RTM, and relatively small size of treatment sites were two major limitations (Fayish & Gross, 2010).

The short comings of the previous study were overcome by a FHWA study, which used before-after EB method to develop CMF for LPI. The 105 treatments sites were selected from three US cities-Charlotte, Chicago, and NYC. The effect of LPI on total crashes and pedestrian crashes was significant with a CMF of 0.87 (or 17% reduction), same for both, for all the cities combined (Goughnour et al., 2021). Similarly, another crash-based study that reported a reduction in pedestrian vehicle crashes was also conducted in New York City.

Sze (2019) focused on the influence of phased LPI introduction on crash and injury outcomes at more than 12,000 signalized intersections in New York City from 2012 to 2018. Using a difference-in-difference fixed-effects panel regression, the study found a 5.45% reduction in quarterly collision counts and a 14.7% decrease in pedestrian injuries during the intervention period. These findings

suggest that LPIs effectively decrease both the number of crashes and resulting injuries. It should be noted that variations in sample sizes, assessment durations, and evaluation methodologies yield diverse outcomes for the same urban area.

2.2.1.2 Surrogate Safety Measures (SSMs)-Based Studies

Beyond traditional safety datasets, SSMs offer an alternative means to assess road safety effectiveness. Surrogate measures, including conflicts between road users, and failures to yield, occur more frequently than actual crashes, allowing for early identification of safety risks. However, their surrogate nature introduces potential inaccuracies in predicting crash outcomes.

Surrogate safety data is typically collected through in-field observations or recordings capturing road user behaviours and interactions. Advances in technology have facilitated automated event identification, reducing the need for manual video scanning. These observations provide valuable insights into the safety impact of various road elements and user interactions under different conditions. The common surrogate measures used are Post-Encroachment time (PET) and time to collision (TTC) (Arun et al., 2023; Guo et al., 2020). Along with these measures, other supplementary measures like user speeds, and severity of conflicts can also be extracted.

Nevertheless, a significant challenge in utilizing SSMs lies in establishing quantitative relationships with crash data. The lack of robust research linking surrogate measures to crash outcomes hinders their widespread adoption in safety evaluations. Establishing such relationships would enable practitioners to conduct efficient assessments using surrogate measures, circumventing the lengthy wait for sufficient crash data (Carter, 2017).

In several studies, alternative non-crash-based metrics have been employed to evaluate the effectiveness of LPI, offering additional perspectives on their influence on pedestrian safety.

Van Houten et al. (2000) studied three signalized intersections in St. Petersburg, Florida, where a 3-second LPI was implemented. Their results showed a substantial decrease of 95% in conflicts between pedestrians crossing and turning vehicles, accompanied by a roughly 60% decline in the probability of pedestrians yielding to turning vehicles. These outcomes indicate that LPIs have the potential to enhance pedestrian comfort and perceived safety, offering a safer environment for walking at busy signalized intersections.

Another study evaluates the introduction of a 4-second LPI at two three-leg signalized intersections in Surrey, British Columbia. Video-based automated traffic conflict analysis was conducted, focusing on conflicts between pedestrians and vehicles. The severity of these conflicts was assessed using the post-encroachment time (PET) conflict indicator. The findings revealed a notable decrease in both the frequency and severity of conflicts, with an overall reduction of 21% in conflict occurrence and a 29% reduction in conflict severity. This approach proves particularly effective in intersections with higher pedestrian and vehicle volumes (Osama et al., 2015).

In Vancouver, British Columbia, researchers found that implementing a 5-second LPI resulted in an 18.1%–20.9% reduction in extreme conflicts. The research employed a hierarchical Bayesian with peak over threshold (POT) approach to conduct safety evaluations based on conflicts before and after the implementation at two sites. The analysis focused on conflicts between pedestrians and vehicles making left turns, using automated computer vision technology to assess these conflicts during the designated periods. The findings highlighted the effectiveness of LPIs in reducing the occurrence of severe conflicts between pedestrians and left-turning vehicles (Guo et al., 2020).

Arun et al. (2023) examined the impacts of LPI interventions on the risks of vehicle-pedestrian and vehicle-vehicle collisions before and after treatment, at three intersections in the City of Bellevue, Washington, using traffic conflict analysis methods. They devised a quantile regression method within an extreme value model to assess and contrast crash risks pre- and post-LPI implementation. The analysis indicates that LPI treatments significantly decrease the risk of extreme conflicts between vehicles and pedestrians by approximately 42%. Additionally, LPI treatments did not adversely affect rear-end conflicts.

Despite the majority of evidence from these studies indicates a beneficial effect of LPI on pedestrian safety, there are dissenting studies that present an alternative perspective. Hubbard et al. (2008) conducted research on LPI's effects at a suburban intersection in Anaheim, CA near Convention Centre and Disneyland, which resulted in rise of non-yielding behaviour by right turning vehicles. The pedestrian compromised at the curb increased by 3% at low turning vehicle volumes and 11% at high turning vehicle volumes. These results suggested that LPI's impact in an urban setting maybe not be directly applicable to suburban environments.

Another LPI trial was conducted at two intersections in Toronto, Canada. While one intersection experienced a statistically significant 34% reduction in non-yielding incidents, the other yielded

opposite results. The LPI at the skewed intersection was removed within six weeks due to an increase in pedestrians' non-yielding behavior, possibly attributed to the intersection's skewed geometry. The pilot process lacked standardization, which prompted the City of Toronto to develop guidelines for LPI implementation and evaluation.

2.2.2 LPI Implementation Guidelines

As previously mentioned, it is widely acknowledged that LPIs are not suitable for every situation. Various jurisdictions in north America have developed guidelines for implementation of LPI. The one created for City of Toronto is the only known jurisdiction in Canada that has developed standardized and detailed guidelines and evaluation procedure. It includes the following factors for the suitability of LPI at a signalized intersection: intersections with left turns unimpeded by oncoming traffic (e.g., three legged intersections and intersections with one-way roads), visibility issues due to irregular geometry or obstructions, high pedestrian crossing volumes, high rates of pedestrian-vehicle collisions or near-miss incidents, proximity to primary schools, significant presence of elderly residents, and potential impacts on motor vehicle traffic such as increased delay, decreased significant presence of elderly residents, and high vehicle traffic volume (Saneinejad & Lo, 2015). A flowchart and worksheet, as shown in Figure 2-1 and Figure 2-2, respectively, is provided as part of the guidelines. According to the suitability assessment worksheet, additional traffic conflict data should be collected if the total score, without including this information, is between 3 and 5. If conflict information would not raise the overall score to 5 or above, this step should be skipped. Furthermore, the duration of LPI is also recommended by the city of Toronto, given in equation (1). The City of Toronto standard duration for LPI is (Saneinejad & Lo, 2015):

$$LPI = greater\ of\ 5s, or\ \frac{\frac{TL}{2} + PL}{W} \tag{1}$$

where:

LPI = number of seconds from onset of “Walk” signal for pedestrians and green indication for vehicles.

TL = distance on crosswalk to clear the total width of all moving lanes between curb and centerline, not including the parking lanes.

PL = distance on crosswalk to clear the parking and merging lanes, if any.

W = waking speed of 1.0 m/s.

According to the MUTCD (FHWA, 2009), the LPI must be a minimum of 3 seconds in duration and timed so that pedestrians can cross at least one traffic lane or, in instances of wider intersections, proceed far enough for pedestrians to establish their position ahead of turning traffic before it is allowed to proceed. Typically, LPIs range from 3 to 5 seconds but can extend up to 7 seconds if necessary (Furth & Saeidi Razavi, 2019; Hubbard et al., 2008). However, extending the LPI too long can decrease compliance rates as motorists become impatient (Furth & Saeidi Razavi, 2019)

Similarly, the Florida Department of Transportation (FDOT) established statewide guidelines for LPI warrants after conducting a before-and-after study that assessed non-yield, conflict, and vehicular delay as measures of effectiveness. These guidelines were refined into eight warrants, including: Approach Crash Frequency, Reported Visibility Issue, Vehicle Non-Yielding Behavior, Vehicle Peak-Hour, Pedestrian Peak-Hour, Four-Hour Vehicular and Pedestrian Volume, Eight-Hour Vehicular and Pedestrian Volume, and School Crossing (Lin et al., 2017). Table 2-1 summarizes the key conditions and applications for each LPI warrant, aiding in the decision-making process for implementing LPIs at signalized intersections.

Among these warrants, the school crossing warrant is implemented if the approach turning vehicle volume is at least 50 vehicles per hour. LPI should be considered for the period 1 hour before and 30 minutes after school starts, as well as the period 30 minutes before and 1 hour after school ends (Lin et al., 2017). This targeted implementation effectively addresses vehicular delays throughout the day. Additionally, the importance of field observations and evaluations post-LPI implementation was highlighted (Lin et al., 2017).

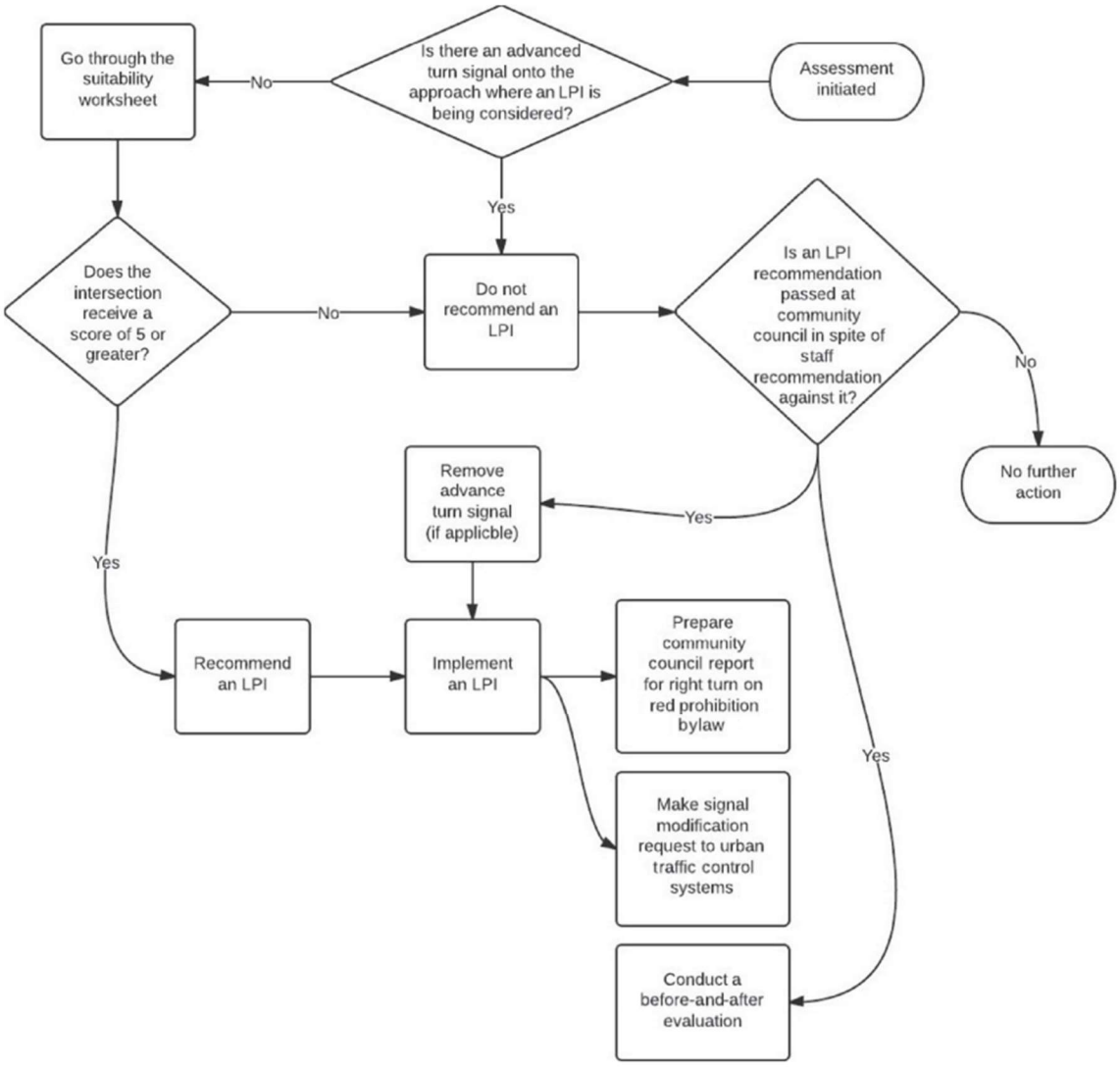


Figure 2-1 Flowchart for Assessing and Implementing LPI Suitability by the City of Toronto (Saneinejad & Lo, 2015)

Factor	Values	Score	Score Allocation Guide	Justification	Notes
a. Is the pedestrian crossing at a T-intersection (crossing is parallel to a road that ends at the intersection) **and/or** **Is the pedestrian crossing parallel to a one-way road?**		0 to 2	Yes = 2 No = 0	High level of potential safety improvement with LPI at T-intersections compared with regular intersections because all vehicles approaching a T-intersection make a left or right turn and left-turning vehicles do not need to wait for and yield to vehicles in the opposing direction. Similarly, left turning vehicles traveling on a one-way road do not need to wait for and yield to vehicles in the opposing direction.	
b. Are there issues such as safety concerns verified by staff or visibility issues caused by features such as irregular intersection geometry, wide-turning radius, crosswalk placement, obstructions such as buildings or base of a bridge, blinding sun angle?		0 to 2	Yes (4 or more issues) = 2 Yes (between 1 to 3 issues) = 1 No = 0	High level of potential safety improvement.	
c. 8-h volume of pedestrians (*p*) crossing the leg being considered for LPI		0 to 2	2 if $p > 1{,}000$ 1 if $200 < p \leq 1{,}000$ 0 if $p \leq 200$	High level of benefit for the highest number of pedestrians.	
d. What is the overall total impact on vehicles using the intersection? **(*a*) What is the increase in intersection total or average delay (%)?** **(*b*) What is the through phase V/C ratio of the signal with LPI?** **(*c*) What is the total 8-h vehicular volume at intersection?**		0 to -6	Overall impact = $-1 \times \lvert \text{Min}(A, B) \times C \rvert$ where $A = \begin{cases} 0 & \text{if } a < 10\% \\ -1 & \text{if } 10\% < a \leq 30\% \\ -2 & \text{if } a > 30\% \end{cases}$ $B = \begin{cases} 0 & \text{if } b < 0.9 \\ -1 & \text{if } b \geq 0.9 \end{cases}$ $C = \begin{cases} -1 & \text{if } c < 16{,}000 \\ -2 & \text{if } 16{,}000 \leq c < 30{,}000 \\ -3 & \text{if } c \geq 30{,}000 \end{cases}$	High level of negative impact on traffic operations for a large number of drivers.	
e. What is the rate of annual collisions between pedestrians and left- or right-turning vehicles per 1,000 8-h pedestrian crossings at the specific crossing in the past 5 years?		0 to 2	None = 0 0–3 = 1 >3 = 2	High level of potential safety improvement.	
f. What is the rate of conflicts* (conflicts per 1,000 8-h observations) between pedestrians and left- or right-turning vehicles at the specific crossing during 8 h of observation during area-specific pedestrian peak and nonpeak periods?**		0 to 2	None = 0 0–3 = 1 >3 = 2		
g. How far is the location from the nearest elementary school?		0 to 2	<200 m = 2 >200 m and <850 m = 1 ≥850 m = 0	High level of benefit to smaller school children who are more negatively affected by visibility issues. Average distance of walk trips to school in Toronto is 850 m (Transportation Tomorrow Survey). 6% of walk trips to school are less than or equal to 200 m in distance (Transportation Tomorrow Survey).	
h. What is the elderly demand score (*e*) of the area where the intersection is located?		0 to 2	2 if $e = 5$ 1 if $4 \leq e < 5$ 0 if $e < 4$	High level of benefit to slower walking pedestrians: elderly.	Look up score using this map.
Total score					

Figure 2-2 LPI Suitability Assessment Worksheet Provided by the City of Toronto (Saneinejad & Lo, 2015)

Table 2-1 Criteria and Usage Guidelines for Each LPI Warrant Based on Florida Department of Transportation (FDOT) Statewide Guidelines (Lin et al., 2017)

Warrant	Description	Condition
Warrant 1: Approach Crash Frequency	Application at intersections with high vehicle-pedestrian crash history.	Average crash frequency of ≥1 per year for turning vehicles hitting pedestrians with "Walk" signal.
Warrant 2: Reported Visibility Issue	Application where visibility issues for pedestrians are reported and verified.	Verified visibility issues due to blockages or limited visibility.
Warrant 3: Vehicle Non-Yielding Behavior	Application where vehicles frequently fail to yield to pedestrians during the "Walk" phase.	Either: A) ≥3 conflicts per day, or B) ≥10% compromised pedestrians at onset of "Walk" signal.
Warrant 4: Vehicle Peak Hour	Application at intersections with high vehicular traffic during peak hours.	A) Turning vehicle volume ≥130/hour and pedestrian volume ≥25/hour, or B) Either volume met with through traffic of cross street ≥500/hour/lane.
Warrant 5: Pedestrian Peak Hour	Application at intersections with high pedestrian volume during peak hours.	A) Turning vehicle volume ≥100/hour and pedestrian volume ≥50/hour, or B) Either volume met with through traffic of cross street ≥400/hour/lane.
Warrant 6: Four-Hour Vehicular and Pedestrian Volume	Application at intersections with high vehicle and pedestrian volume over any 4 hours of a day.	A) Turning vehicle volume ≥105/hour and pedestrian volume ≥30/hour, or B) Either volume met with through traffic of cross street ≥400/hour/lane.
Warrant 7: Eight-Hour Vehicular and Pedestrian Volume	Application at intersections with high vehicle and pedestrian volume over any 8 hours of a day.	A) Turning vehicle volume ≥100/hour and pedestrian volume ≥25/hour, or B) Either volume met with through traffic of cross street ≥400/hour/lane.
Warrant 8: School Crossing	Application at intersections near school crossings to protect students.	Turning vehicle volume ≥50/hour during specific times around school start and end times.

Although numerous studies have highlighted the positive impact of LPIs on pedestrian safety, there are notable limitations in previous research. These limitations include small sample sizes and the use of SSMs, which may not adequately capture comprehensive safety outcomes. Additionally, there is a

significant gap in evaluating LPIs near elementary schools, despite recommendations in various jurisdictional guidelines.

2.3 Effectiveness Evaluation Methods

Before delving into methods based on the type of data used to measure effectiveness, it is important to understand the broader categories in which these studies fall. Generally, studies can be divided into two main types: experimental and observational. Experimental studies involve randomly assigning sites to either a treatment group or a reference group. Conversely, observational studies evaluate sites where treatments have already been implemented, with the reference group chosen based on engineering considerations. In essence, experimental studies are planned interventions, while observational studies rely on data gathered from existing treatments implemented as part of routine efforts to improve road systems (Frank et al., 2010). Due to ethical considerations surrounding research trials on road safety, observational study designs are more prevalent in road safety research, and thus will be the focus of the remaining discussion in this section.

Similarly, study designs can also be categorized as either longitudinal or cross-sectional. Longitudinal studies, also known as before-and-after methods, span over time with distinct before and after periods. Conversely, cross-sectional studies focus solely on the effects observed after treatment implementation by considering the safety conditions of both treated and untreated sites. Methods falling under cross-sectional studies include both cross-sectional and case-control approaches.

2.3.1 Observational Before and After Studies

Observational before-and-after studies encompass several types of methods, each differing in its approach to accounting for potential biases (American Association of State Highway and Transportation Officials (AASHTO) et al., 2010; Hauer, 1997). The simplest before-and-after study, which is also commonly referred as Naïve approach, involves a straightforward comparison of collision frequencies before and after treatment, without adjusting for unrelated changes in site conditions. However, this method is prone to regression-to-the-mean (RTM) bias, where treatments are often applied to sites with historically high collision rates, leading to potentially inflated estimates of treatment effects (Hauer, 1997).

A more advanced approach within before-and-after studies involves the use of comparison groups. This method introduces an untreated comparison group that closely matches the treatment group in

terms of traffic volumes and site characteristics. By comparing the observed collision frequency before and after treatment in the treated group with that in the comparison group, this approach aims to mitigate RTM bias. However, finding suitable comparison sites can be challenging, as treatment prioritization tends to be based on collision history.

Empirical Bayesian (EB) methods represent a significant advancement in observational study design. These methods utilize SPFs derived from reference group data to estimate the expected number of crashes at treated sites post-treatment (which is commonly inferred to as counterfactual inference in the field of causal inference), considering factors such as RTM and temporal trends in traffic volumes. By incorporating these factors, EB methods offer more accurate estimates of treatment effects compared to comparison group methods.

Studies comparing the performance of Comparison Group (CG), and EB methods have shown that CG methods often overestimate post-treatment crash frequencies, while EB methods provide more unbiased estimates. Additionally, comparisons between Naïve and EB approaches have revealed substantial differences in estimated crash reductions (Persaud & Lyon, 2007). Despite their advantages, CG and EB methods require extensive data collection for both treatment and reference sites, which can be time-consuming and costly, limiting their applicability in certain situations.

To address the challenges associated with CG and EB approaches, Full Bayesian (FB) methods have emerged as a promising alternative. These methods utilize data from both treatment and reference sites to develop crash prediction models, offering more accurate estimates of treatment effects and greater flexibility in model selection. FB methods also account for uncertainties in the data, making them a promising approach for treatment evaluation studies (Al-Marafi & Somasundaraswaran, 2023).

Several studies have evaluated the effectiveness of FB methods in comparison to others and demonstrated their utility in various scenarios, such as the conversion of road segments, small sample size, and need to quantify the uncertainty in the estimated effects (Heydari et al., 2014, 2016; Miranda-Moreno et al., 2013). While FB results may be similar to EB results overall, FB methods offer particular advantages in scenarios with limited reference group data, such as road diet evaluations with few comparison sites (Lan et al., 2009; Persaud et al., 2010).

2.3.2 Cross-sectional Studies

Cross-sectional methods offer an alternative approach to before-and-after studies for estimating CMFs in transportation safety research. These methods simplify data collection compared to before-and-after studies, making them particularly useful in scenarios where tracking treatment dates or waiting for several years to collect data may be impractical (Al-Marafi & Somasundaraswaran, 2023). Cross-sectional studies encompass various designs, including cross-sectional and case-control methods, each with its own unique characteristics.

Cross-sectional studies typically compare crash experiences between locations with and without certain features, attributing differences in safety outcomes to those features. In its fundamental form, the CMF is calculated by comparing the average crash frequency between sites with and without the feature. However, ensuring that all locations are similar in other factors influencing crash risk can be challenging. Generalized linear regression models are often employed to account for various factors affecting safety, with the CMF derived from the model parameters. This method, also known as a SPF, establishes a relationship between crash occurrences and the geometric attributes and traffic volumes of roadways (Frank et al., 2010).

While cross-sectional studies allow for the estimation of expected crash numbers on roadway segments or intersections, they face challenges in determining why certain safety countermeasures are present at specific locations. Observed differences in crash experiences may be attributed to other elements aside from the main feature, like traffic volume or geometric attributes. Although multivariate regression models can control for known factors, accounting for unknown or unmeasured factors remains problematic (Gross & Donnell, 2011).

Case-control studies offer another method for assessing the distribution of exposure to potential risk factors between cases and controls, providing an estimate of the odds ratio as a measure of safety effectiveness. These studies allow for the evaluation of multiple risk factors and control for confounding variables through matching. However, they have limitations, including reliance on retrospective data collection and the inability to measure event causality.

Comparative studies, such as that conducted by Gross et al., have assessed the safety effectiveness of roadway lighting and lane and shoulder width using both cross-sectional and case-control methodologies. The findings suggest that the estimated safety effectiveness was similar between the

two methods when developed with careful consideration of covariates and functional forms (Gross & Donnell, 2011).

An overview of the data requirements necessary for the evaluation methods discussed is provided in Table 2-2. Additionally, the advantages and drawbacks of each method, along with their applicability, are delineated in Table 2-3.

Table 2-2 Overview of data requirements for Safety evaluation methods (modified from Highway Safety Manual (AASHTO et al., 2010)

	Evaluation Methods				
Data requirement	**Comparison Group**	**Empirical Bayes**	**Full Bayes**	**Cross-sectional**	**Case-control**
treatment sites	yes	yes	yes	yes	yes
non-treatment sites	yes	maybe[2]	yes	yes	yes
Crash and volume "before data"	yes	yes	yes	no	no
crash and volume "after data"	yes	yes	yes	yes	yes
SPF	maybe[1]	yes	yes	no	no

[1]generally not required but SPFs can be created for both treated and non-treated sites.
[2]generally required but if existing SPFs are used, non-treated sites are not required.

Table 2-3 Advantages, limitations, and suitability of safety evaluation methods.

Method	Advantages	Limitations	Applicability
Before-and-After (Naïve)	Directly compares pre- and post-treatment periods	Susceptible to regression-to-the-mean bias	Useful for initial assessments of treatment effects
	Simple implementation	Fails to control for potential bias	Suitable for straightforward treatment evaluations
Before-and-After (Comparison)	Mitigates regression-to-the-mean bias	Challenges in identifying comparable comparison sites	Appropriate when comparison sites can be identifies
	Provides more robust estimates of treatment effects	Potential biases may not be fully eliminated	Suitable for more comprehensive evaluations
Empirical Bayesian (EB)	Addresses regression-to-the-mean bias	Demands extensive data collection for reference sites	Applicable for complex treatment evaluations
	Adjusts for temporal trends and traffic variations	Resource-intensive data acquisition process	Suitable for analyses with ample data
Full Bayesian (FB)	Delivers precise estimates of treatment effects	Requires less data compared to EB methods	Suitable for evaluations with limited data
	Offers flexibility in model selection	Complex models may necessitate substantial computational resources	Applicable in scenarios with restricted data
Cross-Sectional	Simplifies data acquisition compared to BA methods	Difficulties in discerning rationale for safety countermeasures	Relevant for estimating CMFs for diverse features
	Enables estimation of anticipated crash frequencies	Challenges in accounting for unobserved variables	Suitable when cross-sectional data is available
Case-Control	Controls confounding variables through matching	Relies on retrospective data collection	Appropriate for investigating multiple risk factors
	Estimates odds ratios as a metric of safety effectiveness	Unable to quantify event probability or causal relationships	Pertinent in situations necessitating confounding control

2.4 Summary

This Chapter has provided a comprehensive review on literature related to pedestrian safety, LPI implement and effects, and safety analysis methodologies. It first highlights the findings from the literature on the critical factors influencing pedestrian safety, including traffic characteristics, roadway, and geometric features, and built environment and land use attributes. Traffic characteristics such as vehicle and pedestrian volumes and speeds significantly impact crash frequencies, with higher volumes generally leading to increased risks due to greater exposure. Roadway and geometric features, including the number of lanes, crosswalk lengths, and the presence of slip lanes or medians, also play a crucial role in pedestrian safety. Additionally, the built environment and land use characteristics, such as the presence of commercial and residential areas and the availability of sidewalks, affect pedestrian crash risks by influencing pedestrian activity and behavior.

Extensive research has been conducted on LPI programs, primarily focusing on evaluating their safety benefits, developing implementation guidelines, and comparing them to similar measures. Safety evaluations have transitioned from engineering-based standards to data-driven approaches, utilizing actual crash data and SSMs to assess the effectiveness of LPI implementations. Studies have shown that LPIs effectively reduce pedestrian-vehicle conflicts and crashes, although results may vary based on specific contexts and methodologies.

LPI implementation guidelines have been developed by various jurisdictions, with the City of Toronto providing a comprehensive framework for assessing LPI suitability at intersections. These guidelines consider factors such as intersection geometry, pedestrian and vehicular volumes, and proximity to schools. Other jurisdictions, like the Florida Department of Transportation (FDOT), have established statewide guidelines and warrants for LPI implementation based on detailed studies of non-yield behavior, conflicts, and vehicular delays.

Despite numerous studies demonstrating the positive impact of LPIs on pedestrian safety, previous research has notable limitations. These include reliance on small sample sizes and SSMs, which may not sufficiently capture comprehensive safety outcomes. A significant gap exists in evaluating the effectiveness of LPIs implemented at signalized intersections near schools, despite recommendations in various jurisdictional guidelines.

One of the primary challenges in using SSMs lies in establishing robust quantitative relationships with crash data. The lack of such empirical links impedes the broader adoption of surrogate measures

in safety evaluations. Establishing these relationships would facilitate more efficient assessments, bypassing the lengthy process of waiting for adequate crash data. Crash data remains pivotal due to its reliability and widespread availability for estimating safety effectiveness. It serves as the gold standard in evaluating safety interventions, offering a direct measure of safety outcomes. However, the effectiveness of SSMs in predicting crash data remains an active area of research, posing critical questions regarding their effectiveness in safety evaluations. Most studies employing larger sample sizes and crash data as safety measures originate from the United States. However, transferring these findings to Canadian cities may not be entirely suitable due to socio-cultural differences, urban forms, mobility patterns, and climatic variations.

In summary, while existing research highlights the benefits of LPIs for pedestrian safety, addressing these gaps through rigorous empirical studies is essential to enhance understanding and applicability in diverse urban contexts and conditions.

For this study, the EB method was selected due to its ability to address biases such as prioritizing sites based on crash history and the availability of enough reference sites to create SPFs. Although the Fully Bayesian (FB) method is considered more accurate than EB, it was deemed unnecessary as it tends to yield similar results with little to no improvement in accuracy.

Chapter 3
Methodology

This chapter is divided into two primary sections. The first section focuses on the methodology used for evaluation. In this section, the study's methodology is outlined, which employs a before-after approach with an Empirical Bayesian (EB) method.

Based on this methodology, the second section focuses on the data. This section details the data requirements essential for the study, the processes involved in collecting the necessary data, and concludes with a description of the data.

3.1 EB Before & After Analysis

The EB method for before & after analysis entails comparing the actual crash frequency observed at sites after treatment with the estimated crash frequency that would have occurred if the treatment had not been implemented (AASHTO et al., 2010; Hauer, 1997). Particularly applicable in cases where treatments are initiated due to unusually high crash rates, this approach helps counteract the regression-to-mean (RTM) bias linked to selection bias. By integrating crash prediction models, also referred to as SPFs, the methodology calculates the anticipated crash frequencies.

The process involves five main steps aimed at evaluating the safety effectiveness of the proposed countermeasure LPI, with the CMF serving as the indicator of safety effectiveness within the EB observational before-after method. These steps are outlined in Figure 3-1, with detailed explanations provided in the subsequent sub-sections.

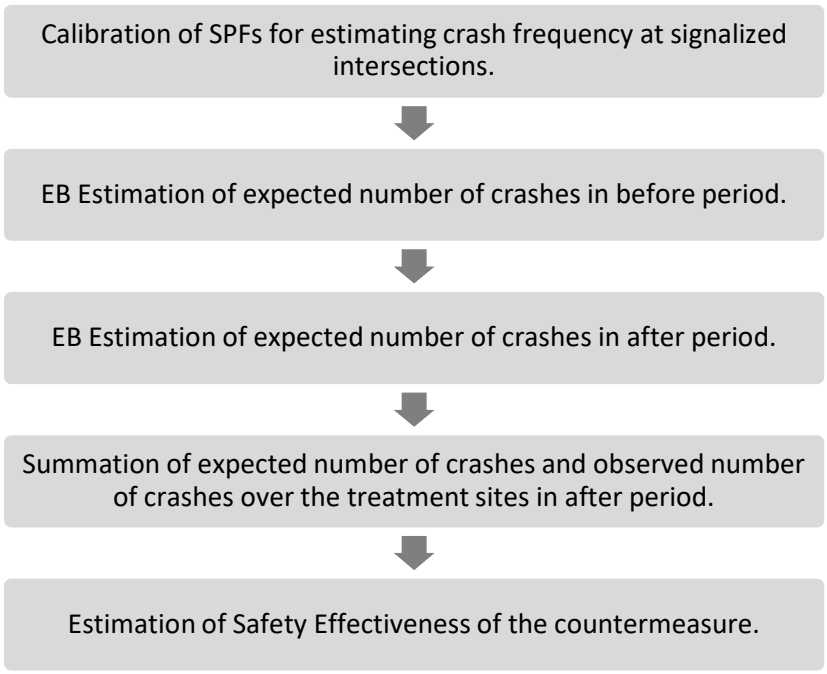


Figure 3-1 Five-step process for evaluating safety effectiveness using CMF in EB observational before-after method.

3.1.1 Calibration of SPFs for estimating crash frequency at signalized intersections.

The crash prediction model underwent calibration using crash data from reference sites without treatment spanning from 2011 to 2016. To develop the model, a correlation analysis was first completed, followed by calibration of the model using STATA.

3.1.1.1 Correlation Analysis

The objective of the correlation analysis was to determine the strength of the relationships between the various variables considered for the prediction model. The resulting correlation matrix provides insights into these relationships. Additionally, highly correlated independent variables were avoided in the same model to mitigate multicollinearity effects. Understanding the strength of these correlations is crucial for selecting variables for stepwise regression. This approach ensures that the regression model includes independent variables that are not highly correlated with one another, thereby enhancing the model's explanatory power.

3.1.1.2 Model Calibration

For the EB method, a negative binomial regression (NB) model, as depicted in equation (2) is employed to calibrate the collision frequency model.

$$Crashes_{spf,i,t} = e^{(\beta_0+\beta_1 x_1+\beta_2 x_2+\cdots+\beta_j x_j)} \quad (2)$$

where:

$Crashes_{spf,i,t}$ represents the predicted number of pedestrian vehicle collisions at signalised intersection i over t years; x_1, x_2, and x_j are the independent variables; and β_0, β_1, β_2, and β_j are the estimated coefficients of the independent variables.

In this research, the statistical software package STATA was used for calibrating the NB model (StataCorp., 2023). The model calibration datasets were imported into STATA for negative binomial regression. The same process was conducted utilizing the highly correlated independent variables in different models to develop regression models in STATA. The detailed STATA code for the final model is provided in supplementary data.

1. A baseline model was generated, containing the dependent variable and all relevant independent variables.
2. An initial backward stepwise regression was performed.
3. The p-values of the variables in the initial model were examined to identify any that were not significant at the 95% confidence level. The variable with the highest p-value was removed, and a new model was calibrated with the remaining variables. This process continued until all variables in the model were significant at least at the 95% level.
4. Any remaining significant variables with unreasonable coefficients, based on their sign direction and/or magnitude, or that were strongly correlated with another variable (as indicated by the correlation matrix), were removed. This was done only if their removal did not result in a significant change in the adjusted R-squared value and both AIC & BIC.

AIC (Akaike Information Criterion) and BIC (Bayesian Information Criterion) are essential criteria used in statistical modelling for model selection. These criteria help compare different models to identify the one that best fits the data while accounting for model complexity. AIC measures the relative quality of a statistical model, grounded in the concept of information entropy, and is typically favoured when predictive accuracy is paramount. BIC, derived from Bayesian principles, imposes a stricter

penalty for models with more parameters and is often preferred when model simplicity and parsimony are prioritized, particularly in larger datasets. The choice between AIC and BIC hinges on the context of the analysis and specific objectives. For this study, both AIC and BIC are considered to balance the need for a predictive model with the necessity for simplicity, facilitating adaptation by other jurisdictions and subsequent studies.

3.1.2 EB Estimation of expected number of crashes in before period.

The predicted number of crashes at treated intersections is calculated by using the SPF in the equation (2):

$$Crashes_{predicted,i,t} = C \times Crashes_{spf,i,t} \quad (3)$$

where $Crashes_{predicted,i,t}$ represents the predicted number of crashes for the treated intersection i over t years; and C is the calibration factor that is assumed to be equal to 1 as the SPF used is calibrated using local data. In addition to the variable coefficients, the dispersion parameter α is extracted from the model results. This parameter represents the variability in crash data that the SPF cannot explain. While the SPF estimates expected crashes based on factors like traffic volume and road characteristics, actual crash counts often deviate due to random, unobserved factors. The dispersion parameter captures this variability, indicating how much actual crash counts deviate from the predicted mean. In the EB method, the dispersion parameter determines the weighting between observed and predicted crashes in the EB estimate (Frank et al., 2010; Hauer, 1997).

The expected number of crashes at intersection over before years is calculated utilizing equation (4).

$$Crashes_{expected,i,b} = w_i \times Crashes_{predicted,i,b} + (1 - w_i) Crashes_{observed,i,b} \quad (4)$$

$$w_i = \frac{1}{1 + \alpha \times Crashes_{predicted,i,b}} \quad (5)$$

where:

$Crashes_{expected,i,b}$ = Expected number of crashes at treated intersection i over before period.

$Crashes_{predicted,i,b}$ = Predicted number of crashes at treated intersection i over before period obtained from equation 2.

$Crashes_{observed,i,b}$ = Observed number of crashes at treated intersection i over before period.

w_i = weight coefficient for each intersection i

α = Dispersion parameter obtained from crash frequency model (SPF)

The variance of the expected number of crashes can be given as follows:

$$Var[Crashes_{expected,i,b}] = (1 - w_i)Crashes_{expected,i,b} \quad (6)$$

3.1.3 EB Estimation of expected number of crashes in after period.

The predicted number of crashes at treatment intersection for after period ($Crashes_{predicted,i,a}$) in the absence of the treatment can be calculated using equation (3). It is to be noted that the predicted crashes obtained are for the number of years in the before period. Therefore, an adjustment factor (μ_i) is calculated to account for the variations in duration and pedestrian & vehicle volumes between before and after periods at each intersection i.

$$\mu_i = \frac{Crashes_{predicted,i,a}}{Crashes_{predicted,i,b}} \times \frac{number\ of\ years\ in\ after\ period}{number\ of\ years\ in\ before\ period} \quad (7)$$

The expected number of crashes at intersection without LPI treatment is estimated utilizing equation (8).

$$Crashes_{expected,i,a} = \mu_i \times Crashes_{expected,i,b} \quad (8)$$

where:

$Crashes_{expected,i,a}$ = Expected number of crashes at treated intersection i over after period.

$Crashes_{expected,i,b}$ = Expected number of crashes at treated intersection i over before period obtained from equation 3.

μ_i = adjustment factor for each intersection i, calculated using equation (7).

Similarly, the estimated variance can be given as:

$$Var\left[Crashes_{expected,i,a}\right] = (1 - w_i) \times \mu_i \times Crashes_{expected,i,b}$$
$$= (1 - w_i) Crashes_{expected,i,a} \quad (9)$$

3.1.4 Summation of expected number of crashes and observed number of crashes over the treatment sites in after period.

The expected number of crashes at treatment intersections for after period without implementation of the treatment is computed as:

$$\sum Crashes_{expected,a} = \sum_{i=1}^{I} Crashes_{expected,i,a} \quad (10)$$

where $\sum Crashes_{expected,a}$ is the sum of expected number of crashes in the after period for the group of treatment intersections had there been no countermeasure implemented, and I denotes the total number of treatment intersections. Similarly, the sum of observed number of crashes at all the countermeasure treated intersections ($\sum Crashes_{observed,a}$) can be calculated as:

$$\sum Crashes_{observed,a} = \sum_{i=1}^{I} Crashes_{observed,i,a} \quad (11)$$

As per the assumption of a Poisson distribution, the estimated variance of $Crashes_{observed,i,a}$ is equal to $Crashes_{observed,i,a}$. Hence, the estimated variance of $\sum Crashes_{expected,a}$ can be computed as:

$$Var\left[Crashes_{observed,i,a}\right] = Crashes_{observed,i,a} \quad (12)$$

Therefore, Equations (11) & (12) can be re-written as follows:

$$Var\left[\sum Crashes_{observed,a}\right] = \sum_{i=1}^{I} Var\left[Crashes_{observed,i,a}\right] \quad (13)$$

Similarly, the estimated variance of $\sum Crashes_{expected,a}$ can be re-written using equation 8 as:

$$Var\left[\sum Crashes_{expected,a}\right] = \sum_{i=1}^{I} Var\left[Crashes_{expected,i,a}\right] \quad (14)$$

3.1.5 Estimation of Safety Effectiveness of the countermeasure.

The Safety Effectiveness, defined as a CMF, can be estimated by equation (15):

$$CMF = \frac{\frac{\sum Crashes_{observed,a}}{\sum Crashes_{expected,a}}}{1 + \frac{Var\left[\sum Crashes_{expected,a}\right]}{\left[\sum Crashes_{expected,a}\right]^2}} \quad (15)$$

The estimated variance of CMF is given by:

$$Var[CMF] = CMF^2 \times \frac{\left(\frac{1}{\sum Crashes_{observed,a}} + \frac{Var\left[\sum Crashes_{expected,a}\right]}{\left[\sum Crashes_{expected,a}\right]^2}\right)}{\left(1 + \frac{Var\left[\sum Crashes_{expected,a}\right]}{\left[\sum Crashes_{expected,a}\right]^2}\right)} \quad (16)$$

$$SE\,[CMF] = \sqrt{Var[CMF]} \quad (17)$$

The adjustment in the CMF calculation is necessary to account for the inherent variability in the expected crash counts, which ensures a more accurate and reliable estimate of the CMF. When calculating the CMF as a simple ratio of observed to expected crashes, any random fluctuations or uncertainty in the expected crash data could lead to bias. This bias might result in an inaccurate reflection of the treatment's effectiveness. To address this, the adjustment incorporates the variance of the expected crashes into the CMF formula. This variance reflects the uncertainty or spread in the expected crash counts, which is crucial because predictions made by models like the SPF are not perfect and can vary. The adjustment term $\left(1 + \frac{Var\left[\sum Crash\quad_{expected,a}\right]}{\left[\sum Crashes_{expected,a}\right]^2}\right)$ modifies the CMF calculation to account for this variability. By including this adjustment, the CMF calculation becomes more robust, reducing the potential bias and improving the precision of the estimate.

The treatment is considered effective in reducing the number of crashes if the CMF is less than 1. To assess the statistical significance of the estimated CMF of the countermeasure, the Confidence interval (CI) is computed as $CMF \pm (1.96 \times SE\ [CMF])$. If the CI contains value one, it is concluded that the treatment is not significant at 95% CI.

3.2 Data Sources and Preparation

3.2.1 Study Area: Region of Waterloo

The research focuses on the effectiveness of LPIs near elementary schools, utilizing data sourced from the Region of Waterloo. Commencing in May 2017, the Region embarked on a pilot project aimed at implementing LPIs within signalized intersections proximate to elementary schools. Situated in Southwestern Ontario, the Region of Waterloo encompasses a mid-sized community with a population of 647,540 as of the conclusion of 2022, comprising three cities: Cambridge, Kitchener, and Waterloo, alongside four townships: North Dumfries, Wellesley, Wilmot, and Woolwich. The road network within the Region consists of roads of various classes such as municipal roads (ranging from local to arterial), in addition to rural and urban highways.

Over the past decade (2011-2020), the Region of Waterloo had a total of 1,146 pedestrian-vehicle collisions. Notably, a significant majority of these collisions, accounting for 83% (953 crashes), occurred at intersections. Despite constituting only 5% of the total intersection count in the region, fully signalized intersections were associated with a notable 79% of all intersection-related pedestrian-vehicle collisions. A primary contributing factor to these collisions was identified as drivers' failure to yield the right of way to pedestrians, which accounted for 60% of all accidents at signalized intersections. Supporting this narrative, the distribution of yearly pedestrian collisions is provided in Table 4.1. A comprehensive summary of collision data pertaining to this topic can be found in Appendix A.

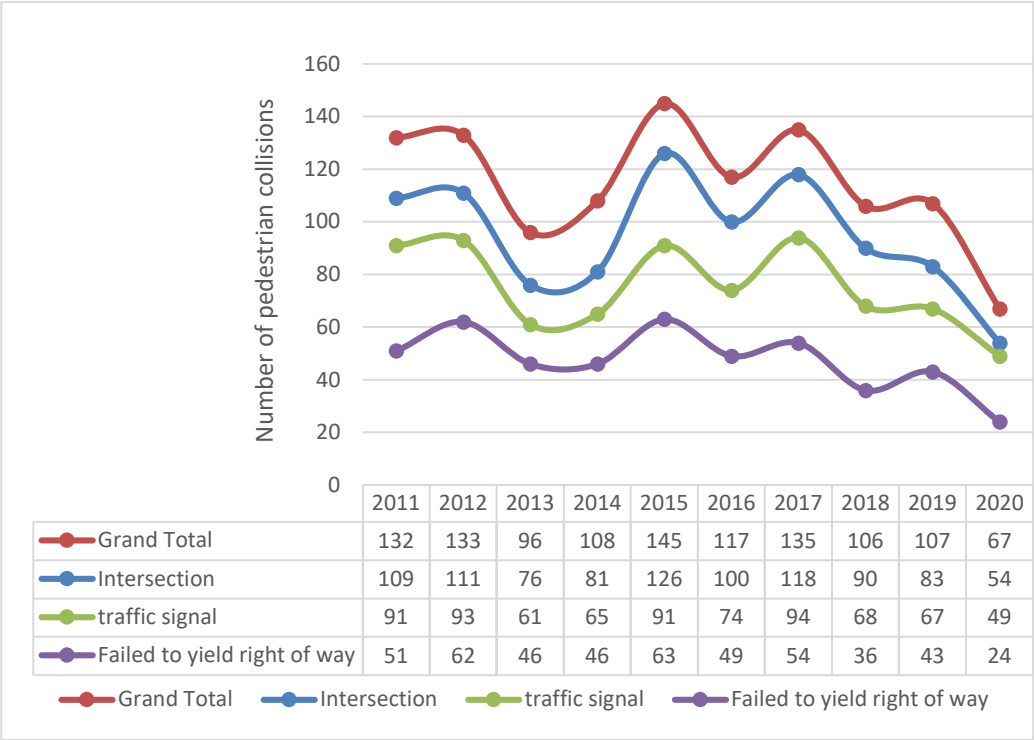


Figure 3-2 Year wise distribution pedestrian collisions in Region of Waterloo (2011-2020)

3.2.2 Data Requirements

According to the Highway Safety Manual (HSM), the Data Requirements for the EB and After Evaluation Method are as follows:

- **Study Period**: A minimum duration of 3-5 years for the before period and at least 2 years for the after period is required.
- **Study Sites**: This includes both treatment sites for evaluation and reference sites for developing SPFs.
- **Collision Data**:
  - For treatment sites, collision data must be collected for both the before and after periods.
  - For reference sites, collision data is needed only for the before period.
- **Vehicular and Pedestrian Volumes**:
  - For treatment sites, volume data is required for both the before and after periods.

- For reference sites, volume data is necessary only for the before period.

- **Safety Performance Functions (SPF)**: To develop SPFs, traffic volume data is essential. However, to create a more accurate model, it is recommended to also include geometric and operational characteristics as well as built environment features.

The specifics of these requirements and the corresponding data utilized to satisfy them are elaborated upon in the following subsections.

3.2.2.1 Study Period

The study encompasses data from 2011 to 2020. The before-treatment period spans six years, from 2011 to 2016, while the after-treatment period covers two years, from 2019 to 2020. The years 2017 to 2018 serve as a buffer period, during which the LPI treatment was implemented.

3.2.2.2 Study Sites

The Region of Waterloo comprises 479 signalized intersections. Selection criteria for both treatment and reference sites include excluding intersections with more than four legs, ensuring the installation of traffic signals prior to 2011, ensuring no major changes made to the intersection geometry and availability of vehicular and pedestrian traffic volume data for at least one year in before treatment period and one year in after treatment period.

Treatment sites

Out of the 41 signalized intersections where LPI was implemented between 2017 and 2018, 33 were included in the study after considering exclusion criteria (as mentioned in section 3.2.2.2) and LPI is implemented dynamically for a period before the school starts and after school ends. Among these, 17 locations are situated in Kitchener, 6 in Waterloo, and 10 in Cambridge, each located within a one-kilometre radius of a school. Details on these Treatments Sites are provided in Appendix B.

Reference sites

Approximately four reference sites were selected for each treatment site, chosen based on the presence of a school within a one-kilometer radius and similarity in intersection geometry, pedestrian, and vehicle volumes with each treatment site. Details on these Reference Sites are provided in Appendix B.

For each intersection, collision data, vehicular & ped volumes and geometric & land use are collected from different sources, as detailed in the following section.

3.2.2.3 Collision Data

Collision data for the study period, spanning from 2011 to 2020, was obtained from the Region of Waterloo. This database contained all recorded crashes, which were filtered to isolate pedestrian-vehicle crashes that occurred at or near intersections. Only fatal and injury crashes involving pedestrians were considered for analysis, while property damage crashes lacking a clear definition were excluded from the study due to ambiguity.

3.2.2.4 Vehicular and Pedestrian Volumes

Vehicular traffic and pedestrian volumes were sourced from the Region of Waterloo, initially provided in PDF format. Despite attempts to convert them into Excel using various online software tools, inconsistencies in formatting necessitated manual extraction of turning movement counts. The PDFs included counts for each turning movement and pedestrians, collected over 8-hour shifts spanning morning (7:30 am to 10:30 am), afternoon (12:00 noon to 2:00 pm), and evening (3:00 pm to 6:00 pm). While the Region provided a set of adjustment factors to convert vehicular traffic counts to 24-hour daily volume, similar factors are not available for adjusting the pedestrian counts. To address this problem, a separate effort was taken to derive adjustment factors using continuous pedestrian counts collected by Miovision systems installed at 83 signalized intersections across the Region of Waterloo. These factors, extracted based on both monthly and hourly variations, were essential to mitigate seasonal fluctuations, particularly critical for the winter season. Monthly factors, detailed in Table 3-1, adjusted for seasonal variations, while hourly factors, including a final hourly expansion factor of 1.78 (derived from the remaining 16 hours of the day), were utilized to convert 8-hour counts to 24-hour equivalents (Table 3-2). For example, if a pedestrian count for an intersection over 8 hours is 300 in June, it would be multiplied by both the hourly and monthly expansion factors—1.78 and 0.784, respectively—to yield the average daily pedestrian volume, rounded to the nearest whole number, such as 419 pedestrians.

Table 3-1 Monthly Expansion Factors for Pedestrian Daily Volume

Month	Monthly multiplication factor
January	1.418
February	1.346
March	1.036
April	0.906
May	0.775
June	0.784
July	0.909
August	0.986
September	0.762
October	0.841
November	0.965
December	1.272

Table 3-2 Hourly expansion factors for Pedestrian Daily Volume

Hour	Hourly Proportion			Hourly Factor
00:00-01:00	0.108			
01:00-02:00	0.063			
02:00-03:00	0.044			
03:00-04:00	0.031			
04:00-05:00	0.032		1.164	
05:00-06:00	0.096			
06:00-07:00	0.378			
07:00-08:00	0.823	0.411		
08:00-09:00	1.284	0.411		Sum of recorded proportions=13.709
90:00-10:00	1.278		3.712	Sum of unrecorded proportions=10.290
10:00-11:00	1.475	0.737		
11:00-12:00	1.801	0.737	2.539	13.70 : 1 :: 10.30 : ?
12:00-13:00	1.888			? = 0.78
13:00-14:00	1.882		3.771	
14:00-15:00	2.333		2.332	Conversion Factor = (1+0.78) =1.78
15:00-16:00	2.338			
16:00-17:00	2.108		6.228	
17:00-18:00	1.781			
18:00-19:00	1.366			
19:00-20:00	1.099			
20:00-21:00	0.798		4.254	
21:00-22:00	0.478			
22:00-23:00	0.305			
23:00-24:00	0.207			
Total	24			

3.2.2.5 Intersection geometric data

The intersection geometry and built environment data provided by the Region of Waterloo's open data portal were found to be insufficient for the specific requirements of this study, particularly in terms of selecting reference sites. As such, additional detailed data on intersection geometry and built environment features were obtained from other sources for each of the 388 intersections within the study area. This extensive data collection process utilized alternative sources such as Google Maps and Google Earth to augment the available dataset. Information was gathered for various aspects of each intersection, including attributes applicable to the entire intersection and those specific to directional legs denoted as North, South, West, and East legs, corresponding to their approximate compass orientation. Geometric details were acquired through visual inspection of aerial and location photography provided by Google Earth and Google Maps, while operational data were sourced from Waterloo Region Open Data using GIS tools. The majority of the variables essential for the study were extracted from these digital platforms. Each intersection was documented on its own distinct geometric Excel data sheet, with a sample of the data collection sheet included in Appendix C for reference. It is important to note that the data items recorded in these sheets were not directly utilized as variables but post processed so that they meet the requirements of the analytical framework and research objectives of this study.

The final list of variables and their respective sources are shown in Table 3-3. The Data Collection Procedure involved accessing data from various sources, such as direct outreach to the Region of Waterloo, accessing its Open Data platform, and using Google Maps & Google Earth. Appendix C includes detailed data collection processes for the final variables based on their sources.

- **C.1** for data from the Department of Transport Service, Region of Waterloo
- **C.2** for data from Region of Waterloo Open Data
- **C.3** for data from google earth & google maps

Table 3-3 List of Final Variables for SPF

Variable Name	Definition	Data Type	Units or Values	Source
Colped	Number of vehicle-pedestrian collisions from 2011 to 2020	Continuous	Number of Collisions	Region of Waterloo
colped2011_16	Number of vehicle-pedestrian collisions from 2011 to 2016	Continuous	Number of Collisions	Region of Waterloo
colped2019_20	Number of vehicle-pedestrian collisions from 2019 to 2020	Continuous	Number of Collisions	Region of Waterloo
Legs	Number of legs in an intersection	Binary	If 0, three-legged intersection. If 1, four-legged intersection	Google Maps and Earth
speed0123	Speed on the major road of the intersection	Continuous	Kilometer per hour	Region of Waterloo Open Data
grt_stop	Number of bus stops at the intersection	Continuous	Number of Stops	Region of Waterloo Open Data
school_500_yn	Presence of a school within 500m of the intersection	Binary	If 0, no school; if 1, school present	Region of Waterloo Open Data
Total_numlanes	Total number of lanes at the intersection	Continuous	Number of lanes	Google Maps and Earth
Avglanes	Average number of lanes at the intersection	Continuous	Number of lanes	Google Maps and Earth
T_numthro	Total number of through lanes at the intersection	Continuous	Number of lanes	Google Maps and Earth
T_numright	Total number of right-turn lanes at the intersection	Continuous	Number of lanes	Google Maps and Earth
T_numleft	Total number of left-turn lanes at the intersection	Continuous	Number of lanes	Google Maps and Earth
sliplane_presence_yn	Presence of at least one slip lane at the intersection	Binary	If 0, no slip lane; if 1, slip lane present	Google Maps and Earth
residential_yn	Presence of residential establishments at least one corner of the intersection	Binary	If 0, no residential; if 1, residential present	Google Maps and Earth

Table 3-3 List of Final Variables for SPF, continued

Variable Name	Definition	Data Type	Units or Values	Source
commercial_yn	Presence of commercial or industrial establishments at least one corner of the intersection	Binary	If 0, no commercial; if 1, commercial present	Google Maps and Earth
school_atint	Presence of educational establishments at least one corner of the intersection	Binary	If 0, no school; if 1, school present	Google Maps and Earth
open_yn	Presence of open space or playground at least one corner of the intersection	Binary	If 0, no open space; if 1, open space present	Google Maps and Earth
skewness	Presence of skewness at the intersection (non-90-degree angles)	Binary	If 0, no skewness; if 1, skewness present	Google Maps and Earth
comm	One of the legs is a commercial entry or exit	Binary	If 0, no commercial entry; if 1, commercial entry present	Google Maps and Earth
local	One of the legs is a local road	Binary	If 0, no local road; if 1, local road present	Region of Waterloo Open Data
collector	One of the legs is a collector road	Binary	If 0, no collector road; if 1, collector road present	Region of Waterloo Open Data
arterial	One of the legs is an arterial road	Binary	If 0, no arterial road; if 1, arterial road present	Region of Waterloo Open Data
commercial_exent_int_yn	Presence of commercial entry/exits or residential driveways within 50m of the intersection	Binary	If 0, no commercial exits; if 1, commercial exits present	Google Maps and Earth
oneway_leg_yn	Presence of at least one leg with one-way traffic at the intersection	Binary	If 0, no one-way leg; if 1, one-way leg present	Google Maps and Earth

Table 3-3 List of Final Variables for SPF, continued

Variable Name	Definition	Data Type	Units or Values	Source
median_presence_yn	Presence of at least one median at the intersection	Binary	If 0, no median; if 1, median present	Google Maps and Earth
raisedmedian_yn	Presence of at least one raised median at the intersection	Binary	If 0, no raised median; if 1, raised median present	Google Maps and Earth
non_standardmarking	Presence of non-conventional crosswalk markings	Binary	If 0, no non-standard marking; if 1, non-standard marking present	Google Maps and Earth
T_crosswalklength	Total length of all crosswalks at the intersection	Continuous	Meters	Google Maps and Earth
Avg_crosswalklength	Average length of all crosswalks at the intersection	Continuous	Meters	Google Maps and Earth
num_sidewalk_missing	Number of missing sidewalks at the intersection (assuming 2 per side of each approach)	Continuous	Number of sidewalks	Google Maps and Earth
bicyclepresence_210	Presence of at least one conventional bicycle lane at the intersection	Binary	If 0, no bicycle lane; if 1, bicycle lane present	Google Maps and Earth
Ped_total	Estimated daily pedestrian volume crossing the intersection	Continuous	Pedestrians per day	Region of Waterloo
ln_Ped_total	Log of Estimated daily pedestrian volume crossing the intersection	Continuous	Log of pedestrians per day	Region of Waterloo
EDT_fac	Estimated daily vehicle volume crossing the intersection	Continuous	Vehicles per day	Region of Waterloo
Right_TMC	Estimated daily right-turn vehicle volume crossing the intersection	Continuous	Vehicles per day	Region of Waterloo
Through_TMC	Estimated daily through movement vehicle volume crossing the intersection	Continuous	Vehicles per day	Region of Waterloo

Table 3-3 List of Final Variables for SPF, continued

Variable Name	Definition	Data Type	Units or Values	Source
Left_TMC	Estimated daily left-turn vehicle volume crossing the intersection	Continuous	Vehicles per day	Region of Waterloo
ln_EDT_fac	Log of Estimated daily vehicle volume crossing the intersection	Continuous	Log of vehicles per day	Region of Waterloo
prop_left	Proportion of left-turn vehicle volume	Ratio	Proportion	Region of Waterloo
prop_right	Proportion of right-turn vehicle volume	Ratio	Proportion	Region of Waterloo
prop_lr	Proportion of combined left and right-turn vehicle volume	Ratio	Proportion	Region of Waterloo
MajorEDT	Estimated daily vehicle volume entering the intersection from the major road	Continuous	Vehicles per day	Region of Waterloo
MinorEDT	Estimated daily vehicle volume entering the intersection from the minor road	Continuous	Vehicles per day	Region of Waterloo
ln_majorEDT	Log of Estimated daily vehicle volume entering the intersection from the major road	Continuous	Log of vehicles per day	Region of Waterloo
ln_minorEDT	Log of Estimated daily vehicle volume entering the intersection from the minor road	Continuous	Log of vehicles per day	Region of Waterloo

3.2.3 Data Description

A summary of the data descriptive statistics is provided for treatment sites and reference sites in Table 3-4 and Table 3-5, respectively. Detailed data description is provided in Appendix D-Appendix G.

- Appendix D: Collision Data
- Appendix E: Traffic Characteristics

- Appendix F: Roadway & Geometric Characteristics
- Appendix G: Land Use & Built Environment Characteristics

Table 3-4 Summary of Descriptive Statistics of Treatment Sites (33 sites)

Variable	Mean	Std. dev.	Min	Max
Collision Data				
Colped	2.151515	2.108335	0	9
colpedyearly	1.075758	1.054167	0	4.5
colped2011_16	1.424242	1.521313	0	6
colped2011_16_peryear	0.237374	0.253552	0	1
colped2019_20	0.30303	0.683961	0	3
colped2019_20_peryear	0.151515	0.341981	0	1.5
Traffic Characteristics				
Ped_total_before	600.635	362.4737	80.84995	1716.771
ln_Ped_total_before	6.194896	0.706102	4.392595	7.448201
Ped_total_after	620.9621	438.9257	110.1603	1889.954
ln_Ped_total_after	6.206468	0.69582	4.701937	7.544308
EDT_fac_before	18.54397	7.833687	5.5419	37.74408
ln_EDT_fac_before	9.734997	0.456473	8.620093	10.53858
EDT_fac_after	18.0283	7.521193	4.5675	39.4806
ln_EDT_fac_after	9.705356	0.465189	8.426721	10.58356
MajorEDT_before	14811.41	7090.23	4670.16	34439.82
MinorEDT_before	3732.564	2467.536	859.56	9897.12
MajorEDT_after	14027.14	7068.734	937.86	36256.38
MinorEDT_after	3628.533	2586.167	664.68	11758.92
Through_TMC	13.75496	6.659839	4.437	32.08908
Through_TMC_after	13.12218	6.416217	3.71316	33.91086
Left_TMC_before	2.382851	1.246225	0.57072	5.13126
Left_TMC_after	2.408265	1.145532	0.42108	4.86504
Right_TMC_before	2.406156	1.29685	0.53418	5.00076
Right_TMC_after	2.497849	1.17836	0.43326	4.7502
prop_left_before	0.132765	0.054563	0.037201	0.30044
prop_left_after	0.139399	0.053453	0.044305	0.291322
prop_right_before	0.134983	0.06088	0.039648	0.308457
prop_right_after	0.145578	0.059218	0.04619	0.337681
prop_lr_before	0.267748	0.113368	0.078483	0.608897
prop_lr_after	0.284977	0.1108	0.090495	0.629003
speed0123	1.060606	0.496198	0	3

Table 3-4 Summary of Descriptive Statistics of Treatment Sites, continued

Variable	Mean	Std. dev.	Min	Max
Roadway & Geometric Characteristics				
T_numlane_ent	7.212121	2.011802	3	12
T_numlane_ext	4.818182	1.130668	3	7
Mx_lanes_perleg	4	1.089725	2	6
Total_numlanes	12.0303	2.778093	6	18
Avglanes	3.24899	0.715975	2	4.5
T_numthro	4.515152	1.253027	2	6
T_numright	0.69697	0.769937	0	2
T_numleft	2	1.198958	0	4
median_presence_yn	0.333333	0.478714	0	1
Raisedmedian_yn	0.212121	0.415149	0	1
T_crosswalklength	63.31515	17.06957	29.8	100.6
Avg_crosswalklength	17.14116	3.898823	9.933333	25.15
non_standardmarking	0.272727	0.452267	0	1
comm	0.060606	0.242306	0	1
local	0.363636	0.488504	0	1
collector	0.787879	0.415149	0	1
Arterial	0.69697	0.466694	0	1
Legs	0.69697	0.466694	0	1
oneway_leg_yn	0.030303	0.174078	0	1
sliplane_presence_yn	0.090909	0.291937	0	1
Skewness	0.181818	0.391675	0	1
num_sidewalk_missing	0.363636	0.742386	0	2
Bicyclepresence_210	0.363636	0.488504	0	1
Land Use & Built Environment Characteristics				
Residential_yn	0.909091	0.291937	0	1
Commercial_yn	0.424242	0.50189	0	1
open_yn	0.181818	0.391675	0	1
school_atint	0.212121	0.415149	0	1
school_500_yn	0.818182	0.391675	0	1
grt_stop	2.818182	1.130668	1	5
T_commerial_exent_int	2.757575	1.173411	1	4
commerial_exent_int_yn	1	0	1	1

Table 3-5 Summary of Descriptive Statistics of Reference Sites (147 sites)

Variable	Mean	Std. dev.	Min	Max
Collision Data				
Colped	1.741497	2.074266	0	13
colpedyearly	0.17415	0.207427	0	1.3
colped2011_16	1.176871	1.56021	0	9
colped2011_16_peryear	0.196145	0.260035	0	1.5
colped2019_20	0.217687	0.475668	0	2
colped2019_20_peryear	0.108844	0.237834	0	1
Traffic Characteristics				
Ped_total_before	1132.801	1891.998	13.76169	11227.05
ln_Ped_total_before	6.116094	1.407088	2.621889	9.326081
Ped_total_after	1132.801	1891.998	13.76169	11227.05
ln_Ped_total_after	6.129455	1.262632	2.25959	9.675582
EDT_fac_before	20.01968	8.12185	3.06414	48.27804
ln_EDT_fac_before	9.816201	0.442734	8.027522	10.78473
EDT_fac_after	20.01968	8.12185	3.06414	48.27804
ln_EDT_fac_after	17.59457	8.217859	0.73428	44.66406
MajorEDT_before	15028.34	6075.876	2951.04	36341.64
MinorEDT_before	4839.165	4097.244	113.1	19373.16
MajorEDT_after	13354.13	6225.061	417.6	34145.76
MinorEDT_after	4240.439	3702.686	121.8	22064.94
Through_TMC	14.10233	6.162839	1.16928	32.364
Through_TMC_after	14.10233	6.162839	1.16928	32.364
Left_TMC_before	2.848936	2.398782	0.1218	16.57002
Left_TMC_after	2.848936	2.398782	0.1218	16.57002
Right_TMC_before	3.073728	2.444977	0.12006	13.28838
Right_TMC_after	3.073728	2.444977	0.12006	13.28838
prop_left_before	0.135785	0.077396	0.009576	0.470495
prop_left_after	0.135784	0.077396	0.009576	0.470495
prop_right_before	0.148956	0.084711	0.016798	0.498986
prop_right_after	0.148956	0.084711	0.016798	0.498985
prop_lr_before	0.28474	0.151298	0.038036	0.957176
prop_lr_after	0.28474	0.151298	0.038036	0.957176
speed0123	1.231293	0.483538	0	3

Table 3 5 Summary of Descriptive Statistics of Reference Sites, continued

Variable	Mean	Std. dev.	Min	Max
Roadway & Geometric Characteristics				
T_numlane_ent	7.306122	2.250151	3	16
T_numlane_ext	4.92517	1.170929	3	8
Mx_lanes_perleg	4.197279	1.144609	2	8
Total_numlanes	12.23129	3.140692	6	24
Avglanes	3.332755	0.80158	1.75	6
T_numthro	4.585034	1.275929	2	8
T_numright	0.734694	0.901494	0	4
T_numleft	1.931973	1.337857	0	4
median_presence_yn	0.340136	0.475374	0	1
Raisedmedian_yn	0.251701	0.435474	0	1
T_crosswalklength	62.46395	27.7562	18.3	276.1
Avg_crosswalklength	17.60634	6.464036	8.1	69.025
non_standardmarking	0.22449	0.418672	0	1
num_sidewalk_missing	0.687075	1.297008	0	7
Bicyclepresence_210	0.421769	0.595936	0	2
comm	0.108844	0.312508	0	1
local	0.421769	0.49553	0	1
collector	0.44898	0.499091	0	1
Arterial	0.809524	0.394019	0	1
Legs	0.693878	0.462457	0	1
oneway_leg_yn	0.07483	0.264016	0	1
sliplane_presence_yn	0.095238	0.294547	0	1
Skewness	0.163265	0.370871	0	1
num_sidewalk_missing	0.687075	1.297008	0	7
Bicyclepresence_210	0.421769	0.595936	0	2
Land Use & Built Environment Characteristics				
Residential_yn	0.632653	0.48373	0	1
Commercial_yn	0.455782	0.377787	0	1
open_yn	0.217687	0.414084	0	1
school_atint	0.07483	0.264016	0	1
school_500_yn	0.666667	0.473016	0	1
grt_stop	2.680272	1.227462	1	5
T_commerial_exent_int	2.578231	1.452089	0	4
commerial_exent_int_yn	0.741497	0.439309	0	1

Chapter 4
Results & Discussion

Chapter 4 delves into the results and discussion regarding the effectiveness of LPIs in enhancing pedestrian safety at signalized intersections. This chapter explores the overall safety benefits of LPIs, beginning with an exploratory analysis. It proceeds with the calibration of SPFs and subsequently conducts an EB before-and-after analysis to quantify the impact of LPI implementation on pedestrian safety using CMFs. Additionally, a sensitivity analysis of CMFs to Calibration factor is included.

4.1 Exploratory Analysis

The traditional Before & After Analysis, conducted before the more comprehensive EB Before & After Analysis, compared crashes and crash rates between before and after periods. Here, "crashes" refer to the number of incidents per year per intersection; while "crash rates" indicate crashes per 10 million exposure units per intersection per year, with exposure units derived from the product of estimated daily traffic volume and estimated daily pedestrian volume.

The percentage reductions in crashes and crash rates following the implementation of LPI treatments are depicted in Figure 4-1. Overall Reduction statistics compare crashes and crash rates before and after LPI implementation across all times of the day, regardless of when LPI is active. Specifically, reductions during LPI Active Periods measure the impact during designated times, such as 7:30 am to 9:30 am and 2:30 pm to 4:30 pm when school-related activities occur.

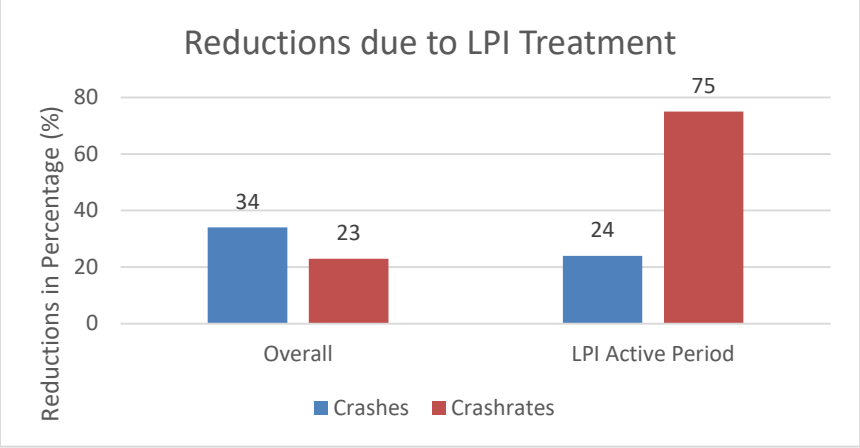


Figure 4-1 Observed Reductions due to LPI Treatment: Overall & LPI Active Period

Interestingly, the overall reduction in crashes is 34%, which exceeds the 24% reduction observed during LPI Active Periods. However, when considering crash rates, which adjust for exposure, the results align more logically: there is a 75% reduction in LPI Active Periods compared to a 23% reduction throughout the entire day. The detailed Traditional Before and After Study results can be found in the Table 4-1 and Table 4-2, for crashes and crash rates respectively.

Table 4-1 Traditional Before After Study: Reductions in Crashes due to LPI Treatment

Crashes	Units	Before	After	Reduction (%)
Overall	*crashes per year per intersection*	0.2373	0.1515	34%
LPI timings	*crashes per year per intersection per hour*	0.0252	0.0198	24%

Table 4-2 Traditional Before After Study: Reductions in Crash rates due to LPI Treatment

Crash rates	Units	Before	After	Reduction (%)
Overall	*crashes per 10 million exposure unit per year per intersection*	0.3284	0.2501	23%
LPI timings	*crashes per 10 million exposure unit* per year per intersection per hour*	0.0065	0.0015	75%
*Exposure unit=EDT*EDP				

4.2 Calibration of SPFs

The crash prediction model, also known as the SPF, was developed using negative binomial regression. As part of the model calibration process, an analysis on the correlation between all variables was first conducted. The correlation matrix is provided in supplementary material. Following the typical stepwise regression process, the model with the best fit is selected as the final model. In this study, two models were chosen. The rationale behind this is that the best predictive model, based on both AIC and BIC, was the one without including Estimated Daily Traffic (EDT) but instead with a surrogate exposure measure - number of legs with commercial entry/exits or driveways within 50 meters of the intersection (NCE). Therefore, the two best models with EDT and NCE as the exposure measure are presented in Table 4-3 (Model 1 with NCE and Model 2 with EDT). The results of the models, including the coefficients, standard errors (S.E.), and p-values for each explanatory variable, are provided below. The signs and significance levels of these coefficients offer insights into the factors influencing pedestrian crashes at intersections.

Table 4-3 Safety Performance Function for Pedestrian Crashes at Signalized Intersections

Variable	Model 1 with NCE			Model 2 with EDT		
	Coeff	S. E.	P-value	Coeff	S. E.	P-value
Constant	-4.8313	0.70	0.000	-11.3549	2.20	0.000
Presence of at least one slip lane at the intersection	-1.5214	0.38	0.000	-0.7623	0.33	0.022
Presence of residential establishments at least one corner of the intersection	x	x	x	0.4843	0.18	0.008
Presence of commercial or industrial establishments at least one corner of the intersection	x	x	x	0.5660	0.24	0.018
Number of legs with commercial entry/exits or driveways within 50m of the intersection	0.2977	0.08	0.000	x	x	x
Presence of commercial entry/exits or driveways within 50m of the intersection	x	x	x	1.5884	0.73	0.029
Presence of non-conventional crosswalk markings	0.5517	0.19	0.004	0.6005	0.21	0.004
Average length of all crosswalks at the intersection	0.0952	0.02	0.000	x	x	x
Number of missing sidewalks at the intersection (assuming 2 per side of each approach)	-0.2939	0.13	0.019	-0.2612	0.16	0.037
Log of Estimated daily pedestrian volume crossing the intersection	0.2899	0.08	0.000	0.2264	0.09	0.012
Log of Estimated daily vehicle volume crossing the intersection	x	x	x	0.7801	0.20	0.000
The dispersion parameter (α)	0.0079	0.08	-	0.0284	0.08	
Log Likelihood	-178.809			-177.007		
AIC	373.618			374.013		
BIC	397.542			403.918		

In Model 1, the positive coefficients for certain variables indicate an increased likelihood of pedestrian crashes under specific conditions. The number of legs with commercial entry/exits or residential driveways within 50 meters of the intersection shows a positive coefficient (0.2977), suggesting that intersections with more commercial driveways or entries are associated with a higher

frequency of pedestrian crashes. Similarly, the presence of non-conventional crosswalk markings has a positive coefficient (0.5517), indicating that these types of markings are linked to an increase in pedestrian crashes. This finding is somehow counterintuitive as this type of crosswalk markings are often introduced to improve visibility and thus pedestrian safety. Additionally, the average length of all crosswalks at the intersection is positively correlated (0.0952) with pedestrian crashes, implying that longer crosswalks heighten the risk of collisions. The estimated daily pedestrian volume crossing the intersection also exhibits a positive coefficient (0.2899), demonstrating that higher pedestrian volumes contribute to a greater number of pedestrian crashes. Model 1 also identifies variables with negative coefficients that suggest a positive effect on pedestrian safety. The presence of a slip lane at the intersection is associated with a decrease in pedestrian crashes, as indicated by the negative coefficient (-1.5214). Another interesting finding is that the number of missing sidewalks at the intersection has a negative coefficient (-0.2939), suggesting that intersections with missing sidewalks tend to experience fewer pedestrian crashes.

In Model 2, several variables with positive coefficients indicate an increased risk of pedestrian crashes. The presence of residential establishments at corners of the intersection has a positive coefficient (0.4843), suggesting that such intersections see a higher number of pedestrian crashes. The presence of commercial or industrial establishments at corners of the intersection also has a positive coefficient (0.5660), further indicating an increased risk. The presence of commercial entry/exits or residential driveways within 50 meters of the intersection has a large positive coefficient (1.5884), signifying a significant rise in pedestrian crashes in these areas. Non-conventional crosswalk markings again show a positive coefficient (0.6005), corroborating the finding from Model 1 that these markings are associated with higher crash rates. Additionally, the daily pedestrian volume (0.2264) and vehicle volume (0.7801) both have positive coefficients, indicating that higher volumes of pedestrians and vehicles at intersections are linked to more pedestrian crashes. Model 2 also highlights variables with negative coefficients that correlate with a decrease in pedestrian crashes. The presence of a slip lane at the intersection shows a negative coefficient (-0.7623), indicating a reduction in pedestrian crashes, although this effect is less pronounced compared to Model 1. The number of missing sidewalks at the intersection continues to show a negative coefficient (-0.2612), indicating fewer pedestrian crashes in areas with missing sidewalks. These results suggest that specific infrastructural elements can significantly influence pedestrian safety at intersections.

Model 1 is preferred over Model 2 based on statistical criteria. Despite Model 2 showing a slightly higher Log Likelihood, Model 1 has lower AIC (373.618 versus 374.013) and BIC (397.542 versus 403.918), indicating better balance between fit and complexity. It should be noted that while increasing the number of variables in a statistical model generally enhances the Log Likelihood, reflecting improved capability in capturing data intricacies, this benefit must be weighed against the penalties imposed by AIC and BIC. Both criteria penalize models with additional variables to mitigate overfitting, with BIC imposing a stricter penalty than AIC. Therefore, while AIC may occasionally favour models with more variables if they significantly enhance fit, both criteria typically advocate for simpler models that achieve a favourable balance between improved fit and reduced complexity. Therefore, simpler models are typically favoured in model selection, balancing enhanced fit with clearer interpretation and generalizability.

To gain a comprehensive understanding of the intricate dynamics affecting pedestrian safety at intersections, these key variables, namely the presence of slip lanes, residential and commercial area presence, driveways or commercial entry/exits, crosswalks, and pedestrian and vehicular volumes, are discussed in depth.

The presence of a slip lane at intersections is found to be associated with a reduction in pedestrian crashes in both Model 1 and Model 2 as the coefficients of this variable is negative (-1.5214 in Model 1 and -0.7623 in Model 2). This result is quite intriguing, adding additional mixed findings on this factor from the previous studies. For example, a study by Potts et al., (2013) concluded that channelized right turns, which include slip lanes, did not increase pedestrian crash risk. However, this conclusion was questioned by researchers like Jiang et al. (2020) , who argued that the data from that period might not reflect current modal share and road user behavior (Jiang et al., 2020). Jiang et al.'s study, collected video data to extract various SSMs as such PET measurement, speed measurement, and behavior measures. They found that channelized right-turn lanes increase pedestrian risks at signalized intersections. Muley et al. (2017) also supports this view, highlighting that only a small percentage of vehicles yielded to pedestrians at such locations. The contradictions in these findings can be attributed to several factors, including differences in study method and context, methodological variations, and sample size and data variability. For instance, the context in which slip lanes are implemented and the specific design features of these lanes can vary widely, affecting their safety outcomes. Additionally, the methodologies used in different studies, such as crash data-based versus conflict-based, can lead to different conclusions. The sample size and the variability in the data sets used for these studies can also

influence the results. Therefore, the positive effect on pedestrian safety by slip lanes observed in this study may be specific to this area highlighting the need for further research to verify these findings across different settings and conditions.

The presence of residential and commercial establishments at intersections has been identified as a significant factor influencing pedestrian crash risk, aligning with past research findings (Loukaitou-Sideris et al., 2007; Schneider et al., 2010; Wier et al., 2009). In Model 2, the coefficients for the presence of residential establishments (0.4843) and commercial or industrial establishments (0.5660) indicate a positive association with pedestrian crashes. These results suggest that intersections with such land-use features experience higher pedestrian crash frequencies. Land-use variables often serve as proxies for pedestrian activity, as residential and commercial areas typically attract more foot traffic. This increased pedestrian activity inherently raises the likelihood of vehicle-pedestrian interactions, thus elevating the risk of collisions. Past studies have also shown that higher percentages of neighbourhood commercial and residential-commercial areas are positively associated with vehicle-pedestrian collisions (Wier et al., 2009). Similarly, it has been pointed out that commercial and high-density residential areas tend to have more pedestrian crashes due to the higher concentration of people and activities that attract pedestrian movement (Loukaitou-Sideris et al., 2007). These areas have built environments, where pedestrians frequently cross streets, often in complex traffic situations, thereby increasing the potential for accidents.

The presence of commercial entry and exits or residential driveways near intersections has a notable impact on pedestrian crash risk, as evidenced by the two variables considered in this study. Model 2 includes a variable representing the presence of these features, with a coefficient of 1.5884, indicating a significant increase in pedestrian crashes when at least one commercial entry or exit is present within 50 meters of the intersection. This aligns with past research, which consistently shows that commercial areas, due to their higher levels of both pedestrian and vehicular traffic, pose a greater risk for collisions. The number of legs with residential driveways and commercial entries or exits within 50 meters also significantly contributes to pedestrian crash risk, as indicated by the positive coefficient of 0.2977 in Model 1. This result suggests that each additional leg with a commercial entry or exit amplifies the risk of pedestrian crashes. The presence of multiple entry and exit points introduces additional conflict zones where vehicles and pedestrians interact, thereby increasing the likelihood of accidents. Past studies support these findings, indicating that the proximity of commercial activities and the resulting driveways create more conflict points between vehicles and pedestrians. In commercial zones, drivers

are more likely to be preoccupied with locating parking spaces or navigating busy traffic, which can divert their attention away from pedestrians (Schneider et al., 2010). The heightened pedestrian activity around shops and restaurants further exacerbates this risk, as more people are likely to be crossing streets or walking near intersections. Furthermore, non-residential driveways within 50 feet of an intersection add to the complexity of the traffic environment. Drivers exiting these driveways may be more focused on merging into traffic and less aware of pedestrians on the sidewalks (Schneider et al., 2010). This creates a hazardous situation where pedestrians are at a greater risk of being overlooked, leading to a higher incidence of crashes.

The presence of non-conventional crosswalk markings, such as zebra, ladder, or continental patterns, is associated with a higher frequency of pedestrian crashes in both models. Model 1 and Model 2 show positive coefficients of 0.5517 and 0.6005, respectively, indicating that these markings, while designed to enhance visibility and safety, may paradoxically lead to an increased risk of pedestrian collisions. Non-conventional crosswalk markings are intended to make pedestrian crossings more noticeable to drivers, theoretically reducing the likelihood of accidents. The impact of non-conventional crosswalk markings on pedestrian safety has been a focus of past studies with mixed results. While some studies have indicated that such markings can lead to increased pedestrian collisions (Islam et al., 2022); others, such as the comprehensive study by Zegeer et al. (2005), found no significant correlation between crosswalk marking patterns and crash rates. This discrepancy highlights the complexity of the issue and suggests that the effectiveness of non-standard markings may vary based on local context and specific traffic conditions (Islam et al., 2022). For instance, the findings from this study can be further justified by considering the specific characteristics of the sites included in the analysis. One possible explanation for the higher crash frequencies is that pedestrians could be less cautious at these locations, drawn by the perceived safety of the enhanced visibility. Due to small sample size (33 out of 147 intersections have this type of crosswalk markings), a further investigation with a larger sample size is needed to corroborate this finding. In summary, although non-conventional crosswalk markings are implemented with the intention of improving pedestrian safety, they may inadvertently contribute to a rise in pedestrian crashes. Further investigation is required to fully understand the impact of non-conventional crosswalk markings.

The significant association between average crosswalk length and an increase in pedestrian collisions is evident, with a coefficient of 0.0952 in Model 1, highlighting the considerable impact of this variable on pedestrian safety at intersections. Longer crosswalks inherently increase the time pedestrians are

exposed to traffic, thereby elevating the risk of collisions. When pedestrians spend more time crossing the roadway, they are more vulnerable to interactions with vehicles. This increased exposure time is a critical factor contributing to the higher incidence of pedestrian crashes. The findings in this study align with past research, which has consistently linked longer crossing distances to higher crash frequencies. Specifically, pedestrian crashes are estimated to increase by about 5% for every additional 3.7 meters (12 feet) of crossing distance (Islam et al., 2022). This highlights the importance of designing shorter, more manageable crosswalks to enhance pedestrian safety. This association between average crosswalk length and pedestrian crashes highlights a critical area of concern for pedestrian safety. The findings suggest that longer crosswalks substantially increase the risk of collisions, primarily due to the extended exposure time for pedestrians.

The finding on the effect of missing sidewalks on pedestrian safety was also found be intriguing. Notably, an increase in the number of missing sidewalks is associated with a decrease in pedestrian crash risk, with Model 1 and Model 2 showing negative coefficients of -0.2939 and -0.2612, respectively. This finding appears counterintuitive at first glance, given that the presence of sidewalks, particularly in residential and mixed residential areas, has been shown to enhance pedestrian safety, as reported by previous studies (McMahon et al., 1999; Schneider et al., 2010). One possible explanation for this result is that with missing or lower number of sidewalks pedestrian traffic is expected to be more concentrated on fewer paths, limiting the conflict zones.

The positive association between pedestrian volume and pedestrian crashes is evident in both models, with coefficients of 0.2899 in Model 1 and 0.2264 in Model 2. This aligns with past research, showing that increased pedestrian volume leads to a higher probability of crashes due to greater exposure (Fernandes, 2013; Shankar et al., 2003). Higher pedestrian volumes result in more individuals crossing streets, increasing the likelihood of interactions between pedestrians and vehicles. As pedestrian traffic intensifies, the number of potential conflict points rises, elevating the chances of crashes.

The variable representing estimated daily vehicle volume (EDT) in Model 2 shows a significant positive association with pedestrian crashes, with a coefficient of 0.7801. This finding aligns with existing research, indicating that higher vehicular volumes at intersections increase the likelihood of pedestrian crashes due to more frequent interactions between vehicles and pedestrians, thereby raising the potential for conflicts and crashes (Fernandes, 2013; Miranda-Moreno et al., 2011; Pulugurtha & Sambhara, 2011; Schneider et al., 2010). In contrast, when the variable NCE was introduced in the

model, the EDT variable was found to be not statistically significant. Result suggests that the number of legs with commercial entry/exits or driveways might serve as a good traffic exposure measure as EDT for predicting pedestrian crashes at the intersections. The number of legs with commercial entry/exits or driveways reflects the level of activity in the area, indicating higher EDT. Similarly, the average crosswalk length corresponds to the width of the road, which is related to the number of lanes and, consequently, to EDT. These variables collectively provide a comprehensive representation of traffic interactions and pedestrian activities, compensating for the absence of EDT in the model. Overall, while higher vehicular volumes generally increase the risk of pedestrian crashes due to more frequent interactions and potential conflicts, the inclusion of different exposure forms in Model 1 and Model 2 highlight the variability and complexity of factors influencing pedestrian safety in different contexts.

4.3 EB Before & After Analysis

This section presents the findings from the study on the safety effectiveness of LPIs at intersections. The first part presents the overall CMF to quantify the reduction in pedestrian crashes due to the LPI implementation. The following part examines how the effectiveness of LPIs varies based on different intersection features. The third part provides a sensitivity analysis of the CMF.

4.3.1 Effectiveness of LPI

The safety effectiveness of the LPI was measured using the CMF through an EB before-and-after analysis described in Chapter 3. Table 4-4 presents the effectiveness of treatment applications in reducing pedestrian collisions at intersection sites, comparing CMF values for Models 1 and 2. The table lists specific intersection GeoIDs along with corresponding values for number of EB estimated & observed collision after treatment application, and CMF values. CMF values indicate the degree of collision reduction or increase compared to baseline conditions. Furthermore, the results shown in Table 4-5 highlight the overall effectiveness of LPIs in reducing pedestrian crashes for both the models.

Table 4-4 Effectiveness of Treatment Applications in Reducing Pedestrian Collisions: Comparison of CMF for Models 1 and 2 at each Intersection Sites

	Model 1			Model 2		
	Collision After Treatment Application			*Collision After Treatment Application*		
GeoID	**EB estimated**	**Observed**	**CMF**	**EB estimated**	**Observed**	**CMF**

19222	0.386	1	2.525	0.250	1	3.705
19285	0.409	0	0	0.221	0	0
19657	0.190	0	0	0.139	0	0
19960	0.227	1	4.285	0.324	1	2.910
20086	1.256	0	0	1.168	0	0
14619	0.201	0	0	0.251	0	0
16008	0.180	2	10.921	0.244	2	7.574
16278	0.501	0	0	0.484	0	0
18421	0.225	0	0	0.096	0	0
18433	0.236	0	0	0.266	0	0
21941	0.386	1	2.515	0.362	1	2.615
22199	0.195	0	0	0.206	0	0
10934	0.447	0	0	0.531	0	0
11137	2.404	0	0	0.732	0	0
11148	0.185	0	0	0.183	0	0
11728	0.123	0	0	0.126	0	0
20795	0.572	0	0	0.354	0	0
21837	0.417	0	0	0.223	0	0
22058	0.584	0	0	0.706	0	0
6504	0.380	1	2.566	0.482	1	1.971
6521	0.198	0	0	0.281	0	0
6751	0.764	0	0	0.448	0	0
8558	0.487	0	0	0.438	0	0
8754	0.322	1	3.037	0.361	1	2.438
9207	0.504	0	0	0.412	0	0
9540	0.398	0	0	0.395	0	0
10715	0.119	3	24.616	0.269	3	10.546
13070	0.224	0	0	0.277	0	0
25799	0.160	0	0	0.186	0	0
5982	0.397	0	0	0.399	0	0
7468	0.146	0	0	0.286	0	0
7496	0.155	0	0	0.448	0	0
8076	0.243	0	0	0.255	0	0

Table 4-5 Comparative Effectiveness of LPI using CMF in Models 1 and 2

MEASURE	MODEL 1	MODEL 2

BEFORE PERIOD	EB Expected Collisions		41.31	37.88
	Observed Collisions		47	47
AFTER PERIOD	EB Expected Collisions		13.63	11.82
	Variance of EB Expected Collisions		0.26	0.51
	Observed Collisions		10	10
EFFECTIVENESS EVALUATION	**CMF**		**0.732**	**0.84**
	Reduction in Collisions		26.78%	15.71%
	Standard Error of CMF		0.25	0.31
	Range of CMF	Upper Limit	1.22	1.45
		Lower Limit	0.24	0.23

The interpretation of measures includes the EB expected collisions, observed collisions, CMF, and reduction in collisions. For the EB expected collisions before the period, Model 1 predicted 41.31 collisions, while Model 2 predicted 37.88, representing the expected number of collisions in the six-year period prior to the LPI implementation. The observed number of collisions before the LPI implementation was 47, indicating that both models underestimated the actual number of collisions by approximately 12.1% for Model 1 and 19.4% for Model 2. After the LPI implementation, the expected number of collisions estimated using the EB approach was 13.63 for Model 1 and 11.82 for Model 2, reflecting the number of collisions anticipated in the two-year post-implementation period. The variance of EB expected collisions, which indicates the variability in predictions, was 0.26 for Model 1 and 0.51 for Model 2, suggesting greater uncertainty in Model 2. The observed collisions after the implementation were 10 for both models. The CMF, which measures the effectiveness of the LPI implementation, was 0.732 based on Model 1 and 0.84 based on Model 2, indicating reductions in collisions by 26.78% and 15.71%, respectively. The standard error of the CMF was 0.25 for Model 1 and 0.31 for Model 2, with lower values signifying more precise estimates. The range of the CMF varied from 0.24 to 1.22 for Model 1 and from 0.23 to 1.45 for Model 2, providing a range within which the true CMF is likely to lie with 95% confidence.

Model 1 shows a greater reduction in collisions (26.78%) compared to Model 2 (15.71%). These findings are generally consistent with those from the past studies that reported reductions of 58% (Fayish & Gross, 2010) and 13% (Goughnour et al., 2021) in pedestrian-vehicle collisions. The higher precision in Model 1, indicated by a lower standard error and narrower range of CMFs, suggests it might be more reliable. The differences in outcomes between the two models can be attributed to the different variables included. Model 1 does not incorporate the Estimated Daily Traffic (EDT) variable, whereas Model 2 does.

The results show that the CMF range in both models overlaps with 1, indicating no conclusive evidence that the true CMF is below 1, which would confirm a reduction in crashes. Although the point estimates suggest a reduction, the wide CMF range means we cannot rule out the possibility of no reduction or even an increase in crashes. This broad range is likely due to the underprediction of collisions by the SPFs, which not only widens the confidence interval but also inflates the CMF value, complicating the assessment of LPI effectiveness. Using a calibration factor, as discussed in Section 3.1.2, could address this issue by adjusting SPF predictions more accurately to local conditions. Additionally, the inclusion of intersections with diverse features in the study led to some showing negative or no effect on pedestrian safety, further contributing to the variability and uncertainty in the CMF estimates.

Model 1 compensates for the absence of EDT by relying on other variables such as the number of legs with commercial entries/exits and average crosswalk length to capture the level of activity and potential exposure. These factors likely provide a more direct measure of pedestrian exposure to traffic, thus affecting the CMF more significantly.

In contrast, Model 2 includes EDT, which directly measures vehicular volume, potentially offering a more nuanced understanding of the impact of vehicular traffic on pedestrian safety. However, the higher variance and lower reduction percentage in Model 2 suggest that while EDT is an important factor, its inclusion introduces more uncertainty and results in a less overall reduction in collisions when combined with other variables.

In this study, the two models were calibrated using the same data with similar overall statistical performance as measured by log-likelihood, AIC, and BIC; however, their application for estimating CMFs of LPI yielded quite different results. Model 1 indicates that factors like commercial activity and crosswalk length are critical while Model 2 includes vehicular volume as a predictor for pedestrian

collisions. This highlights the complexity of factors influencing pedestrian safety and underscores the importance of using extensive data for evaluations and the need to calibrate a reliable SPF using local data whenever feasible.

4.3.2 Variation of CMFs with Different Intersection Features

The effectiveness of LPIs varies with different intersection features. Table 4-6 summarizes the CMFs for various intersection characteristics as per Model 1.

Table 4-6 CMF for Different Intersection Features

Variable	Number of Sites	EB estimated	Observed	CMF	S.E.
Presence of Slip Lane = No	30	12.9	9	0.692	0.248
Presence of Slip Lane = Yes	3	0.6	1	1.531	1.531
Number of Legs with Driveways/ Commercial Entry-Exit = 1	7	1.2	5	4.136	1.865
Number of Legs with Driveways/ Commercial Entry-Exit = 2	6	2.1	1	0.481	0.481
Number of Legs with Driveways/ Commercial Entry-Exit = 3	8	2.8	1	0.359	0.359
Number of Legs with Driveways/ Commercial Entry-Exit = 4	12	7.6	3	0.394	0.233
Standard Crosswalk Marking	24	7.2	9	1.245	0.429
Non-standard Crosswalk Marking	9	6.4	1	0.155	0.155
Average Crosswalk Length ≤15	11	3.1	4	1.268	0.642
Average Crosswalk Length >15	22	10.5	6	0.571	0.246
Sidewalk Missing =No	26	11.9	5	0.417	0.194
Sidewalk Missing =Yes	7	1.7	5	2.980	1.353
Pedestrian Volume ≤500	17	6.2	5	0.809	0.372
Pedestrian Volume >500	16	7.5	5	0.667	0.312

The presence of slip lanes significantly impacts the CMFs. Intersections without slip lanes exhibit a CMF of 0.692, indicating a reduction in crashes, whereas those with slip lanes have a CMF of 1.531, suggesting an increase in crashes. These results suggest that the LPI may not be an effective solution for intersections with slip lanes.

The number of legs with residential driveways or commercial entries/exits within 50 meters significantly influences crash rates. Intersections with fewer legs with driveways (one) have a higher

CMF (4.136), indicating increased crashes, whereas those with more legs with driveways (four) exhibit reduced crash rates, with a CMF of 0.394. This finding suggests that LPI is expected to be more effective at intersections with a higher number of legs with commercial entries/exits.

Crosswalk characteristics further impact pedestrian safety. For intersections with conventional crosswalk markings, the CMF of LPI is 1.245, implying an increase in crashes, while, for intersections with non-standard markings, the CMF is 0.155, a significant reduction of collisions by nearly 84.5%. This suggests that LPI is more effective at intersections with non-conventional markings than those with conventional markings.

The length of crosswalks also plays a crucial role in pedestrian safety. LPI was more effective at intersections with long crosswalks than those with shorter ones. The CMF is 0.571 for intersections with an average crosswalk length of 15 or longer as compared to a CMF of 1.268 at intersections with shorter crosswalks. This finding makes intuitive sense as it suggests that LPI is more beneficial for larger intersections (with longer crosswalks) as compared to smaller intersections.

As discussed previously, sidewalk presence was found to be associated with pedestrian safety. For intersections lacking sidewalks (No. of sidewalks per leg < 2), the CMF of LPI was estimated to be greater than 1.0 (as high as 2.980), indicating ineffectiveness of LPI implementation. Conversely, intersections with sidewalks have a CMF of 0.417, indicating improved safety due to LPI. This suggests that the LPI is less effective at intersections with missing sidewalks compared to those with complete sidewalk infrastructure.

Pedestrian volume also has a noticeable impact on the effectiveness of LPI. Intersections with higher pedestrian volumes (>500) have a lower CMF of 0.667, indicating a greater reduction in crashes and effectiveness of LPI. In contrast, intersections with lower pedestrian volumes (≤500) have a CMF of 0.809. While both categories show a general improvement, the greater reduction in crashes at intersections with higher pedestrian volumes aligns with the "safety in numbers" effect, where increased pedestrian presence enhances overall safety due to heightened driver awareness. This effect is also evident in the case of LPI implementation.

These findings underscore the importance of considering specific intersection features when evaluating the effectiveness of LPIs in improving pedestrian safety. LPI was found to be generally more effective at intersections with well-maintained sidewalks, non-conventional crosswalks (like ladder or

zebra markings) and no slip lanes. Additionally, intersections with higher pedestrian activity and exposure benefit more from LPI.

4.3.3 Effect of Calibration Factor on CMFs

This calibration factor is used to adjust the SPF to better reflect the local conditions of the site under study, as shown in equation (3). For this study, calibration factor was assumed to be 1, as the SPFs were calibrated using local data. The calibration factor is calculated as the ratio of the total observed crashes to the total predicted crashes. The sensitivity analysis of CMFs for pedestrian vehicle collisions shows how the CMFs and their confidence intervals change as the calibration factor increases, as shown in Figure 4-2 and Figure 4-3 for Model 1 & Model 2, respectively. There is a trend where the CMFs decrease as the calibration factor increases. This decrease indicates a greater reduction in crashes when adjustments are made for the calibration factor. For both the models, the CMF starts at approximately 1.5 and gradually declines to below 1 as the calibration factor increases from 0.5 to 1.5. The confidence interval, represented by the shaded area, also narrows as the calibration factor increases, suggesting increased reliability of the CMF estimate.

The reduction in CMFs and the narrowing of confidence intervals with increasing calibration factors suggest that the initial models likely under-predicted collisions. By adjusting the model using calibration factors, the accuracy and reliability of the CMF estimates improve. For instance, calibrating the first model by a factor of 1.13 results in a CMF drop to 0.65. The adjusted confidence interval (0.21 to 1.08) indicates that after applying the LPI treatment, there is not only a significant reduction in crashes but also an improved reliability of the estimate. This confidence interval suggests that the CMF could range from a significant reduction (79% reductions) in crashes to having no effect (0% reductions), thereby reinforcing the importance of calibration in accurately assessing the safety effectiveness of implementations like LPI.

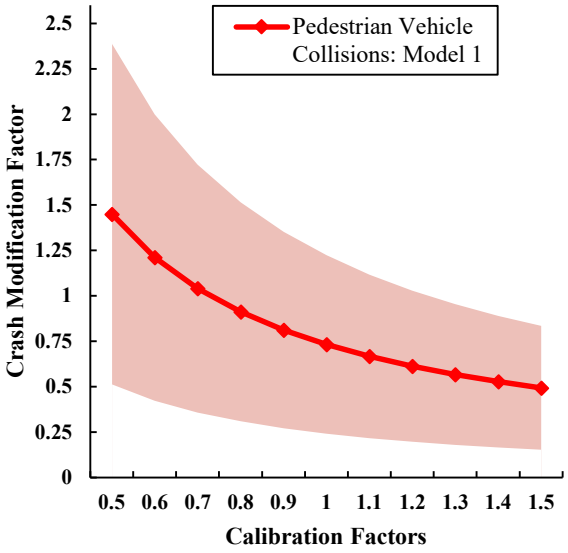


Figure 4-2 Variation in CMF by Calibration Factor for Model 1

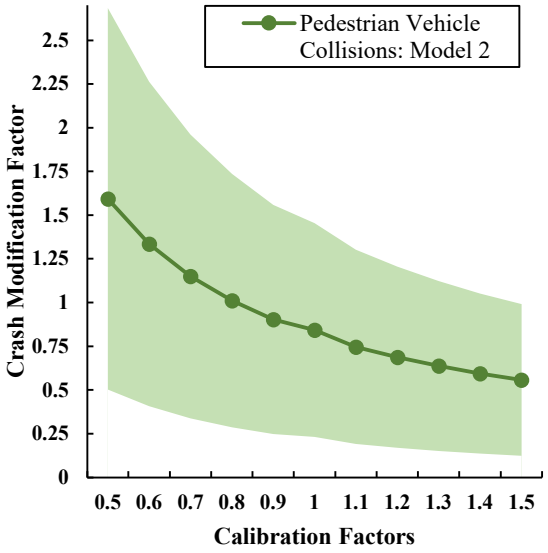


Figure 4-3 Variation in CMF by Calibration Factor for Model 2

In summary, the sensitivity analysis underscores the importance of using appropriate calibration factors to adjust for potential under-prediction or over-predictions in existing models. This adjustment results in more reliable and accurate CMF estimates, reflecting the true impact of pedestrian safety implementations.

Chapter 5
Conclusion

The conclusion chapter synthesizes the key findings of this study, offering a comprehensive understanding of the effectiveness of LPIs in enhancing pedestrian safety. It provides a summary of the research & key findings, highlights key contributions, and addresses limitations and future research directions. By integrating these elements, this chapter underscores the practical implications of the research and suggests avenues for future studies.

This study aimed to evaluate the effectiveness of LPIs at signalized intersections near schools and analyse factors influencing pedestrian crash risk. LPIs enhance pedestrian safety by providing a head start for pedestrians, thus reducing conflicts with turning vehicles. The implementation of LPIs showed promising results in enhancing pedestrian visibility and reducing crash incidences, particularly benefiting vulnerable groups like children and the elderly. However, the negative effects of LPI such as increased vehicular delays and the need for additional infrastructure modifications should also be considered. The literature review also highlighted critical factors impacting pedestrian safety, including traffic volumes, roadway, and geometric features, and built environment characteristics. Higher vehicle and pedestrian volumes, increased speeds, and specific intersection features like slip lanes and crosswalk lengths were found to significantly affect pedestrian crash risks. Despite the general effectiveness of LPIs, the study identified gaps in existing research, particularly in evaluating LPIs near schools. These findings underscore the importance of context-specific evaluations and the need for further research to optimize LPI implementation and enhance pedestrian safety comprehensively.

To evaluate the effectiveness of LPIs, an EB before-and-after study was conducted using data from the Region of Waterloo involving a total of 33 signalized intersections. The methodology focused on the development and calibration of SPFs, which are essential for the EB analysis. SPFs were calibrated using a Negative Binomial (NB) regression model, which is well-suited for modelling crash data due to its ability to handle over-dispersion. Extensive data collection efforts were undertaken to gather the necessary information for creating the SPF model. This dataset included detailed records of traffic volumes, pedestrian counts, roadway and intersection characteristics, and historical crash data. By integrating these diverse data sources, the SPFs could accurately predict expected crash frequencies, which were crucial for the subsequent EB analysis and analysing factors influencing pedestrian crash risk.

5.1 Key Findings

This section outlines the key findings of the study, focusing on the development and evaluation of SPFs and the effectiveness of LPIs in enhancing pedestrian safety at intersections. The findings are categorized into three main areas: the influence of various factors on pedestrian crash risk as determined by SPFs, the overall effectiveness of LPIs as measured by CMFs, and the impact of calibration factors on CMFs. Each category provides insights into the critical elements that contribute to pedestrian safety and highlights the importance of tailored and locally calibrated safety measures.

5.1.1 Safety Performance Function: Influence of factors on pedestrian crash risk

- **Best Predictive Model:** The final model selection process identified two top-performing models: Model 1, which uses the number of legs with commercial entries/exits (NCE) as a surrogate measure of exposure, and Model 2, which includes Estimated Daily Traffic (EDT). Model 1 was found to be superior based on statistical criteria (lower AIC and BIC), despite Model 2 having a slightly higher Log Likelihood.
- **Surrogate Exposure Measures**: Surrogate exposure measures such as NCE and average crosswalk length were found to be more effective than EDT in predicting pedestrian crashes. This highlights the importance of including diverse and context-specific variables in SPFs to enhance model accuracy.
- **Factors Increasing Pedestrian Crash Risks**: Several key factors influencing pedestrian safety at intersections were identified that increase crash risks, such as intersections in residential and commercial areas, presence of commercial entries-exits or residential driveways, longer crosswalks and higher pedestrian volumes and vehicular volumes. It was interesting that non-conventional crosswalk markings, such as zebra or ladder patterns, are linked to higher pedestrian crash frequencies, possibly leading pedestrians to be less cautious under the impression of increased safety.
- **Factors Decreasing Crash Risks:** Conversely, certain factors were found to decrease pedestrian crashes at intersections. The presence of slip lanes is associated with a reduction in pedestrian crashes, though this finding contradicts some previous research and may vary depending on the specific context and design features. Interestingly, intersections with more missing sidewalks are associated with a lower risk of pedestrian crashes. This may be due to

concentrated pedestrian traffic on fewer paths, reducing potential conflict zones. These findings highlight the importance of tailored infrastructure improvements to enhance pedestrian safety at intersections.

5.1.2 Effectiveness of LPI

- **Effectiveness of LPIs measured by CMF:** Model 1 demonstrated a higher reduction in collisions (26.78%) compared to Model 2 (15.71%), with greater precision and reliability. Model 1 did not include Estimated Daily Traffic (EDT), relying instead on variables like NCE and average crosswalk length to capture activity levels and potential exposure. This provided a more direct measure of pedestrian exposure to traffic. Model 2 included EDT, offering a detailed understanding of vehicular traffic's impact on pedestrian safety but introduced more uncertainty and a lower reduction in collisions. Both models highlighted different aspects of pedestrian safety, emphasizing the importance of factors such as commercial activity and crosswalk length (Model 1) and vehicular volume (Model 2). The findings underscore the complexity of pedestrian safety factors and the need for extensive data and locally calibrated SPFs for accurate evaluations.
- **Need for Locally Calibrated SPFs:** The findings emphasize the complexity of pedestrian safety factors and the importance of extensive data and local calibration for accurate evaluations.
- **Conditions Enhancing LPI Effectiveness:**
    - Intersections with more commercial driveways would benefit more from LPI.
    - LPI was found to be more beneficial at intersections with non-standard crosswalk markings (e.g., ladder or zebra patterns) and longer crosswalks.
    - Intersections with more complete sidewalks and higher pedestrian volumes would benefit more from LPI.
- **Conditions Limiting LPI Effectiveness:**
    - LPI was shown to be less effective at intersections with slip lanes, likely due to shorter crossing distance and the presence of pedestrian crossing island.
    - Intersections lacking sidewalks exhibited increased crash rates, stressing the importance of complete pedestrian infrastructure.

- Intersections with lower pedestrian activities would benefit less from LPI.

5.1.3 Effects of Calibration Factor on CMFs

- **Impact of Calibration:**
  - The use of calibration factor was found to have a noticeable effect on the magnitude of the estimated effectiveness of LPI, with higher calibration factors leading to lower estimated CMF values and narrower confidence intervals, indicating improved accuracy and reliability.
  - This finding underscores the necessity of proper calibration to accurately assess the true impact of pedestrian safety measures.

5.2 Contribution to Understanding LPI Effectiveness and Pedestrian Safety

The findings from this study provide a nuanced understanding of how LPIs impact pedestrian safety at various types of intersections. Here are the key contributions:

- **Intersection Design and Infrastructure:**
  - The effectiveness of LPIs varies significantly with the presence of specific intersection features. For example, LPIs showed greater effectiveness in reducing crashes at locations without slip lanes, while their impact is less pronounced at intersections that do have slip lanes. This indicates the need for tailored LPI implementations based on intersection design.
  - Intersections with complete sidewalks and non-conventional crosswalk markings enhances the effectiveness of LPIs, suggesting that well-maintained pedestrian infrastructure is crucial for maximizing safety benefits of LPI.
- **Traffic and Pedestrian Volume:**
  - Higher pedestrian volumes at intersections correlate with greater reductions in crashes, supporting the "safety in numbers" effect. This highlights the importance of considering pedestrian activity levels when implementing LPIs.
  - The study shows that intersections with more commercial driveways and higher vehicular volumes also benefit from LPIs, suggesting that LPIs are particularly effective in areas with high traffic and pedestrian interactions.

- **Safety Measures and Crash Risks:**
    - The findings reinforce the need for comprehensive safety measures at intersections. LPIs alone may not suffice in high-risk areas without supporting infrastructure, such as sidewalks and properly marked crosswalks.
    - The varied effectiveness of LPIs across different intersection features underscores the complexity of pedestrian safety and the importance of context-specific safety interventions.
- **Policy and Implementation:**
    - These insights can inform policymakers and urban planners about the critical factors to consider when implementing LPIs. For example, prioritizing intersections with high pedestrian traffic and ensuring complete pedestrian infrastructure can enhance LPI effectiveness.
    - The study emphasizes the need for further research and data collection to refine LPI implementation strategies, ensuring they are tailored to specific intersection characteristics and pedestrian behaviours.

By highlighting the influence of intersection features, pedestrian and vehicle volumes, and the presence of supportive infrastructure, these findings contribute to a more comprehensive understanding of how LPIs can be optimized to improve pedestrian safety. They underscore the importance of context-specific strategies and the need for continued evaluation and adaptation of safety measures to address the dynamic nature of urban intersections.

5.3 Limitations and Future Research

The study has several limitations that highlight areas for future research:

- **Active Period Analysis:** This study examined the overall safety benefits of LPIs without differentiating between the specific times of day when LPIs are active. Future research should focus on the safety benefits during these active periods to gain better insights.
- **Generalizability of Findings:** The data used in this study was limited to the Region of Waterloo, which may not be representative of other regions. Future studies should include

larger and more diverse data sets from different jurisdictions to provide a more generalizable understanding of LPI effectiveness.

- **Signal Timing and Features**: Although extensive data on road infrastructure and the built environment was collected, this study did not account for signal timing characteristics (e.g., bus priority, lag left turn) or the presence of other LPI features (e.g., activation through push buttons). Future research should explore these aspects to better understand how they interact with LPI implementation and influence its effectiveness.
- **Comprehensive Safety Assessment:** Despite the low occurrence of pedestrian crashes observed in the current study, which limited the robustness of the findings, future research should aim to incorporate both crash-based data and SSMs. This integrated approach would provide a more comprehensive understanding of LPI impacts, encompassing immediate behavioural changes and long-term safety outcomes. Additionally, examining the behavioural changes of drivers and pedestrians in the presence of LPIs can offer valuable insights into how these intervals affect road user interactions and compliance with traffic signals.

By addressing these limitations and exploring these future research directions, a more robust and detailed understanding of the effectiveness of LPIs in enhancing pedestrian safety can be achieved.

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Appendix A

Region of Waterloo Data: LPI Implementations and Collisions

This Appendix provides a comprehensive overview of the Region of Waterloo's LPI implementations at signalized intersections (A.1) and collision history (A.2), focusing on the year 2022.

A.1. LPI Implementations

As of the year 2022, there are 8843 intersections in the Region of Waterloo. Out of which 488 are signalized intersections. Leading Pedestrian Interval is installed on 60 of these signalized intersections. The number of these signalized intersections in each municipality is given in Table A- 1.

Table A- 1 Distribution of Signalized Intersections & LPI Implementations Across the Region's Municipalities

Municipality	Intersection Type	
	Signalized	*LPI Implemented*
Cambridge (CAM)	102	15
Kitchener (KIT)	233	34
North Dumfries (NOR)	9	0
Waterloo (WAT)	108	10
Wellesley (WEL)	2	0
Wilmot (WIL)	9	0
Woolwich (WOO)	25	1
Total	488	60

A.2. Collision History

Figure A- 1 shows the average pedestrian collisions from 2011 to 2020 for five municipalities: Cambridge (CAM), Kitchener (KIT), Waterloo (WAT), Wilmot (WIL), and Woolwich (WOO). There are significant fluctuations in collision rates over the period. No Collisions were reported in the municipality of North Dumfries (NOR) and the municipality of Wellesley (WEL). City municipalities exhibit higher and more variable collision rates, with peaks in 2012 and 2015, and a decline toward

2020. In contrast, the townships of Wilmot and Woolwich have rare collisions, likely due to fewer signalized intersections.

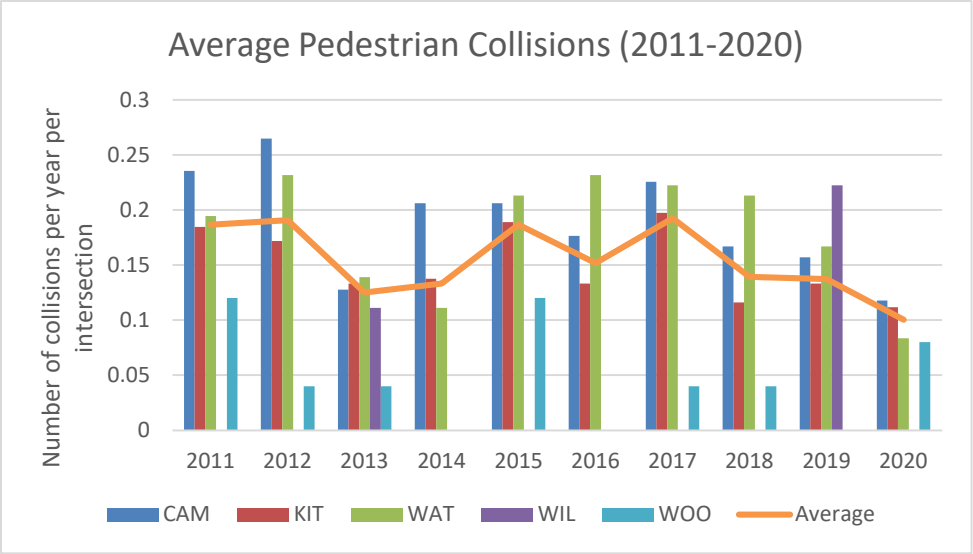


Figure A- 1 Yearly Average Pedestrian Collisions per Intersection by Municipalities

Figure A- 2 illustrates the number of pedestrian collisions by severity across five municipalities. Non-fatal injury crashes are the major contributors to the total collisions. In contrast, property damage and fatal crashes are rare.

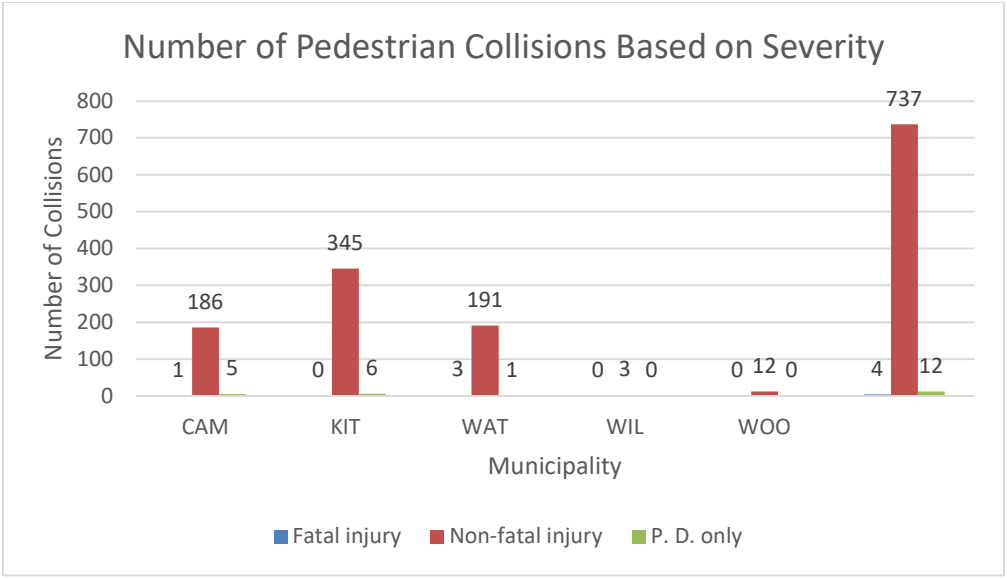


Figure A- 2 Number of Pedestrian Collisions by Severity

Table A- 2 Number of Pedestrian Collisions by Pedestrian & Driver Action presents the number of pedestrian collisions categorized by both pedestrian and driver actions. The data indicates that the major cause of collisions over the ten-year period was drivers failing to yield the right-of-way, accounting for 474 collisions. On the pedestrian side, the majority of collisions involved pedestrians crossing with the right-of-way, totalling 394 incidents.

Table A- 2 Number of Pedestrian Collisions by Pedestrian & Driver Action

DRIVER ACTION / PEDESTRIAN ACTION	Unknown	Crossing with Right-of-way	Crossing without right-of-way	Crossing-no traffic control	Crossing Ped. Crossover	Crossing marked crosswalk without right of way	Walking on roadway with traffic	On sidewalk or shoulder	Playing or working on highway	Running onto roadway	Others	Total
Unknown	8	21	1	0	1	0	0	0	0	0	0	31
Driving Properly	27	7	34	4	0	22	0	2	0	5	11	112
Exceeding speed limit	0	1	0	0	0	0	0	0	0	0	0	1
Speed too fast for condition	0	2	0	0	0	0	0	0	0	0	0	2
Improper turn	36	37	0	1	0	1	0	0	1	0	5	81
Disobeyed traffic control	7	11	0	0	1	1	0	0	0	0	2	22
Failed to yield right-of-way	147	299	1	1	14	1	1				10	474
Improper passing	0	0	0	0	0	0	0	1	0	0	0	1
Lost control	2	2	0	0	0	0	0	1	0	0	0	5
Wrong way on one-way	1	0	0	0	0	0	0	0	0	0	0	1
Others	4	14	0	0	0	1	0	1	0	0	3	23
Total	232	394	36	6	16	26	1	5	1	5	31	753

Table A- 3 Number of Pedestrian Collisions by Vehicle Manoeuvre & Driver Action details the number of pedestrian collisions based on driver actions and vehicle manoeuvres. The data shows that turning manoeuvres were significant contributors to collisions, with turning left and right accounting for 53.9% and 28.8%, respectively. This highlights the critical need for improved safety measures at intersections to reduce these types of incidents.

Table A- 3 Number of Pedestrian Collisions by Vehicle Manoeuvre & Driver Action

DRIVER ACTION / VEHICLE MANOEUVER	Unknown	Going Ahead	Slowing or stopping	Overtaking	Turning Left	Turning Right	Making "U" Turn	Reversing	Pulling onto Shoulder or Curb	Others	Total
Unknown	3	2	1	0	9	16	0	0	0	0	31
Driving Properly	0	74	2	0	21	15	0	0	0	0	112
Exceeding speed limit	0	1	0	0	0	0	0	0	0	0	1
Speed too fast for condition	0	0	2	0	0	0	0	0	0	0	2
Improper turn	0	0	0	0	60	20	1	0	0	0	81
Disobeyed traffic control	0	13	0	0	2	7	0	0	0	0	22
Failed to yield right-of-way	3	14	2	1	307	145	1	1	0	0	474
Improper passing	0	0	0	0	0	1	0	0	0	0	1
Lost control	0	0	1	0	1	2	0		1	0	5
Wrong way on one-way	0	0	0	0	0	0	0	1	0	0	1
Others	0	4	0	0	6	11	0	1	0	1	23
Total	6	108	8	1	406	217	2	3	1	1	753

Table A- 4 Number of Pedestrian Collisions by Light & Environment Conditions summarizes the number of pedestrian collisions based on light and environmental conditions. The majority of collisions occurred under clear conditions (558, 74% of the total collisions) and during daylight (446, 59% of the total collisions). A significant number of collisions happened in the dark (271, 36% of the total collisions), highlighting the importance of visibility and lighting. Furthermore, the data indicate that collisions are more likely to occur when it is both dark and raining (96, 13% of the total collisions) compared to daylight and raining (47, 6% of the total collisions), suggesting higher risks in these conditions.

Table A- 4 Number of Pedestrian Collisions by Light & Environment Conditions

ENVIRONMENT CONDITIONS / LIGHT	Daylight	Dawn	Dusk	Dark	Total
Clear	377	11	18	152	558
Rain	47	3	3	96	149
Snow	19			13	32
Freezing rain	1		1	4	6
Drifting snow	2				2
Strong wind				1	1
Fog, mist. Smoke. Dust				4	4
Others				1	1
Total	446	14	22	271	753

Appendix B

Case Study: Reference and Treatment Sites

The number of signalized intersections implemented with LPI in 2017 and 2018 in each of the three municipalities are illustrated in Figure B- 1. Figure B- 2 illustrates the number of reference and treatment sites across three cities: Cambridge, Kitchener, and Waterloo. It shows a higher number of reference sites in Kitchener, followed by Waterloo and Cambridge, with the corresponding reference sites per treatment site ratio indicated for each city.

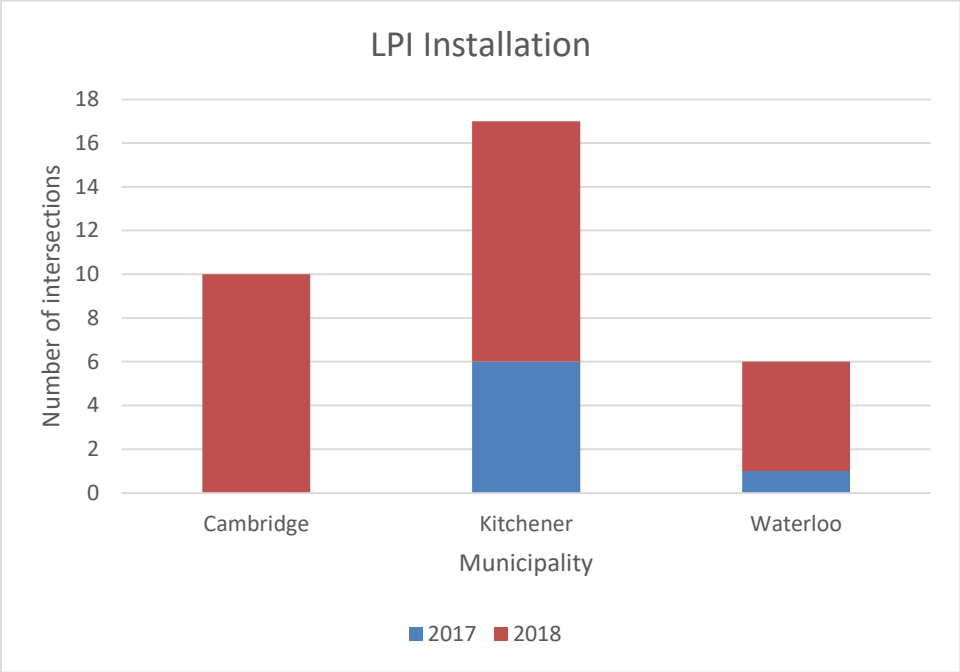


Figure B- 1 Number of Treatment Sites in each municipality based on Year of Installation

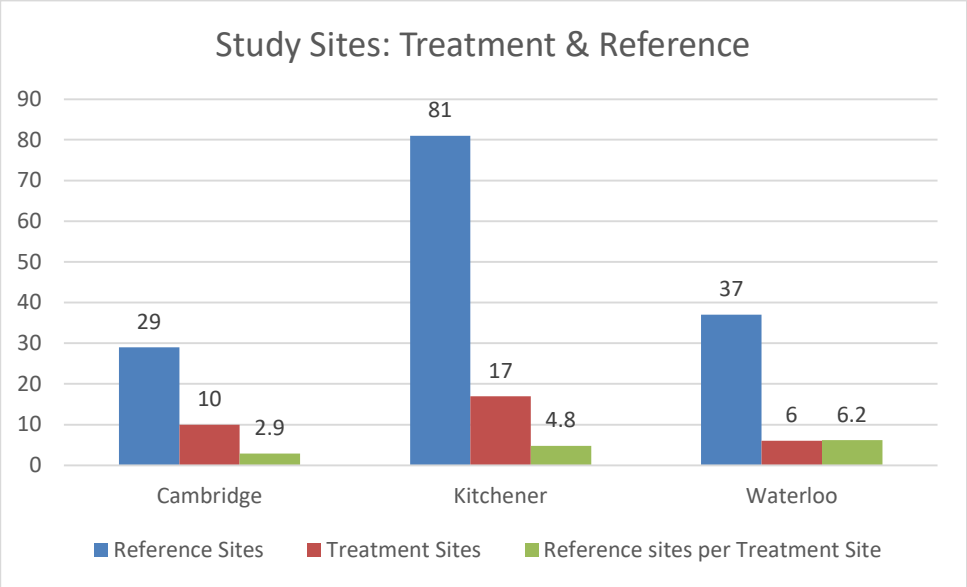


Figure B- 2 Proportion of Reference Sites for each Treatment site

The list of LPI treated intersections & Reference intersections included in the study are provided in Table B- 1 & Table B- 2, respectively.

Table B- 1 List of Treatment sites used in the study.

GeoID	Intersection Name	Signal install	Mun	LPI Install Year	LPI Operating Times
5982	Westmount Rd S @ William St W	1971	WAT	2018	08:30-09:15 & 15:30-16:00
6504	Westmount Rd E @ Greenbrook Dr	1970	KIT	2018	08:00-09:00 & 15:00-15:50
6521	Westmount Rd E @ Laurentian Dr	1992	KIT	2017	08:00-09:00 & 14:45-15:30
6751	Frederick St @ Otto St	1980	KIT	2017	08:30-09:15 & 15:00-15:45
7468	University Ave E @ Glenridge Dr	1973	WAT	2018	08:00-08:40 & 14:55-15:30
7496	University Ave E @ Dale Cres/Lincoln Rd	1988	WAT	2018	07:55-09:15 & 14:50-16:15
8076	Northfield Dr W @ Skylark Rd	2004	WAT	2018	08:15-08:40 & 15:10-15:35
8558	Westmount Rd W @ Glasgow St	1971	KIT	2018	08:30-09:00 & 15:20-15:50
8754	Highland Rd W @ Belmont Ave W	1960	KIT	2018	08:30-09:30 & 15:20-15:50
9207	Highland Rd W @ Patricia Ave	1977	KIT	2018	08:30-09:30 & 15:20-15:50
9540	Westmount Rd E @ Block Line Rd	1997	KIT	2018	08:00-09:00 & 14:45-15:50
10715	Kingsway Dr @ Wilson Ave	1995	KIT	2018	08:10-09:00 & 15:10-16:00

10934	Block Line Rd @ Kingswood Dr	2001	KIT	2017	08:00-09:00 & 15:15-16:15
11137	Frederick St @ Lancaster St E/Ellen St E	1973	KIT	2017	08:30-09:15 & 15:00-15:45
11148	Margaret Ave @ Queen St N	2003	KIT	2018	08:30-09:15 & 15:00-15:45
11728	Weber St E @ Borden Ave N	1988	KIT	2018	08:25-09:05 & 15:15-15:45
13070	Bridge St W @ Bridle Trail	2004	WAT	2017	08:40-09:15 & 15:30-16:00
14619	Dundas St N @ Elgin St N	1966	CAM	2018	08:35-09:20 & 15:50-16:30
16008	Shantz Hill Rd @ Preston Pky	1973	CAM	2018	08:15-08:55 & 15:15-15:50
16278	Eagle St N @ Speedsville Rd/Concession Rd	1979	CAM	2018	08:15-09:00 & 15:05-15:50
18421	Bruce St @ Main St @ Oak St	1994	CAM	2018	08:30-09:00 & 15:15-15:45
18433	Avenue Rd @ Elgin St N	1978	CAM	2018	08:15-09:00 & 15:05-15:50
19222	Bishop St N @ Concession Rd	1975	CAM	2018	08:00-09:00 & 15:00-16:00
19285	Franklin Blvd @ Winston Blvd	1982	CAM	2018	07:50-08:25 & 14:30-15:30
19657	Avenue Rd @ Gail St	1974	CAM	2018	08:00-09:05 & 15:00-15:50
19960	Concession Rd @ Langs Dr	1987	CAM	2018	08:15-09:00 & 15:05-15:50
20086	Hespeler Rd @ Jaffray St/Avenue Rd	1972	CAM	2018	08:00-09:00 & 15:00-15:50
20795	Victoria St S @ Westforest Trail/Eastforest Trail	2004	KIT	2018	08:00-09:15 & 14:55-16:10
21837	Traynor Ave @ Wilson Ave	1991	KIT	2018	08:10-09:00 & 15:10-16:00
21941	Doon Village Rd @ Pioneer Dr	2007	KIT	2018	08:30-09:05 & 15:25-15:55
22058	Homer Watson Blvd @ Pioneer Dr	1979	KIT	2017	08:25-08:55 & 15:25-15:55
22199	Fairway Rd N @ Morgan Ave	1988	KIT	2017	08:15-09:00 & 15:00-15:45
25799	Bridge St W @ Chesapeake Dr	2002	WAT	2018	07:55-08:25 & 14:50-15:10

Table B- 2 List of Reference Sites used in the study.

GeoID	Intersection Name	Signal install	Municipality
240	Weber St N @ Marshall St	1966	WAT
275	University Ave W @ Phillip St	1970	WAT
358	University Ave W @ Hazel St	1988	WAT
406	Bridgeport Rd E @ Regina St N	1969	WAT
692	Northfield Dr W @ Parkside Dr	1992	WAT
1259	Belmont Ave W @ Gage Ave	1988	KIT
1556	King St N/King St S @ Erb St W/Erb St E	1960	WAT
1607	Erb St W @ Caroline St N/Caroline St S	1968	WAT
1618	Erb St E @ Regina St N/Regina St S	1988	WAT
1634	Caroline St N/Bridgeport Rd W @ Albert St	1969	WAT
1755	John St E @ Moore Ave S	1989	WAT
1840	Dearborn Blvd @ Dearborn Pl @ Lexington Rd	2002	WAT

1858	Northfield Dr E @ Wissler Rd	2002	WAT
3220	Lexington Rd @ University Ave E	2010	WAT
3536	Bridge St W @ Lexington Rd	1995	WAT
3545	Bridge St W @ Dansbury Dr	1999	WAT
3976	Erbsville Rd @ Columbia Forest Blvd/Willow Wood Dr	2008	WAT
4229	Westmount Rd N @ Northfield Dr W	2004	WAT
4405	Erb St W @ Erbsville Crt	1995	WAT
5867	Francis St N @ Francis St S @ King St W	1975	KIT
6141	Fischer-Hallman Rd @ McGarry Dr	1971	KIT
6263	King St W @ Pine St	1998	KIT
6313	Highland Rd E @ Stirling Ave S	1966	KIT
6378	Ottawa St S @ Howland Dr	1973	KIT
6615	Charles St W/Charles St E @ Queen St S	1962	KIT
6639	Duke St E @ Scott St	1974	KIT
6654	Duke St W @ Ontario St N	1979	KIT
6669	Gaukel St @ King St W	1988	KIT
6692	Duke St W @ Young St	1993	KIT
6694	King St W @ Ontario St N @ Ontario St S	1975	KIT
6696	Charles St W @ Ontario St S	1975	KIT
6742	Duke St E @ Duke St W @ Queen St N	1973	KIT
6760	Weber St E @ Scott St	1974	KIT
6767	Weber St E @ Queen St N	1974	KIT
6775	Weber St E @ Frederick St	1973	KIT
6861	Weber St E @ Cameron St N	1975	KIT
6883	Weber St E @ Cedar St N/Krug St	1972	KIT
6981	Lancaster St W @ Union St	1981	KIT
7035	Lancaster St W @ Wellington St N	1974	KIT
7057	Weber St W @ Water St N	1973	KIT
7214	Albert St @ Phillip St	1985	WAT
7229	King St N @ Hickory St W/Hickory St E	2004	WAT
7232	Columbia St W @ Hazel St	1980	WAT
7396	Weber St N/Weber St S @ Erb St E	1977	WAT
7519	Weber St N @ Bridgeport Rd E	1968	WAT
7525	King St N @ Central St	1980	WAT
7533	Weber St N @ University Ave E	1968	WAT
7542	Erb St E @ Moore Ave N/Moore Ave S	1974	WAT
7579	University Ave E @ Marsland Dr	1998	WAT
7839	Weber St N @ Forwell Creek Rd	1997	WAT
7853	Davenport Rd @ Lexington Rd	1988	WAT

8511	Westmount Rd W @ Victoria St S	1972	KIT
8522	Victoria St S @ Lawrence Ave	1991	KIT
8538	Victoria St S @ Strange St/West Ave	1984	KIT
8593	King St S @ William St W/William St E	1988	WAT
8625	Victoria St S @ Hazelglen Dr	1992	KIT
8700	Queen St S @ Courtland Ave W/Courtland Ave E	1975	KIT
8715	Highland Rd W @ Queen St S	1960	KIT
8780	Charles St W @ Francis St S	1998	KIT
8834	Weber St W @ Wellington St N	1965	KIT
8855	Glasgow St @ Park St	1973	KIT
8893	Moore Ave @ Wellington St N	1989	KIT
8916	Charles St W @ Water St S	1968	KIT
8938	Duke St W @ Water St N	1975	KIT
8953	Charles St W @ Gaukel St	1977	KIT
9088	Fischer-Hallman Rd @ Stoke Dr	2007	KIT
9182	Courtland Ave E @ Benton St	1988	KIT
9193	Westmount Rd E @ Williamsburg Rd	2004	KIT
9234	King St E @ Ottawa St N/Ottawa St S	1964	KIT
9410	Courtland Ave E @ Hayward Ave	1975	KIT
9738	Bleams Rd @ Thistledown Dr/Trillium Dr	2003	KIT
10231	Lorraine Ave @ River Rd E	1980	KIT
10327	Victoria St N @ Frederick St	1990	KIT
10499	Lancaster St W @ Guelph St	1990	KIT
10611	Bridgeport Rd E @ Ellis Cres N	1999	WAT
10613	Bridgeport Rd E @ Bluevale St N	1989	WAT
10641	Moore Ave S @ Union St E	1968	WAT
10706	Courtland Ave E/Fairway Rd S @Manitou Dr	1972	KIT
10740	Courtland Ave E @ Shelley Dr	1990	KIT
10816	Block Line Rd @ Strasburg Rd	1984	KIT
10948	Homer Watson Blvd @ Hanson Ave	1982	KIT
10967	Weber St E @ Franklin St N	1972	KIT
11062	King St W @ Green St	2002	KIT
11077	Guelph St @ Margaret Ave	1970	KIT
11178	Weber St W @ Guelph St	1964	KIT
11257	East Ave @ Krug St	1972	KIT
11321	Frederick St/Benton St @ King St E	1965	KIT
11367	Charles St E @ Cameron St S	1970	KIT
11388	Courtland Ave E @ Madison Ave S	1970	KIT
11398	Mill St @ Stirling Ave S	1969	KIT

11422	Hoffman St @ Homer Watson Blvd	1980	KIT
11452	Courtland Ave E @ Carwood Ave	1985	KIT
11493	Cameron St N @ East Ave	1982	KIT
11577	Hickson Dr @ River Rd E	2005	KIT
11692	Charles St E @ Borden Ave S	1972	KIT
12387	Lancaster St W @ Bridgeport Rd	1990	KIT
12669	Frederick St @ Bruce St	1969	KIT
13288	Weber St E @ Montgomery Rd	1966	KIT
13815	Main St @ Chalmers St N/Chalmers St S	1974	CAM
13957	Dundas St N @ Main St	1978	CAM
14053	Water St S @ Ainslie St S	2003	CAM
14222	Concession St @ Christopher Dr	1995	CAM
14470	Cedar St @ Drew Ave/Southwood Dr	1997	CAM
14478	Ainslie St N @ Dickson St	1972	CAM
14504	Ainslie St N @ Parkhill Rd E	1972	CAM
14513	Dickson St @ Wellington St	1993	CAM
14675	Myers Rd @ Elgin St S/Cheese Factory Rd	2008	CAM
14770	Myers Rd @ Christopher Dr	2002	CAM
15297	Goebel Ave @ Queen St W	1990	CAM
15344	Eagle St N @ Industrial Rd	1991	CAM
15395	Goebel Ave @ Groh Ave @ Holiday Inn Dr	1998	CAM
17179	Shantz Hill Rd @ Fountain St S	2005	CAM
17215	King St E @ Bishop St N/Bishop St S	1978	CAM
17258	King St E @ Montrose St N/Montrose St S	1978	CAM
17278	King St E @ Westminister St N/Westminister St S	1977	CAM
17338	King St E @ Eagle St N/Eagle St S	1965	CAM
17349	King St W @ Fountain St N/Fountain St S	1977	CAM
18017	Water St N @ Dando Ave	1998	CAM
19083	Franklin Blvd @ Elgin St N/Saginaw Pky	1993	CAM
19342	Bishop St N @ Conestoga Blvd	1998	CAM
19649	Ainslie St N @ Simcoe St	2002	CAM
19717	Conestoga Blvd @ Dunbar Rd @ Lena Cres	2009	CAM
19875	King St E @ Concession Rd/Blue Heron Ridge	1971	CAM
19943	King St E @ Dolph St N/Dolph St N	1977	CAM
20003	King St E @ Lowther St N/Lowther St S	1978	CAM
20275	Industrial Rd @ Langs Dr	2007	CAM
20416	Fischer-Hallman Rd S @ Thorndale Dr	1990	WAT
20562	University Ave W @ Keats Way	1992	WAT
20569	University Ave W @ Erb St W	1983	WAT

20685	Belmont Ave E @ Belmont Ave W @ Queens Blvd	1988	KIT
20890	Homer Watson Blvd @ Stirling Ave S	1979	KIT
20961	Highland Rd W @ Lawrence Ave	1999	KIT
21001	Westmount Rd W @ Queens Blvd	1967	KIT
21967	Bleams Rd @ Century Hill Dr	2002	KIT
23215	Ottawa St N @ Old Chicopee Dr	2004	KIT
25605	Huron Rd @ Trillium Dr	2001	KIT
25836	Fischer-Hallman Rd @ Activa Ave	2002	KIT
26664	Old Chicopee Dr @ River Rd E	2000	KIT
28343	Maple Grove Rd @ Vondrau Dr	2001	CAM
28405	Battler Rd @ Huron Rd	2001	KIT
28430	Fischer-Hallman Rd @ Highland Hills Mall	2002	KIT
28432	Highland Rd W @ Highland Hills Mall	2003	KIT
28658	Ottawa St S @ Sunrise Shopping Centre	2003	KIT
28659	Ottawa St S @ Laurention Power Centre	2002	KIT
29000	Ottawa St N @ Stanley Park Mall	2003	KIT
29001	Strasburg Rd @ 700 Strasburg Rd @ 695 Strasburg Rd	2003	KIT
29714	Erb St W @ 658 Erb St W	2007	WAT

Appendix C
Data Sources

C.1. Intersection Turning Movement Counts

This part provides a detailed description of the data collection procedure for variables sourced from the Department of Transportation Services, Region of Waterloo. Table C- 1 lists the variables obtained from the Region of Waterloo.

Table C- 1 List of Final Variables from Region of Waterloo

Variable Name	Definition	Units or Values
Colped	Number of vehicle-pedestrian collisions from 2011 to 2020	Number of Collisions
colped2011_16	Number of vehicle-pedestrian collisions from 2011 to 2016	Number of Collisions
colped2019_20	Number of vehicle-pedestrian collisions from 2019 to 2020	Number of Collisions
Ped_total	Estimated daily pedestrian volume crossing the intersection	Pedestrians per day
ln_Ped_total	Log of Estimated daily pedestrian volume crossing the intersection	Log of pedestrians per day
EDT_fac	Estimated daily vehicle volume crossing the intersection	Vehicles per day
Right_TMC	Estimated daily right-turn vehicle volume crossing the intersection	Vehicles per day
Through_TMC	Estimated daily through movement vehicle volume crossing the intersection	Vehicles per day
Left_TMC	Estimated daily left-turn vehicle volume crossing the intersection	Vehicles per day
ln_EDT_fac	Log of Estimated daily vehicle volume crossing the intersection	Log of vehicles per day
prop_left	Proportion of left-turn vehicle volume	Proportion
prop_right	Proportion of right-turn vehicle volume	Proportion
prop_lr	Proportion of combined left and right-turn vehicle volume	Proportion
MajorEDT	Estimated daily vehicle volume entering the intersection from the major road	Vehicles per day
MinorEDT	Estimated daily vehicle volume entering the intersection from the minor road	Vehicles per day

ln_majorEDT	Log of Estimated daily vehicle volume entering the intersection from the major road	Log of vehicles per day
ln_minorEDT	Log of Estimated daily vehicle volume entering the intersection from the minor road	Log of vehicles per day

For Collision Data, the Region of Waterloo provided a spreadsheet containing collisions spanning from 2011 to 2020. The Collision Data Spreadsheet can be accessed in the supplementary data set provided. The Extraction Process:

- Pedestrian collisions were isolated from the dataset, while property damage collisions were excluded from further analysis.
- These collisions were then linked to the GEOID of the signalized intersections, and annual collision counts were extracted.
- The collisions were aggregated for each intersection according to the defined variable criteria.

For the traffic data, the Region of Waterloo provided the Turning Movement Counts (TMCs) in a set of PDF documents, which cover Morning Peak, Mid-day Peak, and Afternoon Peak at an interval of 15mins. It also includes Total Counts, which is sum of the total 8hr counts (Figure C- 1).

The TMC data in the PDF was extracted manually and tabulated in an Excel spreadsheet (Figure C- 2). The raw TMC collected for 8hr was converted into 24hr by using conversion factors. The Region of Waterloo provided a conversion factor for vehicle count, which is 1.74. However, a similar factor was not provided for pedestrians. Monthly and Hourly factors were derived from the data provided by Miovision Cameras. The Hourly factors were compiled to get an 8 hr. to 24 hr. conversion factor, which is 1.78. These Factors were then multiplied to get the daily counts. The list of TMC related variables and the modifications made to the raw data to extract the final variables is shown in Table C- 2.

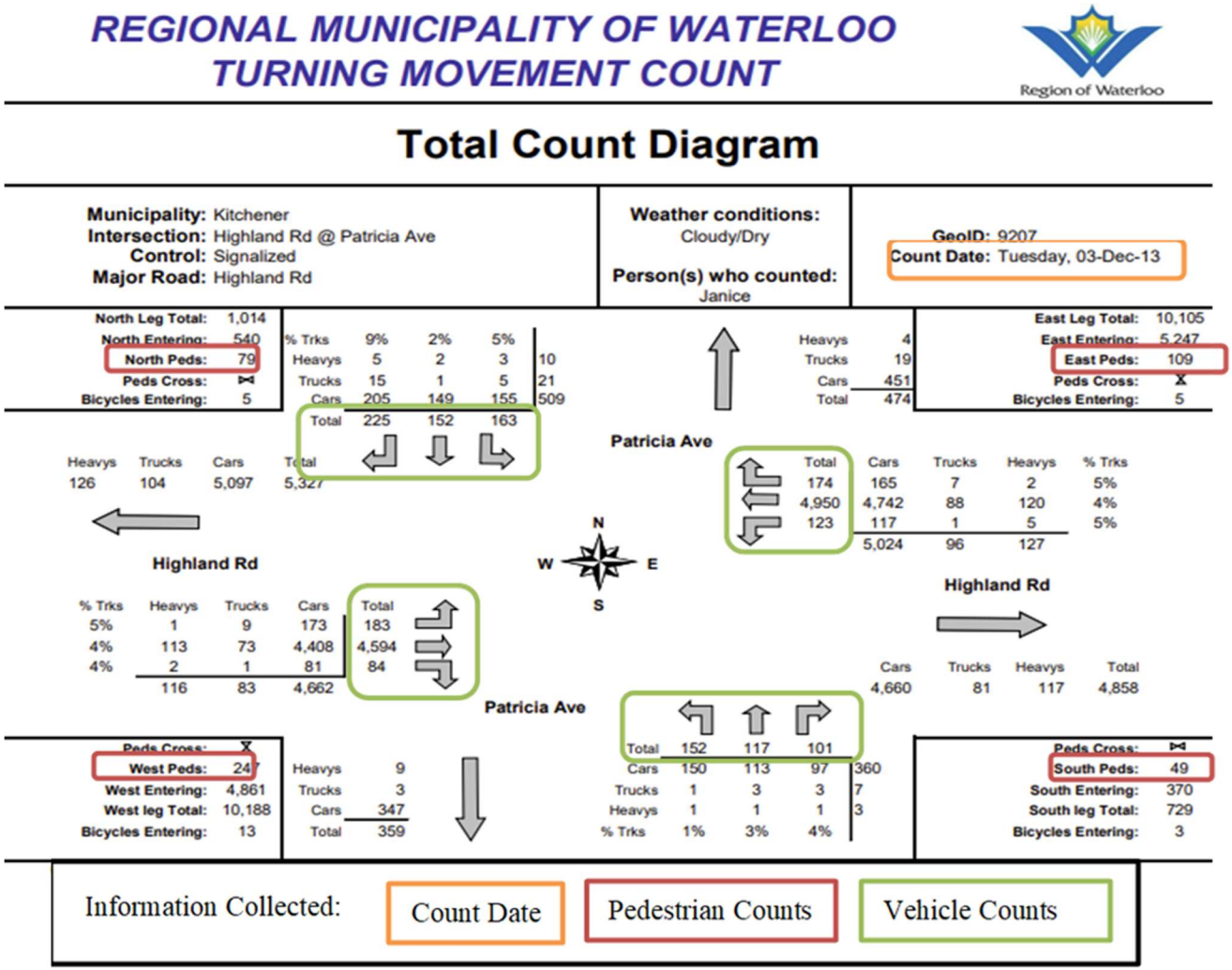


Figure C- 1 Screenshot of Turning Movement Counts at a Sample Intersection

				North Leg				East Leg				south leg				west leg			
Geoid	Date	Month	Year	ped	right	through	left	ped	right	through	left	ped	right	through	left	ped	right	through	left
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20
a	b	c	d	e	f	g	h	i	j	k	left	m	n	o	p	q	r	s	t
240	11	11	13	137	203	6110	282	113	328	127	102	99	79	4777	132	140	168	156	150
275	10	9	15	2368	915	28	864	1438	1308	4267	65	1231	78	30	35	2726	50	4112	897
358	9	12	13	581	267	99	290	2185	309	5248	233	335	196	100	175	576	300	5638	236
406	6	5	15	101	284	1554	0	135	531	6475	1346	86	0	1275	353	130	0	0	0
692	28	3	13	15	12	7	56	21	59	7511	2460	21	3326	1	104	8	217	8511	9
1259	21	5	14	142	1110	3310	101	79	198	682	210	93	202	3084	570	150	601	554	1078
1556	4	9	14	941	0	4394	852	796	0	0	0	1099	427	3726	1	1849	639	5626	836
1607	4	9	14	594	4422	2694	1042	416	0	0	0	544	2276	2	1326	674	635	5773	0
1618	14	1	13	195	0	1538	596	111	0	0	0	165	879	898	0	110	256	5275	393
1634	5	9	14	92	2393	3	0	95	1478	5626	2	23	1	2079	137	105	2	0	0

Figure C- 2 Processed TMC Data

Table C- 2 List of TMC related variables and their extraction procedure

VARIABLE NAME	DEFINITION	UNITS OR VALUES
Ped_total	Estimated daily pedestrian volume crossing the intersection	Pedestrians per day
	*= Column (e + i + m + q) * P_Monthly_factor*1.78*	
ln_Ped_total	Log of Estimated daily pedestrian volume crossing the intersection	Log of pedestrians per day
	*= Log [Column (e + i + m + q) * P_Monthly_factor*1.78]*	

				North Leg				East Leg				south leg				west leg						
Geoid	Date	Month	Year	ped	right	through	left	ped	right	through	left	ped	right	through	left	ped	right	through	left		P_Monthly_factor	Ped_total
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20			
a	b	c	d	e	f	g	h	i	j	k	left	m	n	o	p	q	r	s	t			
240	11	11	13	137	203	6110	282	113	328	127	102	99	79	4777	132	140	168	156	150		1.028591371	895.307
275	10	9	15	2368	915	28	864	1438	1308	4267	65	1231	78	30	35	2726	50	4112	897		0.812486115	11227
358	9	12	13	581	267	99	290	2185	309	5248	233	335	196	100	175	576	300	5638	236		1.356194281	8876.37
406	6	5	15	101	284	1554	0	135	531	6475	1346	86	0	1275	353	130	0	0	0		0.826282492	664.794

Table C-2 List of TMC related variables and their extraction procedure, continued

VARIABLE NAME	DEFINITION	UNITS OR VALUES
EDT_fac	Estimated daily vehicle volume crossing the intersection	Vehicles per day
	*= Column (f + g +h + j + k + l + n + o + p + r + s+t) *1.74*	
ln_EDT_fac	Log of Estimated daily vehicle volume crossing the intersection	Log of vehicles per day
	*= Log [Column (f + g +h + j + k + l + n + o + p+ r + s+t) *1.74]*	

				North Leg				East Leg				south leg				west leg				EDT
Geoid	Date	Month	Year	ped	right	through	left	ped	right	through	left	ped	right	through	left	ped	right	through	left	EDT_fac
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20	
a	b	c	d	e	f	g	h	i	j	k	left	m	n	o	p	q	r	s	t	
240	11	11	13	137	203	6110	282	113	328	127	102	99	79	4777	132	140	168	156	150	21948.36
275	10	9	15	2368	915	28	864	1438	1308	4267	65	1231	78	30	35	2726	50	4112	897	22009.26
358	9	12	13	581	267	99	290	2185	309	5248	233	335	196	100	175	576	300	5638	236	22778.34
406	6	5	15	101	284	1554	0	135	531	6475	1346	86	0	1275	353	130	0	0	0	20563.32
Right_TMC				Estimated daily right-turn vehicle volume crossing the intersection																Vehicles per day
				*= Column (f + j + n +r) *1.74*																
Through_TMC				Estimated daily through movement vehicle volume crossing the intersection																Vehicles per day
				*= Column (g + k + o +s) *1.74*																
Left_TMC				Estimated daily left-turn vehicle volume crossing the intersection																Vehicles per day
				*= Column (h + l + p +t) *1.74*																

				North Leg				East Leg				south leg				west leg				Turning Movements		
Geoid	Date	Month	Year	ped	right	through	left	ped	right	through	left	ped	right	through	left	ped	right	through	left	Right_TMC	Through_TMC	Left_TMC
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20			
a	b	c	d	e	f	g	h	i	j	k	left	m	n	o	p	q	r	s	t			
240	11	11	13	137	203	6110	282	113	328	127	102	99	79	4777	132	140	168	156	150	1353.72	19435.8	1158.84
275	10	9	15	2368	915	28	864	1438	1308	4267	65	1231	78	30	35	2726	50	4112	897	4090.74	14680.38	3238.14
358	9	12	13	581	267	99	290	2185	309	5248	233	335	196	100	175	576	300	5638	236	1865.28	19287.9	1625.16
406	6	5	15	101	284	1554	0	135	531	6475	1346	86	0	1275	353	130	0	0	0	1418.1	16188.96	2956.26
692	28	3	13	15	12	7	56	21	59	7511	2460	21	3326	1	104	8	217	8511	9	6288.36	27892.2	4574.46
1259	21	5	14	142	1110	3310	101	79	198	682	210	93	202	3084	570	150	601	554	1078	3673.14	13276.2	3408.66

Table C-2 List of TMC related variables and their extraction procedure,

VARIABLE NAME	DEFINITION	UNITS OR VALUES
MajorEDT	Estimated daily vehicle volume entering the intersection from the major road	Vehicles per day
	=Maximum of (NS and EW) *where,* *NS= Column (f + g +h + n + o + p) *1.74* *EW= Column (j + k + l + r + s+t) *1.74*	
ln_majorEDT	Log of Estimated daily vehicle volume entering the intersection from the major road	Log of vehicles per day
	=Log [Maximum of (NS and EW)]	
MinorEDT	Estimated daily vehicle volume entering the intersection from the minor road	Vehicles per day
	=Minimum of (NS and EW) *where,* *NS= Column (f + g +h + n + o + p) *1.74* *EW= Column (j + k + l + r + s+t) *1.74*	
ln_minorEDT	Log of Estimated daily vehicle volume entering the intersection from the minor road	Log of vehicles per day
	=Log [Minimum of (NS and EW)]	

				North Leg				East Leg				south leg				west leg				Major Minor			
Geoid	Date	Month	Year	ped	right	through	left	ped	right	through	left	ped	right	through	left	ped	right	through	left	NS	EW	MajorEDT	MinorEDT
1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18	19	20				
a	b	c	d	e	f	g	h	i	j	k	left	m	n	o	p	q	r	s	t				
240	11	11	13	137	203	6110	282	113	328	127	102	99	79	4777	132	140	168	156	150	11583	1031	20154	1794
275	10	9	15	2368	915	28	864	1438	1308	4267	65	1231	78	30	35	2726	50	4112	897	1950	10699	18616	3393
358	9	12	13	581	267	99	290	2185	309	5248	233	335	196	100	175	576	300	5638	236	1127	11964	20817	1961
406	6	5	15	101	284	1554	0	135	531	6475	1346	86	0	1275	353	130	0	0	0	3466	8352	14532	6031
692	28	3	13	15	12	7	56	21	59	7511	2460	21	3326	1	104	8	217	8511	9	3506	18767	32655	6100

prop_left	Proportion of left-turn vehicle volume	Proportion
	= Left_TMC/ EDT_fac	
prop_right	Proportion of right-turn vehicle volume	Proportion
	= Right_TMC/ EDT_fac	
prop_lr	Proportion of combined left and right-turn vehicle volume	Proportion
	= Through_TMC/ EDT_fac	

C.2. Intersection Inventory Data

This part details the intersection inventory data obtained from the Region of Waterloo's Open Data Portal (https://www.regionofwaterloo.ca/en/regional-government/open-data.aspx). Table C- 3 shows the list of variables extracted from this data source.

Table C- 3 List of Variables from Region of Waterloo Open Data

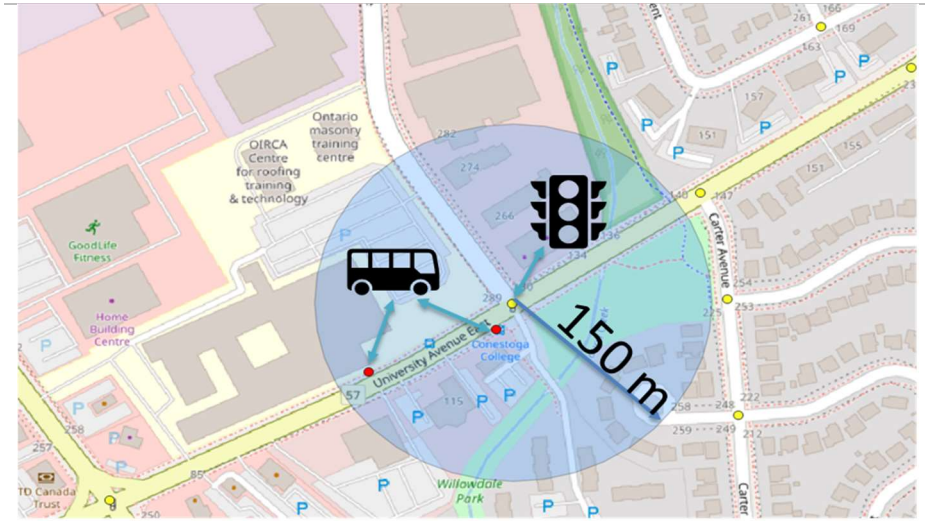
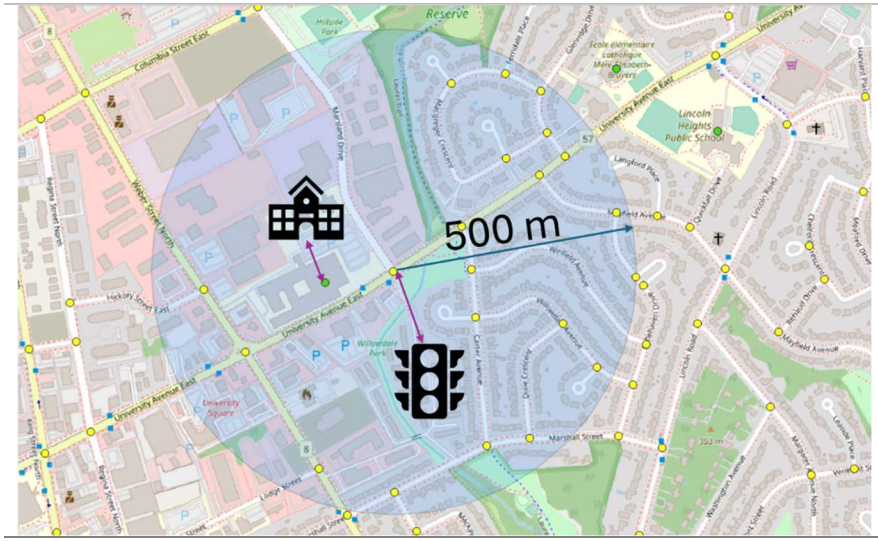
Variable Name	Definition	Units or Values	Data Collection Procedure
speed0123	Speed on the major road of the intersection	Kilometer per hour	• Spreadsheet was available with Speed for the major road (available in Supplementary Data) • Extracted by matching with GEOID
grt_stop	Number of bus stops within 150m of the intersection	Number of Stops	• QGIS was used to join "Road intersection" and "GRT Stops" using "join attributes by near" tool. • Number of bus stops within 150m were aggregated
			• Yellow points are the intersections. • Red points are bus stops. • Buffer circle is a buffer of radius 150m

Table C-3 List of Variables from Region of Waterloo Open Data, continued

Variable Name	Definition	Units or Values	Data Collection Procedure
school_500_yn	Presence of a school within 500m of the intersection	If 0, no school; if 1, school present	• QGIS was used to join "Road intersection" and "Schools" using "join attributes by near" tool. • Number of schools within 500m were aggregated.
			• Yellow points are the intersections. • Green point is School. • Buffer circle is a buffer of radius 500m
local	One of the legs is a local road	If 0, no local road; if 1, local road present	• "Roads" CSV file extracted from Open Data was manual matched with the Road Names
collector	One of the legs is a collector road	If 0, no collector road; if 1, collector road present	• Roads" CSV file extracted from Open Data was manual matched with the Road Names
arterial	One of the legs is an arterial road	If 0, no arterial road; if 1, arterial road present	• Roads" CSV file extracted from Open Data was manual matched with the Road Names

C.3. Data from Google Earth & Google Maps

Additional data on individual intersections were manually extracted from Google Earth/Maps, as summarized in Table C- 4.

Table C- 4 List of Final Variables from Google Earth & Google Maps

Variable Name	Definition	Units or Values
Legs	Number of legs in an intersection	If 0, three-legged intersection. If 1, four-legged intersection
Total_numlanes	Total number of lanes at the intersection	Number of lanes
Avglanes	Average number of lanes at the intersection	Number of lanes
T_numthro	Total number of through lanes at the intersection	Number of lanes
T_numright	Total number of right-turn lanes at the intersection	Number of lanes
T_numleft	Total number of left-turn lanes at the intersection	Number of lanes
sliplane_presence_yn	Presence of at least one slip lane at the intersection	If 0, no slip lane; if 1, slip lane present
residential_yn	Presence of residential establishments at least one corner of the intersection	If 0, no residential; if 1, residential present
commercial_yn	Presence of commercial or industrial establishments at least one corner of the intersection	If 0, no commercial; if 1, commercial present
school_atint	Presence of educational establishments at least one corner of the intersection	If 0, no school; if 1, school present
open_yn	Presence of open space or playground at least one corner of the intersection	If 0, no open space; if 1, open space present
skewness	Presence of skewness at the intersection (non-90-degree angles)	If 0, no skewness; if 1, skewness present
comm	One of the legs is a commercial entry or exit	If 0, no commercial entry; if 1, commercial entry present
commercial_exent_int_yn	Presence of commercial entry/exits or driveways within 50m of the intersection	If 0, no commercial exits; if 1, commercial exits present

Table C-4 List of Final Variables from Google Earth & Google Maps, continued

Variable Name	Definition	Units or Values
oneway_leg_yn	Presence of at least one leg with one-way traffic at the intersection	If 0, no one-way leg; if 1, one-way leg present
median_presence_yn	Presence of at least one median at the intersection	If 0, no median; if 1, median present
raisedmedian_yn	Presence of at least one raised median at the intersection	If 0, no raised median; if 1, raised median present
non_standardmarking	Presence of non-conventional crosswalk markings	If 0, no non-standard marking; if 1, non-standard marking present
T_crosswalklength	Total length of all crosswalks at the intersection	Meters
Avg_crosswalklength	Average length of all crosswalks at the intersection	Meters
num_sidewalk_missing	Number of missing sidewalks at the intersection (assuming 2 per side of each approach)	Number of sidewalks
bicyclepresence_210	Presence of at least one conventional bicycle lane at the intersection	If 0, no bicycle lane; if 1, bicycle lane present

Figure C- 3 shows the excel spreadsheet used for data collection from google maps & google Earth. Table C- 5 & Table C- 6 provides the definitions of these characteristics and their data collection procedure for intersections and each leg, respectively. Each intersection is assigned a unique GEOID. Approaches at each intersection are labelled according to the direction from which they enter.

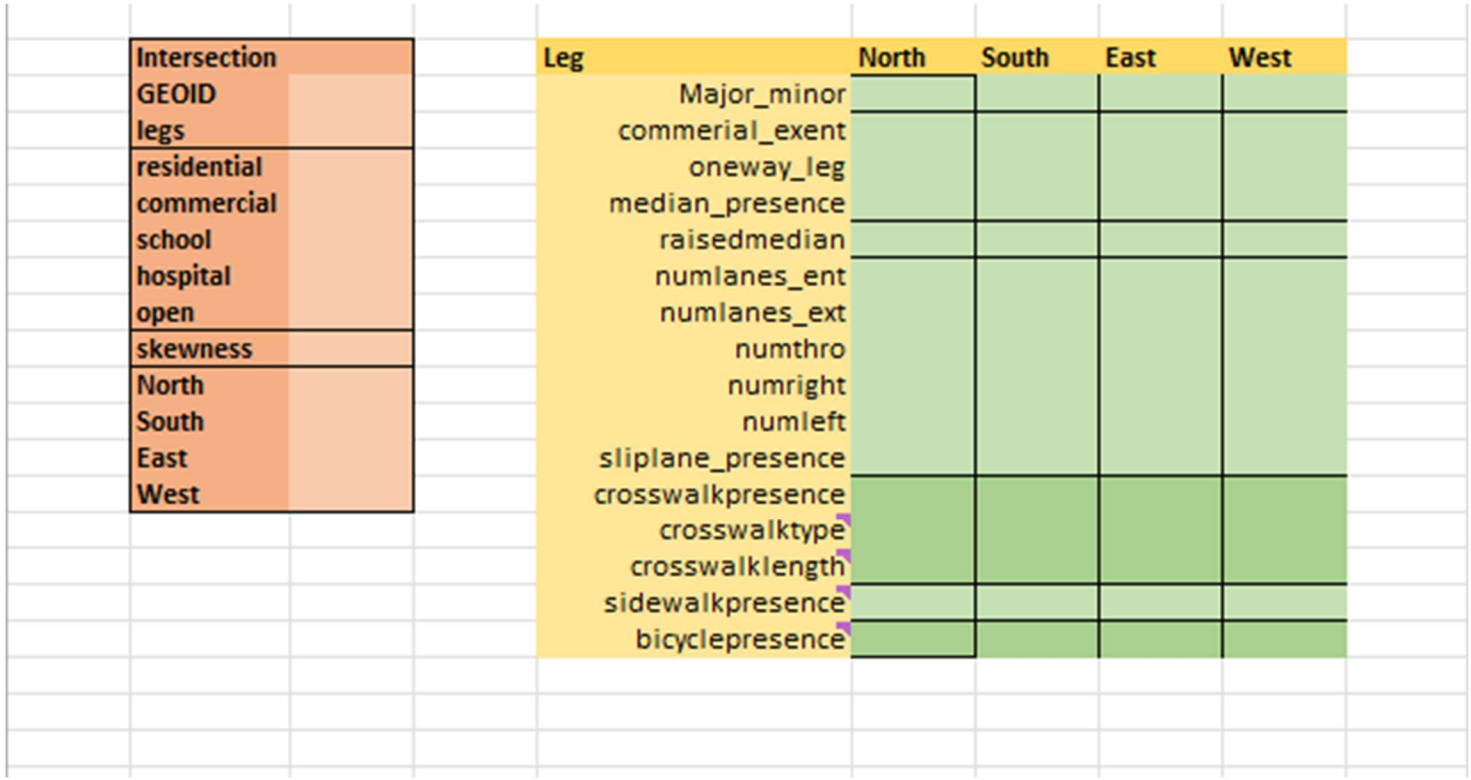


Figure C- 3 Screenshot of Data Collection Spreadsheet

Table C- 5 Data Collection Sheet: Intersection Characteristics

Name	Definition	Data Collection Procedure
GEOID	Unique intersection identification number	Assigned by Region of Waterloo for matching purposes
Legs	Number of legs	Count the number of legs at the intersection. • Legs=4
Residential	Presence of residential area	Count the number of corners with residential areas. • Residential=1
Commercial	Presence of commercial area	Count the number of corners with commercial or industrial areas. • Commercial=3



Table C-5 Data Collection Sheet: Intersection Characteristics, continued

Name	Definition	Data Collection Procedure	
School	Presence of educational institutions	Count the number of corners with educational institutions. • School= 1	
Open	Presence of playgrounds or open spaces	Count the number of corners with playgrounds or open areas. • Open=1	

Table C-5 Data Collection Sheet: Intersection Characteristics, continued

Name	Definition	Data Collection Procedure	
Skewness	Presence of skewness	Record if the intersection is skewed (not angled at 90 degrees) • Skewness=Yes	
North	Name of road entering from the north side	Record the name of the road for the approach in the north side. • North= Weber Street	
South	Name of road entering from the south side	Record the name of the road for approach in the south side. • South=Weber Street	
East	Name of road entering from the east side	Record the name of the road for approach in the south side. • East= Union Street	
West	Name of road entering from the west side	Record the name of the road for approach in the west side. • West= Union Street	

Table C- 6 Data Collection Sheet: Intersection Approach Characteristics

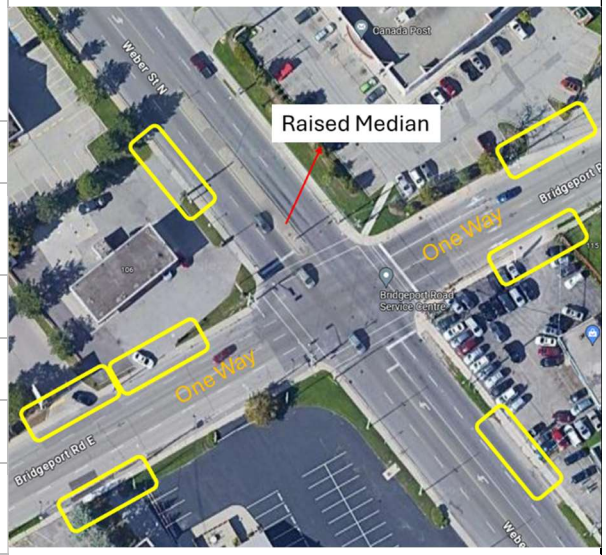
Name	Definition	Data Collection Procedure	
Commercial_Extent	Presence of commercial entry/ exit or driveways	Record if driveways or commercial entry-exits are present within a 50m radius of the intersection	
North: Yes | South: Yes | East: Yes | West: Yes			
Oneway_Leg	Presence of one-way traffic	Record if there is one-way traffic on the leg based on the configuration of lanes	
North: No | South: No | East: Yes | West: Yes			
Median_Presence	Presence of median	Record if there is a median present on the leg	
North: Yes | South: No | East: No | West: No			
Raised_Median	Presence of raised median	Record if there is a raised median present on the leg	
North: Yes | South: No | East: No | West: No			

Table C-6 Data Collection Sheet: Intersection Approach Characteristics, continued

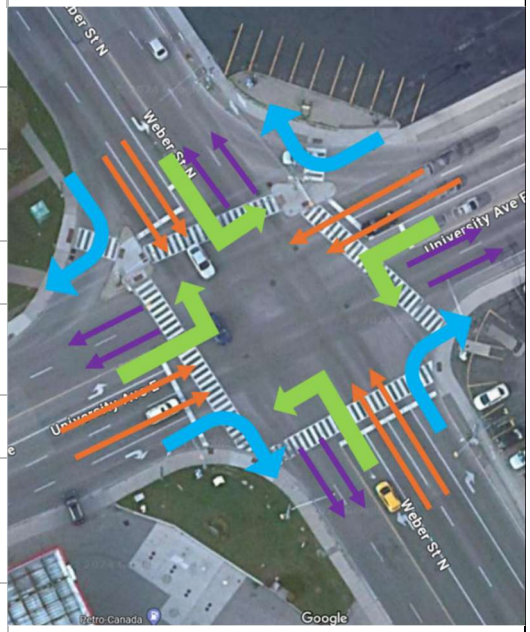
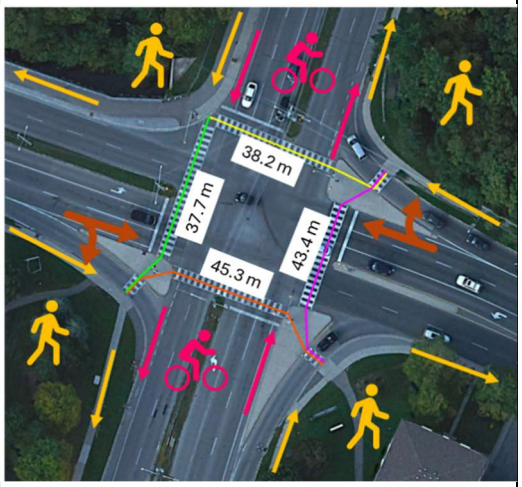
Name	Definition	Data Collection Procedure	
Numlanes_Ent	Number of entering lanes	Count the number of lanes entering the intersection on the leg, including slip lane	
North: 4 | South: 4 | East: 4 | West: 4			
Numlanes_Ext	Number of exiting lanes	Count the number of lanes exiting the intersection on the leg, excluding slip lane	
North: 2 | South: 2 | East: 2 | West: 2			
Numthro	Number of through lanes	Count the number of through lanes entering the intersection on the leg, including shared through left and through right lanes	
North: 2 | South: 2 | East: 2 | West: 2			
Numright	Number of exclusive right turn lanes	Count the number of exclusive right turn lanes entering the intersection on the leg, including slip lane	
North: 1 | South: 1 | East: 1 | West: 1			
Numleft	Number of exclusive left turn lanes	Count the number of exclusive left turn lanes entering the intersection on the leg, Shared left and right turn lane is included as left turn lane and not to be included in both the categories	
North: 1 | South: 1 | East: 1 | West: 1			

Table C-6 Data Collection Sheet: Intersection Approach Characteristics, continued

Name	Definition	Data Collection Procedure
Sliplane_Presence	Presence of slip lane	Record if slip lane is present; the lane is recorded in the leg where it starts
North: Yes | South: No | East: Yes | West: No		
Crosswalk_Presence	Presence of crosswalk	Record if crosswalk is present
North: Yes | South: Yes | East: Yes | West: Yes		
Crosswalk_Type	Type of crosswalk	Record the type of crosswalk: Standard, Ladder, Painted
North: Ladder | South: Ladder | East: Ladder | West: Ladder		
Crosswalk_Length	Length of crosswalk	Measure and record the crosswalk from centre-to-centre distance between the curbs; if slip lane present measure the center-to-center distance along the path, i.e., slip lane crosswalk(s) + island(s) + main road crosswalk
North: 38.2m | South: 45.3m | East: 43.4m | West: 37.7m		
Sidewalk_Presence	Presence of sidewalk	Record if sidewalk is present, if yes, on one (1) or both (2) directions of the leg
North: 2 | South: 2 | East: 2 | West: 2		
Bicycle_Presence	Presence of bicycle lane	Record if conventional bicycle lane is present, if yes, on one (1) or both (2) directions of the leg
North: 2 | South: 2 | East: 0 | West: 0		



Appendix D

Data Description: Collision Data

The yearly average pedestrian collisions across the reference sites and treatment sites from 2011 to 2020 are depicted in Figure D- 1. Treatment sites show considerable variability, with collision peaks noted around 2015 followed by a gradual decline through 2020. This peak likely prompted the launch of the LPI pilot project in the region. Initiated in 2017, the project began with 8 implementations, 7 of which were included in the study. By 2018, the project expanded to an additional 33 intersections, with 25 included in the study. In contrast, reference sites show more stability, with minor fluctuations and a gradual decrease over the years. The annual pedestrian collision data across three cities (CAM, KIT, WAT) from 2011 to 2020 is presented in Table D- 1. The data is segmented into three categories: all sites, reference sites, and LPI sites.

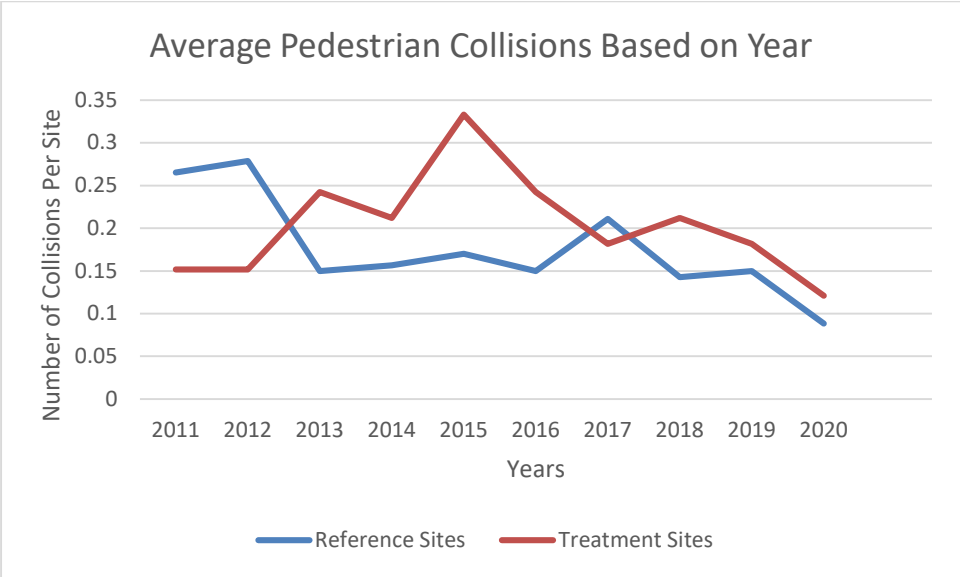


Figure D- 1 Year wise Average Pedestrian Collisions Based on Type of Study site.

Table D- 1 Year wise Number of Pedestrian Collisions Based on Type of Study site & Municipality.

MUN	Study Sites	2011	2012	2013	2014	2015	2016	2017	2018	2019	2020
CAM	*All*	14	13	7	12	11	8	8	6	7	4
	Reference	11	10	3	9	7	4	8	6	5	2
	LPI	3	3	4	3	4	4	0	0	2	2
KIT	*All*	21	20	17	14	20	18	24	14	12	10
	Reference	19	18	14	10	14	14	17	7	8	8
	LPI	2	2	3	4	6	4	7	7	4	2
WAT	*All*	7	12	5	4	8	9	5	8	6	3
	Reference	7	12	4	4	6	7	5	8	6	3
	LPI	0	0	1	0	2	2	0	0	0	0
Total		**42**	**45**	**29**	**30**	**39**	**35**	**37**	**28**	**25**	**17**

Similarly, the month-wise and weekday-wise fluctuations in average pedestrian collisions across reference sites, treatment sites, and all sites combined from 2011 to 2020 are shown in Figure D- 2 & Figure D- 3, respectively. Along with this, the month-wise and weekday-wise pedestrian collision data across three cities (CAM, KIT, WAT) from 2011 to 2020 is presented in Table D- 2 and Table D- 3, respectively.

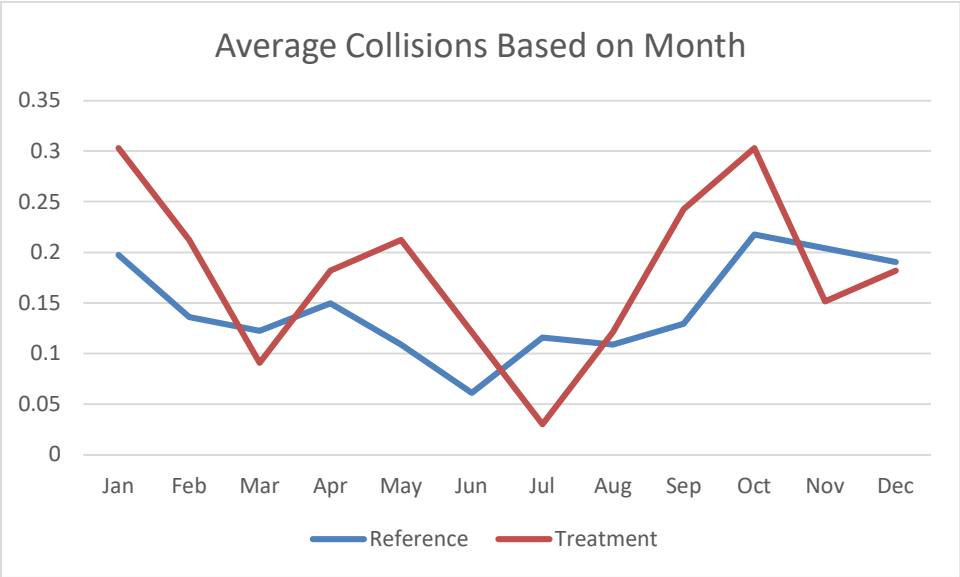


Figure D- 2 Month wise Average Pedestrian Collisions Based on Type of Study site.

Table D- 2 Month wise Number of Pedestrian Collisions Based on Type of Study site & Municipality.

MUN	Study Sites	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
CAM	*All*	9	8	7	7	5	4	3	8	8	15	7	9
	Reference	6	6	5	3	3	2	3	7	5	11	7	7
	LPI	3	2	2	4	2	2	0	1	3	4	0	2
KIT	*All*	20	13	7	13	13	9	11	12	9	23	20	20
	Reference	14	8	6	11	8	7	11	9	6	18	15	16
	LPI	6	5	1	2	5	2	0	3	3	5	5	4
WAT	*All*	10	6	7	8	5	0	4	0	10	4	8	5
	Reference	9	6	7	8	5	0	3	0	8	3	8	5
	LPI	1	0	0	0	0	0	1	0	2	1	0	0
Total		**39**	**27**	**21**	**28**	**23**	**13**	**18**	**20**	**27**	**42**	**35**	**34**

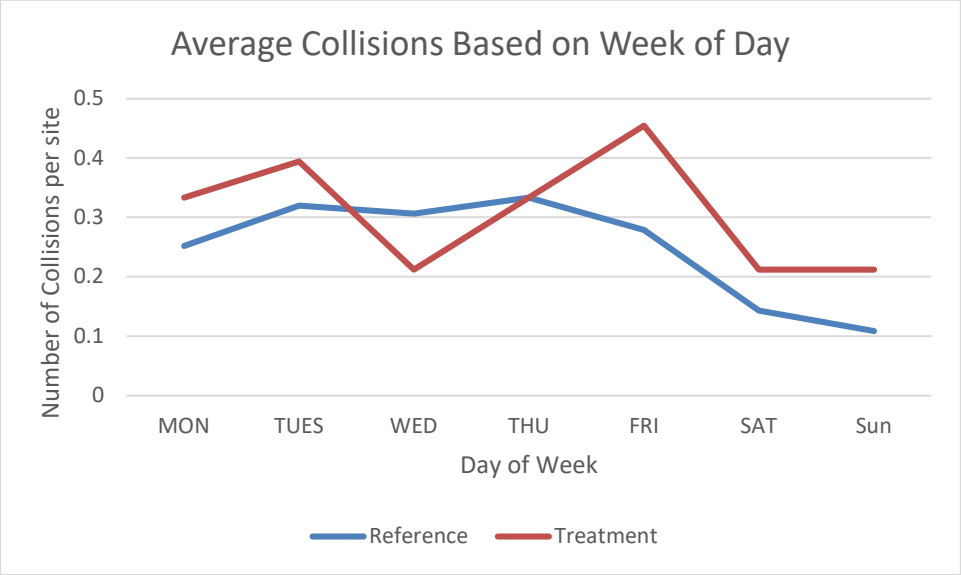


Figure D- 3 Weekday wise Average Pedestrian Collisions Based on Type of Study site.

Table D- 3 Weekday wise Number of Pedestrian Collisions Based on Type of Study site & Municipality.

MUN	Study Sites	MON	TUES	WED	THU	FRI	SAT	SUN
CAM	*All*	8	15	10	14	26	10	7
	Reference	7	8	8	11	21	6	4
	LPI	1	7	2	3	5	4	3
KIT	*All*	23	31	34	33	23	12	14
	Reference	17	25	29	25	14	9	10
	LPI	6	6	5	8	9	3	4
WAT	*All*	17	14	8	13	7	6	2
	Reference	13	14	8	13	6	6	2
	LPI	4	0	0	0	1	0	0
Total		**48**	**60**	**52**	**60**	**56**	**28**	**23**

Table D- 4 & Table D- 5 presents the distribution of pedestrian collisions based on the actions of drivers and pedestrians for Treatment Sites for Before (2011-2016) & After (2019-2020) period, respectively. In before period, the majority of collisions, 63.4%, occurred due to drivers failing to yield to the right-of-way, making it the most significant factor. Additionally, 19.1% of collisions were attributed to improper turns by drivers. Pedestrian actions that predominantly led to collisions involved crossing with the right-of-way, accounting for 31% of the total collisions. In the After period, the majority of collisions were due to drivers failing to yield the right-of-way and improper turns by drivers, each accounting for 40% of incidents. There has been a noticeable reduction in non-yielding behavior by drivers compared to the Before period. Results for Reference Sites are presented in Table D- 6.

Table D- 4 Treatment Sites: Number of Pedestrian Collisions Based on Pedestrian & Driver Action for Before Period

DRIVER ACTION / PEDESTRIAN ACTION	Unknown	Crossing with Right-of-way	Crossing without right-of-way	Crossing Ped. Crossover	Others	Total
Unknown		2				2
Driving Properly		1	1			2
Improper turn	5	4				9
Disobeyed traffic control	1	1		1		3
Failed to yield right-of-way	8	22				30
Others					1	1
Total	14	30	1	1	1	47

Table D- 5 Treatment Sites: Number of Pedestrian Collisions Based on Pedestrian & Driver Action for After Period

DRIVER ACTION \ PEDESTRIAN ACTION	Unknown	Crossing with Right-of-way	Others	Total
Driving Properly	0	0	1	1
Improper turn	3	0	1	4
Disobeyed traffic control	0	1	0	1
Failed to yield right-of-way	0	4	0	4
Total	3	5	2	10

Table D- 6 Reference Sites: Number of Pedestrian Collisions (2011-2020) Based on Pedestrian & Driver Action

DRIVER ACTION \ PEDESTRIAN ACTION	Unknown	Crossing with Right-of-way	Crossing without right-of-way	Crossing Ped. Crossover	Crossing marked crosswalk without right of way	Walking on roadway with traffic	On sidewalk or shoulder	Running onto roadway	Others	Total
Unknown	1	6								7
Driving Properly	4	3	12		11		1	3	3	37
Exceeding speed limit		1								1
Improper turn	15	14			1				1	31
Disobeyed traffic control	5	5							1	11
Failed to yield right-of-way	37	114		7	1	1			1	161
Lost control	1	1								2
Wrong way on one-way	1									1
Others		3			1				1	5
Total	64	147	12	7	14	1	1	3	7	256

Moreover, turning manoeuvres are the primary causes of pedestrian collisions at both treatment and reference intersections. This trend is consistent in the Before period for both treatment (Table D- 7) and reference sites (Table D- 9), with left turns being the most frequent cause of collisions, followed by right turns. However, there was a shift in this trend at treatment sites in the After period (Table D- 8), where right turns became the most frequent cause of collisions, followed by left turns.

Table D- 7 Treatment Sites: Number of Pedestrian Collisions by Vehicle Manoeuvre & Driver Action for Before Period

DRIVER ACTION / VEHICLE MANEOUVER	Unknown	Going Ahead	Turning Left	Turning Right	Making "U" Turn	Total
Unknown	0	0	0	2	0	2
Driving Properly	0	2	0	0	0	2
Improper turn	0	0	9	0	0	9
Disobeyed traffic control	0	1	1	1	0	3
Failed to yield right-of-way	1	0	18	10	1	30
Others	0	0	1	0	0	1
Total	**1**	**3**	**29**	**13**	**1**	**47**

Table D- 8 Treatment Sites: Number of Pedestrian Collisions by Vehicle Manoeuvre & Driver Action for After Period

DRIVER ACTION / VEHICLE MANEOUVER	Going Ahead	Turning Left	Turning Right	Total
Driving Properly	1	0	0	**1**
Improper turn	0	2	2	**4**
Disobeyed traffic control	0	0	1	**1**
Failed to yield right-of-way	0	2	2	**4**
Total	**1**	**4**	**5**	**10**

Table D- 9 Reference Sites: Number of Pedestrian Collisions by Vehicle Manoeuvre & Driver Action

DRIVER ACTION / VEHICLE MANEOUVER	Going Ahead	Slowing or stopping	Turning Left	Turning Right	Reversing	Total
Unknown	0	1	3	3	0	**7**
Driving Properly	26	1	7	3	0	**37**
Exceeding speed limit	1	0	0	0	0	**1**
Improper turn	0	0	25	6	0	**31**
Disobeyed traffic control	11	0	0	0	0	**11**
Failed to yield right-of-way	6	0	121	34	0	**161**
Improper passing	0	1	0	1	0	**2**
Wrong way on one-way	0	0	0	0	1	**1**
Others	3	0	1	1	0	**5**
Total	**47**	**3**	**157**	**48**	**1**	**256**

Appendix E
Data Description: Traffic Characteristics

This Appendix provides detailed data description on the traffic exposure measures used in this study, including Estimated Daily Traffic (EDT), Estimated Daily Pedestrians (EDP), and Speed.

E.1. Estimated Daily Traffic (EDT)

"Estimated Daily Traffic" is the term used by the Region of Waterloo to describe the average annual daily traffic volume encompassing all vehicular movements at an intersection. This data is derived from 8-hour vehicular counts conducted across three time slots on a single day of the year. To extrapolate this to represent a full 24-hour period, the counts are adjusted by multiplying them by a factor of 1.74, as determined by the Region of Waterloo.

The distribution of estimated daily traffic across various intersections is depicted in Figure E- 1. The blue bars represent the number of intersections for different ranges of daily traffic volumes, measured in thousands. The red line indicates the cumulative relative frequency of intersections. The majority of intersections have an estimated daily traffic between 10,000 and 20,000 vehicles, with the peak frequency occurring around 16,000 to 18,000 vehicles per day. The cumulative relative frequency line shows that approximately 80% of intersections have daily traffic volumes up to around 28,000 vehicles. Beyond this point, the number of intersections with higher traffic volumes decreases significantly. This distribution highlights the varying levels of traffic across intersections and emphasizes that most intersections experience moderate traffic volumes.

Figure E- 2 shows a scatter plot, which illustrates the relationship between the number of pedestrian collisions (2011-2020) and estimated daily traffic volumes at various intersections. Each point represents an intersection, with the x-axis showing estimated daily traffic in thousands of vehicles and the y-axis displaying the number of pedestrian collisions. The plot reveals that intersections with higher estimated daily traffic tend to have a higher number of pedestrian collisions. However, there is a wide dispersion in the data, indicating variability in collision occurrences even at similar traffic volumes. Some intersections with lower traffic volumes also exhibit a significant number of collisions, suggesting that factors other than traffic volume alone contribute to pedestrian collisions.

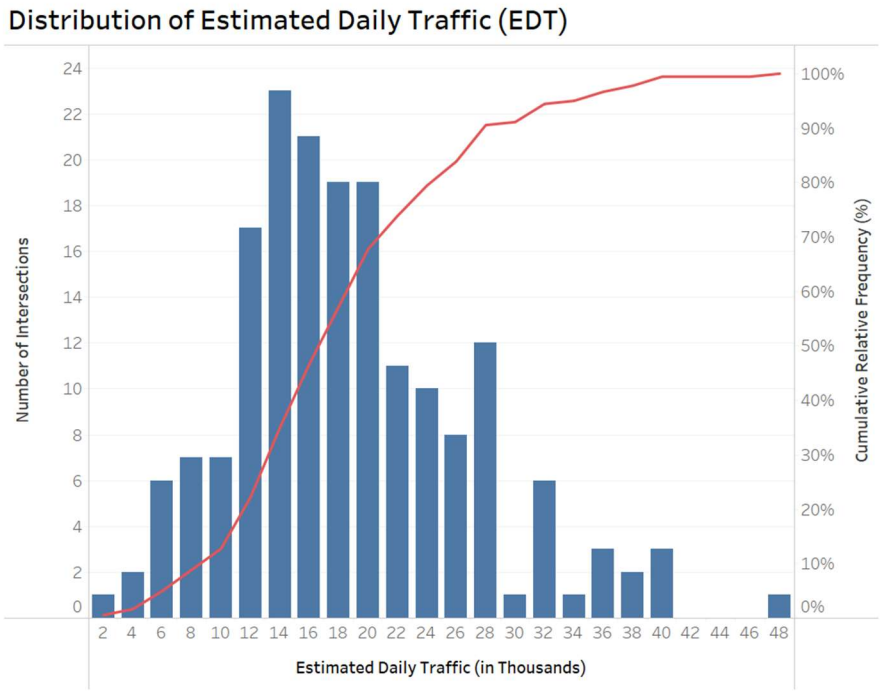


Figure E- 1 Distribution of Estimated Daily Traffic: All Study Sites

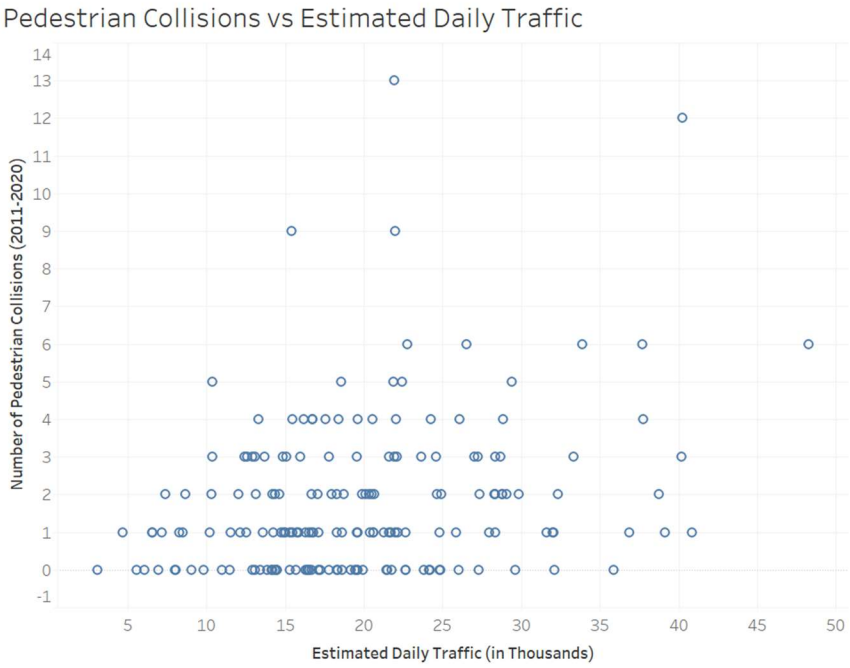


Figure E- 2 Pedestrian Collisions vs Estimated Daily Traffic: All Study Sites

Figure E- 3 illustrates the relationship between Estimated Daily Traffic (EDT) and average pedestrian collisions from 2011 to 2020. The blue bars show the number of intersections per traffic volume category, while the orange dots represent the average number of pedestrian collisions.

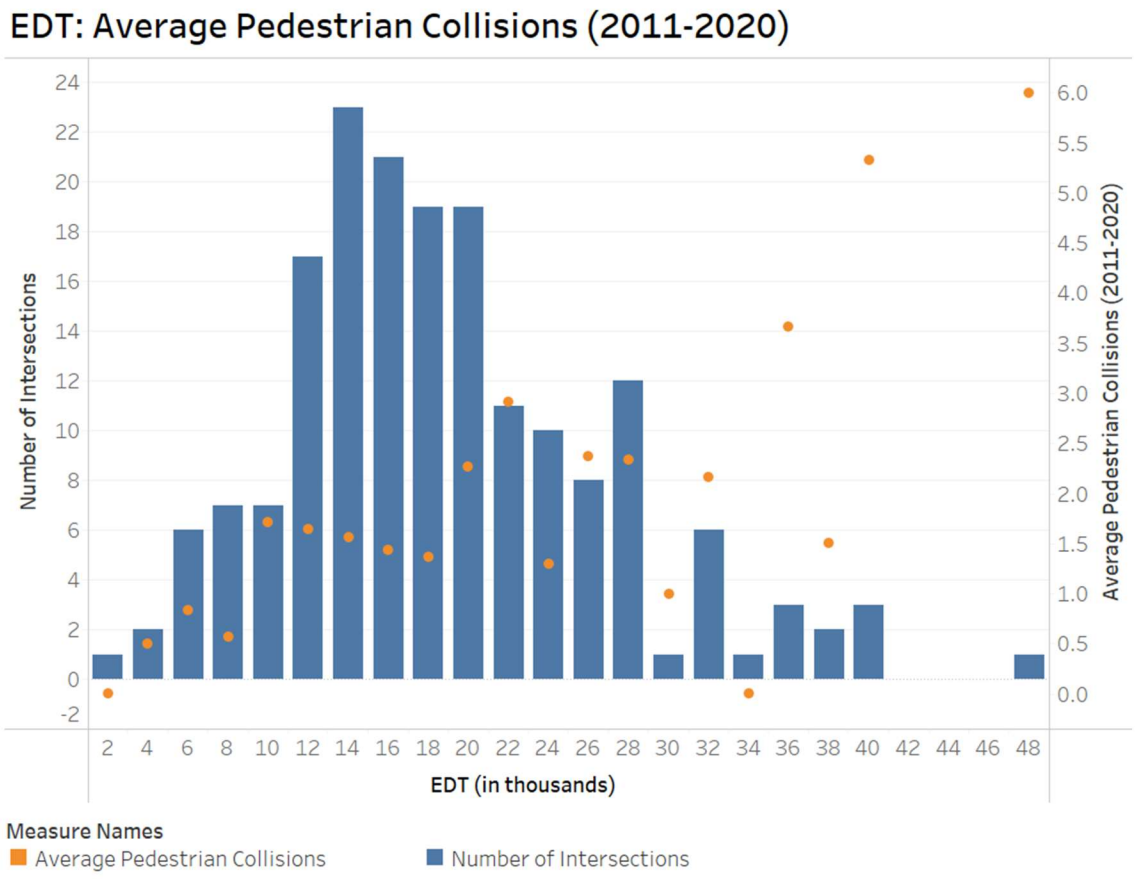


Figure E- 3 Average Pedestrian Collisions Based on Estimated Daily Traffic: All Study Sites

In Figure E- 4, the bar chart shows the absolute change in Estimated Daily Traffic (EDT) across treatment sites. Each bar represents the change in traffic volume, in thousands of vehicles per day, for a specific GEOID.

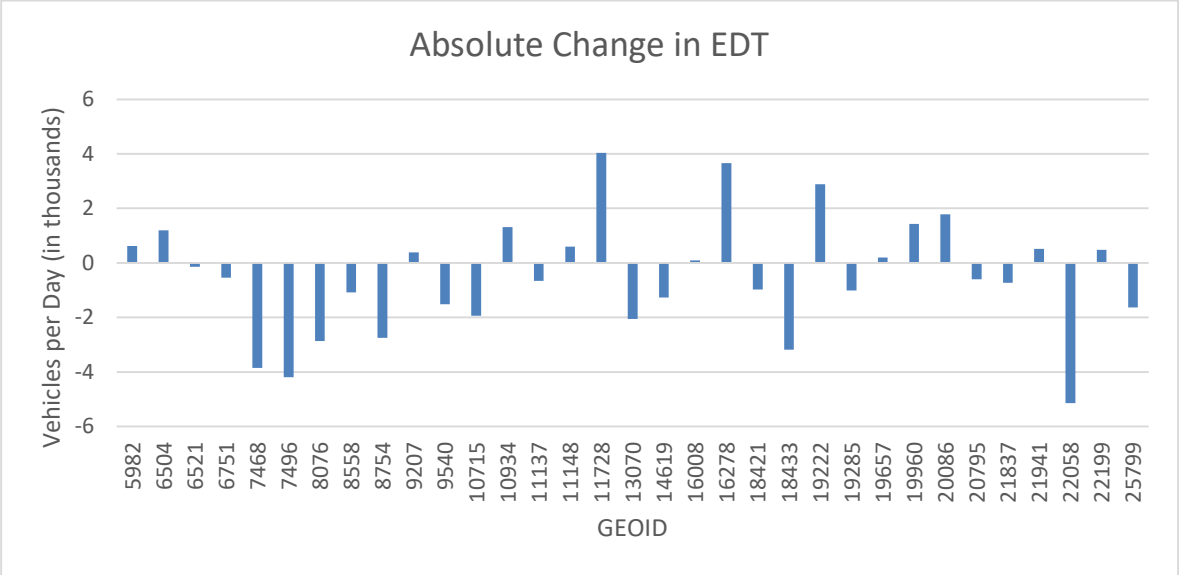


Figure E- 4 Absolute Change in Before period & After period Estimated Daily Traffic for each Treatment Sites

E.2. Estimated Daily Pedestrians (EDP)

"Estimated Daily Pedestrian" refers to the average annual daily pedestrian volume encompassing all pedestrian crossings at an intersection. This data is obtained from 8-hour pedestrian counts conducted across three time slots on a single day of the year. To account for seasonal variations, monthly adjustment factors are applied, varying from month to month. These counts are then extrapolated to represent a full 24-hour period by multiplying them by a factor of 1.78, determined using data from Miovision. For detailed information on these conversions, please refer to Section 3.2.2.4.

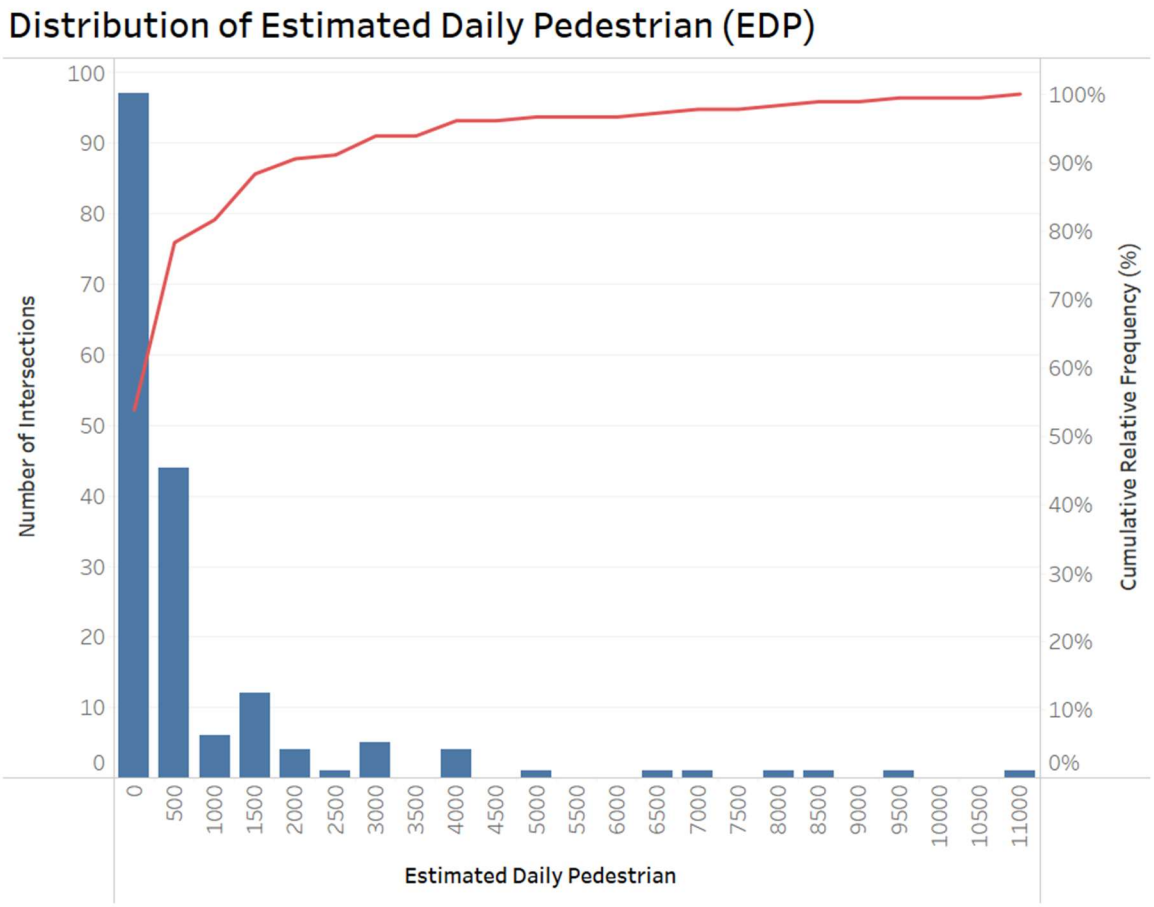


Figure E- 5 Distribution of Estimated Daily Pedestrians: All Study Sites

The distribution of estimated daily pedestrian traffic across various intersections is shown in Figure E- 5. The blue bars represent the number of intersections for each range of daily pedestrian volumes, while the red line indicates the cumulative relative frequency. The majority of intersections have low

pedestrian volumes, with the highest frequency observed in the range of 0 to 500 pedestrians per day. Few intersections exceed 1,000 pedestrians daily. The cumulative relative frequency curve rises steeply initially and then levels off, indicating that nearly all intersections have pedestrian volumes below 1,500 per day. This distribution suggests that most intersections experience relatively low pedestrian traffic.

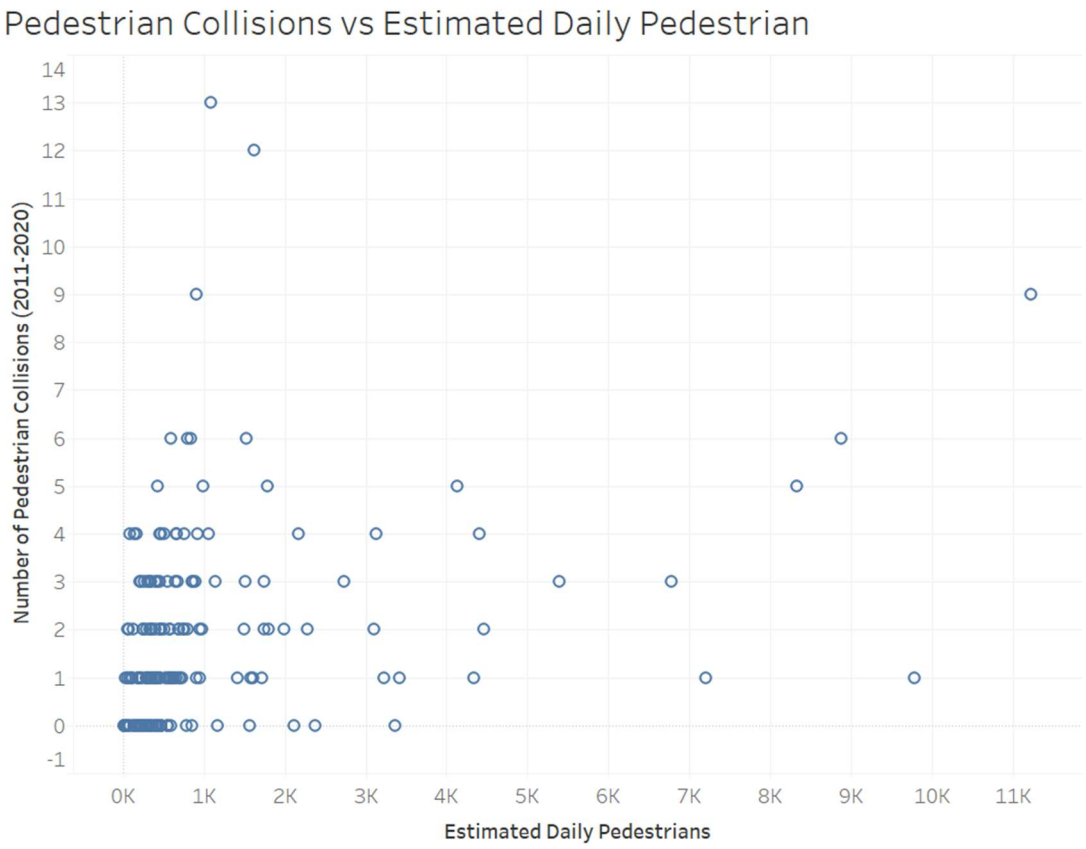


Figure E- 6 Pedestrian Collisions vs Estimated Daily Pedestrians: All Study Sites

In Figure E- 6, the scatter plot shows the relationship between the number of pedestrian collisions (2011-2020) and estimated daily pedestrian volumes at various intersections. Each point represents an intersection, with the x-axis showing estimated daily pedestrian traffic and the y-axis displaying the number of pedestrian collisions. The plot reveals that intersections with lower pedestrian volumes (0-2,000 pedestrians per day) have a wide range of collision occurrences, including several intersections with multiple collisions. As pedestrian volumes increase beyond 2,000 per day, the number of collisions tends to scatter, with some high-volume intersections experiencing fewer collisions and others more.

Notably, intersections with very high pedestrian volumes (over 10,000 per day) also show higher collision numbers, indicating a potential correlation between pedestrian traffic and collision rates.

Figure E- 7 shows the relationship between Estimated Daily Pedestrian (EDP) volumes and average pedestrian collisions from 2011 to 2020. The blue bars represent the number of intersections for each EDP category, while the orange dots indicate the average number of pedestrian collisions. The data shows that intersections with lower pedestrian volumes (0-500 pedestrians per day) have a relatively lower average number of collisions. However, as pedestrian volumes increase, particularly beyond 5,000 pedestrians per day, the average number of collisions also tends to rise. Intersections with very high pedestrian volumes (around 11,000 pedestrians per day) exhibit the highest average collisions, indicating a potential correlation between increased pedestrian traffic and higher collision rates.

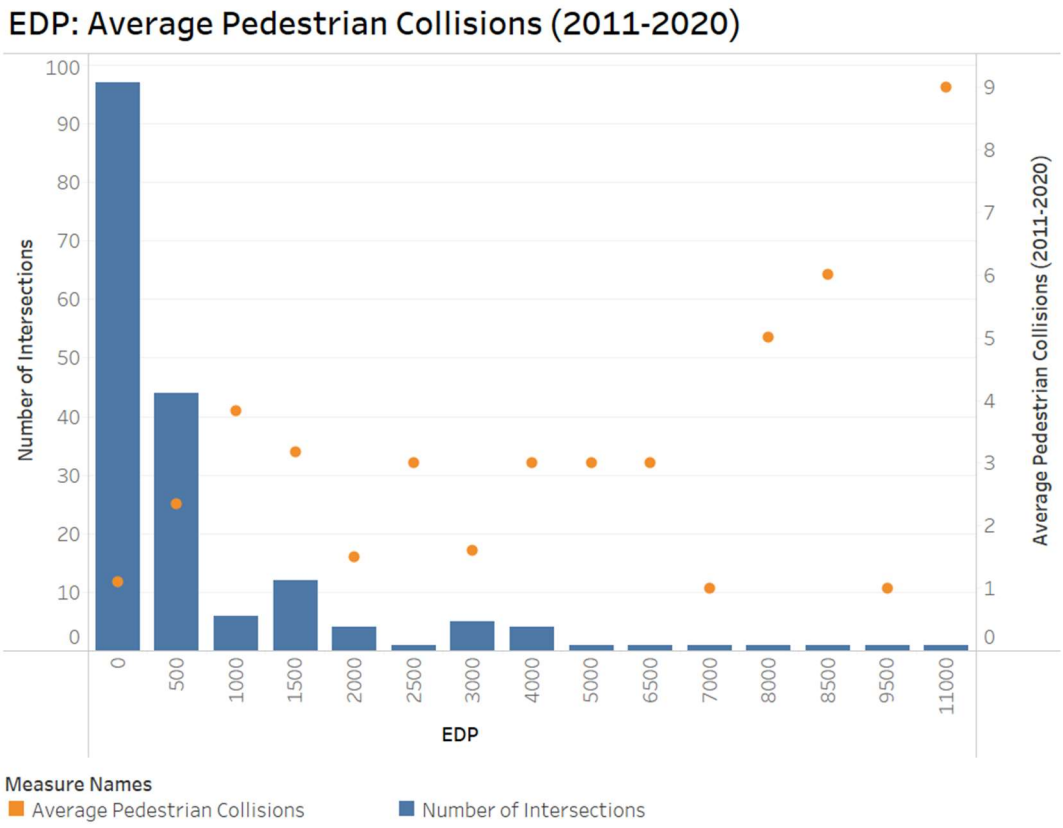


Figure E- 7 Average Pedestrian Collisions Based on Estimated Daily Pedestrians: All Study Sites

In Figure E- 8, the bar chart displays the absolute change in Estimated Daily Pedestrian (EDP) volumes across treatment sites. Each bar represents the change in the number of pedestrians per day for a specific GEOID.

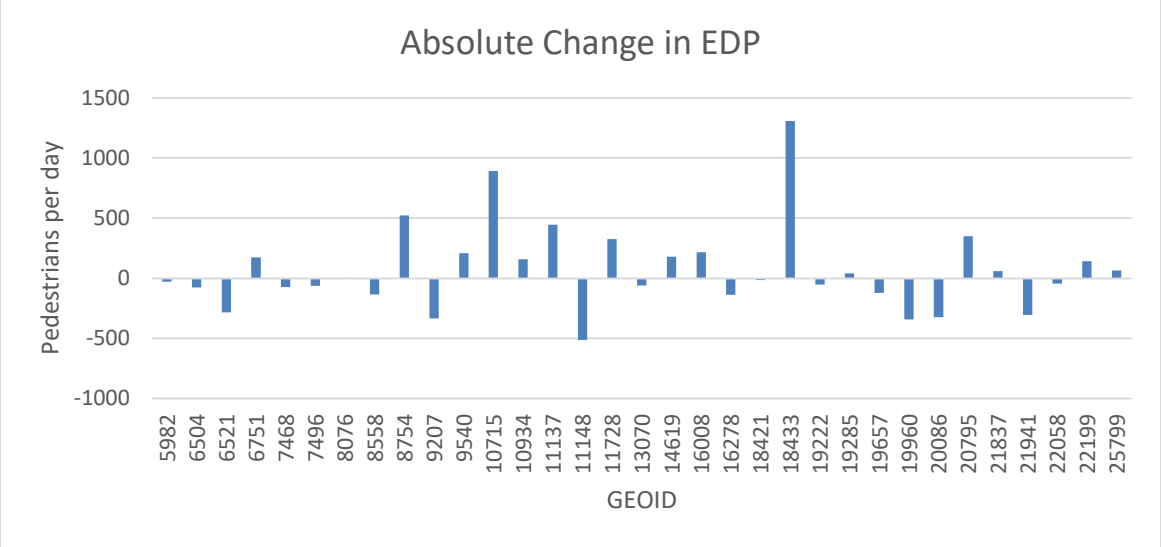


Figure E- 8 Absolute Change in Before period & After period Estimated Daily Pedestrians for each Treatment Sites

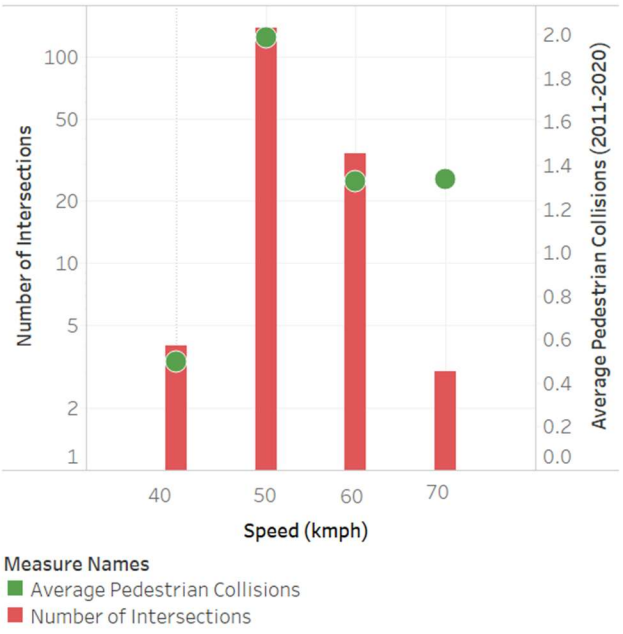
Table E- 1 provides the before and after values of Estimated Daily Traffic (EDT) and Estimated Daily Pedestrians (EDP), along with their absolute changes, for treatment sites.

Table E- 1 Absolute Change in EDT & EDP for each Treatment Sites

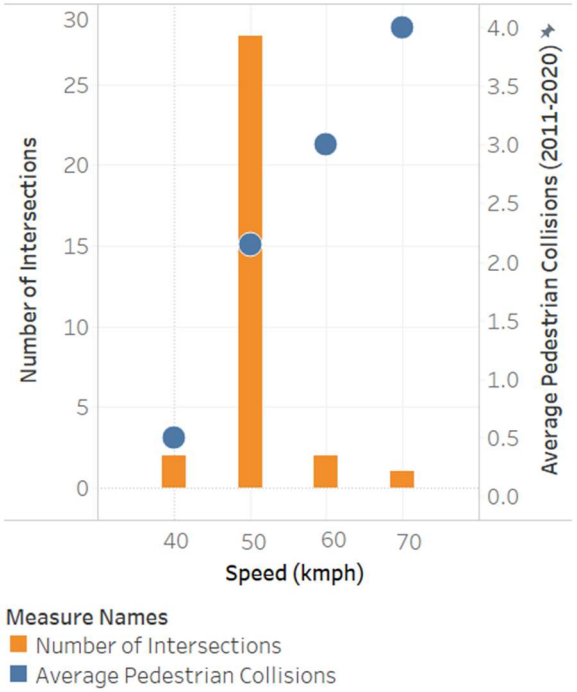
GeoID	EDT Before	EDT After	Absolute Change	EDP Before	EDP After	Absolute Change
5982	19.55238	20.17704	*0.62466*	581	552	*-29*
6504	21.86658	23.05674	*1.19016*	428	352	*-76*
6521	15.76614	15.6252	*-0.14094*	944	661	*-284*
6751	12.15216	11.61102	*-0.54114*	1717	1890	*173*
7468	26.00604	22.1502	*-3.85584*	202	130	*-73*
7496	32.34138	28.1445	*-4.19688*	513	450	*-64*
8076	21.74304	18.87204	*-2.871*	107	110	*3*
8558	25.85118	24.76368	*-1.0875*	614	478	*-136*
8754	26.5089	23.75448	*-2.75442*	795	1316	*522*
9207	19.17132	19.56108	*0.38976*	1168	834	*-334*
9540	20.63814	19.12608	*-1.51206*	473	680	*207*
10715	15.41118	13.47456	*-1.93662*	910	1802	*892*
10934	15.05274	16.36122	*1.30848*	397	555	*158*
11137	16.5126	15.8514	*-0.6612*	903	1347	*444*
11148	6.5424	7.13748	*0.59508*	1410	897	*-513*
11728	16.8084	20.8452	*4.0368*	579	904	*325*
13070	15.83052	13.7721	*-2.05842*	411	349	*-62*
14619	18.39702	17.12508	*-1.27194*	162	340	*178*
16008	24.25038	24.33738	*0.087*	81	296	*215*
16278	21.2628	24.92202	*3.65922*	303	165	*-138*
18421	5.5419	4.5675	*-0.9744*	474	458	*-16*
18433	17.0868	13.89912	*-3.18768*	584	1890	*1306*
19222	18.75198	21.64038	*2.8884*	253	200	*-53*
19285	13.1457	12.1278	*-1.0179*	332	372	*39*
19657	7.1427	7.34454	*0.20184*	629	507	*-122*
19960	13.06218	14.4855	*1.42332*	850	505	*-344*
20086	37.70406	39.4806	*1.77654*	599	275	*-323*
20795	11.45616	10.85238	*-0.60378*	551	899	*348*
21837	8.0736	7.34106	*-0.73254*	783	841	*58*
21941	14.21058	14.72388	*0.5133*	753	449	*-305*
22058	37.74408	32.60238	*-5.1417*	515	471	*-44*
22199	22.03188	22.50516	*0.47328*	657	798	*141*
25799	14.33412	12.69504	*-1.63908*	141	205	*64*

E.3. Speed

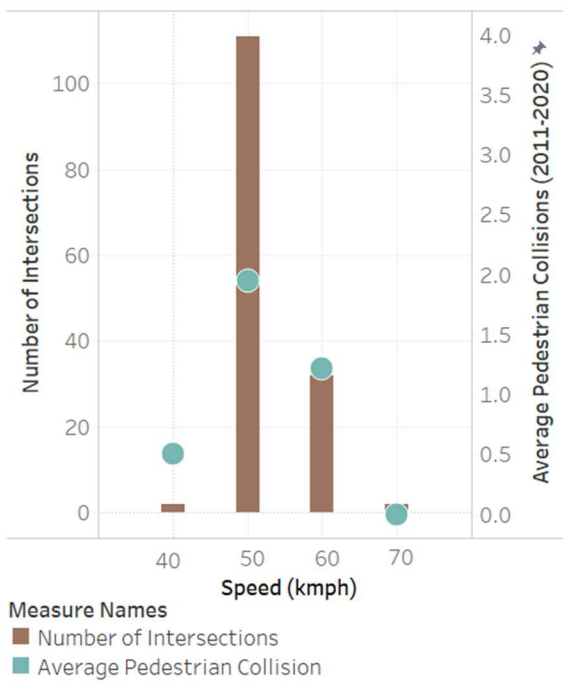
The average pedestrian collisions (2011-2020) by speed limit on major road for all sites, LPI sites, and reference sites, is illustrated in Figure E- 9. Across all types of intersections, the highest number of intersections are found at the 50 km/h speed limit, which also shows the highest average pedestrian collisions. For LPI sites, the data indicates a concentration of intersections with speed at 50 km/h, correlating with significant average pedestrian collisions. Similarly, reference sites also demonstrate a high number of intersections and average collisions at the 50 km/h speed limit. These trends highlight the prevalence and impact of the 50 km/h speed limit on pedestrian safety across different intersection types.



a. All Sites



b. LPI Sites



c. Reference Sites

Figure E- 9 Average Pedestrian Collisions (2011-2020) by Speed Limit

Appendix F

Data Description: Roadway and Geometric Characteristics

This appendix provides a summary statistics of the key intersection geometric characteristics, including lanes, median, crosswalks, road class, and others relevant factors.

F.1. Lanes

The distribution of intersections and average pedestrian collisions across different total number of lanes for both LPI sites and reference sites is shown in Table F- 1. For LPI sites, the majority of intersections have 12 lanes (21.21%), with an average of 2.00 pedestrian collisions. Notably, intersections with 16 lanes (4.33) and 18 lanes (6.00) have a higher average number of collisions per intersection. For reference sites, the highest percentage of intersections (20.41%) also have 12 lanes, with an average of 1.63 pedestrian collisions. There is a significant spike in average collisions at intersections with 21 lanes (13.00), indicating a potential correlation between the number of lanes and pedestrian collisions in these instances.

Table F- 1 Distribution of Intersections and Average Pedestrian Collisions by Total Number of Lanes for LPI Sites and Reference Sites

Total Number of Lanes	LPI Sites			Reference Sites		
	Number of Intersections	*%*	*Average Collisions*	*Number of Intersections*	*%*	*Average Collisions*
6	1	3.03	1.00	2	1.36	0.50
7	-	-	-	6	4.08	1.83
8	3	9.09	0.33	5	3.4	1.00
9	2	6.06	2.00	6	4.08	1.17
10	3	9.09	3.67	22	14.97	1.14
11	4	12.12	0.75	24	16.33	1.46
12	7	21.21	2.00	30	20.41	1.63
13	4	12.12	2.50	13	8.84	1.38
14	4	12.12	1.00	11	7.48	2.00
15	-	-	-	7	4.76	3.57
16	3	9.09	4.33	8	5.44	2.88
17	1	3.03	4.00	2	1.36	3.00
18	1	3.03	6.00	5	3.4	1.60
19	-	-	-	1	0.68	1.00

20	-	-	-	2	1.36	3.50
21	-	-	-	1	0.68	13.00
22	-	-	-	1	0.68	4.00
24	-	-	-	1	0.68	3.00

Table F- 2 presents the distribution of intersections and average pedestrian collisions for LPI sites, categorized by the number of left turn lanes, through lanes, and right turn lanes. Similarly, Table F- 3 presents the distribution of intersections and average pedestrian collisions for Reference Sites

Table F- 2 Distribution of Intersections and Average Pedestrian Collisions by Type of Lanes for LPI Sites

Number of Type of Lane at intersection	Type of Lanes								
	Left turn lanes			Through lanes			Right turn lanes		
	*Num of int.**	*%*	*Avg. Crashes*	*Num of int.**	*%*	*Avg. Crashes*	*Num of int.**	*%*	*Avg. Crashes*
0	5	15.15	1.40	-	-	-	16	48.48	1.25
1	4	12.12	1.00	-	-	-	11	33.33	3.27
2	14	42.42	2.36	3	9.09	1.33	6	18.18	2.50
3	6	18.18	2.33	2	6.06	5.00	-	-	-
4	4	12.12	3.25	13	39.39	1.23	-	-	-
5	-	-	-	5	15.15	2.00	-	-	-
6	-	-	-	10	30.3	3.10	-	-	-
*Number of Intersections									

For LPI sites, intersections with 2 left turn lanes are the most common (42.42%), averaging 2.36 pedestrian collisions, with those having 4 left turn lanes experiencing the highest average crashes (3.25). Most intersections have 4 through lanes (39.39%) and average 1.23 crashes, while those with 3 through lanes see the highest average crashes (5.00). The majority of intersections lack right turn lanes (48.48%) and average 1.25 crashes, whereas those with 1 right turn lane have a higher average of 3.27 crashes. For reference sites, intersections with 2 left turn lanes are the most common (1.43%), averaging 2.36 pedestrian collisions, with those having 4 left turn lanes experiencing the highest average crashes (3.25). Most intersections have 4 through lanes (45.58%) and average 1.52 crashes, while those with 8 through lanes see the highest average crashes (4.20). The majority of intersections lack right turn lanes

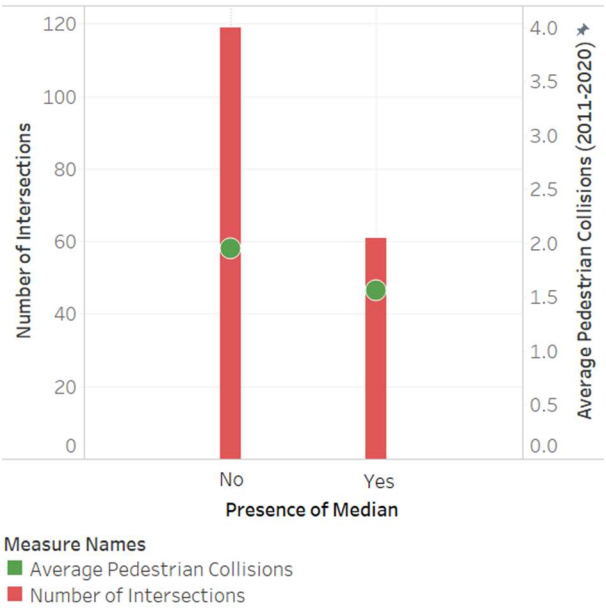
(52.38%) and average 1.91 crashes, whereas those with 4 right turn lanes have the highest average of 3.00 crashes.

Table F- 3 Distribution of Intersections and Average Pedestrian Collisions by Type of Lanes for Reference Sites

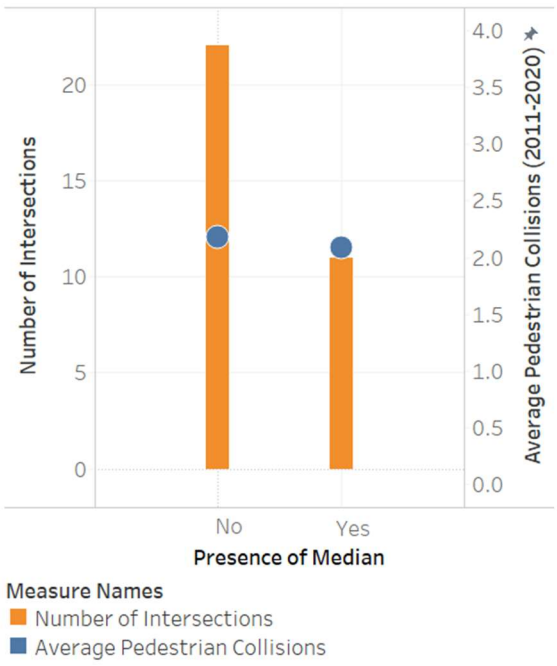
Number of Type of Lane at intersection	Type of Lanes								
	Left turn lanes			Through lanes			Right turn lanes		
	*Num of int.**	*%*	*Avg. Crashes*	*Num of int.**	*%*	*Avg. Crashes*	*Num of int.**	*%*	*Avg. Crashes*
0	26	1.12	1.40	-	-	-	77	52.38	1.91
1	31	1.23	1.00	-	-	-	38	25.85	1.76
2	44	1.43	2.36	7	4.76	0.71	27	18.37	1.30
3	19	2.58	2.33	12	8.16	0.92	4	2.72	1
4	27	2.85	3.25	67	45.58	1.52	1	0.68	3
5	-	-	-	22	14.97	1.05	-	-	-
6	-	-	-	32	21.77	2.84	-	-	-
7	-	-	-	2	1.36	1.5	-	-	-
8	-	-	-	5	3.4	4.2	-	-	-
*Number of Intersections									

F.2. Median

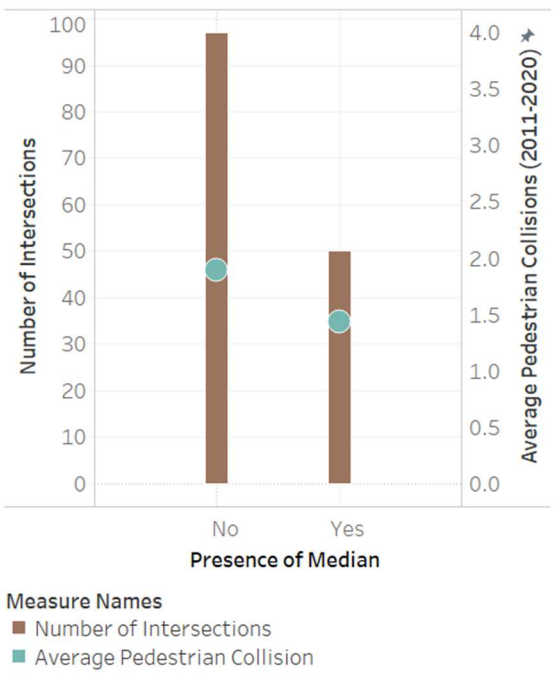
The number of intersections and average pedestrian collisions based on the presence of a median for all sites, LPI sites, and reference sites, is compared in Figure F- 1. Across all categories, intersections without a median are more common. For all sites and reference sites, intersections without a median, exhibit higher average pedestrian collisions compared to those with a median. However, for LPI sites, intersections with a median show a similar average number of pedestrian collisions compared to those without a median. These observations suggest that the presence of a median generally correlates with lower pedestrian collision rates at all sites and reference sites, while LPI sites do not show a significant difference in collision rates based on the presence of a median. Figure F- 2 shows similar results trends for Raised Medians. However, for LPI sites, intersections with a raised median show a higher average number of pedestrian collisions compared to those without a raised median.



a. All Sites



b. LPI Sites



c. Reference Sites

Figure F- 1 Average Pedestrian Collisions (2011-2020) by Presence of Median

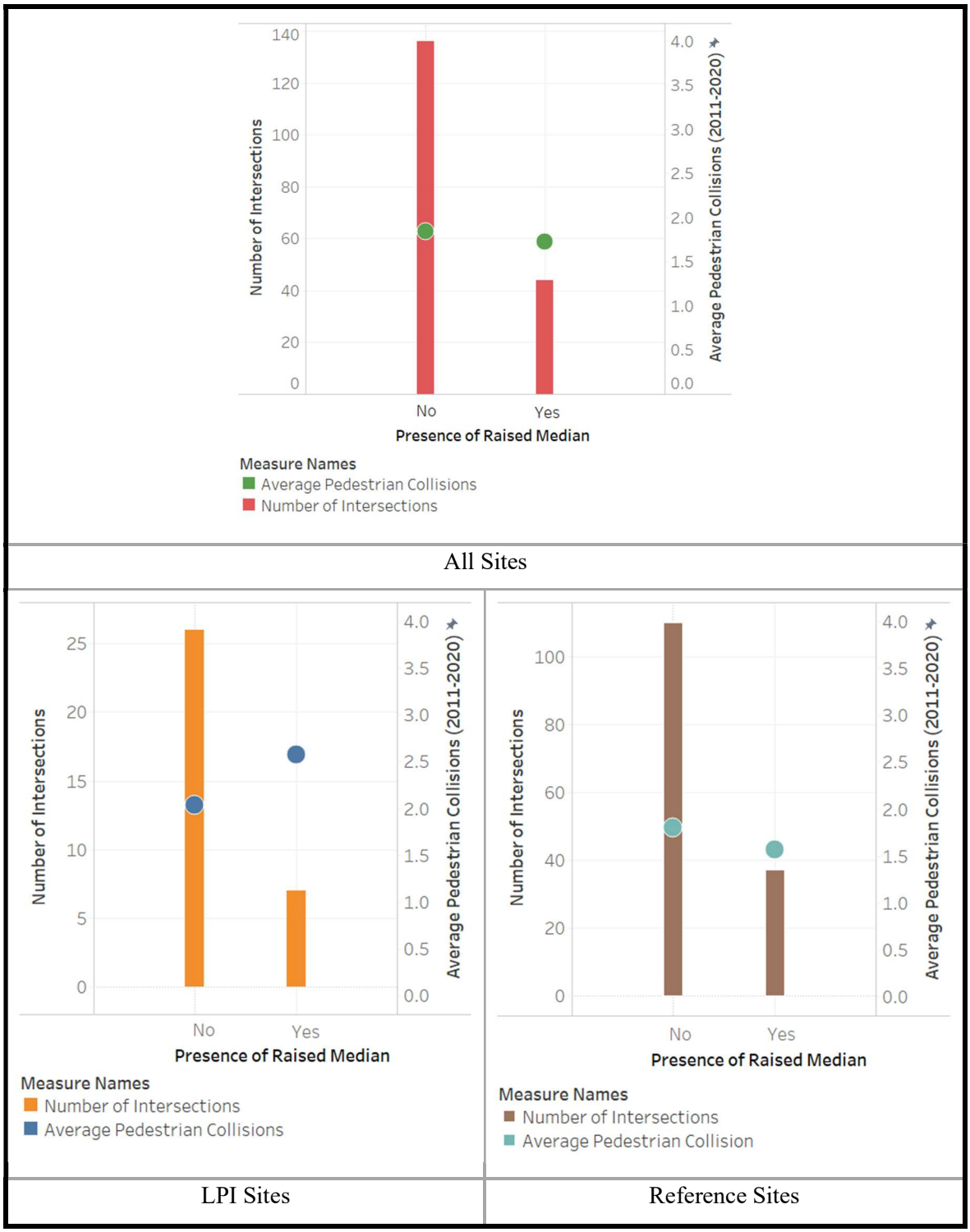


Figure F- 2 Average Pedestrian Collisions (2011-2020) by Presence of Raised Median

F.3. Crosswalk

Total crosswalk length impacts the number of intersections and average pedestrian collisions for all sites, LPI sites, and reference sites, as shown in Figure F- 4. Across all categories, intersections with crosswalk lengths between 30 to 60 meters are the most common. For all sites, the highest number of intersections is at 45 meters, with a notable peak in average pedestrian collisions at 105 meters. For LPI sites, intersections with crosswalk lengths of 45 and 60 meters are most prevalent, with the highest average pedestrian collisions occurring at 75 meters. Reference sites show a similar trend, with the highest number of intersections at 45 meters and the highest average pedestrian collisions also at 105 meters. These observations suggest that crosswalk lengths between 30 to 60 meters are prevalent across all intersection types, with longer crosswalk lengths associated with increased pedestrian collisions.

The standard or conventional crosswalk marking, as shown in Figure F- 3, consists of two parallel lines that define the edges of the crosswalk. These lines are typically painted perpendicular to the direction of traffic flow to indicate where pedestrians should cross the street. Non-standard or non-conventional crosswalk markings refer to any crosswalk patterns that deviate from the basic "standard" design of two parallel lines. The non-standard markings observed in the region of Waterloo are Ladder, Painted, and Textured.

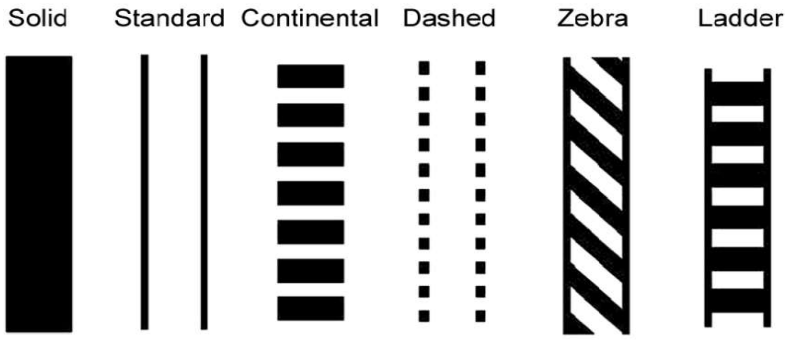
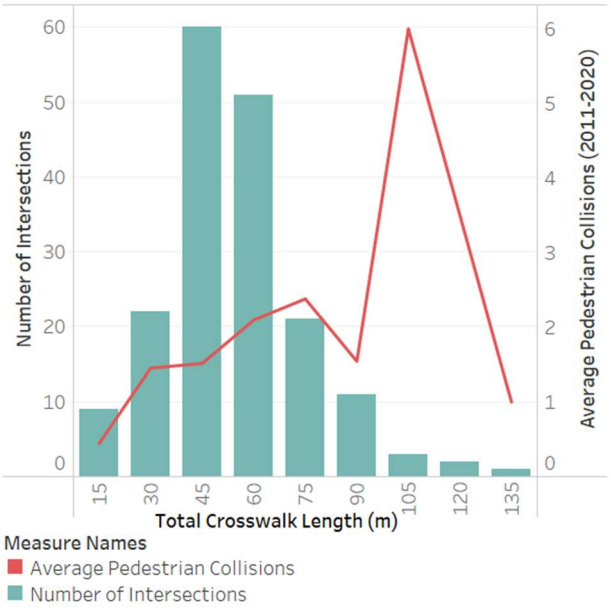
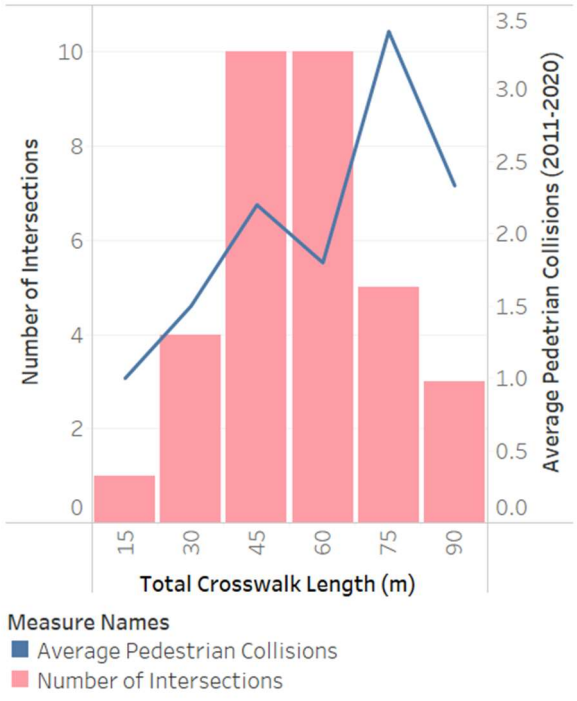


Figure F- 3 Crosswalk marking patterns (Zegeer et al., 2005)

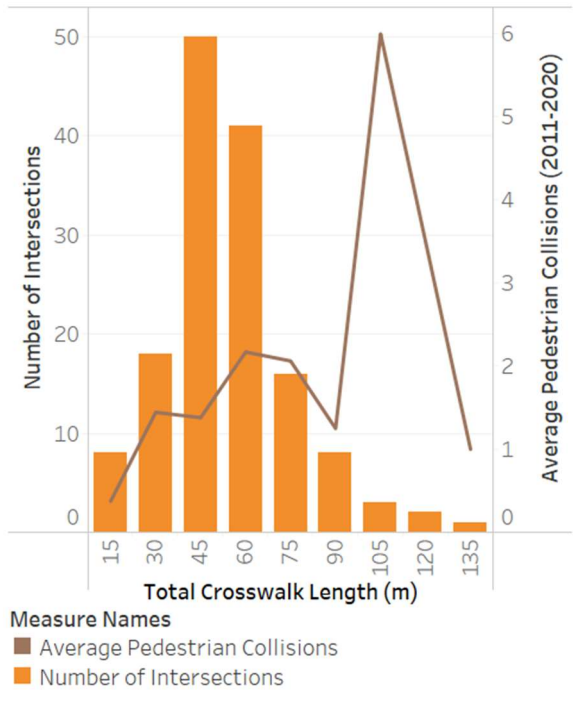
Across all categories, intersections with standard crosswalk markings are more common, as shown in Figure F- 5. However, intersections with non-standard markings exhibit higher average pedestrian collisions compared to those with standard markings across all categories. These observations suggest that non-standard markings are associated with increased pedestrian collision rates at all types of intersections.



a. All Sites



b. LPI Sites



c. Reference Sites

Figure F- 4 Average Pedestrian Collisions (2011-2020) by Total Crosswalk Length

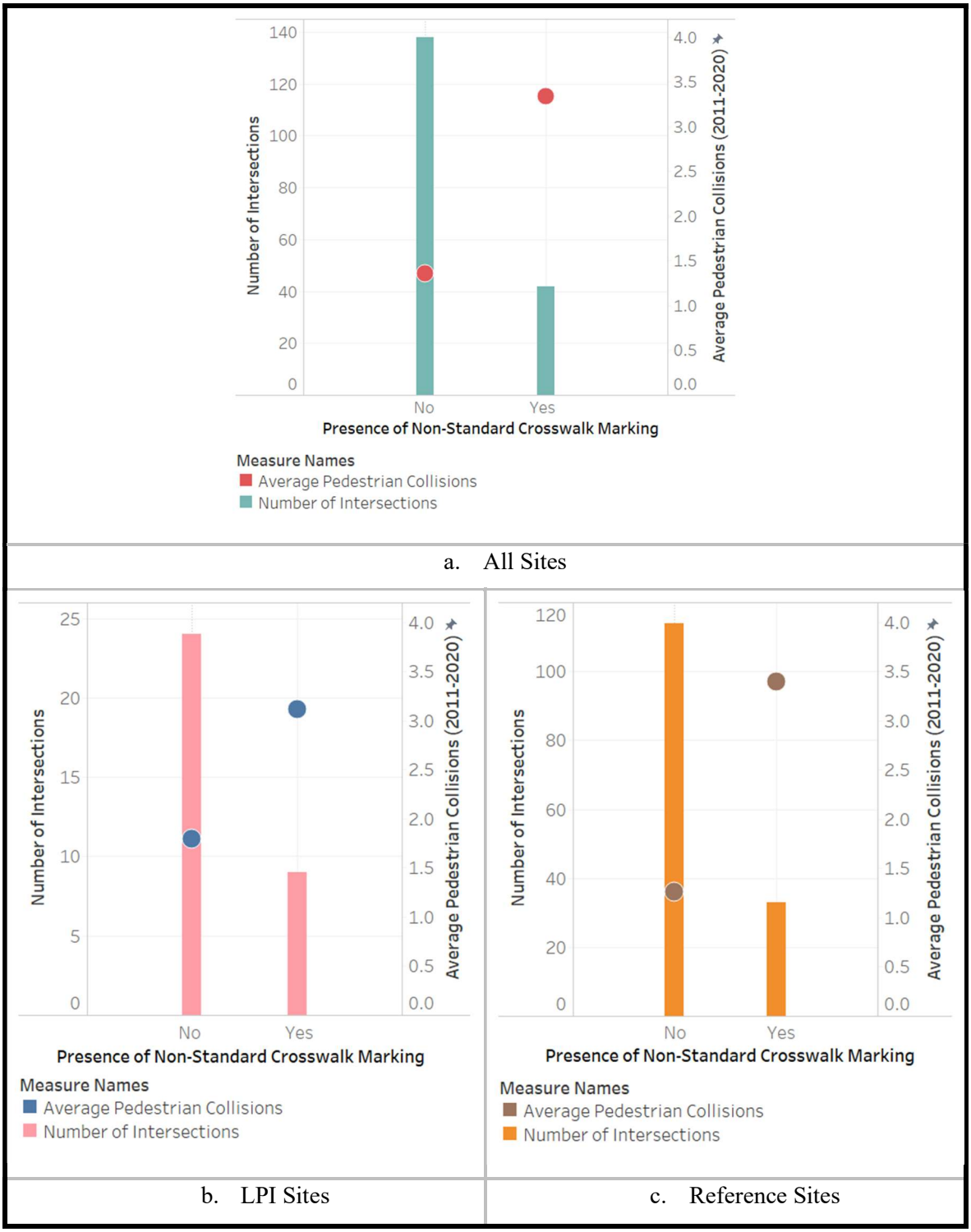
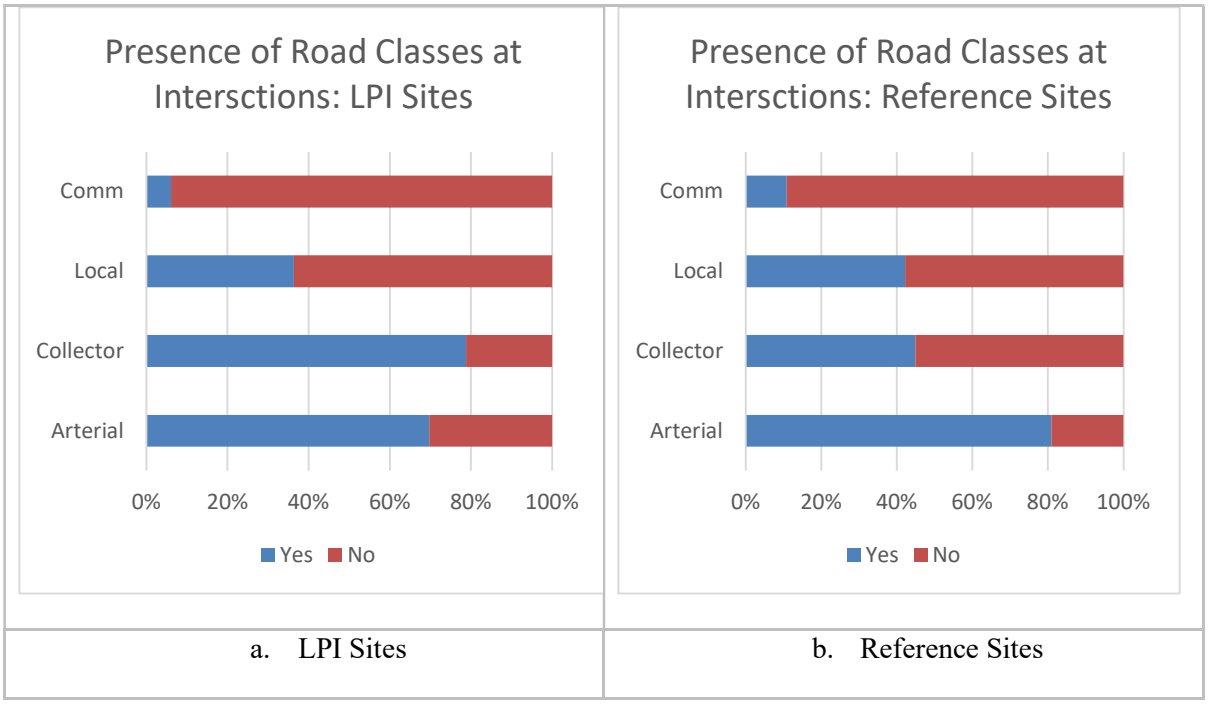


Figure F- 5 Average Pedestrian Collisions (2011-2020) by Presence of Non-Standard Crosswalk Marking

F.4. Road Classification

Figure F- 6 compare the presence of different road classes (Commercial, Local, Collector, and Arterial) at intersections for LPI sites and reference sites. For both LPI and reference sites, arterial and collector roads are the most common road classes at intersections. Commercial roads are the least common, followed by local roads.

The detailed distribution of intersections and corresponding average pedestrian collision based on different road use is presented in Table F- 4 for LPI sites and in Table F- 5 for Reference Sites.



a. LPI Sites

b. Reference Sites

Figure F- 6 Presence of Road Classes at Intersections for LPI and Reference Sites

Table F- 4 Distribution of Intersections by Road Classification and Average Crashes: LPI Sites

Number of Type of Road Classification at intersection	Type of Road Classification											
	Arterial			Collector			Local			Comm		
	*Num of int.**	%	*Avg. Crashes*	*Num of int.**	%	*Avg. Crashes*	*Num of int.**	%	*Avg. Crashes*	*Num of int.**	%	*Avg. Crashes*
0	10	30.30	2.4	7	21.21	0.8	21	63.63	2.1	31	93.94	1.9
1	-	-	-	12	36.36	2.7	5	15.15	2	2	6.06	5
2	19	57.58	2.2	10	30.30	2.3	6	18.18	2.7	-	-	-
3	1	3.03	1	-	-	-	-	-	-	-	-	-
4	3	9.09	1.3	4	12.12	2.2	1	3.03	0	-	-	-
*Number of Intersections												

Table F- 5 Distribution of Intersections by Road Classification and Average Crashes: Reference Sites

Number of Type of Road Classification at intersection	Type of Road Classification											
	Arterial			Collector			Local			Comm		
	*Num of int.**	%	*Avg. Crashes*	*Num of int.**	%	*Avg. Crashes*	*Num of int.**	%	*Avg. Crashes*	*Num of int.**	%	*Avg. Crashes*
0	28	19.05	1.3	81	55.10	1.8	85	57.82	1.8	131	89.12	1.7
1	2	1.36	0	13	8.84	1.1	23	15.64	1.8	14	9.52	1.6
2	89	60.54	1.7	41	27.89	1.6	37	25.17	1.5	2	1.3	0
3	7	4.76	0.8	4	2.72	0.7	1	0.68	3	-	-	-
4	21	14.29	2.9	8	5.44	2.2	1	0.68	1	-	-	-
*Number of Intersections												

F.5 Others

Based on number of Legs (3-legged and 4-legged intersections), The number of intersections and average pedestrian collisions for all sites, LPI sites, and reference sites, is illustrated in Figure F- 7. Across all three categories, 4-legged intersections are more prevalent than 3-legged intersections. For all sites and reference sites, the average pedestrian collisions are higher at 4-legged intersections compared to 3-legged ones. This trend is also observed in LPI sites, indicating that 4-legged intersections consistently exhibit higher pedestrian collision rates across different intersection types.

Figure F- 8 compare the number of intersections and average pedestrian collisions based on the presence of one-way traffic for all sites, LPI sites, and reference sites. Across all types of intersections, those without one-way traffic are significantly more common and exhibit higher average pedestrian collisions. In all sites and reference sites, intersections with two-way traffic show a notably higher number of pedestrian collisions compared to those with one-way traffic. For LPI sites, while fewer intersections have one-way traffic, the trend of higher pedestrian collisions at two-way intersections remains consistent.

Figure F- 9 compare the number of intersections and average pedestrian collisions based on the presence of slip lanes for all sites, LPI sites, and reference sites. Across all categories, intersections without slip lanes are significantly more common. This is because treatment sites with slip lanes constitute only 10% of all treatment sites. Consequently, the proportion of reference sites with slip lanes is similar to that of the treatment sites. For all sites and reference sites, intersections without slip lanes exhibit higher average pedestrian collisions. However, for LPI sites, intersections with slip lanes show a higher average number of pedestrian collisions compared to those without slip lanes. These observations suggest that while the absence of slip lanes is generally associated with higher pedestrian collision rates, the presence of slip lanes at LPI sites may present specific challenges that result in increased pedestrian collisions.

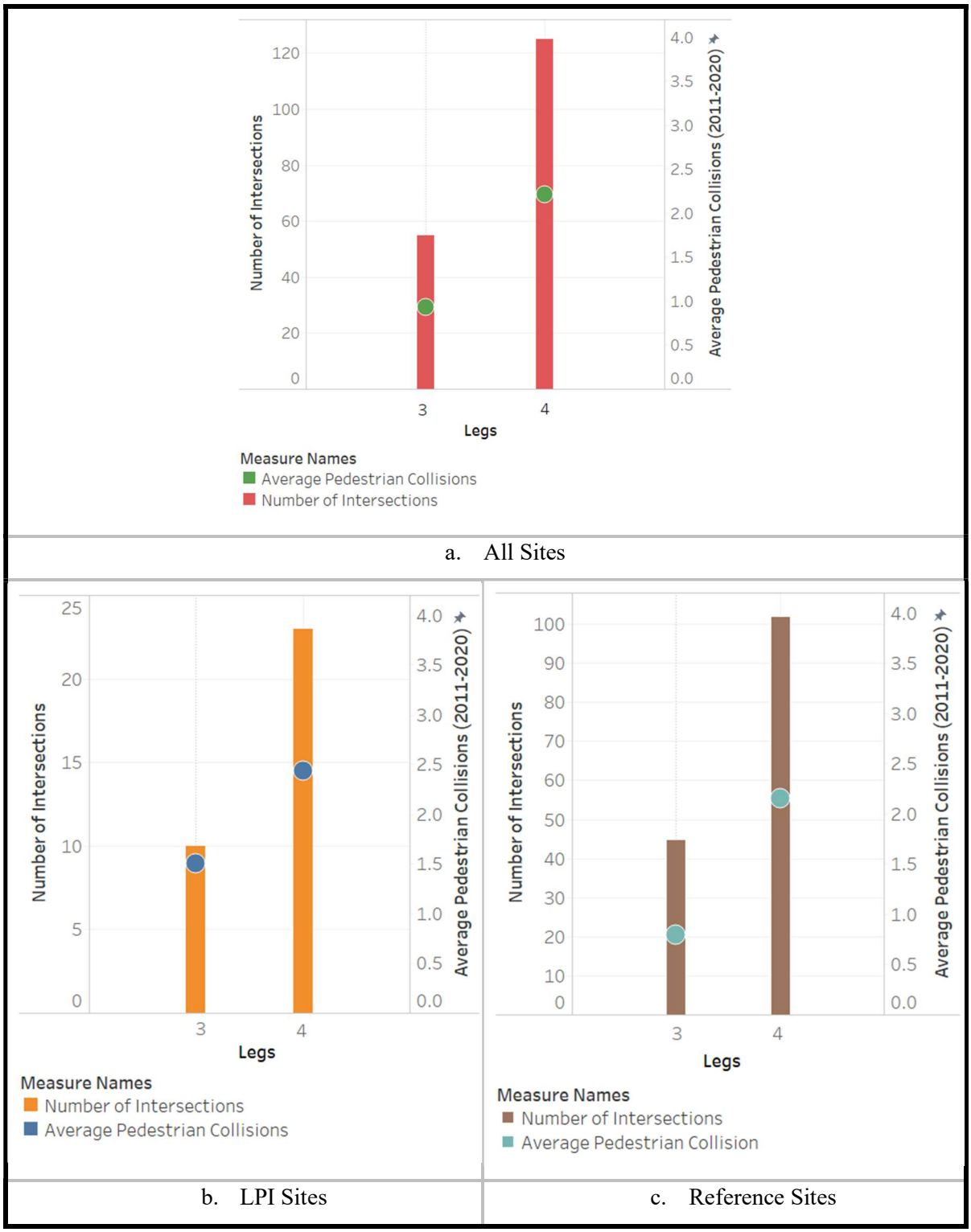
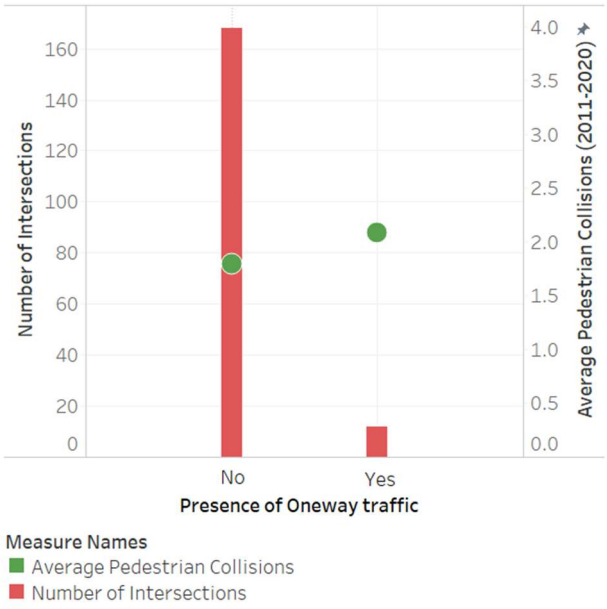
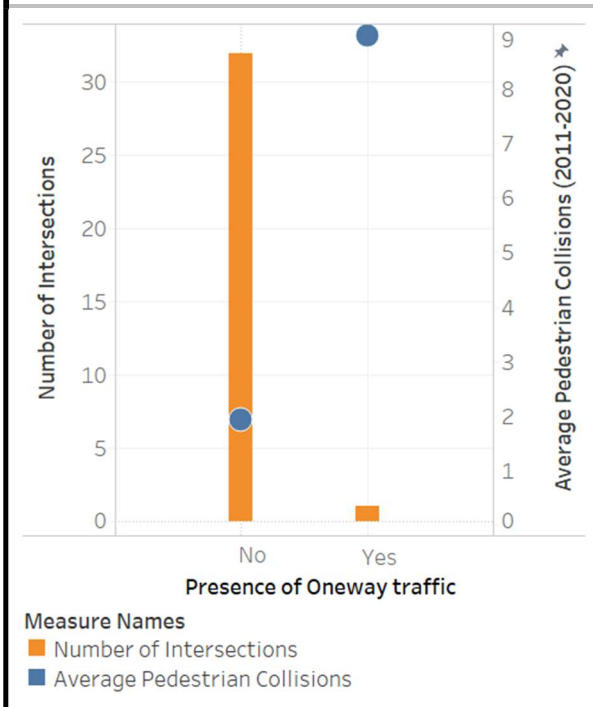


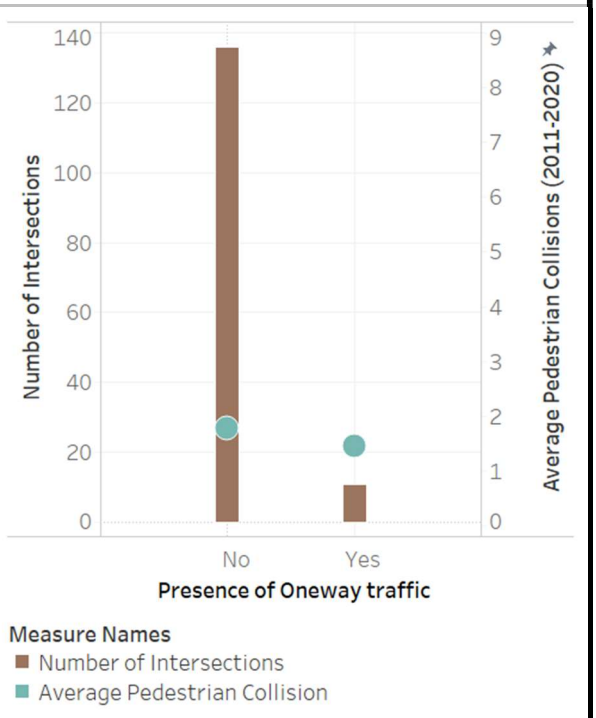
Figure F- 7 Average Pedestrian Collisions (2011-2020) by Number of Legs



d. All Sites



e. LPI Sites



f. Reference Sites

Figure F- 8 Average Pedestrian Collisions (2011-2020) by Presence of One-way Traffic

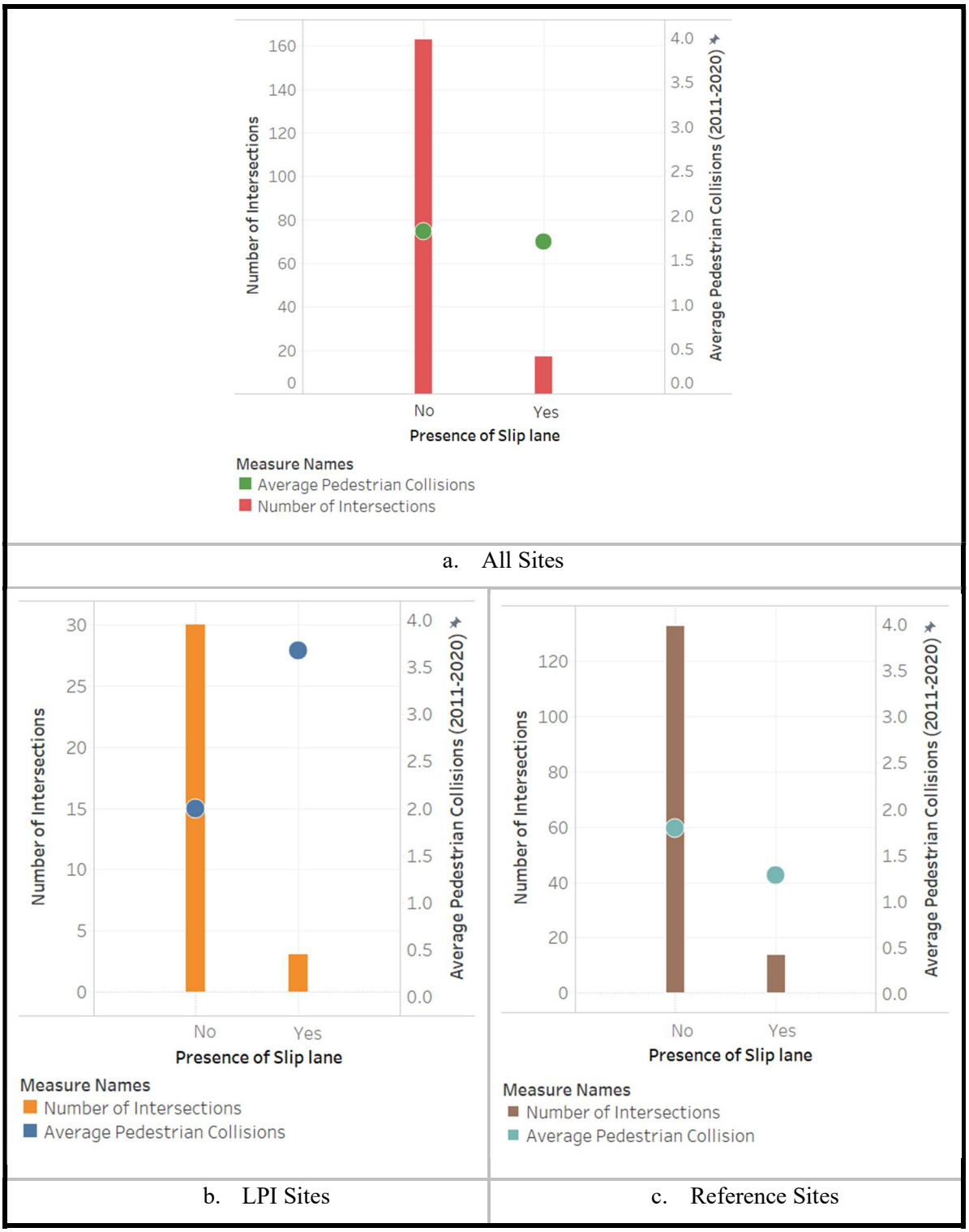


Figure F- 9 Average Pedestrian Collisions (2011-2020) by Presence of Slip Lane

Figure F- 10 compare the number of intersections and average pedestrian collisions based on the presence of skewness for all sites, LPI sites, and reference sites. Across all categories, intersections without skewness are significantly more common. For all sites and LPI sites, intersections without skewness exhibit higher average pedestrian collisions compared to those with skewness. In contrast, for reference sites, intersections with skewness show a slightly higher average number of pedestrian collisions.

The number of intersections and average pedestrian collisions based on the number of sidewalks missing for all sites, LPI sites, and reference sites, is shown in Figure F- 11. In all categories, intersections without any missing sidewalks are the most prevalent. Both all sites and reference sites exhibit variability and fluctuations in average pedestrian collisions. Notably, for LPI sites, intersections with two missing sidewalks experience the highest average pedestrian collisions.

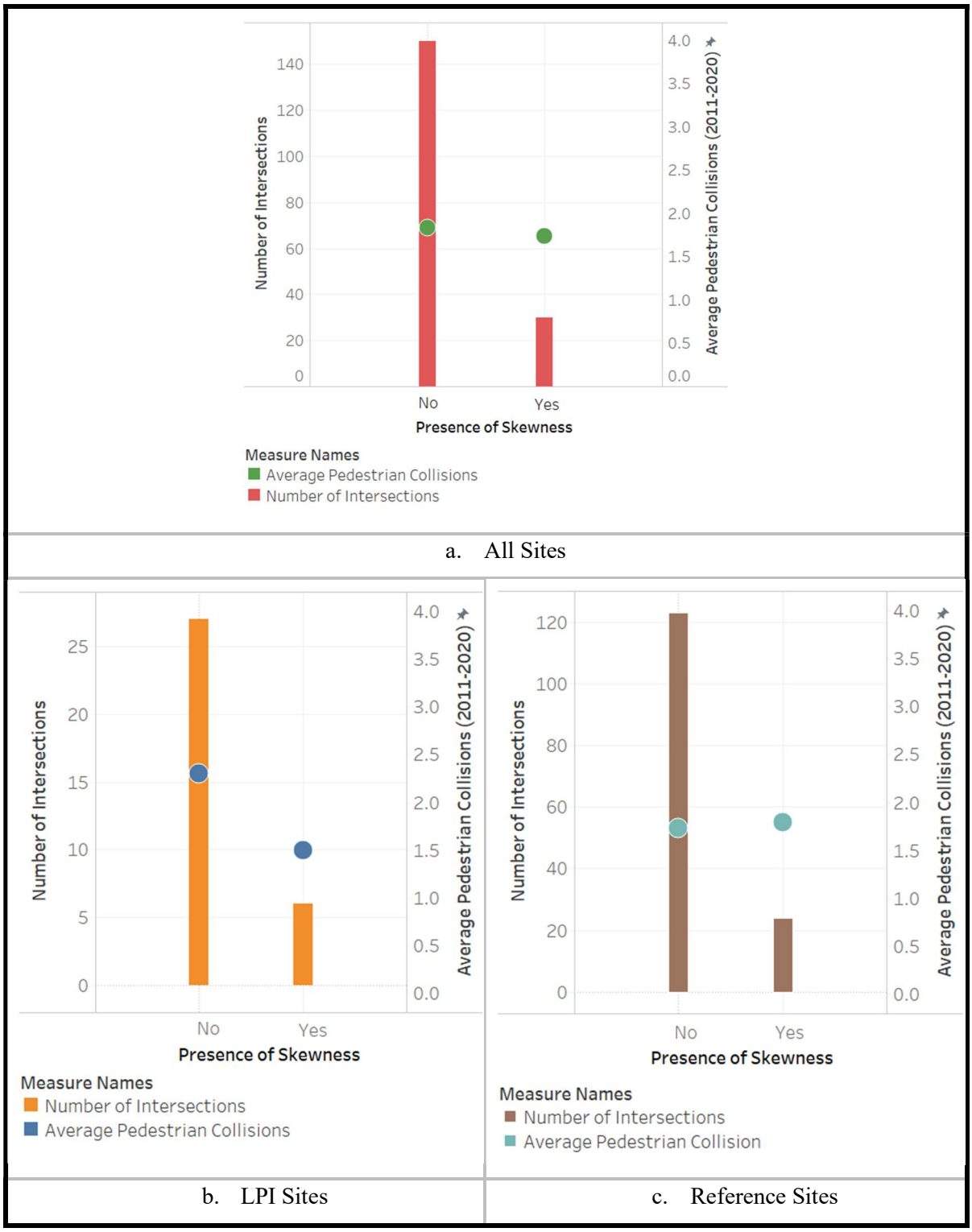


Figure F- 10 Average Pedestrian Collisions (2011-2020) by Presence of Skewness

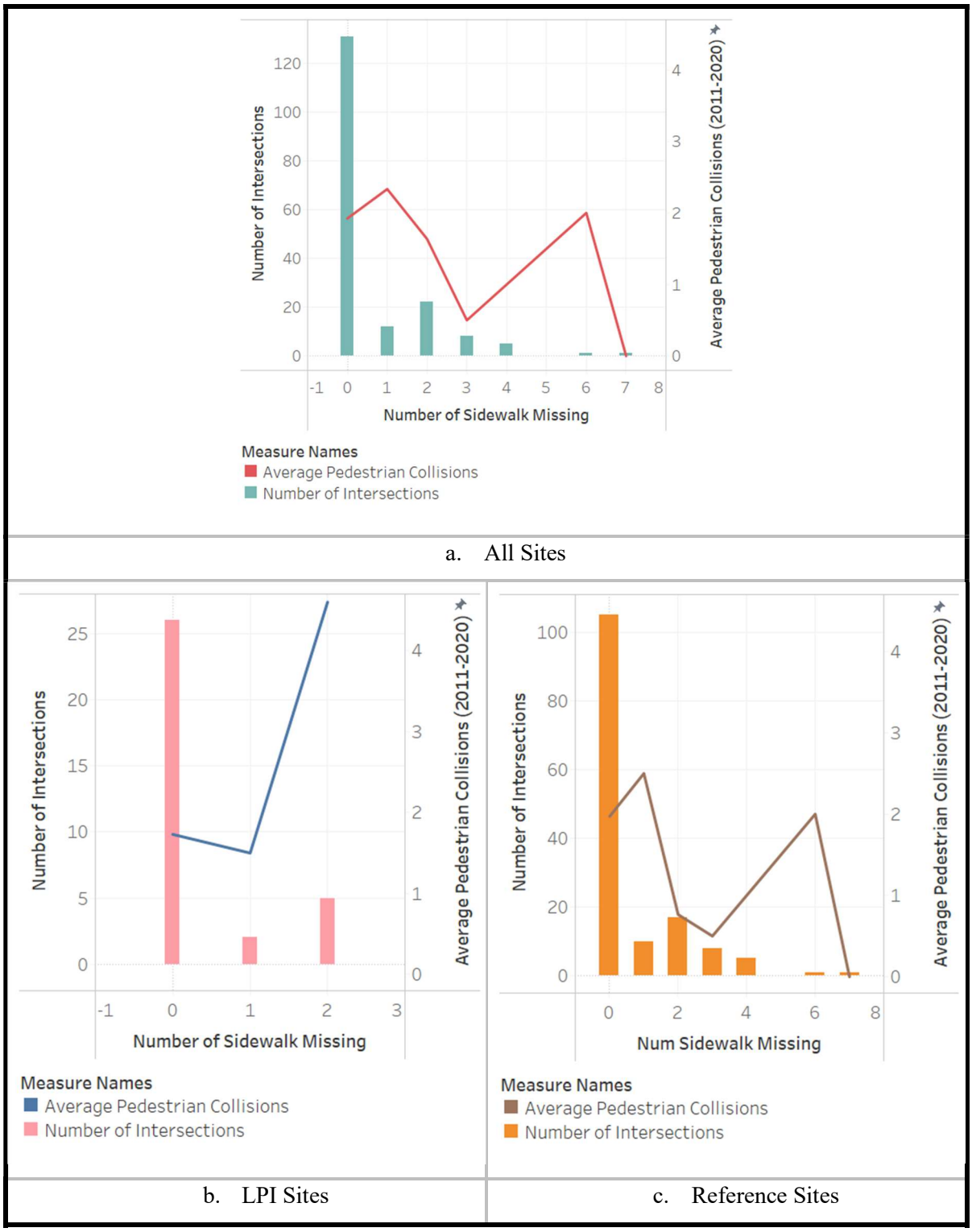


Figure F- 11 Average Pedestrian Collisions (2011-2020) by Number of Sidewalks Missing

Appendix G

Data Description: Land Use & Built Environment Characteristics

G.1. Land Use

The presence of different types of land use (school, open space, commercial, and residential) at intersections for LPI sites and reference sites is compared in Figure G- 1 & Figure G- 2. For LPI sites, residential and commercial land uses are the most common, while open spaces and schools are less prevalent. Reference sites show a similar pattern with a higher prevalence of residential and commercial land uses, but also a notable presence of open spaces compared to LPI sites. Schools are the least common type of land use at intersections for both LPI and reference sites. The detailed distribution of intersections and corresponding average pedestrian collision based on different land use is presented in Table G- 1 for LPI sites and in Table G- 2 for Reference Sites.

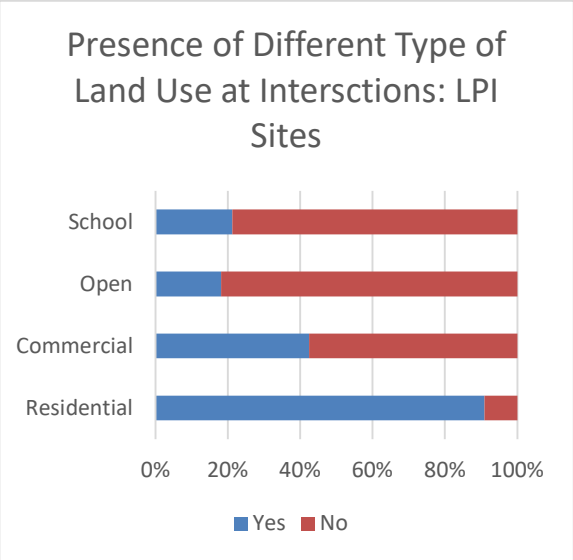


Figure G- 1 Presence of Different Type of Land Use at Intersections: LPI Sites

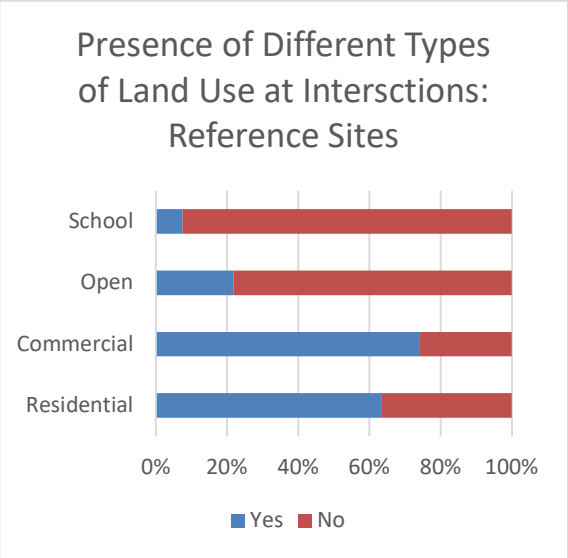


Figure G- 2 Presence of Different Types of Land Use at Intersections: Reference Sites

Table G- 1 Distribution of Land Use Types at Intersections and Corresponding Average Pedestrian Collisions: LPI Sites

Number of Type of Land Use at intersection	Type of Land Use											
	Residential			Commercial			Open			School		
	*Num of int.**	%	*Avg. Crashes*	*Num of int.**	%	*Avg. Crashes*	*Num of int.**	%	*Avg. Crashes*	*Num of int.**	%	*Avg. Crashes*
0	3	9.09	3.7	19	57.57	1.5	27	81.81	2.2	26	78.78	2.2
1	3	9.09	2.3	5	15.15	2	6	18.18	2	5	15.15	2
2	5	15.15	3.2	8	24.24	2.7	0	0	0	2	6.06	1
3	9	27.27	2.1	0	0	0	0	0	0	0	0	0
4	13	39.39	1.3	1	3.03	9	0	0	0	0	0	0
*Number of Intersections												

Table G- 2 Distribution of Land Use Types at Intersections and Corresponding Average Pedestrian Collisions: Reference Sites

Number of Type of Land Use at intersection	Type of Land Use											
	Residential			Commercial			Open			School		
	*Num of int.**	%	*Avg. Crashes*	*Num of int.**	%	*Avg. Crashes*	*Num of int.**	%	*Avg. Crashes*	*Num of int.**	%	*Avg. Crashes*
0	54	36.73	1.6	38	25.85	1.1	115	78.23	1.9	136	92.51	1.7
1	17	11.56	2.5	33	22.44	1.5	12	8.16	2.1	6	4.08	1.1
2	29	19.72	1.7	28	19.04	2.1	14	9.52	0.4	5	3.40	1.4
3	24	16.32	1.9	13	8.84	2.8	6	4.08	0	0	0	0
4	23	15.64	1.2	35	23.80	2	0	0	0	0	0	0
*Number of Intersections												

G.2. School Proximity

All study sites are typically located within a 1000-meter radius of a school. The impact of school proximity (within 500 meters) on pedestrian collisions at intersections for both LPI sites and reference sites is presented in Table G- 3. For LPI sites, 66.67% of intersections are within 500m of schools, with an average of 1.57 pedestrian crashes. In contrast, for the intersections that are not within 500m of schools, a higher average crash rate of 1.82 was observed. For reference sites, 81.82% of intersections are near schools, with an average of 1.78 pedestrian crashes, whereas for intersections that are not near schools the pedestrian crash rate is much higher (3.83). The Proportion of school presence near intersections is also illustrated in Figure G- 3. Furthermore, Table G- 4 details the influence of the number of schools within 500 meters on pedestrian collisions at intersections for both LPI sites and reference sites.

Table G- 3 Distribution of Intersections and Average Pedestrian Collisions by Presence of School within 500m of intersection for LPI Sites and Reference Sites

Presence of School within 500m	LPI Sites			Reference Sites		
	Number of intersections	*%*	*Average Crashes*	*Number of intersections*	*%*	*Average Crashes*
Yes	49	66.67	1.57	27	81.82	1.78
No	98	33.33	1.82	6	18.18	3.83

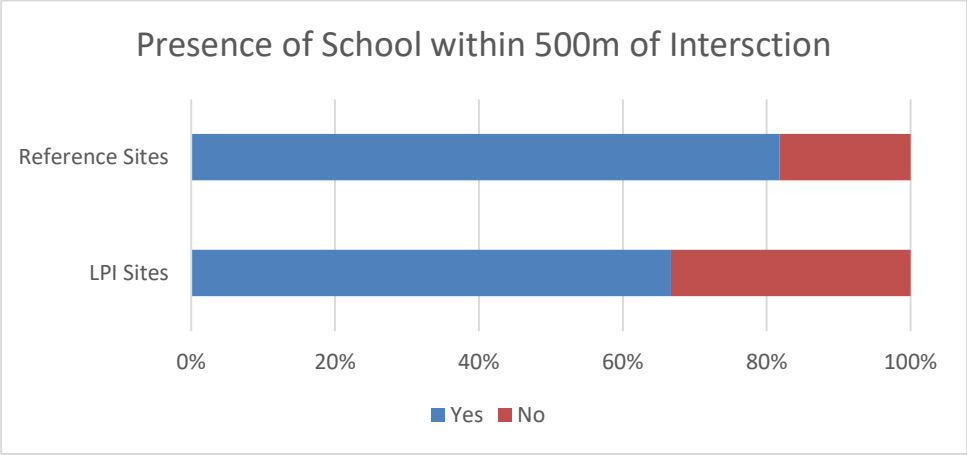


Figure G- 3 Presence of School within 500m of intersection for LPI Sites and Reference Sites

Table G- 4 Distribution of Intersections and Average Pedestrian Collisions by Number of School within 500m of intersection for LPI Sites and Reference Sites

Number of School within 500m	LPI Sites			Reference Sites		
	Number of intersections	*%*	*Average Crashes*	*Number of intersections*	*%*	*Average Crashes*
0	6	18.18	3.83	49	33.33	1.57
1	17	51.51	2	50	34.01	1.66
2	7	21.21	1.28	23	15.64	2.13
3	3	9.09	1.67	8	5.44	1.5
4	0	0	0	10	6.80	1.4
5	0	0	0	6	4.08	2.67
6	0	0	0	1	0.68	5

G.3. Bus Stops

The number of intersections and average pedestrian collisions based on the number of bus stops for all sites, LPI sites, and reference sites is illustrated in Figure G- 4. It should be noted that all intersections have at least one bus stop located within 150 meters. Across all categories, intersections with two bus stops are the most common. For all sites, the average pedestrian collisions generally increase with the number of bus stops, peaking at intersections with four bus stops. LPI sites show a sharp increase in average pedestrian collisions at intersections with five bus stops, despite lower overall intersection numbers. Reference sites show the highest average pedestrian collisions at intersections with six bus stops, though these intersections are less common. These observations suggest that intersections with a higher number of bus stops tend to have increased pedestrian collisions, particularly for LPI sites.

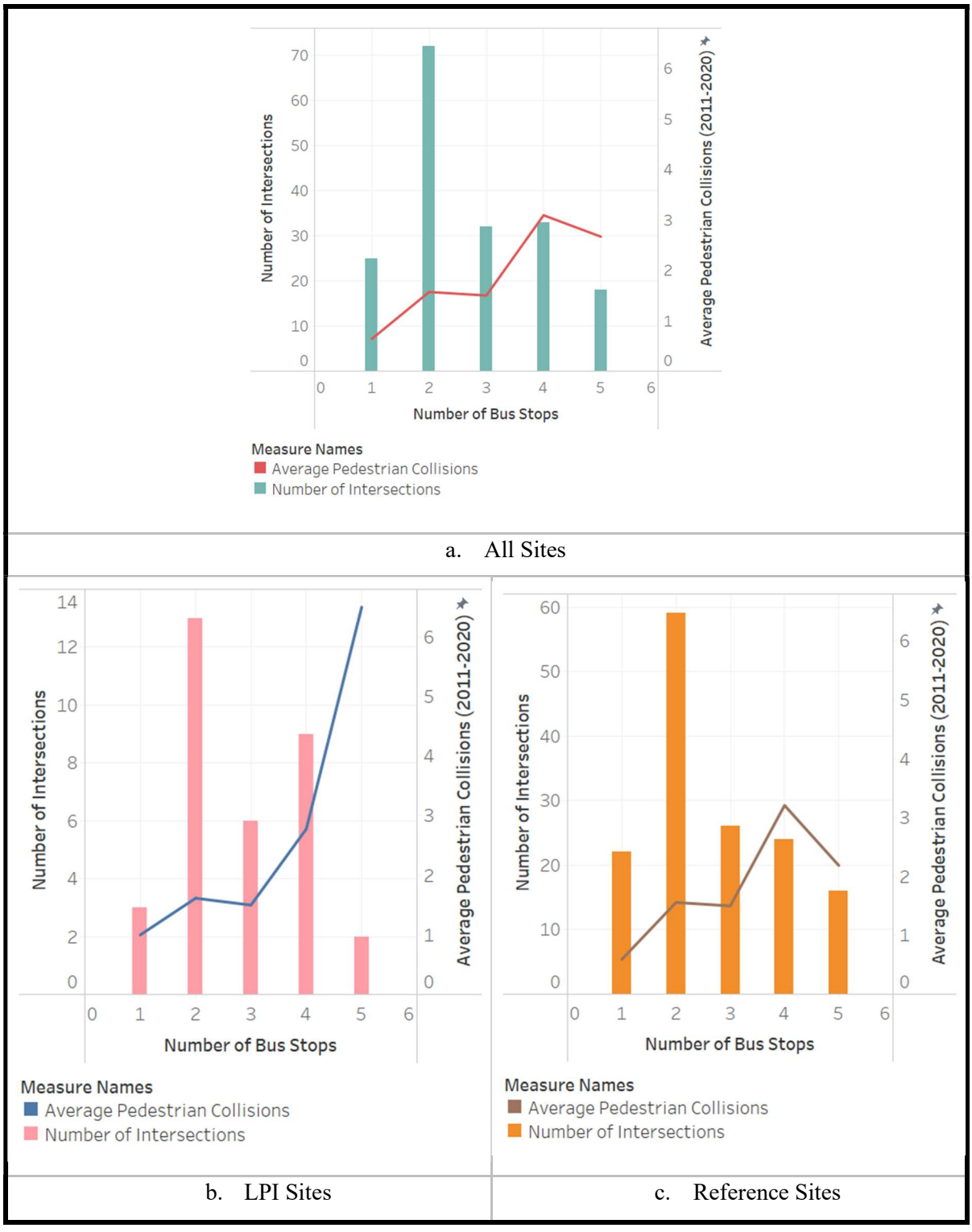


Figure G- 4 Average Pedestrian Collisions (2011-2020) Number of Bus Stops

G.4. Driveways & Commercial Entry/Exits

Table G- 5 details the number of intersections, percentage of total intersections, and average pedestrian crashes associated with different numbers of approaches that have commercial entries/exits or driveways for both LPI sites and reference sites. Similarly, Table G- 6 displays the presence of commercial entries/exits or driveways and the corresponding pedestrian collisions at LPI and reference sites.

Table G- 5 Number of Approaches with Commercial Entries/Exits or Driveways and Corresponding Pedestrian Collisions at LPI and Reference Sites

Number of Approaches with Commercial entry exits or Driveways	LPI Sites			Reference Sites		
	Number of intersections	*%*	*Average Crashes*	*Number of intersections*	*%*	*Average Crashes*
0	0	0	0	18	12.24	0.28
1	7	21.21	2.42	23	15.64	0.73
2	6	18.18	1.83	21	14.28	2
3	8	24.24	2.12	26	17.68	2.53
4	12	36.36	2.17	59	40.13	2.13

Table G- 6 Presence of Commercial Entries/Exits or Driveways and Corresponding Pedestrian Collisions at LPI and Reference Sites

Number of Approaches with Commercial entry exits or Driveways	LPI Sites			Reference Sites		
	Number of intersections	*%*	*Average Crashes*	*Number of intersections*	*%*	*Average Crashes*
No	0	0	0	18	12.24	0.28
Yes	7	100	2.42	129	87.76	1.95