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16. Abstract

For intersections with a permissive or protected-permissive left-turn mode, pedestrians cross during the permissive period. This operation requires the left-turn driver to yield to both opposing vehicles and pedestrians, prior to accepting a gap and completing the turn. Pedestrian crash risks are increased in these complicated driving conditions because left-turn drivers sometimes fail to yield to pedestrians.

This document summarizes the research conducted and the conclusions reached during the development of guidelines for pedestrian safety treatments at signalized intersections. The guidelines are focused on treatments that alleviate conflicts between left-turning vehicles and pedestrians. One treatment addressed in the document is the use of protected or protected-permissive left-turn operation. The guidelines are based on consideration of pedestrian safety and vehicle operation. These considerations include the road-user costs associated with pedestrian-vehicle crashes and vehicle delay. The guidelines were incorporated in the *Traffic Signal Operations Handbook*. The guidelines were also incorporated into a spreadsheet that was developed to accompany the *Handbook*. The *Handbook* was previously developed for Project 0-5629. It provides guidelines for timing traffic control signals at intersections that operate in isolation or as part of a coordinated signal system.

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DEVELOPMENT OF GUIDELINES FOR PEDESTRIAN SAFETY TREATMENTS AT SIGNALIZED INTERSECTIONS

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the facts and the accuracy of the data published herein. The contents do not necessarily reflect the official view or policies of the Federal Highway Administration (FHWA) and/or the Texas Department of Transportation (TxDOT). This report does not constitute a standard, specification, or regulation. It is not intended for construction, bidding, or permit purposes. The engineer in charge of the project was James Bonneson, P.E. #67178.

NOTICE

The United States Government and the State of Texas do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of this report.

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- Mr. Adam Chodkiewicz, Project Director (TxDOT, Traffic Operations Division).
- Mr. James Bailey (TxDOT, Waco District).
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- Mr. John Gianotti (TxDOT, San Antonio District).
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- Ms. Wendy Simmons (TxDOT, Tyler District).
- Mr. Wade Odell, Research Engineer (TxDOT, Research and Technology Implementation Office).

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CHAPTER 1. INTRODUCTION

OVERVIEW

There are about 6000 pedestrian-involved crashes each year in Texas. This number is small compared to the 300,000 vehicle-vehicle crashes in Texas. However, an examination of pedestrian-related crash rates on a nationwide basis indicates that Texas ranks in the top 16 states. This trend suggests that there is potential for pedestrian safety improvement on Texas highways. Closer examination of the data indicate that this trend extends to pedestrian safety at signalized intersections in Texas.

For intersections with a permissive or a protected-permissive left-turn mode, pedestrians cross during the permissive period along with the parallel through vehicular movement. This requires the left-turn driver to yield to both opposing vehicles and pedestrians prior to accepting an appropriate gap. Pedestrian crash risks are increased in these complicated driving conditions because left-turn drivers sometimes make misjudgments and fail to yield to pedestrians.

Existing left-turn mode selection guidelines focus mainly on the vehicular traffic conditions at the intersection. Few of them include specific consideration of pedestrian safety. For example, existing guidelines for protected-permissive control typically focus on the left-turn and opposing through traffic volumes. Very few of these guidelines include a sensitivity to pedestrian volume or other pedestrian safety-related factors (e.g., crossing distance, median presence and width, driver sight distance, pedestrian compliance).

OBJECTIVES

The primary objective of this project was to incorporate pedestrian safety considerations into the guidelines for selecting left-turn operational mode (i.e., protected, protected-permissive, or permissive). A secondary objective was to develop guidelines addressing a broader range of treatments that may be used to improve pedestrian safety at signalized intersections. The focus of the research was on conflicts between left-turning vehicles and pedestrians.

To achieve these objectives, the research was comprehensive in its consideration of pedestrian safety issues at signalized intersections in Texas. The guidelines were documented in two forms. Guidelines to assist in the determination of the appropriate left-turn mode were documented in the report titled *Pedestrian Safety Guidelines and Proposed Left-Turn Phase Warrant*. This document serves as a quick reference guide that identifies conditions where protected or protected-permissive operation is a cost-effective treatment for pedestrian-related safety problems.

Guidelines were also documented in an updated version of the *Traffic Signal Operations Handbook* (previously developed for TxDOT in Project 0-5629). The guidelines that were added to the Handbook address changes to the signal timing, phase sequence, or pedestrian crossing distance to minimize left-turn-related pedestrian-vehicle conflicts and improve pedestrian safety.

RESEARCH APPROACH

A two-year program of research was developed to satisfy the project's research objectives. During the first year of research, city, county, and state engineers were interviewed, and field data were collected to ascertain the range of pedestrian safety concerns at intersections. The data were subsequently used to quantify the impacts of alternative left-turn modes (and other treatments) on safety and efficiency. During the second year, the field data and input from an expert panel were used to develop guidelines that are sensitive to a wide range of intersection conditions, and are applicable on a statewide basis.

The research approach consists of eight tasks that represent a logical sequence of review, research, evaluation, and workshop development. These tasks are identified in the following list.

1. Finalize Work Plan.
2. Evaluate State-of-the-Practice.
3. Develop Data Collection Plan and Collect Data.
4. Reduce Data.
5. Develop and Evaluate Preliminary Guidelines.
6. Conduct Before-After Study.
7. Conduct Pilot Workshop and Revise Guidelines.
8. Prepare Research Report.

The research conducted in Tasks 1 through 8 is documented in this report.

TERMINOLOGY

This section defines various terms that are used in this report.

Crosswalk Area

The crosswalk area is the area of pavement outlined by the curb line and a line offset outwardly from (and parallel to) the crosswalk by 10 ft. Thus, the crosswalk area for a crosswalk that is 12 ft wide is effectively 32 ft wide (= 10 + 12 + 10). This definition recognizes that some pedestrians crossing at the intersection do not walk fully within the marked crosswalk for some or all of their crossing, but are considered to be compliant with the crosswalk's intended purpose (*1*).

Pedestrian-Vehicle Conflict

A pedestrian-vehicle conflict is defined as an event where the projected path of a vehicle and a pedestrian cross and either the pedestrian or the vehicle, or both, make a last-second change in their path direction, speed, or both to avoid a collision. This definition is consistent with that used by several researchers (*2, 3*). Lord (*4*) compared crash data and conflict data for common intersections, where conflicts were defined using this definition. He found very good agreement (R^2 = 0.59) between the two statistics.

In their definition of conflict, Carter et al. (5) considered the time span associated with the change in path direction, speed, or both. They consider the most sudden changes in course to be a conflict and the non-sudden (i.e., slower) changes to be an "avoidance maneuver." However, during their field studies, they found it difficult to distinguish between these two categories and chose to combine them for purposes of pedestrian safety assessment. For this reason, the aforementioned definition of pedestrian-vehicle conflict is defined to include avoidance maneuvers.

Pedestrian-Based Conflict

A pedestrian-based conflict is a conflict where a pedestrian in the crosswalk changes his or her path direction, speed, or both to avoid a vehicle. The vehicle may, or may not, alter its course. For a given left-turn vehicle, there can be several conflicts if several pedestrians alter their course. In the extreme, the number of pedestrian-based conflicts is equal to the product of the pedestrian volume and the vehicular volume (i.e., every pedestrian is conflicted by every vehicle). Typical pedestrian-based conflicts include (5):

- Pedestrian stepped into roadway and then stepped back onto the curb to let vehicle pass.
- Pedestrian went around vehicle that was blocking crosswalk.
- Pedestrian hurried while crossing to avoid oncoming vehicle.
- Pedestrian stopped (or noticeably slowed) while crossing to let vehicle cross.
- Pedestrian delayed leaving the origin curb due to a vehicle.
- Pedestrian attempted to cross but did not leave the origin curb.

Vehicle-Based Conflict

A vehicle-based conflict is a conflict where one or more vehicles change path direction, speed, or both to avoid pedestrians *and* no pedestrians alter their course. A second vehicle may be involved in this conflict (e.g., same lane, opposing through). In the extreme, the number of vehicle-based conflicts is equal to the subject vehicle volume.

Pedestrian Signal Violation

A pedestrian signal violation occurs when a pedestrian begins the crossing (i.e., steps from behind the curb into the crosswalk) during the flashing DON'T WALK or the steady DON'T WALK indications.

Following field measurement of pedestrian signal violations, Kattan et al. (6) observed that some pedestrians could enter the crosswalk 2 to 3 s after the end of the WALK indication and still complete the crossing before the end of the flashing DON'T WALK indication. They rationalized that, while pedestrians in this group were technically violating the signal, they were not associated with as high a safety risk as those pedestrians that started crossing well after the end of the WALK indication.

Pedestrian-Vehicle Conflict Area

When evaluating conflicts between left-turning vehicles and pedestrians, some researchers have found it useful to define the conflict area within which the associated conflicts occur (4, 7).

One benefit to this approach is that it focuses the analysis of turn-related conflicts and minimizes the potential for non-turn-related conflicts to be included in the conflict count. Figure 1-1 illustrates the location of the pedestrian-vehicle conflict area for left-turning vehicles. It is shown to be as wide as the crosswalk area and as long as the width of the receiving lanes.

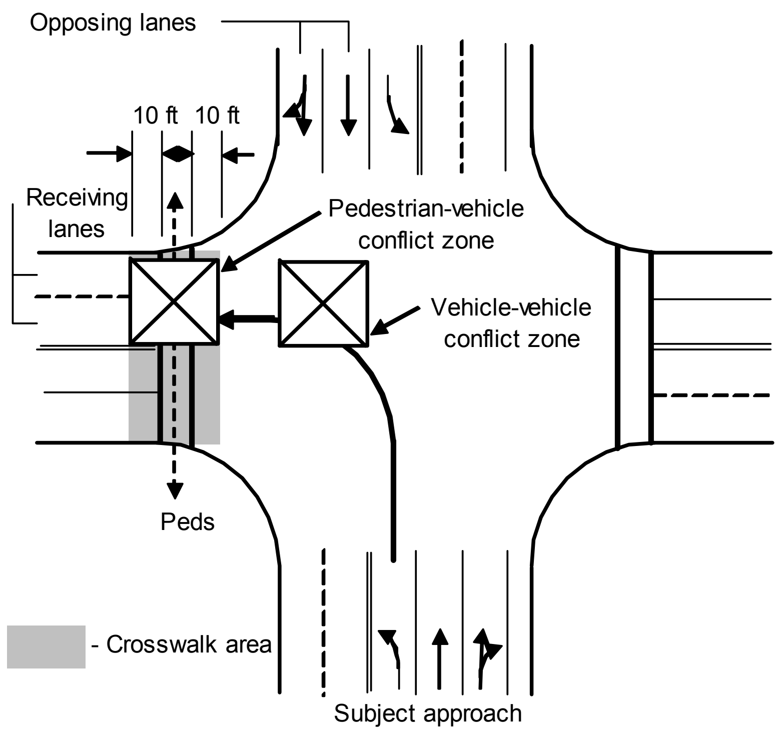

Figure 1-1. Intersection Conflict Areas.

Vehicle-Vehicle Conflict Area

Left-turning vehicles sometimes conflict with vehicles in the opposing traffic stream. These conflicts can occur when the left-turn vehicle misjudges the adequacy in a gap in the opposing stream. They can also occur when the gap is judged accurately but pedestrian presence in the conflicting crosswalk was not detected until after committing to the left turn. In this situation, the left-turning vehicle stops in the path of the opposing traffic stream, which often causes a conflict with one or more opposing vehicles. These conflicts are relevant to pedestrian safety research because they are indirectly related to pedestrian activity in the crosswalk. Figure 1-1 illustrates the location of the vehicle-vehicle conflict area for left-turning vehicles. It is shown to be as wide as the opposing through traffic lanes and as long as the width of the receiving lanes.

Legal Pedestrian

A legal pedestrian is considered to be a pedestrian that: (1) enters the crosswalk area during the WALK indication, (2) attempts to enter the crosswalk area during the WALK indication but is prevented from doing so by a turning vehicle, or (3) is present to cross during the WALK indication but the pedestrian density is so great that the crossing is delayed until the flashing DON'T WALK is displayed.

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CHAPTER 2. LITERATURE REVIEW

OVERVIEW

For intersections with a permissive or protected-permissive left-turn mode, pedestrians cross during the permissive period. This period occurs during the phase serving opposing through vehicles such that pedestrians cross when the adjacent through vehicles receive a green indication. This operation requires the left-turn driver to yield to both opposing vehicles and pedestrians, prior to accepting a gap and completing the turn. Pedestrian crash risks are increased in these complicated driving conditions because left-turn drivers sometimes fail to yield to the pedestrians.

Existing guidelines for the selection of left-turn mode (e.g., permissive, protected, and protected-permissive) focus mainly on vehicular traffic conditions at the intersection. Very few of these guidelines include a sensitivity to pedestrian volume or other pedestrian-safety-related factors.

This chapter documents a review of the literature that addresses the topic of pedestrians at signalized intersections. The focus of the review is on research that describes the conflict between pedestrians and left-turning vehicles.

There are four parts to this chapter that follow this introductory part. The first part provides some background information on pedestrian safety at intersections in Texas. The second part describes the traffic control elements at signalized intersections that apply to either left-turn movements or pedestrian movements. The third part summarizes research that has quantified pedestrian safety and service quality at intersections. The fourth part summarizes the findings related to traffic engineering treatments that address left-turn-related pedestrian safety at intersections.

PEDESTRIAN SAFETY IN TEXAS

Data maintained by the National Highway Traffic Safety Administration (NHTSA) indicate that 4654 pedestrian fatalities occurred in the U.S. in 2007, 387 of which occurred in Texas. This number has gradually declined about 1.5 percent each year during the past seven years. NHTSA also estimates that an additional 70,000 pedestrians were injured in 2007, for a total of 74,654 pedestrian involvements.

The NHTSA data indicate that 933 pedestrian fatalities occurred at signalized intersections in the U.S. in 2007, 78 of which occurred in Texas. These data indicate that about 20 percent of pedestrian fatalities occur at signalized intersections, which is consistent with the findings reported by Campbell et al. (*1*) in their analysis of data from the early 1990s. These statistics are summarized in Table 2-1.

There are several statistics of note in the data in Table 2-1. The exposure analysis indicates that Texas has a higher rate of pedestrian fatalities and involvements than the U.S. average. A comparison of these rates with those of other states indicates that Texas ranks in the top 16 states. Texas' over-representation in these rates extends to signalized intersections.

Table 2-1. Pedestrian Crash Statistics.

Location	Units	Texas	U.S.
Crash Frequency			
All	Pedestrian fatalities/yr	387	4654
	Pedestrian involvements/yr	6214	74,654
	Vehicle-vehicle crashes/yr	300,000	--
Signalized intersections	Pedestrian fatalities/yr	78	933
	Pedestrian involvements/yr	1541	18,509
Exposure Analysis			
Exposure	Million-vehicle-miles (mvm)	24.4	301.9
All	Pedestrian fatalities/mvm	15.9	15.4
Signalized intersections	Pedestrian fatalities/mvm	3.2	3.1
Crash Cost Analysis (Willingness-to-Pay Basis)			
Pedestrian-vehicle crash	$200,000/ped. involvement	$1.2 billion/yr	--
Vehicle-vehicle crash	$50,000/veh-veh crash	$15 billion/yr	--

Note:
1 - Involvements = number of pedestrians that are injured or killed as a result of pedestrian-vehicle crashes.

The number of pedestrian involvements each year in Texas (6214) is small compared to the annual number of vehicle-vehicle crashes in Texas (300,000). In fact, pedestrian involvements constitute only about 2 percent of the state's total crashes. However, the severity of a pedestrian crash is much greater than that of a typical vehicle-vehicle crash. A crash cost analysis (based on the willingness-to-pay approach that includes a fatal crash cost estimate of $4 million) indicates that the average cost of a pedestrian involvement is about $200,000, compared to a cost of $50,000 for the average vehicle-vehicle crash. Thus, the estimated cost of pedestrian-related crashes to Texas travelers is $1.2 billion/yr, which is about 8 percent of the total Texas crash cost.

INTERSECTION TRAFFIC CONTROL

This part of the chapter describes the traffic control elements at signalized intersections that apply to either left-turn movements or pedestrian movements. The first section reviews the various left-turn operational modes and phase sequences used. The second section describes pedestrian signal settings and controller operation to accommodate pedestrian movements.

Left-Turn Control

Operational Mode

The left-turn operational mode is described as protected, protected-permissive, or permissive. A variety of guidelines exist that indicate conditions where the benefits provided by one mode typically outweigh those of other modes. Many of these guidelines indicate that a left-turn phase can be justified based on consideration of several factors that ultimately tie back to the operational or safety benefits derived from the phase. These factors include:

- Left-turn and opposing through volumes.
- Number of opposing through lanes.
- Cycle length.
- Speed of opposing traffic.
- Sight distance.
- Crash history.

Of note about this list is its lack of a factor that reflects pedestrian presence or flow rate.

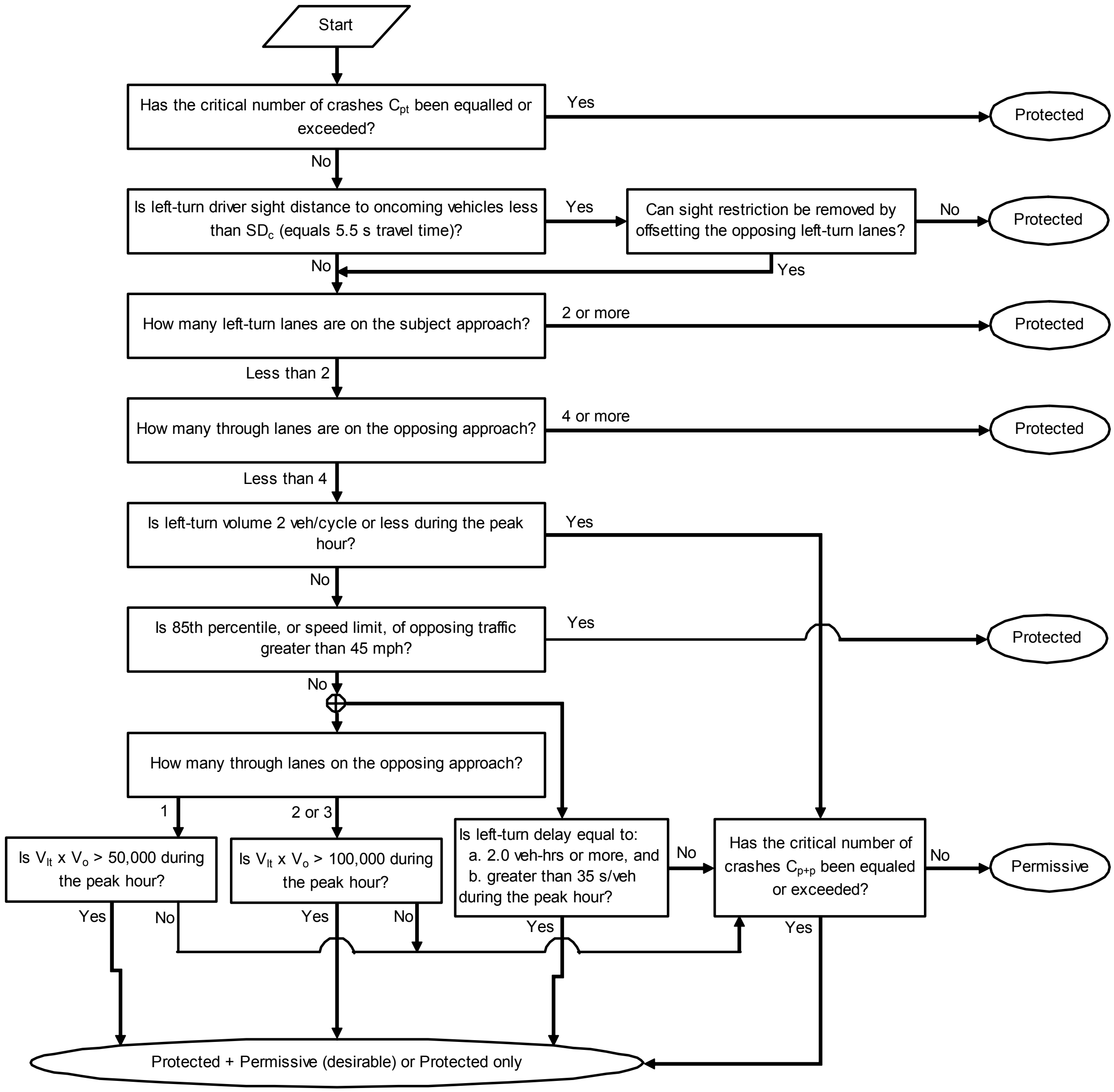
The flowchart shown in Figure 2-1 presents the guidelines provided in the TxDOT *Traffic Signal Operations Handbook* (*2*). They are used to assist in the determination of whether a left-turn phase is needed for a given left-turn movement and whether the operational mode should be permissive, protected, or protected-permissive. These guidelines were derived from a variety of authoritative reference documents (*3, 4, 5*). The criteria used to determine the operational mode are identified in the various boxes of the flow chart.

Guidelines were more recently developed by Yu et al. (*6*) to address left-turn mode selection. These guidelines include many of the same considerations represented in Figure 2-1. However, there is a notable difference in the thresholds used for the Volume Cross Product check.

Phase Sequence

Leading, lagging, or split phasing is used when a left-turn phase operates in the protected or protected-permissive mode. The terms leading and lagging indicate the order in which the left-turn phase is presented, relative to the phase serving the conflicting through movement. Leading left-turn phasing has the left-turn phase occurring before the phase serving the conflicting through movement. Lagging left-turn phasing has the left-turn phase occurring last. Split phasing allows all movements on one approach to proceed before those on the opposing approach.

For typical intersections, research indicates that lead-lead, lag-lag, and lead-lag phasing provide about the same operational efficiency and safety. Split phasing tends to be less efficient than the other sequences at typical intersections. Thus, the choice between lead-lead, lag-lag, and lead-lag is often based on agency preference or identified benefits to signal coordination. Lag-lag and split phasing are sometimes beneficial at intersections with atypical geometric configurations or volume conditions.



Number of Left-Turn Movements on Subject Road	Period during which Crashes are Considered (years)	Critical Left-Turn-Related Crash Count: When Considering Protected-only, C_{pt} (crashes/period)	Critical Left-Turn-Related Crash Count: When Considering Prot.+Perm, C_{p+p} (crashes/period)
One	1	6	4
One	2	11	6
One	3	14	7
Both	1	11	6
Both	2	18	9
Both	3	26	13

Oncoming Traffic Speed Limit (mph)	Minimum Sight Distance to Oncoming Vehicles, SD_c (ft)
25	200
30	240
35	280
40	320
45	360
50	400
55	440
60	480

Variables

V_{lt} = left-turn volume on the subject approach, veh/h

V_o = through plus right-turn volume on the approach opposing the subject left-turn movement, veh/h

Figure 2-1. Guidelines for Determining Left-Turn Mode. (*2*)

Lead-Lead Left-Turn Phasing. The most commonly used left-turn phase sequence is the lead-lead sequence, which has both opposing left-turn phases starting at the same time. The advantages of this phasing option are:

- It is consistent with driver expectation such that drivers react quickly to the leading green arrow indication.
- It minimizes conflicts between left-turn and through vehicles on opposing approaches by clearing left-turn vehicles first and, thereby, reducing the number of left-turn drivers that must find safe gaps.
- It minimizes conflicts between left-turn and through movements on the same approach when the left-turn volume exceeds its available storage length.

Lag-Lag Left-Turn Phasing. This left-turn phase sequence has both opposing left-turn phases ending at the same time. The advantages of the lag-lag phasing option are:

- It ensures that both adjacent through phases start at the same time—a characteristic that is particularly amenable to efficient signal coordination with pretimed control.
- If used with the protected-permissive mode, it minimizes presentation of the left-turn phase during low-volume conditions by clearing left-turn vehicles during the initial through phase.
- If used with the protected-permissive mode for the major road as part of a coordinated signal system, then it reduces delay to major-road left-turn movements by serving them soon after arrival.

The "yellow trap" problem is created when lag-lag phasing is used for opposing left-turn movements, and the left-turn phases operate in the protected-permissive mode. Flashing-yellow-arrow operation is one technique for eliminating this problem. It retains a permissive indication for left-turn drivers during the change period for the adjacent through movement phase (*7*).

Lead-Lag Left-Turn Phasing. The lead-lag left-turn phase sequence is sometimes used to accommodate through movement progression in a coordinated signal system. The aforementioned yellow trap may occur if the leading left-turn movement operates in the protected-permissive mode and the two through movement phases time concurrently during a portion of the cycle. This sequence may also be used at intersections where the leading left-turn movement is not provided an exclusive storage bay (or a bay is provided but it does not have adequate storage).

Split Phasing. Split phasing refers to the sequential service of opposing intersection approaches in two phases. This phasing is typically less efficient than lead-lead, lead-lag, or lag-lag left-turn phasing. It often increases the cycle length, or if the cycle length is fixed, it reduces the time available to the intersecting road. Split phasing may be helpful if there is a need to serve left turns from the opposing approaches, but sufficient width is not available to ensure their adequate separation in the middle of the intersection if served concurrently.

Pedestrian Control

This section describes pedestrian signal settings and controller operation to accommodate pedestrian movements. Specific topics of discussion include pedestrian signal heads, pedestrian intervals, leading pedestrian interval, and exclusive pedestrian phase.

Pedestrian Signal Heads

The *Texas Manual on Uniform Traffic Control Devices* (*TMUTCD*) indicates that pedestrian signal heads should be used under any of the following conditions:

- If it is necessary to assist pedestrians in making a reasonably safe crossing or if engineering judgment determines that pedestrian signal heads are justified to minimize vehicle-pedestrian conflicts;
- If pedestrians are permitted to cross a portion of a street, such as to or from a median of sufficient width for pedestrians to wait, during a particular interval but are not permitted to cross the remainder of the street during any part of the same interval; and/or
- If no vehicular signal indications are visible to pedestrians, or if the vehicular signal indications that are visible to pedestrians starting or continuing a crossing provide insufficient guidance for them to decide when it is reasonably safe to cross, such as on one-way streets, at T-intersections, or at multiphase signal operations (*8*).

The *Manual on Uniform Traffic Control Devices* (*MUTCD*) includes additional guidance on the use of countdown indications in conjunction with the pedestrian signal. Specifically, it states, "All pedestrian signal heads used at crosswalks where the pedestrian change interval is more than 7 seconds shall include a pedestrian change interval countdown display..." (*9*).

Pedestrian Intervals

This section provides guidelines for determining the duration of the walk interval and the pedestrian change (i.e., pedestrian clear) interval.

Walk Interval. The walk interval gives pedestrians adequate time to perceive the WALK indication and depart the curb before the pedestrian change interval begins. The *TMUTCD* indicates that the minimum walk duration should be at least 7 s, but indicates that a duration as low as 4 s may be used if pedestrian volume is low or pedestrian behavior does not justify the need for 7 s (*8*). Consideration should be given to longer walk duration in school zones and areas with large numbers of older pedestrians.

Pedestrian Change Interval. Pedestrian clearance time must follow the walk interval. It should allow a pedestrian crossing in the crosswalk to leave the curb (or shoulder) and walk at a normal rate to at least the far side of the traveled way, or to a median of sufficient width for pedestrians to wait (*8*).

The *TMUTCD* (*8*) recommends a walking speed value of 4.0 ft/s. However, Fitzpatrick et al. (*10*) recommend a maximum walking speed of 3.5 ft/s for general pedestrian populations and

3.0 ft/s if older pedestrians are a concern. The *MUTCD* indicates that a walking speed of 3.5 ft/s should be used (*9*). However, it also indicates that "a walking speed of up to 4.0 ft/s may be used to evaluate the sufficiency of the pedestrian clearance time at locations where an extended push button press function has been installed to provide slower pedestrians an opportunity to request a longer pedestrian clearance time" (*9*).

The pedestrian clearance time is computed as the crossing distance divided by the walking speed. Crossing distance is typically measured from curb to curb along the crosswalk. Clearance time can be obtained from Table 2-2 for typical pedestrian crossing distances and walking speeds.

Table 2-2. Pedestrian Clearance Time.

Pedestrian Crossing Distance, ft	Walking Speed, ft/s		
	3.0	3.5	4.0
	Pedestrian Clearance Time (*PCT*), s [1]		
20	7	6	5
30	10	9	8
40	13	11	10
50	17	14	13
60	20	17	15
70	23	20	18
80	27	23	20
90	30	26	23
100	33	29	25

Note:
1 - Clearance times computed as $PCT = D_c / v_p$, where D_c = pedestrian crossing distance (in feet) and v_p = pedestrian walking speed (in feet per second).

The *TMUTCD* indicates that the pedestrian clearance time can be provided during: (1) the pedestrian change interval during which a flashing DON'T WALK indication is displayed, and (2) a second interval that times concurrent with the vehicular yellow change and red clearance intervals and displays either a flashing or steady DON'T WALK indication (*8*). This practice minimizes the impact of pedestrian service on phase duration and allows the phase to be responsive to vehicular demand. Following this guidance, the pedestrian change interval (also called the pedestrian clear interval) is computed using Equation 1.

$$PCI = PCT - (Y + R_c) \quad (1)$$

where,
PCI = pedestrian change interval duration, s.
PCT = pedestrian clearance time, s.
Y = yellow change interval, s.
R_c = red clearance interval, s.

Leading Pedestrian Interval

The leading pedestrian interval is a feature available in most modern traffic controllers. It displays the WALK indication a few seconds before the green ball indication. In this manner the pedestrians can establish a presence in the crosswalk before turning vehicles receive the permissive green indication. A lagging pedestrian interval is also available in most controllers, but it gives preference to vehicular traffic by allowing them to start before the pedestrians.

Exclusive Pedestrian Phase

An exclusive pedestrian phase serves all pedestrian crossing movements simultaneously, while holding all vehicular movements with a red signal indication. The minimum duration of the phase is sufficient to allow the pedestrian to react to the WALK indication and cross one intersection leg, perpendicular to the direction of traffic flow. This type of phasing is occasionally used in the central business district of large cities.

A variation of the exclusive pedestrian phase is the "pedestrian scramble." It permits pedestrians to cross on a diagonal path through the intersection conflict area. It also allows the more traditional, perpendicular crossing movements across an intersection leg. The timing of this phase is sufficient to allow the pedestrian to react and cross the longest diagonal path.

LEFT-TURN-RELATED SAFETY ISSUES

This part of the chapter summarizes the research that has quantified intersection pedestrian service quality and safety, as influenced by left-turning vehicles. Initially, a model is described for estimating the pedestrian's perception of service quality provided at an intersection. Then, a series of safety prediction models are examined. These models predict the frequency of pedestrian crashes at intersections. Next, the effect of left-turn control on pedestrian safety is examined. Finally, alternative pedestrian controls are examined in the context of their reported ability to improve pedestrian safety.

Pedestrian Service at Signalized Intersections

Dowling et al. (*11*) developed procedures for quantifying the level of service provided to pedestrians at signalized intersections. The procedure consists of a series of calculations that focus on quantifying the service provided by one crosswalk at the intersection; it is repeated as needed for each crosswalk of interest. The procedure is sensitive to the volume of right-turning and left-turning vehicles crossing the crosswalk. It also considers the delay incurred by pedestrians and the speed of the through traffic stream. Output from the procedure is a numeric score ranging from 1 to 6. Lower values indicate a very good level of service. In fact, values less than or equal to 2.0 represent level-of-service A, values between 2.0 and 2.75 represent level-of-service B, and so on.

The procedure was used to evaluate the sensitivity of pedestrian level of service to traffic volume and turn percentage. The intersection used for the evaluation had four legs and two lanes on each approach. Two volume scenarios were evaluated. In one scenario, the turn movements were each 10 percent of the approach volume. In the other scenario, turn movements were each 20 percent of the approach volume. The major-street volume equaled the minor-street volume for both scenarios. Each phase duration was computed to be in proportion to its flow ratio. The results of the evaluation are shown in Figure 2-2.

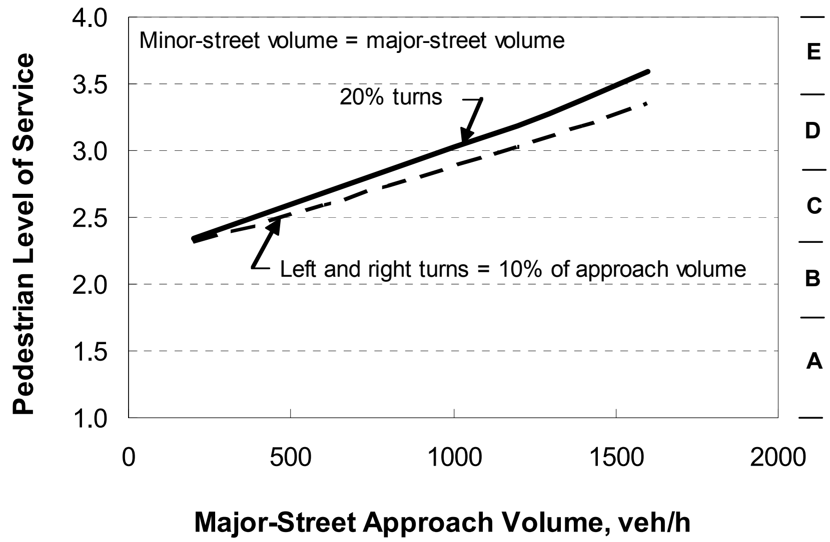


Figure 2-2. Pedestrian Level of Service Based on Traffic Volume.

The trends in Figure 2-2 reflect the analysis of one crosswalk at a signalized intersection. The numeric scores indicating level of service are reflected on the y-axis on the left side of the figure. The corresponding level-of-service letter is indicated on the right side of the figure. The two trend lines indicate that pedestrian level of service degrades as approach volume increases. The increase in turn percentage is also shown to have a negative effect on service quality. It reflects the increased conflict between turning vehicles and pedestrians when using the crosswalk.

Pedestrian Safety at Signalized Intersections

Lyon and Persaud (*12*) examined pedestrian crash frequency for signalized intersections in Toronto, Canada. They gathered pedestrian volume and vehicle volume data for 684 four-leg intersections and 263 three-leg intersections. Eleven years of pedestrian crash data were obtained for each intersection.

Lyon and Persaud used the data to calibrate one crash prediction model for four-leg intersections and a second model for three-leg intersections. Both models predicted the expected annual pedestrian crash frequency at an intersection. They included a sensitivity to the total daily entering volume, count of pedestrians using each sidewalk during an eight-hour period (totaled for all crosswalks), and total daily left-turning volume entering the intersection. It is noted that the models predict the annual number of reported crashes for an intersection even though the input pedestrian volume represents only eight hours of the day.

The models calibrated by Lyon and Persaud were used to evaluate the sensitivity of pedestrian crash frequency to daily vehicular volume and left-turn percentage. For four-leg intersections, the major-street volume equaled the minor-street volume. For three-leg intersections, the minor-street volume equaled one-half of the major-street volume. The eight-hour pedestrian volume was based on an assumed 50 p/h in each crosswalk during each of the eight hours. The results of the evaluation are shown in Figure 2-3.

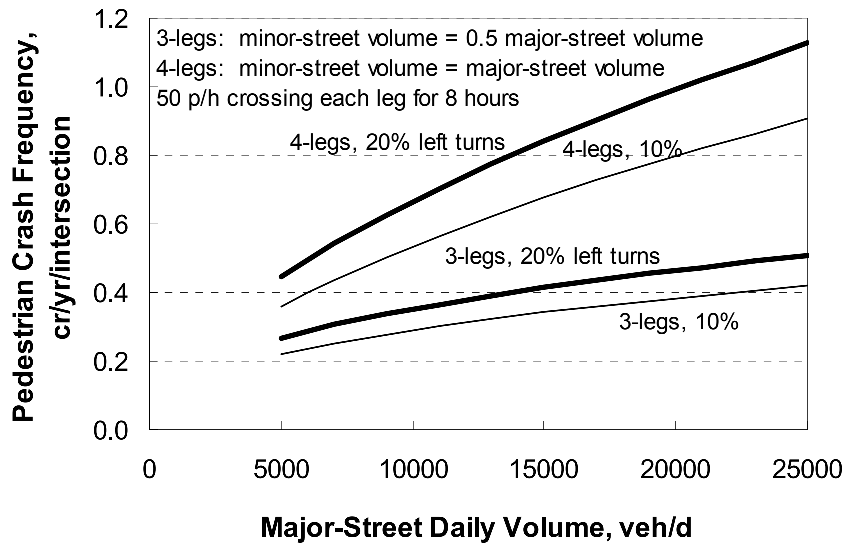


Figure 2-3. Crash Frequency Based on Traffic Volume.

The trend lines in Figure 2-3 indicate that pedestrian crash frequency increases with an increase in vehicular volume. A four-leg intersection with an average daily volume of 20,000 veh/d on each street, 20 percent left turns, and 20 percent right turns is likely to have one reported pedestrian crash each year. The four-leg intersections have more than twice as many crashes as the three-leg intersections for a given volume and turn percentage. A 15 percent increase in daily volume corresponds to about an 8 percent increase in crashes. In contrast, a 15 percent increase in left-turn volume corresponds to a 4 percent increase in crashes. These trends suggest that left-turn volume and through volume do not increase crash risk (i.e., that intersections with higher volume have a lower crash rate). It is possible that, once the first left-turn vehicle initiates its maneuver safely, the remaining left-turn vehicles also proceed safely—regardless of their number. It follows then, that crash risk may increase more notably with an increase in the number of signal cycles per hour.

Effect of Left-Turn Control on Pedestrian Safety

Lord (*13*) reviewed several research reports on the topic of left-turn-related pedestrian-vehicle crashes. He found that left-turn maneuvers account for 20 to 30 percent of all pedestrian crashes at intersections. Left-turn-related pedestrian crashes are exceeded in number only by collisions between pedestrians and through vehicles (51 percent).

Research indicates that left-turn mode (i.e., permissive, protected-permissive, or protected) and phase sequence have some influence on the safety of the pedestrian crossing maneuver. Each of these influences is discussed in the following subsections.

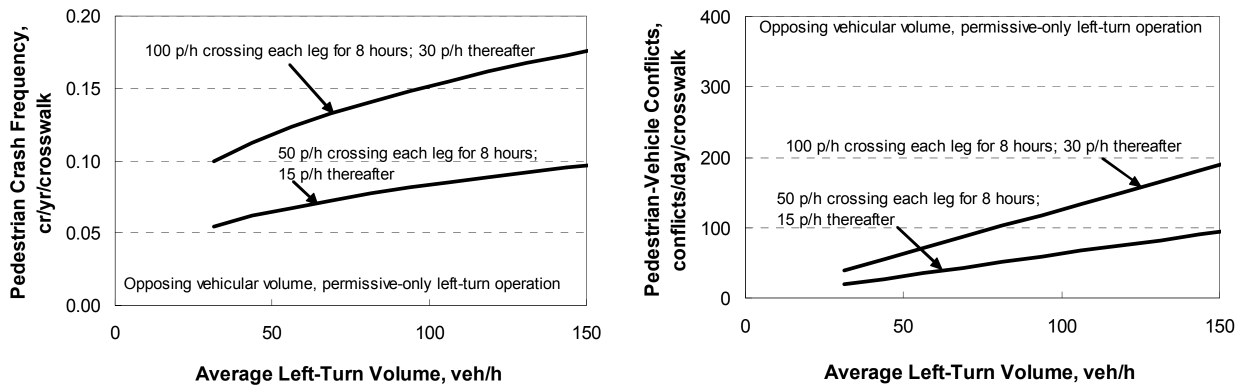
Permissive Left-Turn Mode

A driver turning left at a signalized intersection during a permissive period has to monitor multiple information sources during the maneuver. These sources include the signal indication, opposing vehicle stream, and pedestrian activity in the crosswalk that is adjacent to the opposing through traffic lanes. These multiple sources make the left-turn maneuver relatively complex and place a significant demand on the driver workload. Sometimes, when this workload exceeds the driver's processing capability, an incorrect decision is made and a left-turn-related crash occurs.

Quaye et al. (*14*) examined left-turn-related pedestrian crash frequency for individual crosswalks as a function of the pedestrian volume and left-turn volume in the crosswalk. They collected pedestrian and vehicular volume data for 547 crosswalks at 200 intersections in Canada. They combined this data with left-turn-related crash data for a four-year period. The resulting database was used to develop a model for predicting the expected annual number of left-turn-related pedestrian crashes during a specified hour of the day. Thus, the model is applied to each of the 24 hours during a representative day, and the 24 estimates are then added to obtain an estimate of the annual crash frequency for the subject crosswalk.

One of the models calibrated by Quaye et al. applies to crosswalks where the conflicting left-turn movement operated in the permissive mode and was opposed by a through vehicle traffic movement. The predicted relationship between left-turn-related pedestrian crash frequency, left-turn volume, and pedestrian volume is shown in Figure 2-4a.

The trends in Figure 2-4a are consistent with those in Figure 2-3 and indicate that crash frequency increases with increasing left-turn volume. A 15 percent increase in left-turn volume corresponds to a 5 percent increase in crash frequency. This trend suggests that left-turn volume does not increase crash risk—a trend that is consistent with that observed in Figure 2-3. A 15 percent increase in pedestrian volume corresponds to a 12 percent increase in crash frequency. The nearly one-to-one ratio of these percentages suggests that pedestrian volume has negligible effect on risk (i.e., crash rate is uninfluenced by pedestrian volume). The trends in Figure 2-4a also suggest that there is one pedestrian crash every 6 to 12 years for a given crosswalk, when the conflicting left-turn volume ranges from 100 to 150 veh/h.



a. Crash Frequency. **b. Conflict Frequency.**

Figure 2-4. Crash and Conflict Frequency for Permissive Operation.

Akin and Sisiopiku (*15*) collected pedestrian-vehicle conflict data at three signalized intersections in Michigan. One crosswalk at each intersection was videotaped for a period of three to four hours during one day. Pedestrian volume, left-turn volume, and pedestrian-vehicle conflicts were extracted from the videotape for each 30-minute time period. Two of the intersections had permitted left-turn operation with an opposing through vehicle movement. Their examination of the data indicated that hourly conflict frequency was linearly related to the product of the hourly left-turn volume and the hourly pedestrian volume. The linear relationship shown in Figure 2-4b is derived by the authors of this report using data reported by Akin and Sisiopiku.

The trends in Figure 2-4b indicate that the number of conflicts in a 24-hour period is roughly equal to the left-turn volume. More specifically, when the left-turn volume averages 100 veh/h, the pedestrian volume averages 50 p/h during eight hours, and 15 p/h during the remaining hours, then about 60 conflicts occur each day. If the pedestrian volume doubles, then about 120 conflicts occur each day.

A relationship between conflict and crash frequency can be derived by combining the functions represented in Figure 2-4. This relationship is shown in Figure 2-5. The trends in this figure give an indication of the large number of conflicts that occur relative to the number of crashes. Roughly speaking, if a crosswalk is found to experience conflicts at a rate of 100 per day, then it will experience one crash every 7 to 10 years.

Unopposed Left-Turn Operation

In addition to examining left-turn-related pedestrian crash frequency at intersections with permitted left-turn operation, Quaye et al. (*14*) also examined crash frequency at intersections where there was no opposing through vehicle movement. This condition is found at: (1) intersections where one or both intersecting streets serve only one travel direction and (2) three-leg intersections. The left turns from a one-way leg or from the terminating leg of a three-leg intersection do not have an opposing through vehicle movement.

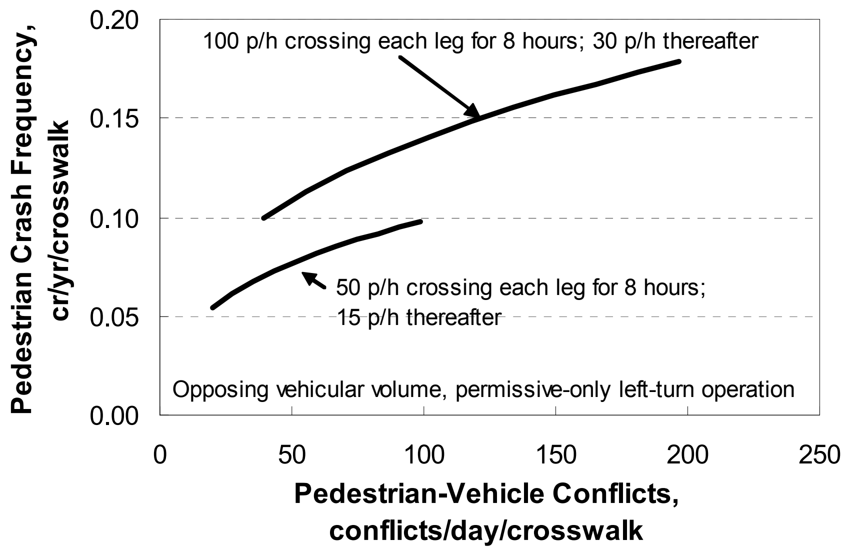
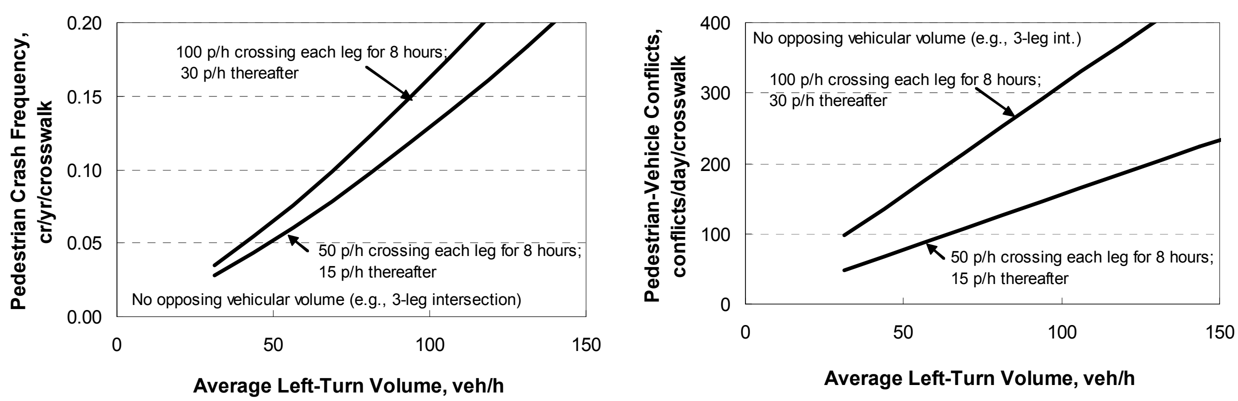


Figure 2-5. Crash and Conflict Relationship for Permissive Operation.

Quaye et al. developed a pedestrian-vehicle crash prediction model for crosswalks with unopposed left-turn operation. The relationship between left-turn-related pedestrian crash frequency, left-turn volume, and pedestrian volume is shown in Figure 2-6a.



a. Crash Frequency. **b. Conflict Frequency.**

Figure 2-6. Crash and Conflict Frequency for Unopposed Left-Turn Operation.

The trends in Figure 2-6a are not fully consistent with those in Figures 2-3 or 2-4a. They indicate that crash frequency increases rapidly with increasing left-turn volume. This finding suggests that pedestrians are less safe in crosswalks where the conflicting left-turn volume is high and the left-turn movement does not have an opposing through vehicle movement to partially "shield" pedestrians at the start of the phase.

More specifically, the trend lines in Figure 2-6a indicate that a 15 percent increase in left-turn volume corresponds to a 20 percent increase in crash frequency. This trend suggests that increasing left-turn volume increases crash risk. On the other hand, a 15 percent increase in pedestrian volume corresponds to a 4 percent increase in crash frequency. This trend suggests that risk decreases with increasing pedestrian volume—a trend that was also noted by Leden (*16*) in a subsequent re-examination of the Quaye et al. data. The trends in Figure 2-6a also suggest that there is one pedestrian crash every 3 to 8 years for a given crosswalk, when the conflicting left-turn volume ranges from 100 to 150 veh/h.

One of the intersections studied by Akin and Sisiopiku (*15*) was a three-leg intersection. They collected conflict data on the left turn from the terminating leg. The linear relationship is derived by the authors of this report using the data reported by Akin and Sisiopiku. It is shown in Figure 2-6b.

The trends in Figure 2-6b indicate that the number of conflicts in a 24-hour period is roughly equal to twice the left-turn volume. More specifically, when the left-turn volume averages 100 veh/h, the pedestrian volume averages 50 p/h during eight hours, and 15 p/h during the remaining hours, then about 155 conflicts occur each day. If the pedestrian volume doubles, then about 310 conflicts occur each day.

A relationship between conflict and crash frequency was derived by combining the functions represented in Figure 2-6. This relationship is shown in Figure 2-7. The trend lines in this figure illustrate the large number of conflicts that occur relative to the number of crashes. A comparison between Figures 2-5 and 2-7 indicates that, while conflicts are more frequent at left-turn locations with unopposed left-turn operation, they tend to result in fewer crashes per year for typical pedestrian and vehicle volume combinations. Roughly speaking, if a crosswalk is found to experience conflicts at a rate of 100 per day, then it will experience only one crash every 13 to 29 years.

Protected-Permissive Left-Turn Mode

The relationship between pedestrian safety and the protected-permissive mode has not been established through research. It could be rationalized that protected-permissive operation is less safe than a protected left-turn operation and more safe than permissive operation, given that it combines the operation of both modes.

A flashing yellow arrow implementation of protected-permissive operation was researched by Brehmer et al. (*7*) in terms of its safety and operational benefits. They found that the flashing yellow arrow indication has a lower "fail-critical" rate as compared to the circular green indication when used to indicate the permissive period. A fail-critical response occurs when the left-turning driver incorrectly interprets the permissive indication as a protected turn indication, thus creating the potential for a crash with opposing vehicles or pedestrians. By inference, the flashing-yellow-arrow display would offer some benefit to pedestrian safety through better driver comprehension of the signal display; however, there is no research to confirm this inference.

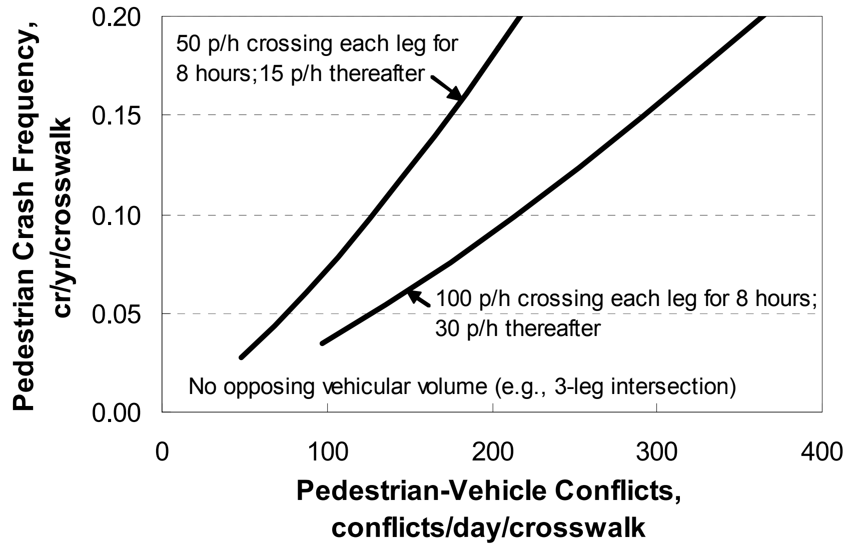


Figure 2-7. Crash and Conflict Relationship for Unopposed Left-Turn Operation.

Koonce et al. (*17*) point out the use of the permissive period omit as a technique to improve pedestrian safety. With this technique, the controller is set up to omit the permissive period during any cycle in which a detection is received for a conflicting pedestrian movement. However, this technique has the possible disadvantage of violating driver expectancy.

One issue that is related to the use of the protected-permissive mode is its possible negative impact on pedestrian compliance with the pedestrian signal. One factor that affects pedestrian compliance is waiting time, which is typically increased when permissive operation is replaced by protected-permissive operation. Studies indicate that pedestrian compliance degrades with waiting time. Pedestrians are reluctant to wait more than 30 s, and compliance is notably poor if the wait is 60 s or more (*18*).

Protected Left-Turn Mode

Guidance on p. 457 of the *Traffic Control Devices Handbook* (*19*) indicates that the choice of left-turn mode should be based on consideration of the overall safety and efficiency of the intersection. They caution that "protected-only left-turn phases may improve the safety of left-turning vehicles, but this will be accomplished at the expense of other movements and pedestrians." The implied "expense" is an increase in delay to vehicles and pedestrians. One additional concern is whether the increase in pedestrian delay will lead to a decrease in pedestrian compliance.

Leading vs. Lagging Phase Sequence

Hummer et al. (*20*) measured conflicts between pedestrians and left-turn vehicles at signalized intersections. Some of the intersections they evaluated had a leading left-turn phase. Other intersections had a lagging left-turn phase. They found that the leading left-turn phase was associated with six times as many conflicts as the lagging left-turn phase. In most instances, the leading-left-turn-related conflicts were a result of the pedestrian mistaking the end of the cross street through phase for the start of the through phase in the direction they were traveling (when, in fact, it was the start of the left-turn phase). The pedestrians would not see, or disregard, the DON'T WALK indication and step into the crosswalk and the path of the left-turn vehicle. In contrast, the lagging sequence not only meets pedestrian expectations, but its through-vehicle queue provides a natural left-turn vehicle "shield" for pedestrians at the start of the permissive period.

Effect of Pedestrian Control on Pedestrian Safety

Research indicates that there are several traffic control techniques that can be used to address left-turn-related pedestrian-vehicle conflicts and crashes. These techniques include: leading pedestrian interval, exclusive pedestrian phase, pedestrian clear interval, and selected warning signs or markings. Each of these techniques is described in the following subsections.

Leading Pedestrian Interval

Lalani (*21*) indicates that agencies have typically implemented a leading pedestrian interval at locations where 3 to 20 percent of turning vehicles typically violate the pedestrian right-of-way. The leading interval always increases vehicle delay (*22*) so its safety benefit must outweigh its adverse impact on vehicle operation. A lagging pedestrian interval is available in most controllers but it does *not* reduce left-turn-related pedestrian conflicts, and may even increase them.

Fayish and Gross (*23*) examined pedestrian crash data at 10 signalized intersections in State College, Pennsylvania, at which a leading pedestrian interval was installed. For each intersection, they gathered crash data for four years before the leading pedestrian interval was installed and for three years after installation. The leading pedestrian interval was 3.0 s in duration at each intersection. Their analysis indicated that pedestrian-vehicle crash frequency at intersections decreased by 58.7 percent after the leading pedestrian intervals were implemented. This reduction includes pedestrian crashes associated with both left-turning and right-turning vehicles.

Exclusive Pedestrian Phase

An exclusive pedestrian phase provides temporal separation between vehicles and pedestrians by providing each travel mode exclusive use of the intersection during a signal phase. Research by Zegeer et al. (*24*) found that this phasing arrangement is associated with a 50 percent reduction in pedestrian crashes, relative to signalized intersections with concurrent service of pedestrians during the through vehicle phases and intersections with no pedestrian signals.

A scramble phase is a special type of exclusive pedestrian phase. It was also found to provide a similar safety benefit as the exclusive pedestrian phase; however, it is reported to work best when pedestrian volume exceeds 1200 pedestrians per day, street widths are narrow (e.g., less than 60 ft), and through movement volume is low (*22, 24*).

Provide Pedestrian Clear Entirely during Green

Some agencies prefer to minimize the duration of the pedestrian change interval by subtracting the yellow change interval and red clearance interval (see Equation 1). However, this practice may cause some conflict between pedestrians and left-turning vehicles that are clearing the intersection following the permissive portion of the phase. A similar conflict can occur if permissive or protected-permissive left-turn operation is used with the rest-in-walk mode.

If permissive or protected-permissive left-turn operation is used and vehicular volume is low enough that the phase ends after timing the pedestrian walk and change intervals, then the pedestrian change interval (also known as pedestrian clear interval) can be set to equal the pedestrian clearance time, as defined in the text associated with Table 2-2. Under these conditions, the pedestrian clear times entirely during the green interval, and some vehicle-pedestrian conflicts that occur at the end of the phase may be alleviated.

Turn Vehicle Warning Signs and Markings

Signs and/or markings with a message such as, “Pedestrians Watch for Turning Vehicles” have been used to increase the awareness of pedestrians at intersections. The marking is placed in the crosswalk near the curb. The sign is placed on the far-side pole facing pedestrians in the crosswalk. Research indicates that these treatments reduce left-turn-related pedestrian-vehicle conflicts by 20 to 60 percent (*21*).

A sign with the message, “Yield to Pedestrians When Turning” was evaluated by Zegeer et al. (*24*) using a before-after study. They installed the sign at four intersections and used it to inform turning drivers of pedestrian presence. They used vehicle-pedestrian conflicts as the measure of effectiveness. They found that the sign had no significant effect on left-turn-related conflict frequency, but total pedestrian-vehicle conflicts were reduced 25 to 37 percent.

Effect of Pedestrian Flow on Vehicle Operation

Chapter 16 of the 2000 *Highway Capacity Manual* (*25*) describes a methodology for evaluating vehicle operation at a signalized intersection. The methodology is sensitive to pedestrian volume. It models the effect of pedestrian presence on discharging left- and right-turn vehicles by decreasing the vehicle’s saturation flow rate. Higher pedestrian volume in a crosswalk corresponds to lower saturation flow rate and a higher delay.

The Chapter 16 methodology was used to examine the sensitivity of delay to vehicle and pedestrian volume. A four-leg intersection was devised for this examination. Each leg served two-way traffic and provided two lanes in each travel direction. No turn bays or phases were provided. Vehicular demand on each street was the same, 20 percent of the approach traffic turned left, and another 20 percent turned right. A pedestrian volume of 400 p/h was used, which is typical of an intersection in a central business district (*25*). The results are shown in Figure 2-8.

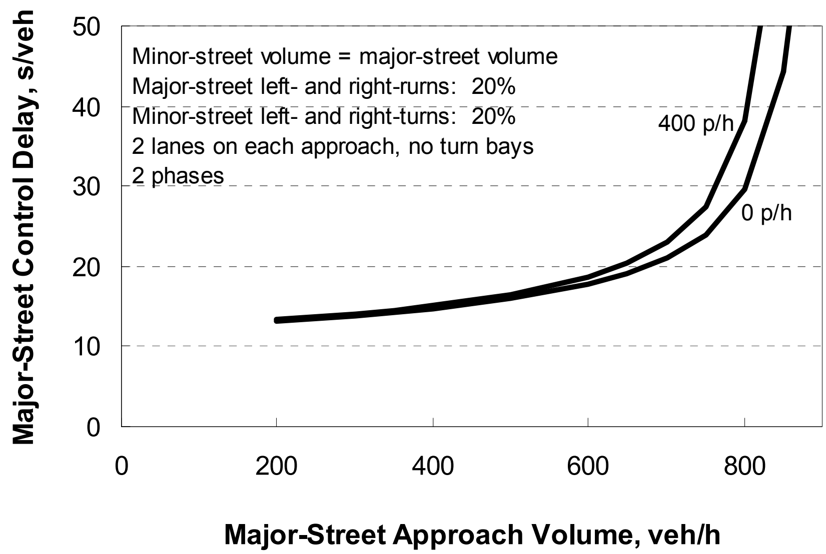


Figure 2-8. Relationship between Pedestrian Volume and Vehicle Delay.

The trend lines in Figure 2-8 indicate that pedestrian volume has a minimal effect on vehicle delay when approach volumes are less than 600 veh/h (i.e., 300 veh/h/ln). As the volume increases above 600 veh/h, a pedestrian volume of 400 p/h is shown to increase delay by several seconds per vehicle. In fact, at a vehicular volume of 800 veh/h, the increase in delay due to pedestrian presence is about 10 s/veh.

CANDIDATE TRAFFIC ENGINEERING TREATMENTS

A review of the literature indicates a range of traffic engineering treatments are available to address left-turn-related pedestrian-vehicle conflicts. The use of the protected or protected-permissive mode is a commonly cited treatment. However, there were instances where other treatments were found to provide some safety benefit without increasing vehicle delay or degrading progression quality as much as the addition of a left-turn phase. These treatments are summarized in Table 2-3. The effectiveness of each treatment may vary, depending on whether the subject left-turn movement is opposed by a through vehicular movement.

Table 2-3. Traffic Engineering Treatments for Improving Pedestrian Safety at Intersections.

Treatment	Description	Issues
Treatments Based on Conversion from Permissive Mode		
Provide protected-permissive mode	Reduce the number of left-turn vehicles that turn during the permissive period by providing a protected arrow indication.	Permissive period presents opportunity for some pedestrian-vehicle conflicts. If used with lagging left-turn phase sequence, safety problems associated with the yellow trap may occur.
Provide protected-permissive mode using flashing yellow signal display	Reduce the number of left-turn vehicles that turn during the permissive period by providing a protected arrow indication.	Safety benefits of protected-permissive phasing with flashing yellow display not quantified through research.
Provide protected left-turn mode (*19, 22*)	Separate vehicles and pedestrians on problem approach by providing each a separate time in cycle to be served.	Left-turn phase may increase pedestrian waiting time and decrease their compliance with the pedestrian signal.
Provide lagging phase sequence (*20*)	Through phase (and pedestrian service) occur after cross street phase ends and is consistent with pedestrian expectation.	Treatment is viable with protected mode, and with protected-permissive mode provided that yellow trap is eliminated.
Treatments Used in Conjunction with Permissive Mode		
Provide leading pedestrian interval (*19*, *21*, *22*)	Provide a small amount of time (say, 3 s) to allow pedestrians to start crossing before displaying green ball.	Increases delay to vehicles. May require the use of accessible pedestrian signals to provide crossing cues to visually impaired pedestrians.
Provide exclusive pedestrian phase (*19*,*22*)	Separate vehicles and pedestrians at intersection by providing each a separate time in cycle to be served.	Significant delay and waiting time may result if used at large intersections. May require the use of accessible pedestrian signals to provide crossing cues to visually impaired pedestrians.
Provide pedestrian clear interval entirely during green (*2*)	Some agencies time a portion of the pedestrian clearance time during the yellow change and red clearance intervals to reduce delay.	Increases delay to vehicles. May only provide pedestrian safety benefit if used with protected left-turn mode or with permissive omit when ped. is detected.
Add turning vehicle warning signs and markings (*19*, *21*)	Add "Pedestrians Watch for Turning Vehicles" signs and/or markings to remind pedestrians to look for turning vehicles.	Markings tend to wear away when used in typical crosswalk locations.
Prohibit pedestrian crossing	Redirect pedestrians to alternative crosswalks or crossing locations.	May shift safety problem to another intersection. May cause negative public reaction unless it is part of a larger traffic management strategy.

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CHAPTER 3. STATE OF THE PRACTICE REVIEW

OVERVIEW

This chapter documents the findings from a survey of practitioners regarding the state-of-the-practice in addressing pedestrian safety at signalized intersections. It consists of two parts. The first part documents the information obtained during interviews with practitioners in Texas and several other states. The second part documents the findings from an electronic discussion (e-discussion) that was conducted with an expert panel comprised of 12 state and city traffic engineers.

PRACTITIONER INTERVIEW

This part of the chapter documents the information obtained during interviews with traffic engineers responsible for signalized intersection operations in various cities and states. The interview addressed pedestrian safety at signalized intersections in urban areas, with a focus on conflicts between left-turn vehicles and pedestrians. The interview objectives were as follows:

- Assess the state of the practice regarding control for left turns and pedestrians.
- Determine how pedestrian needs are assessed and accommodated.
- Identify treatments used to address left-turn-related pedestrian safety concerns.

In addition to providing the aforementioned information, the interviews were also used to identify people who could serve on an expert panel. The expert panel was used to conduct an in-depth exploration of pedestrian safety problems and potential treatments. The findings from this activity are documented in the next part of this chapter.

Background

The researchers conducted interviews with practitioners in several TxDOT districts, Texas cities, and public agencies in other states. The interviewees were asked questions about their left-turn signalization practices, methods for accommodating pedestrian needs, and use of treatments to address pedestrian safety. The Texas interviewees were also asked to assist in identifying candidate field data collection sites. The specific questions asked during the interviews are listed in Figures 3-1 and 3-2. The responses to the interview questions are documented in the following subsections.

INTERVIEW QUESTIONS

Inventory and Practice

1. How many urban signalized intersections do you operate in your jurisdiction?
2. What percentage of these intersections have crosswalks. . .
   a. On all approach legs? b. On some approach legs?
3. What percentage of your signalized left-turn movements are. . .
   a. Protected-permissive? b. Permissive-only?
4. For the preceding left-turn modes, what percentage of the “crossed” pedestrian movements (see drawing on page 1) are controlled by pedestrian signal heads?
   a. Protected-permissive b. Permissive-only
5. Are you using the flashing yellow arrow display for any of your protected-permissive left turns? If so, what percentage of the protected-permissive movements?
6. What role does pedestrian volume play in the selection of. . .
   a. Left-turn mode? b. Left-turn phase sequence?
7. What percentage of your urban signalized intersections do you consider to have “high” pedestrian volumes?
8. How many of the high-pedestrian-volume intersections are in areas that you would describe as. . .
   a. Downtown / business district? b. School (K-8)? e. Other?
   c. High school? d. University?
9. Which of these sites are the most “problematic” with respect to pedestrians and left-turn movements?
10. At what percentage of your urban signalized intersections are you using. . .
    a. Pedestrian countdown signal heads? b. Leading pedestrian intervals?
    c. Other special pedestrian treatments?

Issues Affecting Pedestrian Safety

11. How many pedestrian crashes per year do you have at your urban signalized intersections?
12. What percentage of the crashes are related to left-turn movements?
13. Consider the following pedestrian and signalized intersection characteristics.
    a. Left-turn volume d. Transit stop presence at intersection g. Coordination
    b. Approach speed e. Left-turn mode
    c. Pedestrian volume f. Phase sequence
    How influential are these site characteristics on pedestrian safety?
    Influence: 2 = very important, 1 = somewhat important, 0 = little or no importance
    How often are the characteristics considered in the design or operation of your signalized intersections?
    Discussion frequency: 2 = always discussed, 1 = sometimes discussed, 0 = rarely or never discussed
14. Consider the following pedestrian safety treatments.
    a. Add protected mode e. Prohibit left turns i. Provide leading ped. interval
    b. Add protected-permitted (PPLT) f. Add far-left signal head j. Provide ped. clear in green
    c. Add permissive omit with PPLT g. Provide ped. signal heads k. Add special signs or markings
    d. Change from leading to lagging h. Provide countdown heads l. Prohibit pedestrian crossing
    At what percentage of your signalized intersections have you used the treatments to improve ped. safety?
    Usage: Approximate percentage of intersections with the treatment
    How effective have they been in improving pedestrian safety?
    Effectiveness: 2 = very effective, 1 = somewhat effective, 0 = not effective at all
15. Do you use any criteria to decide where the previously discussed treatments should be installed?

Figure 3-1. Interview Questions for Texas Agencies.

INTERVIEW QUESTIONS

Inventory and Practice

1. What cities or states are you most familiar with regarding pedestrian practices at signalized intersections?
2. How many urban signalized intersections do you operate in your jurisdiction?
3. What role does pedestrian volume play in the selection of. . .
   a. Left-turn mode?
   b. Left-turn phase sequence?
4. What percentage of your urban signalized intersections do you consider to have "high" pedestrian volumes?
5. How many of the high-pedestrian-volume intersections are in areas that you would describe as. . .
   a. Downtown / business district?
   b. School (K-8)?
   c. High school?
   d. University?
   e. Other?
6. Which of these sites are the most "problematic" with respect to pedestrians and left-turn movements?

Issues Affecting Pedestrian Safety

7. Consider the following pedestrian safety treatments.
   a. Add protected mode
   b. Add protected-permitted (PPLT)
   c. Add permissive omit with PPLT
   d. Change from leading to lagging
   e. Prohibit left turns
   f. Add far-left signal head
   g. Provide ped. signal heads
   h. Provide countdown heads
   i. Provide leading ped. interval
   j. Provide ped. clear in green
   k. Add special signs or markings
   l. Prohibit pedestrian crossing

   At what percentage of your signalized intersections have you used the treatments to improve ped. safety?
   Usage: Approximate percentage of intersections with the treatment
   How effective have they been in improving pedestrian safety?
   Effectiveness: 2 = very effective, 1 = somewhat effective, 0 = not effective at all
8. Do you use any criteria to decide where the previously discussed treatments should be installed?

Figure 3-2. Interview Questions for Agencies Outside of Texas.

Most of the interviewees were engineers, but a few engineering assistants and signal technicians were also interviewed. A total of 27 practitioners in Texas were visited in person, and an additional six in other states were contacted by telephone. The in-person meetings were about an hour in length, and the telephone calls were about a half-hour in length. The agencies represented by the interviewees are listed in Table 3-1.

Table 3-1. Public Agencies Represented in the Practitioner Interview.

Agency Representation	Agency Name	Number of Signalized Intersections
Texas city	Bryan	64
	Tyler	145
	Waco	174
	Corpus Christi	250
	Fort Worth	710
	Austin	900
	Dallas	1300
	San Antonio	1230
TxDOT district	Bryan	52
	Corpus Christi	160
	Tyler	188
	Waco	220
	Austin	300
	San Antonio	500
	Fort Worth	508
	Dallas	339
Agency outside of Texas	City of San Luis Obispo, California	57
	City of Cambridge, Massachusetts	134
	Salt Lake City Transportation Division, Utah	100
	City of Madison, Wisconsin	249
	City of Phoenix, Arizona	1082
	City of Los Angeles, California	4500

Inventory and Practice

To establish some overall perspective on the issues, the interviewees were asked questions relating to their inventory and general practice. These questions related to the number of urban signalized intersections within the interviewees' jurisdiction, the use of crosswalks and pedestrian control, the selection of left-turn signalization parameters, and the location of intersections with high pedestrian volumes. The number of signalized intersections within each jurisdiction is listed in the last column of Table 3-1.

Left-Turn Phasing

The Texas interviewees were asked what percentage of their signalized left-turn movements are controlled with the protected-permissive or permissive-only modes. These left-turn movements are of the greatest interest because conflicts between pedestrians and left-turning vehicles can occur during the permissive period. The distribution of left-turn modes used by the agencies is provided in the following list. As indicated in this list, 75 percent of the left-turn movements are operated with modes that result in possible conflict between left-turning vehicles and pedestrians.

- Protected-permissive mode – 51 percent.
- Protected, split phasing, or other – 25 percent.
- Permissive – 24 percent.

All of the Texas interviewees indicated that pedestrian volume is rarely considered in the selection of left-turn mode. The selection of left-turn mode is typically based on vehicular volume and intersection geometry.

More generally, they indicated that pedestrian safety is considered in two situations. One situation is where pedestrian crash data indicate the existence of a safety problem that can be addressed by protected left-turn operation. A second situation applies to intersections near schools. Several interviewees stated that they consider providing left-turn protection at school intersections or intersections near special-event facilities, even if vehicular volumes and intersection geometry do not justify providing left-turn protection. Two city engineers use the permissive period omit with protected-permissive mode at school intersections during school hours.

All of the Texas interviewees stated that pedestrian volume plays little or no role in the selection of left-turn phase sequence (i.e., leading versus lagging). Phase sequence is usually chosen either by default (i.e., the agency always uses a certain phase sequence), or based on coordination issues (i.e., to maximize progression bandwidth). One interviewee stated that he had tried changing a left-turn phase from leading to lagging to improve pedestrian safety, but changed it back to leading because he did not believe it yielded any benefit. Another interviewee stated that he changed a left-turn phase from leading to lagging at one intersection near a university in response to complaints from the public, and that the complaints stopped after he implemented the change.

Two of the interviewees from other states indicated that they consider pedestrian volume in the selection of left-turn control. In one city, the protected-permissive mode is used if the left-turn cycle failure rate is more than 80 percent and the delay to the opposing through movement is 40 s/veh or less. With this guidance, pedestrian volume can indirectly influence the choice of left-turn control to the extent that pedestrian timing affects the left-turn cycle failure rate and the opposing through movement delay. In another city, pedestrian volumes are collected and used in a simulation model to quantify performance measures. This city also conducts field visits to assess whether gaps in the pedestrian stream are sufficiently large to serve left-turning vehicles. They may consider the protected-permissive mode if adequate gaps are too infrequent. This assessment is done on a qualitative basis.

Most of the Texas interviewees responded that their agencies are not using the flashing yellow arrow signal display for left-turn movements. Of all the contacted agencies, only the Cities of Tyler and San Antonio are using the flashing yellow arrow display. Tyler uses the flashing yellow arrow display for 40 percent of their protected-permissive left-turn movements, while San Antonio uses this display for 2 percent of their protected-permissive movements.

Pedestrian Control

The Texas interviewees were asked about the provision of crosswalks at their urban signalized intersections. Specifically, they were asked to indicate what percentage of their intersections had crosswalks on all, some, or none of their approach legs.

The Texas interviewees' responses to the questions about crosswalks are summarized in Table 3-2. Their responses indicate that crosswalks are provided more frequently by cities than by TxDOT districts. Cities provide crosswalks on some or all approach legs at 84 percent of their intersections, while TxDOT districts do so at about 64 percent of their intersections. Crosswalks are provided more often by cities because more of the city-operated signals are in areas with higher population density and pedestrian demand.

Table 3-2. Crosswalk Provision Trends at Urban Signalized Intersections.

Intersection Crosswalks	Percentage of Intersections by Texas Agency		
	City	TxDOT	Overall
Crosswalks on all legs	61	37	49
Crosswalks on some legs	23	27	25
No crosswalks	16	36	26
Total:	100	100	100

The Texas interviewees indicated that their agencies will occasionally omit crosswalks because of lack of pedestrian demand, a desire to avoid conflict with vehicles, or the existence of site-specific constraints that prevent the provision of crosswalks. For example, at three-leg intersections, it is common to provide only one crosswalk across the major street. This approach eliminates the conflict between pedestrians and vehicles turning left from the minor street. Crosswalks are also usually omitted in the inside of diamond interchanges. All agencies provide crosswalks that are compliant with Americans with Disabilities Act (ADA) requirements. They sometimes omit crosswalks if pedestrian signal heads are not present.

The Texas interviewees were asked how often they provide pedestrian signal heads for the "crossed" pedestrian movements for the various left-turn modes. The "crossed" pedestrian movement is the movement that potentially conflicts with left-turning vehicles during the green signal indication. The provision of pedestrian signal heads for these pedestrian movements indicates recognition of the potential conflict and a desire to provide basic pedestrian control. The responses indicate that about 74 percent of pedestrian movements that are crossed by protected-permissive left-turn movement are provided with pedestrian signal heads. About 62 percent of pedestrian movements that are crossed by permissive-only left-turn movements are provided with signal heads.

Description of Intersections with High Pedestrian Volumes

The interviewees indicated that 10 to 15 percent of their urban signalized intersections have high pedestrian volumes. The percentage was slightly higher for cities (15 percent) than for TxDOT districts (12 percent). The interviewees were asked to classify their intersections by providing the approximate number of intersections that are located around downtown areas or business districts, K-8 schools, high schools, universities, or other area types. The total count of intersections within these area type categories is shown in Table 3-3. For all area type categories, more high-pedestrian-volume signalized intersections are operated by cities than by TxDOT districts.

Table 3-3. Classification of High-Pedestrian-Volume Intersections.

Location of High-Pedestrian-Volume Intersections	Percentage of Intersections by Agency		
	City	TxDOT	Overall
Downtown, business area	474	66	540
K-8 school	236	24	260
High school	70	17	87
University	67	53	120
Other	93	57	150
Total:	940	217	1157

The bulk of the high-pedestrian-volume intersections are located within downtown areas or other business districts. A significant number also exist near K-8 schools. A total of about 150 intersections were located in area types that were described as “other.” These intersections included tourist areas, facilities that host special events, hike and bike trail crossings that occur at signalized intersections, hospitals, and assisted-living facilities.

The interviewees were asked which intersections are the most problematic in terms of conflicts between pedestrians and left-turning vehicles. Their responses varied widely, though they gave different reasons for each area type to be problematic. The area type categories are discussed in greater detail in the following paragraphs.

Business District. Six interviewees considered their downtown or business district intersections to be the most problematic for pedestrians and left-turning vehicles. They explained that left-turn movements in downtown areas are often operated in permissive-only mode. At times when pedestrian volumes are high, pedestrians tend to dominate the crosswalks, making it difficult for drivers to find safe gaps to execute left turns. This condition may cause drivers to attempt left turns using pedestrian gaps that are too narrow. Other issues include the presence of many distractions for drivers in downtown areas and the provision of light rail transit service.

School. Eleven interviewees considered intersections near schools to be the most problematic. Signalized intersections near schools tend to have safety and operational problems because they experience high volumes of both pedestrians and vehicles simultaneously. Another common problem is that pedestrians at school intersections often do not comply with the pedestrian control (i.e., they do not wait for the WALK indication) or they place too much trust in the pedestrian control (i.e., they cross as soon as they are given a WALK indication, without first checking for vehicles). These mistakes tend to be most prevalent among younger pedestrians, like students at K-8 schools.

Issues Affecting Pedestrian Safety

The Texas interviewees were asked to provide input on which intersection-related factors they think have the greatest influence on pedestrian safety at signalized intersections. Their responses are summarized in the following subsections.

Characteristics Affecting Pedestrian Safety

The Texas interviewees were asked whether various traffic and signalization characteristics had an influence on pedestrian safety. Some of the characteristics describe the intersection control, while others describe the users (vehicle traffic or pedestrians). For each characteristic, interviewees indicated (1) the amount of influence it has on safety and (2) the frequency it is considered as part of intersection design or operation. A numeric score was used to indicate the interviewee's response.

Pedestrian volume ranks highest in terms of both influence and discussion frequency. The Texas interviewees believe that approach speed, left-turn volume, and left-turn mode are relatively influential on pedestrian safety. In contrast, left-turn phase sequence and signal coordination were indicated to have little influence and are rarely discussed.

Use of Pedestrian Safety Treatments

The interviewees were asked if they had used various safety treatments. Most of the treatments considered are listed in the first column of Table 2-3 in Chapter 2. The following additional treatments were added to this list:

- Use permissive period omit with protected-permissive mode.
- Prohibit left turns.
- Add far-left supplemental signal head.
- Provision of conventional pedestrian heads.
- Provision of countdown pedestrian signal heads.

The interviewees were asked to indicate the percentage of their urban signalized intersections at which they have used these treatments specifically to improve pedestrian safety. Instances where the treatment was used for reasons other than pedestrian safety were not considered. For those treatments that they have used, the interviewees were asked how they would rate the effectiveness of the treatments in improving pedestrian safety. A numeric score was used to indicate the interviewee's response.

The two most commonly used treatments in Texas are (1) providing conventional pedestrian signal heads and (2) providing the pedestrian clear interval entirely during green. These two treatments are rated between "somewhat effective" and "very effective" in improving pedestrian safety.

Cities outside of Texas commonly use four treatments. Two of the four treatments are those identified in the previous paragraph. The other two commonly used treatments are (1) add far-left supplemental signal head and (2) provide countdown pedestrian signal head. The interviewees indicated that countdown heads are being used at more intersections each year.

Another common treatment is prohibiting a pedestrian crossing. According to the interviewees, crossings are often prohibited on one leg of three-leg intersections to avoid conflict with left-turning vehicles from the minor street, on the inside of diamond interchanges, or at sites that do not comply with ADA requirements. This treatment is rated between "somewhat effective" and "very effective" in improving pedestrian safety.

Criteria for Using Safety Treatments

The interviewees were asked whether they use criteria or rules-of-thumb to decide where to use pedestrian safety treatments. The most commonly mentioned consideration regarding the decision to use a pedestrian safety treatment is citizen feedback and observations made during field visits. Criteria commonly cited include some consideration of pedestrian volume or evidence of pedestrian demand (e.g., worn footpaths observed on the roadside), visibility and sight distance, ADA requirements, and presence of school facilities. Some agencies provide treatments near schools when requested by the school district. Some of the treatments are used simply as a matter of policy or current practice. For example, some cities or districts provide pedestrian signal heads at all new traffic signals.

Summary

Interviews with 27 practitioners were conducted regarding their agency's left-turn signalization and pedestrian control practices. According to information provided by the interviewees, about 75 percent of urban signalized left-turn movements are operated in protected-permissive or permissive-only modes, which result in potential conflicts between left-turning vehicles and pedestrians.

On average, the interviewees indicated that pedestrian volume is the most influential intersection characteristic on pedestrian safety. Most of the state's signals with high pedestrian volume are located in cities, specifically in urban areas or near schools. Other characteristics that influence pedestrian safety include approach speed, left-turn volume, and left-turn mode.

When asked about treatments used to improve pedestrian safety, the most frequently mentioned options included adding pedestrian signal heads (conventional or countdown), provision of the pedestrian clear interval entirely during green, and prohibiting crossings.

The interviewees explained that they do have guidance to select left-turn mode, but the guidance does not incorporate pedestrian considerations. The interviewees do not have comprehensive guidance on when to implement special pedestrian safety treatments, and often implement these treatments in response to citizen feedback.

EXPERT PANEL DISCUSSION

This part of the chapter documents an electronic discussion (e-discussion) that was conducted to assess pedestrian safety issues at urban signalized intersections. The e-discussion was conducted with an expert panel comprised of 12 state and city traffic engineering practitioners. The panel was provided with information about three signalized intersections where conflicts occurred between pedestrians and drivers executing permissive left-turn maneuvers. The purpose of the e-discussion was to obtain insight into the causes of the demonstrated conflicts, to assess their severity, and to identify treatments to reduce conflict frequency.

Background

The e-discussion was conducted using a survey website to minimize time demands on the participants. This approach was rationalized to result in greater participation in the expert panel discussion. It was also a convenient method for presenting visual materials to the panel members.

During the interviews that were in a previous part of this chapter, interviewees were asked if they would be willing to participate in an expert panel discussion. Those who indicated willingness to participate were invited to join the e-discussion. There were a total of 21 invitations sent out, and 12 people participated. The agencies represented by the participants are identified in Table 3-4.

Table 3-4. Public Agencies Represented in the Expert Panel Discussion.

Agency Representation	Agency Name	Number of Signalized Intersections
Texas city	Austin	900
	Waco	174
	San Antonio	1230
TxDOT district	Bryan	52
	Corpus Christi	160
	Waco	220
	Austin	300
	San Antonio	500
	Fort Worth	508
Agency outside of Texas	City of San Luis Obispo, California	57
	City of Cambridge, Massachusetts	134
	City of Los Angeles, California	4500

Website Content

The website that was used to host the e-discussion had seven pages. The first page included background information about the purpose and length of the e-discussion. On the second page, the participants were given a list of treatments that may be used to reduce conflicts between pedestrians and left-turning vehicles. On the next three pages, the participants were shown three different scenarios where conflicts occurred at signalized intersections. Each scenario consisted of site description information, video clips of a conflict event observed from two angles, and questions about the contributing factors to the demonstrated conflict and possible treatments. On the last two pages, the participants were asked to indicate which agency they represented, and then given a brief concluding statement thanking them for their participation.

On page 2 of the e-discussion website, a list of treatments was provided, along with a graphic image to illustrate each treatment. These images included signal heads that are used for the different left-turn modes, examples of signs, or drawings indicating the type of phasing used. The participants were given the list of treatments identified in Table 2-3 of Chapter 2.

Conflict event scenarios were shown on pages 3, 4, and 5 of the e-discussion. For each of the three scenarios, a conflict event was demonstrated using video clips. Each event was shown from the two viewing angles. One view was provided by a tripod-mounted camcorder located on the curb end of the subject crosswalk and pointed toward the crosswalk, along a line parallel to the crosswalk. The second view was provided by a pole-mounted camcorder located on the curb diagonally opposite from the subject crosswalk. It provided a side view of pedestrians using the subject crosswalk.

The expert panel members were also provided with plan-view drawings, street-level photographs, and information about the traffic volumes and signalization characteristics of the sites. This information was intended to help the expert panel members understand the nature of the problems so they could assess the contributing factors and identify treatments to alleviate the problems.

The expert panel members were asked the questions listed in Figure 3-3 after they reviewed the site description information and the video clips of the conflict event. The questions were repeated for each of the three scenarios.

Scenarios

The scenarios are described in greater detail in the following three sections. The expert panel members' responses to the questions about contributing factors and treatments are also provided. The members' responses to the questions about conflict occurrence frequency is discussed in an aggregated manner in the next section because of the high degree of variability in the responses.

Scenario 1

The intersection is located near a university campus, and experiences moderate pedestrian volumes and light left-turn volumes. The opposing intersection approach is a campus exit-only driveway that experiences light traffic volumes. The subject left-turn movement is operated in the permissive mode. Conventional pedestrian signal heads are provided, but pedestrian push buttons are not provided.

E-DISCUSSION QUESTIONS

Contributing Factors

1. Assume that events similar to the one shown in the video clip occur often at this site. What are the contributing factors to the problem? Choose up to three.
    a. Inadequate sight distance
    b. High vehicular volume
    c. High pedestrian volume
    d. Inadequate opportunity for drivers to make a permissive left turn (protected left-turn phase not provided or not long enough)
    e. Inadequate time for pedestrians to complete the crossing (walk and/or pedestrian clear intervals are too short for individual pedestrians, or more time is needed due to high pedestrian volume)
    f. Left-turn phase sequence violates pedestrians' expectations
    g. Aggressive driving
    h. Other (please specify—open-ended)

Treatments

2. You have been directed to implement one or more treatments to address this problem. Which of the following treatments would you use? Choose up to three.
    a. Change the left-turn mode to protected-permissive
    b. Change the left-turn mode to protected-permissive with the flashing yellow arrow display
    c. Change the left-turn mode to protected
    d. Make the protected left-turn phase lagging instead of leading
    e. Provide a leading pedestrian interval
    f. Provide an exclusive pedestrian phase
    g. Provide the pedestrian clear interval entirely during green (i.e., do not use the yellow change and red clearance intervals as part of the pedestrian clearance time)
    h. Add turning vehicle warning signs and markings
    i. Remove the crosswalk and prohibit crossing at this location
    j. Other (please specify—open-ended)

Conflict Occurrence Frequency

3. How often would events like the one in the video clip need to occur before you would deem it necessary to treat the site? Consider only daytime cycles when pedestrians are present.
    a. Occurs in 1% of cycles
    b. Occurs in 5% of cycles
    c. Occurs in 25% of cycles
    d. Occurs in ≥ 50% of cycles
    e. This problem is never important enough to require treatment

Figure 3-3. E-Discussion Questions.

The video clip shows that, as the pedestrians started to cross, a left-turning driver pulls into the intersection to wait for a safe gap in the pedestrian stream. The driver starts steering into the turn at a time that there are no opposing through vehicles present, but is delayed because a group of pedestrians start crossing after the start of the flashing DON'T WALK indication. While the left-turning driver moves very slowly through the vehicle-vehicle conflict area (see Figure 1-1), a slow-moving opposing through vehicle arrives and is forced to maneuver around the waiting left-turning vehicle.

Scenario 2

The intersection is located near a university campus. Both the pedestrian volume and the left-turn volume are high. The opposing intersection approach is a campus street that experiences light traffic volume. The subject left-turn movement is operated in protected-permissive mode with a leading sequence. Conventional pedestrian signal heads are provided, but pedestrian push buttons are not provided.

The video clip shows that a large number of pedestrians are present on both corners. Many of them start crossing prior to the start of the WALK indication, especially those originating from the near-side corner. Some pedestrians also start crossing after the start of the flashing DON'T WALK indication. As the pedestrian platoons from the near-side and far-side corners approach each other, several left-turning vehicles pass through the closing gap in pedestrians. The gap for the last vehicle is short enough that several approaching pedestrians slow while the vehicle passes.

Scenario 3

The intersection is located in a downtown grid area, with several restaurants, retail stores, and parking lots nearby. Both the pedestrian volume and the left-turn volume are low. The subject left-turn movement is operated in permissive mode. Conventional pedestrian signal heads are provided, but pedestrian push buttons are not provided.

The video clip shows that, as a single pedestrian is crossing, a fast-moving left-turning vehicle arrives. The left-turning driver apparently does not notice the pedestrian and has to stop abruptly to avoid hitting the pedestrian. The pedestrian stops walking when he sees the left-turning driver approaching.

Findings

The responses of the expert panel members were aggregated across the three scenarios presented in the e-discussion. Common themes emerging from the aggregated responses are summarized in the following paragraphs, along with their implications for guideline development.

Contributing Factors

The expert panel members' aggregated responses regarding contributing factors are shown in Figure 3-4. Overall, the most commonly identified contributing factors for conflicts between pedestrians and left-turning vehicles are: "aggressive driving," "high pedestrian volume," and "inadequate opportunity to turn." Turning opportunities decrease with increasing volumes of pedestrians or opposing through or right-turning vehicles. As turning opportunities become less frequent, aggressive driving behaviors on the part of left-turning drivers may increase. Hence, treatment selection guidelines that consider pedestrian and vehicular volumes are likely to account for the influence of the most commonly identified contributing factors.

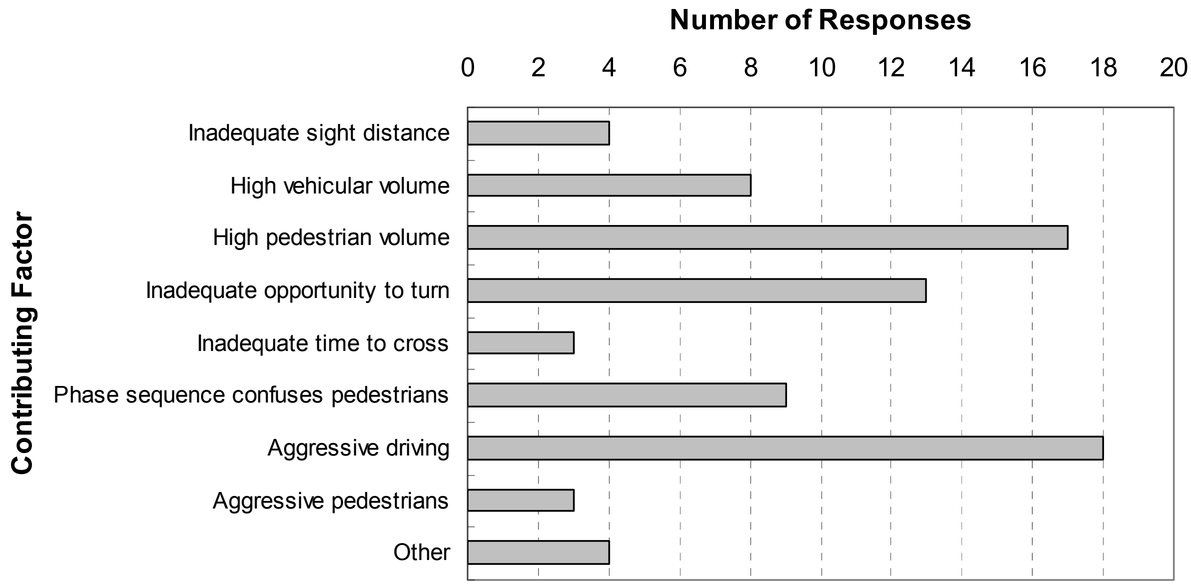


Figure 3-4. Factors Contributing to Conflicts.

One expert panel member stated that turning vehicle speed increases with intersection size, and opined that permissively turning drivers are less likely to stop for pedestrians if their speed is higher. Guidelines for selecting left-turn mode often account for the speed of opposing through vehicles. However, these guidelines do not directly account for turning vehicle speed. It is possible that these two speeds are correlated, as both are likely influenced by intersection geometry and area type.

Selected Treatments

The expert panel members' aggregated responses regarding treatments are shown in Figure 3-5. The four most commonly identified treatments include: "provide a protected left-turn phase," "provide a leading pedestrian interval," "provide an exclusive pedestrian phase," and "add turning vehicle signs and markings." These treatments are discussed in Chapter 2.

One expert panel member observed that the subject left-turn movements depicted in the scenarios lacked turn bays. This member suggested restriping the intersection approach at one of the scenario intersections to provide a turn bay. He opined that left-turning drivers in shared left/through lanes are more likely to turn hastily because they think they are more likely to be rear-ended. Left-turning drivers in shared left-and-through lanes may also feel greater pressure to turn if they see a long queue forming behind them. Hence, it may be desirable to add "provide exclusive left-turn bay" to the list of treatments for alleviating conflicts between pedestrians and left-turning vehicles. This treatment would apply for cases when the permissive mode is retained.

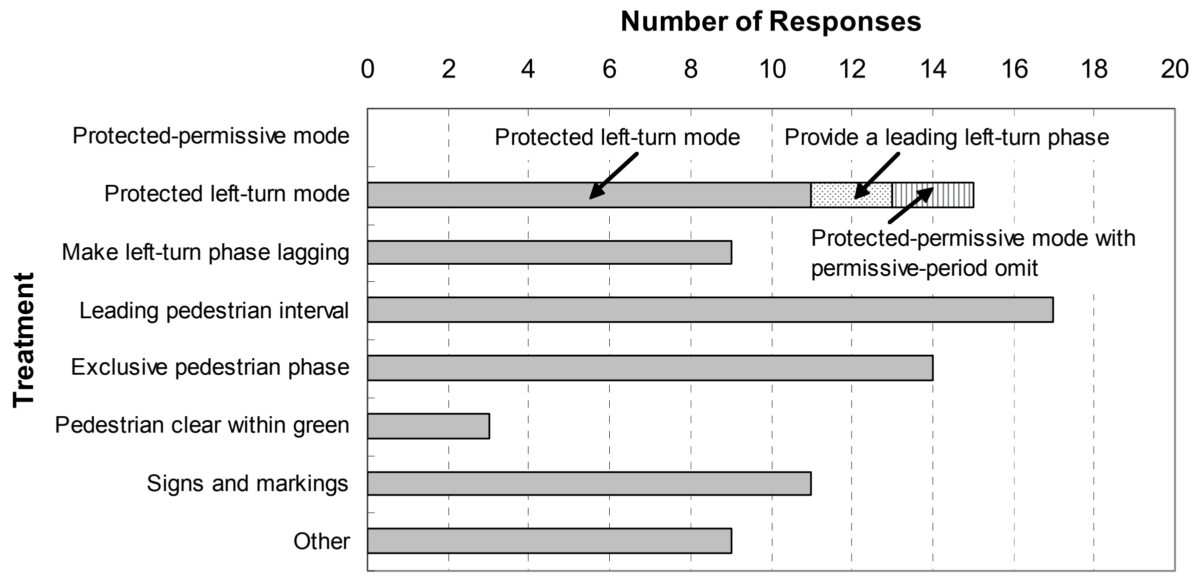


Figure 3-5. Rank of Selected Treatments.

Another expert panel member opined that a permissive left-turn period should never be allowed to run concurrently with pedestrian service if the street being crossed is six or more lanes in width. This member expressed support for adding curb extensions and reducing lane counts on the street being crossed to reduce crossing distances. He also generally favored eliminating conflicts between pedestrians and left-turning vehicles by providing either protected left-turn mode or exclusive pedestrian phases.

Two treatments that were not commonly supported by the expert panel members include providing protected-permissive mode and providing the pedestrian clear interval entirely during green. The expert panel members apparently did not see these treatments as being effective in reducing conflicts between pedestrians and left-turning vehicles.

Conflict Occurrence Frequency

For each of the three scenarios, the expert panel members were asked to indicate how often the demonstrated conflict would need to occur before they would consider the problem significant enough to justify treatment. They were asked to consider only daytime cycles with pedestrians present. In other words, cycles occurring during periods of negligible pedestrian demand (e.g., nighttime cycles) were not considered. The choices allowed are listed at the bottom of Figure 3-3.

The expert panel members' responses varied significantly for each specific scenario. However, when the responses were aggregated across the three scenarios, a useful threshold emerged. To compute this threshold, the five discrete choices listed at the bottom of Figure 3-3 were regarded as ranked intervals indicating the probability of conflict occurrence. The width of an interval was based on splitting the difference between the percentages of each adjacent choice. The expert panel members' responses were counted for each choice and scenario. Then, the average threshold conflict frequency was computed for each scenario using Equation 2. These thresholds represent the frequency at which the scenario's conflict would need to occur (in terms of percent of signal cycles) before the average expert panel member would deem it necessary to treat the site.

$$T_j = \frac{\sum c_{i,j}\, w_j}{\sum c_{i,j}} \quad \textbf{(2)}$$

where,

T_j = threshold conflict frequency for scenario j (j = 1, 2, 3), percent of cycles.
$c_{i,j}$ = response count for scenario j and interval i (i = 1, 2,..., 5).
w = probability interval width, percent.

Equation 2 was used to compute the averages shown in the last row of Table 3-5. The threshold conflict frequencies are 25, 20, and 25 percent of cycles, respectively, for the conflicts shown in scenarios 1, 2, and 3. The consistency of this percentage among scenarios suggests that treatments should generally be considered for a site if conflicts between pedestrians and left-turning vehicles can be observed in 25 percent or more of the signal cycles.

Table 3-5. Conflict Occurrence Response Analysis.

Interval (i)	Description	Interval Width (w), %	Response Count by Scenario (c)		
			Scenario 1	Scenario 2	Scenario 3
1	Occurs in 1% of cycles	3.0	4	3	2
2	Occurs in 5% of cycles	12.0	1	5	5
3	Occurs in 25% of cycles	23.0	4	2	1
4	Occurs in ≥ 50% of cycles	63.0	3	2	3
5	Never important	0.0	0	0	1
Average Threshold Conflict Frequency (T), %:			25	20	25

Summary

In addition to the exposure variables of pedestrian and vehicular volumes, the expert panel responses suggest that turning vehicle speed may be an appropriate consideration when selecting left-turn mode. Based on the expert panel responses shown in Figure 3-5, the provision of a protected-permissive left-turn mode and the provision of the pedestrian clear interval entirely during green do not appear to be highly regarded options to reduce conflicts between pedestrians and left-turning vehicles. The expert panel responses suggest that treatments should be considered if conflicts between pedestrians and left-turning vehicles occur in 25 percent or more of signal cycles.

CHAPTER 4. MODEL DEVELOPMENT AND DATA COLLECTION

OVERVIEW

This chapter describes the development of a data collection plan. The data elements to be collected were identified through the examination of models used to represent pedestrian and vehicle behavior. There are two components of the data collection plan. One component is focused on the plan for collecting vehicle operations data. The data collected will be used to quantify the effect of alternative pedestrian-safety-related treatments on vehicle operations. The second component is focused on the plan for collecting pedestrian safety data. The data collected will be used to quantify the effect of alternative pedestrian-safety-related treatments on pedestrian safety.

This chapter consists of two parts. The first part describes the operations model and data collection plan. The second part describes the safety model and data collection plan.

OPERATIONS MODEL AND DATA COLLECTION PLAN

This part of the chapter describes the steps taken to develop a data collection plan to quantify the effect of alternative pedestrian-safety-related treatments on vehicle operations at signalized intersections. A simulation model is used to obtain the data. The first section summarizes the rationale for selecting a specific simulation model. The second section describes the elements of the data collection plan.

Evaluation of Alternative Simulation Models

This section summarizes the findings from an evaluation of two candidate simulation tools. The evaluation separately considered each tool's ability to quantify the effect of pedestrian treatments on vehicular performance. The features and capabilities discussed in this section are referenced to the specific versions of the tools evaluated (i.e., VISSIM 5.10 and Synchro 6.0). These findings may not be applicable to newer versions of these tools.

Pedestrian Models

There are two levels of pedestrian modeling in VISSIM. The first level is a standard pedestrian model which treats pedestrians as one type of vehicle. In the standard model, VISSIM allows users to create their own "pedestrian" vehicles. Users can modify the pedestrian vehicles' characteristics to replicate pedestrian attributes. These characteristics include pedestrian volume, walking speed, critical gap, and "pedestrian" car-following logic. The "pedestrian" car-following logic allows pedestrians to follow each other with much less restriction than vehicular traffic.

The second level is an advanced implementation of pedestrian modeling in VISSIM where the movement of pedestrians is based on the Social Force Model (SFM). Under SFM, pedestrians are able to move in all directions (including counter-flow situations), and the trips are based on designated origin-destination patterns. The main advantage of the SFM is the ability to model interactions among pedestrians. While the SFM module is much more realistic than the standard pedestrian level model, it is not a standard add-on in the VISSIM version used. Based on this examination, the standard pedestrian model was rationalized to be appropriate for the evaluation of the pedestrian safety treatments identified in Chapter 2.

Synchro does not explicitly treat pedestrians as separate objects. Pedestrian characteristics that are provided as input to the models include: pedestrian calls per hour and pedestrian crosswalk volume. The former input represents the number of pedestrian push button calls for the phase. The latter input represents the number of pedestrians per hour that conflict with the right-turn movement during permitted operation.

Pedestrian-Vehicle Interactions

VISSIM provides two alternative methods for modeling pedestrian-vehicle interactions. They are the "priority-rules method" and the "conflict-area method." Both methods have unique advantages. With the priority-rules method, priority rules are used to define the right of way for non-signal-protected conflicting movements. Vehicles and pedestrians recognize the presence of each other, even if they are on different links or connectors.

The conflict-area method is based on a defined conflict area at the intersection of two links. For each conflict area, the user can select which of the conflicting links has right of way (if any). As they approach a conflict area, drivers and pedestrians plan how to cross the conflict area. A yielding driver (or pedestrian) observes the approaching vehicles (or pedestrians) in the main stream and identifies an acceptable gap. Then, the driver (or pedestrian) plans an acceleration profile for the next few seconds that will allow him or her to cross the conflict area.

Realistic representation of pedestrian-vehicle interactions is more critical to the evaluation of pedestrian treatments because it will influence the accuracy to which VISSIM can estimate the effect of pedestrians and various treatments on vehicle performance. The most appropriate method may depend on the treatment being evaluated.

In Synchro, pedestrian-vehicle interactions are incorporated into the calculation of saturation flow rate for the conflicting vehicle traffic stream. It is based on the model used in the 2000 *Highway Capacity Manual* (*1*), which is discussed in Chapter 2.

Modeling Pedestrian Treatments

Table 4-1 summarizes the options for modeling pedestrian treatments with VISSIM and Synchro. Both simulation tools are shown to possess the features required for evaluating pedestrian treatments.

Table 4-1. Comparison of Simulation Tool Capabilities.

Treatment	VISSIM	Synchro
Treatments Based on Conversion from Permissive Mode		
Provide protected-permissive mode	Yes	Yes
Provide protected-permissive mode using flashing yellow signal display	Right-of-way rules must be defined	Yes
Provide protected left-turn mode	Yes	Yes
Provide lagging phase sequence	Yes	Yes
Treatments Used in Conjunction with Permissive Mode		
Provide leading pedestrian interval	No, for ring-based control	No
Provide exclusive pedestrian phase	Yes	Yes
Provide pedestrian clear interval entirely during green	Yes	Yes
Add turning vehicle warning signs and markings	not applicable	not applicable
Prohibit pedestrian crossing	Yes	Yes

Measures of Effectiveness

Both VISSIM and Synchro are capable of reporting operational performance measures such as vehicle delay, queue length, and stop rate. However, VISSIM features data collection points that can be strategically placed in the network to log event-based data. These event data can be post-processed to extract useful surrogate safety measures. This capability gives VISSIM a major advantage over Synchro because it can be used to evaluate both vehicle performance and pedestrian safety.

Summary

Both software tools were found to be capable of modeling pedestrian treatments that involve changing the left-turn operational mode and phase sequence. However, VISSIM uses more sophisticated pedestrian models, and it is slightly more capable at modeling some complex pedestrian safety treatments. Therefore, VISSIM was determined to be the more viable option relative to the objectives of the research.

Data Collection Plan

The operations data collection plan was designed to produce data that could be used to quantify the effect of alternative pedestrian-safety-related treatments on vehicle operations. Specifically, these data would be used to develop a quantitative method for predicting the change in intersection delay due to the implementation of a single or a combination of pedestrian treatments. Intersection delay is defined as the weighted average delay of all vehicular traffic movements at the intersection. The weight used in computing this average is the vehicular volume for the corresponding movement. Pedestrian delay was not considered in this analysis.

This section describes the data collection plan based on the use of VISSIM. The plan consisted of three tasks. The first task was the development of test bed intersections for simulation analysis. The second task was the development of modeling techniques for VISSIM so that each candidate pedestrian safety treatment could be accurately evaluated. The third task was the development of simulation run control criteria to guide the assembly of the simulation data. Each of these tasks is discussed in one of the following three subsections.

Test Bed Intersections and Baseline Conditions

The simulation modeling approach required the development of six test bed intersections, each with specified baseline conditions. Collectively, the test beds and baseline conditions are intended to represent typical isolated, fully actuated intersections in Texas.

Table 4-2 and Table 4-3 summarize the baseline conditions. These conditions represent a range of typical intersection geometry, signal control, and traffic conditions. Table 4-2 indicates that six test bed intersections were developed to collectively represent a range of approach legs (i.e., 3 or 4) and approach through lanes (i.e., 2, 3, or 4). The test bed intersection is fully actuated with stop-line detection on all approaches.

Table 4-2. Test Bed Geometric and Signalization Characteristics.

Characteristics	Comments
Geometry ● Intersection legs: 3 and 4 ● Major street lanes: 2, 4, or 6 (total both directions) ● Minor street lanes: 1(each direction) ● Left-turn bay length: 250 ft or longer to prevent bay overflow ● No exclusive right-turn lane.	● Six different test beds were required to capture the proposed variation in intersection legs and lanes.
Signalization ● Left-turn mode on major street: permissive ● Left-turn mode on minor street: permissive ● Phase sequence on major street: lead-lead ● Phase sequence on minor street: lead-lead ● Detection: 40-ft stop line loops, presence mode ● Max. green for through phases: 50 s ● Max. green for left-turn phases: 25 s ● Min. green through phases: 10 s ● Min. green for left-turn phases: 5 s ● Yellow (Y): 3.0 s ● Red clearance (Rc): 2.0 s ● Passage time: 2.0 s ● Min. recall: major through phases ● Walk: 7.0 s ● Ped. clear interval: crossing distance/3.5 $-(Y+Rc)$ ● Ped. detectors and signal heads for all crosswalks ● Right turn on red: allowed on all approaches ● Leading pedestrian interval: no ● Exclusive pedestrian phase: no	● The baseline signalization characteristics were the same for all test beds. ● The calculation for pedestrian clear is based on average pedestrian speed recommended in MUTCD 2009. ● Pedestrians were modeled to the extent that they press the button and cross in the crosswalk at the intersection. ● Left-turn phases were not used under baseline conditions where all left turns are permissive-only mode.

Table 4-3. Test Bed Traffic Characteristics.

Characteristics	Comments
<u>Traffic Characteristics</u> ● Major approach volume (veh/h/ln): 400, 600, and 800 ● Minor approach volume: 30% and 50% of major approach volume ● Turn percentages for four-leg intersection: ○ Left turn: 10% ○ Right turn: 10% ● Turn percentages for three-leg intersection: ○ Left-turn from minor approach: 45% ○ Right-turn from minor approach: 55% ○ Left-turn from major approach: 10% ○ Right-turn from major approach: 10% ● 2-way pedestrian crosswalk volume (p/h/crosswalk): 0, 100, and 400 ● Average pedestrian speed: 3.5 ft/s ● Approach speed: 35 mi/h ● Left- and right-turn speeds: 15 mi/h ● Percent trucks: 0%	● The delay difference between non-zero and zero-pedestrian scenarios determines the amount of delay incurred by pedestrians. ● The saturation flow rate is a result of a combination of parameters specified in the car-following models and cannot be explicitly defined in VISSIM. ● Standard pedestrian feature in VISSIM does not allow bidirectional movements for the link. Therefore, the 2-way pedestrian volumes are coded as two separate directional links with the 2-way volume split in half for each direction.
<u>Yielding Characteristics</u> ● Front and rear gaps for permissive lefts and opposing through: 0.5 s ● Front and rear gaps for permissive lefts and pedestrians: 0.5 s ● Front and rear gaps for permissive rights and pedestrians: 0.5 s	● Conflict zones in VISSIM were used to model vehicle and pedestrian interactions. ● Front Gap: Minimum gap in seconds between the rear end of a vehicle/pedestrian on the priority movement and the front end of a vehicle on the yielding movement. ● Rear Gap: Minimum gap in seconds between the rear end of a vehicle on the yielding movement and the front end of a vehicle/pedestrian on the priority movement.

Table 4-3 indicates that there are three levels of major approach volume, two levels of minor approach volume, and three levels of pedestrian volume. These variations produce 18 unique levels of traffic and pedestrian volume.

The full factorial design represents a total of 108 unique combinations (= 6 test beds × 18 volume levels) for simulation analysis. The 108 combinations described in this section represent the "base" conditions. These conditions were established to provide a basis for estimating the effect of each pedestrian treatment identified in Table 2-3 of Chapter 2.

Pedestrian Treatments

Each pedestrian treatment listed in Table 2-3 of Chapter 2 was simulated in VISSIM by modifying the base conditions. Table 4-4 describes these modifications as well as the changes made to the test beds for each treatment. All of the pedestrian treatments were implemented using VISSIM's ring-barrier control mode, which is very similar to the dual-ring signal control logic used in U.S. controllers.

Table 4-4. Test Bed Modifications for Each Pedestrian Treatment.

Treatment	Modifications	Changes to VISSIM Test Beds
Treatments Based on Conversion from Permissive Mode		
1. Provide protected-permissive mode	• Left-turn mode on major street: protected-permissive • Left-turn mode on minor street: protected-permissive	• Adding left-turn phases in the controller. • Map the left-turn detector to the corresponding left-turn phase. • Permissive (circular) green for left turns is driven by the concurrent through phase.
2. Provide protected-permissive mode using flashing yellow (FY) signal display	• Left-turn mode on major street: protected-permissive (FY operation) • Left-turn mode on minor street: protected-permissive (FY operation)	• Same as treatment 1 but permissive (circular) green for left turns is driven by an overlap of opposing through and left.
3. Provide protected left-turn mode	• Left-turn mode on major street: protected-only • Left-turn mode on minor street: protected-only	• Same as treatment 1 but no permissive green indication is provided.
4. Provide lagging phase sequence	• Phase sequence on major street: lag-lag • Phase sequence on minor street: lag-lag • Left-turn mode on major street: lag-lag • Left-turn mode on minor street: lag-lag	• Apply the changes as in treatment 1 and then modify the phase sequence in the controller from lead-lead to lag-lag. • The effect of this treatment will be a combination of treatments 1 and 4.
Treatments Used in Conjunction with Permissive Mode		
5. Provide leading pedestrian interval (LPI)	• Leading pedestrian interval: 3 s for all crosswalks.	• LPI is not directly implemented in the VISSIM ring-barrier controller. • To simulate LPI, the through phase is defined to have a delayed green overlap driven by its own phase. The standard through phases (2, 4, 6, 8) will drive both the pedestrian heads and the delayed green overlap. As a result, the green for each through phase will be delayed by the specified LPI.
6. Provide exclusive pedestrian phase	• Add exclusive pedestrian phase. • Prohibit RTOR on all approaches. • Pedestrian clear on all crossings: crossing distance divided by 3.5 ft/s • All red: 0 s	• Remove pedestrian phases from concurrent vehicle phases. • Remove RTOR on all approaches. • Add exclusive pedestrian phase after the barrier of the major street phases. • Invoke the scramble phase option in the controller. • Use walk interval of 7 s.
7. Provide pedestrian clear interval entirely during green	• Pedestrian clear on all crossings: crossing distance divided by 3.5 ft/s	• Update the pedestrian clear setting in the controller.
8. Add turning vehicle warning signs and markings	not applicable	not applicable
9. Prohibit pedestrian crossing	not applicable	not applicable

Simulation Approach

Run Control. A total of 864 simulation runs were completed. This total represented 108 runs to define the performance of the base conditions and an additional 756 runs (= 7 treatments x 108 combinations) to define the performance of the treatments. One replication was used for each combination. Each simulation run consisted of a 5-minute warm-up period and then a 60-minute data collection period.

The results from each set of 108 simulation runs for a treatment were paired with the corresponding 108 runs for the base conditions. A one-to-one pairing of the performance estimates for each combination was used to determine the effect of the treatment. This approach allowed the researchers to quantify the effect of a treatment on delay, in isolation of the effect of other changes or treatments.

Intersection Delay. The delay measurement obtained from VISSIM is equivalent to control delay. It is computed as the difference between the actual travel time and the ideal travel time. The ideal travel time represents the travel time when there are no other vehicles present, and control devices have no influence on vehicle speed. Intersection delay is a volume-weighted average control delay for the intersection, where the delay to each intersection movement is weighted by its volume.

In VISSIM, delay is based on one or more "travel time sections." Delay is measured for all vehicles that pass through these travel time sections, independently of the vehicle classes selected in these travel time sections.

To collect intersection delay in VISSIM, 12 travel time sections (three movements per leg) were placed in the test bed for the four-leg intersections while six sections (two movements per leg) were used in the case of three-leg intersections. Each travel time section logs the average vehicle travel time and the number of vehicles traversing the section. The delay for the segment was calculated based on individual or a group of travel time sections.

A post-processing tool was developed to help with extracting and reducing the simulated travel time data. This tool was designed to extract travel time and other key data elements from the simulation output files. It was also designed to perform any necessary calculations. The results from the simulation runs were reported in a spreadsheet with the output for each run placed in one row of the spreadsheet.

Issues That Prevented Use of Some Combinations. VISSIM does not directly model the leading pedestrian interval (LPI) operation. In modern controllers, pedestrian signal heads are actuated, and LPI is activated only when there are pedestrian calls. However, in VISSIM ring-barrier control, LPI is active every phase, regardless of whether a pedestrian is present. This limitation was overcome by not simulating the cases of zero pedestrian volume with the LPI treatment.

The results from a series of initial simulation runs indicated that the permissive-only mode used in several of the treatments was unable to accommodate heavy left-turn volumes, particularly in combinations that included 800 veh/h/ln and six lanes on the major street. This caused the queued vehicles in the left-turn bay to grow indefinitely with the simulation time (i.e., an unsteady state). Such cases were identified and excluded from subsequent analyses.

SAFETY MODEL AND DATA COLLECTION PLAN

This part of the chapter describes the steps taken to develop a data collection plan to support the development of a pedestrian-vehicle conflict prediction model. This model would be applicable to conflicts at signalized intersections. It would be used to evaluate the safety benefits of alternative pedestrian treatments. The data are collected during field studies at several intersections. The first section describes the development of predictive models to guide the formulation of the data collection plan. The second section describes the elements of the data collection plan.

Model Development

Two models are described in this section. One model predicts the frequency of pedestrian-vehicle conflicts based on the legal pedestrian volume. The second model predicts the legal pedestrian volume based on the total pedestrian volume. One variable that was included in the second model is pedestrian delay. Thus, this section also describes a model for predicting pedestrian delay.

Pedestrian Delay

Pedestrians crossing the street at a signalized intersection can experience delay due to the signal operation. If this delay is excessive, some pedestrians may choose to cross illegally (i.e., jaywalk). The average pedestrian delay is computed using Equation 3. This equation is obtained from Chapter 18 - Pedestrians of the *Highway Capacity Manual* (*1*).

$$d_p = \frac{(C - g_{ped})^2}{2\ C} \quad \textbf{(3)}$$

where,

d_p = pedestrian delay due to signal, s/p.
C = cycle length, s.
g_{ped} = pedestrian service time (= *Walk* + 4.0), s.
Walk = walk interval duration, s.

Pedestrian-Vehicle Conflict Model

The model for predicting conflicts between legally crossing pedestrians and left-turn vehicles is shown as Equation 4. A similar model form is used for conflicts between left-turn vehicles and pedestrians crossing illegally.

$$N_{co,L} = (v_{lt})^{b_1}\ (v_{ped,L})^{b_2}\ e^{\sum b_i X_i} \quad \textbf{(4)}$$

where,

$N_{co,L}$ = frequency of pedestrian-vehicle conflicts involving legal pedestrians, conflicts/h.
v_{lt} = conflicting left-turn volume, veh/h.

$v_{ped,L}$ = legal pedestrian volume in the crosswalk (walking in either direction), p/h.
X_i = independent variable i.
b_i = calibration coefficients, i = 0, 1, 2,....

The first two terms in parentheses represent the left-turn volume term and the pedestrian volume term, respectively. Their product represents the combined exposure to pedestrian-vehicle conflict. The legal pedestrian volume represents the count of legal pedestrians divided by the count period duration. The third term in the equation represents the risk of conflict, given this exposure.

The independent variables X_i in the third term represent any variables that are found during model calibration to have some influence on the risk of conflict. Example variables include crosswalk length, vehicle travel time to conflict area, phase sequence, left-turn mode, cycle length, pedestrian delay, portion of the yellow interval used for pedestrian clearance, and queue clearance time for the opposing through movement.

Legal Pedestrian Volume Model

The preceding section described a model that is based on the legal pedestrian volume. A model for estimating this volume is described in Equation 5.

$$v_{ped,L} = v_{ped,t} \, (p_p)^{c_3} \left(\frac{e^{\sum c_i X_i}}{1 + e^{\sum c_i X_i}} \right) \tag{5}$$

with

$$p_p = 1 - e^{(-v_{ped,t}/3600) \, P_b \, C} \tag{6}$$

where,

$v_{ped,L}$ = legal pedestrian volume in the crosswalk (walking in either direction), p/h.
$v_{ped,t}$ = pedestrian volume in the crosswalk (walking in either direction), p/h.
p_p = probability that the WALK indication is presented (= 1.0 if pretimed or on ped. recall).
P_b = probability of a pedestrian pressing the detector button.
C = cycle length, s.
c_i = calibration coefficients, i = 0, 1, 2,....

The first term in Equation 5 represents total pedestrian volume for the crosswalk during the analysis period. It is considered to be an exposure term for this model.

The second term represents the probability that the WALK indication is presented. It is also considered to be an exposure term for this model. This probability is 1.0 if the signal operates under pretimed control or the phase is set for pedestrian recall. Equation 6 is used to compute this probability for pedestrian actuated operation. The probability of a single pedestrian pressing the detector button reflects the tendency of some pedestrians not to use the detector button before crossing a street. Research indicates that about 51 percent of crossing pedestrians will push the button to place a call for pedestrian service (*2*).

The third term represents the probability that a pedestrian using the crosswalk is "legal," as defined in Chapter 1, given that the phase was called. It is a logistic regression model, similar to that used by Hubbard et al. (*3*) to estimate the probability of conflict.

The independent variables X_i in the third term represent any variables that are found to have some influence on pedestrian compliance with the signal. Example variables include crosswalk length, median presence, average pedestrian age, pedestrian delay, conflicting vehicle flow rate, and type of pedestrian signal display (i.e., symbol or countdown). The variable for pedestrian delay was considered because it is rationalized that the probability of a legal crossing will decrease with an increase in delay due to the signal.

Data Collection Plan

This section describes the data collection plan. It consists of three subsections. The first subsection identifies the variables collected. The second subsection identifies the study sites. The third subsection describes the data collection procedures followed during each field study.

Database Elements

The data collected during this study were used to calibrate the models described in the previous section. Table 4-5 lists the types of data that were needed for model calibration. The characteristics and conflict measures listed were counted each cycle and summarized for each 15-min count period. The cycle length was measured each cycle and similarly summarized. The other variables listed were quantified during a site survey conducted prior to the start of the study period.

Table 4-5. Variables in Conflict Database.

Category	Variable
Vehicle characteristics	• Count of left-turn vehicles crossing subject crosswalk • Count of left-turn vehicles crossing subject crosswalk during opposing through green interval • Count of through and right-turn vehicles opposing subject left-turn movement • Count of vehicles crossing crosswalk during steady DON'T WALK indication
Pedestrian characteristics	• Count of pedestrians in subject crosswalk (walking in either direction) by age group[1] • Count of pedestrians that enter crosswalk (or attempted to enter it) during the WALK indication by age group[1] • Count of pedestrians that enter the crosswalk during the flashing or steady DON'T WALK indication
Intersection geometry	• Length of subject crosswalk (curb face to curb face) • Width of subject crosswalk (center of marking to center of marking) • Number of lanes serving subject left-turn movement • Number of receiving lanes for subject left-turn movement • Number of opposing through lanes • Skew angle • Distance from left-turn stop line to representative crosswalk conflict point • Presence of a median and its width
Signalization	• Cycle length • Walk interval duration for subject crosswalk • Pedestrian clear interval duration for subject crosswalk • Left-turn mode (permissive or protected-permissive) • Phase sequence (permissive, leading, lagging, split) • Use of a leading or lagging pedestrian interval • Allowance of right-turn-on-red • Control type (pretimed, full-actuated, semi-actuated, coordinated-actuated)
Traffic control devices	• Speed limit of traffic crossing subject crosswalk • Presence of count-down pedestrian display
Conflict measures	• Count of legal pedestrian-vehicle conflicts in conflict area of subject crosswalk • Count of illegal pedestrian-vehicle conflicts in conflict area of subject crosswalk

Note:
1 - Age groups: Child (less than 12 years), Teen (12 - 17), Young (17-25), Adult (25-60), Senior (60 or more).

Study Sites

At total of 20 study sites were chosen from among those available in the cities of College Station and Austin. A "site" is defined to be one crosswalk. Each site is associated with one left-turning movement. This is the movement that crosses the crosswalk as it exits the intersection. The College Station sites are located close to the Texas A&M University campus. The Austin sites were chosen from the downtown city grid and the area surrounding the University of Texas campus. The sites are identified in Table 4-6. A more detailed description of these sites is provided in Appendix A. Collectively, these sites represent a range of vehicular and pedestrian volumes.

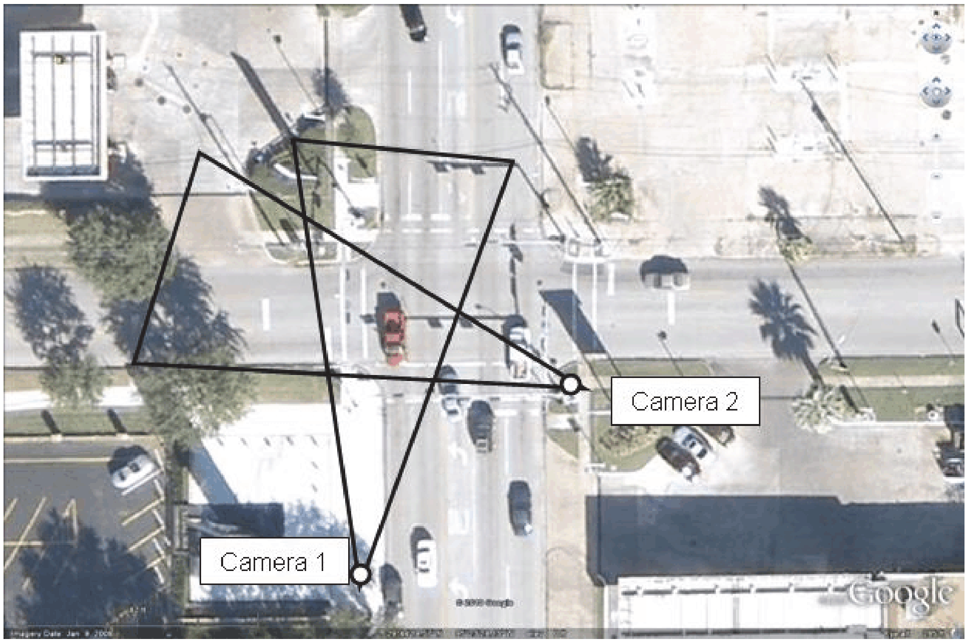
Table 4-6. Study Site Description.

City	Intersecting Street by Direction		Subject Left-Turn Movement	Phase Sequence	Left-Turn Volume, veh/h	Pedestrian Volume, p/h
	North-South	East-West				
Austin	Congress Ave.	4th Street	Northbound	Perm. only	25	179
			Eastbound	Perm. only	21	84
			Southbound	Perm. only	15	109
			Westbound	Perm. only	74	53
	Congress Ave.	5th Street	Eastbound	Perm. only	78	84
	Congress Ave.	6th Street	Northbound	Lagging	196	123
			Westbound	Perm. only	165	253
	Congress Ave.	7th Street	Southbound	Lagging	64	113
	Guadalupe St.	21st Street	Eastbound	Perm. only	18	198
			Westbound	Perm. only	50	234
	Guadalupe St.	22st Street	Eastbound	Perm. only	12	162
	Guadalupe St.	24st Street	Eastbound	Leading	214	232
	Guadalupe St.	Dean Keeton St.	Southbound	Leading	202	96
	Guadalupe St.	27st Street	Westbound	Perm. only	55	60
	San Jacinto Blvd.	Dean Keeton St.	Northbound	Perm. only	62	30
			Southbound	Perm. only	146	45
	Medical Arts St./ Robert Dedman Dr.	Dean Keeton St.	Northbound	Perm. only	103	43
			Southbound	Perm. only	42	21
College Station	Spence Street	University Drive	Northbound	Perm. only	33	155
			Southbound	Perm. only	49	357

Data Collection Procedure

The data collection at each site consisted of a site survey followed by a video recording of vehicle and pedestrian activity. The recordings took place during the two-hour period that spans the peak hour of pedestrian demand at the site. Data were not collected during rain events.

Pedestrian-vehicle conflicts were recorded by video camera during each field study. Two video cameras were used at each site to ensure full coverage of the intersection. Figure 4-1 illustrates a typical two-camera setup for evaluating the northbound left-turn movement and associated conflict area. One camera was located in line with the subject crosswalk. This camera monitored the pedestrian signal head, left-turn signal head, and crosswalk area. The second video camera was used to monitor the left-turn stop line, left-turn vehicle travel path, vehicle brake lights, and crosswalk. Together, the two cameras were able to provide three-dimensional coverage of pedestrian activity in the conflict area.



a. Plan View of Video Camera Locations.

b. Camera 1 Location.

c. Camera 2 Location.

Figure 4-1. Video Camera Locations.

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CHAPTER 5. DATA REDUCTION AND SUMMARY

OVERVIEW

This chapter describes the data reduction process and summarizes the data collected. There are two databases assembled for this project. One database describes the effect of alternative pedestrian-safety-related treatments on vehicle operations. The second database describes the effect of alternative pedestrian-safety-related treatments on pedestrian safety.

This chapter consists of two parts. The first part describes the operations data that were obtained from a simulation tool. The second part describes the safety data that were collected at several intersections in Texas.

OPERATIONS DATA

This part of the chapter describes the findings from an evaluation of seven pedestrian treatments using traffic simulation. These treatments were identified in Table 4-4 of Chapter 4. The evaluation quantified the operational impact of each treatment in terms of the resulting change in intersection delay. The impacts were used to develop predictive models for estimating the change in delay due to the treatment and other factors. These models are described in Chapter 6.

Delay Summary by Treatment

Table 5-1 summarizes the intersection delay statistics for each treatment. As noted in Chapter 4, the results from a series of initial simulation runs indicated that the permissive-only mode used in several of the treatments was unable to accommodate heavy left-turn volumes. This caused the queued vehicles in the left-turn bay to grow indefinitely with the simulation time (i.e., an unsteady state). Such cases were identified and excluded from subsequent analyses.

The use of leading pedestrian interval also presented some issues and required the elimination of combinations that had zero pedestrian volume. The run combinations excluded were:

- Those combinations where the queue grows indefinitely with the simulation due to the use of the permissive left-turn mode with high through volume.
- Those combinations with leading pedestrian interval treatment and zero pedestrian volume.

Columns 2, 3, and 4 in Table 5-1 list the simulation results before the aforementioned combinations were removed. Columns 5, 6, and 7 list the results after the invalid combinations were removed. A comparison of these columns shows that the average and standard deviation of the delay data are significantly lower when the invalid combinations are excluded. The effects of invalid delay data are more pronounced in the base case, leading pedestrian interval, exclusive pedestrian phase, and pedestrian clear treatments. When these invalid cases are excluded, the mean delay values range from 18 to 26 s/veh for all the treatments evaluated.

Table 5-1. Summary of Intersection Delay Statistics by Treatment.

Treatment Description	All Delay Data [1]			Selected Delay Data [1]		
	Average, s/veh	Standard Deviation, s/veh	Obser-vations	Average, s/veh	Standard Deviation, s/veh	Obser-vations
Base condition	28.1	32.7	108	18.0	7.1	98
Provide protected-permissive mode	23.1	10.0	108	23.1	10.0	108
Provide protected-permissive mode using flashing yellow signal display	23.0	10.3	108	23.0	10.3	108
Provide protected left-turn mode	28.3	14.9	108	26.0	9.1	104
Provide lagging phase sequence	22.0	7.5	108	22.0	7.5	108
Provide leading pedestrian interval	33.4	35.6	108	23.6	8.9	63
Provide exclusive pedestrian phase	47.7	50.9	108	24.2	10.7	86
Provide pedestrian clear interval entirely during green	31.4	33.1	108	20.8	10.0	96

Note:
1 - Only the delay data from valid simulation cases were retained for subsequent analysis.

Change in Intersection Delay

The percent change in intersection delay due to a treatment was used as the basis for treatment evaluation. This statistic compares the delay due to the treatment with that found for the base condition. A positive percentage signifies an increase in intersection delay associated with the treatment and a negative percentage signifies a decrease in intersection delay.

A paired-observation approach was used to control for (i.e., eliminate) changes in delay due to influences not tied to the change in treatment. This approach required pairing the delay estimate for each combination of the base conditions with the delay estimate for the exact same combination for the treatment. Given that there is only one replication for each combination, the maximum possible number of observation pairs for a given treatment is 108 (i.e., one pair for each combination).

The distribution of percent change in intersection delay for each treatment is shown in Table 5-2. All of the treatments increased delay relative to the base condition. The negative values shown are primarily from the treatments where the base condition has exceptionally high delay values (e.g., from a combination of heavy left-turn volumes and permissive-only mode operation).

Four treatments have large negative percentages for their minimum observed values. The common characteristic for these treatments is that they utilize either a protected or protected-permissive mode which helps reduce their delay (under certain volume levels) relative to the base condition (which has the permissive mode).

Table 5-2. Percent Change in Intersection Delay by Treatment.

Treatment Description	Percent Change in Intersection Delay				
	Minimum, %	Average, %	Maximum, %	Standard Deviation, %	Obser-vations
Base condition					98
Provide protected-permissive mode	−69.4	19.7	56.9	17.3	98
Provide protected-permissive mode using flashing yellow signal display	−68.2	18.1	53.7	16.9	98
Provide protected left-turn mode	−65.4	42.2	87.5	24.5	98
Provide lagging phase sequence	−65.2	18.7	72.3	20.7	98
Provide leading pedestrian interval	3.1	20.9	116.7	22.7	63
Provide exclusive pedestrian phase	0.0	42.8	144.7	32.1	86
Provide pedestrian clear interval entirely during green	−3.6	15.4	132.9	24.7	96

The last column of Table 5-2 indicates the number of observation pairs for each treatment. The combinations are less than 108 in all cases. This reduction reflects the need to reduce the base condition treatment combinations from108 to 98 because 10 combinations resulted in a high delay value from unsteady queue conditions. This reduction translated into a 10-observation reduction for the other treatments because the base combinations were used to form data pairs for each treatment. The LPI treatment has only 63 observation pairs because the combinations with zero pedestrian volume were excluded from the analysis (for reasons described in a previous section).

SAFETY DATA

This section summarizes the safety data collected at 20 field study sites in Texas. The safety data collection plan was described in Chapter 4. The safety database will be used to calibrate models to predict the effects of pedestrian safety treatments on pedestrian-vehicle conflict frequency. These models are described in Chapter 6.

Pedestrian Demographics

More than 1400 cycles were observed at the collective set of study sites. During these cycles, approximately 7600 pedestrians were observed in the subject crosswalks. About 5200 of these pedestrians were legal pedestrians (as defined in Chapter 1). The distributions of cycle and pedestrian counts are provided in Table 5-3.

The gender and age group of each legal pedestrian were determined using visual appearance. The count of legal pedestrians for each combination of gender and age group is given in Table 5-4. Most of the pedestrians at the university campus sites were in the "young" category, while most of the pedestrians at the downtown grid sites were in the "adult" category.

Table 5-3. Cycle and Pedestrian Counts by Site Category.

Conflict Area Length [1]	Cycle and Pedestrian Counts by Left-Turn Mode			
	Permissive		Protected-Permissive	
	Cycles	Legal Pedestrians	Cycles	Legal Pedestrians
Long	487	1950	178	465
Short	598	2132	110	652

Note:
1 - Conflict area length is equal to the combined width of the receiving lanes. It is "short" if the site has two or fewer receiving lanes. It is "long" if the site has three or more receiving lanes.

Table 5-4. Legal Pedestrian Distribution by Gender and Age Group.

Age Group	Gender			Total
	Female	Male	Undetermined	
Child (less than 12 years)	10	6	0	16
Teen (12 to 17)	2	1	0	2
Young (17 to 25)	1427	1817	1	3245
Adult (25 to 60)	738	1176	1	1915
Senior (60 or more)	3	26	0	29
Total:	2180	3026	2	5208

Signalization Characteristics

A cycle length of 80 s was observed at the downtown sites, while the university campus sites had cycle lengths that ranged from 110 to 150 s. The walk intervals at the sites ranged from 4 to 30 s, and the pedestrian clear intervals ranged from 14 to 28 s.

Vehicular Volumes

The following vehicular counts were extracted from the videotape recordings on a cycle-by-cycle basis:

- Left-turning vehicles crossing the subject crosswalk during the protected left-turn phase.
- Left-turning vehicles crossing the subject crosswalk during the opposing through green interval.
- Through and right-turning vehicles opposing the subject left-turn movement.
- Cross-street vehicles crossing the subject crosswalk.

The cross-street vehicles were counted during the cross-street phases preceding the subject crosswalk's WALK indication. Hence, the cross-street volume serves as a surrogate measure for the "busyness" of the site as observed by pedestrians waiting to cross. Vehicles turning left during the permissive period and opposing through and right-turning vehicles were counted during the phases running concurrently with the subject crosswalk's WALK indication. Vehicles turning left during the protected period were counted during the phases immediately preceding or following the subject crosswalk's WALK indication. These counts were used to compute the hourly flow rates provided in Table 5-5. For each site category, the observed ranges and averages across sites are provided.

Table 5-5. Vehicular Volumes by Site Category.

Left-Turn Mode	Conflict Area Length	Vehicular Volume, veh/h							
		Left Turns During Protected Period		Left-Turns During Permissive Period		Opposing Through and Right Turns		All Cross Street Movements	
		Average	Range	Average	Range	Average	Range[1]	Average	Range
Permissive	Long			70	20–165	55	0–185	1640	900–2800
	Short			55	10–145	175	0–575	1190	230–1935
Protected-permissive	Long	35	15–55	95	45–140	400	305–490	590	560–625
	Short	140	140–170	50	30–75	490	75–900	1040	450–1620

Note:
1 - Zero volume was recorded for a movement that did not exist due to intersection geometry or lane assignment.

Pedestrian Volumes

Counts of total and legal pedestrians were extracted from the videotape recordings on a cycle-by-cycle basis. Directional counts were conducted for pedestrians originating from the near and far corners of the subject crosswalk, and then summed to obtain aggregated counts. A range of values for these volumes was observed for each site category. These volumes are provided in Table 5-6. The pedestrians that cross legally range from 66 to 79 percent, with the higher percentages in this range found at the sites with a permissive left-turn mode.

Table 5-6. Pedestrian Volumes by Site Category.

Left-Turn Mode	Conflict Area Length	Total Volume, p/h		Legal Volume, p/h		Total Volume, p/cycle	
		Average	Range	Average	Range	Average	Range
Permissive	Long	210	70–465	165	55–360	5	2–14
	Short	145	45–265	110	20–235	5	2–11
Protected-permissive	Long	160	160–160	115	110–125	4	4–4
	Short	250	135–370	165	95–235	9	5–13

A more detailed analysis of the directional pedestrian counts revealed that when the pedestrian demand was high on a per-cycle basis, the pedestrians tended to simultaneously cross the crosswalk in both travel directions. Specifically, when pedestrian volume exceeded five pedestrians per cycle, about 91 percent of the cycles had pedestrians originating from both corners. This distribution is shown in Table 5-7. This trend is of interest because when pedestrians originate from both corners, there are likely to be two separate pedestrian platoons that pass through the conflict area at different times, such that left-turning vehicles are blocked by pedestrians for a longer period of time. Thus, intersections with long cycle lengths due to the use of protected-permissive left-turn phases may have a larger exposure to pedestrian conflict.

Table 5-7. Pedestrian Volumes and Platoon Patterns.

Pedestrian Platoon Pattern	Number of Cycles by Pedestrian Count		
	≥ 5 p/cycle	≤ 4 p/cycle	Total
No pedestrians	--	158	158
Originating from far corner only	25	223	248
Originating from near corner only	26	156	182
Originating from both corners	530	255	785
Total:	581	792	1373

Conflict Measures

Pedestrian-based conflicts were counted during the data reduction process. These conflicts were separately counted for legal pedestrians (as defined in Chapter 1) and illegal pedestrians. The discussion in this section is focused on conflicts involving legal pedestrians.

A pedestrian-based conflict is considered to have occurred if a pedestrian performs any of the following actions:

- Slows down due to a vehicle.
- Stops and waits for a vehicle in the crosswalk.
- Steps sideways to avoid a vehicle.
- Runs or speeds up to avoid a vehicle.
- Runs or speeds up to clear the crosswalk after starting the crossing late due to a vehicle.
- Turns back to the origin curb to avoid a vehicle.
- Turns back to the origin curb to clear the crosswalk after starting the crossing late due to a vehicle.
- Delays leaving the origin curb due to a vehicle.
- Attempts to cross but does not leave the origin curb.

If an interaction occurred between one vehicle and multiple pedestrians, and all of the pedestrians were observed performing one of these actions, the number of pedestrian-based conflicts occurring was taken as the number of pedestrians present. For example, if a vehicle encroached on the crosswalk and four pedestrians stopped and waited for the vehicle to pass, the event would be counted as four pedestrian-based conflicts.

The numbers of pedestrian-based conflicts observed for each of the site categories are provided in Table 5-8. The pedestrian volumes listed in Table 5-3 were used to compute conflict rates. These rates are also shown in Table 5-8.

Table 5-8. Pedestrian-Based Conflicts by Site Category.

Conflict Area Length	Conflicts by Left-Turn Mode				Total Conflicts	
	Permissive		Protected-Permissive			
	Count, conflicts	Rate, conflicts/1000 p	Count, conflicts	Rate, conflicts/1000 p	Count, conflicts	Rate, conflicts/1000 p
Long	21	10.8	3	6.4	24	9.9
Short	15	7.0	30	46.0	45	16.2
Total:	36	8.8	33	29.5	69	13.3

A total of 24 pedestrian-based conflicts were observed at sites with long conflict areas (i.e., sites with three or more receiving lanes). Almost twice as many conflicts (45) were observed at sites with short conflict areas (i.e., two or fewer receiving lanes). This trend is also found in the conflict rates shown in Table 5-8. It suggests that a larger number of receiving lanes allows left-turning drivers more flexibility to find gaps in the pedestrian stream.

Further examination of the aforementioned trend suggests that there is an interaction between left-turn mode and conflict area length. Specifically, the trend in conflict rates suggests that the combination of protected-permissive left-turn mode and short conflict area produces a significantly larger potential for conflict.

CHAPTER 6. MODEL CALIBRATION AND GUIDELINE DEVELOPMENT

OVERVIEW

This chapter describes the process used to develop guidelines for selecting alternative pedestrian-safety-related treatments for signalized intersections. These guidelines are based on consideration of road-user costs associated with pedestrian-vehicle crashes and vehicle delay. Threshold conditions for which a change in mode or sequence result in a reduction in road-user costs provide the basis for the guidelines.

The chapter consists of three parts. The first part describes the calibration of several pedestrian safety prediction models. The second part describes the use of these models to develop a model for predicting road-user costs based on estimates of predicted crash frequency and predicted average intersection delay. The third part describes the development of guidelines for using the calibrated models to evaluate alternative treatments and determine the most appropriate treatment for a given crosswalk.

SAFETY PREDICTION MODEL CALIBRATION

This section describes the procedure used to calibrate a series of predictive models. It also describes the results from the model calibration process. Initially, the calibration procedure is described. Then, the calibrated models are presented.

Calibration Procedure

A preliminary analysis of the conflict data indicated that they have a random distribution characterized by the Poisson distribution. When count data are Poisson distributed at a site of interest, then data for a collection of sites with similar attributes can be described by the negative binomial distribution. The variance of this distribution is:

$$V(x) = E(m) + \frac{E(m)^2}{k} \qquad (7)$$

where,

x = count frequency for a given site having an expected frequency of $E(m)$.
k = dispersion parameter.

The first term of Equation 7 accounts for the Poisson variability in the count data at each site. The second term accounts for the additional variability that occurs among sites. This distribution was used in the regression analysis to model the error distribution of the dependent variable.

The Nonlinear Mixed Regression procedure (NLMIXED) in the SAS program was used to estimate the model coefficients (*1*). The benefits of using this procedure are: (1) nonlinear model forms can be evaluated, and (2) the dispersion parameter k can be held fixed during the model building process (as described in the next paragraph). The "loss" function associated with

NLMIXED was specified to equal the log likelihood function for the negative binomial distribution. The procedure was set up to estimate model coefficients based on maximum-likelihood methods.

The goal of the regression model development was to build a parsimonious model. This type of model explains as much of the systematic variability as possible using the fewest number of variables. A modified version of the procedure described by Sawalha and Sayed (*2*) was used to achieve this goal.

The first step of the model development procedure is based on a forward-building procedure where the candidate explanatory variables are added to the base model one at a time and individually evaluated. The dispersion parameter is held fixed at the base-model value to properly assess the contribution of the candidate variable (*2*). Those variables that are illogical in sign and have a t-statistic between −2.0 and +2.0 are considered for removal. Based on this evaluation, a list of viable explanatory variables is identified. The second step is based on a backward-building procedure where all viable variables are combined with the base model to create a full model. The variables in the full model are then individually evaluated and removed from the model based on (1) the logic of their sign, (2) the value of their t-statistic, and (3) their impact on the overall fit of the model. This step produced the final model form.

Alternative model structures were hypothesized using theoretic constructs and latent variables. The Akaike information criterion (AIC) is a useful statistic for evaluating the overall fit of each model, with the model producing the smallest AIC value providing the better fit.

Legal Pedestrian-Vehicle Conflict Model Calibration

The regression analysis revealed that conflict frequency is correlated with left-turn volume, legal pedestrian volume, crosswalk length, median width, cycle length, and presence of a leading left-turn phase. Several alternative model forms and variables were evaluated. The best-fit prediction model was specified using the following equation:

$$N_{co,L} = \left(v_{lt}\right)^{b_1} \left(v_{ped,L}\right)^{b_2} e^{b_0 + b_3 t^2 + b_4 C + b_5 I_{lead}} \qquad \textbf{(8)}$$

with

$$t = \left(\frac{L_{cw}}{2} + \frac{W_m}{2} \right) \frac{1}{20} \qquad \textbf{(9)}$$

where,

$N_{co,L}$ = frequency of pedestrian-vehicle conflicts involving legal pedestrians, conflicts/h.
v_{lt} = conflicting left-turn volume, veh/h.
$v_{ped,L}$ = legal pedestrian volume in the crosswalk (walking in either direction), p/h.
t = vehicle travel time to conflict area, s.
L_{cw} = crosswalk length (curb to curb), ft.
W_m = median width (inclusive of any left-turn bay that may be present), ft.
C = cycle length, s.
I_{lead} = indicator variable for leading left-turn phase (= 1.0 if leading, 0.0 otherwise).
b_i = calibration coefficients, i = 0, 1, 2,....

The variable for vehicle travel time is based on the distance from the left-turn stop line to the conflict area, as measured along the crosswalk. The value of "20" in Equation 9 represents an average left-turn vehicle speed. The exponent "2" that is attached to the travel time variable in Equation 8 represents an empirically based adjustment to improve model fit to the data.

The statistics related to the calibrated model are shown in Table 6-1. The calibration coefficient values shown can be used with Equation 8 to estimate the pedestrian-vehicle conflict frequency for a given left-turn movement and its associated conflicting crosswalk.

Table 6-1. Calibrated Model Statistical Description–Legal Pedestrian-Vehicle Conflict Model.

Model Statistics		Value		
	R^2 (R_K^2):	0.70 (0.81)		
	Scaled Pearson χ^2:	1.03		
	Pearson χ^2:	41.2 ($\chi^2_{0.05, 35}$ = 49.8)		
	Dispersion Parameter k:	3.69		
	Observations n_o:	41 hours (120 conflicts at 20 sites)		
	Standard Error:	±2.2 conflicts/h		
Range of Model Variables				
Variable	**Variable Name**	**Units**	**Minimum**	**Maximum**
v_{lt}	Left-turn volume	veh/h	9	226
$v_{ped,L}$	Legal pedestrian volume	p/h	14	422
L_{cw}	Crosswalk length	ft	41	107
W_m	Median width	ft	0	27
C	Cycle length	s	80	150
I_{lead}	Indicator for leading left-turn phase	none	0	1
Calibrated Coefficient Values				
Variable	**Definition**	**Value**	**Std. Dev.**	**t-statistic**
b_0	Intercept	-6.13	1.58	-3.9
b_1	Effect of left-turn volume	0.444	0.191	2.3
b_2	Effect of legal pedestrian volume	0.756	0.177	4.3
b_3	Effect of vehicle travel time	0.144	0.041	3.5
b_4	Effect of cycle length	0.0094	0.0061	1.5
b_5	Effect of leading left-turn phase	-0.630	0.520	-1.2

The Pearson χ^2 statistic for the model is 41.2, and the degrees of freedom are 35 (= $n - p - 1$ = 41 − 5 − 1). As this statistic is less than $\chi^2_{0.05, 35}$ (= 49.8), the hypothesis that the model fits the data cannot be rejected. The R^2 for the model is 0.70. An alternative measure of model fit that is better suited to negative binomial error distributions is R_K^2, as developed by Miaou (*3*). The R_K^2 for the calibrated model is 0.81.

The regression coefficients for the calibrated model are listed in the last rows of Table 6-1. The *t*-statistics shown indicate that, with two exceptions, all coefficients are significant at a 5 percent level. A positive coefficient indicates that conflicts increase with an increase in the associated variable value. Thus, conflicts increase with increasing left-turn volume.

The coefficient value associated with vehicle travel time indicates that wider intersections are associated with more conflicts. In fact, for the same curb-to-curb width, those intersections with wider medians are associated with more conflicts. These findings suggest that longer travel distances create a situation where the left-turning vehicle and pedestrians are more likely to arrive to the conflict area at the same time. In contrast, narrower intersections without medians are likely to have the left-turn vehicle clear the conflict area before the pedestrians arrive.

The coefficient value associated with cycle length indicates that longer cycle lengths are associated with more frequent conflicts. This trend is logical because a longer cycle length is likely to lead to a larger number of pedestrians (and vehicles) in queue just prior to the start of the walk interval (and permissive left-turn period). The pedestrians and drivers will also have incurred a longer delay and will be more anxious to get through the intersection. The t-statistic associated with the effect of cycle length corresponds to a 94 percent level of confidence (one-tail). There is a probability of 0.06 that the stated trend is incorrect. Nevertheless, the effect is logical in sign and magnitude and so it is retained in the model.

The coefficient value associated with leading left-turn phase suggests that a leading left-turn phase reduces the conflict rate by 47 percent [= 100 (1 − $e^{-0.630}$)]. The t-statistic associated with the effect of leading left-turn phase presence corresponds to an 89 percent level of confidence (one-tail). There is a probability of 0.11 that a leading left-turn phase does not reduce the conflict rate. Nevertheless, the effect is logical in sign and magnitude so it was retained in the model.

The calibrated coefficients were inserted into Equation 8 to yield the following model:

$$N_{co,L} = \left(v_{lt}\right)^{0.444} \left(v_{ped,L}\right)^{0.756} e^{-6.13 + 0.144 t^2 + 0.0094 C - 0.630 I_{lead}} \quad \textbf{(10)}$$

This model can be used with Equation 9 to estimate the legal pedestrian-vehicle conflict frequency for an intersection approach.

One means of assessing a model's fit is through the graphical comparison of the observed and predicted conflict frequencies. This comparison is provided in Figure 6-1. The trend line in this figure does *not* represent the line of best fit; rather, it is a "$y = x$" line. The data would lie on this line if the model predictions exactly equaled the observed data. The clustering of the data around this line indicates that the model is able to predict conflict frequency without bias.

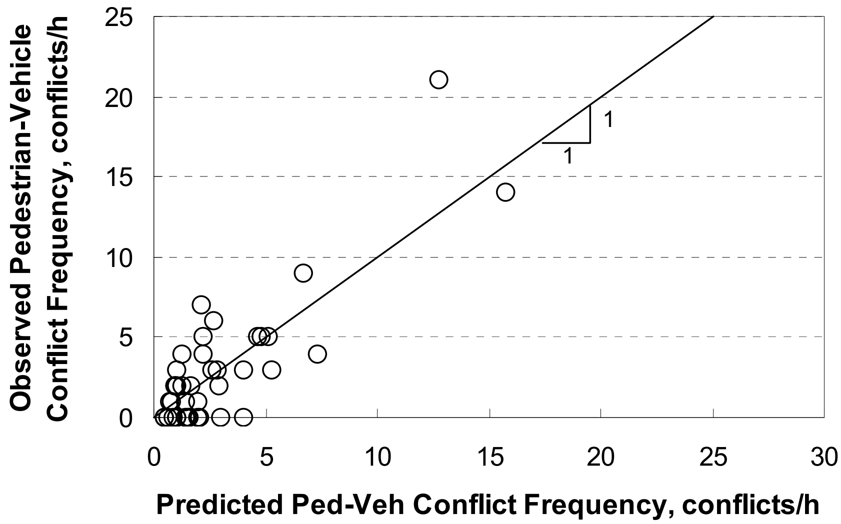


Figure 6-1. Comparison of Observed and Predicted Legal Conflict Frequency.

Illegal Pedestrian-Vehicle Conflict Model Calibration

The regression analysis revealed that conflict frequency is correlated with left-turn volume and illegal pedestrian volume. Several alternative model forms and variables were evaluated. The best-fit prediction model was specified using the following equation:

$$N_{co,I} = \left(v_{lt}\right)^{b_1} \left(v_{ped,I}\right)^{b_2} e^{b_0} \quad \textbf{(11)}$$

where,

$N_{co,I}$ = frequency of pedestrian-vehicle conflicts involving illegal pedestrians, conflicts/h.
v_{lt} = conflicting left-turn volume, veh/h.
$v_{ped,I}$ = illegal pedestrian volume in the crosswalk (walking in either direction), p/h.
b_i = calibration coefficients, i = 0, 1, 2,....

The statistics related to the calibrated model are shown in Table 6-2. The calibration coefficient values shown can be used with Equation 11 to estimate the pedestrian-vehicle conflict frequency for a given left-turn movement and its associated conflicting crosswalk.

The Pearson χ^2 statistic for the model is 43.9, and the degrees of freedom are 38 (= $n - p - 1$ = 41−2−1). As this statistic is less than $\chi^2_{0.05,\,38}$ (= 53.4), the hypothesis that the model fits the data cannot be rejected. The R^2 for the model is 0.61. The R_K^2 for the calibrated model is 0.94.

The regression coefficients for the calibrated model are listed in the last rows of Table 6-2. The t-statistics shown indicate that, with one exception, all coefficients are significant at a 5 percent level. A positive coefficient indicates that conflicts increase with an increase in the associated variable value. Thus, conflicts increase with increasing left-turn volume.

**Table 6-2. Calibrated Model Statistical Description–
Illegal Pedestrian-Vehicle Conflict Model.**

Model Statistics		Value		
	R^2 (R_K^2):	0.61 (0.94)		
	Scaled Pearson χ^2:	1.10		
	Pearson χ^2:	43.9 ($\chi^2_{0.05,\,38}$ = 53.4)		
	Dispersion Parameter k:	11.2		
	Observations n_o:	41 hours (77 conflicts at 20 sites)		
	Standard Error:	±1.5 conflicts/h		
Range of Model Variables				
Variable	**Variable Name**	**Units**	**Minimum**	**Maximum**
v_{lt}	Left-turn volume	veh/h	9	226
$v_{ped,L}$	Illegal pedestrian volume	p/h	6	146
Calibrated Coefficient Values				
Variable	**Definition**	**Value**	**Std. Dev.**	**t-statistic**
b_0	Intercept	-5.38	1.01	-5.3
b_1	Effect of left-turn volume	1.134	0.199	5.7
b_2	Effect of illegal pedestrian volume	0.266	0.204	1.3

The coefficient value associated with pedestrian volume corresponds to an 81 percent confidence interval. There is a probability of 0.095 that pedestrian volume does not increase the conflict rate. Nevertheless, the effect is logical in sign and magnitude so it was retained in the model.

The calibrated coefficients were inserted into Equation 11 to yield the following model:

$$N_{co,I} = \left(v_{lt}\right)^{1.134} \left(v_{ped,I}\right)^{0.266} e^{-5.38} \qquad \textbf{(12)}$$

This model can be used to estimate the illegal pedestrian-vehicle conflict frequency for an intersection approach.

One means of assessing a model's fit is through the graphical comparison of the observed and predicted conflict frequencies. This comparison is provided in Figure 6-2. The clustering of the data around the "$y = x$" line indicates that the model is able to predict conflict frequency without bias.

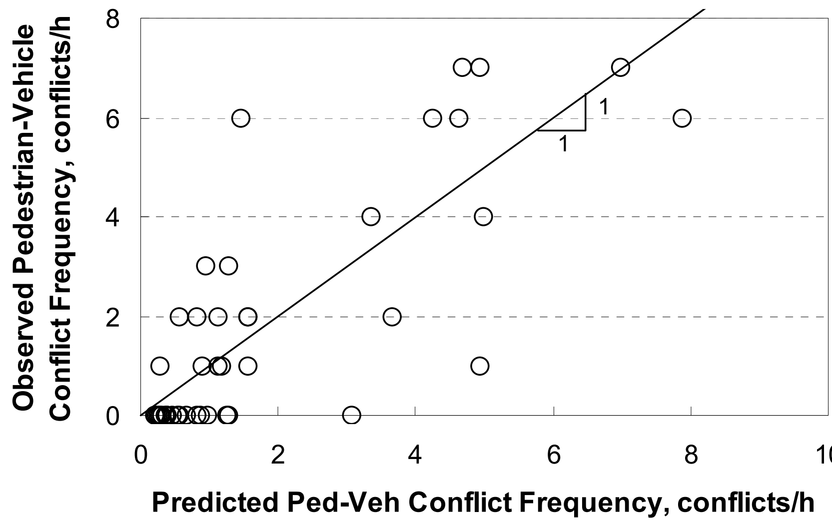


Figure 6-2. Comparison of Observed and Predicted Illegal Conflict Frequency.

Legal Pedestrian Volume Model Calibration

The regression analysis revealed that legal pedestrian volume is correlated with pedestrian delay, the conflicting vehicle flow rate, and the probability that the WALK indication is presented. Several alternative model forms and variables were evaluated. The best-fit prediction model was specified using the following equation:

$$v_{ped,L} = v_{ped,t} \left(p_p\right)^{c_3} \left(\frac{e^{c_0 + c_1 d_p + c_2 v_c/3600}}{1 + e^{c_0 + c_1 d_p + c_2 v_c/3600}} \right) \quad \textbf{(13)}$$

with

$$p_p = 1 - e^{(-v_{ped,t}/3600)\, P_b\, C} \quad \textbf{(14)}$$

where,

$v_{ped,L}$ = legal pedestrian volume in the crosswalk (walking in either direction), p/h.
$v_{ped,t}$ = pedestrian volume in the crosswalk (walking in either direction), p/h.
p_p = probability that the WALK indication is displayed (= 1.0 if pretimed or on ped. recall).
P_b = probability of a pedestrian pressing the detector button (= 0.66).
C = cycle length, s.
d_p = pedestrian delay due to signal, s/p.
v_c = conflicting (cross street) vehicular traffic volume (both directions), veh/h.
c_i = calibration coefficients, i = 0, 1, 2,....

An analysis of the site data indicated that the probability of a pedestrian pressing the detector button is effectively equal to 0.66. This value is slightly larger than the value of 0.51 reported by Zegeer et al. (*4*).

The statistics related to the calibrated model are shown in Table 6-3. The calibration coefficient values shown can be used with Equation 13 to estimate the legal pedestrian volume for a given crosswalk. Equation 13 can also be used with Equation 10 to estimate the legal pedestrian-vehicle conflict frequency. It can also be used with Equation 12 to estimate the illegal pedestrian-vehicle conflict frequency, where the illegal pedestrian volume equals the total pedestrian volume minus the legal pedestrian volume.

Table 6-3. Calibrated Model Statistical Description–Legal Pedestrian Volume Model.

Model Statistics		Value		
	R^2 (R_K^2):	0.96 (0.98)		
	Scaled Pearson χ^2:	1.12		
	Pearson χ^2:	44.6 ($\chi^2_{0.05,\,37}$ = 52.2)		
	Dispersion Parameter k:	109		
	Observations n_o:	41 hours (120 conflicts at 20 sites)		
	Standard Error:	±17.7 p/h		
Range of Model Variables				
Variable	**Variable Name**	**Units**	**Minimum**	**Maximum**
$v_{ped,t}$	Pedestrian volume	p/h	30	559
d_p	Pedestrian delay due to signal	s/p	13	66
v_c	Conflicting vehicular traffic volume	veh/h	230	3,061
p_p	Prob. that the WALK indication is presented	none	0.54	1.00
Calibrated Coefficient Values				
Variable	**Definition**	**Value**	**Std. Dev.**	**t-statistic**
c_0	Intercept	1.32	0.23	5.7
c_1	Effect of pedestrian delay	-0.020	0.007	-3.0
c_2	Effect of conflicting vehicle flow rate	1.493	0.608	2.5
c_3	Effect of probability WALK is presented	0.310	0.216	1.4

The Pearson χ^2 statistic for the model is 44.6, and the degrees of freedom are 37 (= $n - p - 1$ = 41 − 3 − 1). As this statistic is less than $\chi^2_{0.05,\,37}$ (= 52.2), the hypothesis that the model fits the data cannot be rejected. The R^2 for the model is 0.96. The R_K^2 for the calibrated model is 0.98.

The regression coefficients for the calibrated model are listed in the last rows of Table 6-3. The *t*-statistics shown indicate that, with one exception, all coefficients are significant at a 5 percent level. A positive coefficient indicates that the proportion of pedestrians that cross legally increases with an increase in the associated variable value. Thus, the proportion of crossings that are legal increases with an increase in the conflicting vehicle flow rate. The coefficient value associated with pedestrian delay indicates that the proportion of pedestrians that cross legally decreases with an increase in delay.

The coefficient value associated with the probability that the WALK indication is displayed suggests that the proportion of pedestrians that cross legally increases with an increase in the probability that the WALK indication is displayed. The t-statistic associated with the effect of leading left-turn phase presence corresponds to an 85 percent level of confidence. There is a probability of 0.075 that an increase in this probability does not correspond to an increase in the proportion of legal pedestrians. Nevertheless, the effect is logical in sign and magnitude so it was retained in the model.

The calibrated coefficients were inserted into Equation 13 to yield the following model:

$$v_{ped,L} = v_{ped,t} \left(p_p\right)^{0.310} \left(\frac{e^{1.32 - 0.020 d_p + 1.493 v_c/3600}}{1 + e^{1.32 - 0.020 d_p + 1.493 v_c/3600}} \right) \quad \textbf{(15)}$$

This model can be used with Equation 14 to estimate the legal pedestrian volume for a crosswalk.

One means of assessing a model's fit is through the graphical comparison of the observed and predicted conflict frequencies. This comparison is provided in Figure 6-3. The clustering of the data around the "$y = x$" line indicates that the model is able to predict legal pedestrian volume without bias.

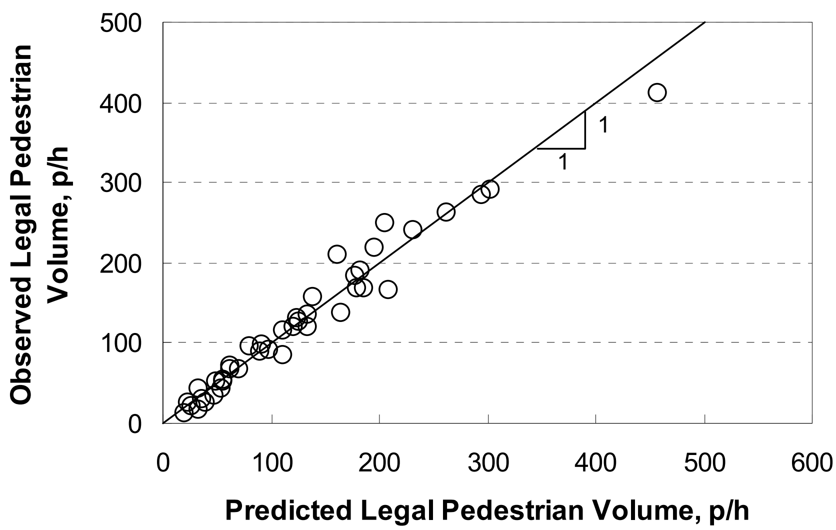


Figure 6-3. Comparison of Observed and Predicted Legal Pedestrian Volume.

Pedestrian Crash Prediction Model

Crash data were obtained from TxDOT's crash record information system (CRIS) for the most recent available seven-year period (i.e., 2003 to 2009). The database was screened to include only crashes that occurred at signalized intersections in urban areas. The subset data are summarized in Table 6-4 by crash severity. The data in the table indicate that there were 393 left-turn-related pedestrian-vehicle crashes during the seven-year period, or about 56 crashes per year.

Table 6-4. Crash Distribution at Urban Signalized Intersections in Texas.

Crash Severity Category	Pedestrian-Vehicle Crash Frequency by Crash Type, cr/7years		Vehicle-Vehicle Plus Ped.-Vehicle Crash Frequency, cr/7 years
	Left-Turn-Related	Other	
Fatal	10	51	697
Incapacitating injury	50	151	6,126
Non-incapacitating injury	146	335	29,833
Possible injury	173	342	73,901
Property damage only	13	44	136,682
Unknown	1	7	1,827
Total:	393	930	249,066

One characteristic that is important to this research is whether the pedestrian involved in the crash was crossing legally. A preliminary examination of the CRIS data indicated that this characteristic could not be reliably determined for many of the 1323 crashes. However, this information is reported by Habib (*5*) based on his examination of 455 pedestrian-vehicle crash reports for 43 intersections in New York City. He found that 62 percent of the left-turn-related crashes were associated with a driver that failed to yield the right-of-way to the pedestrian.

The crash data for the intersections listed in Table 4-6 of Chapter 4 were also obtained for the most recent five-year period for which they were available. The data for the Austin intersections were obtained from the City of Austin for the period from 9/2005 to 9/2010. The data for the College Station intersection were obtained from TxDOT for the years 2005 to 2009. The narratives provided by the investigating officer were also obtained for each pedestrian-vehicle crash. The data were screened to identify those crashes associated with each of the crosswalk study sites identified in the table. These data are summarized in Table 6-5. The table indicates that there were 12 crashes during the five-year period, or about 0.12 left-turn related crashes per year for each crosswalk studied.

A total of 120 left-turn-related legal pedestrian-vehicle conflicts were observed at the study sites identified in Table 4-6 of Chapter 4. The study period at each site was effectively two hours in duration; however, the data were collected for complete signal cycles so some time was lost at the start and end of each study period. Table 6-5 shows the conflict frequency for each site for an equivalent two-hour period, and a total of 122.2 left-turn-related legal pedestrian-vehicle conflicts. The non-integer values shown reflect the few minutes lost during each two-hour study period. A similar calculation for illegal pedestrian-vehicle conflicts indicated a total of 77.6 left-turn-related *illegal* pedestrian-vehicle conflicts at the study sites.

Table 6-5. Study Site Left-Turn-Related Pedestrian-Vehicle Safety Statistics.

City	Intersecting Street by Direction		Subject Left-Turn Movement	Reported Crashes [1], cr/5 yr	Conflict Frequency [2], conflicts/2 h	Expected Crash Freq. [1], cr/yr/2 h	Expected Total Crash Freq. [1], cr/5 yr
	North-South	East-West					
Austin	Congress Ave.	4th Street	Northbound	2	6.1	0.000094	0.64
			Eastbound	0	0.0	0.000046	0.31
			Southbound	0	1.0	0.000051	0.35
			Westbound	1	3.0	0.000048	0.32
	Congress Ave.	5th Street	Eastbound	1	0.0	0.000054	0.47
	Congress Ave.	6th Street	Northbound	0	9.0	0.000125	0.85
			Westbound	1	3.0	0.000213	1.88
	Congress Ave.	7th Street	Southbound	0	2.0	0.000085	0.58
	Guadalupe St.	21st Street	Eastbound	1	6.4	0.000085	0.58
			Westbound	1	8.2	0.000131	0.89
	Guadalupe St.	22st Street	Eastbound	0	1.0	0.000069	0.47
	Guadalupe St.	24st Street	Eastbound	1	7.1	0.000204	1.38
	Guadalupe St.	Dean Keeton St.	Southbound	0	6.0	0.000059	0.40
	Guadalupe St.	27st Street	Westbound	0	7.3	0.000046	0.27
	San Jacinto Blvd.	Dean Keeton St.	Northbound	0	2.1	0.000036	0.25
			Southbound	1	0.0	0.000077	0.52
	Medical Arts St./ Robert Dedman Dr.	Dean Keeton St.	Northbound	1	10.0	0.000061	0.41
			Southbound	0	5.0	0.000027	0.19
College Station	Spence Street	University Drive	Northbound	1	9.1	0.000096	0.65
			Southbound	1	35.8	0.000213	1.45
			Total:	12	122.2	0.001820	12.86

Notes:
1 - Left-turn-related pedestrian-vehicle crashes for the identified subject left-turn movement and associated crosswalk.
2 - Conflicts between subject left-turning vehicles and pedestrians that are crossing legally.

Models developed by Quaye et al. (6) were used to estimate the expected number of left-turn related pedestrian-vehicle crashes at each of the study sites. These models are based on four years of crash data for 306 signalized intersection crosswalks in Ontario, Canada. Two model types were developed. One model type applies to crosswalks where the conflicting left-turn movement does not face an opposing vehicular traffic stream (e.g., the left-turn movement from a one-way street or from the terminating leg of a three-leg intersection). The form of this model is:

$$N_{cr} = \left(v_{lt}\right)^{1.32} \left(v_{ped,t}\right)^{0.338} e^{-17.82} \qquad \textbf{(16)}$$

where,
N_{cr} = expected left-turn-related pedestrian-vehicle crash frequency during the analysis hour, cr/yr.
v_{lt} = left-turn volume, veh/h.
$v_{ped,t}$ = pedestrian volume in the crosswalk (walking in either direction), p/h.

A second model type was developed by Quaye et al. (*6*) for crosswalks where the conflicting left-turn movement faces an opposing queue (e.g., the left-turn movement from a two-way street). The form of this model is:

$$N_{cr} = \left(v_{lt}\right)^{0.363} \left(v_{ped,t}\right)^{0.865} e^{-15.86} \qquad \textbf{(17)}$$

where all variables are defined previously.

Equation 16 or 17, as appropriate, was used to estimate the expected annual crash frequency for each hour of study at each study site. Each hourly estimate was then summed for the two-hour study period at each site to obtain the expected annual crash frequency for the study period. These values are shown in the second-to-last column of Table 6-5. They are quite small because the analysis period is only two hours in duration and because pedestrian-vehicle crashes are relatively rare.

Equations 16 and 17 each predict the expected crash frequency for the analysis hour over a one-year period. Thus, an estimate of the expected total crash frequency at a crosswalk during a one-year period would require the separate application of the appropriate equation for each hour in the average day. The sum of these 24 values would represent the expected *total* annual crash frequency for the crosswalk.

The aforementioned technique was applied to each of the study sites to estimate the expected total annual crash frequency for each crosswalk study site. The pedestrian volume for each of the 24 hours was estimated by using the distribution of hourly pedestrian volumes reported by Zegeer et al. (*4*, Table 28). The observed pedestrian volume was assumed to occur during the peak pedestrian demand hour, and the volume during the other hours was determined by distribution ratio. The left-turn volume for each of the 24 hours was estimated in a similar manner using continuous count recorder data collected by TxDOT for an arterial street near to each study site.

The expected total annual crash frequency for each study site crosswalk was multiplied by 5 to obtain a five-year crash frequency estimate. This estimate is shown in the last column of Table 6-5. The last row of Table 6-5 indicates that the expected total crash frequency for all 20 crosswalks studied is 12.86 cr/5 yr. This value compares favorably with the reported 12 cr/5 yr for these same crosswalks.

Table 6-6 lists the left-turn-related conflict frequency for legal and illegal pedestrians at the study sites. This table also lists the observed pedestrian count for the same two categories. A total of 7051 pedestrians were observed to cross at the collective set of study sites during the two-hour study period. Of this total, 5199 pedestrians (74 percent) were observed to cross legally. These values are combined in the last column to determine the conflict rate for legal and illegal pedestrians. The conflict rate for legal pedestrian crossings is 23.5 conflicts per 1000 pedestrians. It is almost twice this amount for illegal pedestrian crossings, which is logical given the inherent risk associated with illegal crossings.

Table 6-6. Left-Turn-Related Pedestrian-Vehicle Conflict Analysis.

Pedestrian Crossing Category	Conflict Frequency, conflicts/2 h	Observed Pedestrian Count, p/2h	Conflict Rate, conflicts/1000 p
Legal crossing	122.2	5199	23.5
Illegal crossing	77.6	1852	41.9
Total:	199.8	7051	28.3

Table 6-7 shows the estimated distribution of left-turn-related crashes at the study sites. The distribution of left-turn-related pedestrian-vehicle crashes reported by Habib (*5*) was used to develop the distribution shown. Thus, the expected crash frequency involving legal pedestrians is estimated as 0.00113 (= 0.00182 × 0.62). This value is combined with the observed conflict frequency to determine the crash rate for legal pedestrians as 0.92 cr/yr/100,000 conflicts (= 0.00113/122.2 × 100,000). The crash rate for illegal crossings is computed in a similar manner, which yields 0.89 cr/yr/100,000 conflicts. It is about the same as that for legal crossings. This result is logical given that the crash rate represents the ratio of crashes per conflict. Thus, it reflects the probability of a crash given that a conflict occurs, regardless of how it occurs. The higher risk that is inherent to the illegal crossing is appropriately reflected in its conflict rate.

Table 6-7. Left-Turn-Related Pedestrian-Vehicle Crash Analysis .

Pedestrian Crossing Category	Expected Crash Frequency, cr/yr/2 h	Conflict Frequency, conflicts/2 h	Crash Rate, cr/yr/100,000 conflicts
Legal crossing	0.00113	122.2	0.92
Illegal crossing	0.00069	77.6	0.89
Total:	0.00182	199.8	0.91

Based on the results in Table 6-7, the annual number of crashes during the analysis period is computed using the following equation.

$$n_{cr} = 365 \; \frac{0.92 \, N_{co,L} \; + \; 0.89 \, N_{co,I}}{100{,}000} \qquad \textbf{(18)}$$

where,

n_{cr} = annual number of pedestrian-vehicle crashes, cr/yr.
$N_{co,\,I}$ = frequency of pedestrian-vehicle conflicts involving illegal pedestrians, conflicts/h.
$N_{co,\,L}$ = frequency of pedestrian-vehicle conflicts involving legal pedestrians, conflicts/h.

The estimates of legal and illegal pedestrian-conflicts used in this equation are obtained from Equations 10 and 12, respectively.

ROAD-USER COST PREDICTION MODEL DEVELOPMENT

This part of the chapter describes the development of a road-user cost prediction model. In fact, two separate models are developed and combined for this purpose. One model is used to predict the change in road-user cost due a change in pedestrian-vehicle crash frequency. The second model is used to predict the change in road-user cost due to a change in intersection delay. The changes in crash frequency and delay are related to various pedestrian safety treatments, including the use of a protected left-turn mode.

This part of the chapter consists of two sections. This section describes the process used to calculate road-user costs associated with pedestrian-vehicle crashes and intersection delay. The second section describes the use of these costs, and the models described in the previous section, to develop road-user cost prediction models.

Road-User Costs

This section describes the procedure used to determine the average road-user cost associated with a pedestrian-vehicle crash and the average value of travel time.

Pedestrian-Vehicle Crash Costs

The cost of a left-turn-related pedestrian-vehicle crash was computed using the crash cost estimates by Council et al. (*7*). They developed estimates for each crash severity category based on crash location, speed limit, and crash type. They also categorized the crash cost into human capital and non-human-capital categories. The human capital costs represent monetary loses associated with medical care, vehicle damage, legal fees, and lost wages. Non-human-capital costs reflect the crash's impact to the person's quality of life. Comprehensive costs represent the sum of these two categories and are recommended by Council et al. for evaluation of alternative transportation projects based on road user costs.

The costs reported by Council et al. were based on prices in 2001. They described a procedure for updating the crash costs to current values by using the Consumer Price Index (CPI) and the Employment Cost Index. These indices were obtained from the sources cited and used to update the reported crash costs to 2009 dollars.

The 2009 crash cost estimates are shown in Table 6-8 for crashes at intersections on roads with a speed limit of 45 mph or less and involving a vehicle and pedestrian. Also shown is the distribution of left-turn-related pedestrian-vehicle crashes that occurred at urban intersections in Texas for the period 2003 to 2009 (shown previously in Table 6-4). The last row of the table indicates the weighted average comprehensive cost of a left-turn-related pedestrian-vehicle crash based on the crash severity distribution shown in column 3.

Table 6-8. Average Cost of a Left-Turn-Related Pedestrian-Vehicle Crash at an Urban Signalized Intersection.

Crash Severity Category	Crash Freq., cr/7years	Crash Severity Distribution	Human Capital Cost [1], $/cr	Non-Human-Capital Cost [1], $/cr	Comprehensive Cost [1], $/cr
Fatal	10	0.03	1,181,883	2,857,322	4,039,205
Incapacitating injury	50	0.13	197,647	193,860	391,507
Non-incapacitating injury	146	0.37	40,423	34,115	74,538
Possible injury	173	0.44	40,423	34,115	74,538
Property damage only	13	0.03	10,311	2,198	12,509
Total:	392	1.00	**Average Crash Cost, $/cr:**		214,050

Note:
1 - Based on 2009 dollars.

A similar calculation was undertaken to estimate the average cost of a crash at an urban intersection. The distribution in the last column of Table 6-4 was used for this purpose. The appropriate severity costs were obtained from the report by Council et al. The weighted average comprehensive cost of an urban intersection crash was computed as $47,455. This cost is about 22 percent of that shown in Table 6-8 and is a reflection of the lower severity of vehicle-vehicle crashes, relative to pedestrian-vehicle crashes.

Intersection Delay Costs

The cost of intersection delay was computed using the value-of-time estimation procedure documented in *User Benefit Analysis for Highways* (*8*). This document provides wage and compensation estimates for automobile travelers and truck drivers, respectively, by trip purpose. Wages refer to the after-tax, direct income of the traveler. Total compensation includes base wages and employment benefits.

The costs reported in *User Benefit Analysis for Highways* were based on prices in 2000. The CPI was used to update the reported wage and compensation estimates to 2009 dollars.

The 2009 value-of-time estimate is shown in Table 6-9 for typical trip purposes and employment. It is based on the assumption that trucks represent 3 percent of the traffic stream at urban intersections.

Table 6-9. Average Value of Travel Time.

Vehicle Type	Traffic Distribution	Average Earning [1], $/h	Time-Value-to-Earnings Ratio	Occupancy, person/veh	Value of Time [1], $/h
Automobile	0.97	23.24	0.50	1.50	17.43
Commercial Truck	0.03	25.20	1.00	1.05	26.46
Total:	1.00		**Average Value of Time, $/h:**		17.70

Note:
1 - Based on 2009 dollars.

Road-User Cost Prediction Model

This section consists of four subsections. The first subsection describes the data that were assembled for model development. The second subsection describes how the critical movement analysis technique was used to characterize the quality of service provided to vehicles at the intersection. The third subsection describes the development of an equation to predict the change in pedestrian-vehicle crash cost associated with a change in left-turn mode or sequence. The fourth subsection describes the development of an equation to predict the change in intersection delay cost associated with a change in left-turn mode or sequence.

Data Assembly

The data used to calibrate the predictive equations were obtained from two sources. The delay data were obtained from simulation analysis of a large number of signalized intersections. These intersections were developed to ensure that the calibration data represented a wide range of intersection geometrics, vehicle volumes, pedestrian volumes, left-turn modes, and left-turn sequences. They are described in more detail in Chapter 4.

Identified in Chapter 4 are 108 base intersection configurations. Each of these base configurations have permissive left-turn operation. These base intersections were then modified to produce 108 identical intersection configurations with the exception that they have protected-permissive left-turn operation and a leading sequence. They were modified again to produce 108 intersection configurations with protected left-turn operation and a leading sequence. They were modified again to produce 108 configurations with protected-permissive left-turn operation and a lagging sequence. A total of 432 intersection configurations were developed and simulated.

The simulation results for the 108 base intersection configurations were individually matched to the results for each of the 108 configurations with protected-permissive operation and a leading sequence. The matched data formed a "paired" database with 108 observations. Each observation had the same volume, geometry, and signalization with the exception of the change in left-turn mode and sequence. In a similar manner, a paired database was developed for protected operation and a leading sequence. A paired database was also developed for protected-permissive operation with a lagging sequence. The combined paired database represented 324 configurations (= 3 × 108).

Each configuration in the database has two delay values. One value represents permissive left-turn operation and the second represents a specified change to the left-turn operation and phase sequence. Each delay value was used to estimate an associated annual road-user delay cost. The change in these costs represents the net benefit of the change. The cost change was used as the dependent variable for equation calibration.

Some of the intersection configurations with permissive operation were found to have one or more traffic movements with inadequate capacity and excessively large delays. The simulation results for these configurations were eliminated from database. This reduced the combined paired database to 288 observations.

A similar process was followed in the development of a paired database for pedestrian safety. The 432 intersections developed for the simulation analysis were also used to develop the safety database. The safety prediction models described previously in this chapter were used to estimate the expected frequency of left-turn-related pedestrian-vehicle crashes for each of the 432 configurations. These data were then combined to develop a paired database with 324 configurations. The overcapacity configurations were eliminated to yield 288 configurations. The crash costs were used to estimate the change in road user cost associated with each treatment, and this value was used as the dependent variable for equation calibration.

Critical Movement Analysis

Critical movement analysis is a useful technique for characterizing the utilization of signalized intersection capacity. It produces a critical flow ratio that varies from 0.0 to 1.0, where values near 0.0 represent low volumes (relative to the available capacity). In contrast, values near 1.0 represent high volumes (relative to the available capacity). The critical flow ratio calculation considers left-turn volume, through volume, number of lanes, saturation flow rate, left-turn mode, and phase sequence. For these reasons, it provides a desirable sensitivity to the key factors that influence the choice of left-turn mode and phase sequence.

The critical movement analysis technique is described in Chapter 16 of the *Highway Capacity Manual* (*9*). The ability to implement this technique is not a requirement for correct use of the guidelines developed for this project (and described in the next part of this chapter).

A preliminary analysis of the data indicated that the change in delay cost was influenced by the critical flow ratio. The following construct was found to provide the best fit to the data.

$$C_y = \left(\frac{t_L \; n_p}{1 - \sum (v/s)_{ci}} \right)_{base} - \left(\frac{t_L \; n_p}{1 - \sum (v/s)_{ci}} \right)_{proposed} \tag{19}$$

where,

C_y = critical flow ratio factor, s.
t_L = total phase lost time (= 4.0), s.
n_p = number of critical phases (= 2 for base mode, 3 or 4 for proposed mode and sequence).
$(v/s)_{ci}$ = flow ratio for critical phase i (i = 1, 2, 3, ..., 8).
v_{ci} = volume served by critical phase i, veh/h.
s_{ci} = saturation flow rate for critical phase i, veh/h.

There are two terms in Equation 19. The first term corresponds to the base configuration. All variables in this term apply to the base mode. The second term corresponds to the proposed mode and phase sequence. All variables in this term apply to the proposed configuration.

A negative value for the critical flow ratio factor C_y corresponds to an increase in cycle length and delay as a result of the change from the base configuration to the proposed configuration.

Prediction of Change in Pedestrian Safety

This section describes the development of an equation to predict the change in pedestrian-vehicle crash cost associated with a change in left-turn mode or sequence. This equation has a logical boundary condition such that it should predict zero change in cost when the base configuration is a match to the proposed configuration. It also predicts zero change in cost when there are no pedestrians or when there are no left-turn vehicles. It is based on the assumption that there is no change in vehicle or pedestrian volume as a result of the change in left-turn mode or sequence.

Several equation forms were evaluated using the assembled database. The form that provided the best fit to the data is shown in the following equation.

$$\Delta c_{cr} = \left(-0.0908 P_{p,prot} - 0.0356 P_{p,pplt,lead} + 0.0122 P_{p,pplt,lag}\right)\left(\sum (v_{lt} \times v_{ped,t})\right) \quad \textbf{(20)}$$

with

$$P_{p,prot} = \frac{\sum (v_{lt} \times v_{ped,t} \times I_{prot})_{proposed} - \sum (v_{lt} \times v_{ped,t} \times I_{prot})_{base}}{\sum (v_{lt} \times v_{ped,t})} \quad \textbf{(21)}$$

$$P_{p,pplt,lead} = \frac{\sum (v_{lt} \times v_{ped,t} \times I_{pplt,lead})_{proposed} - \sum (v_{lt,t} \times v_{ped,t} \times I_{pplt,lead})_{base}}{\sum (v_{lt} \times v_{ped,t})} \quad \textbf{(22)}$$

$$P_{p,pplt,lag} = \frac{\sum (v_{lt} \times v_{ped,t} \times I_{pplt,lag})_{proposed} - \sum (v_{lt} \times v_{ped,t} \times I_{pplt,lag})_{base}}{\sum (v_{lt} \times v_{ped,t})} \quad \textbf{(23)}$$

where,

Δc_{cr} = change in annual crash cost (positive change = cost increase) in 2009 dollars, \$/yr.
$P_{p,prot}$ = change in product of left-turn and pedestrian volume served by protected mode, expressed as a proportion of the total product for all left-turn and pedestrian volume pairs.
$P_{p,pplt,lead}$ = change in product of left-turn and pedestrian volume served by protected-permissive mode with leading phase sequence, expressed as a proportion of the total product for all left-turn and pedestrian volume pairs.
$P_{p,pplt,lag}$ = change in product of left-turn and pedestrian volume served by protected-permissive mode with lagging phase sequence, expressed as a proportion of the total product for all left-turn and pedestrian volume pairs.
I_{prot} = indicator variable (= 1 if left-turn volume is served by protected mode, 0 otherwise).
$I_{pplt, lead}$ = indicator variable (= 1 if left-turn volume is served by protected-permissive mode with leading phase sequence, 0 otherwise).
$I_{pplt, lag}$ = indicator variable (= 1 if left-turn volume is served by protected-permissive mode with lagging phase sequence, 0 otherwise).
v_{lt} = conflicting left-turn volume, veh/h.
$v_{ped,t}$ = pedestrian volume in the crosswalk (walking in either direction), p/h.

The second term in parentheses in Equation 20 is the sum of the product of the left-turn volume and the pedestrian volume for each crosswalk. The left-turn volume associated with a crosswalk is for the left-turn movement that *conflicts* with the crosswalk. A crosswalk's conflicting left-turn movement follows a path that (1) starts from the street that is parallel to the crosswalk and (2) ends by crossing the subject crosswalk. For example, the westbound left-turn movement conflicts with the eastbound crosswalk (i.e., the crosswalk on the south leg).

The numerator of Equations 21, 22, and 23 has two summation terms. The first term corresponds to the proposed configuration. All variables in this term apply to the proposed configuration. The second term corresponds to the base configuration. All variables in this term apply to the base configuration.

A positive value for the proportions computed by Equations 21, 22, or 23 corresponds to an increase in the proportion of conflicting left-turn vehicles and pedestrians that are served by protected or protected-permissive mode, as a result of the change from the base configuration to the proposed configuration.

The fit of Equation 20 is indicated by its coefficient of determination R^2 of 0.97. All of the constants in this equation are regression coefficients. These coefficients are significant at a 95 percent level (i.e., the probability that a coefficient is not different from zero is less than 0.05). The standard deviation of the predicted value is estimated as 0.129 times the predicted value.

Prediction of Change in Intersection Delay

This section describes the development of an equation to predict the change in intersection delay cost associated with a change in left-turn mode or sequence. This equation has a logical boundary condition such that it should predict zero change in cost when the base configuration is a match to the proposed configuration. It also predicts zero change in cost when there are no vehicles at the intersection. It is based on the assumption that there is no change in vehicle or pedestrian volume as a result of the change in left-turn mode or sequence.

Several equation forms were evaluated using the assembled database. The form that provided the best fit to the data is shown in the following equation.

$$\Delta c_d = 0.001\left(-0.0871\,C_y + 5.4034P_{v,prot} + 2.0824P_{v,pplt,lead} + 2.1906P_{v,pplt,lag}\right)\left(\sum v_i\right)^2 \quad \textbf{(24)}$$

with

$$P_{v,prot} = \frac{\sum (v_{lt} \times I_{prot})_{proposed} - \sum (v_{lt} \times I_{prot})_{base}}{\sum v_{lt}} \quad \textbf{(25)}$$

$$P_{v,pplt,lead} = \frac{\sum (v_{lt} \times I_{pplt,lead})_{proposed} - \sum (v_{lt,t} \times I_{pplt,lead})_{base}}{\sum v_{lt}} \quad \textbf{(26)}$$

$$P_{v,pplt,lag} = \frac{\sum (v_{lt} \times I_{pplt,lag})_{proposed} - \sum (v_{lt} \times I_{pplt,lag})_{base}}{\sum v_{lt}} \quad \textbf{(27)}$$

where,

Δc_d = change in annual delay cost (positive change = cost increase) in 2009 dollars, \$/yr.

$P_{v,prot}$ = change in left-turn volume served by protected mode, expressed as a proportion of the total left-turn volume.

$P_{v,pplt,lead}$ = change in left-turn volume served by protected-permissive mode with leading phase sequence, expressed as a proportion of the total left-turn volume.

$P_{v,pplt,lag}$ = change in left-turn volume served by protected-permissive mode with lagging phase sequence, expressed as a proportion of the total left-turn volume.

v_i = vehicle volume for movement i (i = 1, 2, 3, ..., 8), veh/h.

The second term in parentheses in Equation 24 is the sum of the vehicle volume entering the intersection. All traffic movements and all intersection approaches are included in this sum.

The numerator of Equations 25, 26, and 27 has two summation terms. The first term corresponds to the proposed configuration. All variables in this term apply to the proposed configuration. The second term corresponds to the base configuration. All variables in this term apply to the base configuration.

A positive value for the proportions computed by Equation 25, 26, or 27 corresponds to an increase in the proportion of left-turn vehicles that are served by protected or protected-permissive mode, as a result of the change from the base configuration to the proposed configuration.

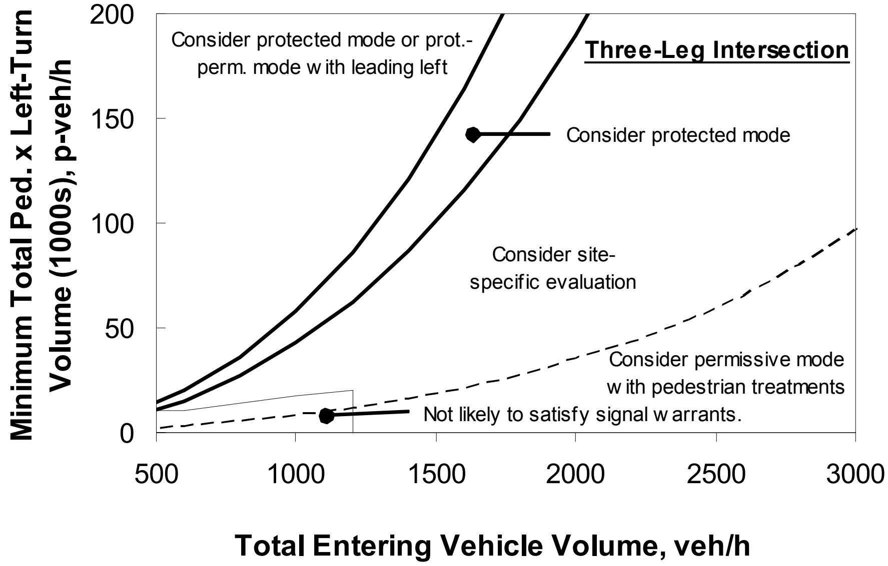
The fit of Equation 24 is indicated by its coefficient of determination R^2 of 0.89. All of the constants in this equation represent regression coefficients. These coefficients are significant at a 95 percent level of confidence or higher (i.e., the probability that a coefficient is not different from zero is less than 0.05). The standard deviation of the predicted value is estimated as 0.269 times the predicted value.

GUIDELINE DEVELOPMENT

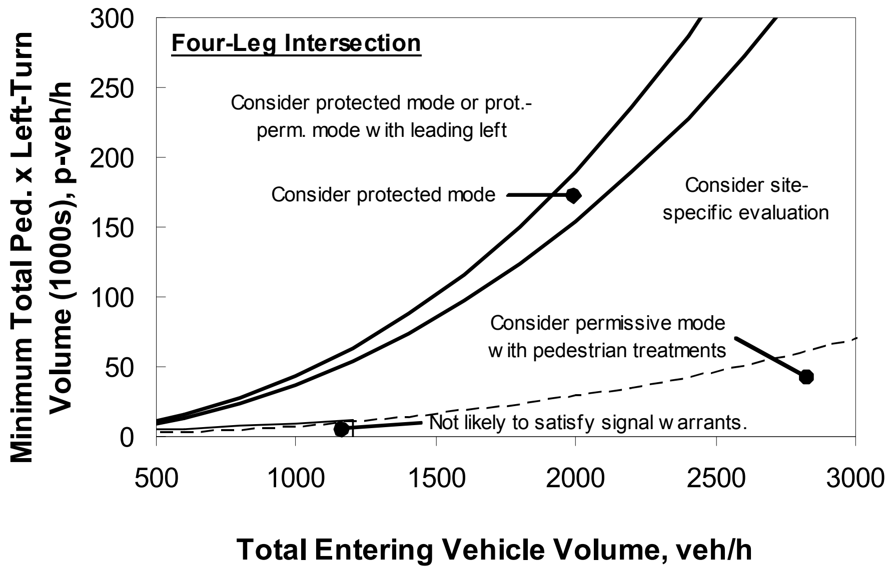
This part of the chapter describes the process used to develop guidelines for selecting the appropriate pedestrian safety treatment for a signalized intersection. The first section describes the development of guidelines for determining the appropriate left-turn mode based on pedestrian safety considerations. The second section describes the development of guidelines for evaluating a wide range of pedestrian safety treatments (including left-turn mode).

Left-Turn Mode Guideline Development

This section describes the process used to develop guidelines for selecting the appropriate left-turn mode and phase sequence at a signalized intersection. These guidelines are described in a report by Bonneson et al. (*10*), and are referred to therein as "pedestrian safety guidelines." They are based on the use of Figure 6-4.



a. Three-Leg Intersection.



b. Four-Leg Intersection.

Figure 6-4. Left-Turn Mode Selection Based on Pedestrian Safety.

Guideline Overview

Figure 6-4 is used to determine the appropriate left-turn mode for each left-turn movement and crosswalk of interest. Figure 6-4a applies to three-leg intersections. Figure 6-4b applies to four-leg intersections. The total volume entering the intersection during the analysis hour and the product of the conflicting pedestrian and left-turn volume is used with the appropriate figure to make this determination. Specifically, a vertical line is visualized extending upward from the x-axis value associated with the total entering volume. Similarly, a horizontal line is visualized extending to the right from the y-axis value associated with the volume product. The appropriate left-turn mode is identified by the point on the figure where these two lines intersect.

Figure 6-4 is based on consideration of road-user costs associated with pedestrian-vehicle crashes and vehicle delay. Threshold conditions for which a change in mode or sequence result in a reduction in road-user costs provide the basis for the guidelines.

The process considered intersection delay and crash frequency so an overall road-user cost could be the basis for guideline development. The delay cost is based on the value of travel time and reflects the delay to *all* vehicles traveling through the intersection. This approach recognizes that many signal-related pedestrian treatments for a crosswalk can change the signal operation and indirectly impact the service provided to most vehicles entering the intersection.

Road-User Cost Calculation

This subsection describes how the predictive equations described in the previous sections were used for guideline development. The objective of this development was to identify volume and geometry conditions where the reduction in pedestrian-vehicle crash costs associated with a change in left-turn mode or phase sequence is very likely to offset any increase in delay costs.

The research findings indicated that the total vehicular volume entering the intersection, left-turn volume, and pedestrian volume have the most significant effect on road-user costs. However, other factors were also found to influence road-user costs, but to a lower degree. These other factors include number of lanes, cycle length, walk interval duration, progression quality, and pedestrian crossing distance.

The research findings also indicated that the protected mode or the protected-permissive mode typically provide a road-user benefit (relative to the permissive mode) when vehicle and pedestrian volumes are high. However, there are some moderate volume combinations where it is uncertain whether the change in mode or phase sequence will provide a benefit. In these situations, the influence of other factors (as noted in the previous paragraph) will dictate whether road-user costs increase or decrease.

Protected, protected-permissive, and permissive modes were considered in the guideline development process. Leading and lagging phase sequence variations were considered for the protected-permissive mode; however, the protected-permissive mode with a lagging sequence was not found to provide significant pedestrian safety benefit.

Based on these findings, guideline development focused on the use of the protected mode or the protected-permissive mode with a leading phase sequence. It also focused on addressing the most influential variables (i.e,. total entering volume, the product of left-turn volume and pedestrian volume, and number of left-turn phases) and identifying conditions where each mode is very likely (or not very likely) to result in a benefit to road users. Conditions where the benefits are uncertain were also identified. A site-specific evaluation was recommended for these situations where other factors could be incorporated into the evaluation to ascertain whether a road-user benefit would be realized.

A series of evaluation scenarios were established for guideline development. The scenarios represented different combinations of entering volume, number of left-turn phases, left-turn operation, number of lanes on the major street approach, and number of lanes on the side street approach. The left-turn operation options considered include the protected mode and the protected-permissive mode with leading phase sequence. A set of base scenarios were also established that have the permissive mode on all approaches. The intersection geometrics and vehicle volumes represented in the set of scenarios are the same as those represented in the database assembled for equation calibration (as described in Chapter 4).

The critical movement analysis technique was used to determine the critical flow ratio for each scenario. Equation 19 was then used to compute the critical flow ratio factor for each scenario.

Equation 24 was used to estimate the change in annual delay cost for each scenario. The computed critical flow ratio factor was used for this estimate. Next, the percentile change in annual delay cost was set equal to the change in annual crash cost and algebraically manipulated to yield the volume product term $V_{lt \times ped}$ (i.e., the second term in Equation 20) as the dependent variable. Finally, the 95th percentile volume product term and the 5th percentile volume product term were computed using the following equations.

$$V_{lt \times ped,95} = V_{lt \times ped} \left(1.0 + 2 f \sqrt{0.269^2 + 0.129^2}\right) \quad \textbf{(28)}$$

$$V_{lt \times ped,5} = V_{lt \times ped} \left(1.0 - 2 \sqrt{0.269^2 + 0.129^2}\right) \quad \textbf{(29)}$$

where,

$V_{lt \times ped}$ = product of left-turn volume and pedestrian volume, veh-ped/h.
$V_{lt \times ped,\,95}$ = 95th percentile volume product term, veh-ped/h.
$V_{lt \times ped,\,5}$ = 5th percentile volume product term, veh-ped/h.
f = adjustment factor to account for non-normal distribution (= 2.0).

In Figure 6-4a or 6-4b, the solid boundary line for the region labeled "Consider protected mode or protected-permissive mode with leading left" is based on the 95th percentile volume for the protected-permissive mode with a leading sequence. Just below this line is the solid boundary line for the region labeled "Consider protected mode." It is based on the 95th percentile volume for the protected mode. The dashed boundary line is based on the 5th percentile volume for the protected mode.

The dependent variable in Figures 6-4a and 6-4b is represented as the "minimum total pedestrian x left-turn volume." Volume products that exceed this minimum, will be associated with conditions that are very likely to justify the use of a protected or protected-permissive mode. In contrast, volume products that are lower than this minimum will be associated with conditions that are very unlikely to justify the use of a protected or protected-permissive mode.

The region between the dashed line and the solid lines represents conditions where the reduction in pedestrian-vehicle crash costs may be sufficient to offset any increase in delay costs. However, the answer to the question of whether the proposed left-turn operation results in a net benefit will depend on other signal timing and geometric factors. For these conditions, the analyst is encouraged to conduct a site-specific evaluation that considers all relevant factors in the determination of the appropriate left-turn mode.

Basis for Crash Experience Threshold

The left-turn mode guidelines include a crash experience check based on the threshold of four or more reported left-turn-related pedestrian-vehicle crashes in a three-year period. This threshold is based on the crash threshold of 14 total left-turn-related crashes in a three-year period that is used to determine the need for protected operation ("total" in this context is the sum of vehicle-vehicle and pedestrian-vehicle crashes) cited in the *Traffic Signal Operations Handbook* (*11*). The threshold value of "four" is computed by multiplying 14 by the ratio of average crash cost to average vehicle-pedestrian crash cost (both for urban intersections) and rounding up. These costs were identified as $47,455 and $214,050, respectively, in Table 6-8 and its related discussion.

Alternative Treatment Guide Development

This section describes the development of guidelines for evaluating alternative pedestrian safety treatments for signalized intersections (not including the use of protected or protected-permissive left-turn mode). These guidelines are described in Appendix E of the *Traffic Signal Operations Handbook: Second Edition* (*12*). A before-after observational study was conducted to evaluate four of the treatments. The findings of this study are documented in Appendix B.

Summary of Treatment Effectiveness

This subsection summarizes the findings from the separate analyses of treatment effect on intersection delay and left-turn-related pedestrian-vehicle conflicts. The description of the conflict analysis is described in a previous part of this chapter. The treatments that are the focus of this subsection are identified in Table 2-3 of Chapter 2.

A simulation model was used to quantify the intersection delay for 108 unique, widely varied combinations of intersection volume and geometry. Treatment effect was quantified by re-simulating each of the 108 combinations with the treatment implemented at the simulated intersection. The analysis of the resulting data indicated that treatment effect varied significantly among the various combinations. The more influential factors included major-street through volume, major-street left-turn volume, number of major-street lanes, minor-street left-turn volume, and pedestrian volume.

The general trend in the change in intersection delay is summarized in Table 6-10. When averaged over all 108 combinations, the change in delay exhibited a trend toward an increase in delay for each treatment. However, treatments numbered 1, 2, 3, 4, and 7 in Table 6-10 were found to reduce delay under specific combinations of volume and geometry.

Table 6-10. Effect of Pedestrian Treatments on Delay and Conflicts at Intersections.

Treatment	Intersection Delay	Left-Turn-Related Conflicts
Treatments Based on Conversion from Permissive Mode		
1. Provide protected-permissive mode with leading phase sequence	10 to 40 percent reduction in delay for large intersections with high volume. All other intersections experience a 10 to 30 percent increase in delay.	47 percent reduction in conflicts to legal pedestrians. Increase in cycle length may increase number of illegal pedestrians and related conflicts.
2. Provide protected-permissive mode with leading phase sequence and flashing yellow display	15 to 45 percent reduction in delay for large intersections with high volume. All other intersections experience a 5 to 25 percent increase in delay.	Safety effect unknown. Increase in cycle length may increase number of illegal pedestrians and related conflicts.
3. Provide protected left-turn mode	10 to 40 percent reduction in delay for large intersections with high volume. All other intersections experience a 15 to 55 percent increase in delay.	100 percent reduction in conflicts to legal pedestrians. Increase in cycle length may increase number of illegal pedestrians and related conflicts.
4. Provide protected-permissive mode with lagging phase sequence	5 to 30 percent reduction in delay for large intersections with high volume. All other intersections experience a 15 to 40 percent increase in delay.	Negligible reduction in conflicts to legal pedestrians. Increase in cycle length may increase number of illegal pedestrians and related conflicts.
Treatments Used in Conjunction with Permissive Mode		
5. Provide leading pedestrian interval	10 to 70 percent increase in delay for large intersections. 0 to 10 percent increase in delay for small intersections.	Previous research indicates a 59 percent reduction in pedestrian-related crashes at intersections (*13*).
6. Provide exclusive pedestrian phase	20 to 40 percent increase in delay for low pedestrian volume. 40 to 80 percent increase in delay for high pedestrian volume.	Previous research indicates a 50 percent reduction in pedestrian-related crashes at intersections (*4*). Increase in cycle length may increase number of illegal pedestrians and related conflicts.
7. Provide pedestrian clear interval entirely during green	0 to 15 percent reduction in delay for small intersections with low volume. All other intersections experience a 0 to 40 percent increase in delay.	Negligible reduction in conflicts to legal pedestrians. Increase in cycle length may increase number of illegal pedestrians and related conflicts.
8. Add turning vehicle warning signs and markings for pedestrians	0 percent change in intersection delay.	Previous research indicates sign and marking treatments reduce conflicts, but the amount varies widely (*4, 14*).
9. Prohibit pedestrian crossing	Varies. May reduce delay if pedestrian accommodations in current signalization increase the cycle length.	100 percent reduction in conflicts to legal pedestrians. Increase in travel distance may increase number of illegal pedestrians and related conflicts.

The pedestrian-vehicle conflict model and the legal pedestrian volume model were used to evaluate the effect of several treatments on conflict frequency. The estimated effect of these treatments is summarized in Table 6-10.

The use of a protected-permitted mode with a leading phase sequence was found to reduce conflicts by 47 percent. In contrast, the protected-permitted mode with a lagging phase sequence was not found to reduce conflicts. None of the sites with the protected-permitted left-turn mode had a flashing yellow display, so this display could not be evaluated on the basis of conflicts.

The use of a protected left-turn mode, exclusive pedestrian phase, or pedestrian crossing prohibition is rationalized to eliminate left-turn-related conflicts. The use of a leading pedestrian interval and the use of warning signs (or markings) for pedestrians were not available to be evaluated at the study sites.

Supplemental Treatments

The calibrated pedestrian-vehicle conflict models (i.e., Equations 10 and 12) and the legal pedestrian volume model (i.e., Equation 15) were examined to determine if additional treatments were evident in the model terms. The findings from this examination revealed the following viable treatments:

- Reduce signal cycle length – reduces pedestrian delay which reduces conflict frequency; also increases the legal pedestrian volume which reduces conflicts due to illegal crossings.
- Reduce crossing distance – reduces vehicle travel time to the conflict area which reduces conflicts.
- Invoke pedestrian recall (when phase is actuated) – increases the legal pedestrian volume which reduces conflicts due to illegal crossings.
- Increase walk interval duration (without increasing cycle length) – reduces pedestrian delay which reduces conflict frequency.

One technique for reducing the crossing distance at an intersection is the use of curb extensions (or bulb-outs). A curb extension can be installed on any number of corners at an intersection. It is a viable treatment when on-street parking is provided and, if bicycle traffic is significant, a bicycle lane is provided. The corner radius and curb edge should be designed to accommodate trucks turning at a slow speed.

If crossing distance is reduced, it may also be possible to reduce the pedestrian clear interval. In some instances, a reduction in the pedestrian clear interval will correspond to a reduction in phase duration, which could reduce cycle length and further reduce conflicts.

The aforementioned models were combined with the crash prediction model (i.e., Equation 18), the pedestrian-vehicle crash cost in Table 6-8, and the value of travel time in Table 6-9, to develop an analytic procedure for estimating the road-user costs associated with the supplemental treatments identified in this subsection. This procedure is described in Appendix E of the *Traffic Signal Operations Handbook: Second Edition* (*12*).

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APPENDIX A

STUDY SITE CHARACTERISTICS

APPENDIX A. STUDY SITE CHARACTERISTICS

OVERVIEW

This appendix describes the safety data collection sites. A "site" is defined as one crosswalk and the left-turn movement that crosses the crosswalk of interest. Hence, one intersection can yield up to four sites. Figure A-1 illustrates the naming conventions for a site, including its two streets, subject left-turn movement, and subject crosswalk. In this appendix, sites are identified by their intersection number and the approach direction from which the subject left-turn movement originates.

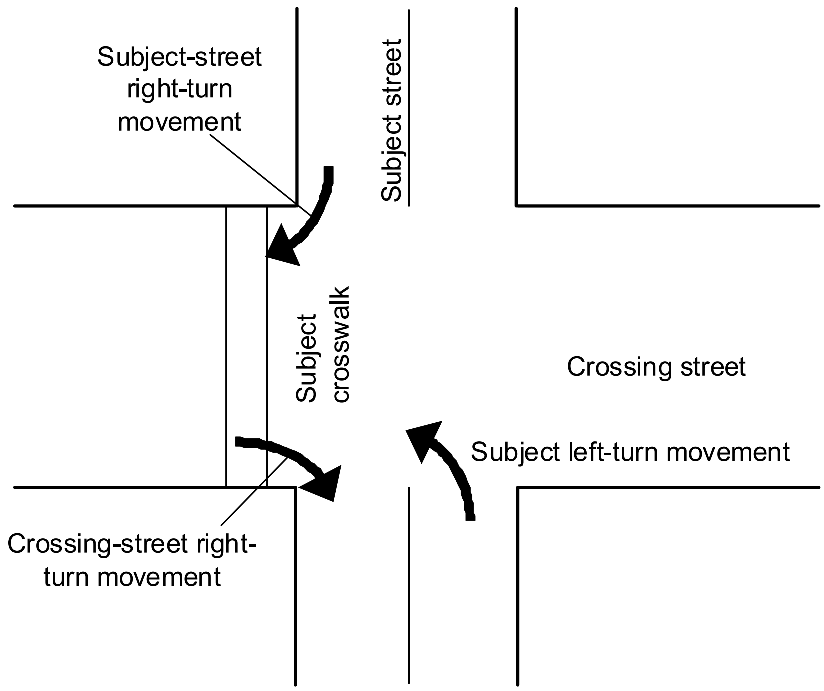

Figure A-1. Study Site Naming Conventions.

This appendix consists of four sections. The first section describes the distribution of the study sites in terms of their geographic location and key characteristics. The second and third sections provide more detailed information about the traffic control and geometric characteristics of the sites as measured in the field or from aerial photography. The last section explains the categorization of sites for data analysis.

SITE LOCATIONS

The site selection process began with interviews that were conducted in an earlier task of this research project. The interviewees included members of the Project Monitoring Committee and practitioners in various Texas cities and TxDOT districts. Each interviewee named a few candidate data collection sites. To obtain additional information about the candidate sites' geometry and traffic control, a review of aerial and street-level photographs was conducted using Google Earth®. The interviewees' responses and the knowledge obtained through the photograph review were combined to yield the list of study sites provided in Table A-1.

Table A-1. Study Site Locations.

City	Area Type	North/South Street	East/West Street	Intersection Number	Subject Left-Turn Movement
Austin	Downtown grid	Congress Avenue	4th Street	4	Northbound
				4	Eastbound
				4	Southbound
				4	Westbound
		Congress Avenue	5th Street	5	Eastbound
		Congress Avenue	6th Street	6	Northbound
				6	Westbound
		Congress Avenue	7th Street	24	Southbound
	University campus	Guadalupe Street	21st Street	7	Eastbound
				7	Westbound
		Guadalupe Street	22nd Street	8	Eastbound
		Guadalupe Street	24th Street	9	Eastbound
		Guadalupe Street	Dean Keeton Street	10	Southbound
		Guadalupe Street	27th Street	12	Westbound
		San Jacinto Boulevard	Dean Keeton Street	15	Northbound
				15	Southbound
		Medical Arts Street / Robert Dedman Drive	Dean Keeton Street	16	Northbound
				16	Southbound
College Station	University campus	Spence Street	University Drive	13	Northbound
				13	Southbound

Study sites were chosen from among the cities of College Station and Austin. The College Station sites are located close to the Texas A&M University campus. The Austin sites were chosen from the downtown city grid and the area surrounding the University of Texas at Austin campus. Collectively, these sites represented a range of vehicular and pedestrian volumes.

The study of each site was a minimum of two hours in duration. During each study, pedestrian and vehicle operations for the subject site were recorded on videotape using discreetly located camcorders. All studies occurred during the hours of peak pedestrian travel. At the sites in the Austin downtown grid, the time periods coinciding with lunch, dinner, and the afternoon peak commute period yielded significant pedestrian volumes. At the sites near the universities, pedestrian volumes were significant throughout most of the day, with noticeable peaks during the lunch hour. A survey was conducted at each site to record its traffic control and geometric characteristics.

TRAFFIC CONTROL CHARACTERISTICS

During the site surveys, the following traffic control characteristics were noted for the study sites: speed limit, pedestrian control type, and use of other special treatments. The following three special treatments were observed at some study sites:

- Audible pedestrian signals (blind pedestrian treatment).
- Prohibition of right-turn-on-red when pedestrians are present.
- Posting of the R10-15 sign ("TURNING TRAFFIC MUST YIELD TO PEDESTRIANS").

The sites' traffic control characteristics are listed in Table A-2. As shown, a range of speed limits and pedestrian control types are represented among the sites. Some of the streets did not have a posted speed limit in the immediate vicinity of a study site. The streets without posted speed limits tended to be driveways, campus streets, or streets within the Austin downtown grid.

Table A-2. Study Site Traffic Control Characteristics.

Intersection Number	Subject Left-Turn Movement	Speed Limit, mph		Pedestrian Signal Type	Push Button Presence	Special Treatments Used [1]
		Subject Street	Crossing Street			
4	Northbound	30	not posted	Countdown	No	None
4	Eastbound	not posted	30	Countdown	No	None
4	Southbound	30	not posted	Countdown	No	None
4	Westbound	not posted	30	Countdown	No	None
5	Eastbound	not posted	30	Countdown	No	None
6	Northbound	30	not posted	Countdown	No	None
6	Westbound	not posted	30	Countdown	No	None
24	Southbound	30	not posted	Countdown	No	R10-15
7	Eastbound	not posted	30	Conventional	No	R10-15
7	Westbound	not posted	30	Conventional	No	R10-15
8	Eastbound	not posted	30	Conventional	No	R10-15
9	Eastbound	not posted	30	Conventional	No	None
10	Southbound	30	30	Conventional	No	Aud, RTOR, R10-15
12	Westbound	not posted	30	Conventional	Yes	None
15	Northbound	15	30	Conventional	Yes	None
15	Southbound	not posted	30	Conventional	Yes	None
16	Northbound	15	30	Conventional	No	Aud
16	Southbound	30	30	Conventional	No	Aud
13	Northbound	20	35	Countdown	Yes	None
13	Southbound	not posted	35	Countdown	Yes	None

Note:
1 - "Aud" = audible pedestrian signal, "RTOR" = right-turn-on-red prohibited when pedestrians are present, "R10-15" = posting of R10-15 sign

Site signalization characteristics were also noted during the site surveys. These characteristics included: left-turn mode (permissive or protected-permissive), phase sequence, and allowance of right-turn-on-red. The signalization characteristics are provided in Table A-3.

Table A-3. Study Site Signalization Characteristics.

Intersection Number	Subject Left-Turn Movement	Left-Turn Mode [1]	Phase Sequence	Right-Turn-on-Red Allowance [2]	
				Subject Street	Crossing Street
4	Northbound	Perm.	No left-turn phase	Yes	Yes
4	Eastbound	Perm.	No left-turn phase	Yes	Yes
4	Southbound	Perm.	No left-turn phase	Yes	Yes
4	Westbound	Perm.	No left-turn phase	Yes	Yes
5	Eastbound	Perm.	No left-turn phase	No	No
6	Northbound	P+P	Lagging	No	No
6	Westbound	Perm.	No left-turn phase	No	No
24	Southbound	P+P	Lagging	Yes	No
7	Eastbound	Perm.	No left-turn phase	No	Yes
7	Westbound	Perm.	No left-turn phase	Yes	Yes
8	Eastbound	Perm.	No left-turn phase	Yes	Yes
9	Eastbound	P+P	Leading	Yes	Yes
10	Southbound	P+P	Leading	When pedestrians are not present	Yes
12	Westbound	Perm.	No left-turn phase	No	Yes
15	Northbound	Perm.	No left-turn phase	Yes	Yes
15	Southbound	Perm.	No left-turn phase	Yes	Yes
16	Northbound	Perm.	No left-turn phase	Yes	Yes
16	Southbound	Perm.	No left-turn phase	Yes	Yes
13	Northbound	Perm.	No left-turn phase	Yes	Yes
13	Southbound	Perm.	No left-turn phase	Yes	Yes

Notes:
1 - “P+P” = protected-permissive, “Perm.” = permissive.
2 - The relevant right-turn movements are illustrated on Figure A-1.

Some of the study sites had right-turn-on-red restrictions for certain times of day. For these sites, the right-turn-on-red allowances listed in Table A-3 reflect the allowances that were in effect during field data collection. None of the sites’ subject crosswalks had leading, lagging, or exclusive pedestrian intervals. All of the sites were located within coordinated signal systems.

GEOMETRIC CHARACTERISTICS

Site geometric characteristics such as lane assignments and crosswalk dimensions were extracted from aerial photographs or observed during the site surveys. Collectively, the study sites represent a range in key geometric variables like crosswalk length and number of lanes. Geometric characteristics for the study sites are provided in Table A-4.

Table A-4. Study Site Geometric Characteristics.

Intersection Number	Subject Left-Turn Movement	Number of Lanes		Number of Travel Directions	
		Receiving Subject Left-Turn Movement	Opposing Through and Right	Subject Street	Crossing Street
4	Northbound	1	3	2	2
4	Eastbound	3	1	2	2
4	Southbound	1	3	2	2
4	Westbound	3	2	2	2
5	Eastbound	3	0	1	2
6	Northbound	4	3	2	1
6	Westbound	3	0	1	2
24	Southbound	4	3	2	1
7	Eastbound	2	2	2	2
7	Westbound	2	1	2	2
8	Eastbound	2	1	2	2
9	Eastbound	2	1	2	2
10	Southbound	2	2	2	2
12	Westbound	2	0	1	2
15	Northbound	2	1	2	2
15	Southbound	2	3	2	2
16	Northbound	2	2	2	2
16	Southbound	2	3	2	2
13	Northbound	3	1	2	2
13	Southbound	3	2	2	2

All of the subject left-turn movements were served by single left-turn lanes. At the sites where the subject street was two-way, the left-turn movement was served by a single exclusive lane. At the sites where the subject street was one-way, the left-turn movement was served by a single shared left/through lane. All but one of the intersections were four-leg intersections, the exception being intersection 10. The crosswalks at the study sites varied from 8 to 16 ft in width and 40 to 110 ft in length.

SITE CATEGORIZATION

One of the goals of site selection was to obtain sites that collectively offered both the permissive and protected-permissive left-turn modes. However, sites with the permissive left-turn mode were favored in the selection process because they provided more exposure to interaction between pedestrians and left-turning vehicles. Another site selection goal was to obtain a balance between sites with short and long crosswalks. It was rationalized that sites with longer crosswalks provided left-turning drivers with more flexibility to find gaps in the pedestrian streams. The longer crosswalks were associated with sites that had a larger number of receiving lanes. Each receiving lane represents an alternative exit path from which the left-turn driver can choose when avoiding pedestrian platoons.

The study sites were categorized based on the following two characteristics:

- Left-turn mode for subject left-turn movement (permissive or protected-permissive).
- Crosswalk conflict area length (short or long).

The crosswalk conflict area is the portion of the crosswalk that left-turning vehicles must cross. Its length is equal to the combined width of the receiving lanes. This length is equal to the crosswalk length at sites where the crossing street serves one-way vehicular travel. A conflict area is considered "short" if the site has two or fewer receiving lanes available for the subject left-turn movement. It is considered "long" if the site has three or more receiving lanes. The number of sites within these categories is shown in Table A-5.

Table A-5. Study Site Categories.

Conflict Area Length	Number of Sites by Left-Turn Mode	
	Permissive	**Protected-Permissive**
Long	6	2
Short	10	2

APPENDIX B

BEFORE-AFTER EVALUATION OF SELECTED TREATMENTS

APPENDIX B. BEFORE-AFTER EVALUATION OF SELECTED TREATMENTS

OVERVIEW

This appendix documents before-after evaluations that were conducted on selected pedestrian safety treatments. The before-after evaluations were conducted to evaluate the safety benefits of these treatments, and to confirm that the level of safety improvement was consistent with that indicated by the guidelines developed in Chapter 6.

This appendix consists of three parts. The first part describes the study experimental design and identifies the treatments that were implemented at the study sites. The second part documents the data analysis for the before-after evaluation. The third part summarizes the findings.

EXPERIMENTAL DESIGN

The before-after evaluation included the identification of candidate treatments, identification of treatment implementation sites, and collection of conflict data. These activities are summarized in the following paragraphs.

Candidate Treatments

The candidate pedestrian safety treatments considered for the before-after evaluation are identified in the following list. The first nine treatments were identified during the literature review and are described in Table 2-3 of Chapter 2. The last four treatments were identified as a result of the examination of data collected and evaluated during the course of the research project. They are described in Chapter 6.

- Provide protected-permissive mode.
- Provide protected-permissive mode using flashing yellow signal display.
- Provide protected left-turn mode.
- Provide lagging phase sequence.
- Provide leading pedestrian interval.
- Provide exclusive pedestrian phase.
- Provide pedestrian clear interval entirely during green.
- Add turning vehicle warning signs and markings.
- Prohibit pedestrian crossing.
- Reduce signal cycle length.
- Reduce crossing distance (by installing curb extensions at the corners).
- Invoke pedestrian recall (when phase is actuated).
- Increase walk interval duration (without increasing cycle length).

Treatment Implementation Sites

The approach used to identify treatment sites was to draw from the pool of sites included in the initial data collection task, as described in Chapter 4. These sites were evaluated using the guidelines described in Chapter 6. Then, those sites with the most potential for pedestrian safety improvement were identified. These sites were labeled the "before" sites. The data previously collected (and summarized in Chapter 5) were labeled the "before" data. This process led to the identification of six sites in the vicinity of the University of Texas-Austin campus.

The selected sites and their corresponding treatments are listed in Table B-1. Additional information about each site is provided in Appendix A.

Table B-1. Before Study Sites and Associated Treatments.

Intersection	Intersection Number	Subject Left-Turn Movement	Treatment
Guadalupe Street & 21st Street	7	Eastbound and Westbound	Add a leading protected-permissive left-turn phase.
Guadalupe Street & 24th Street	9	Eastbound	Change the left-turn operational mode from protected-permissive leading to split.
Guadalupe Street & 27th Street	12	Westbound	Implement a pedestrian recall on all through phases.
Dean Keeton Street & Medical Arts Street	16	Northbound and Southbound	Increase the walk intervals on Medical Arts Street by 5 s without changing the cycle length.

The City of Austin implemented the treatments between November 2010 and January 2011. None of the sites' cycle lengths were changed when the treatments were implemented.

Data Collection

Following treatment implementation, data were collected at each of the treated sites. The data collection procedure was the same as that used to collect the "before" data, as described in Chapter 4.

The data were collected in February 2011. They were labeled the "after" data. Two hours of data were collected at each site. In all cases, at least one month of acclimation occurred between treatment implementation and data collection. At every site, the "after" data were collected on the same day of the week and during the same hours of the day as when the "before" data were collected. No data collection occurred on holidays. Data were collected only when classes at the University of Texas-Austin were in session.

DATA ANALYSIS

This part of the appendix describes the data reduction and analysis. The first section describes the sample size for each treated site. The second section describes the statistical analysis of the reduced data. The last section summarizes the analysis results.

Sample Size

The following data elements were tabulated for each site for both the "before" and "after" study periods:

- Data collection time period.
- Left-turning vehicle volume.
- Number of legal pedestrians.
- Number of illegal pedestrians.
- Total number of pedestrians.
- Number of legal pedestrian-vehicle conflicts.
- Number of illegal pedestrian-vehicle conflicts.
- Number of total pedestrian-vehicle conflicts.

The counts of pedestrians and pedestrian-vehicle conflicts are provided in Table B-2.

Table B-2. Counts of Pedestrians and Pedestrian-Vehicle Conflicts.

Data Period	Intersection Number	Subject Left-Turn Movement	Number of Pedestrians (N_{ped})			Number of Pedestrian-Vehicle Conflicts (N_{co})		
			Legal	Illegal	Total	Legal	Illegal	Total
Before	7	Eastbound	377	80	457	6	0	6
		Westbound	461	54	515	8	3	11
		Both	838	134	972	14	3	17
	9	Eastbound	459	283	742	7	13	20
	12	Westbound	140	46	186	7	2	9
	16	Northbound	85	71	156	10	2	12
		Southbound	41	50	91	5	0	5
		Both	126	121	247	15	2	17
		Total:	1563	584	2147	43	20	63
After	7	Eastbound	262	215	477	3	1	4
		Westbound	389	178	567	2	8	10
		Both	653	393	1046	5	9	14
	9	Eastbound	590	200	790	0	1	1
	12	Westbound	129	43	172	1	0	1
	16	Northbound	59	69	128	11	3	14
		Southbound	32	15	47	4	0	4
		Both	91	84	175	15	3	18
		Total:	1461	720	2181	21	13	34

The left-turn volumes and data collection time periods are provided in Table B-3. In cases where the same treatment was applied at multiple sites, data are provided both for the individual sites and for the aggregation of sites with the same treatment.

Table B-3. Left-Turn Volumes and Data Collection Time Periods.

Data Period	Intersection Number	Subject Left-Turn Movement	Left-Turn Volume (v_{lt}), veh/h	Data Collection Time Period (t), h
Before	7	Eastbound	18	1.91
		Westbound	50	1.96
		Both	68	3.87
	9	Eastbound	214	1.99
	12	Westbound	53	2.33
	16	Northbound	103	2.00
		Southbound	42	1.99
		Both	145	3.99
		Total:	480	12.18
After	7	Eastbound	20	1.99
		Westbound	61	2.00
		Both	81	3.99
	9	Eastbound	191	1.95
	12	Westbound	69	2.01
	16	Northbound	103	1.92
		Southbound	36	1.99
		Both	139	3.90
		Total:	480	11.85

In most cases, the left-turn and pedestrian volumes were similar between the "before" and "after" evaluation periods. The exceptions are the crosswalks at intersection 16, which had roughly two-thirds the number of pedestrians in the "after" period as in the "before" period. This change may be attributed to the closing of a popular restaurant and coffee shop at the intersection between the two data collection time periods.

Statistical Analysis

The following measures of effectiveness were used to evaluate the treatments:

- Legal pedestrian-vehicle conflict rate.
- Illegal pedestrian-vehicle conflict rate.
- Total pedestrian-vehicle conflict rate.
- Pedestrian compliance percentage (percentage of total pedestrians crossing legally).
- Early pedestrian percentage (percentage of pedestrians starting to cross as much as five seconds prior to the start of the WALK indication).

The pedestrian-vehicle conflict rates were computed per 1000 pedestrians per left-turning vehicle volume. Conflict rates were preferred over conflict frequencies because they account for changes in exposure between the two evaluation periods. Reductions in pedestrian-vehicle conflict rates or increases in the pedestrian compliance percentage can be regarded as positive safety impacts.

Conflict Rates

Table B-4 shows the legal, illegal, and total pedestrian-vehicle conflict rates for the "before" and "after" evaluation periods. These rates were computed using the following equation.

$$V_{co,i} = 1000 \frac{t\ N_{co,i}}{N_{ped,i}\ v_{lt}} \quad \textbf{(30)}$$

where,

$V_{co,\,i}$ = conflict rate for pedestrian type i ($i = L$: legal, I: illegal), conflicts/1000 p/veh.
$N_{co,\,i}$ = number of pedestrian-vehicle conflicts involving pedestrian type i, conflicts.
v_{lt} = conflicting left-turn volume, veh/h.
t = study duration, h.
$N_{ped,\,i}$ = number of pedestrians of type i crossing the crosswalk, p.

Table B-4. Pedestrian-Vehicle Conflict Rates.

Intersection Number	Subject Left-Turn Movement	Pedestrian-Vehicle Conflict Rate (V_{co}), conflicts/1000 p/veh					
		Legal		Illegal		Total	
		Before	After	Before	After	Before	After
7	Eastbound	1.69	1.14	0.00	0.46	1.40	0.83
	Westbound	0.68	0.17	2.18	1.47	0.84	0.58
	Both	0.95	0.38	1.28	1.13	1.00	0.66
9	Eastbound	0.14	0.00	0.43	0.05	0.25	0.01
12	Westbound	2.20	0.23	1.91	0.00	2.13	0.17
16	Northbound	2.28	3.47	0.55	0.81	1.49	2.04
	Southbound	5.77	6.90	0.00	0.00	2.60	4.70
	Both	3.27	4.63	0.45	1.00	1.89	2.89
Average:		0.70	0.35	0.87	0.45	0.74	0.38

Inspection of the trends in Table B-4 reveals that in most cases, the conflict rates for legal pedestrians were lower in the "after" period than in the "before" period. One exception is intersection 16, where the walk interval duration was increased from 5 to 10 s. The trends for legal pedestrians and total pedestrians were similar.

With respect to the illegal pedestrian-vehicle conflict rate, the effects of the treatments were mixed. Two of the sites (the eastbound left-turn movement at intersection 7 and the northbound left-turn movement at intersection 16) experienced an increase in conflict rate, three of the sites experienced a decrease, and one site experienced no change.

The effect of a pedestrian safety treatment can be considered "positive" if the treatment reduces the legal pedestrian-vehicle conflict rate. However, if the treatment also tends to reduce the pedestrian compliance percentage while increasing the illegal pedestrian-vehicle conflict rate, the overall result may be an increase in conflicts. Hence, total pedestrian-vehicle conflict rate is a more informative measure of treatment effectiveness; however, the compliance percentage is a measure that should also be considered.

Total pedestrian-vehicle conflict rate was analyzed to determine whether the changes in conflict rate at the treated sites were statistically significant. To address concerns about illegal pedestrians, a statistical analysis was conducted on pedestrian compliance percentage. The analysis of compliance percentage is presented in the next subsection.

The statistical analysis method used for the evaluation of conflict rate is that documented by Griffin and Flowers (*1*, Chapter 2). The method requires conflict counts and an exposure variable as inputs. It produces a *Z*-score that follows the standardized normal distribution. It indicates the statistical significance of conflict rate changes. The method is described by the following equation.

$$Z = \frac{\dfrac{A+0.5}{E_A} - \dfrac{B-0.5}{E_B}}{\sqrt{\dfrac{\dfrac{A+B}{E_A+E_B}}{E_A} + \dfrac{\dfrac{A+B}{E_A+E_B}}{E_B}}} \qquad \textbf{(31)}$$

where,

A = total pedestrian-vehicle conflict count in the "after" period (from Table B-2), conflicts.
B = total pedestrian-vehicle conflict count in the "before" period (from Table B-2), conflicts.
E_A = exposure in the "after" period, 1000 p-veh.
E_B = exposure in the "before" period, 1000 p-veh.

The exposure variable in each data collection period was computed with the following equation.

$$E_j = \frac{\left(N_{ped,I,j} + N_{ped,L,j}\right)\ v_{lt,j}}{1000\ \ t_j} \qquad \textbf{(32)}$$

where,

E_j = exposure in period j ($j = A$: after, B: before), 1000 p-veh.
$v_{lt,\,j}$ = conflicting left-turn volume in period j, veh/h.
t_j = study duration in period j, h.
$N_{ped,\,i,\,j}$ = number of pedestrians of type i crossing the crosswalk in period j, p.

The data used to compute exposure are provided in Table B-2 and Table B-3. The null hypothesis of this test is that the conflict rates in the two periods are equal. It is shown in the following equation.

$$H_o\!: \ \frac{A}{E_A} = \frac{B}{E_B} \qquad \textbf{(33)}$$

The results of the statistical analysis are provided in the two rightmost columns of Table B-5. Changes having p-values less than 0.05 are considered statistically significant.

Table B-5. Statistical Analysis Results for Total Conflict Rates.

Intersection Number	Subject Left-Turn Movement	Z [1]	p-value	Percent Change in Rate	Statistically Significant Change?
7	Eastbound	-0.49	0.62	-40	No
	Westbound	-0.64	0.52	-31	No
	Both	-0.97	0.33	-34	No
9	Eastbound	-3.85	< 0.01	-95	Yes
12	Westbound	-2.77	0.01	-92	Yes
16	Northbound	0.99	0.32	36	No
	Southbound	1.26	0.21	81	No
	Both	1.43	0.15	53	No

Notes:
1 – The *Z*-scores were computed using Equation 31.

The statistical analysis revealed that the conflict rate reductions at intersections 9 and 12 were statistically significant. The conflict rate reductions at intersection 7 were positive but statistically insignificant. The statistically insignificant increases in conflict rates at intersection 16 are more likely attributable to the low pedestrian and vehicle volumes than to effects of the treatment. The total number of conflicts increased by just one at the intersection 16 sites (17 in the "before" period and 18 in the "after" period). Hence, the conflict rate increases at intersection 16 are neither statistically nor practically significant.

Compliance Percentages

Table B-6 provides a summary of compliance percentages observed in the two data collection periods. This percentage was computed using the following equation.

$$P_{L,j} = 100 \frac{N_{ped,L,j}}{N_{ped,L,j} + N_{ped,I,j}} \tag{34}$$

where,
$P_{L,j}$ = percent of pedestrians crossing legally during period j ($j = A$: after, B: before), percent.

The two sites that experienced increases in illegal pedestrian-vehicle conflict rate (i.e., eastbound left turn at intersection 7, northbound left turn at intersection 16) also experienced decreases in the pedestrian compliance percentage. At these sites, there was an increase in the total number of illegal pedestrians and the conflict rate associated with these pedestrians.

Table B-6. Pedestrian Compliance Percentages.

Intersection Number	Subject Left-Turn Movement	Compliance Percentage (P_L), %		Statistically Significant Change?
		Before	After	
7	Eastbound	82.5	54.9	Yes
	Westbound	89.5	68.7	Yes
	Both	86.2	62.4	Yes
9	Eastbound	61.9	74.7	Yes
12	Westbound	75.3	75.0	No
16	Northbound	54.5	46.1	No
	Southbound	45.1	68.1	Yes
	Both	51.0	52.0	No
Average:		68.3	61.8	Yes

An odds-ratio test was conducted on the pedestrian compliance percentages. This test is described by Ott and Longnecker (*2*, Chapter 10). The use of odds accounts for differences in sample sizes and exposure between the "before" and "after" periods. To conduct this test, the compliance percentages in Table B-6 were converted to odds as follows:

$$O_j = \frac{P_{L,j}}{1 - P_{L,j}} \tag{35}$$

where,

O_j = compliance odds for period j ($j = A$: after, B: before).
$P_{L,j}$ = percent of pedestrians crossing legally during period j.

The 95th-percentile confidence intervals were determined for the odds ratios using the following equation.

$$e^{\ln(O_B/O_A) - Z\, s_e} \leq \frac{O_B}{O_A} \leq e^{\ln(O_B/O_A) + Z\, s_e} \tag{36}$$

with,

$$s_e = \sqrt{\frac{1}{N_{ped,L,B}} + \frac{1}{N_{ped,L,A}} + \frac{1}{N_{ped,I,B}} + \frac{1}{N_{ped,I,A}}} \tag{37}$$

where,

s_e = standard error.
Z = standard score (use 1.96).

An odds ratio of 1.0 would indicate no change between the "before" and "after" time periods. If the 95th-percentile confidence interval excludes 1.0, the change would be considered statistically significant. Hence, the null hypothesis for this test is that the 95th-percentile confidence interval contains 1.0.

The results of this test are provided in the rightmost column of Table B-6. As shown, the pedestrian compliance percentages decreased significantly at the two sites at intersection 7. After the leading protected left-turn phase was implemented at these sites, many pedestrians began to cross during the protected left-turn phase, particularly the pedestrians originating from the near corner. Pedestrian compliance percentages were found to increase significantly at intersection 9 and at one of the sites at intersection 16.

Early Pedestrian Percentages

Observations during the field data collection suggested that the percentage of pedestrians crossing early (i.e., starting the crossing movement as much as five seconds before the start of the WALK indication) may have changed at several of the sites. These pedestrians represent a subset of the illegal pedestrians. To explore this trend, the early-crossing pedestrians were counted, and percentages were computed in a similar manner to the pedestrian compliance percentages. These percentages are provided in Table B-7.

Table B-7. Early Pedestrian Percentages.

Intersection Number	Subject Left-Turn Movement	Early Pedestrian Percentage, %		Statistically Significant Change?
		Before	After	
7	Eastbound	5.7	14.9	Yes
	Westbound	0.6	9.8	Yes
	Both	3.0	12.1	Yes
9	Eastbound	12.0	0.5	Yes
12	Westbound	2.7	7.6	Yes
16	Northbound	5.8	10.9	No
	Southbound	4.4	2.1	No
	Both	5.3	8.6	No
	Average:	6.3	7.3	No

An odds-ratio test was conducted on the early pedestrian percentages provided in Table B-7. The results show that the number of early pedestrians increased significantly for the two sites at intersection 7 and also for the site at intersection 12. The magnitude of the increase for intersection 7 was roughly double that of the increase for intersection 12. It is not clear why the pedestrian recall treatment at the intersection 12 site would be associated with a larger percentage of early pedestrians. At the intersection 9 site, the percentage of early pedestrians decreased significantly. At this site, the signal phasing was changed from protected-permissive leading to split, with the pedestrians being served immediately after the crossing-street service was ended.

Analysis Results

Two of the treatments had statistically significant, positive effects on pedestrian safety. Protected-permissive operation was changed to split phasing at intersection 9. This change was associated with a 95 percent reduction in conflicts. Pedestrian recall was invoked at intersection 12. This change was associated with a 92 percent reduction in conflicts. These treatments had positive or neutral effects on pedestrian compliance percentage. As shown in Table B-7, the early pedestrian percentage increased significantly at intersection 12, but none of the early pedestrians experienced conflicts.

The change from permissive to a leading protected-permissive operation at intersection 7 was associated with a 34 percent decrease in the conflict rate. However, the pedestrian compliance percentage dropped by almost 25 percent, and the early pedestrian percentage increased by about 9 percent.

Increasing the walk interval duration at intersection 16 was accompanied by a 53 percent increase in the conflict rate. It is not certain why this treatment would have increased the conflict rate, but it is likely that the pedestrian volumes at intersection 16 were insufficient to allow the potential benefit of the treatment to emerge. This treatment is most commonly considered when pedestrian volumes are sufficiently high that some waiting pedestrians do not have time to enter the crosswalk before the start of the pedestrian clearance interval. Additionally, the presence of low vehicle volumes at intersection 16 made it possible for many pedestrians to cross illegally. Some pedestrians even used the narrow (4 to 5 ft) raised-curb median as a refuge area, crossing one side of the crossing street at a time as traffic gaps allowed.

SUMMARY

The following four treatments were implemented and evaluated:

- Provide protected-permissive mode (leading phase sequence).
- Provide protected left-turn mode (using a split phase sequence).
- Invoke pedestrian recall.
- Increase walk interval duration.

Based on a comparison of total pedestrian-vehicle conflict rate between the "before" and "after" evaluation periods, the first three treatments were found to be beneficial. For some of these treatments, there was a tradeoff between reduced legal pedestrian-vehicle conflict rates and increased illegal pedestrian-vehicle conflict rates. However, the overall result was a reduction in total pedestrian-vehicle conflict rate.

The analysis of conflict rate showed that implementing the fourth treatment, increasing the walk interval, coincided with an increase in total pedestrian-vehicle conflict rate. It is not believed that the increase was caused by the treatment. Rather, the low volumes of pedestrians and vehicles at the evaluation sites for this treatment likely did not justify the treatment. The benefit of an increased walk interval is likely to emerge only when pedestrian volumes are sufficiently high that the large initial group of waiting pedestrians needs more time to begin crossing. Hence, an evaluation of this treatment should include a check of pedestrian volumes and possibly pedestrian delay.

REFERENCES

1. Griffin, L., III, and R. Flowers. *A Discussion of Six Procedures for Evaluating Highway Safety Projects*. Report No. FHWA-RD-99-040. Texas Transportation Institute, College Station, Texas, 1997.
2. Ott, R., and M. Longnecker. *An Introduction to Statistical Methods and Data Analysis*. Fifth Edition. Duxbury, Pacific Grove, California, 2001.