Safety Evaluation of Protected Left-Turn Phasing and Leading Pedestrian Intervals on Pedestrian Safety

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Pedestrian and Bicycle Safety

FOREWORD

The research documented in this report was conducted as part of the Federal Highway Administration's (FHWA's) Evaluation of Low-Cost Safety Improvements Pooled Fund Study (ELCSI-PFS). FHWA established this PFS in 2005 to conduct research on the effectiveness of the safety improvements identified by the National Cooperative Highway Research Program *Report 500 Guides* as part of the implementation of the American Association of State Highway and Transportation Officials (AASHTO) Strategic Highway Safety Plan. The ELCSI-PFS studies provide a crash modification factor and benefit–cost economic analysis for each of the targeted safety strategies identified as priorities by the pooled fund–member States.

The research for this report evaluated the safety effects of two countermeasures with respect to vehicle–pedestrian crashes: the provision of protected or protected/permissive left-turn phasing and the provision of leading pedestrian intervals (LPIs). The strategies aim to improve pedestrian safety at intersections. Study results indicate the left-turn phasing countermeasure reduced vehicle–vehicle injury crashes but did not significantly reduce vehicle–pedestrian crashes, and the LPI countermeasure reduced vehicle–pedestrian crashes. This document is intended for safety engineers; highway designers, planners, and practitioners at State and local agencies involved with the AASHTO Strategic Highway Safety Plan implementation; and those with interests in greater intersection safety.

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Acting Director, Office of Safety
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<tr><td colspan="4">16. Abstract
The objective of the study was to evaluate the safety effects of two countermeasures with respect to vehicle–pedestrian crashes—the provision of protected or protected/permissive left-turn phasing and the provision of leading pedestrian intervals (LPIs)—using a before–after empirical Bayesian methodology. The study used data from North American cities that had installed one or both of the countermeasures of interest, including Chicago, IL; New York City, NY; Charlotte, NC; and Toronto, ON. This study showed that the provision of protected left-turn phasing reduced vehicle–vehicle injury crashes but did not produce statistically significant results for vehicle–pedestrian crashes overall. A disaggregate analysis of the effect of protected or protected/permissive left-turn phasing on vehicle–pedestrian crashes indicated that this strategy may be more beneficial when there are higher pedestrian and vehicle volumes, particularly above 5,500 pedestrians per day. At these high-volume locations, the left-turn phasing evaluation resulted in a potential benefit–cost (B/C) ratio range of 1:15.6::1:38.9. The evaluation of LPIs showed that the countermeasure reduced vehicle–pedestrian crashes. This evaluation produced a crash modification factor of 0.87 with a potential B/C ratio range of 1:207::1:517.</td></tr>
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SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: volumes greater than 1000 L shall be shown in m^3			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
°C	Celsius	1.8C+32	Fahrenheit	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

LIST OF ABBREVIATIONS

AADT	annual average daily traffic
B/C	benefit–cost
CDOT	Chicago Department of Transportation
CMF	crash modification factor
CMFunction	crash modification function
EB	empirical Bayesian
FHWA	Federal Highway Administration
GIS	geographic information system
KABCO	scale used to represent injury severity in crash reporting (K is fatal injury, A is incapacitating injury, B is nonincapacitating injury, C is possible injury, and O is property damage only)
LPI	leading pedestrian interval
LTGA	left-turn green arrow
NYC	New York City
NYCDOT	New York City Department of Transportation
R&D	Research and Development
RTOR	right turn on red
SE	standard error
SPF	safety performance function
TAP	Technical Advisory Panel
USDOT	U.S. Department of Transportation

EXECUTIVE SUMMARY

Pedestrian safety is an important issue for the United States, with pedestrian fatalities representing approximately 16 percent of all traffic-related fatalities in 2016.[1] In recognition of the magnitude of this problem, the Federal Highway Administration (FHWA) funded a study to evaluate the potential of promising infrastructure improvements to increase pedestrian safety. In the first phase of this study, the project team conducted a literature review to summarize the existing knowledge of 18 types of countermeasures that were installed during an FHWA safety effort in the early 2000s and compiled a listing of other countermeasures to consider for evaluation based on prioritized lists obtained from other studies. FHWA and a Technical Advisory Panel of five members from agencies around the country used this compilation to select the countermeasures with the highest priority for evaluation. FHWA selected two—the provision of protected or protected/permissive left-turn phasing and the provision of a leading pedestrian interval (LPI)—to evaluate in this study. Using protected left-turn phasing may reduce potential conflicts between vehicles and pedestrians. An LPI gives pedestrians the opportunity to enter an intersection typically 3 to 7 s before drivers are given a green signal. This is intended to give pedestrians a headstart crossing the intersection and to increase their visibility to drivers.

The objective of the study was to develop statistically rigorous crash modification factors (CMFs) for these countermeasures using state-of-the-art analytical methods. The safety effectiveness of each countermeasure was measured by crash frequency for vehicle–pedestrian crashes (all severities combined), vehicle–vehicle crashes (all severities combined), and vehicle–vehicle injury crashes (K, A, B, and C injuries on the KABCO scale, where K is fatal injury, A is incapacitating injury, B is nonincapacitating injury, C is possible injury, and O is property damage only). The analysis was conducted using a before–after empirical Bayesian study design.

The project team identified cities that had installed one or both of the countermeasures of interest. These included Chicago, IL; New York City (NYC), NY; Charlotte, NC; and Toronto, ON. The team worked with staff in each city to obtain information on the countermeasure installation, including locations, dates, and other details; roadway and intersection characteristics; crash data, including pedestrian-specific crash data; vehicle- and pedestrian-volume data; and signal-timing data. Team members examined resources such as aerial and street-level imagery as well as historical signal-timing plans to ensure that no significant changes had occurred at the sites of interest during the study period.

The protected left-turn phasing evaluation used data from 27 treated sites in Chicago, 7 treated sites in NYC, and 114 treated sites in Toronto. Vehicle–pedestrian crashes increased in Chicago and Toronto and decreased in NYC; however, none of these results were statistically significant at a 95-percent confidence level, and the results in NYC were based on few sites and crashes. For vehicle–vehicle crashes, increases were seen in Chicago and Toronto, but these were not statistically significant. A statistically significant decrease was seen in NYC, although this was based on only 46 after-period crashes. For vehicle–vehicle injury crashes, decreases were seen in all three cities, but only Toronto showed a statistically significant decrease (less than 5 percent). A disaggregate analysis of the effect on vehicle–pedestrian crashes indicated that the expected CMF may be smaller (i.e., the treatment is more beneficial) for higher levels of pedestrian and vehicle volumes, particularly above 5,500 pedestrians per day. This was shown to lead to a potential benefit–cost (B/C) ratio range of 1:15.6::1:38.9.

The LPI evaluation used data from 56 treated sites in Chicago, 42 treated sites in NYC, and 7 treated sites in Charlotte. The effect of LPIs on total crashes for all cities combined was a CMF of 0.87, which was significant at a 95-percent confidence level. The effect on total injury crashes for all cities combined was a CMF of 0.86, which was significant at a 95-percent confidence level. The effect on the number of pedestrian crashes was generally beneficial, showing decreases in pedestrian crashes across all cities. Chicago showed a CMF of 0.81, which was significant at a 95-percent confidence level. NYC sites showed a beneficial but lesser effect on the number of pedestrian crashes with a CMF of 0.91, but this result was not significant at a 95-percent confidence level. Charlotte showed a decrease in pedestrian crashes, but this result was highly unreliable given the large standard error. For all cities together, the CMF for pedestrian crashes was 0.87, which was significant at a 95-percent confidence level. This was shown to lead to a potential B/C ratio range of 1:207::1:517.

Overall, both countermeasures were shown to have safety benefits, though the LPI safety benefit was much more pronounced and was the only result shown to reduce pedestrian crashes. These results can be used by safety practitioners to prioritize locations for safety treatment and estimate the potential benefits to vehicle and pedestrian safety.

CHAPTER 1. INTRODUCTION

In the early 2000s, pedestrian fatalities numbered approximately 4,900 per yr, representing 11 percent of all traffic-related fatalities. Since that time, the percentage has increased to the point that pedestrian fatalities represented approximately 16 percent of all traffic-related fatalities in the United States in 2016.[(1)] In recognition of the magnitude of this problem, the Federal Highway Administration (FHWA) has had a long-standing commitment to addressing pedestrian-safety issues through engineering improvements.

In 2002, FHWA selected Las Vegas, NV; San Francisco, CA; and Miami, FL, to receive grants to install pedestrian-crash countermeasures. These cities installed 18 types of pedestrian-safety treatments designed to increase the visibility and awareness of pedestrian crossings. Results of the postinstallation evaluations were mixed. Some countermeasures showed promise through improvements in driver and pedestrian behaviors, some showed no significant benefit, and others had too few installations to provide insight.

BACKGROUND ON STUDY

Phase 1 of this study was conducted from August 2014 through May 2015 with the purpose of gathering information and setting the stage for evaluating these pedestrian-crash countermeasures. During phase 1, the project team conducted a literature review to summarize the existing knowledge of the 18 types of countermeasures that were installed during the 2002 FHWA effort in the 3 cities. This review was to guide the selection of countermeasures to evaluate under phase 2 of this study, the subject of this report. In addition, the project team provided FHWA with a listing of other countermeasures for possible evaluation based on prioritized lists obtained from other studies. The project team leveraged contacts in the three cities from the previous FHWA effort as well as contacts in other cities to develop a Technical Advisory Panel (TAP). The final panel included five members from agencies around the country.

The project team met with FHWA and the TAP in Washington, DC, to review the results of the literature review and select a small group of priority countermeasures. The selection was based on the existence of crash modification factors (CMFs) for each potential countermeasure, general indications of effectiveness from other non-crash-based studies, and other considerations. The members attending from FHWA and the TAP gave their input, and FHWA staff worked with the project team to identify the following final set of six priority countermeasures:

- In-street pedestrian signs.
- Provision of protected left-turn phasing.
- No-turn-on-red signs.
- High-visibility crosswalk treatment.
- Leading pedestrian intervals (LPIs), also called pedestrian headstart.
- Exclusive right-turn lane design and control (signal versus yield).

From these six potential countermeasures, FHWA selected two—the provision of protected left-turn phasing and the provision of LPIs—to evaluate in phase 2 of the study. This report documents the results of phase 2. The objective of the study was to develop statistically rigorous CMFs for these countermeasures using state-of-the-art analytical methods.

BACKGROUND ON COUNTERMEASURES

This section describes the two countermeasures selected for evaluation in this study.

Protected Left-Turn Phasing

Traffic-signal phasing that allows left-turn movements concurrently with opposing through movements is known as a permissive left turn. Under permissive left-turn phasing (i.e., circular green, flashing yellow arrow, or flashing red arrow), drivers turning left must yield to any conflicting pedestrians or opposing traffic and proceed after choosing an appropriate gap to complete the turn. Figure 1 shows an intersection with a flashing yellow arrow, a type of permissive left-turn phasing.

Figure 1. Photo. Intersection approach operating with permissive left-turn phasing.

Traffic-signal phasing that provides an exclusive phase for left turns and prohibits opposing through movements and pedestrian crossings is known as a protected left turn. Under protected left-turn phasing (i.e., steady green arrow), conflicts between left-turning and opposing through vehicles and between left-turning vehicles and pedestrians are eliminated. Figure 2 shows an intersection with protected left-turn phasing.

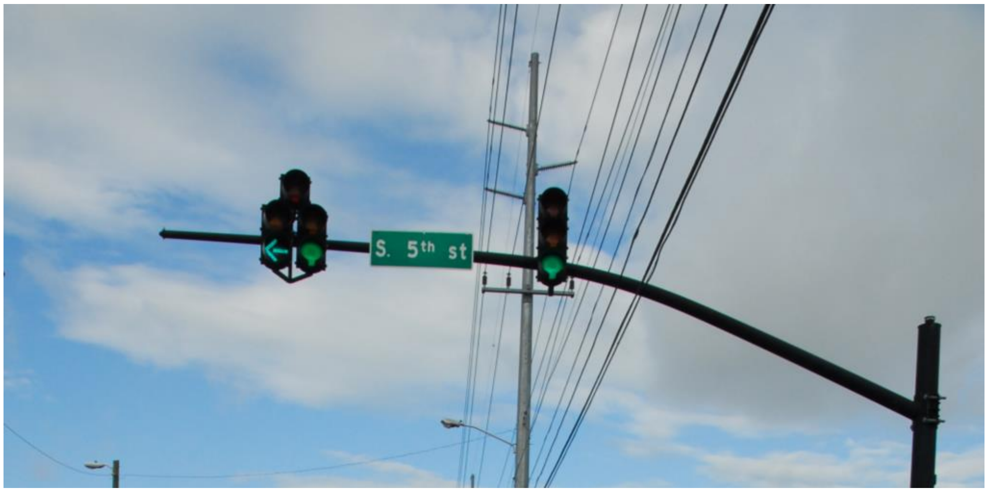


Figure 2. Photo. Intersection approach operating with protected left-turn phasing.

The combination of protected and permissive left-turn phasing is known as protected/permissive left turns. With protected/permissive left-turn phasing, left-turning traffic has a permissive movement phase preceded or followed by a protected phase. Therefore, where left turns are allowed at a signalized intersection, the traffic signal may be operated as permissive only, protected only, or protected/permissive.

The protected left-turn phasing evaluation grouped protected/permissive phasing with protected-only phasing. Prior studies have found that protected-only left-turn phasing is associated with the lowest rate or frequency of left-turn-related vehicle crashes. However, protected-only left-turn phasing may not always provide the operational performance needed at a signalized intersection, making protected/permissive left-turn phasing a common choice to balance safety and operational performance. A majority of the treated sites assembled for this study were converted from permissive-only to protected/permissive left-turn phasing.

LPI

At signalized intersections equipped with pedestrian-signal indications, the pedestrian-crossing phasing is coordinated with concurrent vehicle phases. Pedestrian-crossing phases generally consist of a steady walking person (symbolizing "walk"), flashing upraised hand (symbolizing "do not walk"), and steady upraised hand (also symbolizing "do not walk") and may or may not include countdown timers. It is routine practice for the pedestrian walk interval to coincide with the adjacent circular green vehicle phase. In such cases, there exists a potential conflict between turning vehicles and pedestrians. The LPI timing was introduced as a way to provide the pedestrian walk interval a few seconds (at least 3) before providing the circular green indication to adjacent parallel traffic. The LPI gives pedestrians the opportunity to begin crossing the intersection before drivers are allowed to proceed. This headstart for pedestrians allows them to establish their presence in the crosswalk and places them in a location that is more visible to drivers. The use of LPIs is expected to result in the following benefits:

- Increased visibility of crossing pedestrians.
- Reduced conflicts between pedestrians and vehicles.
- Increased likelihood of motorists yielding to pedestrians.

Figure 3 shows a pedestrian crossing at an intersection with an LPI.

Figure 3. Photo. Intersection with an LPI.

LITERATURE REVIEW

This section presents a summary of past studies that evaluated protected left-turn phasing and LPIs. The focus of this literature review is on crash-based studies as those are the most relevant to this CMF development study. However, other studies that were based on safety measures other than crashes are also included to provide a more comprehensive examination of each countermeasure.

Protected Left-Turn Phasing

The effects of protected and protected/permissive left-turn phasing on pedestrian safety have not been evaluated as extensively as the effects on crashes between vehicles. This section summarizes crash-based and non-crash-based research found during the literature review.

Past Crash-Based Studies

The evaluation team identified only two research efforts that examined the effect of left-turn phasing on pedestrian crashes. Bonneson et al. conducted a literature review to examine the issue of left-turning traffic and pedestrian safety.(2) While it was clear that the literature indicated the strong potential for conflicts between pedestrians and left-turning vehicles with permissive-only phasing, the authors concluded that research had not established a reliable (crash-based) relationship between pedestrian safety and protected/permissive signal phasing. Subsequently, an evaluation of 95 New York City (NYC), NY, intersections that were converted from permissive-only to protected/permissive or protected-only phasing found a statistically significant 43-percent reduction in pedestrian crashes based on an analysis of covariance to correct for regression to the mean.(3) An admitted limitation of this study was the lack of exposure data.

With respect to nonpedestrian or total crashes, Hauer conducted a detailed critical review of 14 studies that were completed over a period of 24 yr in several countries. Hauer noted that the CMF for changing from permissive-only to protected-only phasing most likely depends on the number of opposing lanes and that most of the other evidence is insufficient and contradictory. Based on the review of these studies, Hauer concluded that the CMF for intersections that changed to protected-only phasing from either permissive-only or protected/permissive phasing was approximately 0.3 (i.e., a 70-percent reduction in left-turn crashes); for other intersections, the CMF was 1.0 (i.e., no effect). When changing from permissive-only to protected/permissive phasing, Hauer estimated that the CMF was approximately 1.0 for both left-turn crashes and other crashes (i.e., no effect).(4)

Lyon et al. used the empirical Bayesian (EB) before–after study approach to evaluate the impact of flashing advance green and left-turn-green-arrow (LTGA) treatments on injury and fatal left-turn crashes of all types and specifically left-turn side-impact crashes. Flashing advance green is permitted in Canada but not in the United States. Both flashing advance green and LTGA provide a leading protected followed by a permissive left-turn phase. In some cases, some form of left-turn protection existed beforehand, and in others, additional minor modifications were made. A total of 35 intersections from Toronto, ON, were included; 15 sites received the flashing advance green, while 20 received the LTGA. Left-turn crashes decreased by 16 percent at the flashing advance green sites and 17 percent at the LTGA sites. Left-turn side-impact crashes decreased by 12 percent at the flashing advance green sites and 25 percent at the LTGA sites. All results were statistically significant at a 95-percent confidence level.(5)

Srinivasan et al. evaluated three types of left-turn phasing treatments using data from Charlotte, NC. The first involved replacing a permissive-only left-turn phase with a protected/permissive phase at three sites. The second involved replacing a permissive-only left-turn phase with a protected-only phase at eight sites. The third type involved replacing a protected/permissive phase with a protected-only phase at four sites. The target crashes for these treatments were identified as those involving at least one left-turning vehicle on the treated roadway. For the three sites where the permissive-only phase was replaced by protected/permissive phasing, there was very little change in the target as well as the total crashes. However, since the sample size was small, this result of no apparent effect from this treatment cannot be taken as definitive. For each of the other two treatment sites where the left-turn phase was changed to protected-only phasing (from either permissive only or protected/permissive), left-turn crashes were virtually eliminated, but there was very little change in total crashes.(6)

In another study, Srinivasan et al. evaluated conversion from permissive only to either protected/permissive or protected only for at least part of the day using an EB before–after study approach. The analyses were done separately for the intersections as a whole and for only the treated approaches. At both levels, the results indicated substantial and highly significant benefits for left-turn-opposing crashes involving a left-turning vehicle and a through vehicle from the opposing approach. For intersection-level data, a CMF of 0.862 was estimated for left-turn-opposing crashes. For total and injury crashes, CMFs of 1.031 and 0.962 were estimated, neither of which was statistically significant at a 95-percent confidence level. As expected, the benefit at the intersection level was greater at intersections where more than one approach was treated. At both the intersection and approach levels, there were small percent increases in rear-end crashes, resulting in an estimated CMF of 1.075. Disaggregation of the effects by annual average daily traffic (AADT), either total entering or left turning, did not reveal any trend.(7)

Past Non-Crash-Based Studies

Hurwitz et al. studied the effect of flashing yellow arrows by using a simulator and examining driver eye glances. They found that the increased presence of pedestrians led drivers to focus more attention on these crossing pedestrians; as the number of opposing vehicles increased, drivers spent less time fixating on pedestrians; 4 to 7 percent of drivers did not focus on pedestrians in the crosswalk; and there did not appear to be a difference between any variable and the presence of a three- or four-section signal head. The authors concluded that it may be desirable to limit the permissive operation when pedestrians are present.(8)

Pratt et al. examined the effects of implementing a leading protected left-turn-signal phasing. They studied the effects on pedestrian–vehicle conflicts and determined that the leading protected left-turn phase led to a decrease in conflicts.(9)

LPI

There have been several studies on the safety effects of LPIs, but only a few used crashes as the basis for safety measurement. The non-crash-based studies examined driver and pedestrian behavior. This section summarizes crash-based and non-crash-based research found during the literature review.

Past Crash-Based Studies

King presented a crash-based analysis of the effect of LPIs on pedestrian crashes in NYC and evaluated 26 intersections where LPIs had been implemented then compared the crash rates of the treated sites against those from a group of control sites that had not been changed. A period of 10 yr was used for the crash data. The results indicated that LPIs had a positive effect on pedestrian safety, especially where there was a heavy concentration of turning vehicles. The treated sites experienced a 28-percent decrease in vehicle–pedestrian crash rates relative to control sites.[10]

Fayish and Gross published a crash-based analysis of 10 intersections in Pennsylvania where LPIs of 3 s were implemented. These treated sites had an average of 0.6 pedestrian–vehicle crash per site per yr before the implementation of the LPI. The authors conducted a before–after study design using a comparison group of 14 stop-controlled intersections in the same jurisdiction. Results suggested a 58.7-percent reduction in pedestrian–vehicle crashes, which was statistically significant.[11]

Past Non-Crash-Based Studies

Pécheux et al. evaluated the effectiveness of LPIs in Miami. Results indicated an increase in the percentage of left-turning drivers yielding to pedestrians, no change in the percentage of right-turning drivers yielding to pedestrians, an increase in the percentage of pedestrians who pushed the call button, and an increase in the percentage of pedestrians who crossed during the first 4 s of the walk interval.[12]

Several studies conducted evaluations of observational behaviors using only a small group of sites. Van Houten et al. used conflicts between pedestrians and vehicle drivers as the primary measure of effectiveness. They evaluated three urban intersections where the signal had been programmed to display the pedestrian walk interval 3 s before the circular green for vehicle traffic. Results indicated that pedestrian–vehicle conflicts were reduced as well as incidences of pedestrians yielding right-of-way to turning traffic.[13] Hubbard et al. analyzed video of an LPI at one crosswalk in Anaheim, CA. Results were inconclusive, and the authors suggested further field evaluation to determine effectiveness.[14] Hua et al. conducted video observations and intercept surveys at four intersections in San Francisco with 4-s LPIs. Results indicated a significant reduction in the percentage of vehicles turning in front of pedestrians.[15]

CHAPTER 2. OBJECTIVE

This research aimed to evaluate the safety impacts of two pedestrian-safety improvements—adding either protected/permissive or protected-only phasing to one or more intersection legs of signalized intersections and implementing LPIs on some or all pedestrian crossings at signalized intersections. The objective was to estimate the safety effectiveness of each strategy as measured by crash frequency.

The project team considered the following target crash types for the LPI evaluation:

- Total crashes (all severities combined).

- Total injury crashes (K, A, B, and C injuries on the KABCO scale, where K is fatal injury, A is incapacitating injury, B is nonincapacitating injury, C is possible injury, and O is property damage only).

- Vehicle–pedestrian crashes (all severities combined).

The project team considered the following target crash types for the protected left-turn phasing evaluation:

- Vehicle–pedestrian crashes (all severities combined).
- Vehicle–vehicle crashes (all severities combined).
- Vehicle–vehicle injury crashes (K, A, B, and C injuries).

Another objective of the research was to investigate ways in which safety effects might vary based on site characteristics, including the following:

- Number of intersection legs.
- Number of intersection through lanes.
- Number of left-turn lanes.
- Number of treated approaches.
- Traffic volumes on major and minor roads.
- Left-turn traffic volumes on major and minor roads.
- Pedestrian volumes.
- Site-specific expected crash frequency prior to treatment.
- Overall effect, measured by the economic costs of crashes by crash type and severity.

Meeting these objectives placed some special requirements on the data collection and analysis, including the following:

- Selecting a large enough sample size to detect, with statistical significance, what may be small changes in safety for some crash types.

- Identifying appropriate untreated reference sites.

- Properly accounting for changes in safety due to changes in traffic volume and other nontreatment factors.

- Pooling data from multiple jurisdictions to improve reliability of the results and to facilitate broader applicability of the products of the research.

CHAPTER 3. STUDY DESIGN

When planning a before–after safety evaluation study, researchers must ensure enough data are included to detect the expected change in safety with statistical confidence. Even though those designing the study do not know the expected change in safety in the planning stage, it is still possible to make a rough determination of how many sites are required based on the best available information about the expected change in safety. Alternatively, one could estimate the statistically detectable change in safety for the number of available sites. *Observational Before–After Studies in Road Safety—Estimating the Effect of Highway and Traffic Engineering Measures on Road Safety* contains a detailed explanation of sample-size considerations and estimation methods.[16]

This chapter presents the initial calculations and assumptions used by the project team before initiating the study. The analyses of sample sizes address the assumed sample size that is needed to be statistically likely to detect an expected change in safety and the change in safety that could be detected with available sample sizes.

For both treatments, the project team assumed that a conventional before–after study with comparison group design would be used because available methods for estimating sample size were based on this assumption. The sample-size estimates from this method would be conservative in that the EB methodology proposed would likely require fewer sites. To facilitate the analysis, the project team also assumed that the number of comparison sites was equal to the number of treatment sites, which again was a conservative assumption.

For each of the studies, the required sample size for a before–after study can be estimated using a desired level of statistical significance and assumptions of crash rate and likely treatment effect.

PROTECTED LEFT-TURN PHASING

The project team identified 233 potential sites where permissive-only left-turn phasing was converted to protected-only or protected/permissive left-turn phasing. This was a moderate sample size of treatment sites. Given 233 treated sites and an assumption of 5 yr of data for the before period and 5 yr of data for the after period of installations, it was possible to obtain 1,165 site-yr of data in the before and after periods, individually, where 1 yr of data for one site is 1 site-yr.

A reasonable assumption of the pedestrian-crash rate at the signalized intersection sites where protected or protected/permissive left-turn phasing would be implemented is 0.1 pedestrian crash per yr. This value is based on crash rates observed at signalized intersections in Charlotte.

Using these assumptions, the resulting sample-size requirements for a before–after study are shown in table 1.

Table 1. Site-year requirements in the before and after periods for various confidence levels and magnitudes of safety effects.

Reduction in Pedestrian Crashes (%)	95% Confidence (Site-Years)	90% Confidence (Site-Years)	80% Confidence (Site-Years)
10	12,793	8,956	5,473
15	5,152	3,607	2,204
20	2,612	1,829	1,118
30	926	648	396

It is reasonable to expect an increase in pedestrian safety from prohibiting permissive left turns. Assuming all rules of the road are followed, a protected-only or protected/permissive left-turn phase would separate the movements of the pedestrians and the left-turning drivers. Additionally, as discussed in the literature review, NYC installed left-turn phasing at 95 signals, changing the signal phasing from permissive to protected/permissive or protected only. It was found that there was a 48-percent reduction in pedestrian crashes based on an EB before–after study.(3) If the prohibition of permissive left turns causes a 30-percent or greater reduction in pedestrian–vehicle crashes, table 1 indicates that the analysis with the 1,165 site-yr of data at identified installations would be able to produce a CMF meeting 95-percent confidence. Therefore, the project team decided to proceed with the evaluation using the available sample.

LPI

The project team identified 205 potential sites where LPIs were implemented. This was a moderate sample size of treatment sites. Given an assumed study period of 5 yr of data before and 3 yr of data after the installation (due to the recent nature of the installations), it was possible to obtain 1,025 site-yr of data in the before period and 615 site-yr in the after period.

A reasonable assumption of the pedestrian-crash rate at the type of sites where LPIs would be implemented (signalized intersections) is 0.1 pedestrian crash per yr. This value was based on crash rates observed at signalized intersections in Charlotte.

Using the aforementioned assumptions, the resulting sample-size requirements for a before–after study are shown in table 2.

Table 2. Site-year requirements in the before and after periods for various confidence levels and magnitudes of safety effects.

Reduction in Pedestrian Crashes (%)	95% Confidence (Site-Years)	90% Confidence (Site-Years)	80% Confidence (Site-Years)
10	12,793	8,956	5,473
15	5,152	3,607	2,204
20	2,612	1,829	1,118
30	926	648	396

As previously stated, the identified installations would be expected to provide 615 site-yr of data for the after period. A higher number (1,025 site-yr) was potentially available for the before period, but the project team used the lower number for a conservative estimate. Based on the sample-size requirements in table 2, 615 site-yr would be expected to detect only sizable reductions (30 percent) at a reasonably high confidence level (close to 90 percent). However, a 2009 study by Fayish and Gross found crash reductions from LPIs in the 50- to 60-percent range. Since this may not be an unreasonable estimate of the magnitude of effectiveness, the project team decided to proceed with the evaluation with the available sample.(17)

CHAPTER 4. METHODOLOGY

The project team used an EB methodology for observational before–after studies. This methodology is considered rigorous in that it accounts for regression to the mean using a reference group of similar but untreated sites. In the process, the team used safety performance functions (SPFs) to address the following issues:

- Overcoming the difficulties of using crash rates in normalizing for volume differences between the before and after periods.
- Accounting for time trends.
- Reducing the level of uncertainty in the estimates of safety effects.
- Accounting for differences in crash experience and reporting practices in amalgamating data and results from diverse jurisdictions.

This report summarizes the methodology derived and documented in detail by Hauer and provides a foundation for developing guidelines for estimating the likely safety consequences of a contemplated strategy.(16) The SPFs for intersections that did not have left-turn phasing added can be used with observed crash histories to estimate the number of crashes without treatment, and the CMFs developed can be applied to this number to estimate the number with treatment.

In the EB approach, the estimated change in safety for a given crash type at a site is given by the equation in figure 4.

$$\Delta\, Safety = \lambda - \pi$$

Figure 4. Equation. Estimated change in safety.

Where:

Δ *Safety* = change in safety.
λ = expected number of crashes that would have occurred in the after period without the strategy.
π = number of reported crashes in the after period.

In estimating λ, the effects of regression to the mean and changes in traffic volume were explicitly accounted for using SPFs, which relate crashes of different types to traffic flow and other relevant factors for each jurisdiction based on untreated sites (i.e., reference sites). Annual SPF multipliers were calibrated to account for temporal effects on safety (e.g., variation in weather, demography, and crash reporting).

In the EB procedure, the SPF is first used to estimate the number of crashes that would be expected to occur in each year of the before period at reference sites having traffic volumes and other characteristics similar to the one being analyzed. The sum of these annual SPF estimates (P) is then combined with the count of crashes (x) in the before period at a strategy site to obtain an estimate of the expected number of crashes (*m*) before the installation. This estimate of *m* is calculated using the equation in figure 5.

$$m = w(P) + (1 - w)(x)$$

Figure 5. Equation. EB estimate of expected crashes.

Where *w*, the EB weight, is estimated from the mean and variance of the SPF estimate using the equation in figure 6.

$$w = \frac{1}{1 + kP}$$

Figure 6. Equation. EB weight.

Where *k* is constant for a given model, which is estimated from the SPF calibration process with the use of a maximum likelihood procedure. In that process, a negative binomial distributed error structure is assumed with *k* being the overdispersion parameter of this distribution.

A factor is then applied to *m* to account for the length of the after period and differences in traffic volumes between the before and after periods. This factor is the sum of the annual SPF predictions for the after period divided by *P*, the sum of these predictions for the before period. The result, after applying this factor, is an estimate of λ. The procedure also produces an estimate of the variance (Var) of λ.

The estimate of λ is then summed over all sites in a strategy group of interest (to obtain λ_{sum}) and compared with the count of crashes observed during the after period in that group (π_{sum}). The variance of λ is also summed over all sites in the strategy group. The index of effectiveness (θ) is estimated using the equation in figure 7.

$$\theta = \frac{\pi_{sum}/\lambda_{sum}}{1 + \left(Var(\lambda_{sum}) / \lambda_{sum}^2 \right)}$$

Figure 7. Equation. Index of effectiveness.

The standard deviation (StDev) of θ is given by the equation in figure 8.

$$\mathrm{StDev}(\theta) = \sqrt{\frac{\theta^2 \left(\frac{Var(\pi_{sum})}{\pi_{sum}^2} + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2} \right)}{\left(1 + \frac{Var(\lambda_{sum})}{\lambda_{sum}^2} \right)}}$$

Figure 8. Equation. Standard deviation of index of effectiveness.[(17)]

The percent change in crashes is calculated as $100(1 - \theta)$; thus, a value of $\theta = 0.70$ with a standard error (SE) of 0.12 indicates a 30-percent reduction in crashes with an SE of 12 percent.

To identify the influence of site characteristics on the expected CMF value, the sites are first grouped by each characteristic of interest and the CMF and SE estimated for each group (e.g., CMFs estimated for groups defined by ranges of AADT). The next step is to estimate a crash modification function (CMFunction) using the site characteristics believed to influence the expected CMF as predictor variables.

When estimating CMFunctions, in order to have reliable estimates of these parameters, sites with similar characteristics are often combined. However, this aggregation can lead to a loss of useful information and requires a large number of sites and after-period crashes. Due to these difficulties, an alternate approach was taken in the current study.

The form of the CMFunction is shown in figure 9. In this form, it is possible to estimate this model as a negative binomial count data model with λ_i being the observed after-period crashes and π_i being an offset equal to the EB estimate of the expected crash frequency in the after period.

$$\lambda_i = \pi_i \times f(site\ characteristics)$$

Figure 9. Equation. CMFunction form.

Where *site characteristics* is the site characteristics believed to influence the expected CMF as predictor variables.

CHAPTER 5. DATA COLLECTION

This chapter summarizes the data collection efforts from the participating agencies—Chicago, IL; NYC; Charlotte; and Toronto. The discussion for each agency focuses on how data were collected on the installation of the countermeasure; identification of treatment and reference sites; and how data were collected on the roadway, signals, vehicle and pedestrian volumes, crashes, and cost of the treatments.

CHICAGO

Chicago served as a source of data for both the LPI and protected left turn–phasing evaluations. The following sections provide details on how the team identified study sites in Chicago, what data sources were used, and how the data were collected.

Installation Data

The project team identified treatment sites for both evaluations through the following information provided by Chicago staff:

- **Protected left turn–phasing installations.** The team analyzed a signal inventory file provided by Chicago and identified 119 signals where protected or protected/permissive left-turn phasing was installed between 2008 and 2013 (a period deemed to be appropriate for this study due to the availability of sufficient before and after data).

- **LPI installations.** Chicago staff provided a list of 150 signalized intersections where LPIs had been installed. The list also contained the installation dates, the majority of which were between 2010 and 2015. The LPI installation sites included those where LPIs had been implemented on the crossings for both streets and those where LPIs had been implemented only on the crossings of one street (e.g., only crossings parallel to the major street). Chicago typically provides a period of 3 s for the LPI. All LPI installations used in this study were from intersections where pedestrian phasing and pedestrian-signal heads were already present (i.e., LPIs retrofit to existing signals).

The project team mapped these potentially eligible treatment sites using a spatial point file of signals that had been obtained from Chicago. The team used spatial analysis to join the LPI sites with the underlying road-layer and traffic-volume data to identify those sites that had sufficient traffic-volume information (at least one value on each intersecting road). The spatial mapping of potential treatment sites was also compared to the geographic extent of Chicago's crash data, and any potential sites that lay outside that extent were dropped from consideration. The resulting lists of potential left-turn treatment sites and potential LPI treatment sites were used to direct a visit to Chicago where a team member obtained copies of signal-timing plans.

Once signal-timing plans had been obtained from Chicago, the team proceeded to examine all available data for each potential treatment site. The purpose of this step was to determine if the site met the eligibility criteria to remain in the study (see the following list) and collect all relevant data on the installation details, intersection geometry, traffic volume, and signal timing.

To ensure consistency, the team developed a spreadsheet tool for data collection and an accompanying data-coding guidebook (see the appendix).

The project team considered a potential treatment site ineligible if it met any of the following conditions:

- There was no evidence of LPIs or protected left-turn phasing.
- Any leg of the intersection was a freeway ramp.
- Any leg of the intersection was not a public street (e.g., driveway or alley).
- There was significant construction or changes in roadway or lane geometry during the study period (2005–2015).
- Intersection legs were offset (centerline of one leg (extended) is outside the bounds of the other leg but within 500 ft).
- The site was within 100 ft of any other intersection.
- There was significant skew (angle of the intersecting legs).
- There were fewer than three legs or more than four legs.

Once all potential treatment sites had been investigated and the team had collected all available information on the sites, the team examined overall characteristics of the treatment sites to direct the selection of an appropriately matched set of reference sites. An examination of the number of intersection legs showed that almost all treatment sites were four-legged intersections, thus directing the identification of reference sites to focus primarily on four-legged intersections. An examination of the presence and number of exclusive left-turn lanes showed that both groups of treatment sites (LPI and protected left-turn phasing sites) were diverse in this regard, with approximately 50 percent of each group having at least one exclusive turn lane, about 20 percent having no exclusive turn lanes, and about 30 percent having two or more turn lanes.

Reference Sites

To identify reference sites for the analysis, the project team began with a selection of potentially eligible reference sites using data on treatment locations, roads with available AADT, and a point file of signal locations supplied by Chicago. Within the spatial environment, the team selected signals that were within 0.5 mi of a treatment site (excluding the treatment sites themselves). From that set of sites, the team selected those that were spatially positioned on roads with an AADT value greater than 0. This ensured that the team would only investigate potential reference sites that had traffic-volume data available. This resulted in a set of potentially eligible reference sites the project team used to collect data—such as signal plans—during a visit to Chicago. This set of potential reference sites totaled 900 intersections. During the subsequent collection of intersection and roadway characteristics, this set of potential reference sites served as the basis for the final set of reference sites after dropping sites that did not meet the eligibility criteria (same as those listed above for treatment sites) or did not have all necessary data available.

Roadway Data

The project team utilized Web-based aerial photography and street-level imagery to determine the eligibility of treatment and reference site locations and collect roadway characteristics. The team used the archived timeline of imagery (both aerial and street level) to determine whether any significant changes had taken place at the intersection during the study period. The project team gathered roadway geometry for eligible sites and recorded the following characteristics for each site:

- Number of intersection legs.
- One- or two-way direction of streets.
- Number of through lanes.
- Number of turn lanes.
- Combination of through and turn lanes.
- Presence of a crosswalk.

The appendix contains an example of the roadway data and format collected by the project team.

Signal Data

Chicago Department of Transportation (CDOT) staff provided signal plans in electronic and paper format, which the project team converted to Portable Document Format. The plans contained signal phases, timing, and daily schedules. The project team used these plans to determine the eligibility of a site location. For treatment intersections, the project team verified the installation of a treatment during the study period as well as the absence of the treatment before the scheduled installation date. For reference intersections, the project team verified the absence of the target treatment for any time during the study period. The following characteristics were recorded for each intersection:

- Signal actuation.
- Presence of a pedestrian-only phase.
- Date of treatment installation (treatment sites only).
- Presence of a pedestrian countdown signal.
- Right-turn-on-red (RTOR) prohibition (otherwise assumed to be permitted).
- Phasing schedule and timing for entire study period (reference sites only).
- Phasing schedule and timing before installation (treatment sites only).
- Phasing schedule and timing after installation (treatment sites only).

The appendix contains an example of the signal data and format collected by the project team.

Vehicle-Volume Data

The project team obtained data on traffic volume from CDOT. CDOT collected AADT data in 2006. Each count was accompanied by spatial coordinates. The team also obtained spatial roadway files for Chicago from the Illinois data warehouse. These roadway files contained AADT information for the years 2005, 2009, 2013, and 2015. The team plotted all AADT data on a spatial map and manually associated AADT values with the study sites.

Pedestrian-Volume Data

The team collected data on pedestrian volume at the study sites in two ways. The first was a manual collection of 1-h pedestrian counts that were converted to equivalent daily volumes. The second was a method of using existing pedestrian counts from CDOT taken at midblock locations and estimating pedestrian-crossing volumes from these data. These two methods are explained below.

Expanding Short-Term Manual Pedestrian Counts to Daily Volumes

For the manual count method, a local team conducted pedestrian counts at selected site locations using cameras between 5 and 6 p.m. on a typical weekday evening in November. The project team processed the counts using spreadsheet software and summarized the data by each intersection leg. This manual collection of pedestrian-crossing counts was only conducted over a short period at each site (1 h). However, the analysis required an estimate of daily pedestrian volume. To expand the short counts to daily volumes, the team developed expansion factors based on data obtained from Chicago.

In past years, Chicago had collected numerous detailed pedestrian counts at 474 locations throughout the city. These counts were stored in a database that provided the count of pedestrians in each 15-min interval. The count at each location was conducted over a 9- or 10-h period between the hours of 7:45 a.m. and 9:15 p.m. The counts were collected during weekdays and weekends; however, only weekday counts were used in this development of expansion factors.

Table 3 shows the calculation of pedestrian count expansion factors for Chicago. For each location, the team analyzed the count data to determine what percentage of the total count was contained in each hour. These values were averaged over all 474 locations to determine the average percentage of total pedestrian volume captured in each hour. Dividing 1 by these values produced an expansion factor that could be used as a multiplier to expand a 1-h count to a 10-h volume. However, the team desired to use an equivalent 24-h volume, so the expansion factors needed to include a conversion from daytime counts to full 24-h volumes. The team used the findings from Zegeer et al., which reported that 86 percent of pedestrian volume is captured from 7 a.m. to 7 p.m.[18] Since these Chicago data were based on a 10-h count—not 12 h—this percentage had to be adjusted, as shown in figure 10.

$$Adjustment\ Factor_{12\ Hour} = 0.86 \times \left(\frac{10}{12}\right)$$

Figure 10. Equation. Adjustment factor for 10-h to 12-h count.

As shown in table 3, the results indicated 72 percent of the 24-h pedestrian volume is captured in a daytime 10-h count. Therefore, to convert a daytime 10-h count to a 24-h volume, per hour, these factors were multiplied by the expansion factor (1.39) to arrive at a final expansion factor.

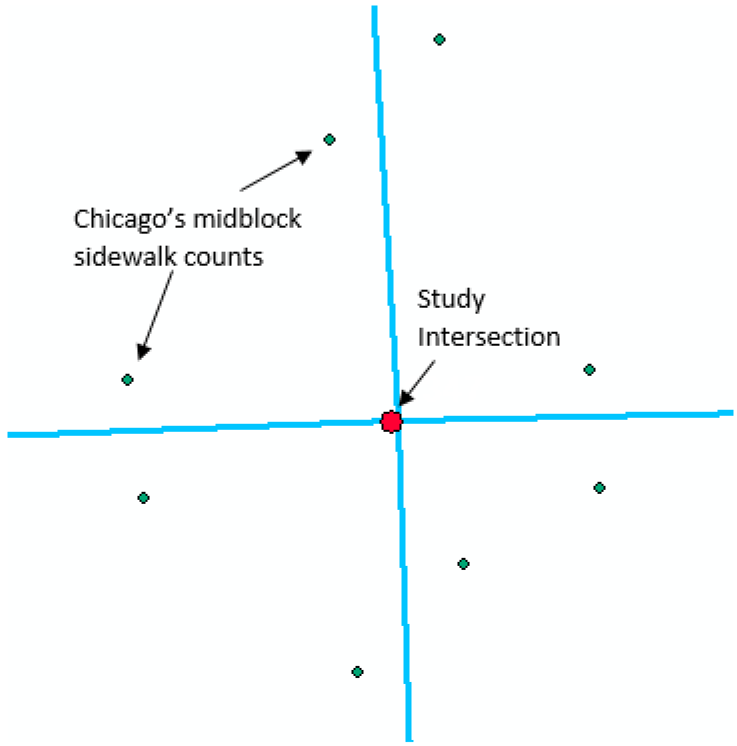
Table 3. Calculation of pedestrian count expansion factors for Chicago.

Time of Count	Percentage of 10-h Count Captured (%)	Expansion Factor for 10-h Daytime Volume	Expansion Factor to 24-h Volume	Total Expansion Factor
8–9 a.m.	11.81	8.5	1.39	11.76
9–10 a.m.	6.44	15.5	1.39	21.57
10–11 a.m.	5.48	18.2	1.39	25.34
11 a.m.–12 p.m.	8.35	12.0	1.39	16.64
12–1 p.m.	13.03	7.7	1.39	10.66
1–2 p.m.	11.51	8.7	1.39	12.06
2–3 p.m.	8.50	11.8	1.39	16.33
3–4 p.m.	8.69	11.5	1.39	15.99
4–5 p.m.	11.84	8.4	1.39	11.73
5–6 p.m.	14.66	6.8	1.39	9.48
6–7 p.m.	12.06	8.3	1.39	11.52
7–8 p.m.	11.72	8.5	1.39	11.85
8–9 p.m.	11.40	8.8	1.39	12.18

Thus, if a count was collected from 5 to 6 p.m. and the count total was 1,000 pedestrians, this value would be multiplied by 9.48 to arrive at an expanded 24-h volume of 9,480 pedestrians.

Estimating Intersection Crossing Volumes From Midblock Sidewalk Counts

The second method used existing midblock pedestrian counts obtained from Chicago. During the first method, the project team conducted manual counts for sites outside the downtown area. However, for intersections downtown, Chicago already had collected pedestrian volumes, as shown in figure 11. Thus, the team used these volume data and did not conduct manual counts at the downtown sites. However, this resulted in a “unit mismatch” since CDOT collected pedestrian volumes as midblock sidewalk flows. This created a need for a method to use the Chicago sidewalk counts to estimate pedestrian-crossing volumes at the study intersections.



Source: FHWA.

Figure 11. Illustration. Pedestrian volumes at midblock sidewalk points collected by CDOT.

The project team's working assumption was that 100 percent of the sidewalk flow of people crossed at the parallel same-side-of-street crosswalks at the adjacent intersections. This assumption was used in the work of Schneider et al.:[19]

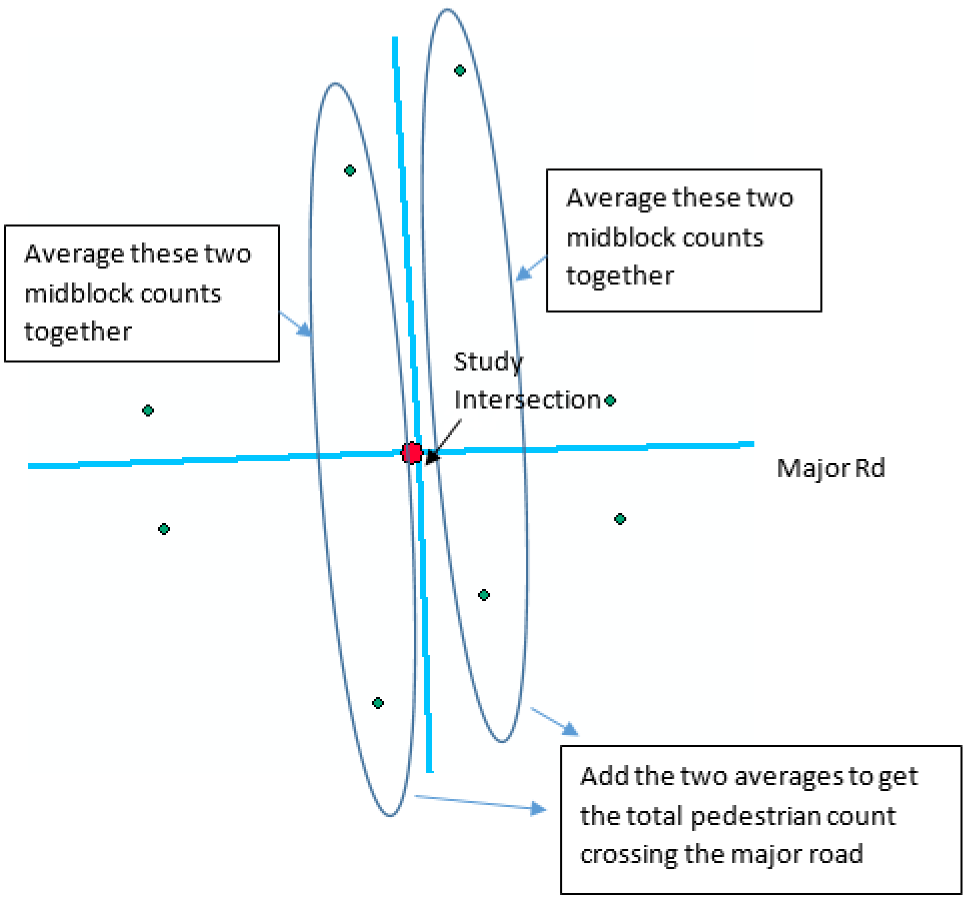
> Automated counters were rotated among 25 of the study intersections between March and September 2010 to document typical weekly pedestrian activity patterns. The sensors were installed on a pole at waist height and pointed across the sidewalk so that pedestrians were counted each time they crossed the infrared beam. The study methodology *assumed the sidewalk pedestrian volume pattern near the intersection was similar to the adjacent intersection crossings*. [Emphasis added.] (p. 4)

Schneider recognizes that the association between sidewalk activity and crossing counts was unknown:[20]

> The assumption that the daily pattern of pedestrian sidewalk activity is similar to that of the adjacent intersection requires additional testing and validation. Future studies should compare the 24-hour sidewalk counts with adjacent 24-hour crossing counts to determine how much variation exists between these pedestrian volume distributions at different types of locations. Variation between pedestrian volume distributions for crosswalks and adjacent sidewalks

may be due to differences in land uses on each corner of the intersection, differences in the difficulty of crossing a particular intersection leg at different times of day, or other site-specific differences.

Despite the need to make assumptions regarding the association of these types of pedestrian activity, the process described by Schneider represents the best available procedure to estimate intersection crossing counts from midblock volumes. For the final pedestrian-crossing counts at these intersections, the team assumed that 100 percent of pedestrians counted in the midblock sidewalk flow crossed at same-side-of-street, parallel-direction crosswalks at the adjacent intersections, as shown in figure 12. If one or more midblock count points were missing, the project team assumed the same value across the street.



Source: FHWA.

Figure 12. Illustration. Method for estimating intersection crossing counts from midblock volumes.

Crash Data

CDOT provided crash data from 2005 to 2014 as a geodatabase with crashes plotted as spatial points. The team used spatial proximity to associate crashes with the study intersections. The team consulted with Chicago staff on the best way to associate crashes to intersections—either based on distance, crash attributes, or a combination of the two. Based on the recommendation from Chicago staff, the crash association process did not involve information from crash attributes, such as “intersection related.” Following Chicago’s standard practice, the team used a distance of 75 ft as the maximum distance for crash association. That is, all crashes within 75 ft of the intersection midpoint were associated with that intersection.

Treatment-Cost Data

The project team was unable to obtain data from Chicago regarding the cost of the LPI or protected left-turn phasing implementation.

NYC

NYC served as a source of data for both the LPI and the protected left turn–phasing evaluations. The following sections provide details on how the team identified study sites in NYC, what data sources were used, and how the data were collected.

Installation Data

The project team identified treatment sites through information provided by the NYC Department of Transportation (NYCDOT). NYCDOT staff provided a list of 773 signalized intersections where LPI timing was present along with the installation date when the LPI timing was enacted. They also provided a list of 243 intersections where protected or protected/permissive left-turn phasing had been implemented.

NYC typically provides 7 s for the LPI. At most locations (approximately 90 percent of the final treatment group), LPIs were implemented at the crossings for only one street at the intersection. All LPI installations used in this study were from signals where pedestrian phasing with pedestrian-signal head was already present at the intersection (i.e., LPIs retrofit to existing signals). Additionally, it should be noted that NYC has a citywide prohibition on RTORs unless otherwise signed.

The team used historical signal plans for each treatment site to determine installation dates for LPI timing for sites where the installation date was vague or unknown. For many of the potential LPI treatment sites, the installation (signal conversion) date was either too far in the past, making reliable crash and volume data difficult to obtain, or too recent, leaving no room for an after period. Eliminating these sites provided a list of 235 intersections that were eligible based on LPI installation date. For many of the potential protected left turn–phasing treatment sites, the date of the signal conversion was unknown, or the protected left-turn phasing had been implemented at the intersection at some point before the beginning of the intended study period, making the site unusable for the before–after study design.

Using these lists of potential treatment sites, the team examined data for each site to determine its eligibility and, where eligible, collect all necessary data on the site. The project team completed this in the exact same manner as was done for the Chicago treatment sites to facilitate analysis of both cities together. The same eligibility criteria were used when examining potential treatment sites, and the same data coding and protocols were used for data collection. Out of the potential group of 235 intersections where LPIs were installed, the project team identified 147 as ineligible for the study due to a lack of minor road traffic-volume data, more than 4 intersection legs, or other geometric oddities that excluded them from the study. Out of the potential group of intersections where protected left-turn phasing had been implemented, the project team found many to be ineligible for the study for these same reasons as well as the lack of knowledge on the date of signal conversion.

Reference Sites

To identify reference sites for the analysis, the project team began with a selection of potentially eligible reference sites using data on treatment locations, roads with AADT, and a point file of signal locations supplied by NYC. Within the spatial environment, the team selected signals that were within 1,000 ft of a treatment site (excluding the treatment sites themselves). From that set of sites, the team selected those that were spatially positioned on roads with an AADT value greater than 0. This ensured that the team would only investigate potential reference sites that had traffic-volume data available. This resulted in a set of potentially eligible reference sites that was used to collect data, such as signal plans. This set of potential reference sites totaled 450 intersections. During the subsequent collection of intersection and roadway characteristics, this set of potential reference sites served as the basis for the final set of reference sites after dropping sites that did not meet the eligibility criteria or did not have all necessary data available.

Roadway Data

The project team used Web-based aerial photography and street-level imagery to determine the eligibility of treatment and reference site locations and collect roadway characteristics. The project team gathered roadway geometry for the eligible sites and recorded the following characteristics for each site:

- Number of intersection legs.
- One- or two-way direction of streets.
- Number of through lanes.
- Number of turn lanes.
- Combination of through and turn lanes.
- Presence of a crosswalk.

The appendix contains an example of the roadway data and format collected by the project team.

Signal Data

NYCDOT staff provided electronic signal plans for requested sites from the project team. These contained signal phases, timing, and daily schedules. The project team used these plans to determine the eligibility of a site location. For treatment intersections, the project team verified the installation of a treatment during the study period as well as the absence of the treatment before the scheduled installation date. For reference intersections, the project team verified the absence of the target treatment for any time during the study period.

The project team recorded the following characteristics for each site:

- Signal actuation.
- Presence of a pedestrian-only phase.
- Date of treatment installation (treatment sites only).
- Presence of a pedestrian countdown signal.
- RTORs permitted (otherwise assumed to be prohibited).
- Phasing timing and schedule for entire study period (reference sites only).
- Phasing timing and schedule before installation (treatment sites only).
- Phasing timing and schedule after installation (treatment sites only).

The appendix contains an example of the signal data and format collected by the project team.

Vehicle-Volume Data

The project team obtained AADT geographic information system (GIS) shapefiles from the online New York State GIS Clearinghouse for all available years within the study period. The project team spatially joined the AADT segments with a draft GIS layer of roadway intersections created by New York State Department of Transportation.(21) The project team input joined data into the master database containing roadway and signal data.

Pedestrian-Volume Data

The team obtained pedestrian volume through two sources. The first was manual counts conducted by the project team. A local team collected pedestrian-crossing counts at each eligible treatment or reference site. These counts were conducted over a short period at each site (typically 1 h). However, an estimate of daily pedestrian volume was required for the analysis. In order to expand the short counts to daily volumes, the team obtained a spreadsheet from NYC staff that contained the necessary information. The expansion factors in this NYC spreadsheet represented the typical values the agency uses in its processes. All of the manual counts were conducted from 5 to 6 p.m. on weekdays. Based on the information in the NYC spreadsheet, this time period captures 7 percent of daily pedestrian volume. Thus, the expansion factor used to convert the 1-h manual counts to equivalent daily volumes was 1 divided by 0.07 (14.29).

The second source of pedestrian-volume information was existing NYC pedestrian counts. Manual counts were not necessary at all study sites since NYC already had existing pedestrian counts at a number of sites. The team obtained these existing counts through a combination of accessing publicly available counts on the NYC data website, direct data delivery from NYC staff, and direct access to data through the NYCDOT Traffic Information Management System. These counts, typically collected as all-day counts (i.e., 7 a.m. to 6 p.m.), were converted to equivalent daily pedestrian volume using the same method as for the manual counts.

Crash Data

All crash data were obtained from NYCDOT staff. The team sent the lists of treatment and reference sites to NYC. The staff conducted an internal query of the crash database and delivered files containing individual records for all crashes associated with each intersection. The crash data covered the years 2001 to 2014 and contained all necessary information to identify all target crash types, such as pedestrian-involved and left-turn.

Treatment-Cost Data

NYC staff estimated that installing an LPI at a single intersection would cost $1,200, primarily due to staff time (cost information relevant to the year 2017). This cost includes collecting pedestrian and vehicle counts in the morning and evening peak hours, conducting a field investigation, performing a traffic capacity analysis, preparing NYC's database for LPIs, and implementing the LPI timing in the field. This cost estimate would be the same for an intersection of one-way to one-way streets or two-way to two-way streets.

CHARLOTTE

Charlotte served as a source of data for the LPI evaluation. The sections below provide details on how the team identified study sites in Charlotte, what data sources were used, and how the data were collected.

Installation Data

Charlotte staff provided a list of 23 intersections where LPIs had been implemented. The list also contained the installation dates, the majority of which were between 2012 and 2015. The LPI installation sites included those where LPIs had been implemented on the crossings for both streets and those where an LPI had been implemented only on the crossings of one street (e.g., only crossings parallel to the major street). Charlotte typically provides a period of 3 to 10 s for the LPI. All LPI installations used in this study were from signals where pedestrian phasing with a pedestrian-signal head was already present at the intersection (i.e., LPIs retrofit to existing signals).

Reference Sites

The team used a group of 116 signalized intersections with pedestrian signals for the reference group. This group represented signals that were similar in nature and geographical placement to the treatment sites but did not have LPI timing implemented. Data on these intersections (e.g., intersection characteristics, vehicle volumes, pedestrian volumes, historical changes, and crash data) were available through a related evaluation conducted under a separate FHWA research project.

Roadway Data

The team used roadway inventory files provided by Charlotte in spatial format, Web-based aerial photography, and street-level imagery to determine the eligibility of treatment and reference site locations and collect roadway characteristics. The project team gathered roadway geometry for the eligible sites and recorded the following characteristics for each site:

- Number of intersection legs.
- Direction of traffic on each road (one-way or two-way).
- Number of through lanes on each road.

- Road division by median.
- Speed limit on the intersection approaches on the major and minor roads.

Vehicle-Volume Data

For the treatment sites, the team used daily vehicle volume data provided by Charlotte in spatial format and associated manually with the study sites. For the reference sites, the team used the data available from the related FHWA study.

Pedestrian-Volume Data

For the treatment sites, the team used pedestrian counts provided by Charlotte as part of its intersection turning movement counts database. The team associated these data manually with the study sites. For the reference sites, the team used the data available from the related FHWA study.

Crash Data

For the treatment sites, the team used crash data provided by Charlotte. The team plotted the crashes spatially and associated these data manually with the study sites using a spatial file of intersections provided by Charlotte. To maintain consistency with the other cities used in this study, a distance of 75 ft was used as the maximum distance to associate crashes with an intersection. For the reference sites, the team used the data available from the related FHWA study.

Treatment-Cost Data

Charlotte staff provided information on the estimated cost of implementing an LPI at a signalized intersection. They reported that their costs range widely due to their policy of accompanying an LPI conversion with installing accessible pedestrian signals to meet accessibility requirements. They report that the low end of the installation cost would be $200 for staff time to implement the timing change. The high end of the installation cost, assuming significant construction related to the addition of accessible pedestrian signals, would be $50,000 to $100,000.

TORONTO

This section describes the installation data, reference sites, roadway data, traffic data, crash data, and treatment-cost data for the Toronto sites used in this evaluation. Toronto provided two sets of data. The first was originally used for a previous evaluation of left-turn phasing that did not consider vehicle–pedestrian crashes on their own. The team supplemented these data with the required vehicle–pedestrian crash counts for this project. The second set of data was obtained for sites more recently treated with a left turn–phasing change on one or more approaches.

Installation Data

Treated sites were identified in a two-step process. First, an electronic file of work orders for signalized intersections was scanned to identify sites where a change in left-turn phasing was made. Using this list, a subsequent search of hard copy signal-timing reports for these sites identified locations where the left-turn phasing on at least one approach was changed to either protected/permissive or fully protected at any time of day.

From the list of treated sites, the project team removed sites from consideration if any of the following applied:

- Any leg was a freeway ramp.
- Any leg was not a public street (e.g., driveway or alley).
- There were significant construction or changes in roadway or lane geometry during the study period.
- Intersection legs were offset (centerline of one leg (extended) is outside the bounds of the other leg but within 500 ft).
- The site was within 100 ft of any other intersection.
- There was significant skew (angle of the intersecting legs).
- There were fewer than three legs or more than four legs.

Reference Sites

The team found reference sites by using Toronto's signalized-intersections database to identify sites with a similar number of legs, entering lanes, turning lanes, and AADTs on major and minor roads as the treatment sites. The project did not use any sites that had undergone construction or changes in signal phasing during the study period.

Roadway Data

The project team obtained all roadway data from Toronto's database of signalized intersections. Available variables include the number of intersection legs and the number of through, right-turn, and left-turn lanes by approach.

Signal Data

Historical signal-timing plans were reviewed by the project team, and for each approach, it was indicated if permitted, protected/permissive, or protected phasing was provided at any point in the day or week. If, for example, a phase was permitted most of the day but provided a protected/permissive phase during the peak hours, the approach was classified as protected/permissive, and it was noted that this applies to the peak-hour periods only.

Traffic Data

Toronto's database of signalized intersections provided AADT estimates for the major and minor roads. The database also provided 8-h pedestrian volumes for each crossing. The 8-h counts were used in the EB analysis of the Toronto sites to retain their accuracy without making assumptions to convert them to full-day counts. When conducting the disaggregate analysis, these 8-h counts were converted to 24-h counts using the same approach as used in Chicago in order to combine the data from all cities. This required applying a factor of 1.75 to each 8-h count.

Crash Data

Crash data, coded by latitude–longitude, were provided in electronic form by Toronto. For the group of older sites, crash data from 1999 to 2007 were used, and for the newer installations, data from 2005 to 2014 were used. Crashes within a radius of about 82 ft of the intersection center and that occurred on the roadway were identified as related to an intersection. This distance had been selected as appropriate in previous studies undertaken by the city after reviewing crash reports in detail.

Treatment-Cost Data

The city estimates an average cost of $25,000 to $28,000 for the purchase of equipment and installation of left-turn-signal phasing.

DATA CHARACTERISTICS AND SUMMARY

This section describes the treatment sites, reference sites, geometric data, traffic data, and crash data used in each evaluation. The information should not be used to make simple before–after or between-city comparisons of crashes per intersection-year because such comparisons would not account for factors, other than the strategy, that might cause differences in safety between the before and after periods or between cities. Such comparisons, which are presented later, are properly done with the EB analysis.

Protected Left Turn–Phasing Evaluation

Toronto comprised the majority of sites in the left-turn phasing evaluation. Table 4 presents the number of treatment and reference sites by city.

Table 4. Number of protected left-turn phasing treatment and reference sites by city.

City	Treatment Sites	Reference Sites
Chicago	27	149
NYC	7	146
Toronto	114	776

Table 5 and table 6 provide a summary of the characteristics and crash data for the treatment and reference sites for Chicago for the protected and protected/permissive left turn–phasing evaluation. The before phasing included 68 permissive-only sites, 2 protected/permissive sites, and 0 protected-only sites. The after phasing included 0 permissive-only sites, 68 protected/permissive sites, and 2 protected-only sites.

Table 5. Chicago treatment site summary statistics (27 sites).

Variable	Minimum	Maximum	Average	Frequency
Years before	3	8	5.07	N/A
Years after	1	6	3.93	N/A
Phasing before*	N/A	N/A	N/A	Permissive only—68 Protected/permissive—2 Protected only—0
Phasing after*	N/A	N/A	N/A	Permissive only—0 Protected/permissive—68 Protected only—2
Number of treated approaches	1	4	2.59	N/A
Number of approaches	3	4	3.93	N/A
Number of major road through lanes	2	6	3.26	N/A
Number of minor road through lanes	2	4	2.52	N/A
Left-turn lanes on major road	1	2	1.78	N/A
Left-turn lanes on minor road	0	2	1.59	N/A
Major road AADT before	6,254	37,355	19,626	N/A
Major road AADT after	9,912	36,500	19,546	N/A
Minor road AADT before	4,055	32,255	12,744	N/A
Minor road AADT after	4,133	26,148	12,917	N/A
Major road left-turn AADT before	N/A	N/A	N/A	N/A
Major road left-turn AADT after	N/A	N/A	N/A	N/A
Minor road left-turn AADT before	N/A	N/A	N/A	N/A
Minor road left-turn AADT after	N/A	N/A	N/A	N/A
Pedestrian AADT	57	36,495	5,036	N/A
Pedestrian crashes/year before	0	3.33	0.93	N/A
Pedestrian crashes/year after	0	2.33	0.85	N/A
Vehicle crashes/year before	2.80	48	15.22	N/A
Vehicle crashes/year after	2	28.50	10.13	N/A
Vehicle injury crashes/year before	0	9.80	2.91	N/A
Vehicle injury crashes/year after	0	4.67	1.78	N/A

*Treated approach(es).
N/A = not applicable.

Table 6. Chicago reference site summary statistics (149 sites).

Variable	Minimum	Maximum	Average
Number of approaches	3	4	3.97
Number of major road through lanes	1	6	2.99
Number of minor road through lanes	1	4	2.42
Left-turn lanes on major road	0	2	0.95
Left-turn lanes on minor road	0	2	0.74
Major road AADT	1,050	70,233	14,333
Minor road AADT	966	22,020	7,631
Major road left-turn AADT	N/A	N/A	N/A
Minor road left-turn AADT	N/A	N/A	N/A
Pedestrian AADT	10	65,684	8,373
Pedestrian crashes/year	0	2.30	0.56
Vehicle crashes/year	0	22.00	6.08
Vehicle injury crashes/year	0	5.30	1.23

N/A = not applicable.

NYC

Table 7 and table 8 provide a summary of the characteristics and crash data for the treatment and reference sites for NYC for the protected left turn–phasing evaluation. The before phasing included four permissive-only sites, four protected/permissive sites, zero protected-only sites, and one prohibited site. The after phasing included zero permissive-only sites, one protected/permissive site, and eight protected-only sites.

Table 7. NYC treatment site summary statistics (7 sites).

Variable	Minimum	Maximum	Average	Frequency
Years before	9	12	10.86	N/A
Years after	1	4	2.14	N/A
Phasing before*	N/A	N/A	N/A	Permissive only—4 Protected/permissive—4 Protected only—0 Prohibited—1
Phasing after*	N/A	N/A	N/A	Permissive only– 0 Protected/permissive—1 Protected only—8
Number of treated approaches	1	2	1.29	N/A
Number of approaches	3	4	3.86	N/A
Number of major road through lanes	2	4	3.50	N/A
Number of minor road through lanes	1	5	2.43	N/A
Left-turn lanes on major road	1	3	1.86	N/A
Left-turn lanes on minor road	0	2	0.86	N/A
Major road AADT before	19,114	32,713	26,359	N/A
Major road AADT after	19,114	36,289	26,288	N/A
Minor road AADT before	3,974	34,924	15,763	N/A
Minor road AADT after	3,887	26,564	14,477	N/A
Major road left-turn AADT before	N/A	N/A	N/A	N/A
Major road left-turn AADT after	N/A	N/A	N/A	N/A
Minor road left-turn AADT before	N/A	N/A	N/A	N/A
Minor road left-turn AADT after	N/A	N/A	N/A	N/A
Pedestrian AADT	1,857	32,772	9,705	N/A
Pedestrian crashes/year before	0	4.42	1.33	N/A
Pedestrian crashes/year after	0	4	1.46	N/A
Vehicle crashes/year before	0	9.22	3.71	N/A
Vehicle crashes/year after	0	8.00	3.00	N/A
Vehicle injury crashes/year before	0	6.89	2.39	N/A
Vehicle injury crashes/year after	0	5	2.14	N/A

*Treated approach(es).
N/A = not applicable.

Table 8. NYC reference site summary statistics (146 sites).

Variable	Minimum	Maximum	Average
Number of approaches	3	4	3.96
Number of major road through lanes	1	7	3.36
Number of minor road through lanes	1	6	1.47
Left-turn lanes on major road	0	2	0.16
Left-turn lanes on minor road	0	2	0.13
Major road AADT	2,102	46,297	22,225
Minor road AADT	531	22,884	6,251
Major road left-turn AADT	N/A	N/A	N/A
Minor road left-turn AADT	N/A	N/A	N/A
Pedestrian AADT	10	168,043	26,264
Pedestrian crashes/year	0	4.07	0.95
Vehicle crashes/year	0	10.00	2.66
Vehicle injury crashes/year	0	5.71	1.67

N/A = not applicable.

Toronto

Table 9 and table 10 provide a summary of the characteristics and crash data for the treatment and reference sites for Toronto for the protected left turn–phasing evaluation. The before phasing included 136 permissive-only sites, 0 protected/permissive sites, and 0 protected-only sites. The after phasing included 0 permissive-only sites, 134 protected/permissive sites, and 2 protected-only sites.

Table 9. Toronto treatment site summary statistics (114 sites).

Variable	Minimum	Maximum	Average	Frequency
Years before	1	8	4.70	N/A
Years after	1	7	3.76	N/A
Phasing before*	N/A	N/A	N/A	Permissive only—136 Protected/permissive—0 Protected only—0
Phasing after*	N/A	N/A	N/A	Permissive only—0 Protected/permissive—134 Protected only—2
Number of treated approaches	1	3	1.19	N/A
Number of approaches	3	4	3.98	N/A
Number of major road through lanes	2	8	4.49	N/A
Number of minor road through lanes	1	7	3.48	N/A
Left-turn lanes on major road	0	3	1.63	N/A
Left-turn lanes on minor road	0	3	1.41	N/A
Major road AADT before	4,355	74,990	32,335	N/A
Major road AADT after	4,355	73,697	32,116	N/A
Minor road AADT before	886	47,128	16,833	N/A
Minor road AADT after	886	47,128	17,109	N/A
Major road left-turn AADT before	28	9,830	3,094	N/A
Major road left-turn AADT after	124	7,442	3,138	N/A
Minor road left-turn AADT before	146	11,110	3,369	N/A
Minor road left-turn AADT after	124	8,586	3,243	N/A
Pedestrian 8-h count	16	32,237	2,267	N/A
Pedestrian crashes/year before	0	4	0.79	N/A
Pedestrian crashes/year after	0	5	0.70	N/A
Vehicle crashes/year before	0	63	21.28	N/A
Vehicle crashes/year after	0	77	22.46	N/A
Vehicle injury crashes/year before	0	22	6.37	N/A
Vehicle injury crashes/year after	0	21	4.85	N/A

*Treated approach(es).
N/A = not applicable.

Table 10. Toronto reference site summary statistics (766 sites).

Variable	Minimum	Maximum	Average
Number of approaches	3	4	3.96
Number of major road through lanes	1	8	4.32
Number of minor road through lanes	1	7	2.52
Left-turn lanes on major road	0	3	1.17
Left-turn lanes on minor road	0	3	0.72
Major road AADT	2,188	63,596	28,594
Minor road AADT	502	47,770	9,071
Major road left-turn AADT	0	12,670	1,675
Minor road left-turn AADT	0	9,021	907
Pedestrian 8-h count	6	27,827	1,650
Pedestrian crashes/year	0	3.70	0.51
Vehicle crashes/year	0	63.80	12.54
Vehicle injury crashes/year	0	18.11	3.48

LPI Evaluation

Chicago and NYC comprised the majority of the sites in the LPI evaluation. Table 11 presents the number of treatment and reference sites by city.

Table 11. Number of LPI treatment and reference sites by city.

City	Treatment Sites	Reference Sites
Chicago	56	183
NYC	42	157
Charlotte	7	111

Table 12 through table 17 provide a summary of the characteristics and crash performance of the treatment and reference sites by city for the LPI evaluation.

Table 12. Data summary for Chicago treatment sites (56 sites).

Variable	Minimum	Maximum	Average
Years of data per site before	2	4	2.25
Years of data per site after	1	7	6.036
Number of major road through lanes	2	6	2.821
Number of minor road through lanes	2	4	2.286
Exclusive left-turn lanes on major road	0	2	0.964
Exclusive left-turn lanes on minor road	0	2	0.857
Major road AADT	6,650	32,363	16,407
Minor road AADT	1,850	25,883	9,843
Pedestrian AADT crossing major road	20	33,569	8,544
Pedestrian AADT crossing minor road	48	34,126	9,328
Total crashes per year per site before	4.714	37.143	14.881
Total crashes per year per site after	1.5	30.5	10.902
Total injury crashes per year per site before	1.286	14.286	4.05
Total injury crashes per year per site after	0	9	2.96
Pedestrian crashes per year per site before	0.25	6	1.793
Pedestrian crashes per year per site after	0	4.5	1.146

Table 13. Data summary for Chicago reference sites (183 sites).

Variable	Minimum	Maximum	Average
Years of data per site	10	10	10
Number of major road through lanes	2	6	3.337
Number of minor road through lanes	1	6	2.533
Left-turn lanes on major road	0	4	1.191
Left-turn lanes on minor road	0	3	0.897
Major road AADT	2,910	64,000	16,994
Minor road AADT	725	23,500	8,519.18
Pedestrian AADT crossing major road	20	25,460	2,890.72
Pedestrian AADT crossing minor road	20	29,142	3,222.7
Total crashes per year per site before	0	59	11.207
Total crashes per year per site after	N/A	N/A	N/A
Total injury crashes per year per site before	0	15	2.891
Total injury crashes per year per site after	N/A	N/A	N/A
Pedestrian crashes per year per site before	0	4	0.598
Pedestrian crashes per year per site after	N/A	N/A	N/A

N/A = not applicable.

Table 14. Data summary for NYC treatment sites (42 sites).

Variable	Minimum	Maximum	Average
Years of data per site before	1	10	3.905
Years of data per site after	3	12	9.071
Number of major road through lanes	1	6	3.762
Number of minor road through lanes	1	6	2.881
Left-turn lanes on major road	0	2	0.548
Left-turn lanes on minor road	0	3	0.5
Major road AADT	1,828	46,599	23,569.4
Minor road AADT	4,944	48,075	15,527.8
Pedestrian AADT crossing major road	586	52,486	13,635.9
Pedestrian AADT crossing minor road	314	92,743	14,959
Total crashes per year per site before	0	18.667	8.415
Total crashes per year per site after	1.167	17.5	7.496
Total injury crashes per year per site before	0	13.111	6.427
Total injury crashes per year per site after	1	14.5	5.45
Pedestrian crashes per year per site before	0	5.333	2.294
Pedestrian crashes per year per site after	0	5.75	2.017

Table 15. Data summary for NYC reference sites (157 sites).

Variable	Minimum	Maximum	Average
Years of data per site	15	15	15
Number of major road through lanes	1	7	3.344
Number of minor road through lanes	0	6	1.408
Left-turn lanes on major road	0	2	0.223
Left-turn lanes on minor road	0	2	0.102
Major road AADT	825	46,482	2,1991.1
Minor road AADT	699	27,682	6,983.82
Pedestrian AADT crossing major road	457	44,505	9,846.23
Pedestrian AADT crossing minor road	300	13,1257	1,7614.1
Total crashes per year per site before	0	17	4.217
Total crashes per year per site after	N/A	N/A	N/A
Total injury crashes per year per site before	0	12	2.917
Total injury crashes per year per site after	N/A	N/A	N/A
Pedestrian crashes per year per site before	0	9	1.013
Pedestrian crashes per year per site after	N/A	N/A	N/A

N/A = not applicable.

Table 16. Data summary for Charlotte treatment sites (7 sites).

Variable	Minimum	Maximum	Average
Years of data per site before	2	4	2.857
Years of data per site after	2	4	3.143
Intersection AADT	17,781	49,687	38,359
Intersection pedestrian AADT	28	672	173
Total crashes per year per site before	3.667	17.667	8.786
Total crashes per year per site after	6	20.333	12.321
Total injury crashes per year per site before	0.667	4	2.429
Total injury crashes per year per site after	1	7.333	4.048
Pedestrian crashes per year per site before	0	0	0
Pedestrian crashes per year per site after	0	0.5	0.119

Table 17. Data summary for Charlotte reference sites (111 sites).

Variable	Minimum	Maximum	Average
Years of data per site before	7	7	7
Years of data per site after	N/A	N/A	N/A
Intersection AADT	12,495	67,089	30,662
Intersection pedestrian AADT	8	512	113
Total crashes per year per site before	0	23	6.207
Total crashes per year per site after	N/A	N/A	N/A
Total injury crashes per year per site before	0	15	2.559
Total injury crashes per year per site after	N/A	N/A	N/A
Pedestrian crashes per year per site before	0	2	0.09
Pedestrian crashes per year per site after	N/A	N/A	N/A

N/A = not applicable.

Data Summary by Treatment Type (Chicago)

Chicago treatment sites were classified into two categories based on how LPIs were implemented, as follows:

- Treatment category 1: LPIs implemented at all crossings (across major and minor roads). There were 42 sites in this category.
- Treatment category 2: LPIs implemented only for crossings across the minor road (parallel to the major road). There were nine sites in this category.

Because some treatment sites could not be classified into either treatment category, the number of sites from these two categories does not equal the total number of treatment sites in Chicago.

Table 18 and table 19 provide a summary of the site characteristics for each category of treatment sites in Chicago.

Table 18. Data summary for Chicago treatment category 1 (42 sites).

Variable	Minimum	Maximum	Average
Years of data per site before	1	7	6.167
Years of data per site after	2	4	2.238
Number of major road through lanes	2	4	2.667
Number of minor road through lanes	2	4	2.238
Left-turn lanes on major road	0	2	0.881
Left-turn lanes on minor road	0	2	0.833
Major road AADT	6,650	22,167	14,870.7
Minor road AADT	1,850	18,433	9,305.86
Pedestrian AADT crossing major road	68	29,492	9,382.86
Pedestrian AADT crossing minor road	48	34,126	10,778.5
Total crashes per year per site before	5.333	37.143	14.751
Total crashes per year per site after	1.5	25.5	10.73
Total injury crashes per year per site before	1.286	14.286	3.987
Total injury crashes per year per site after	0	9	2.95
Pedestrian crashes per year per site before	0.571	6	1.899
Pedestrian crashes per year per site after	0	4.5	1.187

Table 19. Data summary for Chicago treatment category 2 (9 sites).

Variable	Minimum	Maximum	Average
Years of data per site before	4	7	6.111
Years of data per site after	2	3	2.333
Number of major road through lanes	2	4	3.222
Number of minor road through lanes	2	3	2.111
Left-turn lanes on major road	1	2	1.667
Left-turn lanes on minor road	0	2	0.667
Major road AADT	9,550	32,363	21,514.4
Minor road AADT	5,625	14,467	10,025.9
Pedestrian AADT crossing major road	20	21,154	4,518.67
Pedestrian AADT crossing minor road	88	21,590	3,919.22
Total crashes per year per site before	4.714	27.667	14.069
Total crashes per year per site after	4	17.333	9.685
Total injury crashes per year per site before	1.286	10	4.099
Total injury crashes per year per site after	0.5	5.333	2.722
Pedestrian crashes per year per site before	0.25	4.833	1.538
Pedestrian crashes per year per site after	0	3	1.13

CHAPTER 6. DEVELOPMENT OF SAFETY PERFORMANCE FUNCTIONS

This chapter presents the SPFs developed for each city for untreated sites. The SPFs, as noted earlier, were used in the EB methodology to estimate the safety effectiveness of the treatments. Generalized linear modeling was used to estimate model coefficients assuming a negative binomial error distribution, which is consistent with the state of research in developing these models. In specifying a negative binomial error structure, *k*, used in the EB calculations, was estimated iteratively from the model and the data. For a given dataset, smaller values of *k* indicated relatively better models. Estimates of *k* are provided, along with other model parameters. The project team calibrated SPFs separately for each city and for each treatment using the corresponding data for untreated sites.

PROTECTED LEFT TURN–PHASING EVALUATION

This section presents the SPFs and parameters developed for Chicago, NYC, and Toronto as part of the protected left turn–phasing evaluation.

Chicago SPFs

Figure 13 shows the SPF model form for Chicago. Table 20 shows the associated parameter estimates and SEs.

$$Crashes\ per\ year = \exp^{(intercept + a \times LEGS)} AADTMAJ^{b}\, AADTMIN^{c}\, PEDVOL^{d}$$

Figure 13. Equation. Form of Chicago SPFs.

Where:

LEGS = 1 if a 4-legged intersection; 0 if a 3-legged intersection.
AADTMAJ = AADT volume on major road.
AADTMIN = AADT volume on minor road.
PEDVOL = sum of 24-h pedestrian volumes for all crossings.
intercept, a, b, c, d = parameters estimated in the SPF calibration process.

Table 20. Parameter estimates and SEs for Chicago SPFs.

Crash Type	*intercept* (SE)	*a* (SE)	*b* (SE)	*c* (SE)	*d* (SE)	*k* (SE)
Vehicle–pedestrian (all severities combined)	−10.4429 (1.4929)	1.8873 (0.6316)	0.2795 (0.1362)	0.3698 (0.1124)	0.2498 (0.0378)	0.2148 (0.0563)
Vehicle–vehicle (all severities combined)	−6.0691 (0.8396)	1.1330 (0.2399)	0.4375 (0.0912)	0.2943 (0.0644)	—	0.2066 (0.0267)
Vehicle–vehicle injury	−7.4053 (1.2139)	1.5098 (0.4003)	0.3929 (0.1223)	0.2711 (0.0887)	—	0.3352 (0.0491)

Note: Numbers in parentheses are SEs.
—The variable associated with this parameter was not included in the SPF.

NYC SPFs

Figure 14 shows the SPF model form for NYC. Table 21 shows the associated parameter estimates and SEs.

$$Crashes\ per\ year = \exp^{(intercept + a \times LEGS)} AADTMAJ^{b}\, AADTMIN^{c}$$

Figure 14. Equation. Form of NYC SPFs.

Table 21. Parameter estimates and SEs for NYC SPFs.

Crash Type	***intercept*** **(SE)**	***a*** **(SE)**	***b*** **(SE)**	***c*** **(SE)**	***k*** **(SE)**
Vehicle–pedestrian (all severities combined)	−8.2556 (0.9749)	0.6142 (0.2842)	0.4365 (0.0931)	0.3779 (0.1094)	0.3356 (0.0510)
Vehicle–vehicle (all severities combined)	−5.7825 (0.7051)	—	0.3295 (0.0684)	0.4033 (0.0820)	0.2210 (00298)
Vehicle–vehicle injury	−5.6568 (0.8051)	0.4363 (0.2314)	0.2269 (0.0737)	0.4051 (0.0890)	0.2462 (0.0351)

Note: Numbers in parenthesis are SEs.
—The variable associated with this parameter was not included in the SPF.

Toronto SPFs

For the analyses of Toronto data, separate SPFs were estimated for the older and newer treatment sites. Figure 15 shows the model form for newer sites. Table 22 shows the associated parameter estimates and SEs.

$$Crashes\ per\ year = \exp^{(intercept + a \times FlashAdvGreen)} AADTMAJ^{b}\, AADTMIN^{c}\, PEDVOL^{d}\, (AADTMAJ + AADTMIN)^{e}$$

Figure 15. Equation. Form of Toronto SPFs for newer sites.

Where:

FlashAdvGreen = 1 if flashing advance green is present; 0 if not.
PEDVOL = sum of 8-h pedestrian volumes for all crossings.

Table 22. Parameter estimates and SEs for Toronto SPFs for newer sites.

Crash Type	***intercept*** **(SE)**	***a*** **(SE)**	***b*** **(SE)**	***c*** **(SE)**	***d*** **(SE)**	***e*** **(SE)**	***k*** **(SE)**
Vehicle–pedestrian (all severities combined)	−12.2459 (1.5849)	0.1847 (0.1266)	—	—	—	0.7042 (0.1352)	0.2554 (0.0584)
Vehicle–vehicle (all severities combined)	−8.4069 (0.7859)	−0.1460 (0.0730)	0.5548 (0.0794)	0.5819 (0.0387)	—	—	0.1665 (0.0217)
Vehicle–vehicle injury	−10.9712 (0.8861)	—	0.6367 (0.0888)	0.5912 (0.0434)	—	—	0.1579 (0.0278)

Note: Numbers in parenthesis are SEs.
—The variable associated with this parameter was not included in the SPF.

Figure 16 shows the SPF model form for older sites. Table 23 shows the associated parameter estimates and SEs.

$$\begin{aligned}&Crashes\ per\ year\\&= \exp^{(intercept+a\times LEGS+b\times ltmaj+c\times ltmin+Intersection\_Class)} AADTMAJ^{d}\, AADTMIN^{e}\, PEDVOL^{f}\end{aligned}$$

Figure 16. Equation. Form of Toronto SPFs for older sites.

Where:

ltmaj = 1 if one or more left-turn lanes are present on the major road.
ltmin = 1 if one or more left-turn lanes are present on the minor road.
Intersection_Class = constant added dependent on category of intersection.
PEDVOL = sum of 8-h pedestrian volumes for all crossings.
intercept, a, b, c, d, e, f = parameters estimated in the SPF calibration process.

Intersection_Class provides a unique value for each combination of intersecting roads, which are defined as follows:

1. Four-legged intersection with a private, local, or collector road intersecting a private, local, or collector road.
2. Four-legged intersection with a minor arterial intersecting a private or local road.
3. Four-legged intersection with a minor road intersecting a collector road.
4. Four-legged intersection with a minor road intersecting a minor road.
5. Four-legged intersection with a major road intersecting a private or local road.
6. Four-legged intersection with a major road intersecting a collector road.

7. Four-legged intersection with a major road intersecting a minor road.
8. Four-legged intersection with a major road intersecting a major road.
9. Four-legged intersection with an expressway.
10. Three-legged intersection with a private, local, or collector road or minor arterial intersecting a private, local, or collector or minor arterial.
11. Three-legged intersection with a major arterial intersecting a private or local road.
12. Three-legged intersection with a major arterial intersecting a collector road.
13. Three-legged intersection with a major arterial intersecting a minor or major arterial.

The numbers in this list of intersection classes correspond to the numbers in column 6 of table 23.

Table 23. Parameter estimates and SEs for Toronto SPFs for older sites.

Crash Type	*intercept* (SE)	*a* (SE)	*b* (SE)	*c* (SE)	*Intersection_Class* (SE)	*d* (SE)	*e* (SE)	*f* (SE)	*k* (SE)
Vehicle–pedestrian (all severities combined)	−9.2816 (0.8547)	0.3597 (0.1441)	—	—	—	0.1563 (0.0829)	0.3309 (0.0371)	0.5216 (0.0321)	0.2620 (0.0300)
Vehicle–vehicle (all severities combined)	−8.2165 (0.7370)	−0.0908 (0.0904)	0.2133 (0.0520)	0.1986 (0.0435)	2 (0.1824) 3 (0.9302) 5 (0.7306) 6 (0.5383) 8 (0.5836) 9 (0.3608) 10 (−0.6393) 12 (0.4087) 13 (0.0000)	0.4480 (0.0729)	0.6037 (0.0464)	—	0.1649 (0.0111)
Vehicle–vehicle injury	−8.5132 (0.7297)	0.0179 (0.0981)	—	0.1321 (0.0468)	1 (0.0000) 2 (−0.7280) 3 (0.8986) 5 (0.6657) 6 (0.5754) 8 (0.5093) 9 (0.2280) 10 (−0.5442) 12 (0.3404) 13 (0.0000)	0.4630 (0.0717)	0.4894 (0.0514)	—	0.1685 (0.0131)

Note: Numbers in parenthesis are SEs.
—The variable associated with this parameter was not included in the SPF.

LPI EVALUATION

This section presents the variables and parameters used in the SPFs developed for each of the three cities for the LPI analysis. The SPFs were developed using data from the reference group and the treatment group before LPI installation. The before-treatment data were used mainly for two reasons. One was to increase the sample size available for SPF development, given that there were limited data in the reference group. The other was to decrease the effect of possible differences between the treatment (before) and reference groups.

Chicago SPFs

Table 24 through table 26 present the SPFs for total, injury, and pedestrian crashes per year for Chicago.

Table 24. SPF Parameters for Chicago total crashes per year (developed from reference and treatment before data).

Parameter	Estimate	SE
Intercept	−6.28	0.6632
Major road AADT/1,000	−0.0117	0.0024
Minor road AADT/1,000	0.0476	0.0036
Log(major road AADT)	0.715	0.0663
Pedestrian AADT crossing major road/1,000	−0.0272	0.0059
Pedestrian AADT crossing minor road/1,000	0.0161	0.0049
Log(pedestrian AADT crossing major road)	0.1757	0.0242
Log(pedestrian AADT crossing minor road)	−0.1347	0.0240
Protected left-turn phase (intersection)	0.1767	0.0317
4-legged intersection	1.1847	0.2301
Both 1-way and 2-way (major road)	0.8061	0.1833
2-way (minor road)	0.5432	0.1954
More than 1 right lane (intersection)	0.1661	0.0550
Right-turn lane presence (minor)	−0.2517	0.0538
1 left-turn lane (intersection)	−0.2841	0.0515
2 or more left-turn lanes (intersection)	−0.286	0.0589
1 left-turn lane (minor road)	0.1158	0.0504
More than 1 left-turn lane (minor road)	0.2073	0.0448
1 right-turn lane (de facto/daylighting) (minor road)	−0.2217	0.0496
More than 4 through lanes (intersection)	0.3056	0.0728
More than 7 through lanes (intersection)	0.4353	0.1156
2–3 lanes left turn allowed (intersection)	0.5726	0.1440
More than 3 lanes left turn allowed (intersection)	0.8884	0.2176
3–4 lanes right turn allowed (intersection)	0.1708	0.0572
5–6 lanes right turn allowed (intersection)	0.2241	0.0686
More than 6 lanes right turn allowed (intersection)	0.2723	0.0761
4 through lanes (major roadway class)	0.2347	0.0752
2 through lanes (major leg)	−0.4414	0.0965

Parameter	Estimate	SE
3–5 through lanes (major leg)	−0.4959	0.1694
No through lanes (minor leg)	0.861	0.2068
2 through lanes (minor leg)	0.4646	0.1439
3–4 through lanes (minor leg)	0.8879	0.2946
3 through lanes (minor road)	−0.7957	0.2890
More than 3 through lanes (minor road)	−0.7338	0.2773
Marked pedestrian crosswalk on 1 major leg	0.7998	0.2392
Marked pedestrian crosswalk on both major legs	0.5069	0.2145
Marked pedestrian crosswalk on both minor legs	0.39	0.1136
Right turn allowed on 1 major leg	−0.5884	0.1955
Right turn allowed on both major legs	−0.6925	0.3003
Right turn allowed on 1 minor leg	−0.5378	0.1637
Left turn allowed on 1 major leg	−0.2484	0.0924
Left turn allowed on both major legs	−0.5119	0.1268
Left turn allowed on 1 minor leg	−0.3538	0.1136
Left turn allowed on both minor legs	−1.1518	0.1959
Treatment site	0.2967	0.0395
Dispersion	0.1239	0.0072

Table 25. SPF Parameters for Chicago injury crashes per year (developed from reference and treatment before data).

Parameter	Estimate	SE
Intercept	−4.7465	0.8194
Major road AADT/1,000	−0.0146	0.0032
Minor road AADT/1,000	0.0390	0.0048
Log(major road AADT)	0.5483	0.0906
Log(pedestrian AADT crossing major road)	0.1005	0.0290
Log(pedestrian AADT crossing minor road)	−0.0922	0.0293
Protected left-turn phase (intersection)	0.1220	0.0449
2-way road (minor road)	−0.3590	0.1035
Both 1-way and 2-way (minor road)	0.4398	0.2112
Right-turn lane presence (minor road)	−0.1304	0.0521
1 left-turn lane (intersection)	−0.1366	0.0701
More than 1 left-turn lane (intersection)	−0.3536	0.0819
More than 1 left-turn lane (minor road)	0.3438	0.0647
1 right (de facto/daylighting) (minor road)	−0.1522	0.0599
2 right-turn lanes (de facto/daylighting) (minor road)	0.1249	0.0545
5–7 through lanes (intersection)	0.2431	0.0714
More than 7 through lanes (intersection)	0.3671	0.0969
2–3 lanes left turn allowed (intersection)	0.7188	0.1229
More than 3 lanes left turn allowed (intersection)	1.7234	0.2248
2 through lanes (major leg)	−0.1497	0.0732
Marked pedestrian crosswalk on both minor legs	0.2847	0.1002
Right turn allowed on both minor legs	1.2665	0.2256

Parameter	Estimate	SE
Left turn allowed on 1 major leg	−0.4442	0.1094
Left turn allowed on both major legs	−0.7799	0.1616
Left turn allowed on 1 minor leg	−0.2877	0.1086
Left turn allowed on both minor legs	−1.9220	0.2041
Treatment site	0.4204	0.0457
Dispersion	0.1288	0.0154

Table 26. SPF Parameters for Chicago pedestrian crashes per year (developed from reference and treatment before data).

Parameter	Estimate	SE
Intercept	−7.081	1.0515
Intersection AADT	0.3776	0.09
Minor AADT/intersection AADT	0.8025	0.3084
Intersection pedestrian AADT	0.2677	0.0264
Minor pedestrian AADT/intersection pedestrian AADT	−0.66	0.2161
4-legged intersection	1.4288	0.5544
2-way road (minor road)	0.81	0.2421
More than 1 left-turn lane (minor road)	0.2792	0.0973
More than 1 right (de facto/daylighting) (minor road)	0.4522	0.0882
2 through lanes (major leg)	−0.8759	0.2171
3–5 through lanes (major leg)	−1.2433	0.3867
2 through lanes (minor leg)	0.2196	0.0871
3–4 through lanes (minor leg)	0.4232	0.1349
3 through lanes (major road)	0.8646	0.2467
4 through lanes (major road)	1.0207	0.2178
More than 4 through lanes (major road)	1.3706	0.389
Right turn allowed on 1 minor leg	−0.7756	0.1793
Left turn allowed on 1 minor leg	−0.4144	0.1867
Left turn allowed on both minor legs	−0.8807	0.1812
Treatment site	0.7171	0.0639
Dispersion	0.09	0.0371

NYC SPFs

Table 27 through table 29 present the SPFs for total, injury, and pedestrian crashes per year for NYC.

Table 27. SPF Parameters for NYC total crashes per year (developed from reference and treatment before data).

Parameter	Estimate	SE
Intercept	−6.1509	0.9491
Major road AADT/1,000	−0.0141	0.0044
Minor road AADT/1,000	−0.0227	0.0068
Log(major road AADT)	0.3111	0.0767
Log(minor road AADT)	0.5139	0.0646
Pedestrian AADT crossing minor road/1,000	−0.0074	0.0012
Log(pedestrian AADT crossing major road)	0.0925	0.0207
1-way (major road)	−0.2086	0.0915
Both 1-way and 2-way (major road)	−0.6670	0.1499
1-way (minor road)	−0.6131	0.0890
Both 1-way and 2-way (minor road)	−0.8529	0.1180
Protected left-turn phase (intersection)	−0.2836	0.0829
Protected left-turn phase (major)	0.3724	0.1004
3–4 through lanes (major roadway class)	0.5174	0.0710
2 through lanes (minor roadway class)	0.3086	0.0493
Right-turn lane presence (intersection)	0.3785	0.0624
Left-turn lane presence (intersection)	0.0706	0.0349
Right-turn lane presence (major road)	−0.4249	0.1174
1 right-turn lane (de facto/daylighting) presence (major road)	0.3934	0.0680
6 through lanes (intersection)	−0.2250	0.0681
7–11 through lanes (intersection)	−0.2122	0.0889
More than 2 lanes left turn allowed (intersection)	0.5328	0.1289
2 lane right turn allowed (intersection)	0.2585	0.0940
More than 2 lanes right turn allowed (intersection)	0.6494	0.1541
4 through lanes (major leg)	0.2959	0.1195
More than 4 through lanes (major leg)	0.8984	0.1493
1 left-turn lane (minor road)	−0.2327	0.0889
More than 1 left-turn lane (minor road)	−0.8916	0.1280
1 right-turn lane (major road)	−0.2403	0.1181
More than 1 right-turn lane (major road)	−0.8179	0.1727
Right-turn lane presence (major leg)	−0.5670	0.1212
Marked pedestrian crosswalks on both major legs	−0.4834	0.1461
RTORs prohibited	0.9784	0.2655
Treatment site	0.1695	0.0512
Dispersion	0.1982	0.0130

Table 28. SPF Parameters for NYC injury crashes per year (developed from reference and treatment before data).

Parameter	Estimate	SE
Intercept	−5.3258	0.9656
Major road AADT/1,000	−0.0110	0.0046
Minor road AADT/1,000	−0.0266	0.0072
Log(major road AADT)	0.2469	0.08
Log(minor road AADT)	0.5626	0.0703
Pedestrian AADT crossing minor road/1,000	0.0099	0.0021
Log(pedestrian AADT crossing major road)	−0.0063	0.0013
1-way (both major legs)	−0.2584	0.0972
Both 1-way and 2-way (major road)	−0.6066	0.1545
1-way (both minor legs)	−0.6586	0.0974
Both 1-way and 2-way (minor road)	−0.7137	0.1222
Protected left-turn phase (minor road)	−0.1475	0.0741
3–4 through lanes (major roadway class)	0.4989	0.0782
2 through lanes (minor roadway class)	0.2285	0.0533
1 right-turn lane (de facto/daylighting) presence	−0.2821	0.0978
1 right-turn lane (de facto/daylighting) presence (major road)	0.6898	0.1105
6 through lanes (intersection)	−0.2581	0.0722
More than 6 through lanes (intersection)	−0.2721	0.0941
More than 2 lanes left turn allowed (intersection)	0.5565	0.1782
2 lanes right turn allowed (intersection)	0.3736	0.108
More than 2 lanes right turn allowed (intersection)	0.9418	0.1754
4 through lanes (major leg)	0.3884	0.127
More than 4 through lanes (major leg)	0.9774	0.1567
Left turn allowed on 1 major leg	−0.2269	0.1086
More than 1 left-turn lane (minor road)	−1.1033	0.1962
1 right-turn lane (major road)	−0.5759	0.1314
More than 1 right-turn lane (major road)	−1.3295	0.2059
Right-turn lane presence (minor leg)	−0.6290	0.1367
Marked pedestrian crosswalks on both major legs	−0.4654	0.1526
RTORs prohibited	1.0826	0.2575
Treatment site	0.2602	0.0545
Dispersion	0.1773	0.0146

Table 29. SPF Parameters for NYC pedestrian crashes per year (developed from reference and treatment before data).

Parameter	Estimate	SE
Intercept	−10.0307	1.2691
Minor road AADT/1,000	−0.0290	0.0106
Log(major road AADT)	0.1991	0.0605
Log(minor road AADT)	0.5806	0.1063
Pedestrian AADT crossing minor road/1,000	−0.0086	0.0018
Log(pedestrian AADT crossing major road)	0.3141	0.0325
1-way (major road)	−0.4544	0.1698
1-way (minor road)	−0.3536	0.1215
Both 1-way and 2-way (minor road)	−0.3839	0.1780
3–4 through lanes (major roadway class)	0.5677	0.1318
2 through lanes (minor roadway class)	0.3022	0.0644
Right-turn lane presence (intersection)	0.6068	0.1467
Right (de facto/daylighting) presence (intersection)	0.2577	0.0904
Right-turn lane presence (minor road)	−0.6665	0.1778
2 lanes right turn allowed (intersection)	0.3969	0.1699
More than 2 lanes right turn allowed (intersection)	1.3276	0.3351
3 through lanes (major leg)	0.6037	0.2909
More than 4 through lanes (major leg)	0.6811	0.2910
More than 4 through lanes (minor leg)	1.8705	0.4654
3–4 through lanes (major road)	−0.5546	0.1863
More than 4 through lanes (major road)	−1.2675	0.3580
1 left-turn lane (minor road)	−0.2454	0.1062
More than 1 left-turn lane (minor road)	−0.3641	0.1464
More than 1 right-turn lane (major road)	−0.8428	0.2805
1 right-turn lane (minor road)	−0.8490	0.1898
More than 1 right-turn lane (minor road)	−1.2093	0.2642
RTORs prohibited	1.5869	0.6165
Dispersion	0.2069	0.0284

Charlotte SPFs

Table 30 and table 31 present the SPFs parameters for total and injury crashes per year for Charlotte.

Table 30. SPF Parameters for Charlotte total crashes per year (developed from reference and treatment before data).

Parameter	Estimate	SE
Intercept	−8.0296	0.6930
Log(intersection AADT)	0.9202	0.0678
Log(intersection pedestrian AADT)	0.1177	0.0253
4-legged intersection	0.1704	0.0524
Divided (both major legs)	0.1471	0.0560
Divided (only 1 major leg)	0.2603	0.0642
Speed limits ≥40 mph (major road)	0.2301	0.0509
Speed limits ≥40 mph (minor road)	0.5046	0.0780
4 lanes (major road)	−0.4260	0.1198
More than 4 lanes (major road)	−0.3052	0.1206
Dispersion	0.2444	0.0198

Table 31. SPF Parameters for Charlotte injury crashes per year (developed from reference and treatment before data).

Parameter	Estimate	SE
Intercept	−7.2516	0.918
Log(intersection AADT)	0.7671	0.0882
Log(intersection pedestrian AADT)	0.2336	0.0689
Intersection pedestrian AADT/1,000	−0.0115	0.0057
4-legged intersection	0.1552	0.0684
Divided (only 1 major leg)	0.2279	0.09
Speed limits ≥40 mph (major road)	0.2335	0.0653
Speed limits ≥40 mph (minor road)	0.6532	0.0938
4 lanes (major road)	−0.5521	0.1556
3–4 lanes pedestrian has to cross (major)	−0.4292	0.1609
More than 4 lanes pedestrian has to cross (major)	−0.6584	0.3009
Dispersion	0.2534	0.0322

CHAPTER 7. BEFORE–AFTER EVALUATION RESULTS

This chapter presents the results of the before–after evaluations of the protected left-turn phasing and LPI countermeasures.

PROTECTED LEFT-TURN EVALUATION

Aggregate Analysis

Table 32 through table 35 detail the aggregate results for the protected left-turn evaluation by city and for all cities combined. The tables show several differences in the crash experience, although most were not significant at a 95-percent confidence level. For the results by city, vehicle–pedestrian crashes increased in Chicago and Toronto and decreased in NYC. None of these results were statistically significant at a 95-percent confidence level, and the results in NYC were based on few sites and crashes. For vehicle–vehicle crashes, increases were seen in Chicago and Toronto, but these were not statistically significant. A statistically significant decrease was seen in NYC, although this was based on only 46 after-period crashes. There are two aspects of the NYC sites that are noteworthy, even though the sample size was smaller. First, of the three cities represented in the study of left-turn phasing, only NYC had a citywide prohibition on RTORs. Second, the treatment sites from NYC were dominated by conversion to protected only, whereas Chicago and Toronto were dominated by conversion to protected/permissive. For vehicle–vehicle injury crashes, decreases were seen in all three cities, but only Toronto showed a statistically significant decrease of less than 5 percent.

Table 32. Aggregate results for protected left turn–phasing evaluation—Chicago.

Crash Type	EB Estimate of Crashes Predicted in After Period Without Strategy	Count of Crashes Observed in After Period	Estimate of CMF	SE of Estimate of CMF
Vehicle–pedestrian (all severities combined)	78.77	90	1.136	0.146
Vehicle–vehicle (all severities combined)	1,129.87	1,166	1.031	0.040
Vehicle–vehicle injury	230.84	206	0.890	0.079

Note: Of 70 treated approaches, 68 were protected/permissive, and 2 were fully protected.

Table 33. Aggregate results for protected left turn–phasing evaluation—NYC.

Crash Type	EB Estimate of Crashes Predicted in After Period Without Strategy	Count of Crashes Observed in After Period	Estimate of CMF	SE of Estimate of CMF
Vehicle–pedestrian (all severities combined)	21.98	16	0.718	0.196
Vehicle–vehicle (all severities combined)	68.05	46	0.672*	0.110
Vehicle–vehicle injury	41.54	33	0.788	0.153

Note: Of 9 treated approaches, 1 was protected/permissive, and 8 were fully protected. NYC has a citywide prohibition on RTORs.
*A CMF that is statistically significant at a 95-percent confidence level.

Table 34. Aggregate results for protected left turn–phasing evaluation—Toronto.

Crash Type	EB Estimate of Crashes Predicted in After Period Without Strategy	Count of Crashes Observed in After Period	Estimate of CMF	SE of Estimate of CMF
Vehicle–pedestrian (all severities combined)	294.64	326	1.106	0.061
Vehicle–vehicle (all severities combined)	9,093.11	9,317	1.025	0.011
Vehicle–vehicle injury	2,284.05	2,171	0.951*	0.020

Note: Of 136 treated approaches, 134 were protected/permissive, and 2 were fully protected. Canada allows variations of left-turn priority and signal phasing (i.e., flashing circular green) not allowed or used in the United States.
*A CMF that is statistically significant at a 95-percent confidence level.

For all cities combined, nonsignificant increases were seen for vehicle–pedestrian crashes and vehicle–vehicle crashes, while a statistically significant decrease of less than 6 percent was seen for vehicle–vehicle injury crashes.

Table 35. Aggregate results for protected left turn–phasing evaluation—all cities combined.

Crash Type	EB Estimate of Crashes Predicted in After Period Without Strategy	Count of Crashes Observed in After Period	Estimate of CMF	SE of Estimate of CMF
Vehicle–pedestrian (all severities combined)	395.39	432	1.091	0.066
Vehicle–vehicle (all severities combined)	10,291.03	10,529	1.023	0.016
Vehicle–vehicle injury	2,556.42	2,410	0.942*	0.028

*A CMF that is statistically significant at a 95-percent confidence level.

The aggregate results, which were dominated by changes from permissive-only to protected/permissive phasing, were reasonably consistent with the previous findings by Hauer (2004), who reported a CMF of 1.0 (i.e., no effect) for changes to protected/permissive phasing, and Srinivasan (2011), who reported nonstatistically significant CMFs of 1.031 and 0.962 for total and total injury crashes, respectively.[4,7]

The results by city and combined could not show an effect on vehicle–pedestrian crashes following the addition of left-turn protection that was statistically significant at a 95-percent confidence level. However, it is possible that positive or negative effects may exist for a subset of site characteristics. This possibility was explored through a disaggregate analysis and potential development of CMFunctions.

Disaggregate Analysis

Univariate disaggregate analyses were undertaken for all crash types considering the following variables:

- Number of treated approaches.
- Number of approaches with a protected left-turn phase prior to treatment.
- Number of intersection approaches.
- Number of through lanes on major and minor roads at intersections.
- Number of left-turn lanes on major and minor roads at intersections.
- AADT on major and minor roads.
- Left-turning AADT on major and minor roads at intersections.
- 24-h pedestrian-crossing volume.
- EB estimate of expected crashes per year at a signalized intersection prior to treatment.

For vehicle and vehicle injury crashes, no apparent relationships were found between the expected CMF and any of the candidate site characteristics.

For vehicle–pedestrian crashes, the analysis indicated that the CMF may be smaller for higher levels of pedestrian and vehicle volumes. In developing CMFunctions, the dependent variable, the observed number of vehicle–pedestrian crashes, was modeled as a function of pedestrian volumes and vehicle AADTs with the EB estimate of expected crashes as an offset.

The effect of vehicle AADTs was not estimated to be a statistically significant model parameter and did not improve the fit of the model to the data and was, therefore, not included in the final model shown in figure 17. The model parameter estimates are shown in table 36.

$$CMF_i = \frac{\lambda_i}{\pi_i} = \exp^{a} PEDVOL^{b}$$

Figure 17. Equation. CMFunction for vehicle–pedestrian crashes.

Where:

CMF_i = estimated CMF for site i.
λ_i = expected number of crashes that would have occurred in the after period without the strategy at site i.
π_i = number of reported crashes in the after period at site i.

Table 36. CMFunction model estimates for protected left-turn phasing.

Parameter	Estimate (SE)
a	1.4179 (0.4243)
b	−0.1645 (0.0541)
k	0.2668 (0.0868)

The estimated parameters show that the expected CMF decreases as the pedestrian volume increases. At lower pedestrian volumes, the predicted CMF is greater than 1.0; the predicted CMF is less than 1.0 for values of 24-h crossing volumes of approximately 5,500 and above. At the present time, how to estimate the SE, and thus statistical significance, of CMF estimates derived in this manner is unknown. Therefore, the CMF estimates derived for a given level of pedestrian volume should not be considered robust given the lack of statistical significance for the results overall and from the univariate disaggregate analysis.

If vehicle–pedestrian crashes do increase following the addition of left-turn protection at low pedestrian volumes, it may be that pedestrians are not obeying the “do not walk” signal during the protected left-turn phase, and/or left-turning vehicles are turning left at too high a rate of speed immediately after their protected phase is over and pedestrians have begun to cross. When pedestrian volumes are high, this type of behavior may be less prevalent, or vehicles are more conscious of the presence of pedestrians. This hypothesis is only speculative, however.

LPI EVALUATION

This section presents the results of the LPI evaluation by city and for all cities combined. The aggregate results are presented first, followed by an exploration of disaggregate results from Chicago according to the manner in which the LPI timing was implemented.

Aggregate Analysis

Table 37 through table 40 present the aggregate results of the before–after evaluation of the LPI treatment by city and for all cities combined. The effects of LPIs on total crashes were consistent across all cities, with CMFs ranging from 0.84 to 0.90. The CMF for all cities combined was 0.87, which was significant at a 95-percent confidence level.

The effect on total injury crashes was also consistent across the cities, ranging from 0.83 to 0.86 (omitting the result from Charlotte, which was not significant). The effect on total injury crashes for all cities combined was 0.86, which was significant at a 95-percent confidence level.

The effect on pedestrian crashes was generally beneficial, showing decreases in pedestrian crashes across all cities. The results in Chicago showed a CMF of 0.81, which was significant at a 95-percent confidence level. NYC sites showed a beneficial but lesser effect on pedestrian crashes, with a CMF of 0.91, but this result was not significant at a 95-percent confidence level. The result from Charlotte showed a decrease in pedestrian crashes, but this result was highly unreliable given the large SE. For the combined group of all cities together, the CMF for pedestrian crashes was 0.87, which was significant at a 95-percent confidence level.

Table 37. Aggregate results for LPI evaluation—Chicago.

Crash Type	EB Estimate of Crashes Predicted in After Period Without Strategy	Count of Crashes Observed in After Period	Estimate of CMF	SE of Estimate of CMF
Total	1,636.29	1,472	0.90*	0.027
Total injury	492.51	407	0.83*	0.046
Vehicle–pedestrian	190.77	154	0.81*	0.070

*A CMF that is statistically significant at a 95-percent confidence level.

Table 38. Aggregate results for LPI evaluation—NYC.

Crash Type	EB Estimate of Crashes Predicted in After Period Without Strategy	Count of Crashes Observed in After Period	Estimate of CMF	SE of Estimate of CMF
Total	1,470.28	1,234	0.84*	0.031
Total injury	1,039.88	893	0.86*	0.037
Vehicle–pedestrian	387.12	351	0.91	0.062

*A CMF that is statistically significant at a 95-percent confidence level.

Table 39. Aggregate results for LPI evaluation—Charlotte.

Crash Type	EB Estimate of Crashes Predicted in After Period Without Strategy	Count of Crashes Observed in After Period	Estimate of CMF	SE of Estimate of CMF
Total	284.80	257	0.90	0.09
Total injury	76.70	85	1.09	0.18
Vehicle–pedestrian	3.60	2	0.54	0.38

Table 40. Aggregate results for LPI evaluation—Chicago, NYC, and Charlotte (105 treatment sites).

Crash Type	EB Estimate of Crashes Predicted in After Period Without Strategy	Count of Crashes Observed in After Period	Estimate of CMF	SE of Estimate of CMF
Total	3,391.39	2,963	0.87*	0.02
Total injury	1,609.09	1,385	0.86*	0.03
Vehicle–pedestrian	581.44	507	0.87*	0.05

*A CMF that is statistically significant at a 95-percent confidence level.

Disaggregate Analysis

The team conducted a disaggregate analysis on Chicago data according to how the LPI timing was implemented at the treatment sites. The treatment sites were classified into two categories based on how LPIs were implemented, as follows:

- Treatment category 1: LPIs implemented at all crossings (across major and minor roads).
- Treatment category 2: LPIs implemented only for crossings across the minor road (parallel to the major road).

Table 41 and table 42 present the results by each treatment category. For total crashes and total injury crashes, the CMFs are lower for treatment category 2 compared to category 1. However, a statistical test for homogeneity shows that the difference in the CMFs is not statistically significant for either total crashes or total injury crashes. Therefore, the aggregate results from Chicago as presented in table 37 (combined group from both treatment categories) should be used as the primary results from the analysis of Chicago sites.

Table 41. Aggregate results for LPI evaluation—Chicago treatment category 1 (42 sites).

Crash Type	EB Estimate of Crashes Predicted in After Period Without Strategy	Count of Crashes Observed in After Period	Estimate of CMF	SE of Estimate of CMF
Total	1,218.13	1,096	0.90*	0.03
Total injury	360.04	306	0.85*	0.06
Vehicle–pedestrian	146.57	119	0.81*	0.08

*A CMF that is statistically significant at a 95-percent confidence level.

Table 42. Aggregate results for LPI evaluation—Chicago treatment category 2 (9 sites).

Crash Type	EB Estimate of Crashes Predicted in After Period Without Strategy	Count of Crashes Observed in After Period	Estimate of CMF	SE of Estimate of CMF
Total	261.7	217	0.83*	0.06
Total injury	85.8	62	0.72*	0.10
Vehicle–pedestrian	28.7	26	0.90	0.19

*A CMF that is statistically significant at a 95-percent confidence level.

The project team also explored the potential for developing CMFunctions that would relate the effect of major site characteristics on the effectiveness of the LPI. However, the low magnitude of the sample size available led to convergence issues, and the team was unable to develop any meaningful functions for any of the studied crash types.

CHAPTER 8. ECONOMIC ANALYSIS

This chapter presents the economic analysis of the two countermeasures, the provision of LPIs and the provision of protected left-turn phasing. The cost of installation is weighed against the benefit from crash reductions to provide a benefit–cost (B/C) ratio. The project team focused only on vehicle–pedestrian crashes for the economic analysis since the main objective of the project was the safety evaluation of such crashes.

PROTECTED LEFT-TURN PHASING

Although pedestrian-safety benefits were not evident considering all treated sites, the CMFunction developed in the disaggregate analysis indicated the installation of protected or protected/permissive left-turn phasing could be beneficial in reducing pedestrian crashes at sites with pedestrian-crossing volumes at or exceeding 5,500 per day. The economic analysis focused, therefore, on the 16 sites with such crossing volumes. On the cost side, the analysis was based on the $28,000 upper limit per installation cost provided by Toronto.

The analysis assumed, likely conservatively, that the useful service life for safety benefits was 20 yr. The FHWA Office of Safety Research and Development (R&D) has suggested, based on the 2017 Office of Management and Budget *Circular A-4*, a conservative real discount rate of 7 percent be applied to calculate the annual cost of the treatment for the 5-yr service life.(22) With this information, the capital recovery factor is 0.094 for all intersections, giving annual costs of $2,632 per intersection.

For the benefit calculations, the project team used the most recent FHWA mean comprehensive crash costs disaggregated by crash severity and location type as a base.(23) Council et al. developed these costs based on 2001 crash costs and found that the unit cost (in 2001 dollars) for a vehicle–pedestrian crash at an urban intersection was $164,029. This was updated to 2016 dollars by applying the ratio of the U.S. Department of Transportation (USDOT) 2016 (the latest year available) value of a statistical life of $9.6 million to the 2001 value of $3.8 million.(23,24) The project team applied this ratio of 2.53 to the unit crash cost, which resulted in an aggregate 2016 unit cost for vehicle–pedestrian crashes of $414,993 at urban intersections.

The team calculated the total pedestrian-crash reduction at the 16 sites (8.30) by subtracting the actual crashes in the after period from the expected crashes in the after period had the treatment not been implemented. The project team divided the total crash reduction by the average number of after-period years per site (2.938) to compute the total crashes saved per year. The number of total crashes saved per year was 2.821 for all intersections. Considering the number of treated intersections (16), this resulted in an average savings of 0.1763 pedestrian crash per intersection per year.

By multiplying the crash reduction per site-year by the cost of a crash, the project team determined the annual dollar benefit from reduced crashes to be $73,163 per intersection. The B/C ratio, calculated as the ratio of the annual benefit to the annual cost, is 1:27.8. USDOT has recommended that sensitivity analysis be conducted by assuming values of a statistical life of 0.56 and 1.40 times the recommended 2016 value.(24) These factors can be applied directly to the estimated B/C ratio, resulting in a range of 1:15.6::1:38.9. These results suggest that the strategy, even with conservative assumptions on cost, service life, and the value of a statistical life, can be cost effective for reducing pedestrian crashes at signalized intersections with high pedestrian volumes. However, it should be noted that this B/C ratio result is based only on a small sample of sites (the 16 sites with high pedestrian volumes).

LPI

The project team used the statistically significant reduction in vehicle–pedestrian crashes for the three cities combined as the benefit for this treatment strategy. On the cost side, the analysis was based on cost information obtained from the cities involved in this project. Charlotte reported that the cost of implementing an LPI alone (without other accompanying improvements) would be $200. NYC indicated that its cost per installation was approximately $1,200 where only the LPI signal adjustment was done. For this economic analysis, the project team used the more conservative value of $1,200.

The analysis assumed, likely conservatively, that the useful service life for safety benefits was 20 yr. The FHWA Office of Safety R&D has suggested, based on the 2017 Office of Management and Budget *Circular A-4*, a conservative real discount rate of 7 percent be applied to calculate the annual cost of the treatment for the 5-yr service life.(22) With this information, the capital recovery factor is 0.094 for all intersections, giving annual costs of $112.80 if only the basic LPI adjustment was made.

For the benefit calculations, the project team used the most recent FHWA mean comprehensive crash costs disaggregated by crash severity and location type as a base.(23) Council et al. developed these costs based on 2001 crash costs and found that the unit cost (in 2001 dollars) for a vehicle–pedestrian crash at an urban intersection was $164,029. This was updated to 2016 dollars by applying the ratio of the USDOT 2016 (the latest year available) value of a statistical life of $9.6 million to the 2001 value of $3.8 million.(23,24) Applying this ratio of 2.53 to the unit crash cost resulted in an aggregate 2016 unit cost for vehicle–pedestrian crashes of $414,993 at urban intersections.

The project team calculated the total crash reduction (74.443) by subtracting the actual crashes in the after period from the expected crashes in the after period had the treatment not been implemented. The total crash reduction was then divided by the average number of after-period years per site (7.057) to compute the total crashes saved per year. The number of total crashes saved per year was 10.549 for all intersections. Considering the number of treated intersections (105), this resulted in an average savings of 0.1005 crash per intersection per year.

The annual dollar benefit for crashes of $41,707 per intersection was obtained by multiplying the crash reduction per site-year by the cost of a crash. The B/C ratio is calculated as the ratio of the annual benefit to the annual cost. The B/C ratio is 1:369.7 if only the basic LPI adjustment was made. USDOT has recommended that sensitivity analysis be conducted by assuming values of a statistical life of 0.56 and 1.40 times the recommended 2016 value.(24) These factors can be applied directly to the estimated B/C ratios to get a range of 1:207::1:517 if only the basic LPI adjustment was made. These results suggest that the strategy, even with conservative assumptions on cost, service life, and the value of a statistical life, can be cost effective for reducing pedestrian crashes at signalized intersections.

CHAPTER 9. SUMMARY AND CONCLUSIONS

This study examined the effects of protected left-turn phasing and LPIs on the safety of signalized intersections with particular focus on pedestrian safety. The protected left turn–phasing evaluation used data from 27 treated sites in Chicago, 7 treated sites in NYC, and 114 treated sites in Toronto. The results showed many differences in the crash experience, although most were not significant at a 95-percent confidence level. Vehicle–pedestrian crashes increased in Chicago and Toronto and decreased in NYC. However, none of these results were statistically significant at a 95-percent confidence level, and the results in NYC were based on few sites and crashes. For vehicle crashes, increases were seen in Chicago and Toronto, but these were not statistically significant. A statistically significant decrease was seen in NYC, although this was based on only 46 after-period crashes. For vehicle injury crashes, decreases were seen in all three cities, but only Toronto showed a statistically significant decrease of less than 5 percent. A disaggregate analysis of the effect on vehicle–pedestrian crashes indicated that the CMF was smaller (i.e., the treatment was more beneficial) for higher levels of pedestrian and vehicle volumes, particularly pedestrian volumes above 5,500 pedestrians per day. This was shown to lead to a potential B/C ratio range of 1:15.6::1:38.9. Figure 18 shows a left-turn signal that could be operated as permissive or protected.

Figure 18. Photo. Closeup of signal heads.

The LPI evaluation used data from 56 treated sites in Chicago, 42 treated sites in NYC, and 7 treated sites in Charlotte. The effect of LPIs on total crashes for all cities combined was a CMF of 0.87, which was significant at a 95-percent confidence level. The effect on total injury crashes for all cities combined was a CMF of 0.86, which was significant at a 95-percent confidence level. The effect on pedestrian crashes was generally beneficial, showing decreases in pedestrian crashes across all cities. The results in Chicago showed a CMF of 0.81, which was significant at a 95-percent confidence level. NYC sites showed a beneficial but lesser effect on pedestrian crashes, with a CMF of 0.91, but this result was not significant at a 95-percent confidence level. The result from Charlotte showed a decrease in pedestrian crashes, but this result was highly unreliable given the large SE. For the combined group of all cities together, the CMF for pedestrian crashes was 0.87, which was significant at a 95-percent confidence level. This was shown to lead to a potential B/C ratio range of 1:207::1:517. Figure 19 shows pedestrians crossing at an intersection with an LPI.

Figure 19. Photo. Pedestrians crossing at urban intersection with an LPI.

The results of these evaluations provide information that can be used by safety practitioners to prioritize safety treatments and estimate potential benefits. The protected left turn–phasing treatment did not produce statistically significant changes to vehicle–pedestrian crashes overall. However, it was shown to possibly have a benefit to pedestrian safety if implemented at intersections with pedestrian volumes greater than 5,500 pedestrians per day. The protected left turn–phasing treatment also resulted in decreases to vehicle–vehicle injury crashes of 5 percent. The LPI treatment was shown to have significant benefits for safety, both in reducing vehicle–pedestrian crashes by approximately 13 percent and reducing vehicle–vehicle crashes (all severities and KABC injury crashes) by approximately 13 percent.

TREATMENT RECOMMENDATIONS AND IMPLEMENTATION ISSUES

The results from this protected left turn–phasing evaluation showed that the effect was more beneficial for intersections with higher pedestrian volumes, particularly pedestrian volumes above 5,500 pedestrians per day. A safety practitioner may use this information to prioritize potential treatment sites to give more preference to installing the protected or protected/permissive left turn–phasing treatment at sites with higher pedestrian volumes.

The LPI results did not lead to any particular guidance on implementation. There were clear differences in some aspects of the treatment cities used in the evaluation; for instance, NYC almost entirely prohibits RTORs, and Chicago allows RTORs in most cases, but the results for each city were similar. NYC also had generally higher pedestrian volumes than Chicago (sometimes by a factor of 3 to 4), but again, the effect of LPIs were similar. The project team also examined the effects of installing LPIs on two crossings compared to all crossings using data from Chicago, but the sample for installations only on two crossings was small, and there was not a statistically significant difference in the effect of the LPIs.

The cities involved did not report particular implementation issues regarding either treatment. Charlotte reported that its current general practice is to implement other changes along with the LPI, particularly the addition of accessible pedestrian signals, which sometimes necessitates relocation or new installation of pedestrian-signal poles.

APPENDIX: DATA COLLECTION GUIDE

The following guidance was provided to the project team data collectors to ensure consistency and to document which elements should be collected at all treatment and reference sites. The sections are separated per the type of information collected: Main (general information), Geometric, and Signal Timing.

MAIN

Table 43 displays general data collection guidance.

Table 43. Data collection guide—general information.

Field	Description	Additional Coding Instructions
Site type (treatment or reference)	Type of site based on eligibility criteria	Code as T (treatment) or R (reference).
Major road name	Name of the major road of the intersection	Major road would be the road with higher traffic volume, more lanes, or a higher functional classification.
Minor road name	Name of the minor road of the intersection	None
Major road direction (N/S or E/W)	Compass orientation of the major road	This information is needed to understand all the following fields that describe lanes and phasing by compass direction.
Minor road direction (N/S or E/W)	Compass orientation of the minor road	This information is needed to understand all the following fields that describe lanes and phasing by compass direction.
Longitude	Longitude of intersection center point coordinates	None
Latitude	Latitude of intersection center point coordinates	None
Drop	Indication of whether the site should be dropped according to eligibility criteria	Code as Y (yes) or N (no).
Drop reason	Reason why the site should be dropped from the study	Use as short a description as possible. If dropping because another intersection is too close, make a note of the distance.
Notes	Any special notes about the site, including unique features that make it stand out from the group and might interfere with a clean analysis	None

GEOMETRIC

Table 44 displays data collection guidance for geometric information.

Table 44. Data collection guide—geometric.

Field	Description	Additional Coding Instructions
Number of intersection legs	Total number of intersection legs (should only be 3 or 4)	None
N/S road 1-way or 2-way	Designation of the travel flow on the north-south road	Code as 1 or 2 or "both" (if the road changes from 1-way to 2-way across the intersection).
E/W road 1-way or 2-way	Designation of the travel flow on the east/west road	None
N/S road total through lanes	General road classification according to number of lanes (e.g., 2-lane road, 4-lane road)	Code as a number (e.g., 2, 4). Note: It may be easiest to see this if you look up and down the road away from the intersection.
E/W road total through lanes	General road classification according to number of lanes (e.g., 2-lane road, 4-lane road)	Code as a number (e.g., 2, 4). Note: It may be easiest to see this if you look up and down the road away from the intersection.
Right (marked)*	Exclusive right-turn lanes that are marked as a right-turn lane (with arrow)	Code as a number according to how many lanes of this type are present on the approach.
Right (de facto/ daylighting)*	Paved space in which a right-turning driver could bypass a waiting through vehicle and turn right	This is commonly the case if there is on-street parking prior to the approach.
Right/through*	Number of shared right and through lanes	Code as a number according to how many lanes of this type are present on the approach.
Through*	Number of through lanes	Code as a number according to how many lanes of this type are present on the approach.
Left/through*	Number of shared left and through lanes	Code as a number according to how many lanes of this type are present on the approach.
Left*	Number of exclusive left-turn lanes	Code as a number according to how many lanes of this type are present on the approach.
Left/right*	Number of shared left-turn and right-turn lanes (i.e., at the stem of a 3-legged intersection)	Code as a number according to how many lanes of this type are present on the approach.

Field	Description	Additional Coding Instructions
Left/through/right*	Number of lanes from which a driver may turn left, go through, or turn right	Code as a number according to how many lanes of this type are present on the approach.
Marked ped Xwalk*	Presence of a marked pedestrian crosswalk on the approach	Code as Y or N. Code as Y if present, even if the markings are faded or worn.

*These fields are required for each intersection approach and apply to the incoming lanes of the intersection only. Exiting lanes are ignored here.
ped Xwalk = pedestrian crosswalk.

SIGNAL TIMING

Table 45 displays data collection guidance for signal timing and is accompanied by the following instructions:

- Record the information about left-turn phasing for each approach, before and after any change.
- When deciding how to code the phasing type of the left-turn signal, the general rule is that it should be coded according to the most protected the left-turn signal ever is at any point in the week.

Table 45. Data collection guide—signal timing.

Field	Description	Additional Coding Instructions
Pedestrian-only phase	Presence of pedestrian-only phase in which all vehicle traffic is stopped and all pedestrian movements are given the walk signal	Code as Y or N.
Left turn–phasing change date	Date of any change to the left-turn phasing of the intersection	If any left-turn phasing changed at the intersection, this applies. If there was no change in left-turn phasing, enter "N/A."
Left turn–phasing type before change*	Type of left-turn phasing present on the approach before the above-mentioned change date	See table below for coding instructions.
Left turn–phasing schedule before change*	Schedule of left-turn phasing on the approach before the above-mentioned change date	See table below for coding instructions.
Left turn–phasing type after change*	Type of left-turn phasing present on the approach after the above-mentioned change date	See table below for coding instructions. If there was no change in left-turn phasing, enter "N/A."
Left turn–phasing schedule after change*	Schedule of left-turn phasing on the approach after the above-mentioned change date	See table below for coding instructions. If there was no change in left-turn phasing, enter "N/A."

*These fields are required for each intersection approach. They should be completed for the approaches where the left-turn phasing changed and the approaches where it did not change.

Table 46 and table 47 show coding for left-turn phasing type and schedule.

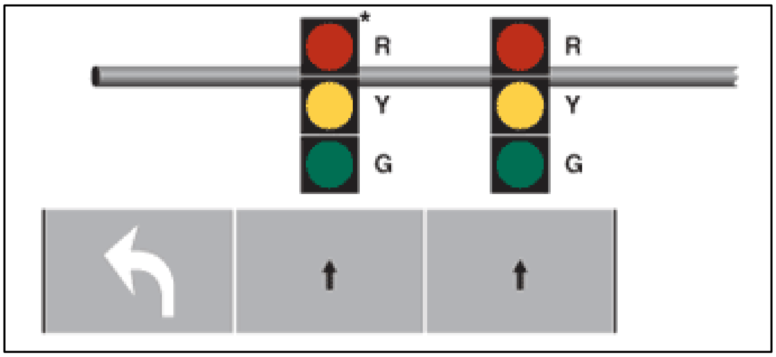
Table 46. Coding for left turn–phasing type.

Left Turn–Phasing Type	Description
Prohibited	If left turns are never allowed even though the movement is possible in theory, i.e., not because the intersecting road is 1-way or the intersection is a 3-legged intersection and there is no road to the left of the approaching direction
Permissive	If always permitted
Protected/permissive	If a protected/permissive phase exists at any time of day or week and there are no fully protected phases
Protected	If a fully protected phase exists at any time of day or week

Table 47. Coding for left turn–phasing schedule.

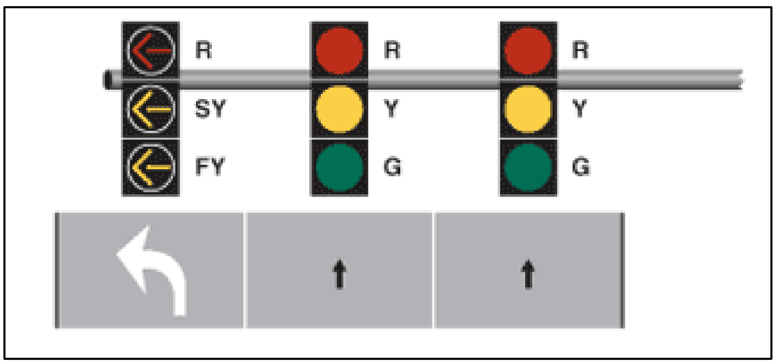
Left Turn–Phasing Schedule	Description
N/A	If always prohibited or always permitted phasing
Full week	If left-turn phasing occurs each day of the week
Weekday	If left-turn phasing occurs only on weekdays
Weekend	If left-turn phasing occurs only on weekends
Other—describe	If left turn–phasing schedule does not fit into one of the descriptions above
ampeak	If during the a.m. peak period
pmpeak	If during the p.m. peak period
allpeak	If during both the a.m. and p.m. peak periods
allday	If at all times of the day

Figure 20 through figure 22 show illustrations of possible left turn–phasing configurations for permitted, protected/permissive, and protected and how they would be coded. Figure 23 shows the turning movement designations.



Source: FHWA.
*Shared signal face.
R = red; Y = yellow; G = green.

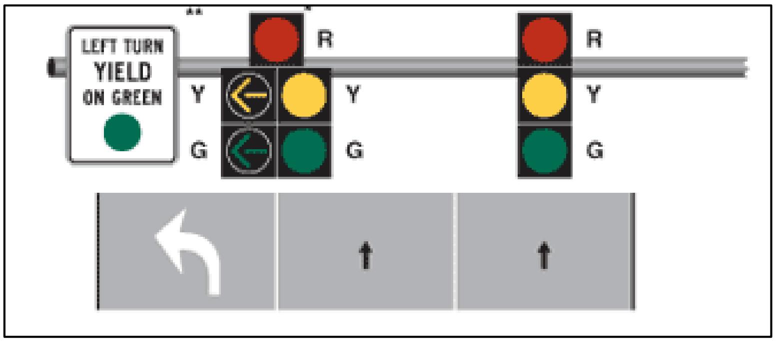
A. Typical position of shared signal faces for permissive left turns.[25]



Source: FHWA.
R = red; Y = yellow; G = green; SY = steady yellow; FY = flashing yellow.

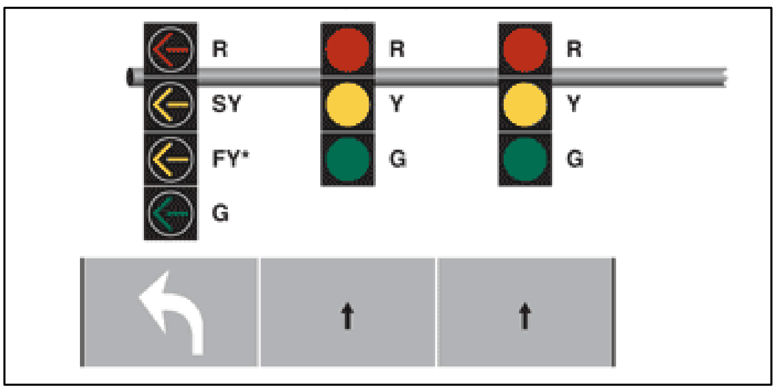
B. Typical position of separate signal faces with flashing yellow arrow for permissive left turns.[26]

Figure 20. Illustrations. Permissive phasing configurations.



Source: FHWA.
**Optional sign.
*Shared signal face.
R = red; Y = yellow; G = green.

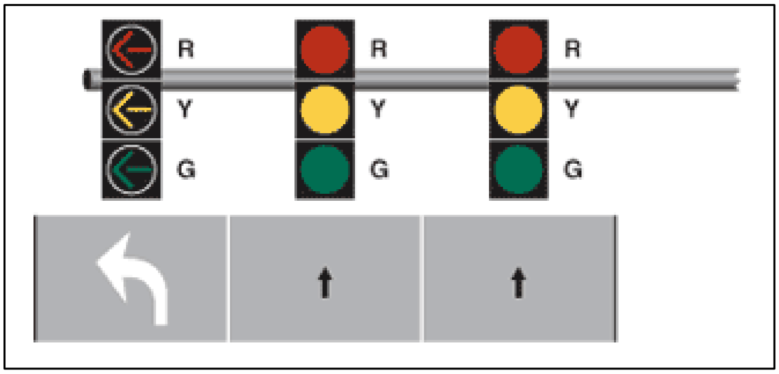
A. Typical position of shared signal faces for protected/permissive left turns.[27]



Source: FHWA.
*Shall not be displayed when operating in the protected-only mode.
R = red; Y = yellow; G = green; SY = steady yellow; FY = flashing yellow.

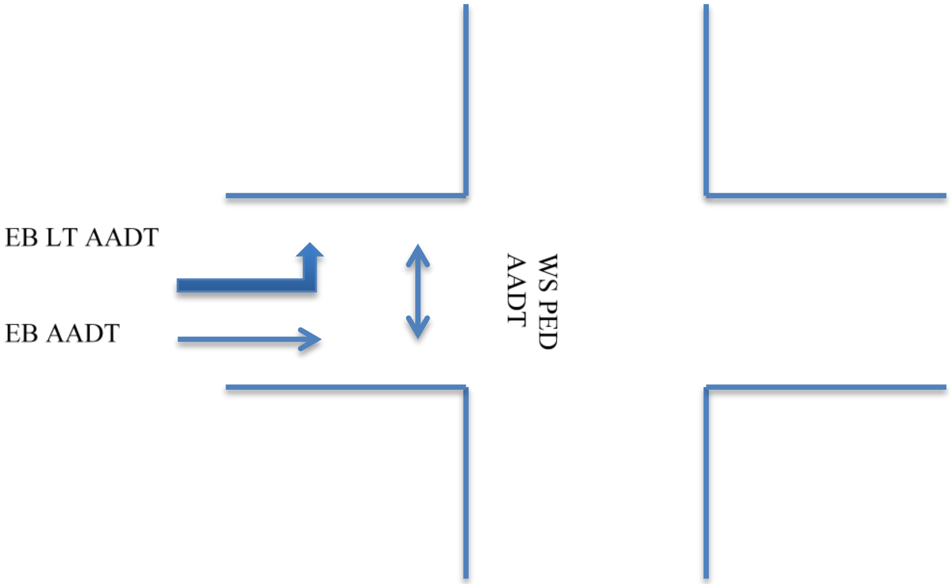
B. Typical position of separate signal faces with flashing yellow arrow for protected/permissive left turns.[28]

Figure 21. Illustrations. Protected/permissive phasing configurations.



Source: FHWA.
R = red; Y = yellow; G = green.

Figure 22. Illustration. Protected phasing configuration.[29]



Source: FHWA.
WS PED AADT = west side pedestrian AADT; EB LT AADT = eastbound left-turn AADT; EB AADT = eastbound AADT.

Figure 23. Illustration. Turning movement designations.

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