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Development of Left-Turn Operations Guidelines at Signalized Intersections

August 2008

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16. Abstract
This project developed guidelines for recommending the most appropriate left-turn phasing treatments at signalized intersections. It investigated all aspects of left-turn operations, including the mode of left-turn signal control, the sequence of left-turn phasing, and left-turn signal displays. Both the operational and safety impacts of different types of left-turn signal operations were analyzed. In the operational impact analysis, based on the results of traffic simulation, cross products of left-turn and opposing through volume (CPOV)–based criteria for selecting the left-turn signal mode between the protected-only and protected/permissive left-turn modes were developed. In the safety impact analysis, by analyzing the historical accident data collected from more than 100 intersections, the safety performances of different types of left-turn signal phasing treatments and signal displays were ranked. In addition, this project also evaluated the benefits of regional standardization of left-turn operations. It was found that the mixed application of left-turn signal operations, including signal control modes, phasing sequences, and displays, increases the risk of accidents at intersections.

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DISCLAIMER

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

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SUMMARY

Left-turn operation is a critical component of the safe and efficient operation of a signalized intersection. The proper type of left-turn phasing results in reduced traffic delay and improved traffic progress, as well as decreased accident rates. In the design of left-turn signal phasing, traffic engineers face the following three critical decisions: (1) how to determine the mode of left-turn operation, (2) how to determine the sequence of left-turn signal phasing, and (3) how to display the left-turn signal appropriately. The selection of an appropriate left-turn phasing treatment is a rather complicated process in which tradeoffs between safety and operational efficiency may be required. Currently, there exist no uniform methods of applying left-turn signal phasing throughout the state. Different jurisdictions use different approaches to determine which mode of left-turn phasing — permissive-only (Per), protected-only (PO), or protected/permissive left turn (PPLT) — should be used. Consistency in left-turn signal control is another concern for traffic engineers. In urban areas with multiple jurisdictions, it is helpful to the motoring public to have consistency among traffic control devices while traveling between the various jurisdictions.

Therefore, this research is intended to achieve two goals: (1) develop guidelines for recommending the most appropriate left-turn phasing treatments at signalized intersections by investigating all aspects of left-turn operations, including the mode of left-turn signal control, the sequence of left-turn phasing, and signal display; and (2) estimate the benefits of regional standardization of left-turn operations. To this end, the research entails the following specific objectives: (1) review and synthesize the state and/or national practices of left-turn signal design and operation, (2) analyze the safety and operational impacts of different left-turn phasing treatments (mode and sequence of left-turn phasing) at a signalized intersection, (3) develop guidelines for determining the mode and sequence of left-turn phasing at a signalized intersection, (4) evaluate the operational and safety benefits of regional standardization of left-turn operation, (5) provide guidelines on the placement of signal heads and signal displays, and(6) conduct case studies to demonstrate the application of the developed guidelines at selected signalized intersections.

First, a review of the state-of-the-art and the state-of-the-practice was conducted. This review focused on the studies of three topics: (1) the warrants and guidelines for the mode of left-turn operation, (2) the warrants and guidelines for the sequence of left-turn signal phasing,

and (3) the guidelines for left-turn signal display. It was found that most of the quantitative criteria or guidelines for selecting left-turn signal phasing only consider the operational efficiency or the safety impacts, and few of them take into account both the impacts and the tradeoffs between them. In addition, most traffic volume–based criteria are used to determine when the protected left-turn phase should be provided, instead of to select between the use of PO or PPLT modes. Actually, for an intersection with very heavy volume, PO would be a better choice than PPLT due to the accident risk associated with the permissive left turn under such traffic volume conditions. For left-turn signal display, the following most critical problems in the current left-turn signal display for PPLT were indentified: confusion about the green ball indication for the permissive phase, confusion about simultaneous signal indication of conflicting colors, the yellow trap problem, and the lack of uniformity.

To solicit information regarding the current practices of left-turn operations, a survey was conducted of traffic engineers in different jurisdictions, both in and out of the state. Based on the survey results, the major parameters and variables that are essential to the determination of left-turn signal phasing and signal indication are identified and prioritized. In addition, the information about the important issues in left-turn signal design and the guidelines/methods currently used by traffic engineers in practice are collected.

The operational and safety impacts of different types of left-turn signal phasing were analyzed. For this purpose, field studies were conducted in 26 selected intersections in Austin, Houston, Lufkin, and Nacogdoches, Texas. For each study intersections, about 3 hr of traffic data were collected, which include the traffic flow information collected from the recorded traffic videos, the intersection travel time data collected by probe vehicles, signal timing information and historical accident records collected from traffic management centers (TMCs), and intersection geometric information collected from field survey. In addition, extra historical accident records were collected from more than 80 additional intersections for safety impact analysis.

In the operational impact analysis, the traffic simulation–based method was used for analyzing the operational performance of the study intersections with different types of left-turn signal control modes and phasing sequences. The results show that the PPLT left-turn signal control mode results in less delay than the PO control mode at all studied intersections. Furthermore, based on the simulation results, cross products of left-turn and opposing through volume (CPOV)–based criteria for selecting the left-turn signal control mode between PO and PPLT modes were developed. The signal phasing sequence affects the operation of intersections mainly through its impacts on the signal coordination of the network. From the literature review and the results of traffic simulation, the following are recommended: for an intersection in a two-way coordinated arterial, the signal phasing sequence that maximizes through bandwidth should be selected; for an intersection in a one-directional coordinated arterial during the peak hour periods, the lead-lag sequence should be considered because it can cause less delay for the subject left-turn movements than other signal phasing sequences.

In the safety impact analysis, three different types of safety studies were conducted: (1) traffic conflicts study, comparing the traffic conflicts observed at the study intersections with different types of left-turn signal phasing; (2) cross-sectional study, comparing the left-turn accident rates at different types of intersections and analyzing the influencing factors on left-turn accidents; and (3) before-and-after study, comparing the accident rates of the intersection approaches before and after the left-turn signal phasing is changed. In the second and third studies, both the simple comparison method and the advanced statistic modeling method were employed for analyzing the collected historical accident data from more than 100 intersections. The results of the safety study indicate that (1) protected-only is the safest signal control mode, followed by permissive-only and protected/permissive left turn; (2) in terms of signal phasing sequence, in PO mode, lead-lag is the safest, followed by lead-lead and lag-lag, and in PPLT mode, lead-lead and lag-lag are safer than lead-lag when left-turn volume is low while lead-lag is safer than lead-lead when left-turn volume is high; (3) split signal phasing results in lower accident rates than non-split signal phasing; and (4) five-section cluster signal display is associated with less accident risk than five-section horizontal signal display.

By combining the findings from operational and safety impact analysis with the findings from the literature review and the survey of traffic engineers, comprehensive guidelines for determining the left-turn signal phasing, i.e., left-turn signal control mode and sequence, were developed. In addition, guidelines on how to select different signal displays for different types of left-turn signal phasing and how to place the signal heads appropriately were developed.

The safety benefits of regional standardization of left-turn signal phasing and display were analyzed by comparing the accident rates at four different corridors with different mix levels of left-turn signal operations. The mixed application of left-turn signal operation, including signal control modes, phasing sequences, and displays, increases the risk of accidents at intersections. Thus, it is suggested that regional standardization of left-turn signal operation is needed to increase the consistency of left-turn operations in a region.

Finally, case studies were conducted to demonstrate the application of the developed guidelines. The guidelines for left-turn signal phasing were applied to four selected study intersections, and the guidelines for signal display were applied to three intersections, including two study intersections and one newly selected intersection in Houston, Texas.

In addition, this study also developed training strategies and materials for providing training sessions to TxDOT and TMC personnel (see Yu et al. 2008 for details).

Based on the results of the research conducted in this project, it is recommended that regional standardized guidelines be used for left-turn operations at signalized intersections. The guidelines developed by this study are recommended to determine the left-turn phasing treatments and signal displays at signalized intersections because both the safety and operational efficiency impacts of different types of left-turn operations have been taken into account by these guidelines.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

The left-turn operation is a critical component for the safe and efficient operation of a signalized intersection. The proper type of left-turn phasing results in reduced traffic delay and improved traffic progress, as well as decreased accident rates. PPLT phasing has been considered the most efficient left-turn operation mode because it increases left-turn capacity by providing a protected turn phase as well as a permissive phase during which left turns can be made as opposing traffic allows. However, safety is the main concern in the implementation of PPLT control. Some argue that when PPLT is implemented with a lead-lag phase arrangement, a left-turn "yellow trap" may be created, which puts drivers in a risky situation. Therefore, the selection of an appropriate left-turn phasing treatment is a rather complicated process in which tradeoffs between safety and efficiency may be required. Currently, there exist no uniform methods of applying left-turn signal phasing throughout the state. Different jurisdictions use different approaches to determine which mode of left-turn phasing — permissive-only, protected-only, or protected/permissive — should be used. Consistency in left-turn signal control is another concern for traffic engineers. In urban areas with multiple jurisdictions, it is helpful to the motoring public to have consistency among traffic control devices while traveling between the various jurisdictions. Therefore, research is needed to develop standard and implementable guidelines for determining the most appropriate left-turn phasing treatments at signalized intersections and to evaluate the benefits of regional standardization of left-turn operations.

There are two major aspects of left-turn signal phasing design: (1) the mode of left-turn operation and (2) the sequence of left-turn phasing.

The *Manual on Uniform Traffic Control Devices* (MUTCD) defines three major modes of left-turn controls:

- Permissive-only left-turn control: Left turns do not have dedicated right-of-way and can be made when an acceptable gap exists in the opposing through movement, under the green ball indication.
- Protected-only left-turn control: Left turns have dedicated right-of-way with a green arrow indication.

- Protected/permissive left-turn control: This is a combination of the above two left-turn controls. Left turns have a dedicated right-of-way during the protected interval. In another part of the cycle, left turns may be made when an acceptable gap exists in the opposing through movement.

The sequence of left-turn phasing is the order and combination of movements that make up the signal phasing, which can also have great impacts on the safety and operational efficiency of a signalized intersection. Generally, there are three types of sequence arrangements:

- lead-lead sequence: moves both of the opposing left turns before the through movements,
- lag-lag sequence: moves both of the opposing left turns after the through movements, and
- lead-lag sequence: opposing left turns move separately from each other but simultaneously with their associated through phase.

The signal diagram of these three types of left-turn phasing sequence is provided in Figure 1.

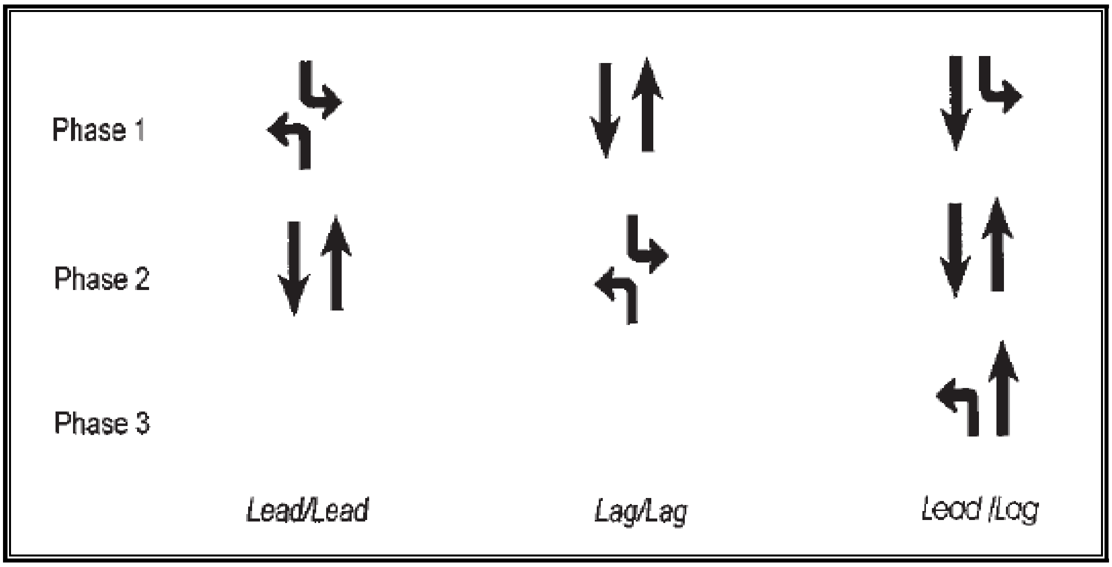


Figure 1: Three Types of Phasing Sequence for Left-Turn Operations

These two aspects of left-turn signal phasing (mode of left-turn operation and sequence of left-turn phasing) need to be carefully designed by considering various factors, including traffic volume (both left-turn and through-traffic volumes), speed limit, the intersections' geometric design, traffic progress efficiency, historical accident rate, type of intersections, etc.

Both safety and operational benefits need to be considered in the selection of the best left-turn signal phasing. Recently, signal optimization models and intersection performance analysis tools (such as SYNCHRO and HCS+) have been widely used in intersection signal design. However, these models can only be used for intersection operational efficiency analysis, not for safety performance evaluation. Thus, other approaches, such as accident data analysis and field traffic conflicts study, need to be used to analyze the safety impacts of different types of left-turn signal phasing designs.

After selecting the appropriate left-turn signal phasing, the placement of signal heads and signal face/lens arrangements also need to be carefully designed. The proper signal display may fix some of the problems associated with left-turn signal phasing. For example, the Dallas signal display can fix the left-turn "yellow trap" problem in the PPLT control with lead-lag phasing by using a separate five-section left-turn signal head in which the green ball indication is shielded or louvered from the adjacent through traffic. On the other hand, the poor signal display may confuse motorists, which will result in a hazardous traffic situation.

Left-turn signal phasing is very complicated, involving design, operational, and safety issues. Generally, traffic engineers face the following three critical decisions in the design and operation of left-turn signals:

- how to determine the mode of left-turn operation,
- how to determine the sequence of left-turn signal phasing, and
- how to display the left-turn signal appropriately.

This research develops comprehensive guidelines to help traffic engineers make these three decisions. The following are brief discussions of the existing practices for addressing these three questions.

1.1.1 Guidelines for the Selection of Left-Turn Operation Mode

There have been no universal guidelines used in determining the mode of left-turn operations. In general, the less-restrictive control mode, i.e., permissive left turn, is considered at first because it results in lower delays to all traffic. Then, warrants/criteria are used for determining the need for protected left-turn control or PPLT control. Various guidelines have been developed in past studies of such criteria. Existing criteria for the selection of the left-turn control mode can be categorized into four groups:

- traffic volume–based criteria: through and left-turn volumes at the intersection, etc.;
- geometry features–based criteria: number of opposing lanes, presence of exclusive left-turn lanes, number of exclusive left-turn lanes, sight distance, etc.;
- operational characteristics–based criteria: traffic delays, intersection capacity, etc.; and
- accident experience–based criteria: historical accident rates, observed traffic conflict rates, etc.

Among these criteria, the traffic volume–based criteria are the most important criteria, which include the criteria for left-turn (LT) volume, opposing through (TH) volume, and cross product of left-turn volume and opposing volume. However, most of these criteria are used for determining when the protected left-turn phase should be provided instead of for selecting between the use of PO or PPLT modes. In other words, when the traffic volume of an intersection exceeds a given threshold, either PO or PPLT can be used. However, for an intersection with very heavy volume, the operational benefits gained by using PPLT mode may not be significant because it is difficult to make permissive left turns when the traffic volume is heavy. In this case, considering the reduced safety associated with PPLT mode, PO mode would be the better choice. Therefore, criteria based on traffic volume should be used for making the selection between the PPLT and PO modes as well.

1.1.2 Guidelines for the Selection of Left-Turn Phasing Sequence

In addition to the modes of left-turn operations, the sequence of left-turn phase (the order and combination of movements that make up the signal phasing) can also have a great impact on the safety and efficient operation of an intersection.

Guidelines for the determination of the sequence of left-turn phasing generally provide that the sequence of the left-turn phasing is selected by considering the influencing factors, mainly from four categories:

- geometric features of the intersection: number of left-turn lanes, width of the median, storage length of the left-turn lane, etc.;
- operation efficiency: signal coordination, intersection capacity, traffic delay, etc.;
- safety: left-turn trap, conflict with pedestrians, historical accident rate, etc.; and
- driver acceptance.

However, there are still no commonly accepted guidelines for the signal phasing sequence selection. Studies have been conducted on the operational and safety impacts of different signal phasing sequences. But, the results of these studies are inconsistent. Detailed discussions about these studies and their findings can be found in section 2 of Chapter 2.

1.1.3 Guidelines for Left-Turn Signal Display

A great concern in dealing with left-turn phasing treatment is motorists' understanding of the intended signal control, in which left-turn signal display plays an important role. Left-turn signal display involves three important aspects, including (1) indication of left-turn signal display, (2) arrangement of left-turn signal face, and (3) placement of the left-turn signal head. Current standards for the selection of appropriate indication and arrangement for different types of signal phasing, and for the placement of the left-turn signal head, have been provided in the MUTCD.

However, several studies have indicated the limitations of current standards for left-turn signal display, especially when it comes to the use of a combination of permissive and protected phasing. The PPLT signal display could confuse the driver for a variety of reasons, including a lack of nationwide uniformity, the type of display, and the use of leading or lagging left-turn phasing. Also, due to the flexibility of the MUTCD standards, there are also variations in the signal indications for the permissive phase in PPLT, the signal face arrangements, and the signal head placements. This variability in the display types and placement has led to a myriad of PPLT signal display throughout the United States. A detailed discussion of the existing problems and potential solutions regarding the current standards for left-turn signal display and placement is presented in section 3 of Chapter 2.

In sum, there is a lack of nationally accepted guidelines for left-turn signal phasing design and signal display. Currently, different jurisdictions use different approaches for determining which type of left-turn phasing should be used and how it should be displayed. In addition, few studies have been conducted to investigate the operational and safety benefits of regional standardization of left-turn signal operations.

1.2 RESEARCH GOALS AND OBJECTIVES

In light of the context provided by past research, this project has two goals: (1) develop guidelines for recommending the most appropriate left-turn phasing treatments at signalized intersections by investigating all aspects of left-turn operations, including the mode of left-turn signal control, the sequence of left-turn phasing, and signal display; and (2) estimate the benefits of regional standardization of left-turn operations. To this end, the research involves the following specific objectives:

- review and synthesize state or national practices on left-turn signal design and operation,
- analyze the safety and operational impacts of different left-turn phasing treatments (mode and sequence of left-turn phasing) at a signalized intersection,
- evaluate the operational and safety benefits of regional standardization of left-turn operation,
- develop guidelines for determining the mode and sequence of left-turn phasing at a signalized intersection,
- provide guidelines on the placement of signal heads and signal displays, and
- conduct case studies to demonstrate the application of the developed guidelines at selected signalized intersections.

1.3 OUTLINE OF THIS REPORT

This report covers all tasks conducted during the research period. First, the major existing methodologies proposed or adopted for left-turn signal phasing design and signal display are presented. Then, the surveys for soliciting information regarding the current practices for left-turn operations in jurisdictions across the state are introduced, and the survey results are analyzed. Data collection is described in Chapter 4. In Chapter 5, the safety impacts of different left-turn phasing treatments at signalized intersections are analyzed. Chapter 6 describes the operational impact analysis of different left-turn signal phasing treatments. The benefits of regional standardization of left-turn signal operations are evaluated in Chapter 7. The guidelines for determining the mode and sequence of left-turn signal phasing are in Chapter 8, and the guidelines for left-turn signal display are in Chapter 9. In Chapter 10, case studies at several selected signalized intersections demonstrate the application of the developed guidelines. Finally, conclusions and recommendations are given in Chapter 11.

CHAPTER 2: LITERATURE REVIEW

The left-turn operation is a critical component for the safe and efficient operation of a signalized intersection. Proper left-turn signal treatments result in reduced traffic delay, improved traffic progress, and decreased accident rates. Because of its significance, numerous studies have been conducted to find the appropriate left-turn signal treatments for an intersection. Most of these studies explored the following three decisions:

- how to determine the mode of left-turn operation,
- how to determine the sequence of left-turn signal phasing, and
- how to display the signal appropriately.

Therefore, this literature review focuses on studies of the following three topics: (1) the warrants and guidelines for the mode of left-turn operation, (2) the warrants and guidelines for the sequence of left-turn signal phasing, and (3) the guidelines for left-turn signal display.

2.1 WARRANTS AND GUIDELINES FOR THE MODE OF LEFT-TURN OPERATION

The left-turn operation modes include: permissive-only, protected-only, and protected/permissive left turn. Various studies have been conducted to develop guidelines, standards, or warrants for selecting the best mode for the left-turn operation at a signalized intersection. These previous studies tried to answer the following questions:

- For an intersection with permissive-only left-turn phasing, when should a protected left-turn phase be provided?
- If protection is needed, which type of left-turn control mode should be used, PPLT or PO?

The studies that targeted the first question are introduced in part 2.1.1, "Warrants for Protected Left-Turn Mode," and the studies that tried to answer the second question are introduced in part 2.1.2, "Guidelines for Selection between Protected-Only and PPLT Modes." Papers that investigated both questions are discussed in both parts.

2.1.1 Warrants for Protected Left-Turn Mode

The warrants for protected left-turn mode developed in previous studies were mainly based on the following criteria:

1. left-turn delay;

2. accident/conflict experience;
3. volume, including left-turn volume, opposing volume, and the cross product of left-turn and opposing volumes;
4. geometric conditions, including number of left-turn lanes, number of opposing lanes, etc.; and
5. approach speed limit.

A one-by-one discussion introduces important studies of the development of warrants for protected left-turn mode. Afterwards is a summary table of the warrants proposed by these studies.

2.1.1.1 Agent and Deen (1979)

This paper developed four types of warrants for providing a protected left-turn phase at a signalized intersection. These are accident-based warrant, delay-based warrant, volume-based warrant, and traffic conflict–based warrant.

Accident-Based Warrant. The average number of left-turn accidents per year for all the permissive intersections was used to calculate the critical number of left-turn–related accidents per year as follows:

$$N_c = N_a + K\sqrt{N_a} + 0.5 \qquad (1)$$

where:

N_c = critical number of left-turn accidents,

N_a = average number of left-turn accidents, and

K = constant related to level of statistical significance selected

(for P = 0.95, K = 1.645; for P = 0.995, K = 2.576).

When the number of left-turn accidents per year for an intersection exceeds this critical number, i.e., N_c, a protected phase should be provided. *The critical number of left-turn–related accidents found in this paper was four in 1 year, six in 2 years, or eight in 3 years.*

Delay-Based Warrant. The delay warrant developed in this paper consists of three criteria. All three criteria must be met to warrant a protected left-turn phase:

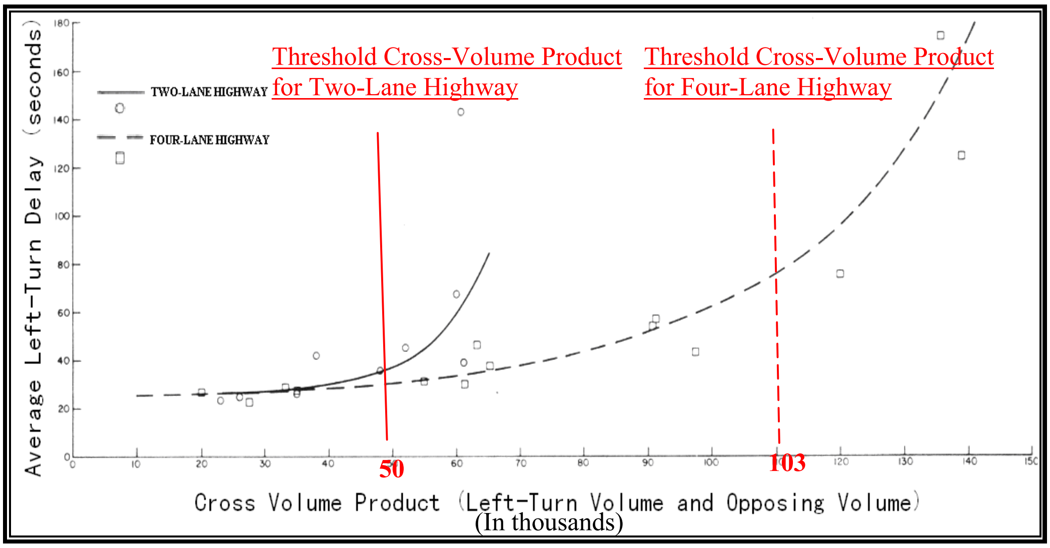
1. a minimum of 50 left-turn vehicles during peak hour,
2. a minimum average delay of 35 s/vehicle, and

3. a minimum total left-turn delay of 2.0 vehicle-hours during peak hour for a critical approach.

Note that criterion 2 was developed based on a survey of engineers about the maximum tolerable left-turn delay. In that survey, about 90 percent of the maximum tolerable delays given by the respondents are greater than 35 seconds.

Volume-Based Warrant. The volume warrants provide the threshold left-turn volume or cross products of left-turn and opposing volume for determining the needs of left-turn protection. This paper developed volume-based warrants by following four different approaches:

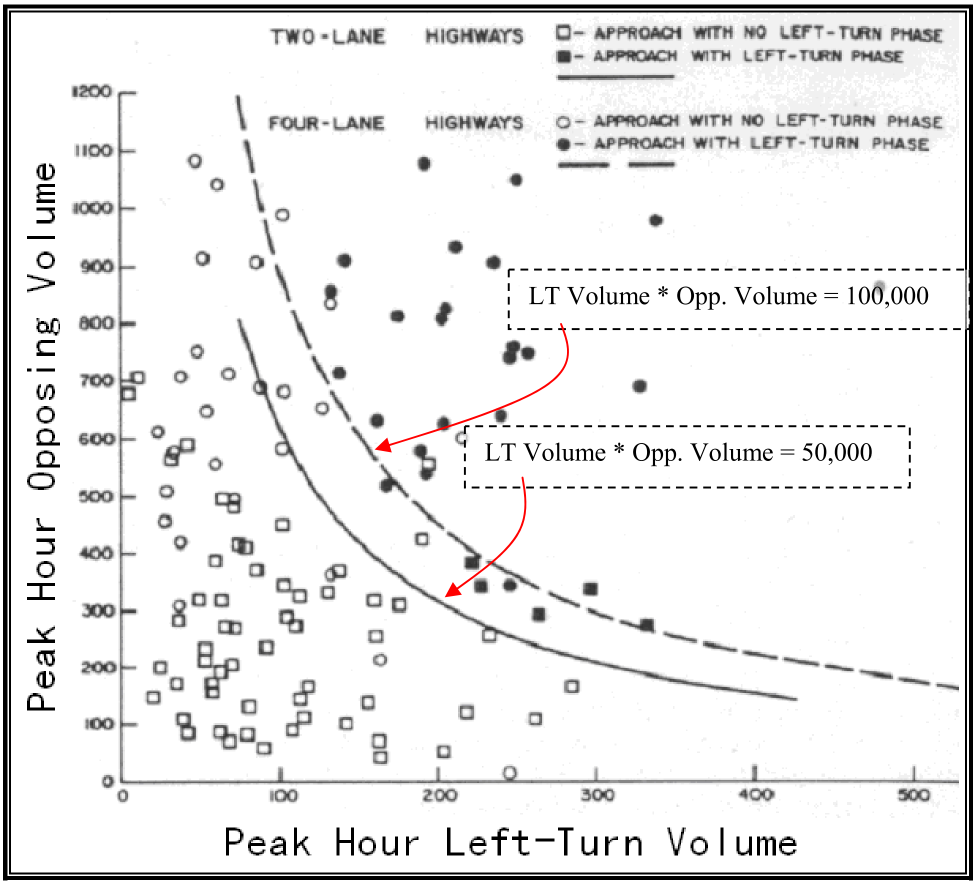
1. Derive the threshold cross-volume products (left-turn and opposing volume) based on the average left-turn delay. Based on the traffic data collected from the intersections with permissive-only left-turn control modes, the authors plotted the cross product of left-turn and opposing volume, and the average left-turn delay on a chart (see Figure 2). Then, by fitting these plots, curves that represent the relationship between cross-volume products and left-turn delay for different types of intersections were developed. From Figure 2, it was found that the curve for two-lane highway intersections increases quickly at the point where the cross-volume product equals 50,000, and the curve for four-lane highway intersections increases quickly at the point where the cross-volume product equals 103,000. Therefore, the cross-volume products at these critical points should be the threshold volumes for providing the protected left-turn mode because, without protection, the left-turn delay will increase dramatically if the cross-volume products exceed these thresholds.



Source: Agent and Deen (1979)

Figure 2: Relationship between Volume Product and Left-Turn Delay

2. Derive the threshold cross products of left-turn and opposing volumes based on the historical traffic volume data collected at the intersections both with and without left-turn protection. Plots of the peak hour opposing volume and left-turn volume were drawn in a chart (see Figure 3) based on the historical traffic data collected from the intersections in the city of Lexington. In this chart, a solid curve with a constant cross-volume product of left-turn and opposing volumes of 50,000 was the one that separated the intersections with and without a left-turn protection phase for two-lane highways. A dashed curve with a constant cross-volume product of left-turn and opposing volumes of 100,000 was the one that separated the intersections with and without a left-turn protection phase for four-lane highways. These two curves were the proposed warrants for installing a left-turn protection phase. If the actual plot of one intersection is above the corresponding curve, a left-turn protection phase should be provided.



Source: Agent and Deen (1979)

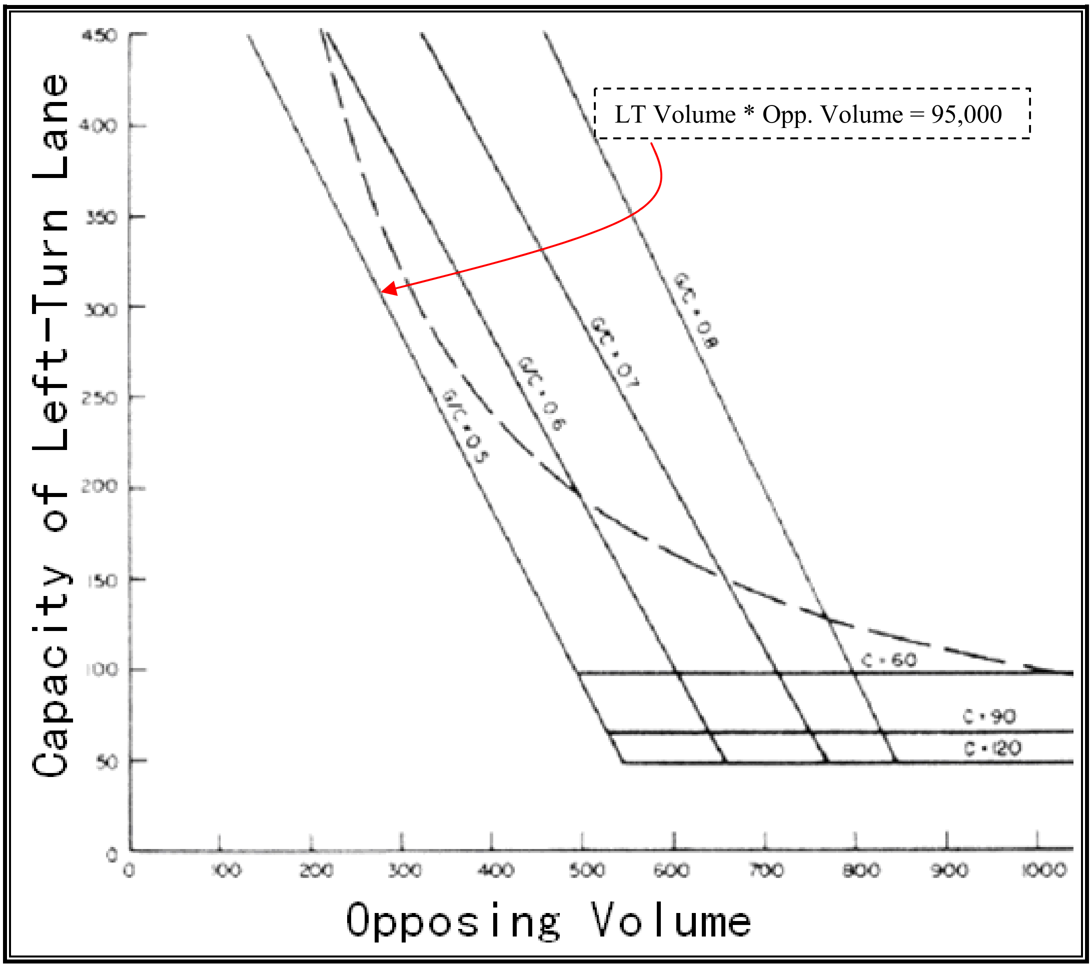
Figure 3: Comparison of Volumes at Intersections with and without Protected LT Phasing

3. Derive the volume warrant from the perspective of gap acceptance. First, in this paper, the critical gap was defined as the gap that drivers will accept at 50 percent probability. In order to derive the critical cross-volume product of left-turn and opposing volume, the critical opposing volume and critical left-turn volume must be derived. In this paper, the critical opposing volume is defined as the volume at which the left-turn vehicles cannot find gaps greater than the critical gap during the green interval and have to make a left turn during the amber interval. According to the definition of critical opposing volume, the critical left-turn volume was the number of left-turn vehicles that could clear the intersection during the amber interval only. Then, assuming the opposing traffic was equally spaced, the critical opposing volume can be derived based on the length of critical gap and available green time. With the critical left-turn and opposing volume, the critical cross volume was derived by using Equation (2):

$$\textit{Critical Cross Product} = \textit{Critical LT Volume} \times \textit{Critical Opposing Volume} \quad (2)$$

From data collected in the field, the value of the critical gap was found to be 4.2 s, and the critical left-turn volume was found to be two vehicles/cycle. Using these values, the critical cross products of left-turn and opposing volume were derived. They were 50,000 for two-lane streets and 100,000 for four-lane streets.

4. Develop volume warrants based on capacity analysis. The left-turn capacity of intersections was calculated for intersections with different green-time-to-cycle-length ratios, opposing traffic volumes, and signal cycle lengths and then drawn as a monograph (see Figure 4). The dashed line (the product of left-turn and opposing volume equals 95,000) is the curve that depicts the proposed volume warrants for providing protected left-turn phase If the plot of the opposing volume versus the left-turn volume is above the drawn lines, it means protected left-turn phase is needed at the studied intersection.

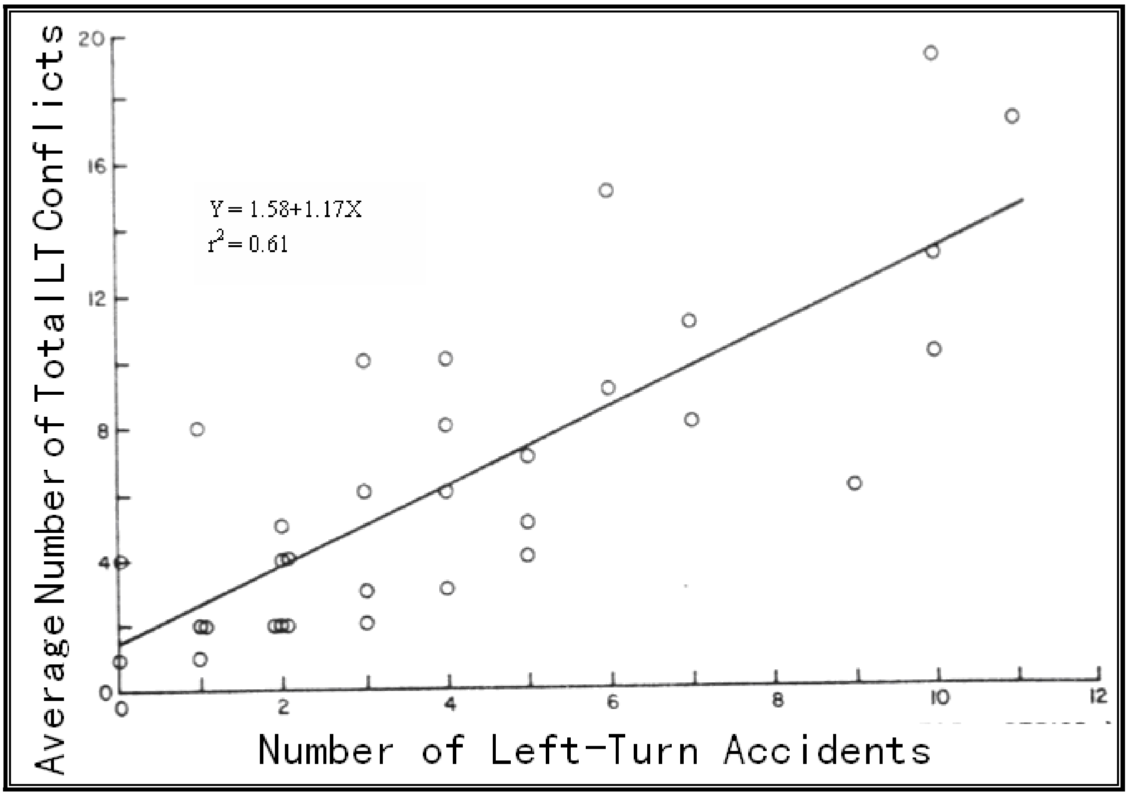


Source: Agent and Deen (1979)

Figure 4: Capacity of Left-Turn Lane on the Basis of a Capacity Monograph

In conclusion, in this study, the left-turn volume warrants developed in different ways are quite consistent. Finally, the cross-volume products of 50,000 for two-lane streets and 100,000 for four-lane streets were recommended as the volume warrants by this study.

Traffic Conflict–Based Warrant. This study tried to relate left-turn conflicts with left-turn accidents. The number of left-turn accidents and conflicts at the same intersection was collected and plotted. The regression method was applied to establish the relationships between them (see Figure 5).



Source: Agent and Deen (1979)

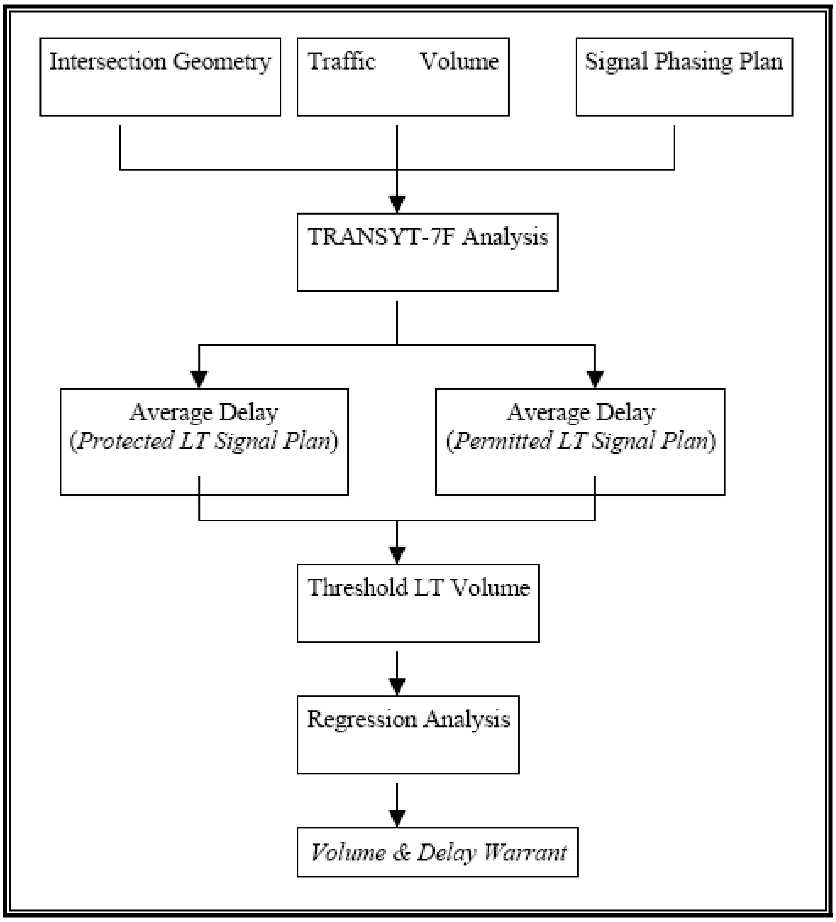
Figure 5: Relationship between Left-Turn Accidents and Conflicts

Then, based on the critical number of left-turn accidents per year (which was four according to the study conducted in the "Accident-Based Warrant" section), it was suggested that an average of 14 total conflicts or 10 basic conflicts would warrant a protected phase.

2.1.1.2 Al-Kaisy and Stewart (2001)

This paper proposes a method for developing volume-based warrants for a protected phase by minimizing the overall average delay of the intersection. The overall modeling structure is provided in Figure 6, which includes following four steps:

1. Assume the basic characteristics of the intersection, including the intersection geometry, traffic volumes, and the type of signal phasing. By applying the simulation software SIGNAL EXPERT, the overall delays of an intersection under permissive phasing and PPLT phasing were calculated.
2. Compare the intersection delays under different types of signal phases. The boundary points of left-turn volume, above which the protected left-turn phase will result in less delay than the permissive left-turn phase, is derived for the intersection with pre-assumed characteristics.
3. Based on the left-turn volumes of the boundary points, the relationship between the left turn, number of adjacent through lanes, number of opposing through lanes, and cross volumes was modeled by employing a multivariate linear regression model.
4. Given the information about the number of adjacent through lanes, number of opposing through lanes, and cross volumes, the maximum left-turn volume can be calculated by the regression model. The calculated left-turn volume is the left-turn volume warrant. When the left-turn volume of an intersection is higher than the left-turn volume warrant, left-turn protection should be provided.



Source: Zhang et al. (2005)

Figure 6: Method Proposed by Al-Kaisy and Stewart (2001) for Determining Volume-Based Warrants

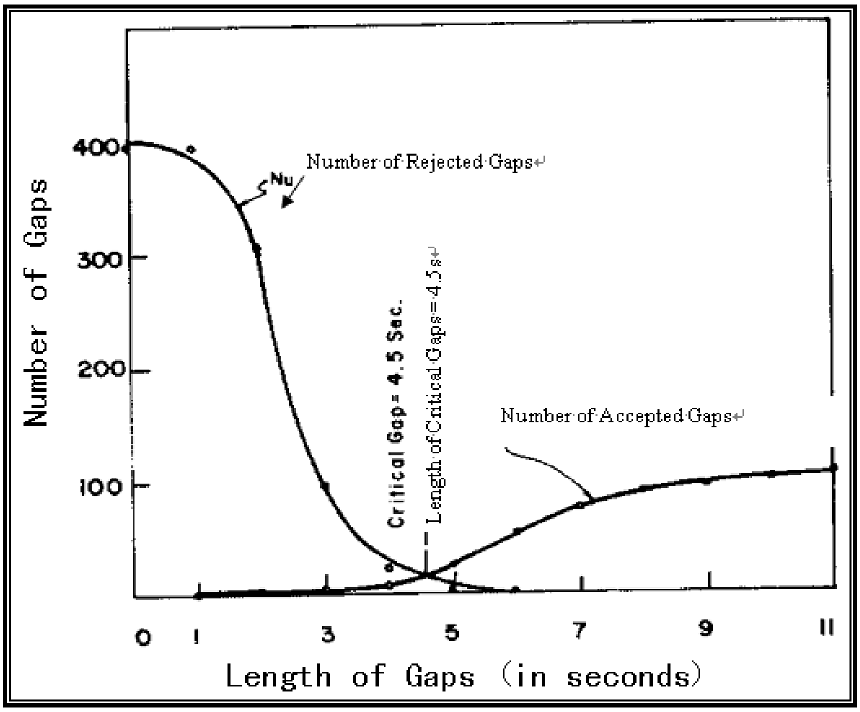
Comments on This Method. There are two major problems with the methods proposed by Al-Kaisy and Stewart (2001):

1. Safety effects are not considered in developing the traffic volume–based warrant for the protected left-turn phase. When traffic volume increases, the protected left turn is needed not just to reduce the intersection delay but to reduce the risk of accidents. Actually, the major concern in developing the traffic volume–based warrant is safety.
2. Since this approach was based on simulation, the warrants are very highly sensitive to different geometric conditions. If the user wants to use the developed warrants, he or she must provide a lot of information about the study intersection, including the intersection geometric layout and intersection traffic volume for each movement. After that, the user needs to find the right curve for traffic volume–based warrants and find the right

threshold left-turn volume from the curve. Considering all these inputs and the efforts to find the threshold left-turn volume, it may be easier and more direct to just input all the intersection information into a traffic simulation model (or traffic signal optimization software) and then compare the derived intersection delay under different left-turn signal phases to select the left-turn signal phase that causes minimum delay. Therefore, the practical value of the proposed approach is very questionable.

2.1.1.3 Behnam (1972)

This paper introduces an approach for developing left-turn warrants based on gap acceptance. Similar to Agent and Deen (1979), in this study, the critical gap with length *t* was defined as the gap in which the number of accepted gaps less than *t* is equal to the number of rejected gaps greater than *t*. Figure 7 indicates how to derive the critical gap length *t* based on the data collected from the field.



Source: Behnam (1972)

Figure 7: Cumulative Distribution of Accepted and Rejected Gaps

By assuming the arrival of the opposing traffic at a signalized intersection with permissive left-turn only phasing following a Poisson distribution, the probability that a gap is larger than *t* seconds was:

$$\Pr ob\ (gaps \geq t)\ =\ e^{-q_O t} \tag{3}$$

where:

q_O = opposing traffic flow rate in vehicles/s and

t = critical gap in s.

The number of gaps that are larger than *t* can be derived as follows:

$$Number\ of\ ((gaps \geq t) = V_0\ \Pr ob\ (gaps \geq t)\ =\ V_O e^{-q_O t} \tag{4}$$

where:

V_O = volume of opposing traffic in vehicles per hour (veh/h).

Similarly, the number of gaps that are larger than 2t, 3t,… nt can also be derived. Then, by adding them together, the maximum number of left-turn vehicles that can clear the intersection can be estimated by the following equation:

$$V_1 = V_O\left(\frac{e^{-q_O t}}{1 - e^{-q_O t}}\right) \tag{5}$$

where:

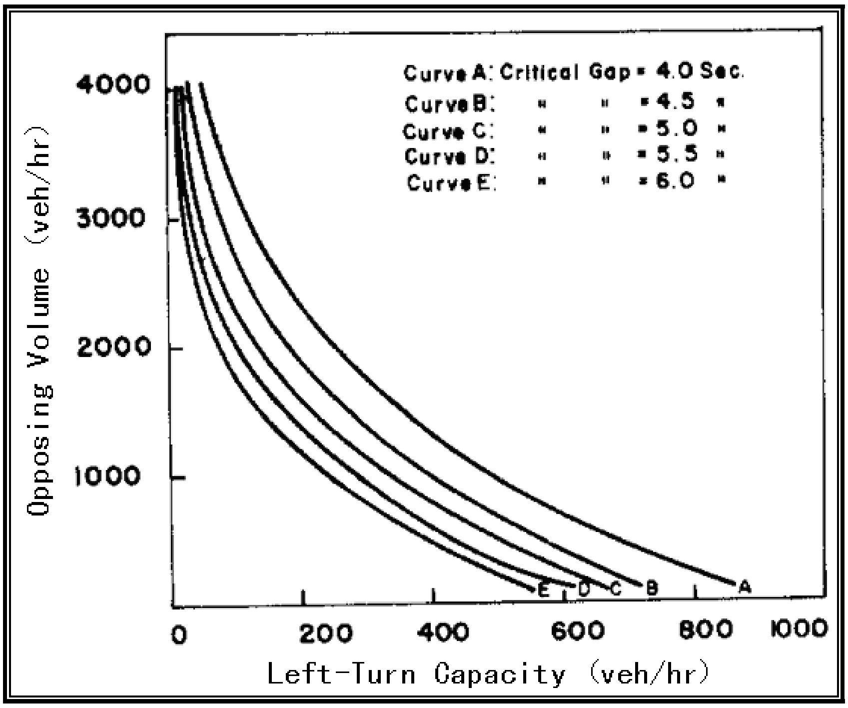
V_O = volume of opposing traffic in veh/h,

V_1 = maximum volume of left-turn traffic that can clear the intersection in veh/h,

q_O = opposing traffic flow rate in vehicles/s, and

t = critical gap in s.

The estimated V_1 is the threshold left-turn volume for determining the needs of left-turn protection because the intersection with a permissive left-turn phase cannot accommodate left-turn traffic volume greater than V_1. Figure 8 presents different warranted left-turn volumes for the intersections with different opposing volumes and critical gaps. According to the left-turn volume warrant developed in this study, the threshold cross product of left-turn and opposing volumes is not a constant as in the volume warrants developed by other studies.



Source: Behnam (1972)

Figure 8: Relationship between Opposing and Warranted Left-Turn Volumes for Different Critical Gaps

2.1.1.4 Lin and Machemehl (1983)

This paper argues that a constant cross-volume product of left-turn and opposing volume was not appropriate as a warrant for left-turn protection, and proposes an analytical way of developing cross-volume product warrants. Based on intersection left-turn capacity analysis, the left-turn volume warrant was developed as follows:

$$Q_W = f_C Q_C (G/C) - e_0 Q_O \tag{6}$$

where:

Q_W = left-turn volume warrant,

f_C = allowable utilization factor,

Q_O = opposing volume,

G = green time,

C = cycle length,

Q_C = effective capacity of the conflicting area, and

e_0 = equivalent factor to convert opposing volume to left-turn volume.

The basic idea of this study is to find the left-turn capacity of the intersection under different opposing volumes, G/C ratios, and permissive left-turn control conditions. Then, when the actual left-turn volume is greater than the left-turn capacity, a left-turn protection phase is warranted. Note that to utilize Equation (6), the G/C ratio and opposing volume Q_O has to be provided by the user according to the actual conditions of the study intersections. The value of the constants, the Q_C and e_0, are two constants whose values are determined by Q_O and the G/C ratio according to Table 1.

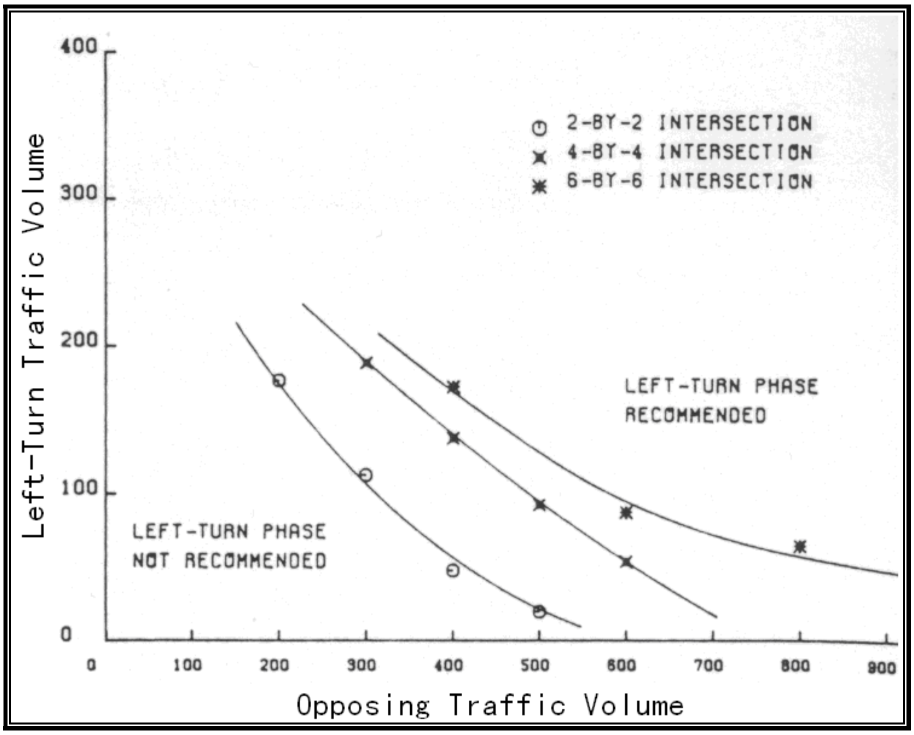
Table 1: Values of e_0, Q_c, and f_c under Different Opposing Lanes and Volumes

No. of Opposing Lanes	Opposing Volume Q_O (vph)	Equivalence Factor e_0	Effective Capacity of Conflict Area (Vehicles/ Green Hour)	Allowable Utilization Factor f_C
Single	$0 < Q_O\ G/C < 1000$	0.634	879	0.84-0.87
	$1000 < Q_O\ G/C < 1350$	0.348	590	0.79-0.82
Two	$0 < Q_O\ G/C < 1000$	0.500	930	0.86-0.92
	$1000 < Q_O\ G/C < 1350$	0.353	780	0.82-0.87
	$1350 < Q_O\ G/C < 2000$	0.167	465	0.79-0.84
Three	$0 < Q_O\ G/C < 1000$	0.448	930	0.91-0.96
	$1000 < Q_O\ G/C < 1350$	0.297	780	0.88-0.94
	$1350 < Q_O\ G/C < 2400$	0.112	465	0.72-0.84

Source: Lin and Machemehl (1983)

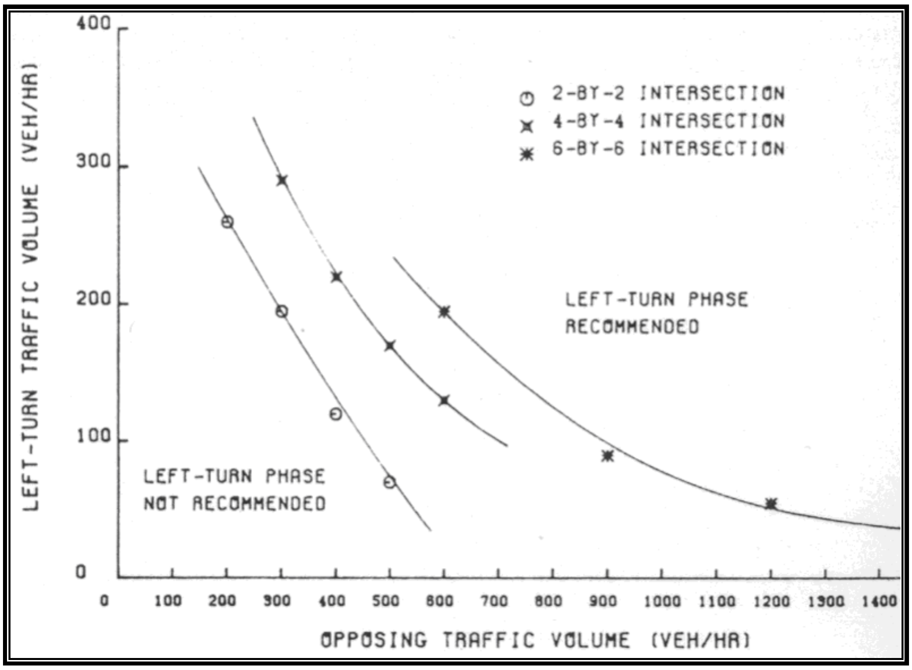
Given the G/C ratio, the curve of left-turn capacity under different opposing volumes can be derived by using Equation (6), which is presented in Figures 9 and 10. Then, based on these curves, the decision about providing left-turn protection can be made. In other words, if the plot of actual left-turn volume and the opposing volume of an intersection is above the curve, left-turn protection phasing should be provided to this intersection.

Comments on This Method. This paper proposed a simulation-based approach of warrants for protected left-turn mode, and it has the typical problems of all simulation-based approaches. First, it was too sensitive to the intersection signal timing plan and geometric conditions. The second problem was that it did not take safety issues into consideration, which was a major concern for providing a protected left-turn phase.



Source: Lin and Machemehl (1983)

Figure 9: Decision Chart for Left-Turn Protection Phase for Which G/C = 0.4 and C = 60 s

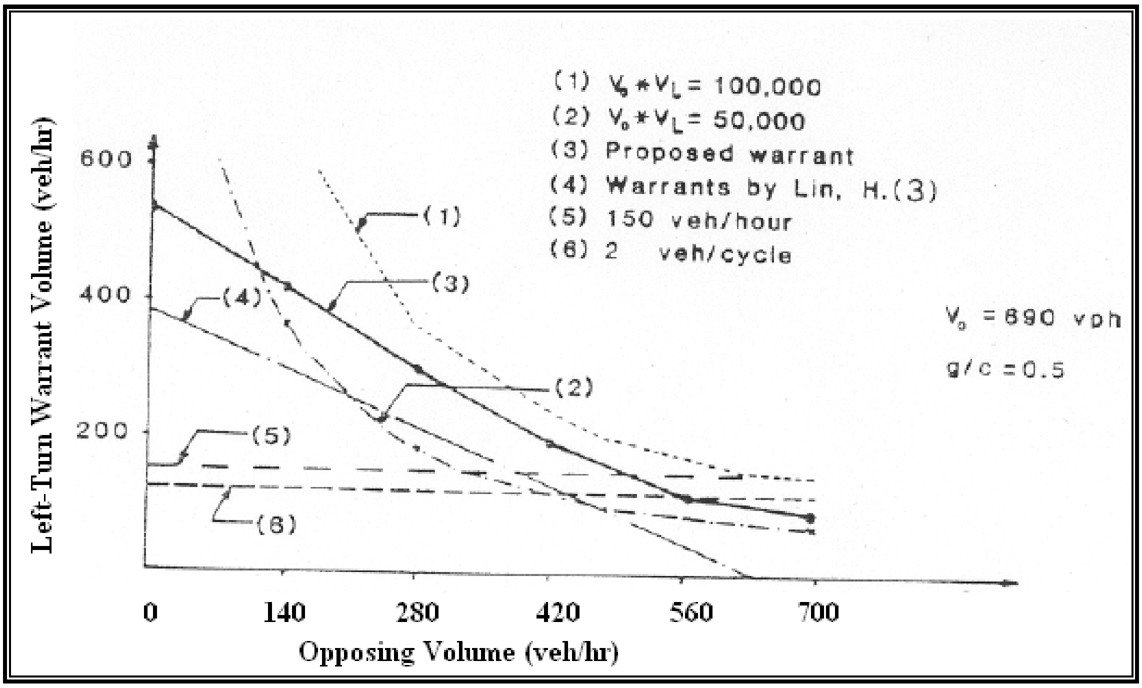


Source: Lin and Machemehl (1983)

Figure 10: Decision Chart for Left-Turn Protection Phase for Which G/C = 0.5 and C = 60 s

2.1.1.5 Rouphail (1986)

This paper develops a new volume warrant for left-turn protection phasing at signalized intersections based on comparing the V/C ratio between left-turn movements and opposing movements. It assumes, for the intersection under unprotected left-turn operation, the left-turn movements should not be the critical movement during the permissive left-turn phase. Therefore, if the V/C ratio of the left-turn movement is greater than the V/C ratio of the opposing movement, a left-turn protection phase should be provided. Based on this idea, the threshold left-turn volumes can be derived according to the opposing through traffic volume. The left-turn volume warrants developed by this study are presented in Figure 11. In this study, the developed volume warrants were compared with the constant cross product of left-turn and opposing volume, and it found that using a constant cross product of left-turn and opposing volume as the warrant for protected left-turn phasing was not enough.



Source: Rouphail (1986)

Figure 11: Left-Turn Warrant Volume versus Opposing Volume under *G/C* = 0.5

Comments. It is too “relative” to develop the left-turn volume warrant only by comparing the left-turn V/C ratio with the opposing through traffic V/C ratio. For the intersection with very light traffic, even though the left-turn movement is the critical movement, left-turn protection should not be needed.

2.1.1.6 Stamatiadis et al. (1997)

This study developed the volume warrant for left-turn protection based on historical accident data collected from intersections with and without protected left-turn phasing. It found that, for the approaches without left-turn protection, accident rates are high when the cross-product volume of left-turn and opposing movements is greater than 50,000 for one-lane approaches and the cross-product volume of left-turn and opposing movements is greater than 100,000 for two-lane approaches. Thus, a threshold cross-product volume equal to 50,000 should be the left-turn protection warrant for one-lane approach, and the cross-product volume equal to 100,000 should be the left-turn protection warrant for two-lanes approaches.

2.1.1.7 Upchurch (1986)

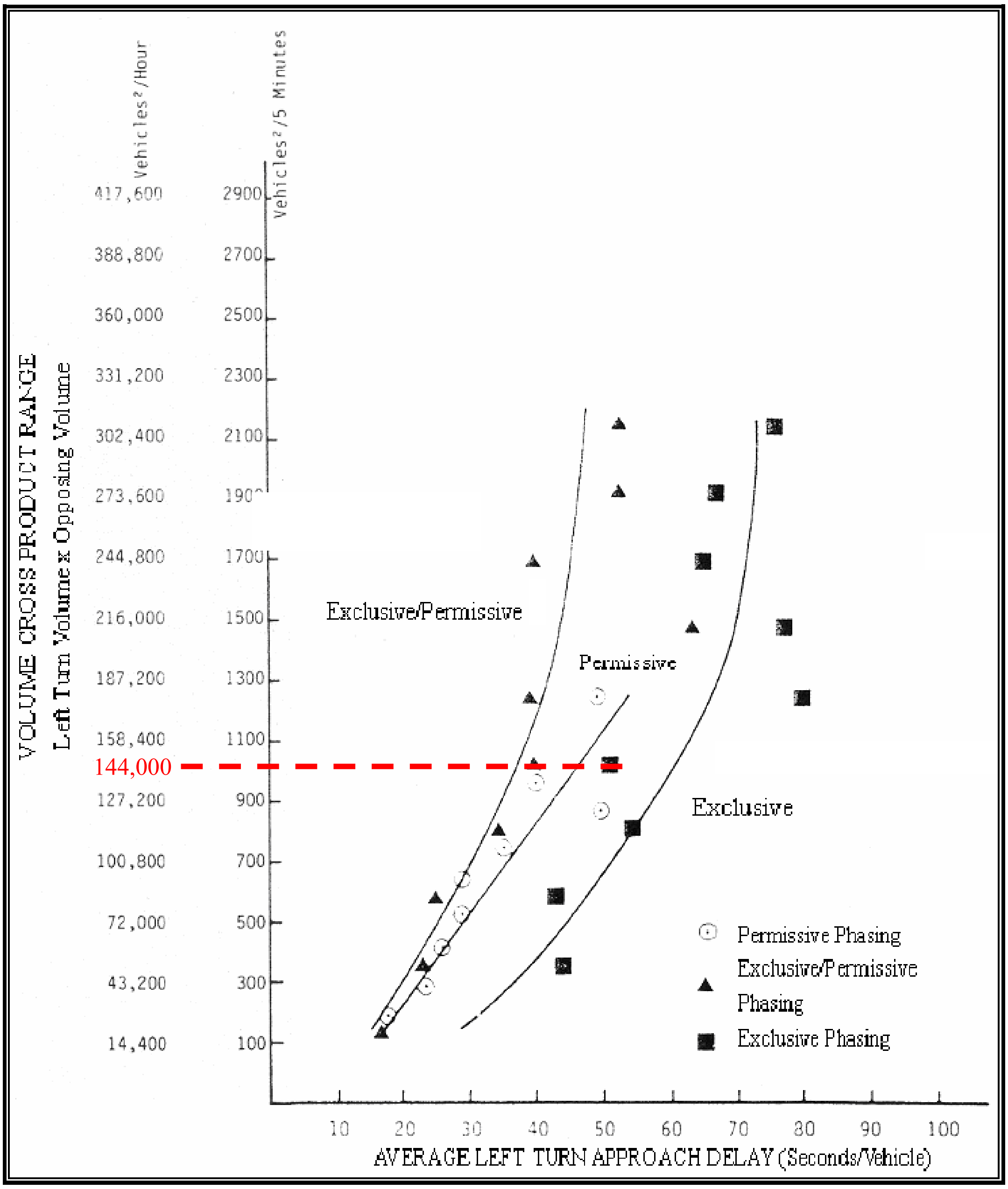
This study developed volume warrants for protected left-turn mode based on the delay of the intersection collected from the field data. By plotting the observed cross product of left-turn and opposing volumes versus left-turn delay on a chart (see Figures 12 and 13), the intersection delay under different control modes can be compared. It was found that:

- For intersections with two opposing lanes, the average left-turn delay of permissive left-turn phasing was significantly higher than that of PPLT phasing when the volume cross product was greater than 144,000, as shown in Figure 12.
- For intersections with three opposing lanes, the average left-turn delay of permissive left-turn phasing was higher than that of PPLT phasing when the volume cross product was greater than 100,000, as shown in Figure 13.

So, it was recommended by the study that:

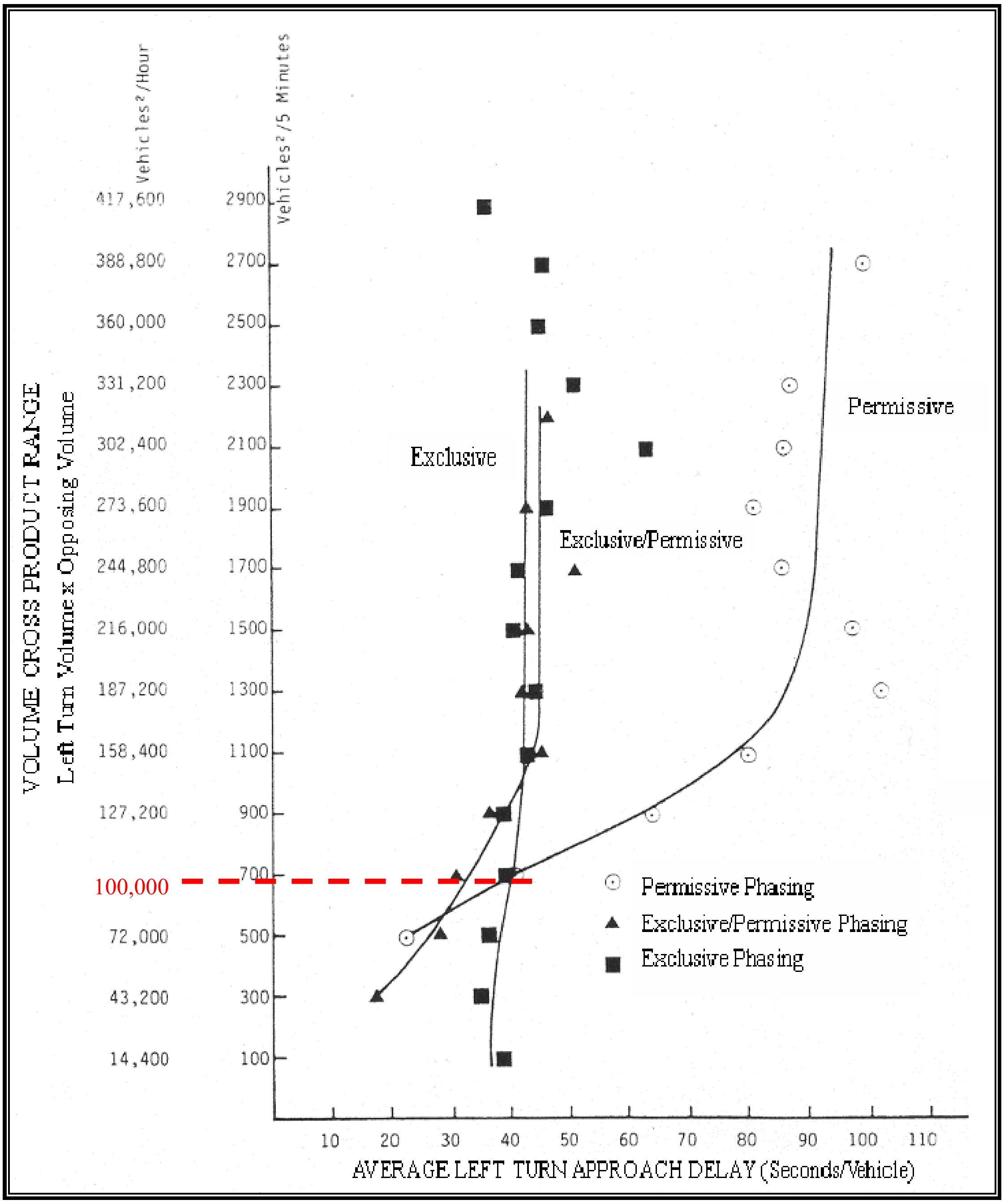
- For intersections with two opposing lanes, a protected phase should be provided when the volume cross product is greater than 144,000.
- For intersections with three opposing lanes, a protected phase should be provided when the volume cross product is greater than 100,000.

Comments on This Study. Even safety was considered in this decision-making tree, but similar to Al-Kaisy and Stewart (2001), safety effects are not considered in developing the volume-based warrants for the protected left-turn phase. If the left-turn volume and opposing volume are high in an intersection, left-turn protection is provided mainly for preventing a crash between left-turn vehicles and opposing vehicles.



Source: Upchurch (1986)

Figure 12: Average Left-Turn Delay versus Volume Cross Product: Two Opposing Lanes



Source: Upchurch (1986)

Figure 13: Average Left-Turn Delay versus Volume Cross Product: Three Opposing Lanes

2.1.1.8 Summary of Warrants for Protected Left-Turn Mode

The review of the literature had the following major findings:

- For left-turn volume warrants based on the constant cross product of left-turn and opposing volumes, the results of different studies are quite consistent. *Studies all recommended a cross product of left-turn and opposing volumes greater than 50,000 for one-lane approaches and a cross product of left-turn and opposing volumes greater 100,000 for two-lane approaches as the left-turn volume warrants* (Agent and Deen 1979, Stamatiadis et al. 1997, Upchurch 1986).
- Although a constant cross product of left-turn and opposing volumes is the most widely used warrant, *many studies found that it was inappropriate to apply a constant cross-product warrant to all types of intersections*. Thus, alternative solutions were proposed by these studies (Al-Kaisy and Stewart 2001, Behnam 1972, Lin and Machemehl 1983, Rouphail 1986).
- The major problem with the previous studies is that most of the volume warrants were developed based on intersection operation efficiency, such as minimizing intersection delay, but not based on intersection safety, such as minimizing potential conflicts.

According to criteria introduced at the beginning of part 2.1.1, "Warrants for Protected Left-Turn Mode," and the papers reviewed above, the major results of previous studies of warrants for protected left-turn mode are summarized in Table 2.

Table 2: Summary of Warrants for Protected Left-Turn Mode

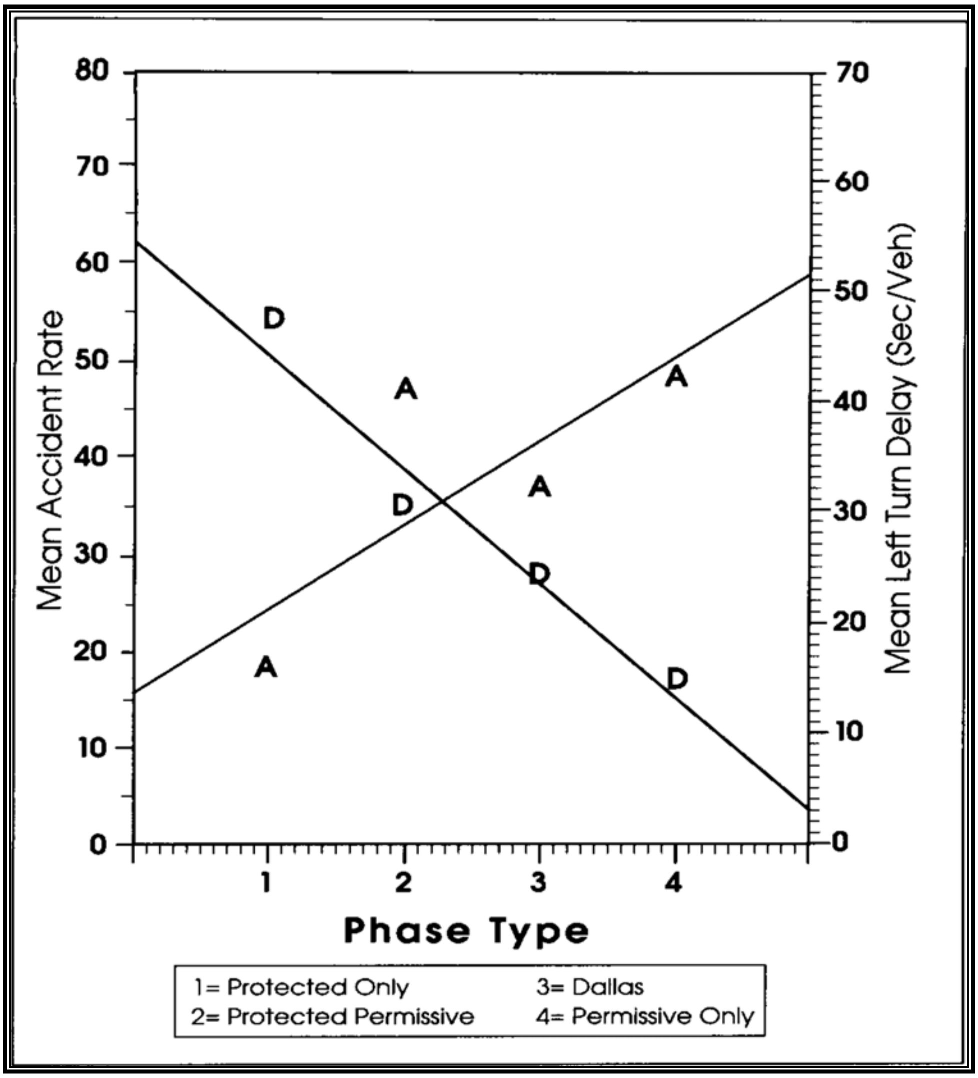
Criterion	Warrants		Reference
Delay	LT Delay	≥ 2 vehicle-hours	Agent and Deen 1979, Cottrell 1986, Lalani et al. 1986
	Average LT Delay	≥ 35 s	
Volume	LT Volume	≥ 50 vph	Agent and Deen 1979, Cottrell 1986, ITE 1991, Lalani et al. 1986, Upchurch 1986
		≥ 2 vehicles/cycle	
		> 300 vph	Stamatiadis et al. 1997
		> 320 vph	Asante et al. 1993
		>50 vph (in one direction)	City of San Diego 2006
	Opposing TH Volume	> 1,100 vph	Asante et al. 1993
	Volume Cross Product (Constant)	> 50,000 (one opposing lane)	Agent and Deen 1979, ITE 1991, Stamatiadis et al. 1997
		> 100,000 (two opposing lanes)	
		> 144,000 (two opposing lanes)	Upchurch 1986
		> 100,000 (three opposing lanes)	
		> 100,000 (one opposing lane)	City of San Diego 2006
	Curve of Left-Turn Threshold Volume versus Opposing Volume	See Figures 9 and 10	Lin and Machemehl 1983
		See Figure 11	Rouphail 1986
		See Figure 8	Behnam 1972
Accident/Conflict Experience	LT-Related Accidents	≥ 4 in 1 year, or ≥ 6 in 2 years, or ≥ 8 in 3 years	Agent and Deen 1979, Agent 1987, ITE 1991, Stamatiadis et al. 1997
		≥ 5 in any 12-month period in 3 years	City of San Diego 2006
		≥ 5 per year	
	LT Conflicts	≥ 10 basic conflicts in a peak hour	Agent and Deen 1979
		≥ 14 total conflicts in a peak hour	
		≥ 4 per 100 left-turn vehicles	Cottrell 1986

Table 2: Summary of Warrants for Protected Left-Turn Mode (Continued)

Criterion	Warrant		Reference
Intersection Geometrics	Sight Distance	≤ 250 ft (75 m) (opposing speed ≤ 35 mph [55 km/h])	ITE 1982, Upchurch 1986, City of San Diego 2006
		≤ 400 ft (120 m) (opposing speed > 35 mph [55 km/h])	
	Number of Opposing TH Lanes	≥ 3	Agent 1987, Asante et al. 1993, Cottrell 1986, City of San Diego 2006
	Number of LT Lanes	≥ 2	Agent 1987, Asante et al. 1993, ITE 1982, City of San Diego 2006
Speed	Opposing Speed	≥ 45 mph (70 km/h)	Agent and Deen 1979, Agent 1987, Asante et al. 1993, Upchurch 1986
Other	Number of Failed Cycles		Fisher 1998
	Benefit/Cost Analysis		Agent and Deen 1979, Cottrell 1986
	Vehicle Queue		Lalani et al. 1986
	LT Storage Length		
	Percent of Heavy Vehicles		
	Political Motivation		
	Public Demand		
	High Truck or Pedestrian Volume		City of San Diego 2006
	50 or More School-Age Pedestrians Crossing the Lane per Hour		
	Access Management Condition		Cottrell 1986
	Angle of the Two Approaches		

2.1.2 Guidelines for Selection between PO and PPLT Modes

It is generally accepted that the protected/permissive left-turn mode offers more operational efficiency benefits, while the protected-only left-turn mode has better safety performance. The tradeoff between intersection operational efficiency and safety for different types of left-turn modes is shown in Figure 14 (Shebeeb 1995). Thus the selection between PO and PPLT, in fact, must find a good balance point between intersection operational efficiency and safety.



Source: Shebeeb (1995)

Figure 14: The Tradeoff between Accident Rate and Left-Turn Delay for Each Left-Turn Control Mode

2.1.2.1 Agent (1981)

This study developed guidelines for selecting between PO and PPLT left-turn control modes based on cost and benefits analysis. Both operational efficiency and safety impacts of PO and PPLT left-turn control modes were investigated in this study.

Efficiency Impacts — Average Intersection Delay. By analyzing the before-and-after delay data collected at four intersections in Kentucky, it was found that delay decreased 61 percent for non-peak hour and 38 percent for peak hour. About 37 percent of vehicles make left-turn turns during the green ball phase, which indicates the effectiveness of PPLT left-turn control mode.

Safety Impacts — Number of Accidents per Year. Table 3 shows the number of accidents before and after the change from PO to PPLT at the same four intersections in Kentucky. The number of accidents increased significantly for the first year after the change, from 44 to 78. However, the number of accidents decreased for the second and third years, and the trend is that the number of accidents is almost a constant number after the third year. This can be explained by the change in drivers' familiarity with the new left-turn signal. In the first year after the change, drivers were unfamiliar with the signal; thus, the number of accidents was high. After a period of time, drivers became accustomed to the new left-turn signal, and the number of accidents decreased. It is important to note that even after 3 years, the number of accidents with PPLT was still higher than that with PO, which indicates that in terms of safety, PO is better than PPLT.

Table 3: Number of Accidents before and after the Change from PO to PPLT

Year	Number of Accidents
1 Year before Installation of PPLT (PO)	44
1 Year after Installation of PPLT	78
2 Years after Installation of PPLT	58
3 Years after Installation of PPLT	55

Source: Agent (1981)

Benefit and Cost Analysis. To compare the benefit and cost of PPLT, this study converted the benefits of delay reduction and the cost of accident rate increase into dollar values for the four studied intersections in Kentucky, as shown in Table 4.

Table 4: Example of Benefit and Cost Analysis

Location	Yearly Reduction in Delay[a] (Vehicle-Hours)	Yearly Savings[b] (Dollars)	Accident Costs (Dollars)	Benefit-Cost Ratio
Tates Creek Road (KY 1974)– Gainesway Drive	11,899	65,920	21,330	3.09
Tates Creek Road (KY 1974)– New Circle Road (KY 4) (Outer Loop)	9,234	51,157	15,370	3.33
Tates Creek Road (KY 1974)– New Circle Road (KY 4) (Inner Loop)	3,212	17,794	16,600	1.07
Harrodsburg Road (KY 68)– New Circle Road (KY 4)	9,636	53,384	49,470	1.08

[a] Sum of reductions in delay of left-turning and opposing through vehicles except as noted.
[b] Yearly savings are equal to yearly reduction in delay multiplied by the dollar value of 1 vehicle-hour.

Source: Agent (1981)

The major findings and recommendations of this paper included:

- At intersections with heavy volume opposing traffic, PPLT left-turn control mode works basically same as PO mode. This is because very few gaps are available for left-turn vehicles during the green ball period. Therefore, in this case, PPLT mode does not have significant efficiency benefits, and it is better to use PO mode because of safety concerns. In this paper, a critical opposing volume, 1,000 vehicles/hr, was suggested for selection between PPLT mode and PO mode.
- The study also showed that, at intersections with a speed limit higher than 45 mph, the PPLT left-turn control mode causes safety problems.
- The savings in time favor the use of permissive left-turn phasing; however, this use was limited to intersections where the number of accidents was not significant. Increased public awareness will enhance the safety performance of intersections with PPLT left-turn control mode.

Comments on This Study. This study had both merits and limitations:

- Merits: This study considered both operational efficiency and safety impacts, and employed benefit-cost analysis to combine them to develop guidelines for selecting between PO and PPLT left-turn modes.
- Limitations: The guidelines given by this study were too general and did not give quantitative criteria. Another limitation was that, to implement these guidelines, before-and-after study data are need. Without implementation of both PO and PPLT left-turn control modes at an intersection, it is difficult for the traffic engineer to follow these guidelines to make a decision on the selection between PO and PPLT.

2.1.2.2 Agent (1987)

This paper continues the author's previous research (Agent 1981) to develop guidelines to aid traffic engineers in deciding whether PPLT left-turn phasing is appropriate for a given location. The author states that "the PPLT phasing provided for a substantial reduction in delay and was popular with local drivers. However, several left-turn related accidents occurred at these locations." Therefore, this paper performed a before-and-after analysis of the accident rates at 44 intersection approaches, and the analysis results were presented for a range of speed limits, as shown in Table 5.

Table 5: Summary of Accident Data before and after Installation of Permissive Phasing

Type of Conversion	Speed Limits	Number of Approaches	Average LT Accident/Year/Approach		Average Total Accident/Year/Approach	
			Before	After	Before	After
From Permissive to PPLT	35 mph or less	18	1.2	0.9	10.1	7.4
	40~45 mph	5	2.3	1.8	6.7	9.9
	More than 45 mph	1	0.0	4.7	6.0	10.0
	All speed limits	**24**	**1.4**	**1.3**	**9.2**	**8.0**
From PO to PPLT	35 mph or less	1	0.0	0.0	8.0	7.0
	40~45 mph	9	1.1	4.6	13.2	12.7
	More than 45 mph	1	1.0	8.7	13.0	18.6
	All speed limits	**11**	**1.0**	**4.6**	**12.7**	**12.7**

Source: Agent (1987)

From Table 5, it is found that (1) an increase in left-turn accident rates occurred at locations with higher speed limits; (2) when the left-turn phasing was converted from permissive to PPLT mode, both left-turn–related and total accident rates decreased at locations with low speed limits, but the total accident rates increased at locations with high speed limits; and (3) when the left-turn phasing was converted from PO to PPLT mode, the left-turn–related accident rates increased, and the total accident rates reduced at locations with low speed limits and increased at locations with high speed limits.

Based on these results, the author recommended that PPLT mode not replace PO mode when any of the following conditions exist:

- The speed limit is over 45 mph.
- PO phasing is currently in operation, and the speed limit is over 35 mph.
- Left-turn movement must cross three or more opposing through lanes.
- Intersection geometrics force the left-turn lane to have a separate signal head.
- Double left-turn-only lanes are on the approach.
- A left-turn accident problem exists (four or more left-turn accidents in 1 year, or six or more left-turn accidents in 2 years on an approach).
- A potential left-turn problem exists as documented by a traffic conflict study.

2.1.2.3 Cottrell (1986)

This study developed guidelines for selecting between PPLT and PO left-turn control modes by considering the following aspects:

- left-turn accidents,
- traffic volume,
- left-turn traffic conflicts,
- left-turn delay,
- site condition,
- delay-accident tradeoff, and
- traffic engineering judgment.

The final developed guidelines are presented in Figure 15.

Left-Turn Accident Warrant

If at a PPLT site, the annual left-turn accidents is more than 5, and the accident rate exceeds the critical accident rate, 32.6 per 100 million cross volume product, use PO, otherwise, use PPLT.

Traffic Volume Warrant

Use PPLT when left-turn volume exceeds 2 vehicles per cycles and The LTOV per lane is between 50,000 and 200,000.

Left-Turn Conflict Warrant

If the average number of traffic conflicts in an hour exceeds 39, and a critical number of 4 conflicts per 200 left-turn vehicles are exceeded, use PO, otherwise, use PPLT.

Left-Turn Delay Warrant

PPLT should be considered when the average left-turn delay exceeds 35 seconds and the total left-turn delay exceeds 2 vehicle-hours.

Site Condition Warrant

Adequate sight distance is required for PPLT. Also, the number of opposing lanes should not exceed 2 for PPLT. Other geometric and access management should be considered if PPLT is desired.

Delay-Accident Tradeoff

If PPLT is suggested by the above warrants except accident warrants, use the benefit-cost analysis proposed in the paper. Use PPLT if it is more beneficial, use PO otherwise.

Traffic Engineer Judgment

Traffic engineering judgment should be used in conjunction with the proposed warrants. This is especially true when one signal phasing is not clearly preferred.

Source: Cottrell (1986)

Figure 15: Summary of Warrants for Selecting between PPLT and PO

Among these warrants, those based on left-turn delay, site condition, and traffic engineering judgment were developed directly based on the literature and experiences, so they are highlighted in Figure 15. The other four types of warrants were developed by this study. The following is a brief introduction to the development of these four types of warrants.

Left-Turn Accident–Based Warrants. Historical accident data were collected for the intersection. The critical number and the rate for conflicts and accidents were determined by the following equation:

$$N_c = N_a + K(N_a)^{0.5} - 0.5 \tag{7}$$

where:

N_c = critical accident number per year for converting PPLT to PO,

N_a = average accident number per year for all the approaches with PPLT left-turn control mode, and

K = constant that determines the level of confidence at which rates (or numbers) are significant. For a 95 percent level of confidence, K = 1.645.

When the actual number of accidents at an intersection is greater than the critical number of accidents, a safer left-turn control mode should be used.

Volume Warrant Based on Accident Data Analysis. The volume warrant based on accident data analysis was developed by separating the intersections with and without serious safety problems. The procedure was as follows:

1. For all the intersections that were studied, judgments were made about whether the intersections had safety problems. If the accident rate at an intersection was greater than the critical accident rate calculated by Equation (7), it indicated that a safety problem existed at that intersection.
2. Count the number of intersections that had safety problems within different ranges of cross products of left-turn and opposing volumes.
3. Identify the value of the critical cross product of left-turn and opposing volumes. For most of the intersections where the cross products of left-turn and opposing volumes were greater than this critical value, safety problems exist. It was found that the critical cross-product volume was 200,000.

Traffic Conflict–Based Warrants. Traffic conflict–based warrants were developed in a way similar to that for left-turn accident–based warrants. The only difference was that the number of accidents was replaced by the number of traffic conflicts.

Benefit and Cost. The author conducted benefit-cost analysis for converting PO left-turn control mode to PPLT mode based on the historical accident data and intersection average delay. The benefits of PPLT in terms of delay savings and the cost of PPLT in terms of accident rate increase were converted to dollar values similar to the manner suggested by Agent (1987). Then, if the estimated benefits are greater than the cost for a particular intersection, PPLT should be warranted. Note that this warrant is applied only to intersections with both accidents and traffic delay information before and after the installation of PPLT.

2.1.2.4 ITE (1982)

This study compared the accident rates of 17 approaches that changed from PO to PPLT and 11 approaches that changed from PPLT to PO. Tables 6 and 7 show the results of the comparison.

Table 6: Left-Turn Phasing Change from PO to PPLT

	Annual LT Angle Accidents (Before)	Annual LT Angle Accidents (After)	Annual Total of Other Intersection Accidents (Before)	Annual Total of Other Intersection Accidents (After)
Total	6.5	41.5	94	114.5
Average/Approach	0.5	2.5	/	/
Average/Intersection	/	/	12	14.5

Source: ITE (1982)

Table 7: Left-Turn Phasing Change from PPLT to PO

	Annual LT Angle Accidents (Before)	Annual LT Angle Accidents (After)	Annual Total of Other Intersection Accidents (Before)	Annual Total of Other Intersection Accidents (After)
Total	53	7	135	219.5
Average/Approach	5	0.5	/	/
Average/Intersection	/	/	19	31.5

Source: ITE (1982)

From Tables 6 and 7, it was found that LT angle accidents were greatly increased when the left-turn control mode was changed from PO to PPLT (from 0.5 per approach to 2.5 per approach), while they were significantly reduced when the left-turn control mode was changed from PPLT to PO (from 5 per approach to 0.5 per approach).

Based on the results of this study, the following guidelines were recommended:

1. PPLT phasing should be employed unless compelling reasons for using other types of phasing exist.
2. PO phasing should be used when:
   a) more than one left-turn lane exists,
   b) sight distance is limited, or
   c) the approach is the lead portion of a lead/lag intersection phasing sequence.
3. PO phasing might be used when:
   a) there is poor sight distance to opposing traffic,
   b) the speed limit of opposing traffic is higher than 45 mph,
   c) there are more than three opposing lanes,
   d) current PPLT phasing has more than six left-turn accidents per year, or
   e) there are unusual intersection geometrics.
4. PPLT phasing might be used at:
   a) an approach of a T intersection, where opposing U-turns are prohibited;
   b) an approach of a four-way intersection where the opposing approach has prohibited left turns or PO left turns; or
   c) opposing approaches to a four-way intersection where the left-turn volumes from the opposing approaches do not substantially differ throughout the various time periods

of the day (because it is impossible to overlap the through movements with the left-turn phases).

2.1.2.5 Upchurch (1986)

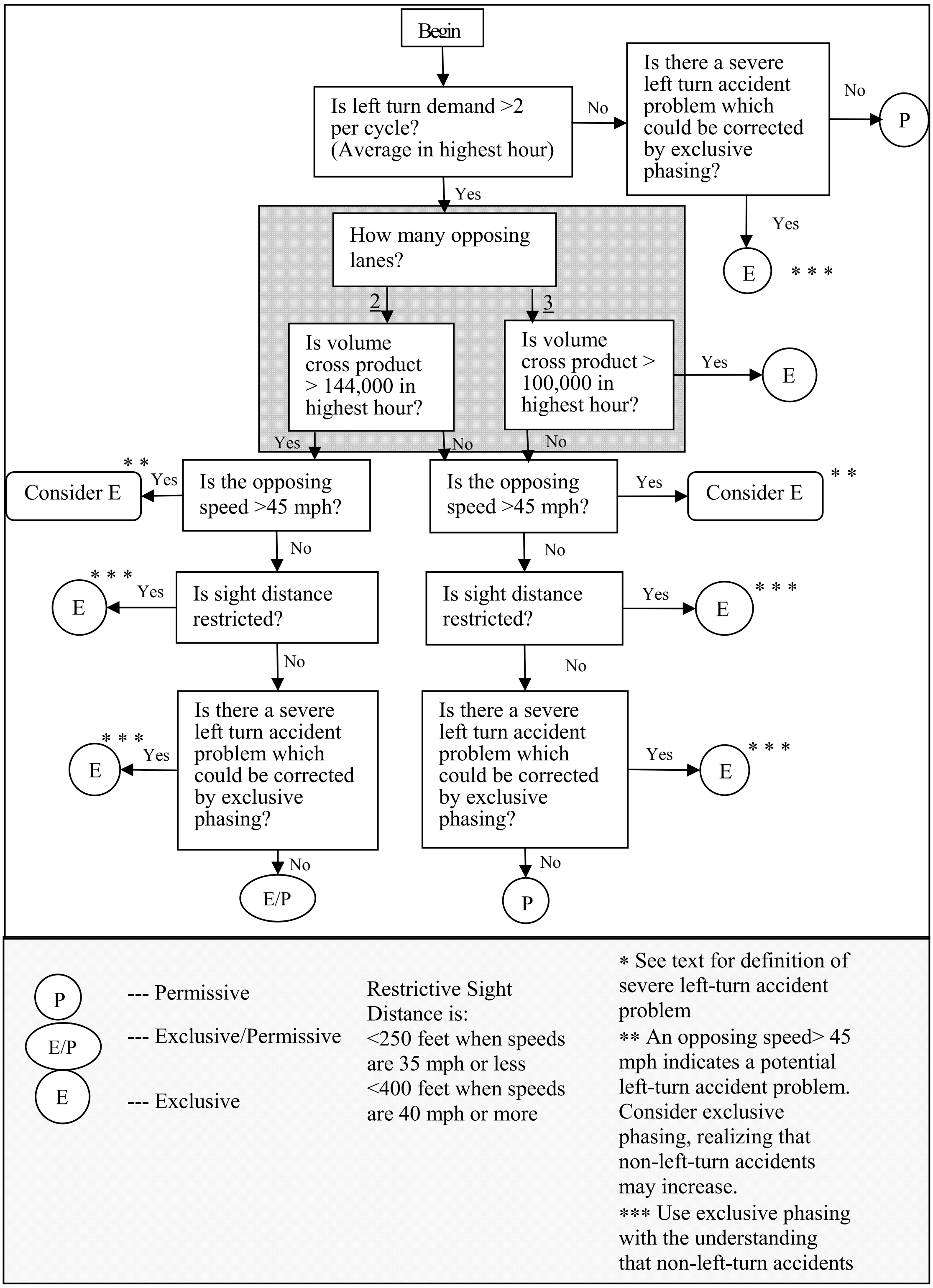
This study developed a comprehensive flowchart for selecting the left-turn control modes by incorporating the volume-based warrants developed by this study with the existing warrants from the literature. As shown in Figure 16, the highlighted parts were developed by this study, and the other parts were from the literature.

Upchurch (1986) shows that, for intersections with two opposing lanes:

- PPLT phasing significantly reduces left-turn delay (as compared with permissive phasing) when the volume cross product exceeds 144,000 vehicles^2/hr.
- PPLT phasing results in significantly less left-turn delay than exclusive phasing at all volume levels.

Also, for intersections with three opposing lanes, for more than 100,000 vehicles^2/hr, the use of exclusive phasing results in the lowest left-turn delay.

With these findings from the author’s previous research and other existing warrants from the literature, the author developed a flowchart for selecting the modes of left-turn control for a given intersection, as shown in Figure 16.

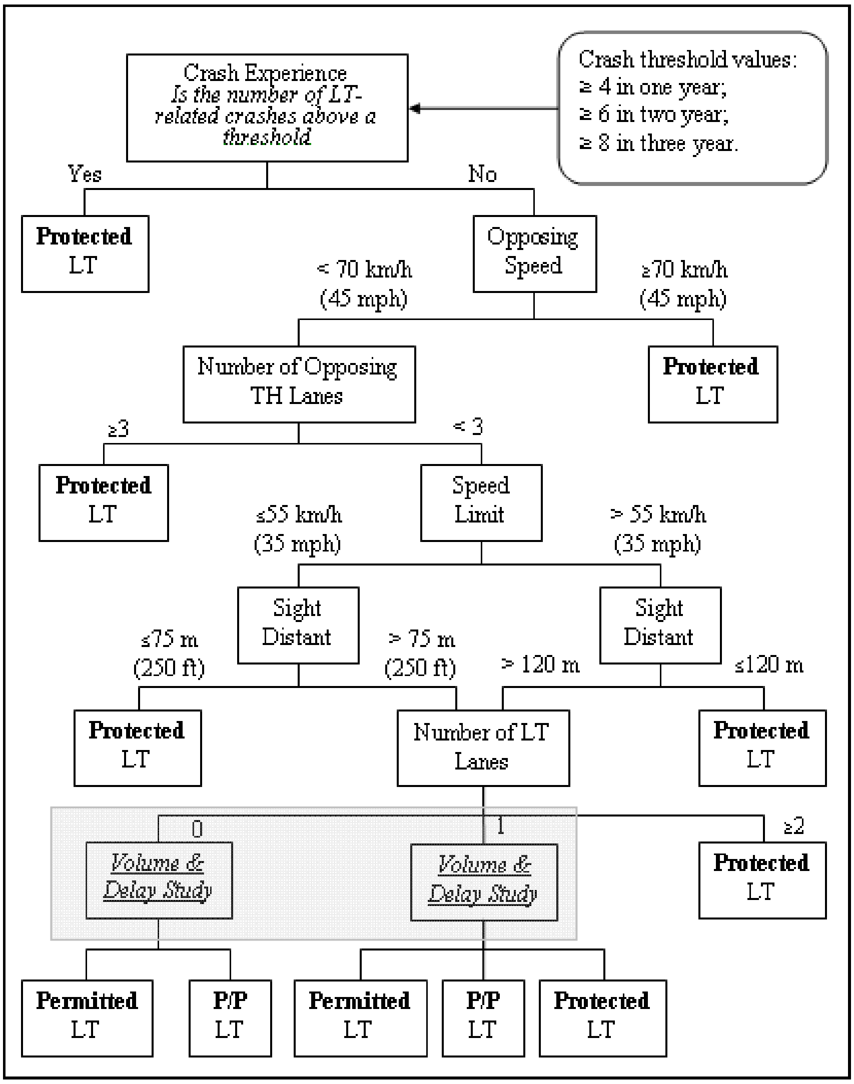


Source: Upchurch (1986)

Figure 16: Recommended Decision Flowchart for Left-Turn Phasing

2.1.2.6 Zhang et al. (2005)

This paper tried to combine both existing empirical warrants and an optimization-based volume warrant similar to that proposed by Al-Kaisy and Stewart (2001) to develop a comprehensive decision flowchart for the selection of left-turn control modes. The product of this study is the decision flowchart shown in Figure 17.



Source: Zhang et al. (2005)

Figure 17: Procedure for Determining Left-Turn Phasing

In this decision procedure, all the decision-making steps were based on the results from the literature except the highlighted part of the "Volume and Delay Study" for deriving volume-based left-turn protection warrants. The procedure for the “Volume and Delay Study” is similar to that proposed by Al-Kaisy and Stewart (2001). As a result, it suffers from the same drawbacks discussed in the comments for Al-Kaisy and Stewart (2001).

2.1.2.7 Summary of Guidelines for Selecting between PO and PPLT Modes

The previous literature generated the following major findings:

- Most of the quantitative warrants and guidelines consider only operational efficiency or safety impacts. Very few of them consider or combine the impacts of both operational efficiency and safety.
- For the studies that tried to combine operational efficiency and safety, all of them used similar methods, i.e., benefit and cost analysis based on before-and-after study (Agent 1981, Cottrell 1986). These studies have their own limitations. The developed guidelines are difficult to implement by field engineers unless both the intersection delay and accident rates are available for before and after study conditions.

Similar to Table 2, the major results of these previous studies on warrants for selecting between PPLT and PO left-turn control modes are summarized in Table 8.

Table 8: Summary of Guidelines for Selecting the Modes of Left-Turn Signal Phasing between PO and PPLT

Criterion	Warrant or Guideline		Reference	Recommendation
Delay	LT Delay	≥ 2 vehicle-hours	Cottrell 1986	Install PPLT
	Average LT Delay	≥ 35 s		
Volume (Developed Based on Delay Analysis)	LT Volume	> 50 vph (in one direction)	City of San Diego 2006	Install PO
	Opposing TH Volume	> 1,000 vph	Agent 1981	Install PO
	Cross-Volume Product	> 100,000 (one opposing lane)	City of San Diego 2006	Install PO
		200,000 ≥ LTOV per lane ≥ 50,000	Cottrell 1986	Install PPLT
Accident/Conflict Experience	LT-Related Accidents	≥ 4 in 1 year, or ≥ 6 in 2 years, or ≥ 8 in 3 years	Agent 1987, ITE 1991	Install PO
		≥ 5 in any 12-month period in 3 years	City of San Diego 2006	Install PO
		≥ 5 per year		
		≥ 14 total conflicts in a peak hour		
		≥ 4 per 100 left-turn vehicles	Cottrell 1986	Install PO
Intersection Geometrics	Sight Distance	≤ 250 ft (75 m) (opposing speed ≤ 35 mph [55 km/h])	ITE 1982, Upchurch 1986, City of San Diego 2006	Install PO
		≤ 400 ft (120 m) (opposing speed > 35 mph [55 km/h])		
	Number of Opposing TH Lanes	≥ 3	Agent 1987, Asante et al. 1993, Cottrell 1986, City of San Diego 2006	Install PO
	Number of LT Lanes	≥ 2	Agent 1987, Asante et al. 1993, ITE 1982, City of San Diego 2006	Install PO
Speed	Opposing Speed	≥ 45 mph (70 km/h)	Agent 1981, Asante et al. 1993, ITE 1982, Upchurch 1986	Install PO
Others	Benefit/Cost Analysis		Agent 1981, Cottrell 1986	Install the One with More Benefit
	High Truck or Pedestrian Volume		Lalani et al. 1986, City of San Diego 2006	Install PO
	50 or More School-Age Pedestrians Crossing the Lane per Hour			
	Access Management Condition		Cottrell 1986	Install PO
	Angle of the Two Approaches			Install PO

2.2 WARRANTS AND GUIDELINES FOR SEQUENCE OF LEFT-TURN SIGNAL PHASING

The sequence of left-turn phase (the order and combination of movements that make up the signal phasing) can also have great impacts on the safety and operational efficiency at signalized intersections. Generally, there are three types of sequence arrangements:

- lead-lead sequence: moves both the opposing left turns before the through movements,
- lag-lag sequence: moves both the opposing left turns after the through movements, and
- lead-lag sequence: opposing left-turns move separately from each other but simultaneously with their associated through phase.

Note that, for individual intersection approaches, there are only two types of phasing sequence:

- lead left-turn sequence and
- lag left-turn sequence.

A relatively small number of studies have been conducted on the sequence of left-turn signal phasing, and most of these studies did not give explicit warrants or guidelines for the selection of proper sequence. They only compared the accident rates or some operational efficiency–related traffic measures at the intersections with different types of signal phasing sequences. Therefore, this part of the literature review will include two sections: (1) studies based on safety impact analysis and (2) studies based on operational impact analysis.

2.2.1 Studies Based on Safety Impact Analysis

2.2.1.1 Box and Basha (2003)

This study evaluated the safety impacts of the left-turn phasing sequence for individual intersection approaches. It compared the rates of left-turn head-on (LTHO) accidents at eight intersections with a lead-lead left-turn phase and at 14 intersections with a lag-lag left-turn phase. The accident rates were calculated by the following equation:

$$(1000\times \text{Number of LTHO Accidents})/(\text{Number of Years} \times \text{Conflict Volume}) \qquad (8)$$

where:

$$\text{Conflict Volume} = \text{Daily Left Turn} + \text{Opposing Straight Ahead Volume}$$

The results of a comparison of accident rates between lead and lag phasing are presented in Table 9.

Table 9: Comparison of Accident Rates between Lead and Lag Phasing

Modes	Category	Lead	Lag
Permissive-Only	Property Damage Only Injury	0.15 0.05	0.07 0.08
	All	0.20	0.15
PPLT	Property Damage Only Injury	0.13 0.12	0.15 0.10
	All	0.25	0.25
Protected-Only	Property Damage Only Injury	0.03 0.02	0.03 0.02
	All	0.05	0.05

Source: Box and Basha (2003)

From this table, it was found that there was no significant difference in accident rates between the intersection approaches with lead and lag left-turn phasing. Therefore, the author concluded that the use of lead or lag left-turn phasing does not have a significant impact on intersection safety in terms of LTHO accident risk.

2.2.1.2 Hummer et al. (1991)

In this study, three major issues relative to left-turn signal sequence were explored, which include: (1) driver's preference and understanding, (2) intersection safety, and (3) operational efficiency. For the driver's preference and safety issues, the following methods were used: (1) motorist survey, (2) traffic conflict studies, and (3) historical accident data analysis.

A motorist survey was conducted at the 1988 Indiana State Fair, and over 400 valid responses were received. The survey results showed that more people preferred the lead sequence to the lag sequence. The preference for lead and lag sequence was somewhat related to the age of the respondents. People from rural counties expressed a preference more often for the lag sequence. People driving less preferred the lag sequence more often.

A traffic conflict study was conducted at three pairs of intersections. Each pair of intersections included one with lag-lag PPLT phasing and one with lead-lead PPLT phasing. These three pairs of intersections represent three different types of intersections. One pair was downtown intersections (many pedestrians and low speed), one was urban intersections (few pedestrians), and one was diamond freeway interchanges. Four conflict types were investigated, including (1) left-turner with pedestrian, (2) left-turner with straight through opposing, (3) left-turner indecision, and (4) left-turner runs red. The study results showed that, except for the indecision conflicts, there were fewer left-turn associated traffic conflicts at the intersections with the lag phase sequence. And, the largest difference between lead and lag sequences was the left and pedestrian conflicts at the intersections in the downtown and urban area, where the lead sequence was associated with six times as many conflict rates as the lag sequence. One possible explanation for the low conflict rates at the lag phase intersection is that in most cases, at the lead site, these left and pedestrian conflicts happened when pedestrians stepped off the curb and into the approach to which left-turning vehicles were destined upon seeing a red signal for the cross street. Another important result is that the lag sequence was associated with significantly lower rates of left and oncoming conflicts than the lead sequence at the downtown and urban pairs of intersections. The first explanation is that vehicles turning left at the lag intersections may have fewer opportunities to turn on the green ball signal than at the lead intersections. The second explanation is the tendency at the lead intersection for left-turn vehicles to try to enter the intersection immediately after the yellow arrow signal has ceased as if they still had the right-of-way.

Accident data were analyzed to evaluate the relative safety of intersection approaches with lead or lag signal sequence. Fourteen approaches with lag phasing were compared with 15 approaches with lead phasing at downtown fixed-time signalized intersections of a one-way street and a two-way street. It was found that accidents occurred at a greater rate at intersections with lead sequences, though the difference was not significant.

Overall, this study found that the lag left-turn phase outperforms the lead left-turn phase in terms of safety. The lag left-turn phase sequence is recommended for intersections serving heavy pedestrian volumes, diamond interchanges or one-way pairs, and intersections with fixed-time signals.

2.2.1.3 Nandam and Hess (2000)

This study investigated the operation and safety effects of the conversion of left-turn phasing sequence from lead-lead to lead-lag by three different studies: (1) traffic safety review,

(2) response time analysis, and (3) simulation analysis. The latter two studies will be discussed in the "Studies Based on Operational Impact Analysis" section later.

Nine intersections in the city of Boca Raton were selected for the safety analysis. The analysis included review of crash data 2 years before and 2 years after the sequence convention had been implemented at each intersection. The analysis included comparison of before and after left-turn crash rates at the intersections. The results indicate that the change in sequence of the left-turn phases from lead-lead to lead-lag did not result in significant changes in both left-turn and total crash experience.

2.2.1.4 Sheffer and Janson (1999)

This paper investigated both the safety impacts and operational efficiency of deferent left-turn phasing sequences for individual intersection approaches. Six intersections with lead-lag left-turn phasing were studied. The six approaches with lead left-turn phasing were compared with six approaches with lag left-turn phasing in terms of their safety and operational efficiency. From an operational efficiency point of view, three traffic measures were used: flow rates, start-up lost times, and fourth vehicle crossing times. From a safety point of view, the accident rate was used for comparison between approaches with lead and lag left-turn phasings. For all four measures, the comparison results show that the approaches with lag phasing have better performance than those with lead phasing, although the differences in saturation flow rates and accident rates were not significant at the 95 percent confidence level.

The accident rates shown in Table 10 were in accidents per million left-turning vehicles based on the estimated daily and yearly traffic volume. In this study, lag protected-only left-turn phasing operated better and safer than lead protected-only phasing.

Table 10: Comparison of Accident Rates between Lead and Lag Phasing

Category	Accident Rate(per Million Turns)	
	Lead	Lag
Sum	21.00	18.11
Mean	3.50	3.02
Standard Deviation	2.10	1.57

Source: Sheffer and Janson (1999)

Comments on This Study. The approaches of six intersections studied during the safety analysis were located on the same arterial. In other words, all the samples were collected in a small area, which did not cover a wide range of signalized intersections. In addition, comparison of accident rates showed only a slight difference between the lag and lead left-turn phasing. Without a statistical test, it is difficult to draw the conclusion that the lag left-turn phase is significantly better than the lead left-turn phase.

2.2.1.5 Upchurch (1991)

This paper used two methods to investigate the safety impacts of different types of left-turn signal control modes with different phasing sequences: (1) cross-section comparison and (2) before-and-after comparison. It was the first paper that compared the accident experience of all five types of left-turn phasing: (1) permissive, (2) lead PPLT, (3) lag PPLT, (4) lead protected-only, and (5) lag protected-only. The following are the major findings of this paper.

Cross-Section Comparison. In the cross-section comparison, the left-turn accident data of 523 intersection approaches were collected. The average accident rates were calculated in terms of left-turn accidents per million left-turning vehicles. The results of this comparison are presented in Table 11.

Table 11: Cross Accident Statistics (LT Accidents per Million LT Vehicles)

Category	Criteria	Permissive	Lead PPLT	Lag PPLT	Lead PO	Lag PO
2 Opposing Lanes	LT Accident Rate	2.62	2.71	3.02	1.02	2.09
	Sample Size (Number of Approaches)	162	62	44	57	4
3 Opposing Lanes	LT Accident Rate	3.83	4.54	2.65	1.33	0.55
	Sample Size (Number of Approaches)	25	52	35	80	2

Source: Upchurch (1991)

Because the sample size for lag protected-only phasing was too small to produce a reliable estimate of average accident rates, it was not considered in this cross-section comparison. By comparing the other four phasing sequences, it was found that, for the approaches with two opposing lanes, the order of safety (from best to worst) was lead protected-only, permissive, lead PPLT, and lag PPLT. For the approach with three opposing lanes, the order of safety (from best to worst) was lead protected-only, lead PPLT, permissive, and lag PPLT. The lead protected-only phasing has a significantly lower accident rate than the other three types of phases.

Before-and-After Comparison. The before-and-after comparison studied 194 intersection approaches that were converted from one mode of left-turn phasing to another. The average accident rates were also calculated in terms of left-turn accidents per million left-turning vehicles. The results of this comparison indicate that, for approaches with two opposing lanes, lead protected-only phasing was always better than other types of left-turn phasing. The order of safety (from best to worst) was lead protected-only, lag PPLT, lead PPLT, and permissive. This result is not exactly the same as the result from the cross-section comparison. In the cross-section comparison, the lead PPLT is better than the lag PPLT in terms of intersection safety.

For the case of three opposing lanes, the before and after accident rates for the approaches that were converted from one type of left-turn phasing to another indicate that lag PPLT was better than lead protected-only, and both of these modes are better than the lead PPLT and permissive mode. The relationship between lead PPLT and permissive cannot be determined because the accident rates for conversions from permissive to lead PPLT and from lead PPLT to permissive contradicted each other.

Comparison of the Results of Both Types of Studies. For comparison purposes, the results of both comparison studies are listed in Table 12. The orders of safety of different types of left-turn phases from these two comparison studies are not consistent, whether there are two or three opposing lanes. However, overall, lead protected-only left-turn phasing is relatively safer than other types of left-turn phases.

Table 12: Comparison of Safety Orders from Both Types of Studies

Number of Opposing Lanes	Comparison Method	1st	2nd	3rd	4th
2 Opposing Lanes	Cross Section	Lead PO	Permissive	Lead PPLT	Lag PPLT
	Before-and-After	*Lead PO*	*Lag PPLT*	*Lead PPLT*	*Permissive*
3 Opposing Lanes	Cross Section	Lead PO	Lead PPLT	Permissive	Lag PPLT
	Before-and-After	*Lag PPLT*	*Lead Protected*	*Not available*	*Not available*

2.2.1.6 Summary of Studies Based on Safety Impact Analysis

Numerous studies have been conducted on analyzing the safety impacts of different types of left-turn phases. These studies used two major comparison methods, i.e., before-and-after and cross-section comparisons, and various criteria of accident rates were used in these comparison studies. By combining the results of these previous studies, a summary table was developed (see Table 13). The table shows that 76 percent of the results indicate that the protected-only mode of left-turn phasing is the safest. The comparisons between permissive and PPLT showed that the PPLT was safer than the permissive. In terms of phasing sequences, two studies were conducted for comparing the safety impacts of protected-only left-turn phases with different sequences. Both results indicated that the lead protected-only was safer than the lag protected-only left-turn phases. For the sequences of PPLT phases, seven studies were conducted for evaluating the safety impacts of lead PPLT and lag PPLT phases. Five of them found that lag PPLT was better, while two of them indicated that lead PPLT was better. In sum, from the literature review, researchers found that (1) protected-only is the safest left-turn phase, (2) lead protected-only was safer than the lag protected-only left-turn phase, and (3) lag PPLT was safer than the lead PPLT left-turn phase. The detailed results of these previous studies are summarized in Table 13.

Table 13: Summary of Studies on Safety Impact Analysis

<table>
<tr><th rowspan="3"></th><th rowspan="3">Reference</th><th rowspan="3">Comparison Method</th><th rowspan="3">Criterion</th><th rowspan="3">Sample Structure</th><th colspan="5">Modes or Sequences Studied</th><th rowspan="3">Comparison Results</th></tr>
<tr><th rowspan="2">Permissive</th><th colspan="2">PO</th><th colspan="2">PPLT</th></tr>
<tr><th>Lead</th><th>Lag</th><th>Lead</th><th>Lag</th></tr>
<tr><td>1</td><td>David and Norman 1975</td><td>Cross section</td><td>Total accidents/intersection; fatal and injury accidents/intersection</td><td>552 intersections</td><td>√[1]</td><td colspan="2">√</td><td colspan="2"></td><td>PO is better[2].</td></tr>
<tr><td>2</td><td>Agent and Deen 1979</td><td>Before-and-after</td><td>Left-turn accidents/ million entering vehicles</td><td>23 intersections</td><td>√</td><td colspan="2">√</td><td colspan="2"></td><td>PO is better.</td></tr>
<tr><td>3</td><td>Benioff and Rorabaugh 1980</td><td>Before-and-after</td><td>LT/total accident number; LT and total accidents/MEV</td><td></td><td></td><td colspan="2">√</td><td colspan="2">√</td><td>PO is better.</td></tr>
<tr><td>4</td><td>Agent 1981</td><td>Before-and-after</td><td>Accident number</td><td></td><td>√</td><td colspan="2">√</td><td colspan="2"></td><td>PO is better.</td></tr>
<tr><td>5</td><td>ITE 1982</td><td>Before-and-after</td><td>LT accidents/year</td><td>11 intersections</td><td></td><td colspan="2">√</td><td colspan="2">√</td><td>PO is better.</td></tr>
<tr><td rowspan="2">6</td><td rowspan="2">Warren 1985</td><td rowspan="2">Before-and-after</td><td rowspan="2">LT and other accident number</td><td>7 intersections (from PO to PPLT)</td><td></td><td colspan="2">√</td><td colspan="2">√</td><td>PO is better.</td></tr>
<tr><td>2 intersections (from permissive to PPLT)</td><td>√</td><td colspan="2"></td><td colspan="2">√</td><td>PPLT is better.</td></tr>
<tr><td>7</td><td>Upchurch 1986</td><td>Cross section</td><td>LT accidents/ million left-turning vehicles</td><td>6 intersections</td><td>√</td><td colspan="2">√</td><td colspan="2">√</td><td>PO is 1st[3];
PPLT is 2nd;
permissive is 3rd.</td></tr>
<tr><td rowspan="2">8</td><td rowspan="2">Agent 1987</td><td rowspan="2">Before-and-after</td><td rowspan="2">LT and total accidents/ (year × approach)</td><td>11 intersections (from PO to PPLT)</td><td></td><td colspan="2">√</td><td colspan="2">√</td><td>PO is better.</td></tr>
<tr><td>24 intersections (from Per to PPLT)</td><td>√</td><td colspan="2"></td><td colspan="2">√</td><td>PPLT is better.</td></tr>
<tr><td rowspan="2">9</td><td rowspan="2">Lee et al. 1991</td><td rowspan="2">Before-and-after</td><td rowspan="2">LT and total accident number</td><td>3 intersections (from lead PPLT to lag PPLT)</td><td></td><td colspan="2"></td><td>√</td><td>√</td><td>Lag PPLT is better.</td></tr>
<tr><td>6 intersections (From lead PO to lag PO)</td><td></td><td>√</td><td>√</td><td colspan="2"></td><td>Lead PO is better.</td></tr>
</table>

Table 13: Summary of Studies on Safety Impact Analysis (Continued)

	Reference	Comparison Method	Criterion	Sample Structure	Modes or Sequences Studied					Comparison Results
					Permissive	PO		PPLT		
						Lead	Lag	Lead	Lag	
10	Hummer et al. 1991	Cross section	Accidents/ million left-turning vehicles					√	√	Lag phasing is better than lead phasing.
11	Upchurch 1991	Cross section	LT accidents/ million LT vehicles	329 approaches (2 opposing lanes)	√	√		√	√	Lead PO is 1st; lead PPLT is 2nd; lag PPLT is 3rd; permissive is 4th.
				194 approaches (3 opposing lanes)	√	√		√	√	Lead PO is 1st; lag PPLT is 2nd; permissive is 3rd; lead PPLT is 4th.
		Before-and-after		94 approaches (2 opposing lanes)	√	√		√	√	Lead PO is 1st; lag PPLT is 2nd; lead PPLT is 3rd; permissive is 4th.
				100 approaches (3 opposing lanes)	√	√		√	√	Lag PPLT is1st; lead PO is 2nd; lead PPLT and permissive are worst.
12	Asante et al. 1993	Cross section	LT accidents/approach	157 approaches	√	√		√		Permissive is 1st; PO is 2nd; PPLT is 3rd.
13	Shebeeb 1995	Cross section	LT accidents × million/ the product of hourly opposing and LT volume	179 approaches of 54 intersections		√	√	√	√	Lead PO is 1st; lag PO is 2nd; lead PPLT is 3rd; permissive is 4th; lag PPLT is 5th.

Table 13: Summary of Studies on Safety Impact Analysis (Continued)

	Reference	Comparison Method	Criterion	Sample Structure	Modes or Sequences Studied					Comparison Results
					Permissive	PO		PPLT		
						Lead	Lag	Lead	Lag	
14	Stamatiadis et al. 1997	Cross section	LT accidents/ (year × LT volume × opposing volume)	152 approaches (1 opposing lane)	√	√		√		PO is 1st; PPLT is 2nd; permissive is 3rd.
				252 approaches (2 opposing lanes)						
			LT accidents/ (year × 100 peak hour LT volume)	152 approaches (1 opposing lane)						
				252 approaches (2 opposing lanes)	√	√		√		PO is 1st; permissive is 2nd; PPLT is 3rd.
15	Washington et al. 1991	Before-and-after	LT, total, and other accidents/ million entering vehicles			√				LT phasing is better than no LT phasing.
16	Sheffer and Janson 1999	Cross section	Accidents/million left turns	6 intersections		√		√		Lag phasing is better than lead phasing.
17	Nandam and Hess 2000	Cross section	Accidents/million left turns	29 approaches		√				Lag phasing is better than lead phasing
			Accidents/million total vehicles			√				
18	Box and Basha 2003	Cross section	1000 × LTHO accidents/ (years × conflict volume)	56 approaches of 22 intersections	√	√		√		PO is 1st; PPLT is 2nd; permissive is 3rd.

1. "√" means this mode or sequence of LT phasing is studied in this research.
2. "Better" means this mode or sequence of LT phasing is safer than others.
3. "1st," "2nd," "3rd," "4th," and "5th" mean the safety order from best to worst.

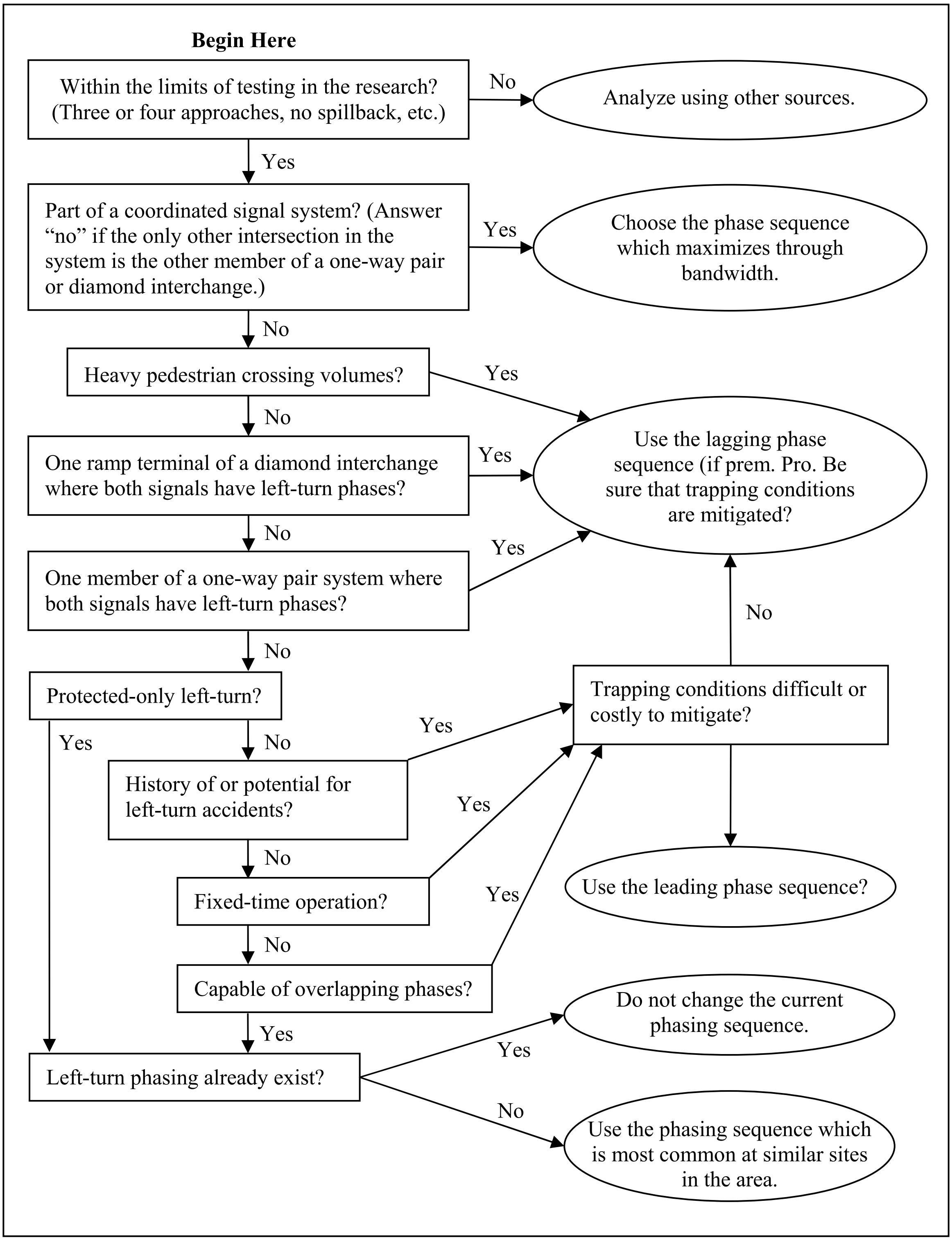
2.2.2 Studies Based on Operational Impact Analysis

2.2.2.1 Hummer et al. (1991)

In this study, three major issues relative to left-turn signal sequence were explored. The driver's preference and safety issues have been reviewed in section 2.1.2 and the following is about the operational efficiency issues.

Traffic simulation was used to analyze the impacts of left-turn signal sequence on traffic delay. A microscopic simulation model, i.e., the 1986 version of NETSIM, was used in this study. Five separate experiments were conducted, including experiments on intersections with four approaches, intersections with three approaches, and diamond interchanges. The results of these experiments showed that PPLT lead phase caused slightly more delay than PPLT lag phase for intersections with four approaches. No significant difference between lead protected-only and lag protected-only signal phases was detected. The experiment on diamond interchanges indicated the superiority of the lag phase over the lead phase in terms of traffic delay and number of vehicle stops.

Overall, this study found that the lag left-turn phase outperforms the lead left-turn phase in both safety and operational efficiency aspects. The lag left-turn phase sequence is recommended for intersections serving heavy pedestrian volumes, diamond interchanges or one-way pairs, and intersections with fixed-time signals. Based on the results of this study, guidelines for selection of a left-turn phase sequence were developed in a flowchart format (see Figure 18).



Source: Hummer et al. (1991)

Figure 18: Guidelines for Selection of Left-Turn Phase Sequence

2.2.2.2 Nandam and Hess (2000)

This study investigated the operation and safety effects of a change in the left-turn phasing sequence from lead-lead to lead-lag. The safety effects have been reviewed in section 2.2.1.3. The operation effects include: (1) response time analysis and (2) simulation analysis.

The response time was the time from the onset of the protected-only left-turn phase green arrow indication to the time the first left-turn vehicle in the queue crossed the stop bar. It was used to determine if the change in sequence of the left turns from lead to lag would result in higher response times. The collected response time data indicated that the probability distributions of the response times under the lead and lag left-turn phases are similar.

The simulation analysis was performed using the SYNCHRO and Simtraffic models. The measures of effectiveness (MOEs) are average travel speed, stops per vehicle, stop delay for the arterial through movements, and overall stop delay for the complete section. Simulation analysis showed that the use of lead-lag compared to lead-lead left-turn phasing does have benefits related to improved traffic flow at the intersections along the arterial sections.

Comments on This Study. Comments concern response time and simulation analysis:

- The magnitude of the response time is usually 2~3 seconds, and the difference in responses times under different left-turn phasing sequences is even smaller, which does not significantly impact left-turn operations at an intersection. Therefore, the response time is not a good measure for analyzing the operational impacts of the left-turn phasing sequence.
- In the simulation analysis, the operational efficiency comparison between different left-turn phasing sequences did not consider some important influencing factors on left-turn operation, such as left-turn lane overflow and blockage problems. The operational efficiency of different types of left-turn sequences will be significantly different under these specific conditions. Therefore, these factors need to be considered in the selection of the proper left-turn phasing sequence.

2.2.2.3 Agent (1981)

The safety-related parts of this study have been introduced in section 2.1.2.1. For the left-turn phasing operational analysis, this study investigated the intersection delay at four T intersections where protected-only left-turn phasing was replaced by permissive phasing. The outcomes of average intersection delays are summarized in Table 14.

Table 14: Delay Changes in the Conversion from Protected-Only to Permissive Phasing

Category	Average Delay (s/Vehicle)	
	Protected-only	Permissive
Left Turn	26.1	13.1
Total Intersection	14.1	10.7
Side Street	8.0	9.0
Opposing Volume	16.3	14.6

Source: Agent (1981)

Except for the delay for the side street, the average delays for left-turn traffic, the total intersection, and opposing traffic are all decreased. Thus, the operational efficiency of permissive phasing was better than that of protected-only phasing in this study.

2.2.2.4 Wright and Upchurch (1992)

This study investigated delay at one intersection whose phasing was changed from protected-only to lead PPLT and then later to lag PPLT. The changes in delay are shown in Table 15.

Table 15: Delay (s/Vehicle) Changes in Left-Turn Phasing Conversion

Category		Protected-only	Lead PPLT	Lag PPLT
Northbound	Left Turn	58.7	28.4	42.3
	Through	18.6	15.7	16.7
Southbound	Left Turn	41.5	19.9	34.8
	Through	18.8	24.3	17.4

Source: Wright and Upchurch (1992)

By comparing the average delay under different left-turn phasing conditions, it is found that the conversion from protected-only to lead PPLT phasing reduced delay, and the conversion from lead PPLT to lag PPLT phasing increased delay for the northbound left-turn, southbound left-turn, and northbound through traffic. The results of southbound through traffic showed that the average delay rank of different left-turn phasing sequences (from short to long) was lag PPLT phasing, protected-only phasing, and lag phasing. In terms of total average delay, lead PPLT was better than lag PPLT, and lag PPLT was better than protected-only left-turn phase.

2.2.2.5 Asante et al. (1993)

This study developed guidelines for left-turn phasing based on a three-level decision process. The first step of the process was whether some protection should be provided to the left-turn movement. If protection was required, the second step of the process was to select PPLT or the protected-only phasing. The third step of the process was to choose the sequence between lead and lag. The left-turn stopped delay of 194 approaches of 108 intersections was estimated for different phasing types. The findings for left-turn phasing operation are presented in Table 16.

Table 16: Average Left-Turn Stopped Delay of Different Types

Phasing	Delay (s/Vehicle)
Protected-only	37.7
PPLT	20.3
Lead Dallas Phasing	29.3
Lag Dallas Phasing	36.0

Source: Asante et al. (1993)

2.2.2.6 Shebeeb (1995)

This study investigated both the safety and efficiency of left-turn phasing at 179 approaches of 54 intersections in Texas and Louisiana. Left-turn stopped delay in peak hours was used to measure the efficiency of left-turn phasing. The results of a comparison of different sequences of left-turn phasing are shown in Table 17.

Table 17: Average Left-Turn Stopped Delay of Different Sequences

Sequence	Delay (s/Vehicle)
Lead Protected-only	46.8
Lag Protected-only	44
Lead PPLT	28.8
Lag PPLT	32
Lead Dallas Phasing	23
Lag Dallas Phasing	24.6
Permissive	13.7

Source: Shebeeb (1995)

2.2.2.7 Sheffer and Janson (1999)

This study has been discussed in section 2.2.1.4 of this report. It used flow rates, start-up lost times, and fourth vehicle crossing times to examine the operational performance between lead and lag left-turn phasing. The comparison results are shown in Table 18.

Table 18: Comparison Results between Lead and Lag Left-Turn Phasing

Phasing	Saturation Flow Rate (Vehicles per Hour)	Start-Up Lost Time (s)	Fourth Vehicle Crossing Times (s)
Lead	2037	1.43	8.67
Lag	2060	0.69	7.92

Source: Sheffer and Janson (1999)

All comparison data indicated that lag left-turn phasing had better performance than lead left-turn phasing.

2.2.2.8 Summary of Studies on Operational Efficiency Analysis

Numerous studies have been conducted on analyzing the operational efficiency of different types of left-turn phases. These studies used two major comparison methods, i.e., before-and-after and cross-section comparisons, and various criteria were used in these comparison studies. By combining the results of these previous studies, a summary table was developed (see Table 19). In terms of operational efficiency, 36 percent of the results showed that PPLT phasing was the best left-turn phase. For evaluating different left-turn phasing sequences, three studies were conducted to compare lead PPLT with lag PPLT phasing. Two results showed that lead PPLT phasing was better than lag PPLT phasing; another result indicated that lag PPLT was better than lead PPLT phasing. Only one study evaluated the operational efficiency of protected-only left-turn control with different phasing sequences. And, the results of this study indicated that lag protected-only phasing was better than lead protected-only phasing. In sum, from the literature review, researchers found that (1) PPLT was better than the protected-only left-turn phase in terms of the operational efficiency, (2) lag PPLT performance was better than that for the lead PPLT left-turn phase, and (3) the lag protected-only phase had better operational performance than the lag protected-only phase. The detailed results of these previous studies are summarized in Table 19.

Table 19: Summary of Studies on Operational Efficiency Analysis

	Reference	Comparison Method	Criterion	Sample Structure	Modes or Sequences Studied: Permissive	PO: Lead	PO: Lag	PPLT: Lead	PPLT: Lag	Comparison Results
1	Agent and Deen 1979	Before-and-after	Delay (s/vehicle) installation of protected	1 T intersection	√[1]	√				Permissive is better[2].
				2 intersections						
2	Agent 1981	Before-and-after	Delay (s/vehicle) from protected to permissive	4 intersections (left turn)	√	√				Permissive is better.
				4 intersections (total intersection)						
				4 intersections (opposing volume)						
				4 intersections (side street)	√	√				PO is better.
3	ITE 1982	Before-and-after	Delay (s/vehicle) from protected to PPLT	3 approaches (left turn)		√		√		PPLT is better.
				3 approaches (opposing)						
4	Wright and Upchurch 1992	Before-and-after	Delay (s/vehicle) from protected to lead PPLT and then to lag PPLT	1 intersection (northbound; through)		√		√	√	Lead PPLT is 1st[3]; lag PPLT is 2nd; PO is 3rd.
				1 intersection (northbound; left turn)						
				1 intersection (southbound; through)		√		√	√	
				1 intersection (southbound; left turn)		√		√	√	Lag PPLT is 1st; PO is 2nd; lead PPLT is 3rd.
5	Asante et al. 1993	Cross section	Stopped delay (s/vehicle)	194 approaches of 108 intersections		√		√		PPLT is better.
6	Shebeeb 1995	Cross section	Stopped delay (s/vehicle)	174 approaches	√	√	√	√	√	Permissive is 1st; lead PPLT is 2nd; lag PPLT is 3rd; lag PO is 4th; lead PO is 5th.
7	Sheffer and Janson 1999	Cross section	Start-up lost time; fourth vehicle crossing time	6 intersections		√				Lag phasing is better than lead phasing.

1. "√" means this mode or sequence of LT phasing is studied in this research.
2. "Better" means the delay of this mode or sequence of LT phasing is lower than others.
3. "1st," "2nd," "3rd," "4th," and "5th" mean the operation order from best to worst.

2.3 SIGNAL DISPLAY

A great concern in dealing with left-turn phasing treatment is motorists' understanding of the intended signal control, of which signal display is a critical issue. Several studies have been conducted to evaluate the safety and operational impacts of different types of signal displays. Most of the left-turn signal display studies are related to the following three topics: (1) placement, (2) arrangement, and (3) indication.

This literature review focuses on these three aspects and will introduce (1) the current standards of left-turn signal display, (2) the existing problems in different types of signal displays, and (3) potential solutions.

2.3.1 Current Standards for Left-Turn Signal Display

2.3.1.1 Manual on Uniform Traffic Control Devices (2003)

Currently, the most used guidelines for left-turn signal display are the MUTCD, which provides the national standards for left-turn signal display regarding its installation and operation.

The guidelines for left-turn signal display provided by the MUTCD summarize standards in regards to the following three aspects:

- the design and application of left-turn traffic control signs, pavement markings, and signal installations;
- several possible combinations of left-turn and through movement signal lens arrangements and signal indications; and
- some general standards for locating left-turn signal heads.

2.3.1.2 King (1977)

This study developed guidelines for optimum traffic signal display configurations. The study conducted field experiments to compare relative visibility and legibility of various signal displays and human factors affecting traffic signal display design. This research resulted in recommendations for changes in the MUTCD at that time regarding the left-turn signal placement, which suggested that the 20 degree placement be reduced to 10 degree placement to improve conspicuity (King 1977).

2.3.1.3 Traffic Design and Illumination

Web-based material provided by FHWA (2008), *Traffic Design and Illumination*, presents an overview of the fundamental principles of traffic signal display as they apply to signalized intersections. This material is mostly based on the guidelines provided by the MUTCD. In addition, it details the types of supplemental left-turn signal displays and illustrates them with some examples.

2.3.2 Existing Problems with Current Left-Turn Signal Display

For decades, traffic engineers have regarded the MUTCD as a guideline to design left-turn signal display. Thus, most of the agencies throughout the United States follow the left-turn signal display criteria introduced above. However, several studies have indicated that some of the current MUTCD standards for left-turn signal display will cause some safety problems. The existing problems in the current standards of left-turn signal display are summarized as follows.

2.3.2.1 Confusion about Green Ball Indication for Permissive Phase

The MUTCD definition of the green ball indication says that drivers facing a green ball indication have the right-of-way to proceed. However, the MUTCD also says, "vehicular traffic, including vehicles turning right or left, shall yield the right-of-way to other vehicles, and to pedestrians lawfully within the intersection or an adjacent crosswalk, at the time such signal indication is exhibited." It is this caveat that allows the green ball indication to be used for permissive left-turn control.

The apparent inconsistency in the definition of the green ball indication may result in confusion for drivers. Several studies have been conducted to validate it:

- Staplin and Fisk (1991) found that the green ball permissive indication was one of the most problematic since drivers interpreted it as a cue for when not to precede, when the previously learned automatic response to green is an assumption of right-of-way.
- A study conducted by Knoblauch et al. (1995) found that nearly 20 percent of drivers over the age of 65 and 14 percent of drivers less than 65 said they could turn left without yielding when facing the green ball indication.

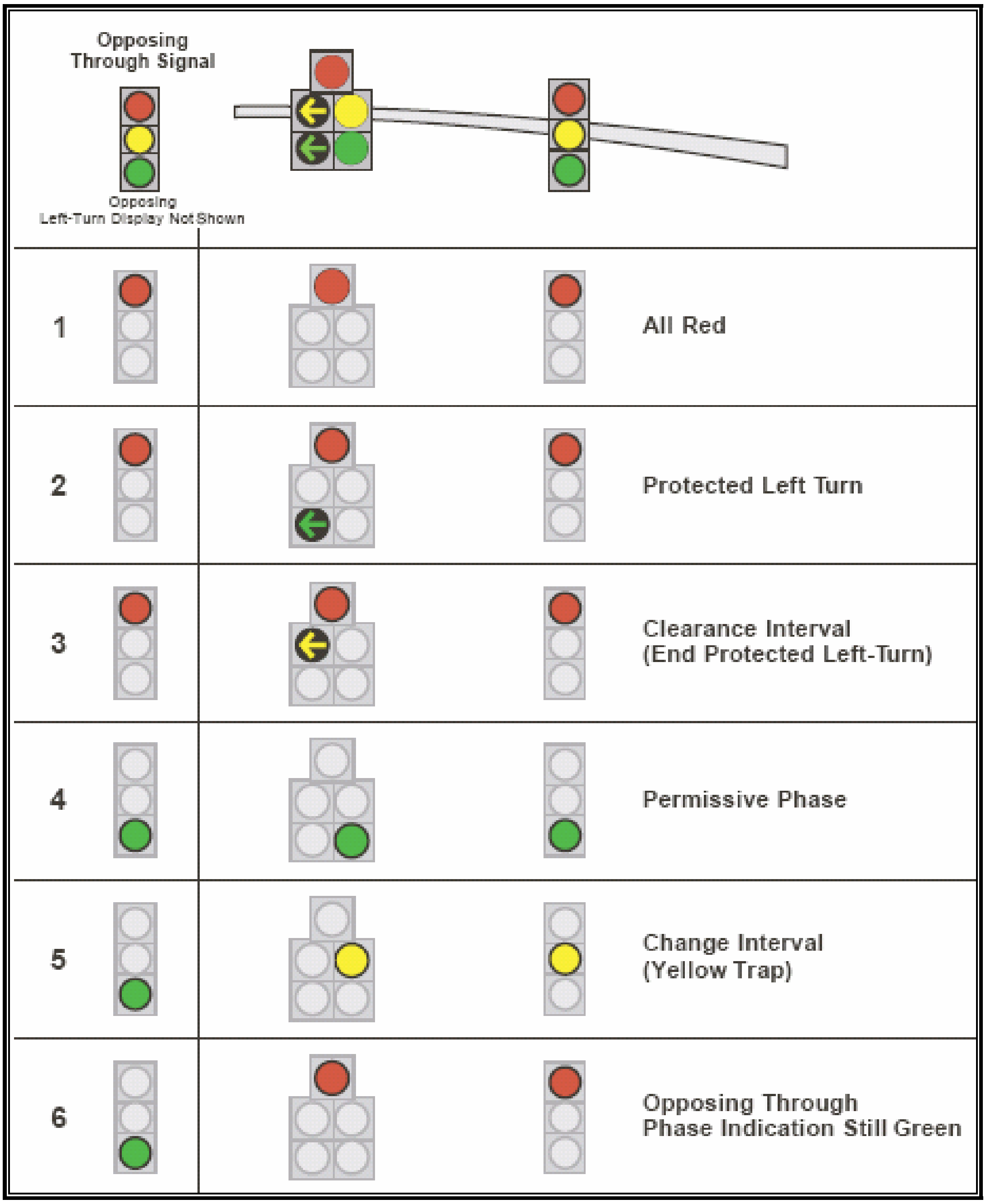
- Freedman and Gilfillan (1988) and Drakopoulos (1993) reported similar problems with drivers' understanding of the green ball permissive indication in studies conducted in Philadelphia, Seattle, Dallas, and Lansing.
- Several research studies have tried to identify the optimal combination of signal display indication and arrangement that results in the maximum level of driver understanding; however, they had inconsistent results (Asante et al. 1993, Bonneson and McCoy 1993, Drakopoulos and Lyles 2000, Hummer et al. 1992, Noyce 1999 a and b).

The literature justifies the concern of many traffic engineers — drivers may wrongly interpret the permissive green ball indication to meaning that the left-turn movement has the right-of-way. It is this concern that has led to the development of several unique permissive left-turn indications, which will be introduced in section 2.3.2.4.

2.3.2.2. Confusion about Simultaneous Signal Indication of Conflicting Color

In PPLT mode, with a separate left-turn signal display, there exists a situation in which a green arrow signal indication for left-turn movement and a circular red signal indication for adjacent through movement are illuminated simultaneously. Figure 19 illustrates this situation (the simultaneous illumination of left-turn green arrow and red ball in phase 2). Several studies have been conducted to evaluate drivers' understanding and identify safety problems in this situation, especially for five-section signal heads in which the red and green balls are shared with through movement:

- Asante et al. (1993) evaluated five-section PPLT display in Texas. Field studies were conducted, and paper-based surveys were mailed to Texas residents. The results indicated that a higher level of driver understanding was achieved when the green arrow indication was displayed alone. Researchers concluded that simultaneously displaying the green arrow and red ball indication in the same signal display confused many drivers.
- Bonneson and McCoy (1993) completed a similar study in Nebraska to evaluate drivers' understanding of different PPLT signal display arrangements. They found that, for five-section display arrangements, approximately 10 percent more drivers understood the green-arrow-only indication compared with the simultaneous indication.



Source: Kacir et al. 2003

Figure 19: Illustration of Simultaneous Display and Yellow Trap

- Noyce (1999a) conducted traffic conflict and traffic event* studies in 24 typical intersections at eight locations, the purpose of which was to observe and evaluate the safety effects of PPLT signal display. The study found that there was a significant increase in traffic events at intersections with separate five-section horizontal signal heads where simultaneous illumination of the left-turn green arrow and red ball exists. Noyce hypothesized that this result suggested an increase in signal display complexity and driver workload with the simultaneous illumination of the green arrow and red ball indications in the horizontal display, ultimately leading to increased driver error.
- Other studies (Noyce and Kacir 2002, Knodler 2007) used simulator technology and a follow-up computer-based photographic survey to evaluate drivers' understanding in different scenarios. The results showed that the simultaneous illumination of the left-turn green arrow and red ball (for separate signal display) resulted in a significantly lower percentage of correct responses to the PPLT display than the simultaneous illumination of the left-turn green arrow and green ball (for shared signal display) situations. Noyce concluded that simultaneously displaying conflicting indications causes confusion.

2.3.2.3 Yellow Trap — for PPLT Mode with Lead-Lag Signal Phasing

Traffic engineers often would like to increase operational efficiency on roadways by implementing PPLT mode. However, it creates what is known as the "yellow trap" problem when PPLT is implemented with lead-lag phasing. Figure 20 indicates when the yellow trap occurs. Phase 5 (from Figure 19) illustrates the signal display during the yellow trap. During the signal change from a permissive left-turn phase to a lag protected left-turn phase (point A in Figure 20), for the traffic in the leading left-turn direction, the circular green indication for the adjacent through traffic turns into yellow (phase 5 in Figure 19). At this time, the left-turner mistakenly believes that the opposing through traffic also gets the yellow change interval and so makes the left turn, in effect becoming a "sneaker." However, with the lead-lag phasing, traffic in the direction of the lagging phase will not stop at the end of this permissive phase. In fact, they will see a circular green indication in the through lanes at this time. Thus, the vehicle that makes a left-turn during the yellow phase may crash into the through traffic in the lag left-turn direction.

* **Traffic event:** left-turn vehicles hesitating or not turning left during the protected left-turn green arrow.

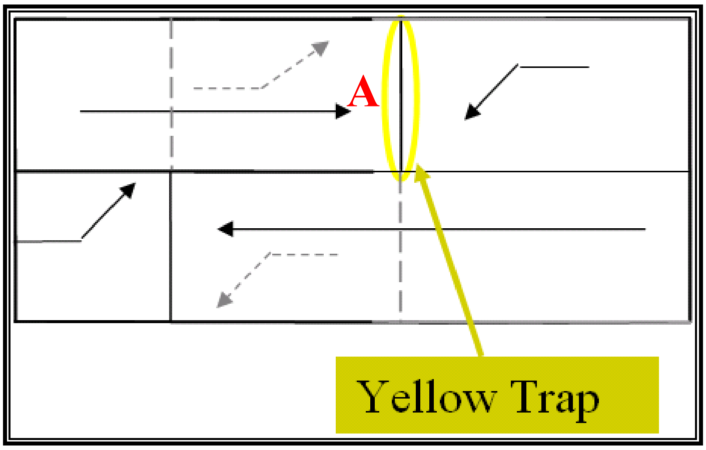


Figure 20: Yellow Trap Illustration in Phasing Graph

2.3.2.4 Lack of Uniformity

Although the MUTCD provides a basic standard for the left-turn signal display design, there is still some flexibility (especially in PPLT mode) in implementation due to some unspecific definition and limited guidance in the MUTCD. This leads to variability in signal display and contributes to a concern in signal display: lack of uniformity. The need for uniformity in traffic signal display as it relates to driver expectancy has been well documented (Benioff and Rorabaugh 1980). The following is a summary of the variability in each aspect:

- For signal display placement: According to the survey results of *NCHRP Report 493* (Kacir et al. 2003), the placement of PPLT signal heads differs among different jurisdictions (see Table 20).

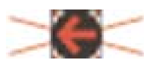
Table 20: Summary of Signal Display Placement

PPLT Signal Display Location	Centered over Left-Turn Lane	Between Left-Turn and Adjacent Through Lane
	40%	52%
The Use of Supplemental Signal Display	Use	Never use
	49%	51%
Left-Turn Display as One of the Two Required Through Displays	Use	Never use
	37%	23%

Source: Kacir et al. 2003

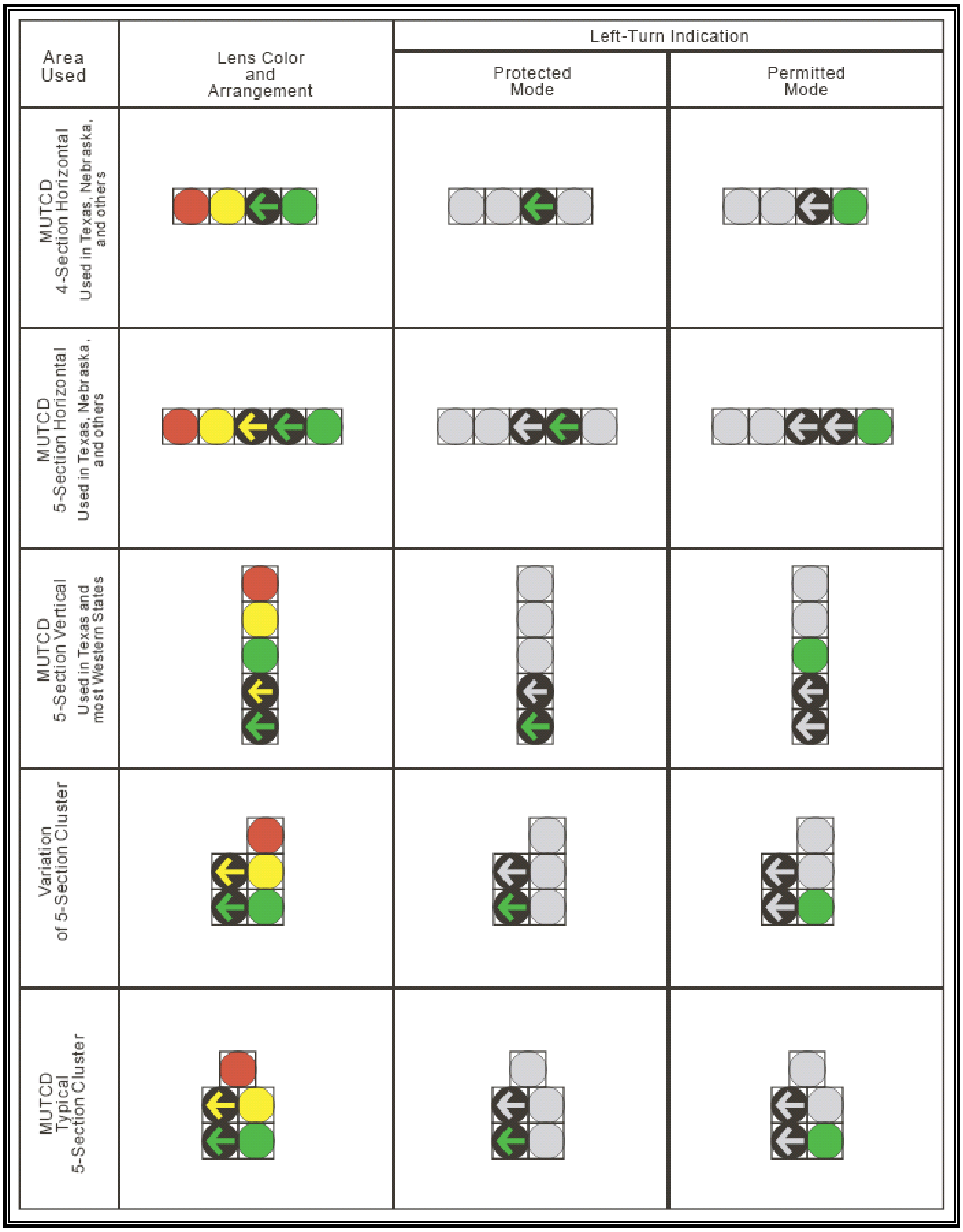
- For permissive indications: As mentioned in section 2.3.2.1, due to the disadvantages of the green ball indication for left-turn signals, some agencies developed several other treatments for left-turn signal display to replace the green ball indication, in an attempt to improve drivers' understanding and safety. Those alternatives include flashing red arrow, flashing red ball, flashing yellow ball, and flashing yellow arrow. Table 21 gives a summary of the variety of permissive indications.

Table 21: Variation in Permissive Indication throughout the United States

Indication	Area Used	Illustration
Green Ball	Most states	
Flashing Red Ball	Maryland Michigan	
Flashing Yellow Ball	Washington	
Flashing Red Arrow	Delaware Cupertino, California	
Flashing Yellow Arrow	Sparks, Nevada Reno, Nevada	

Source: Kacir et al. 2003

- For arrangement: Arrangement varies greatly among different jurisdictions and states. Figure 21 gives an example provided by the MUTCD. Figure 21 is a summary of a variety of PPLT arrangements from *NCHRP Report 493*, in which the predominant use is the five-section cluster arrangement that represents 63 percent of all reported PPLT signal display (Kacir et al. 2003).



Source: Kacir et al. 2003

Figure 21: Variety in PPLT Display

2.3.3 Potential Solutions

Even though the signal display suffers from the problem of "lack of uniformity," some of the varieties do provide some potential solutions to the existing problems, such as confusion about the green ball as a permissive signal or the yellow trap. Below are some suggested or practically implemented alternative signal display that are not included in the MUTCD.

2.3.3.1 Avoiding Yellow Trap — Dallas Display

Concerning the yellow trap, most engineers avoid the problem by not using PPLT and lead-lag phasing at the same time. Since approximately the mid-1980s, some traffic engineers have implemented an innovative signal phasing operation known as the "Dallas display" (Camp and Denney 1992). The Dallas display allows phase overlaps and was designed to eliminate the potentially unsafe yellow trap situation by allowing a continued permissive left turn during the opposite approach lead and lag protected left-turn phase (see Figure 22). It requires the use of a visibility-limited (e.g., louvered) signal face to shield the circular green and yellow indications for left-turn lane traffic from adjacent through traffic (see Figure 23). Research has shown that the Dallas display is operationally efficient and minimizes delay while maintaining safety (Camp and Denney 1992, Brookes 1990).

However, this approach of solving the yellow trap problem cannot be used in all situations (Camp and Denney 1992). Limitations of this technique lie in:

- span wires or free-swinging mast arm signals, where the left-turn signal face cannot be mounted securely enough to provide proper aim of the louvered indications at all times; and
- curved approaches, with far-side LT heads in customary locations and the signal approach with a shared left-turn lane, where the louvered indications cannot be aimed so as to be readily visible only to left-turn traffic.

An alternative to the Dallas display was developed in Arlington, Texas, and is sometimes called the "Arlington display." The Arlington display uses the same Dallas display concept, except that the lag protected left-turn direction does not receive a permissive interval during the lead direction protected interval.

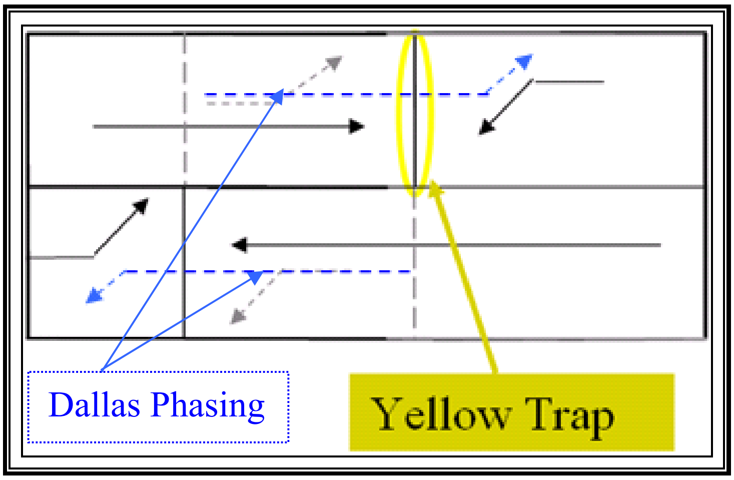


Figure 22: Signal Phasing Diagram for Dallas Display (Based on Original Yellow Trap Phasing)

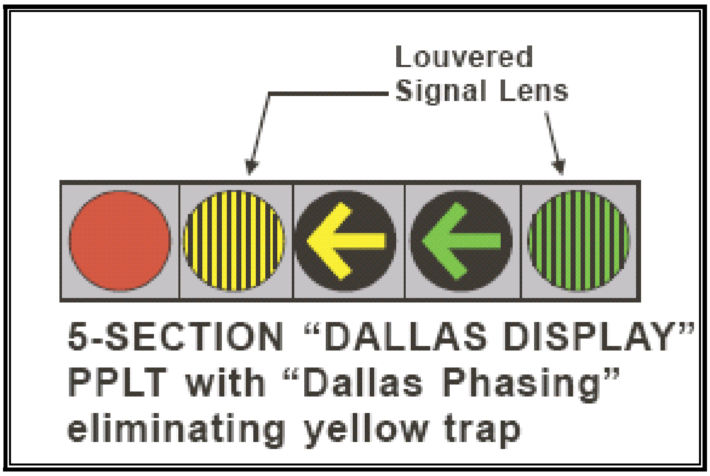


Figure 23: Signal Faces of Dallas Display

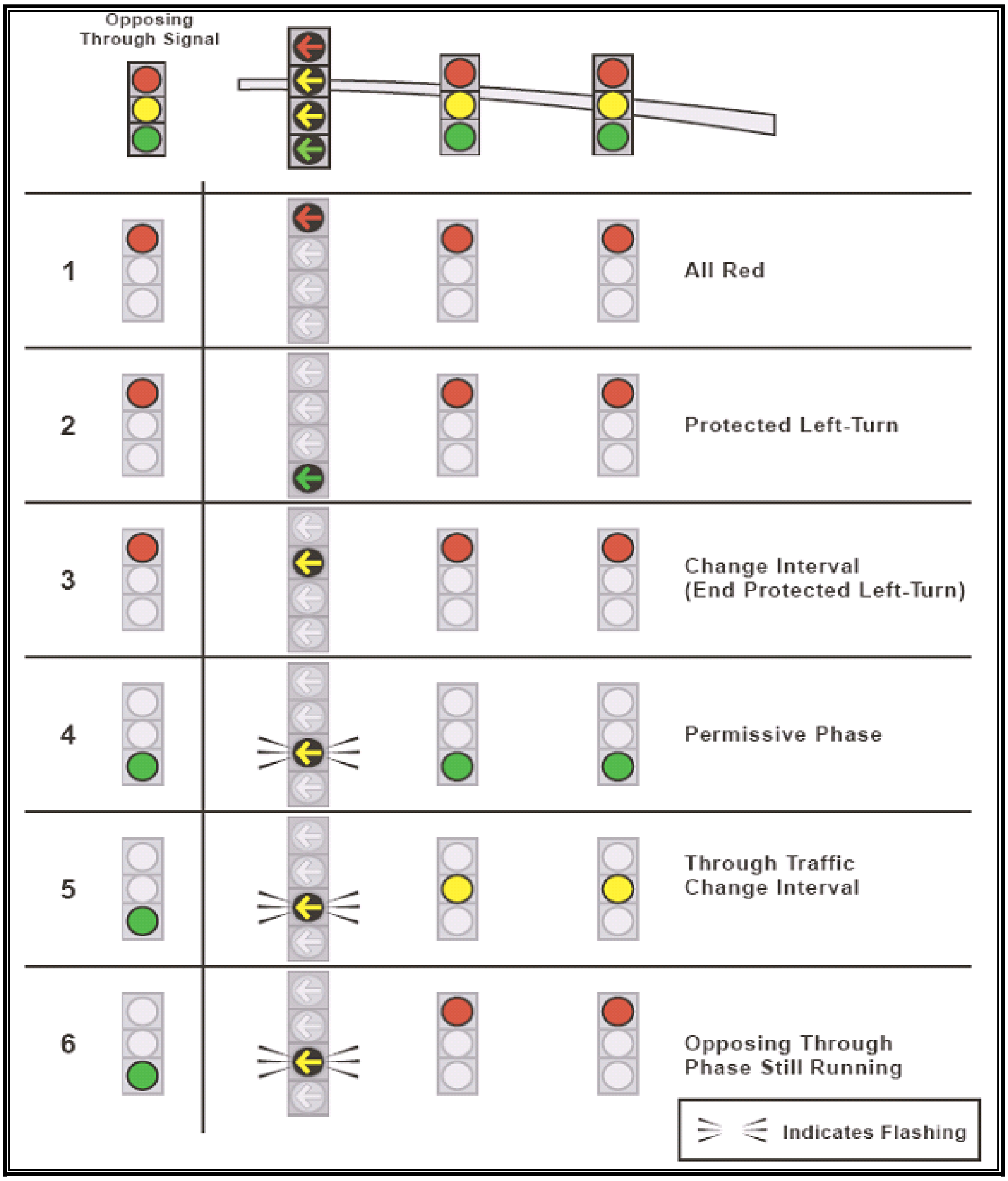
2.3.3.2 A "Best Alternative" — Flashing Yellow Arrow

Research has been done to call for standardization in left-turn signal display. Uniformity can improve driver understanding and expectancy, ultimately improving safety for left-turn drivers (Noyce 1999b). The NCHRP 3-54 project (Kacir et al. 2003) is the most comprehensive study of PPLT display to date, which aimed at identifying the "best" traffic signal display for PPLT and making recommendations to FHWA. After a 7-year study, with laboratory-based methods (a dynamic simulator car and a static video-based tool) and field study data (conflict study, operation study, and implementation study), the project concluded that a flashing yellow arrow (FYA) is a "better alternative" to a green ball (GB) permissive indication, and it recommended that the MUTCD include FYA as an allowable display indication when used in PPLT control. Later, after some experimental practices of FYA implementation in some areas, the research showed positive results for FYA, either from traffic engineers or residents (Niemeyer 2005). The advantages of FYA are summarized as follows (Kacir et al. 2003, ITE 1995):

- The FYA display was as well understood as the circular green indication (measured in terms of correct responses to questions presented).
- It improves safety (eliminates the yellow trap problem) and efficiency (extends the permissive phase during the opposing protected lead and lag phase). See the FYA logic link illustration in Figure 24.
- The FYA display showed a higher fail-safe* response as compared to the circular green indication.
- The conflict studies demonstrated that drivers interpret the FYA display correctly.
- The FYA display was successfully implemented in the field with relatively little or no technical or political issues. Post-implementation public testimony almost unanimously supported use of the FYA display.

Also, there are some accident statistics showing that FYA leads to fewer crashes. For example, Niemeyer (2005) conducted crash data analysis before and after FYA installation in some intersections of Jackson County, Oregon. It showed that left-turn–related crashes reduced by 58 percent after FYA installation during 2.7 years. Also, the study in some locations that converted from protected-only to PPLT using FYA showed that even though six left-turn–related accidents happened during 1.7 years after the conversion, all of them happened during the first 6 months, which indicates that accidents would reduce after drivers get used to FYA indications.

* **Fail-safe response**: the driver did not correctly respond to the PPLT signal display but did not infringe on the right-of-way of the opposing traffic.



Source: Kacir et al. 2003

Figure 24: Flashing Yellow Arrow Logic Link

2.3.3.3 Exclusive Four-Section Signal Head

Besides the proposed FYA, *NCHRP Report 493* also recommended that the "exclusive four-section" signal head with all arrows be used for PPLT signal display. In the driver confirmation studies, Noyce (1999a) found that correct responses to a four-section vertical display (only a yellow arrow for the permissive indication for that arrangement) was significantly higher than that to a five-section vertical/cluster signal head. Then Noyce concluded that the combination of FYA and a four-section arrangement would increase drivers' understanding. This is because the signal head with a four-section arrangement is exclusive for left-turn movements and cannot be shared with the adjacent through traffic movements. As a result, it eliminates the confusion in simultaneous illumination of conflicting displays in a single signal head.

2.3.4 Summary of Signal Display

This part of the literature review introduced the left-turn signal display in regards to three aspects: (1) signal placement, (2) signal arrangement, and (3) signal indication. It introduced the current standards and the existing problems in left-turn signal display. It also discussed some potential solutions for existing problems. The major findings are summarized in Table 22 and 23. From Table 22, it can be found that most of the signal display problems are for PPLT mode. From Table 23, it can be seen that using alternative signal display, i.e., Dallas phasing, flashing yellow arrow, and exclusive four-section signal head, can bring significant benefits by solving or mitigating the existing problems with left-turn signal display.

Table 22: Summary of Existing Problems with Left-Turn Signal Display

		Permissive	Protected-only	PPLT
Existing Problems	**Placement**	/	/	● Lack of uniformity
	Indication	● Confusion of green ball	● Confusion of simultaneous display	● Lack of uniformity in permissive indication
	Arrangement	/	/	● Simultaneous illumination of conflicting colors in separate 5-section signal heads ● Yellow trap ● Lack of uniformity

Table 23: Summary of Potential Solutions

		Comply with MUTCD	Location of Implementation	Advantage	Disadvantage
Some Good Practices or Recommended Signal Display	**Dallas Phasing/ Arlington Phasing**	Yes	• Dallas, Texas • Arlington, Texas	• Eliminates yellow trap	• Not applicable to all situations • Costs associated with the conversion
	Flashing Yellow Arrow	No	• 228 locations nationwide were approved for implementation	• Eliminates yellow trap • Universally understood • Versatility	• Costs associated with the conversion
	Exclusive 4-Section Signal Head	Yes	• 228 locations nationwide were approved for implementation	• Eliminates simultaneous illumination of green arrow to LT[1] and red ball to TH[2]	• Costs associated with the conversion

1. LT means left turn.
2. TH means through.

CHAPTER 3: SURVEY

The purpose of this chapter is to survey field engineers to identify and prioritize the important parameters and variables that are essential to the determination of left-turn signal phasing and left-turn signal display. It also seeks information on the existing guidelines or criteria used for selecting the proper type of left-turn signal operations. The research team developed a survey instrument, which is in Appendix A.

3.1 SURVEY INSTRUMENT DESIGN

This survey included two major parts. The first part is for left-turn signal phasing design, including the mode and sequence of left-turn phasing, and the second part is for left-turn signal display, including signal indication, arrangement, and placement of the left-turn signal. Each part consists of two sections. The first section is to identify and prioritize the important parameters in left-turn signal phasing design and signal display.

For Part I, left-turn signal phasing design, the identified parameters belong to following six main categories:

- Volume
    - left-turn traffic volume
    - opposing traffic volume
- Traffic condition
    - Vehicle types/fleet compositions (percent of heavy vehicles)
    - Pedestrian and/or bicycle crossings
    - Intersection congestion level (V/C ratio)
    - Platoon progression and bandwidth
    - Posted speed limit
- Geometric condition
    - Sight distance
    - Median width
    - Number of left-turn lanes
    - Number of opposing lanes
    - Intersection alignment
    - Left-turn storage length
- Delay
    - Left-turn delay

    - Intersection delay
    - Number of failed cycles
- Traffic safety
    - Historical rate of total accidents at intersection
    - Historical rate of left-turn–related accidents at intersection
- Others
    - Driver acceptance

For Part II, left-turn signal display, the identified parameters belong to the following eight main parameters:

- intersection alignments,
- number of left-turn lanes,
- number of through lanes,
- roadway functional class (interstate, local arterial, etc.),
- median width,
- type of left-turn phasing,
- left-turn volume, and
- accident rate.

The second section of each part of the survey included some general questions. There are 17 questions on the left-turn signal phasing design in Part I and 15 questions on left-turn signal display in Part II.

3.2 SURVEY RESULTS

A web-based survey was conducted June 1-18, 2007. The survey was sent to traffic engineers at the departments of transportation (DOTs) of different states and district engineers in Texas through an email from the project director. Finally, 40 survey responses were received, and among them there were 26 completed survey responses. Based on the survey responses received, the research team analyzed the survey results, which are summarized as follows.

3.2.1 Part I — Left-Turn Signal Phasing Design

3.2.1.1 Section 1 — Priority of Parameters

Six categories, including 19 parameters, were provided in Part I for respondents to give scores that represented the level of importance of the parameter in the determination of the mode and sequence of left-turn phasing. Each parameter listed in the survey was given a score from "1" to "5," with "5" indicating the highest priority and "1" indicating the lowest priority.

Figures 25 and 26 show the survey results about all the parameters related to the mode and sequence of left-turn phasing, respectively.

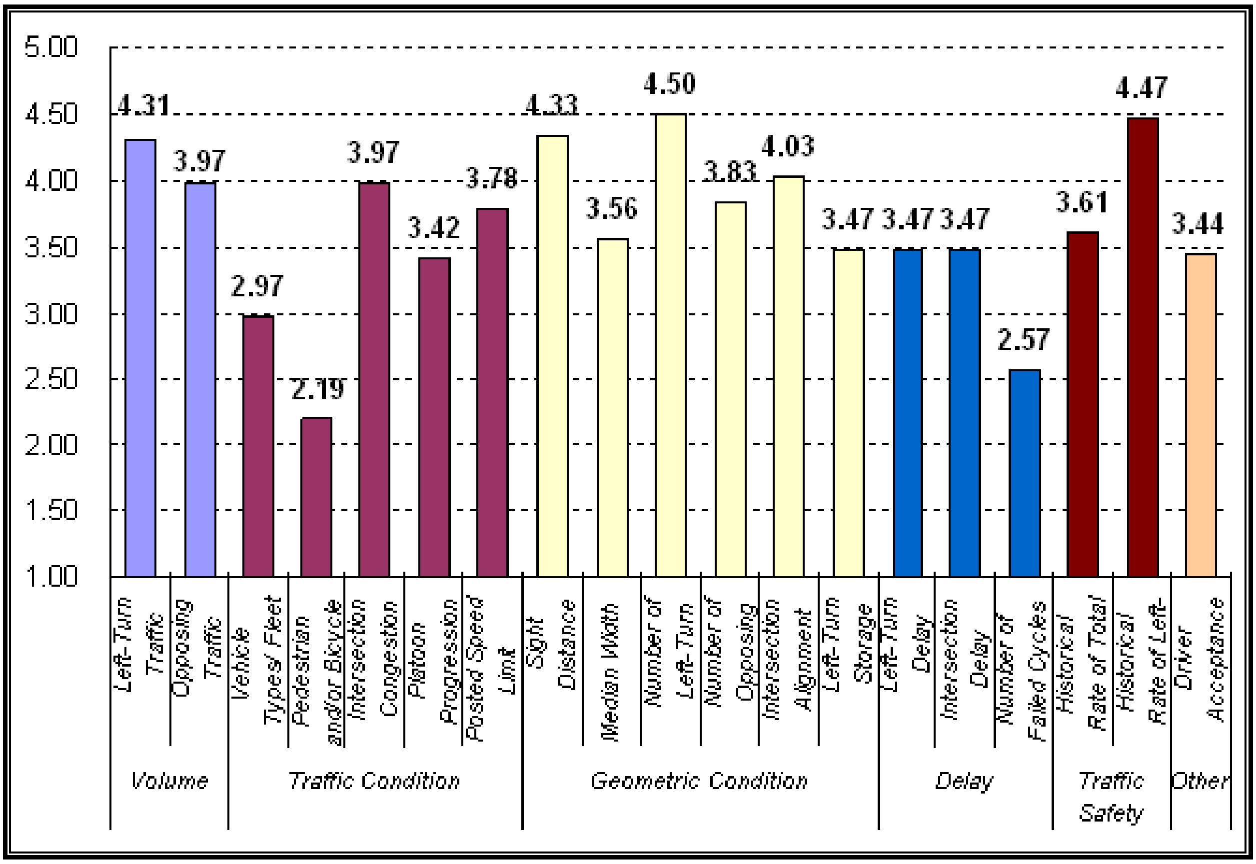


Figure 25: Average Scores of All the Parameters for the Determination of the Mode of Left-Turn Phasing

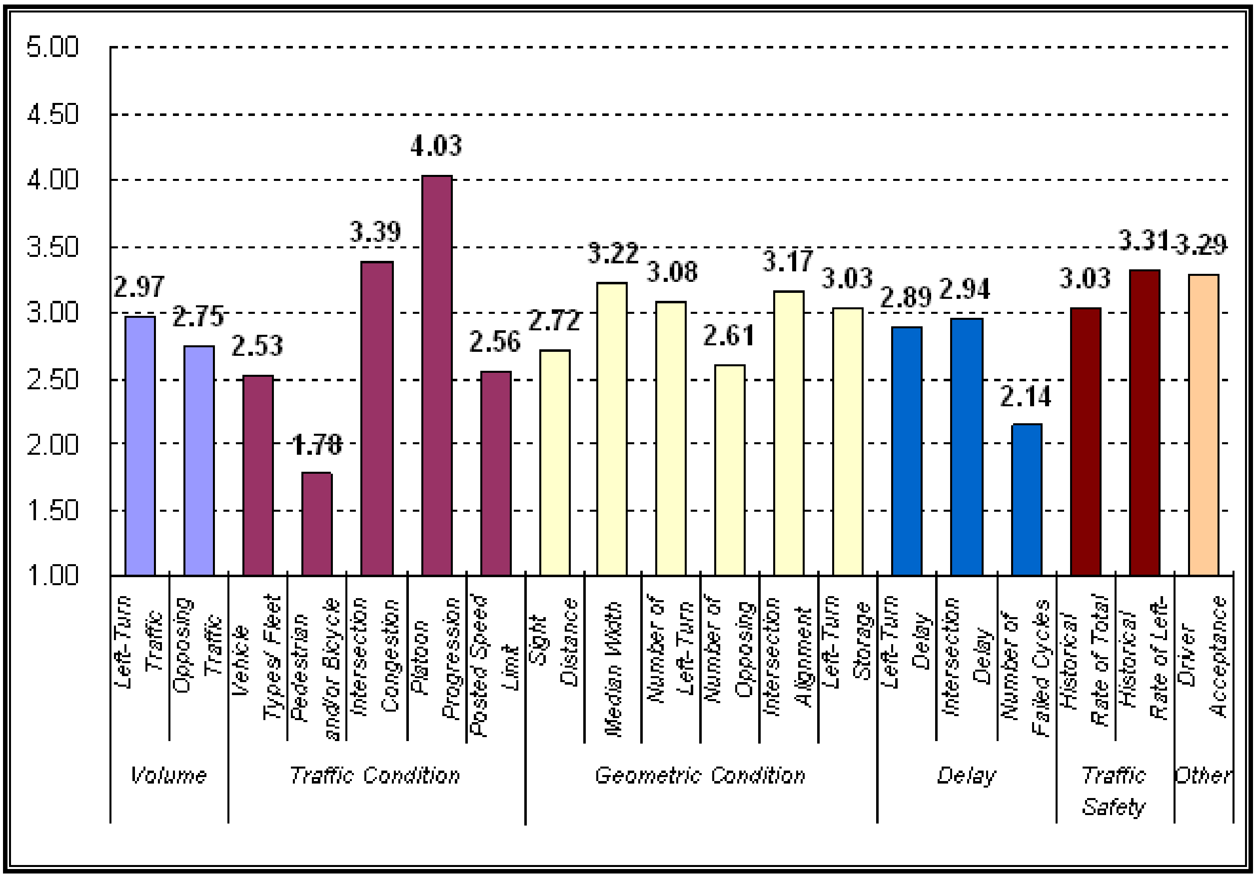


Figure 26: Average Scores of All the Parameters for the Determination of the Sequence of Left-Turn Phasing

According to the average priority scores of all the parameters, the parameters for determining the mode and sequence of left-turn phasing are ranked and compared as shown in Table 24.

Table 24: Parameters' Rank for the Determination of the Mode and Sequence of Left-Turn Phasing

Rank	Mode		Sequence	
	Parameters	**Scores**	**Parameters**	**Scores**
1	*Number of Left-Turn Lanes*	*4.50*	*Platoon Progression and Bandwidth*	*4.03*
2	*Historical Rate of Left-Turn–Related Accidents at Intersection*	*4.47*	*Intersection Congestion Level (V/C ratio)*	*3.39*
3	*Sight Distance*	*4.33*	*Historical Rate of Left-Turn–Related Accidents at Intersection*	*3.31*
4	*Left-Turn Traffic Volume*	*4.31*	*Driver Acceptance*	*3.29*
5	*Intersection Alignment*	*4.03*	*Median Width*	*3.22*
6	Opposing Traffic Volume	3.97	Intersection Alignment	3.17
7	Intersection Congestion Level (V/C Ratio)	3.97	Number of Left-Turn Lanes	3.08
8	Number of Opposing Lanes	3.83	Historical Rate of Total Accidents at Intersection	3.03
9	Posted Speed Limit	3.78	Left-Turn Storage Length	3.03
10	Historical Rate of Total Accidents at Intersection	3.61	Left-Turn Traffic Volume	2.97
11	Median Width	3.56	Intersection Delay	2.94
12	Left-Turn Storage Length	3.47	Left-Turn Delay	2.89
13	Left-Turn Delay	3.47	Opposing Traffic Volume	2.75
14	Intersection Delay	3.47	Sight Distance	2.72
15	Driver Acceptance	3.44	Number of Opposing Lanes	2.61
16	Platoon Progression and Bandwidth	3.42	Posted Speed Limit	2.56
17	Vehicle Types/Fleet Compositions (Percent of Heavy Vehicles)	2.97	Vehicle Types/Fleet Compositions (Percent of Heavy Vehicles)	2.53
18	Number of Failed Cycles	2.57	Number of Failed Cycles	2.14
19	Pedestrian and/or Bicycle Crossings	2.19	Pedestrian and/or Bicycle Crossings	1.78

Based on the above survey results, the following key findings can be obtained:

- For the mode of left-turn phasing, the average scores of all 19 parameters are from 4.50 to 2.19. The highest priority parameter for mode is "Number of Left-Turn Lanes."
- For the sequence of left-turn phasing, the average scores of all 19 parameters are from 4.03 to 1.84. The highest priority parameter for sequence is "Platoon Progression and Bandwidth."

- The top five parameters in each group need to be considered in the determination of the mode or sequence of left-turn phasing.
- The ranks of the parameters for mode and sequence are quite different. "Historical Rate of Left-Turn–Related Accidents at Intersection" is the only parameter in the top five of both mode and sequence ranks. In other words, "Historical Rate of Left-Turn–Related Accidents at Intersection" is a significant parameter for both determinations of mode and sequence of left-turn phasing.
- The ranks of the last three parameters are the same, which means "Vehicle Types/Fleet Compositions (Percent of Heavy Vehicles)," "Number of Failed Cycles," and "Pedestrian and/or Bicycle Crossings" are the low importance parameters for both determinations of mode and sequence of left-turn phasing.

3.2.1.2 Section 2 — General Questions

In the second section of Part I, there are 19 questions, which can be categorized into three groups: (1) current practices in left-turn phasing, (2) existing guidelines on the determination of the mode and sequence of left-turn phasing, and (3) suggestions.

1. Questions for Current Practices
    - Question 1 — How many signalized intersections are currently operated and maintained by your jurisdiction?
    - Question 2 — The approximate percentage of different left-turn control modes in your jurisdiction (a. Permissive-only, b. Protected-only, c. Protected/permissive, d. Others).
    - Question 3 — The approximate percentage of different sequences of left-turn phasing in your jurisdiction (a. Lead-lead sequence, b. Lag-lag sequence, c. Lead-lag sequence, d. Others).
    - Question 4 — Is there any special mode or sequence used in your jurisdiction?
    - Question 5 — In your opinion, which combination of mode and sequence has the lowest crash rate?
    - Question 6 — Are there any intersections in your jurisdiction that have ever experienced changes in left-turn signal mode and/or sequence in the past 5 years? (If yes, please specify the name of the intersection, the before-and-after left-turn signal phasing, the reason for the change, and your opinion whether this change has brought any benefits in terms of safety and operational efficiency.)

- Question 7 — Can you provide the contact information for the person who is in charge of signal timing plans/signal installation in your jurisdiction?
- Question 8 — Can you provide the contact information for the person who is in charge of the accident database in your jurisdiction?

2. Questions for Existing Guidelines
   - Question 9 — What are the existing guidelines for determining the mode of left-turn signal control in your jurisdiction?
   - Question 10 — What are the existing guidelines for determining the sequence of left-turn signal phasing in your jurisdiction?
   - Question 11 — Have regional standardized guidelines for selecting left-turn phasing treatments been implemented in your jurisdiction?
3. Questions for Suggestions
   - Question 12 — Do you have any suggestions/good experiences on the determination of the mode of left-turn signal control that can be shared with us?
   - Question 13 — Do you have any suggestions/good experiences on the determination of the sequence of left-turn signal phasing that can be shared with us?
   - Question 14 — In your opinion, what are the benefits of the regional standardization of left-turn phasing?
   - Question 15 — To evaluate the performance of an intersection, we would like to integrate the safety cost with the operational cost (delay). Therefore, we would like to know, in your opinion, how much delay (in seconds per vehicle) is equivalent to a 1 percent chance that the vehicle will be involved in a potential conflict (the vehicle takes a permissive left turn in a gap less than the critical gap).
   - Question 16 — In terms of safety, which signal phasing sequence is better for PPLT control, lead-lead PPLT, or lag-lag PPLT? Can you specify the reason for your opinion?
   - Question 17 — If the traffic signal control at an intersection was converted from leading PPLT to lagging PPLT, what do you think are the possible reasons for this type of conversion?

3.2.1.2.1 Number of Signalized Intersections in Respondents' Management and Their Mode and Sequence in Percentage (Questions 1, 2, and 3). According to the 34 survey responses, 31,691 intersections were operated and maintained by 31 jurisdictions in

Texas, Wyoming, Iowa, Illinois, Kansas, Delaware, south California, Michigan, West Virginia. The jurisdictions in Texas are displayed on the map given in Figure 27.

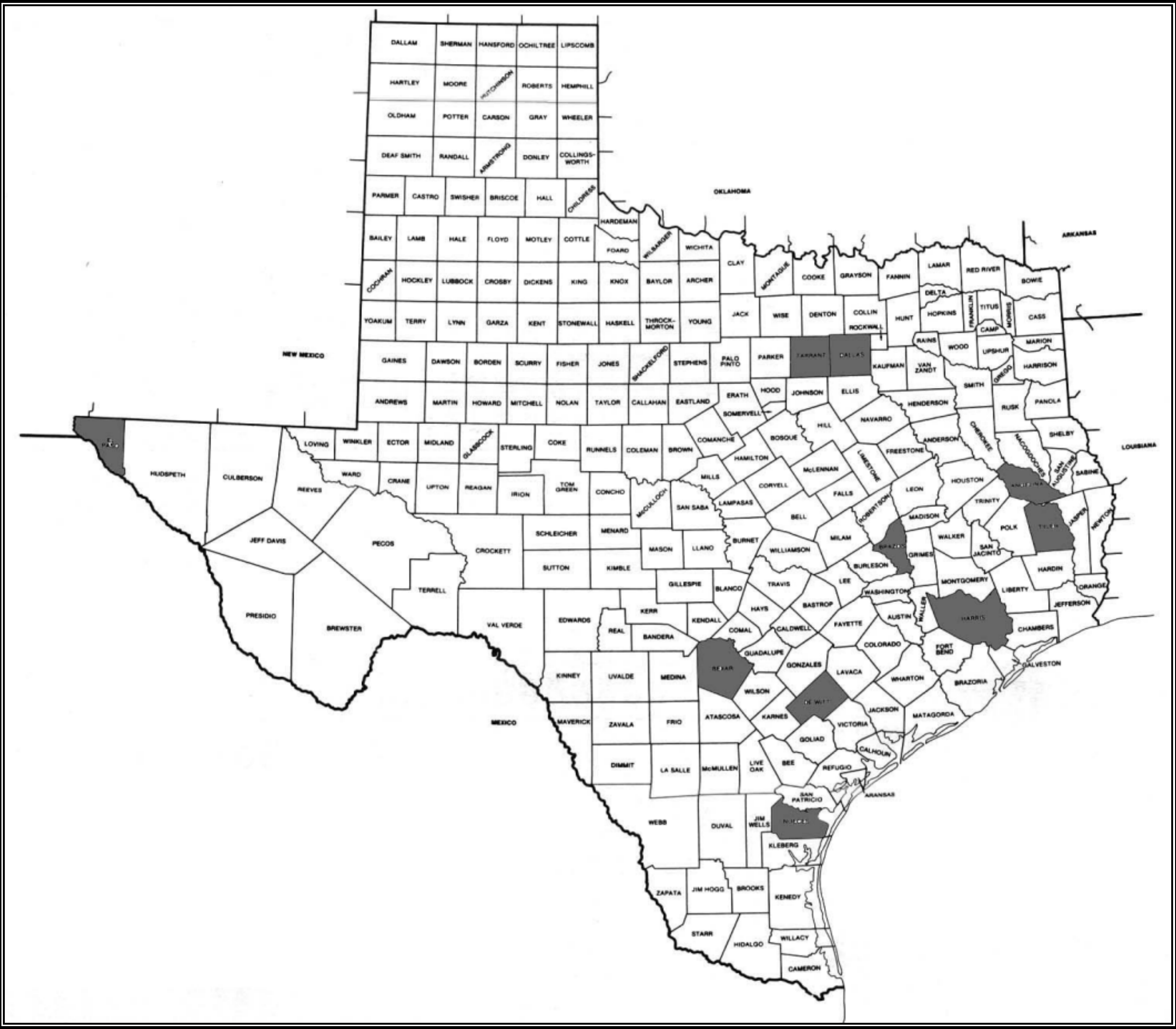


Figure 27: Respondent Jurisdictions in Texas State

The percentages of intersections with different left-turn control modes and sequences in these jurisdictions are represented in Tables 25 and 26.

Table 25: The Number and Percentage of the Mode of Left-Turn Phasing

	Permissive-only	Protected-only	PPLT*	Others
# of Intersections	15,065	6,128	10,225	273
Percentage	47.5%	19.3%	32.3%	0.9%

* PPLT is the protected and permissive left-turn control mode.

Table 26: The Number and Percentage of the Sequence of Left-Turn Phasing

	Lead-Lead	Lag-Lag	Lead-Lag	Others
# of Intersections	27,305	2,698	1,508	2
Percentage	86.6%	8.6%	4.8%	0.0%

3.2.1.2.2 Special Mode or Sequence (Question 4). Nine respondents answered this question, and all of them mentioned left-turn Dallas phasing (a special PPLT with lead-lag left-turn phasing) and some special signal displays, including a flashing yellow arrow in the permissive phase of PPLT and a four-section signal display for PPLT.

3.2.1.2.3 The Safest Combination of Mode and Sequence (Question 5). There were 31 responses for this question, and the results are shown in Table 27. "Lead-Lead Protected-only" had the best preference in terms of safety.

Table 27: Survey Statistic Results for Question 5

Mode	Protected-only			PPLT		Other
Sequence	**Lead-Lead**	**Lead-Lag**	**No Sequence Mentioned**	**Lead-Lead**	**No Sequence Mentioned**	
# of Responses	20	2	6	1	1	1
Percentage	65%	6%	19%	3%	3%	3%

3.2.1.2.4 Changes of Mode and/or Sequence in Past 5 Years and Related Information (Question 6). Twenty respondents indicated that there were changes of mode and/or sequence in the past 5 years in their jurisdictions. Five intersections were provided with complete information about changing left-turn phasing (see Table 28).

Table 28: Information on Intersections with Conversion of Left-Turn Phasing

#	Name	Position	Jurisdiction	Before Phasing	After Phasing	Reason for Conversion
1	2nd & Wyo Blvd.	Casper, Wyoming	Wyoming DOT	PPLT	Protected-only	Reducing crashes
2	Graham @ SH 16	El Paso, Texas	Texas DOT	Protected-only	PPLT	Improving left-turn flow
3	Graham @ 2nd St.	El Paso, Texas	Texas DOT	Protected-only	PPLT	Improving left-turn flow
4	Graham @ 3rd St.	El Paso, Texas	Texas DOT	Protected-only	PPLT	Improving left-turn flow
5	Graham @ 4th St.	El Paso, Texas	Texas DOT	Protected-only	PPLT	Improving left-turn flow

3.2.1.2.5 Contact Information for the Person in Charge of Signal Timing Plans, Signal Installation, and the Accident Database in Respondents' Jurisdictions (Questions 7 and 8). Twenty-seven respondents gave the contact information of the person in charge of signal timing plans, signal installation, and the accident database in their jurisdictions. These jurisdictions are in Texas, Wyoming, Iowa, Illinois, Kansas, Delaware, south California, Michigan, West Virginia.

3.2.1.2.6 Existing Guidelines for Determining Mode and Sequence (Questions 9 and 10). There were 28 responses for these two questions, and most of them just mentioned some important factors for determining the mode and sequence of left-turn phasing, such as volumes, crash history, intersection geometrics, etc. Note that these factors were already evaluated in the parameters' priority for left-turn phasing (section 1 of Part I). Two of the survey respondents provided their comprehensive guidelines:

- "Traffic Signal Policy and Guidelines" by the Oregon DOT and
- "Traffic Operations" by the Kentucky DOT.

3.2.1.2.7 Regional Standardized Guidelines for Left-Turn Phasing (Question 11). Seven respondents indicated that they had regional standardized guidelines. Five of them gave their jurisdictions' information, and these five jurisdictions are presented on the map in Figure 28. In contrast, 19 respondents did not have regional standardized guidelines in their jurisdictions.

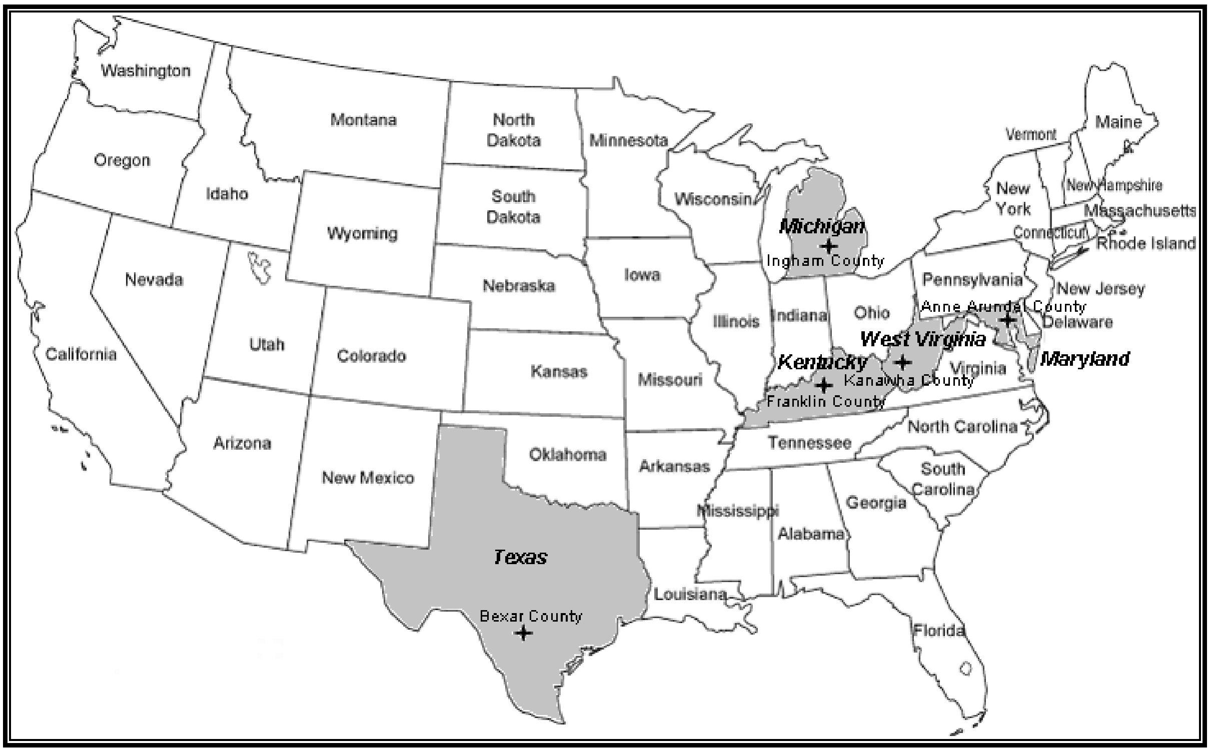


Figure 28: Jurisdictions with Regional Standardized Guidelines for Left-Turn Phasing

3.2.1.2.8 Suggestions or Good Experiences for the Determination of Mode and Sequence (Questions 12 and 13). The respondents had the following suggestions or experiences for determining mode and sequence of left-turn phasing:

- Use protected-only for high-speed approaches.
- Use PPLT only at locations where the posted speed is 35 mph or less.
- PPLT is most effective at speeds lower than 40-45 mph.
- The lead-lead sequence is generally well accepted by our motorists.
- Use lead-lead for protected-only to maximize controller efficiency.
- Use lag-lag for permissive-protected in a case where many vehicles pull into the intersection waiting on permissive left turns.

3.2.1.2.9 Benefits of the Regional Standardization of Left-Turn Phasing (Question 14). There were 25 responses for this question, and most of them considered "Driver Acceptance" the benefit of the regional standardization of left-turn phasing. The results are shown in Table 29.

Table 29: Survey Statistic Results for Question 14

	Driver Acceptance	Consistency/Uniformity	No Idea
# of Responses	19	2	4
Percentage	76%	8%	16%

3.2.1.2.10 Relationship between the Safety Cost (Potential Conflict) and the Operational Cost (Delay) (Question 15). For this question, the research team wanted to know how much delay (in seconds per vehicle) is equivalent to a 1 percent chance that the vehicle will be involved in a potential conflict (the vehicle takes a permissive left turn in a gap less than the critical gap).

Four respondents answered this question. The answers were 2, 10, 30, and 60 s/vehicle in delay. Therefore, on average, a 1 percent chance that the vehicle will be involved in a potential conflict should be equivalent to about 26 seconds of delay per vehicle.

3.2.1.2.11 Safest Sequence of PPLT and Reasons (Question 16). Between lead-lead PPLT and lag-lag PPLT, 22 respondents chose the former and four respondents chose the latter. The following are some major reasons respondents mentioned for selecting lead-lead PPLT:

- Drivers have good expectation and acceptance.
- Lead-lead is safer. Lag-lag functions much like permissive. Drivers want to turn as soon as the light turns green, regardless if it is a ball or arrow.
- Lead-lead lets the left-turn traffic move without getting impatient if the through volumes are heavy.
- Lead-lead allows the movement of most of the left-turn vehicles through the intersection during the protected portion of the operations.

3.2.1.2.12 Possible Reasons for Converting Leading PPLT to Lagging PPLT (Question 17). Respondents considered the following possible reasons to convert leading PPLT to lagging PPLT:

- better progression in a coordination system,
- change in coordination plans and desire to possibly eliminate the left-turn phase during some cycles, and
- reduced delay.

3.2.1.2.13 Conclusion for Section 2 of Part I. From the results of the above 17 questions, the following major conclusions can be drawn:

- Mode
  - The use of PPLT left-turn signal control mode is intense among the surveyed jurisdictions, nearly two times the use of PO left-turn control mode (10,225 compared to 6128).
  - The respondents of the survey suggested considering the speed limit of the approaches and the sight distance when selecting between PPLT and PO left-turn signal control mode.
  - Only 27 percent of the jurisdictions have regional standard guidelines for selecting left-turn control mode.
- Sequence
  - 83.4 percent of the intersections use lead-lead sequence for left-turn signal control.
  - The reason for changing the sequence of left-turn signal control is mostly for signal coordination within the system.
- Others
  - The most significant benefit for a regional standard for left-turn signal control is the improvement in driver acceptance, as 76 percent of the respondents think.
  - In terms of the tradeoff between operational efficiency and safety, the respondents

think that an average of 26 seconds of delay per vehicle is equal to a 1 percent chance of having a potential left-turn conflict.

3.2.2 Part II — Left-Turn Signal Display

3.2.2.1 Section 1 — Priority of Parameters

Similar to section 1 of Part I, section 1 of Part II of this survey is designed to prioritize the parameters for determination of the indication, arrangement, and placement of left-turn signals. This part had the following eight parameters:

- intersection alignments,
- number of left-turn lanes,
- number of through lanes,
- roadway functional class (interstate, local arterial, etc.),
- median width,
- type of left-turn phasing,
- left-turn volume, and
- accident rate.

Based on their knowledge and experience, the respondents gave scores to these parameters according to their importance in the determination of the indication, arrangement, and placement of left-turn signals. Each parameter listed in the survey was given a score from "1" to "5," with "5" indicating the highest priority and "1" indicating the lowest priority.

3.2.2.1.1 Priority of Parameters for Left-Turn Signal Indication. The average scores of the parameters for left-turn signal indication are shown in Figure 29. Respondents identified "Number of Left-Turn Lanes" as the most important parameter for left-turn signal indication.

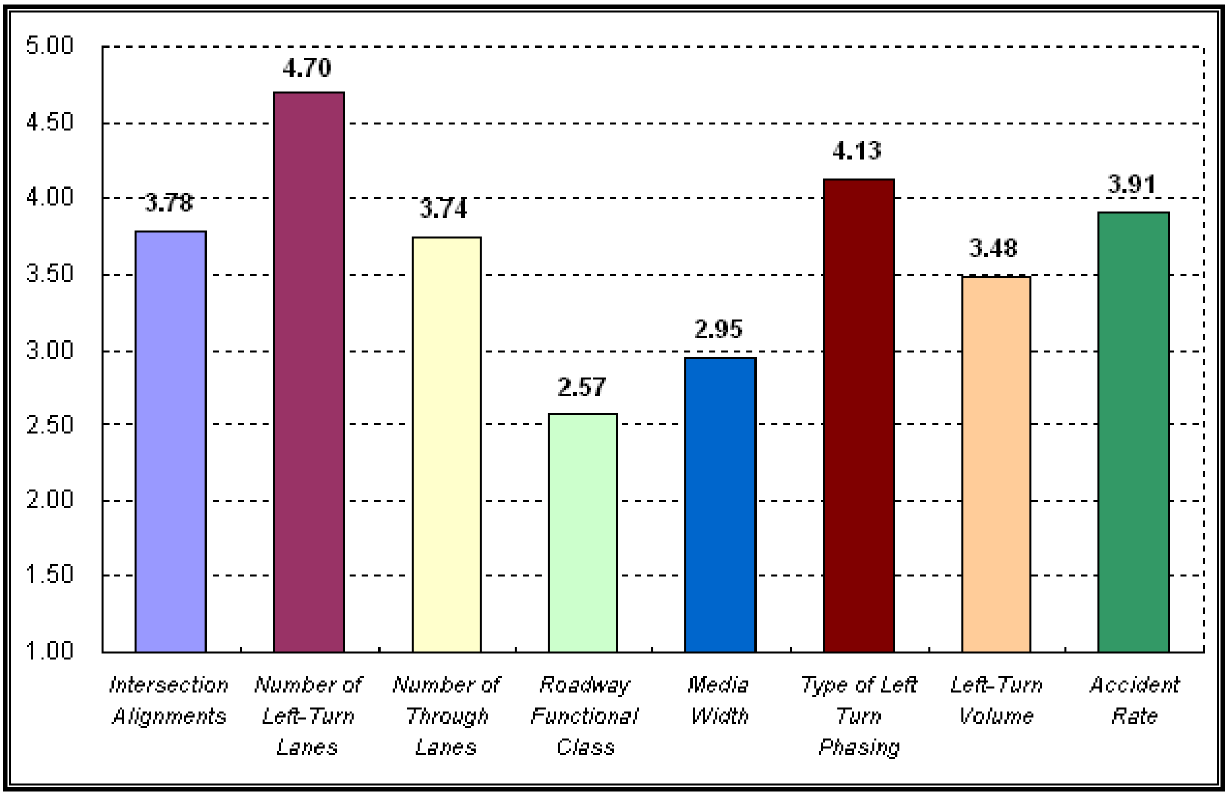


Figure 29: Average Scores of the Parameters for the Determination of Left-Turn Signal Indication

3.2.2.1.2 Priority of Parameters for Left-Turn Signal Arrangement. Figure 30 shows the survey results of the parameters for left-turn signal arrangement. The parameter "Number of Left-Turn Lanes" was also recognized as the most important parameter for left-turn signal arrangement.

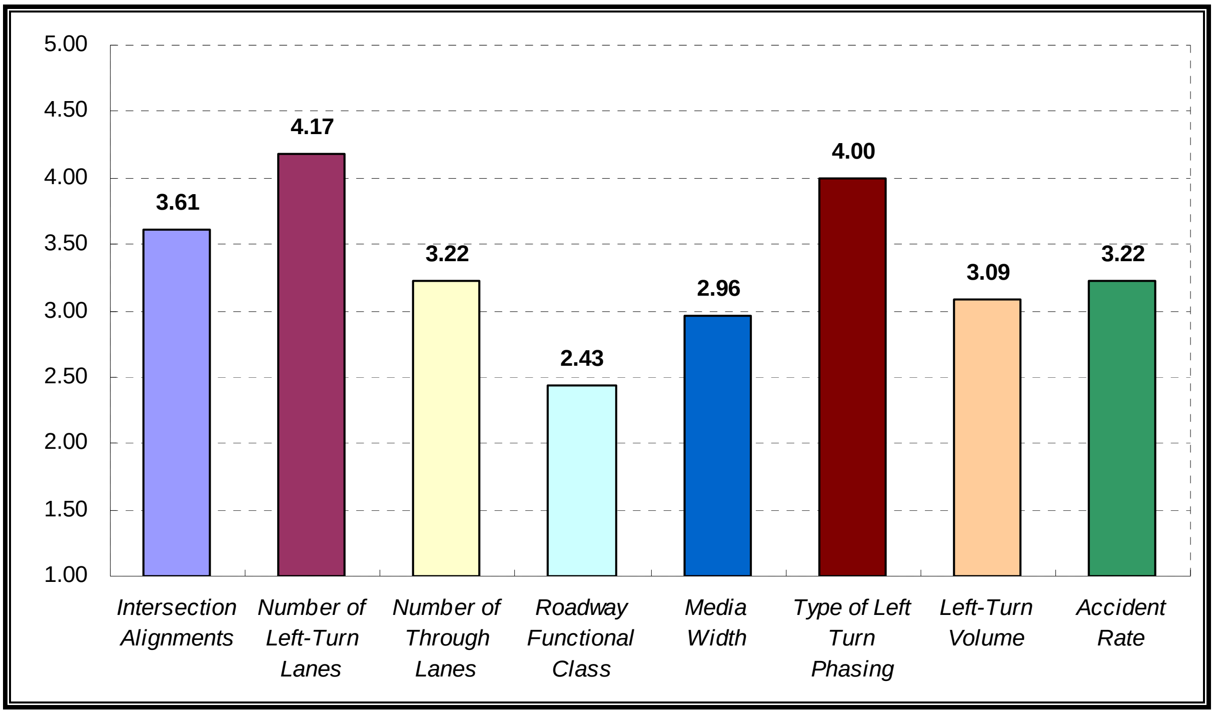


Figure 30: Average Scores of the Parameters for the Determination of Left-Turn Signal Arrangement

3.2.2.1.3 Priority of Parameters for Left-Turn Signal Placement. The scores of parameters for left-turn signal arrangement are presented in Figure 31. The parameter "Number of Left-Turn Lanes" was also the most important parameter of left-turn signal placement.

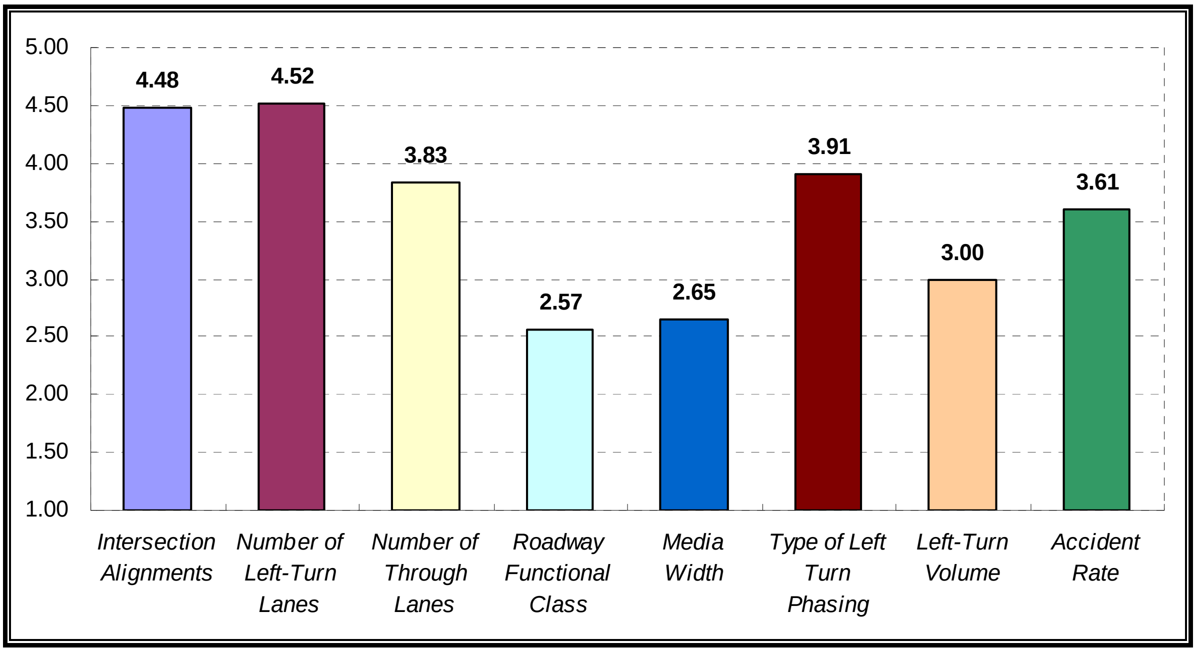


Figure 31: Average Scores of All Parameters for the Determination of Left-Turn Signal Placement

3.2.2.1.4 Conclusion for Section 1 of Part II. Based on the above data analysis, the following key findings can be obtained:

- "Number of Left-Turn Lanes" is always the most vital parameter for left-turn signal indication, arrangement, or placement.
- The top five parameters for left-turn signal indication, arrangement, and placement are the same. They are the number of left-turn lanes, the type of left-turn phasing, the accident rate, the intersection alignments, and the number of through lanes (see Table 30).
- Although there is a little difference in the parameters' ranks for left-turn signal indication, arrangement, and placement (see the shaded cells in Table 30), the difference is quite small. Therefore, the importance of these parameters in the determination of left-turn signal indication, arrangement, and placement is very similar.

Table 30: Parameters' Ranks of Left-Turn Signal Indication, Arrangement, and Placement

Rank	Indication		Arrangement		Placement	
	Parameters	Scores	Parameters	Scores	Parameters	Scores
1	Number of Left-Turn Lanes	4.70	Number of Left-Turn Lanes	4.17	Number of Left-Turn Lanes	4.52
2	*Type of Left-Turn Phasing*	*4.13*	*Type of Left-Turn Phasing*	*4.00*	*Intersection Alignments*	*4.48*
3	*Accident Rate*	*3.91*	*Intersection Alignments*	*3.61*	*Type of Left-Turn Phasing*	*3.91*
4	*Intersection Alignments*	*3.78*	*Number of Through Lanes*	*3.22*	*Number of Through Lanes*	*3.83*
5	*Number of Through Lanes*	*3.74*	*Accident Rate*	*3.22*	*Accident Rate*	*3.61*
6	Left-Turn Volume	3.48	Left-Turn Volume	3.09	Left-Turn Volume	3.00
7	Median Width	2.95	Median Width	2.96	Median Width	2.65
8	Roadway Functional Class (Interstate, Local Arterial, Etc.)	2.57	Roadway Functional Class (Interstate, Local Arterial, Etc.)	2.43	Roadway Functional Class (Interstate, Local Arterial, Etc.)	2.57

3.2.2.2 Section 2 — General Questions

Fifteen general questions were asked about the indication, arrangement, and placement of left-turn signals in the second section of Part II. These questions can be categorized into three groups: (1) current practices in left-turn signal display; (2) existing guidelines on the determination of the indication, arrangement, and placement of left-turn signals; and (3) suggestions.

1. Questions for Current Practices

   - Question 1 — What type of signal indication is used for the permitted left-turn phase? (green ball, flashing yellow arrow, flashing red arrow, flashing red ball, flashing yellow ball, and others)
   - Question 2 — In your jurisdiction, what is the percentage of the left-turn signal display arrangements for different left-turn control modes (or you can give the exact number).

	Protected-only	*PPLT*
5-Section Horizontal		
5-Section Vertical		
5-Section Cluster		
4-Section Horizontal		
4-Section Vertical		
4-Section Cluster		
3-Section Vertical		
Other (Please Specify)		
TOTAL	*100%*	*100%*

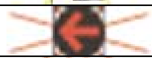
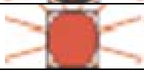
   - Question 3 — If you identified multiple signal display arrangements in Question 2, are there any criteria that your agency used for selecting one left-turn signal display arrangement over another?
   - Question 4 — Do you use the left-turn signal display as one of the two required signal displays for through traffic (use shared left-turn display)?
   - Question 5 — If you identified "yes" in Question 4, does the simultaneous display of a red ball (to through traffic) and a green arrow (to left-turn traffic) occur in the protected left-turn phasing?
   - Question 6 — Do you use special left-turn phasing or techniques to avoid the yellow trap problem in PPLT mode?
   - Question 7 — Please give your opinions on Dallas/Arlington phasing. What are your concerns in using it?
   - Question 8 — Do you use secondary left-turn signal display?
   - Question 9 — If a secondary left-turn signal display(s) is used, where is it mounted? (near side pole mount, median pole mount, far side pole mount, and other)

- Question 10 — In your opinion, which types of left-turn signal displays (indication/arrangement/placement) are related to high crash rates? Please explain the reason.
- Question 11 — Are there any intersections in your jurisdictions that have ever experienced changes in signal display type in the past 5 years? (If yes, please specify the name of the intersection, the before and after left-turn signal displays, the reason for the change, and your opinion whether this change brought any benefits in terms of safety and operation efficiency.)

2. Questions for Existing Guidelines
   - Question 12 — What are the current guidelines used for determining the left-turn signal display and signal head placement in your jurisdiction?
   - Question 13 — Have regional standardized guidelines for left-turn signal display and signal head placement been implemented in your jurisdiction?
3. Questions for Suggestions
   - Question 14 — Do you have any suggestions/good experiences for the determination of the left-turn signal display and signal head placement that can be shared with us?
   - Question 15 — In your opinion, what are the benefits of the regional standardization of left-turn signal display and signal head placement?

3.2.2.2.1 Indication of Left-Turn Signal (Question 1). The main signal indication for the permissive phase is "Green Ball." The detailed results of this question are presented in Table 31.

Table 31: Survey Statistic Results for Question 1

Indication		# of Responses	Percentage
Green Ball		24	83%
Flashing Yellow Arrow		3	10%
Flashing Red Arrow		2	7%
Flashing Red Ball		0	0
Flashing Yellow Ball		0	0
Others		0	0

3.2.2.2.2 Left-Turn Signal Arrangement for Protected-only and PPLT (Question 2). From 25 responses, the answers for this question are summarized as follows:

- A five-section left-turn signal arrangement is usually used for PPLT left-turn phasing.
- A four-section left-turn signal arrangement is used more for protected-only than for PPLT left-turn phasing.
- A three-section left-turn signal arrangement is usually used for protected-only left-turn phasing.

3.2.2.2.3 Criteria for Selecting Left-Turn Signal Arrangement (Question 3). Twenty-one respondents indicated that their agency had criteria for selecting left-turn signal display, and 21 respondents answered that there were no criteria in their agency. Some important criteria are listed as follows:

- When providing protected-only left-turn phasing, a vertical three-section head should be centered over the left-turn lane. When dual left-turn lanes are provided, a three-section vertical head is centered over each of the left turn lanes.
- When PPLT phasing is provided, a five-section cluster head should be placed along the extension of the channelization line between the left-turn lane and the adjacent through lane.
- Left-turn signal arrangement should be consistent within the area or along the corridor.
- The selection of left-turn signal arrangement should be based on the signal display mounting (mounting types: mast arm, pole, and span wire).

3.2.2.2.4 Shared Left-Turn Display (Questions 4 and 5). Nineteen out of the total 24 respondents indicated that they have used shared left-turn display. Sixteen respondents have used the display of a red ball and green arrow simultaneously (see Figure 32) for the protected left-turn phase.

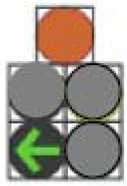


Figure 32: Example of Signal Display in the Protected Left-Turn Phase

3.2.2.2.5 Avoidance of the Yellow Trap in PPLT (Question 6). According to the answers for this question, most respondents use lead-lead or lag-lag phasing to avoid the yellow trap in PPLT left-turn phasing. The results of this question are represented in Table 32.

Table 32: Survey Statistic Results for Question 6

	No Methods	Dallas/Arlington Phasing	Lead-Lead/Lag-Lag Phasing	Other
# of Responses	8	0	8	4
Percentage	40%	0	40%	20%

3.2.2.2.6 Dallas/Arlington Phasing (Question 7). Thirty-one respondents answered this question, but no one indicated that their jurisdiction ever used Dallas/Arlington phasing. The survey results are summarized in Table 33.

Table 33: Survey Statistic Results for Question 7

	Not Familiar	Never Used
# of Responses	22	9
Percentage	71%	29%

3.2.2.2.7 Secondary Left-Turn Signal Display (Questions 8 and 9). Thirteen responses indicated that secondary left-turn signal display was always or sometimes used in their jurisdictions. Most of them explained that they used the secondary left-turn signal display based on the intersection geometric condition, such as approach width, the visibility of the signals, and the number of left-turn lanes. In contrast, 12 respondents admitted that their jurisdictions never used it.

3.2.2.2.8 Impacts of the Types of Signal Displays on Intersection Safety (Question 10). There were 20 responses for this question, and the survey results are summarized in

Table 34. It seems that the left-turn signal arrangement is not related to the high crash rates at the intersections.

Table 34: Survey Statistic Results for Question 10

	Displays			No Idea	Other
	Indication	Arrangement	Placement		
# of Responses	3	0	4	8	5
Percentage	15%	0	20%	40%	25%

3.2.2.2.9 Changes of Display in the Past 5 Years and Related Information (Question 11). Sixteen respondents indicated that there were changes of left-turn signal display in the past 5 years in their jurisdictions. One intersection was provided with complete information about the change (see Table 35). In contrast, eight respondents did not have such experience in their jurisdictions.

Table 35: Information on Intersections Converting Left-Turn Signal Display

Name	Position	Jurisdiction	Before Display	After Display	Reason for Conversion
Lansing Rd. @ Canal	Lansing, Michigan	Michigan DOT	Flashing Red	Flashing Yellow Arrow	Improving Safety

3.2.2.2.10 Existing Guidelines for Determining Left-Turn Signal Display (Question 12). Twenty-one respondents answered this question. Seven of them used the MUTCD, and the other 14 respondents used their judgment alone.

3.2.2.2.11 Regional Standardized Guidelines for Left-Turn Signal (Question 13). Seven respondents indicated that they had regional standardized guidelines. Five of them gave their jurisdictions' information. Two of them gave the following regional standardized guidelines that were used:

- West Virginia Division of Highways practices and
- Nevada DOT practices.

In contrast, 14 respondents did not have regional standardized guidelines in their jurisdictions.

3.2.2.2.12 Suggestions or Good Experiences for the Determination of Left-Turn Signal Display (Question 14). The respondents gave the following suggestions or good experiences for determining left-turn signal display:

- All approach lanes should have individual signal display.

- Install an overhead signal head in the center of each lane.
- Use a five-section head with duel arrows for dual left-turn lanes.
- Avoid dual (green/yellow) arrow indication left-turn light-emitting diode (LED) sections.

3.2.2.2.13 Benefits of the Regional Standardization of Left-Turn Signal Display (Question 15). There were 20 responses for this question, and most of them considered "Driver Acceptance" the benefit of the regional standardization of left-turn signal displays. The survey results are summarized in Table 36.

Table 36: Survey Statistic Results for Question 15

	Driver Acceptance	Delay	Others
# of Responses	16	2	2
Percentage	80%	10%	10%

3.2.2.2.14 Conclusion for Section 2 of Part II. From the results of above 15 questions, the following major conclusions can be drawn:

- Indication
  - o Most jurisdiction (83 percent) use a green ball as a permissive signal display.
  - o Signal indication is considered to have impacts on intersection safety by 15 percent of respondents.
- Arrangement
  - o A five-section arrangement is usually used for PPLT, while a three-section arrangement is mostly used for PO. A four-section arrangement can be used for both PPLT and PO, but more for PO.
  - o Half of the respondents indicated that they have criteria for selecting signal arrangement. The two important criteria are: (1) selection of arrangement depends on mounting (pole, wire, mast, etc.), and (2) arrangement should be consistent within the area or along the corridor.
- Placement
  - o Placement is also considered to have impacts on intersection safety by 20 percent of respondents.
  - o More than half of the respondents indicated that they use secondary display, and the use of secondary display depends on the geometric condition.
  - o The respondents suggested that all approach lanes should have individual signal

display and the signal heads should be placed in the center of each lane.

- Others
  - The most significant benefit for a regional standard for left-turn signal display is the improvement of driver acceptance, as 80 percent of the respondents think.
  - To avoid the yellow trap problem in lead-lag PPLT, 40 percent of the respondents chose not to use lead-lag phasing.

CHAPTER 4: DATA COLLECTION

In this project, two sets of data were collected for two different purposes: (1) data for operational impact Analysis (Chapter 6), collected at the 26 selected intersections by field studies; and (2) data for safety impact Analysis (Chapter 5), intersection historical accident records and other relevant information at 111 pairs of intersection approaches. The reason that different sets of data were collected for different study purposes is as follows. For the operation study, a detailed level of traffic data regarding the intersection operational performance, such as travel time and delay, needed to be collected by field studies. Due to the efforts needed for conducing field studies, just a limited number of intersections could be selected for this purpose. However, for the safety study, accident data needed to be collected from a larger number of intersections. Traffic accidents are very random events, and therefore the sample size for conducting safety studies has to be large enough to get significant results (the research team found this during TxDOT Project 0-5290).

Data collection for operational impact analysis was conducted successfully at 26 intersections in Austin, Houston, Lufkin, and Nacogdoches. At each study intersection, four types of field data were collected: (1) traffic video data, (2) GPS data collected by probe vehicles, (3) signal timing information, and (4) intersection geometric information. The collected field data were processed in the laboratory both manually and automatically to retrieve the information for intersection operational performance analysis. Data collection for safety impact analysis mainly included selecting study intersections as well as gathering accident records and other relevant intersection information. Finally, a total of 111 pairs of intersection approaches in Austin, Houston, and Lufkin were selected.

4.1 DATA COLLECTION FOR OPERATIONAL IMPACT ANALYSIS

4.1.1 Data Collection Plan

Based on the information collected in the literature review and the survey, a detailed field data collection plan was developed. The data collection plan specifies the following:

- selected intersections,
- types and quantities of data needed for each intersection,
- time periods of the day and duration for data collection,
- labor and equipment,
- methods of data collection and the data collection devices to be used, and

- a detailed schedule of the data collection activities.

Basically, the data to be collected for each study intersection can be grouped into two categories: dynamic data and static data. The dynamic data include traffic video and GPS data collected by probe vehicles. The static data are those associated with intersection geometric layout, signal timing plan, signal display, and historical accident data at the study intersections. A detailed list of required data is given in Table 37.

Table 37: Detailed List of Data to Be Collected

Category	Data to Be Collected	Information to Be Retrieved
Dynamic	Traffic video	Left-turn traffic volume
		Opposing through traffic volume
		Number of potential conflicts
		Number of conflicts
	GPS data collected by probe vehicles	Left-turn travel time
		Left-turn delay
		Through travel time
		Through delay
Static	Intersection geometric layout	Number of lanes in all approaches
		Posted speed limits on each street
		Location of surveillance cameras
	Signal timing plan	Mode
		Sequence
		Signal planning (schedule)
		Cycle length
		Splits
	Signal display	Indication
		Arrangement
		Placement
	Historical accident data	Number of left-turn–related accidents

4.1.2 Selection of Study Intersections

To investigate the impacts of different influencing factors on the left-turn operations of signalized intersections, the selected intersections should cover a wide range of intersections with different types of left-turn signal control modes and signal phase arrangements. In addition, geometric features, traffic conditions, and signal displays are also considered in the selection of study intersections. Therefore, the following factors should be included in the selection of study sites:

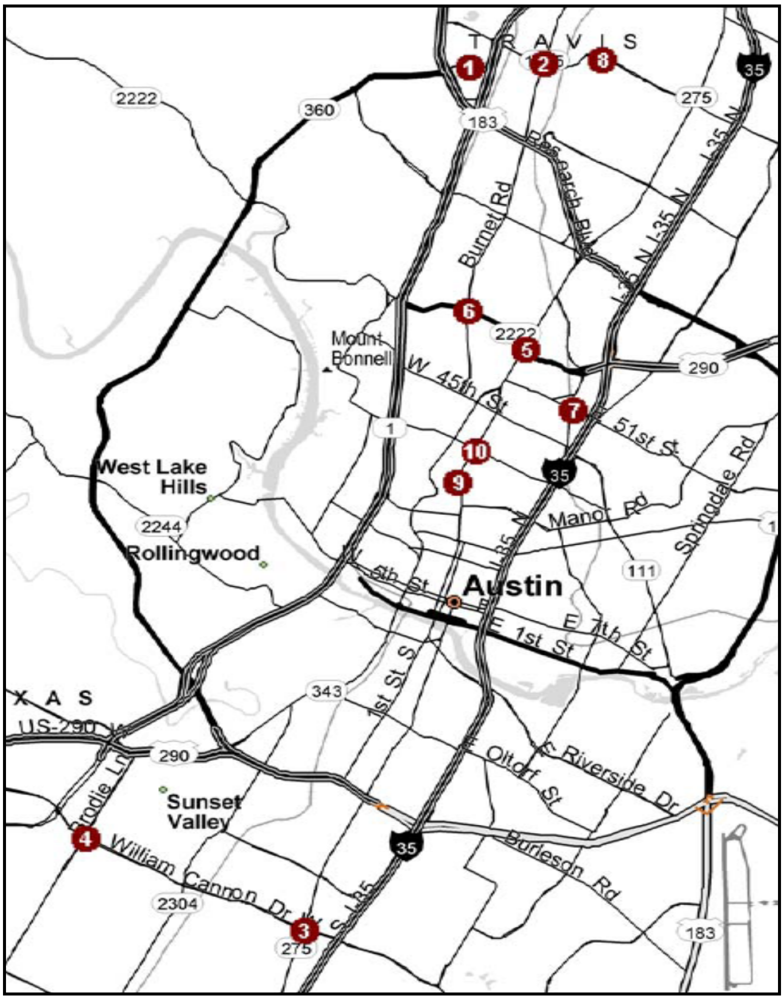
- left-turn control modes: permissive-only, protected/permissive left-turn control, and protected-only left-turn control;
- left-turn control sequence: lead-lead, lead-lag, and lag-lag;
- traffic volumes: low and high volumes;
- geometric conditions: number of left-turn lanes, number of opposing through lanes, speed limit, and intersection alignments; and
- signal display types.

To consider these factors in intersection selection, first, 20 intersection categories for field studies were defined (see Table 38). Then, the research team contacted traffic engineers in different districts to ask their recommendations for the study intersections in each category. Based on the information provided by the project panel and other traffic engineers in different districts, the research team identified 68 intersections as candidate intersections in three locations: (1) 8 in Lufkin and Nacogdoches, (2) 40 in the Houston District, and (3) 20 in the Austin District. For the intersections in Lufkin and Nacogdoches, since the recommended eight intersections experienced signal control change from protected-only to PPLT, they are all very good candidates for this study. For the intersections in Houston, a field visit was conducted to collect more information about the intersections, including traffic condition, intersection layout, and the locations for parking the autoscope van. Based on the field visit results, eight intersections were selected. For the intersections in Austin, since the traffic surveillance cameras installed at the intersections are important tools for field data collection, the field of view of these surveillance cameras needs to be considered. Finally, 10 intersections in Austin with good field of view were selected for this study. Therefore, there were 26 final selected intersections for field study: (1) 10 intersections in Austin, (2) 8 intersections in Houston, (3) 6 intersections in Lufkin, and (4) 2 intersections in Nacogdoches. The locations of these study intersections are presented in the maps in Figures 33 to 36. The whole process of data collection, from the preparation for data collection to the completion of data processing, lasted about 5 months (from May to September 2007).

Table 38: Definition of Intersection Categories for Field Studies

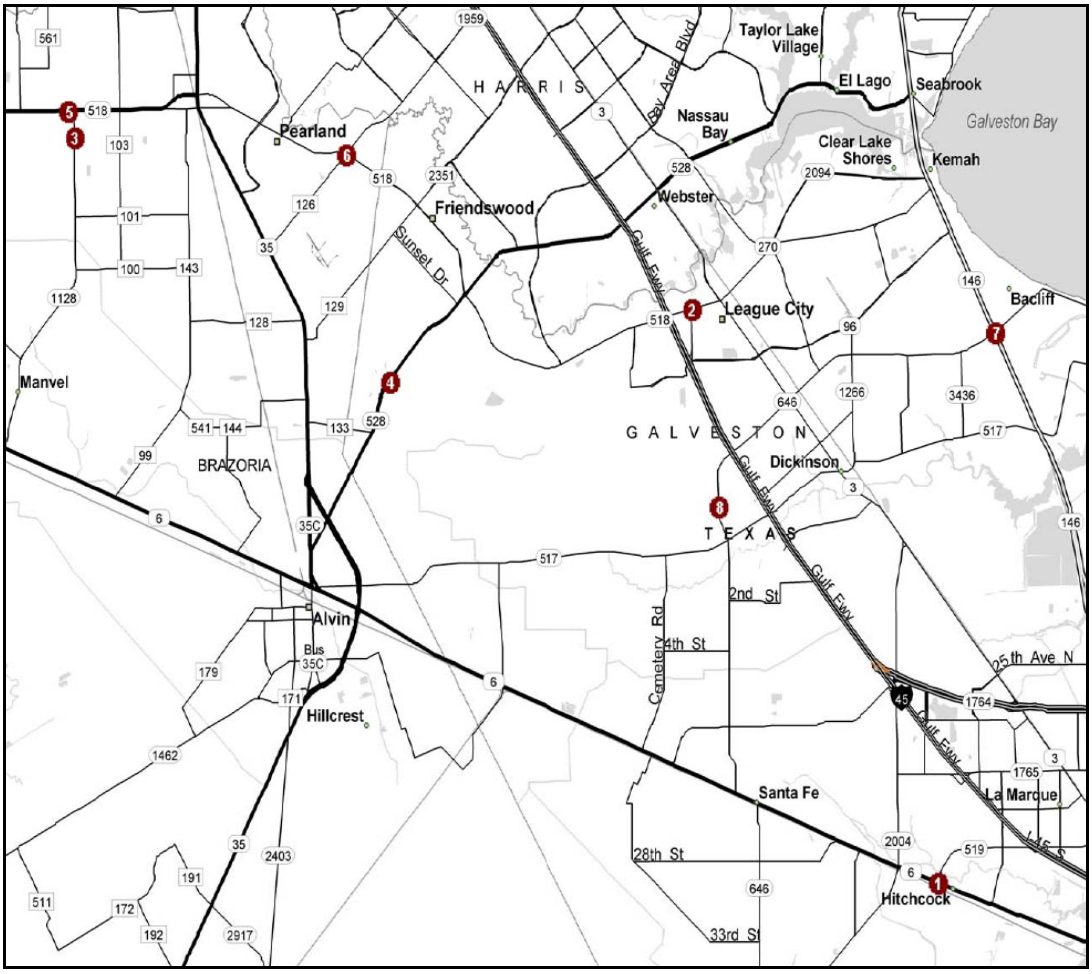
LT Control Mode	LT Phasing Sequence	Geometry: Opposing Lanes	Geometry: LT Lanes	Volume	Speed Limit	Signal Display	Cate. ID
PPLT	**Lead-lead**	1	1	High	High/moderate*	Include • Both 4 sections or 5 sections • Both shared and exclusive display types • Prefer to have indications other than green ball for permissive phase (e.g., flashing yellow arrow)	**1**
		2	1	High/moderate	/**		**2**
		3 or more	1	High	High*		**3**
	Lead-lag	1	1	High	High/moderate		**4**
		2	1	High/moderate	/		**5**
		3 or more	1	High	High		**6**
	Lag-lag	1	1	High	High/moderate		**7**
		2	1	High/moderate	/		**8**
		3 or more	1	High	High		**9**
PO	**Lead-lead**	1	1	High	High/moderate	Include • Both a left-turn green arrow and (*green arrow + green ball) indications	**10**
		2	1	High/moderate	/		**11**
		3 or more	1 or 2	High	High		**12**
	Lead-lag	1	1	High	High/moderate		**13**
		2	1	High/moderate	/		**14**
		3 or more	1or 2	High	High		**15**
	Lag-lag	1	1	High	High/moderate		**16**
		2	1	High/moderate	/		**17**
		3 or more	1or 2	High	High		**18**
Permissive	/	2	/	/	High/moderate	/	**19**
		3	/	/	High		**20**

*High means the speed limit is higher than 40 mph; moderate means the speed limit is 25-40 mph.
**/ means no specific requirements.



Date of the first data collection in Austin: June 17 to 22	
1. Loop 360 @ Stonelake	2. Braker @ Burnet
3. Congress @ William Cannon	6. Burnet @ Koenig
5. Lamar @ Koenig	4. Brodie @ William Cannon
7. 51st @ Airport	8. Braker @ Metric
9. Lamar @ 29th	10. Lamar @ 38th

Figure 33: Map of Study Intersections in Austin

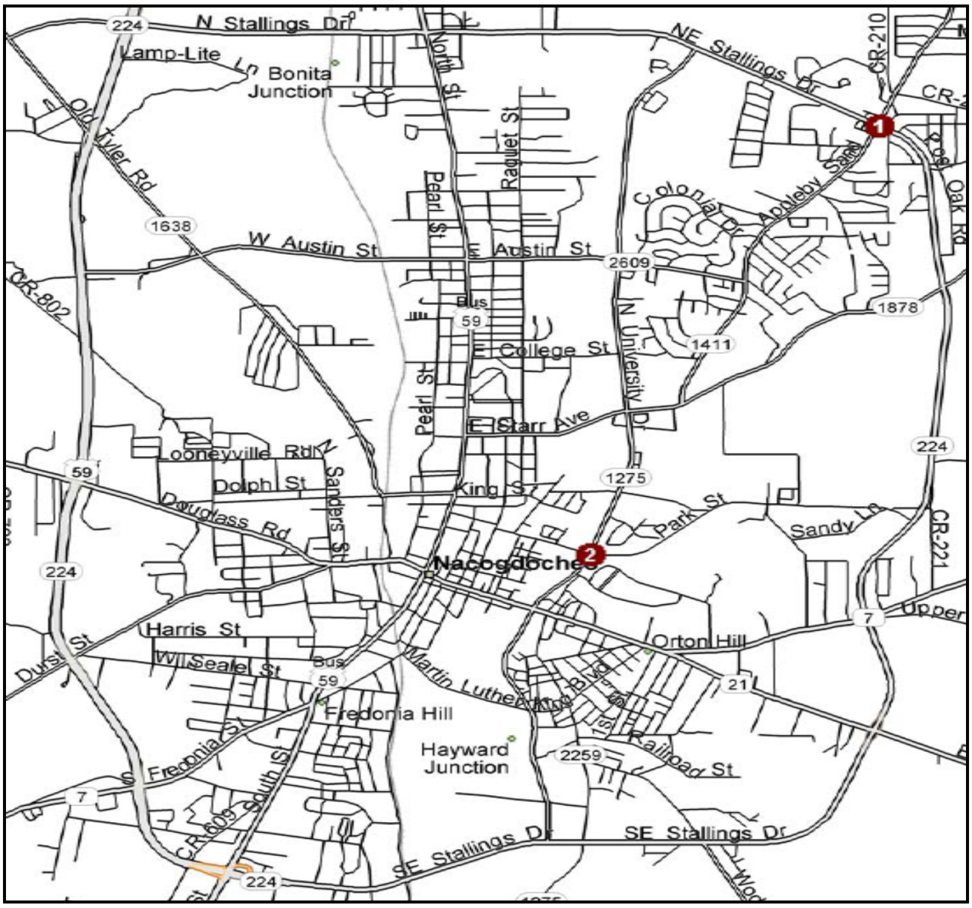


Date of the second data collection in Houston: July 18 and 19	
1. SH 6 @ FM 519	2. FM 518 @ Calder
3. FM 1128 @ Fite	4. FM 528 @ San Joaquin
Date of the third data collection in Houston: August 7 and 8	
5. FM 518 @ Reid	6. FM 518 @ Dixle Farm
7. FM 646 @ FM 146	8. FM 646 @ Bay Creak

Figure 34: Map of Study Intersections in Houston

Date of the fourth data collection in Lufkin: August 19 to 22	
1. Loop 287 @ SH 103	2. Timberland @ Atkinson
3. Timberland @ Paul	4. Timberland @ Lufkin
5. Frank @ First	6. Timberland @ Denman

Figure 35: Map of Study Intersections in Lufkin



Date of the fourth data collection in Nacogdoches: August 22 to 23	
1. Loop 224 @ FM 2609	2. University @ Park

Figure 36: Map of Study Intersections in Nacogdoches

4.1.3 Data Collection Methods

Different methods were used to collect the required data listed in Table 37. These methods include probe vehicle runs, video recording, field visits, and information from traffic management centers.

4.1.3.1 Probe Vehicle Runs

Travel time and delay are two major measures for evaluating intersection operational performance. In order to obtain these two measures for both left-turn and opposing through traffic movements, the research team drove two probe vehicles equipped with GPS units to collect second-by-second vehicle speed and location data at the study intersections. One probe vehicle made a left-turn movement in the subject direction, while the other probe vehicle drove at the opposing through direction, simultaneously. For each study intersection, 3 hr of GPS data for both the left-turn movement and the opposing through movement were collected.

4.1.3.2 Video Recording

Traffic video was recorded for obtaining the intersection traffic volume and traffic conflicts data during the data collection time period. The traffic video is either recorded through the surveillance cameras from the TMC or directly from the autoscope van in the field.

From the TMC. All selected study intersections in Austin are equipped with surveillance cameras, which are controlled by the Austin TMC. During the data collection period in Austin, two research members stayed at the TMC to record the traffic video of the study intersections. The surveillance camera was targeted at the center part of the intersection and could view the approaches of both subject left-turn traffic and the opposing through traffic. The coverage of the field of view of the surveillance is illustrated in Figure 37.

From the Autoscope Van. The autoscope van was used to record traffic video for the data collection in Houston, Lufkin, and Nacogdoches (see Figure 38) because the study intersections in these three cities were not all installed with surveillance cameras. In the field, the van was parked near the intersection with one camera covering the center part of the study intersection and the other targeting the traffic signal display of the subject direction. The van's field of view and the setting of the van in the field are illustrated in Figures 37 and 38, respectively. The recording period for each intersection was 3 hr while two probe vehicles were running at the intersections simultaneously.

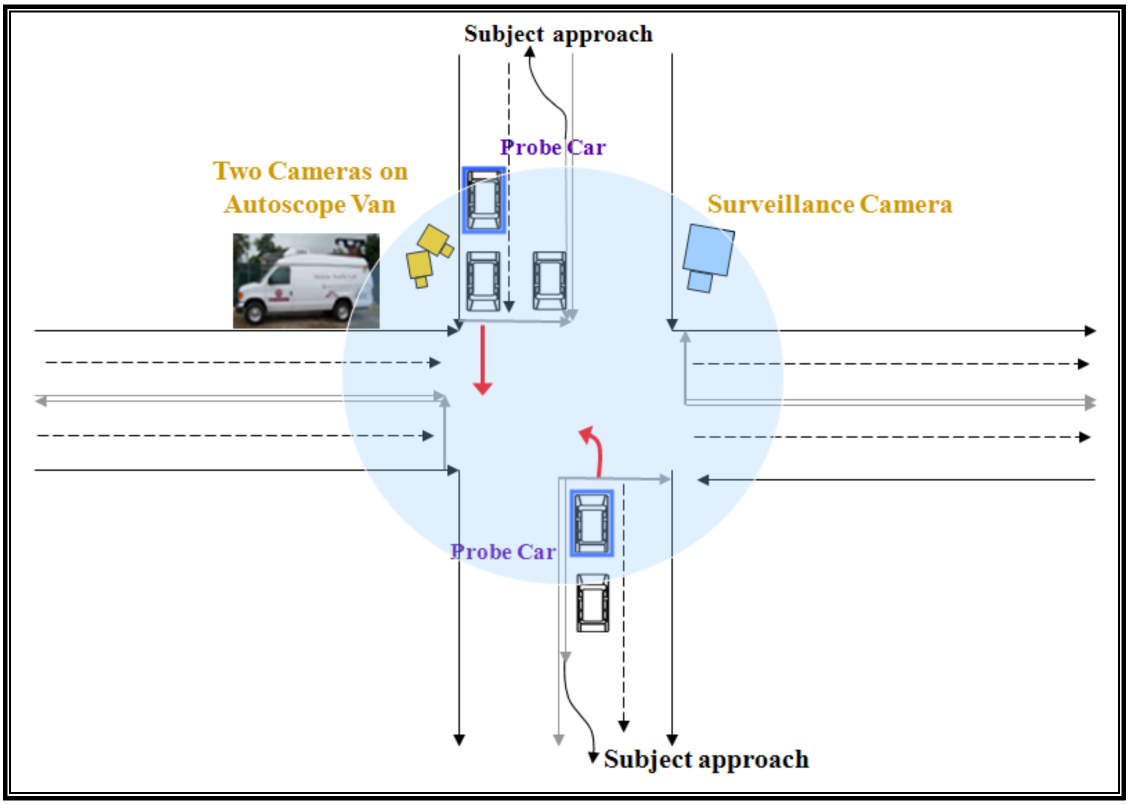


Figure 37: Illustration of Data Collection Methods

Figure 38: Operation of Autoscope Van in the Field

4.1.3.3 Field Visits

Field observation is a direct way to collect the required information for the study intersections, including the geometric layout (number of lanes in all approaches, posted speed limits on each street, etc.), signal controls (mode and sequence), and signal displays (indication, arrangement, and placement).

4.1.3.4 Information from Traffic Management Centers

The following data were directly collected by contacting traffic management centers:

- existing traffic signal timing information, including signal planning (schedule), cycle length, split, and left-turn phase type; and
- intersection historical accident data for the period of 3-4 years.

4.1.3.5 Summary of Data Collection

Table 39 summarized the information about the collected data and the methods for collecting them.

Table 39: Summary of Data Collection Methods

Category	Collected Data	Collection Method
Dynamic	Traffic volume video	Surveillance cameras
		Autoscope van
	GPS data of probe vehicles	Probe vehicles equipped with GPS data logger
Static	Intersection geometric layout	Field observation
	Signal controls	Field observation
	Signal timing plan	TMC
		Field observation
	Signal display	Field observation
	Historical accident data	TMC

The basic information for the study intersections, including geometric layout, signal controls, and signal display of the study intersections, is summarized into one comprehensive table (see Table 40).

Table 40: Summary of Geometric Layout, Signal Controls, and Signal Display Features of Study Intersections

Intersection	Subject Direction	Signal Controls			Geometric Layout						Signal Display				
					# of Lanes			# of Opp. Lanes							
		Mode	Sequence	Pair Sequence	LT	TH	RT	LT	TH	RT	Placement	Arrangement	Per. Indi.	PO Indi.	SH/ EX
Loop 360 @ Stonelake	EB	PPLT	Lag	Lead-lag	1	3	0	1	3	0	CLT	5H	GB	RB+GA	SH
Braker @ Burnet	WB	PO	Lead	Lead-lead	1	3	0	1	3	0	CLT	3H	/	GA	EX
Congress @ William Cannon	SB	PO	Lag	Lead-lag	1	1	0	1	1	0	CLT	3H	/	GA	EX
Brodie @ William Cannon	SB	PO	Lead	Lead-lag	1	2	1	1	2	1	CLT	5H	/	GA	EX
Lamar @ Koenig	NB	PPLT	Lead	Lead-lag	1	2	0	1	2	0	CLT	5H	GB	RB+GA	SH
Burnet @ Koenig	WB	PPLT	Lag	Lead-lag	1	2	0	1	2	0	LLT	5H	GB	RB+GA	SH
51st @ Airport	NB	PPLT	Lead	Lead-lag	1	2	0	1	2	0	CLT	5H	GB	RB+GA	SH
Braker @ Metric	NB	PO	Lead	Lead-lead	1	2	0	1	2	0	CLT	5H	/	GA	EX
Lamar @ 29th	WB	PPLT	Lead	Lead-lead	1	1	0	1	1	0	CLT	5H	GB	RB+GA	SH
Lamar @ 38th	EB	PPLT	Lead	Lead-lag	1	3	1	1	2	1	LLT	5H	GB	RB+GA	SH
SH 6 @ FM 519	EB	Permissive	/	/	1	2	1	1	2	0	CLT	5H	GB	/	EX
FM 518 @ Calder	WB	PPLT	Lag	Lead-lag	1	2	0	1	2	0	CLT	5D	GB	RB+GA	SH
FM 1128 @ Fite	NB	PPLT	Lead	Lead-lead	1	1	1	1	1	1	CLT	5H	GB	RB+GA	SH
FM 528 @ San Joaquin	SB	PPLT	Lead	Lead-lead	1	2	0	1	2	0	CLT	5D	GB	RB+GA	SH
FM 518 @ Reid	WB	PO	Lead	Lead-lag	1	2	0	1	2	0	CLT	4H	/	GA	EX

Table 40: Summary of Geometric Layout, Signal Controls, and Signal Display Features of Study Intersections (Continued)

Intersection	Subject Direction	Signal Controls			Geometric Layout						Signal Display				
					# of Lanes			# of Opp. Lanes							
		Mode	Sequence	Pair Sequence	LT	TH	RT	LT	TH	RT	Placement	Arrangement	Per. Indi.	PO Indi.	SH/EX
FM 518 @ Dixle Farm	EB	PO	Lead	Lead-lead	1	2	0	1	2	0	CLT	4H	/	GA	EX
FM 646 @ FM 146	SB	PO	Lead	Lead-lead	1	2	0	1	2	0	CLT	4H	/	GA	EX
FM 646 @ Bay Creak	SB	PO	Lead	Lead-lead	1	2	0	1	2	0	CLT	4H	/	GA	EX
Loop 287 @ SH 103	NB	PPLT	Lead	Lead-lead	1	2	1	1	2	1	CLT	5D	GB	RB+GA	SH
Timberland @ Atkinson	SB	PPLT	Lag	Lag-lag	1	1	1	1	2	0	CLT	5D	GB	RB+GA	SH
Timberland @ Paul	SB	PPLT	Lag	Lag-lag	1	2	0	1	2	0	CLT	5D	GB	RB+GA	SH
Timberland @ Lufkin	NB	PPLT	Lag	Lag-lag	1	2	0	1	2	1	CLT	5D	GB	RB+GA	SH
Frank @ First	WB	PO	Lead	Lead-lag	1	2	0	1	2	0	CLT	3H	/	GA	EX
Timberland @ Denman	SB	PPLT	Lag	Lag-lag	1	2	1	1	2	1	CLT	5D	GB	RB+GA	SH
Loop 224 @ FM 2609	WB	PPLT	Lead	Lead-lead	1	2	1	1	2	1	CLT	5D	GB	RB+GA	SH
University @ Park	NB	PPLT	Lag	Lead-lag	1	2	0	1	1	1	CLT	5D	GB	RB+GA	SH

Notes:
Placement: CLT means LT signal head is in line with the center of LT lane; LLT means LT signal head is in line with the LT lane line (which is shared with the adjacent TH lane).
Arrangement: 3H means three-section horizontal; 4H means four-section horizontal; 5H means five-section horizontal; 5D means five-section doghouse.
Indication: GA means green arrow; GB means green ball; RB means red ball.
SH/EX: SH means shared LT display; EX means exclusive LT display.

4.1.4 Data Processing

The collected data in each group were processed in the university laboratory both manually and automatically to retrieve the information regarding intersection operational performance. The results of data processing are used for Chapter 6.

4.1.4.1 Traffic Video Data

Traffic videos were processed in the laboratory by manual observation. To facilitate the data processing, a Microsoft Excel macro program was developed to quickly and accurately record the arrival time of each vehicle and the observed conflicts in an Excel file. For the study intersections with protected-only left-turn control mode, the following data were extracted: (1) left-turn traffic volume, (2) opposing through traffic volume, (3) conflicts with opposing right turn and sneakers. For the study intersections with protected and permissive left-turn control mode, the extracted information includes: (1) left-turn traffic volume, (2) opposing through traffic volume, (3) number of potential conflicts, (4) number of conflicts, and (5) difficult-to-turn events.

4.1.4.2 GPS Data Collected by Probe Vehicles

From the collected GPS data, the following information was extracted: (1) travel time and (2) intersection delay for both left-turn and opposing through movements. First, the collected GPS data were processed in ArcGIS®[1] to delete the unwanted GPS points and to join the GPS points with the links at the study intersections. Then, a VC++ program was developed to derive the travel time and delay information for each probe vehicle by runs.

4.2 DATA COLLECTION FOR SAFETY IMPACT ANALYSIS

Two types of safety analyses were conducted for this research, including (1) safety impact analysis for different types of left-turn signal phasing treatments and displays, and (2) safety benefits analysis for signal regional standardization. This section introduces the data collection procedure for these two safety analyses.

[1] ESRI

For analyzing the safety impacts of left-turn phasing treatments, three studies were conducted: (1) traffic conflict study, comparison of the traffic conflicts observed during the field studies at different intersection approaches with different left-turn signal phasing treatments; (2) cross-sectional study, comparison of the accident frequency at different intersection approaches with different left-turn signal phasing treatments; and (3) before-and-after study, comparison of the accident frequency of the intersection approaches before and after left-turn signal phasing is changed. Since the traffic conflict study was conducted during the field study and the data collected from the field study have been introduced in the previous sections, the following sections will discuss just the data collection for the other two types of studies for analyzing the safety impacts of left-turn phasing treatments and for analyzing the safety benefits of signal regional standardization.

4.2.1 Selection of Study Locations

The first step in the data collection effort is to identify a list of intersections that are appropriate for each analysis task. For the cross-sectional study, study intersections were selected to cover a wide range of intersections with different left-turn signal phasing treatments and displays. Similar to the intersection selection for the field study, the predefined intersection categories (see Table 38) were sent to traffic engineers at various districts of the Texas Department of Transportation to ask for their recommendations for the study intersections. For each category in Table 38, at least three or four intersections were requested. Finally, around 155 candidate intersections were selected for this study, of which 70 are located in Austin and 85 are in Houston.

For the before-and-after study, intersections that had experienced left-turn signal phasing or display changes were requested. Based on the recommendations from the traffic engineers in TxDOT and in different TMCs, 10 intersections where the signal phasing had been changed in the past 3 years were selected. Among them, eight intersections are in the Lufkin area and two are in the Austin area.

For analyzing the safety benefits of regional standardization, the following four corridors in Houston, Texas, were recommended: FM 1960, SH 6 North, SH 6 South, and FM 518. On these four corridors, there are a total of 73 intersections with different left-turn signal phasing treatments.

4.2.2 Development of Database for Safety Analysis

In this study, the “sample” used for safety analysis was developed based on the data for a pair of approaches instead of a single approach of an intersection. The reason is that, in terms of safety performance, the leading (lagging) phase in the lead-lag sequence could be different from the leading (lagging) phase in the lead-lead (lag-lag) sequence. Therefore, to analyze the safety performance, the two opposing approaches have to be considered together.

Therefore, the study pairs of intersection approaches needed to be selected from the pool of study intersections. The selections were mainly based on the availability of information. For conducting the safety analysis, both historical accident records and other intersection-related information, including geometric characteristics, signal timing, traffic volume, etc., needed to be collected. A great deal of effort was put into gathering all of this information for the study intersections, including contacting various agencies and conducting field surveys. These collected data were put into the database for safety analysis. The following are brief descriptions of the collected data.

Accident Data

Historical accidents data were collected from the TxDOT Crash Records Information System (CRIS), the TMC in Austin, and the Houston-Galveston Area Council (H-GAC). Traffic accident data were obtained from different sources in different types of formats, such as ArcGIS datasets (Houston), computerized accident reports (Austin), and hardcopies of accident reports (Lufkin). Generally, 3 to 4 years of accident data were obtained for all these study intersections in different Texas cities. Table 41 summarizes the accident data collected for these two analyses.

Table 41: Summary of Accident Data

City	Accident Data Period			Task 6 Safety Impact analysis						Task 2 Regional Standardization Benefits Analysis		
				Cross-Sectional Study			Before-and-After Study			LT Signal Consistency Study		
	Begin Year	End Year	Total No. of Years	No. of Int.	No. of Pairs of Approaches	No. of Left-Turn Accidents	No. of Int.	No. of Pairs of Approaches	No. of Left-Turn Accidents	No. of Int.	No. of Pairs of Approaches	Total No. of Accidents
Austin	2004 or 2005	2007	3 or 4	37	60	944	2	2	67	/	/	/
Houston	1999	2001	3	44	44	929	/	/	/	73	73	2040
Lufkin	2004	2007	3	0	0	0	5	5	156	/	/	/
Total	/	/	/	81	104	1873	7	7	223	73	73	2040

Notes:
"LT" means left turn.
"No. of Int." means number of intersections.
"No. of Pairs of Approaches" is equal to "No. of Samples" for this study.

All the accident records were carefully examined, and the useful information was identified and extracted for safety analysis. The information includes:

- date of accident (month/day/year) and the day of the week,
- accident location (by city, street, intersection related, or mileage point),
- number of vehicles involved,
- direction of travel of involved vehicles,
- accident type, and
- accident severity (fatal, injury, or property damage only).

For the safety impact analysis, special attention was given to left-turn–related accidents. The causes of these accidents were analyzed and inputted into the database as well. For analyzing the safety benefits of regional standardization, the accident data were stored in an ArcGIS format, and the information about the mix level of signal phasing treatments on selected corridors was derived.

Other Information — Geometric, Signal, and Traffic Conditions

The following intersection information related to geometrics, signals, and traffic conditions was collected from the City of Houston, the TMC in Austin, TxDOT, and the field survey conducted by the research team:

- number of lanes (including left-turn lanes, through lanes, and right-turn lanes),
- posted speed limit,
- mode of left-turn phasing,
- sequence of left-turn phasing,
- split phasing,
- display of left-turn signals, and
- average daily traffic (ADT) volume.

If the intersection approaches are using split phasing, traffic on two opposing approaches moves consecutively rather than concurrently. Due to this feature, it can be seen that split phasing is only associated with lead-lag sequence. However, only 37 pairs of approaches to Austin intersections had detailed signal timing plans to allow split phasing to be identified. Left-turn signal display includes information on left-turn signal head placement, arrangement, and left-turn signal indications. Detailed display information was obtained for all 44 intersections in Houston from the field survey. For the intersections in Austin and Lufkin, only the intersections that had field studies in operational impact analysis had detailed signal display information. For the intersections used in the before-and-after study, the date of signal phasing changes was also collected besides the information listed above.

For the safety benefits of regional standardization study, the mode, sequence, and display of left-turn signal information for each intersection were collected. The average ADT volume was also collected for each corridor.

Finally, the complete set of information was gathered for 104 samples (pairs of approaches) used for the cross-sectional study, 7 samples (pairs of approaches) used for the before-and-after study, and 73 samples (pairs of approaches) for analyzing the safety benefits of regional standardization. Table 42 summarizes the number of samples for cross-sectional studies by left-turn signal phasing treatments (both modes and sequences). Table 43 presents the samples for the before-and-after study along with the type of change. Table 44 summarizes the number of samples on each of the four corridors selected for analyzing the safety benefits of regional standardization. The detailed information about the selected intersections for safety studies, including intersection name, volume, signal phasing, display type, speed limit, geometric features, etc. is presented in Appendix II.

Table 42: Number of Pairs of Approaches (Samples) for Cross-Sectional Study

Mode/Sequence		Sequence		
		Lead-Lead	**Lead-Lag**	**Lag-Lag**
Mode	**PO**	12	46	4
	PPLT	14	23	0
	Permissive	5		
Total		104		

Notes:
PO means protected-only left-turn signal control mode.
PPLT means protected/permissive left-turn signal control mode.

Table 43: Number of Pairs of Approaches (Samples) for Before-and-After Study

Type of Change	Number of Samples
Mode changed from PO to PPLT	5
Sequence changed from lag-lag to lead-lead	2
Total	7

Notes:
PO means protected-only left-turn signal control mode.
PPLT means protected/permissive left-turn signal control mode.

Table 44: Number of Pairs of Approaches (Samples) for Analyzing the Safety Benefits of Signal Regional Standardization

Regions	Total No. of Intersections
FM 1960	21
SH 6 (North)	19
FM 518	22
SH 6 (South)	11
Total	73

CHAPTER 5: SAFETY IMPACT ANALYSIS

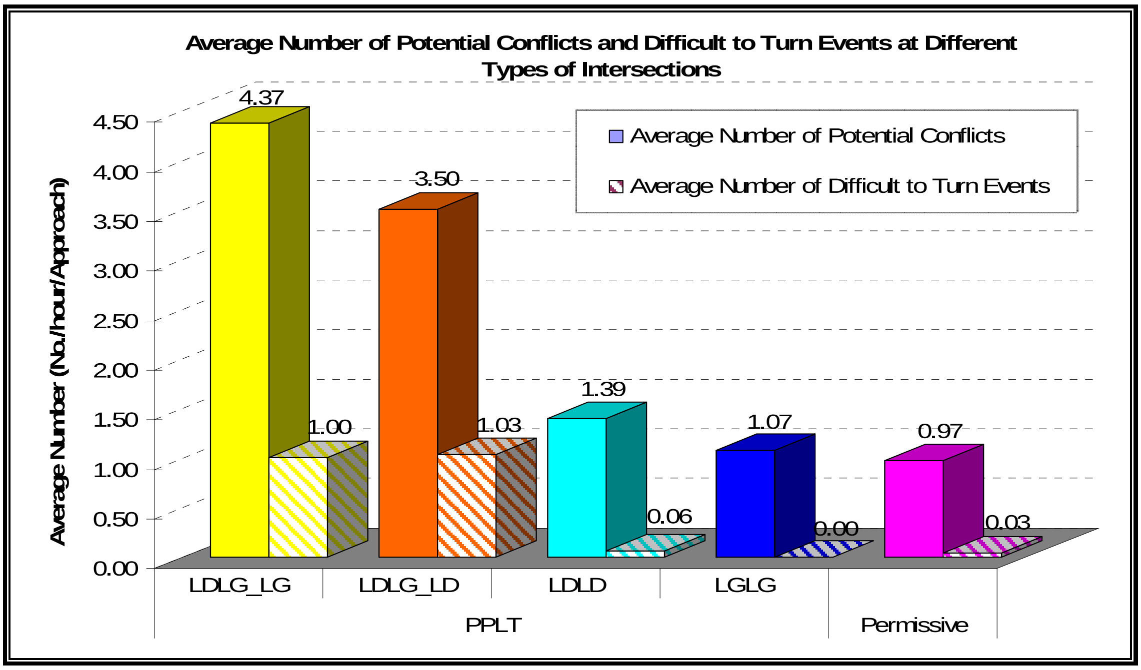
In this chapter, the safety impacts of different types of left-turn signal phasing treatments and displays are analyzed. Results from Chapters 5 and 6 serve as the basis for developing the guidelines for determining left-turn phasing and signal display.

Three types of safety studies were conducted: (1) traffic conflicts study, (2) cross-sectional study, and (3) before-and-after study. The following three sections describe the methodologies and results of these three studies.

5.1 TRAFFIC CONFLICTS STUDY

The traffic conflicts study was conducted at 18 intersections with PPLT and permissive control modes through observing the recorded traffic videos. Traffic conflicts are generally defined as events involving the interaction of two or more road users where one or both users take evasive action such as braking or weaving to avoid collision. However, there were only three obvious traffic conflicts observed in the 26 study intersections during the study time period, which is not enough to derive any significant conclusions. Therefore, to assess the safety risk, especially as related to permissive left turns, two variant conflict events were defined: (1) potential conflicts, vehicles take permissive left turns in a gap less than the critical gap (4 s in this study); and (2) difficult-to-turn events, a left-turn vehicle had to stop in the middle of the intersection for longer than 10 s to find a gap to make a permissive left turn.

The number of potential conflicts and difficult-to-turn events at each intersection was observed and counted. The average number of potential conflicts and difficult-to-turn event conflicts at intersections with different types of phasing treatments was then calculated and is presented in Figure 39.



Note: LD means lead phase; LG means lag phase; LDLG_LG means the approach with lag phase in lead-lag phasing.

Figure 39: Average Number of Potential Conflicts and Difficult-to-Turn Events at Different Types of Intersections

Figure 39 shows that the approaches with PPLT control mode are basically more risky than those with permissive-only control mode. It is probably due to the fact that intersections with PPLT control mode usually have more traffic and more lanes than intersections with permissive-only control. *In addition, among the intersections with PPLT control mode, the approaches with lead-lag phasing are associated with relatively higher conflict risks than those using lead-lead or lag-lag phasing.* And for the approaches with lead-lag phasing, the approaches with a lead phase are safer than those with a lag phase.

5.2 CROSS-SECTIONAL STUDY

The cross-sectional study was designed to compare the accident frequency among the intersections with different left-turn signal phasing treatments and signal displays to find out how left-turn phasing and signal display affect intersection safety. This study was conducted using two approaches: (1) simply comparing the average accident rates of the intersections with different types of signal phasing and display, and (2) using advanced statistical models to analyze the impacts of signal phasing and display on the safety of left-turn operations. The first method is simply and direct. However, intersection safety is affected by various factors besides signal phasing and display, such as traffic volume, speed, and intersection geometric conditions. To control the impacts of these factors, the second approach, i.e., the statistical modeling approach, was used. Poisson and negative binomial regression models, which are the classical models for counted data, were considered in this study for modeling the frequency of left-turn–related accidents. The statistics software package SAS was used for developing these models. These two models are described in the following methodology section along with the method for model selection. Afterwards, the dependent variables and independent variables considered in model development are described. Finally, the results from both approaches, i.e., the simple comparison of accident rates and the accident frequency modeling, are presented, explained, and discussed.

5.2.1 Methodology

5.2.1.1 Model Description

Intersection accidents are random events, and the frequency of accidents is discrete and a positive number. The relationship between the expected number of accidents occurring at intersection approach pair *i* (dependent variable Y_i) and a set of explanatory variables X_{i1}, $X_{i2}, \dots X_{in}$ that represent the features of intersections (i.e., intersection geometric, signal control, and traffic volume conditions) could be modeled as:

$$Function(Y_i) = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_n X_{in} \quad (9)$$

where $\beta_0, \beta_1, \beta_2, \dots \beta_n$ are the coefficients of the independent variables $X_{i1}, X_{i2}, \dots X_{in}$. The regression procedure is to estimate model parameters and the coefficient parameter vector $\beta(\beta_0, \beta_1, \beta_2, \dots \beta_n)$.

The Poisson regression model should be selected for modeling accident frequency, according to the literature (Greene 2000, Hamerslag et al. 1982, Washington and Ivan 2005). This model assumes that given the value of X_i (a vector of possible explanatory variables, i.e., $X_{i1}, X_{i2}, \dots X_{in}$), the independent variable y_i follows a Poisson distribution, which can be expressed as:

$$P(y_i|X_i) = \frac{\exp(-\mu_i)\mu_i^{y_i}}{y_i!} \quad (10)$$

where y_i denotes the number of accidents that occurred at intersection approach pair i and μ_i is the conditional mean of y_i, which is the a nonlinear function of X_i and can be expressed as follows:

$$ln\ \mu_i = \beta X_i = \beta_0 + \beta_1 X_{i1} + \beta_2 X_{i2} + \cdots + \beta_n X_{in} \tag{11}$$

Then, the expected number of accidents that occurred at intersection approach pair i can be estimated by:

$$Y_i = E(y_i|X_i) = \mu_i = e^{\beta X_i} \tag{12}$$

where β is the vector of regression coefficients that can be estimated by the standard maximum likelihood method with the likelihood function given by:

$$L(\beta) = \prod_i \frac{\exp[-\exp(\beta X_i)][\exp(\beta X_i)]^{Y_i}}{y_i!} \tag{13}$$

A limitation of the Poisson model is its implicit assumption that the dependent variance of y_i equals its mean. When accident frequency data are overdispersed, which means that the variance of accident frequency data is greater than its mean, the Poisson regression model cannot be employed. In order to relax the overdispersion constraint, a negative binomial regression model is commonly used. It generalizes the Poisson model by introducing an independently distributed error term into the conditional mean in Equation (11), such that:

$$ln\ \mu_i = \beta X_i + \varepsilon_i \tag{14}$$

where $\exp(\varepsilon_i)$ is a gamma-distributed error term with mean one and variance α. It can be derived that the conditional mean of the independent variable y_i follows a negative binomial distribution, which can be expressed as follows:

$$P(y_i|X_i) = \frac{\Gamma(1/\alpha + y_i)}{y_i! \cdot \Gamma(1/\alpha)} \cdot u_i^{1/\alpha}(1-u_i)^{y_i} \tag{15}$$

where $u_i = 1/\alpha\ (1/\alpha + \mu_i)$. The mean of the negative binomial distribution remains the same as the Poisson distribution, which is μ_i, and its variance can be expressed by the following equation:

$$Var(y_i|X_i) = \mu_i + \alpha \mu_i^2 \tag{16}$$

where α is the variance of the gamma-distributed error term. From Equation (16), it can be seen that the introduction of ε_i results in the variance of y_i differing from its mean. α is a measure of data dispersion, and when $a \to 0$, the negative binomial becomes the Poisson distribution (it can be derived based on Equation [15]). Similar to the Poisson regression model, the value of parameter a and the coefficients of independent variables can be estimated by the standard maximum likelihood method.

5.2.1.2 Model Selection

The selection between the Poisson and negative binomial regression models is based on the goodness of fit of a model. The statistics software SAS provides the following measures for assessing the goodness of fit of a model.

- Deviance/(n-p): the deviance of the model containing all the parameters (including the intercept) divided by its degree of freedom, n-p, with n being the number of observations and p being the number of parameters estimated. Asymptotically, this value tends toward 1, and *its value being close to 1 indicates that the model is a good fit* (McCullagh and Nelder 1989, SAS Institute Inc. 2004).
- Pearson chi-square/(n-p): the Pearson chi-square statistic divided by its degrees of freedom, n-p. *If the value is approximately equal to 1, it indicates that the model is reasonably well fitted* (McCullagh and Nelder 1989, SAS Institute Inc. 2004).
- Log likelihood: a higher log likelihood means better fit of a model.

5.2.1.3 Dependent and Independent Variables

In regression modeling, the dependent variable is the frequency of left-turn–related accidents. From the information collected, a set of explanatory (independent) variables, which represent the intersection geometric, signal control, and traffic conditions, was derived and considered in model development. A description of these variables is presented in Table 45.

Table 45: Dependent and Independent Variables Used in the Model

Variables	Description
Dependent Variable	
Accident Counts	Number of accidents that occurred during 4 years
Left-Turn Signal Mode	
PPLT	1 if protected/permissive, 0 otherwise
Permissive	1 if permissive-only, 0 otherwise
PO	If protected-only, treated as baseline mode
Left-Turn Signal Sequence (Not Applicable for Permissive-Only Mode)	
Lead-Lag	1 if lead-lag, 0 otherwise
Lead-Lead	1 if lead-lead, 0 otherwise
Lag-Lag	If lag-lag, treated as baseline sequence
Left-Turn Signal Display	
Doghouse or Horizontal	1 if doghouse, 0 otherwise (horizontal)
Split Phasing	
Split Phasing	1 if it uses split phase, 0 otherwise
Traffic Flow Characteristics	
ADTPL	Average daily traffic volume per lane
Geographic Characteristics	
No. of Lanes	Total number of lanes of the intersections

5.2.2 Four Cross-Sectional Studies

Information from Chapter 4 indicated that accident data and intersection-related information were collected from different sources. Some information was only available for or applicable to a subset of study intersections. Therefore, researchers could not use one single model to investigate the safety impacts of all aspects of left-turn signal design due to the limitations of the data. In this study, four different studies were conducted for assessing the safety impacts of different aspects of left-turn signal phasing using different sets of data. These four studies are described as follows:

- Study 1: the safety impacts of left-turn signal control mode
  - Purpose: to investigate the safety impacts of left-turn signal control mode
  - Data: 104 pairs of intersection approaches collected for cross-sectional study
  - Reason: The left-turn control mode information is available for all the intersections.
- Study 2: the safety impacts of left-turn signal phasing sequence
  - Purpose: to investigate the safety impacts of left-turn signal phasing sequence
  - Data: 99 pairs of intersection approaches with PO and PPLT control modes
  - Reason: For the intersection approaches using permissive-only control mode, all the traffic is released in one signal phase. Therefore, phasing sequence is not applicable for these intersections.
- Study 3: the safety impacts of split phasing
  - Purpose: to investigate the safety impacts of split phasing
  - Data: 37 pairs of approaches to the intersections in Austin with lead-lag phase sequence
  - Reason: Only some of the intersections in Austin have detailed signal timing information for identifying split phasing, and split phasing must use lead-lag sequence.
- Study 4: the safety impacts of left-turn signal display
  - Purpose: to investigate the safety impacts of left-turn signal display
  - Data: 44 pairs of approaches to the intersections in Houston
  - Reason: The detailed signal display information was collected for the Houston intersections through the field survey. The studied intersections in Austin used very consistent signal display (all studied intersections used horizontal signal face arrangement, and all PO intersections used exclusive signal heads and green arrow indication).

These four studies are described in detail in the following sections.

5.2.2.1 Safety Impacts of Left-Turn Signal Control Mode

The data include 104 pairs of intersection approaches. The left-turn control mode information is available for all the intersections.

Simple Comparison of Accident Rates. First, a simple comparison of accident rates (100,000 * left-turn accident counts/ADT) between the three left-turn signal control modes, i.e., permissive-only, protected-only, and protected-permissive left turn, was conducted. The comparison results are presented in Figure 40. It shows that PO mode is much safer than the permissive and PPLT modes. PPLT mode would cause most left-turn–related accidents. The accident rate for permissive is a little less than that for PPLT mode, which may be due to the relatively low traffic volume and speed limits at the intersections with permissive mode.

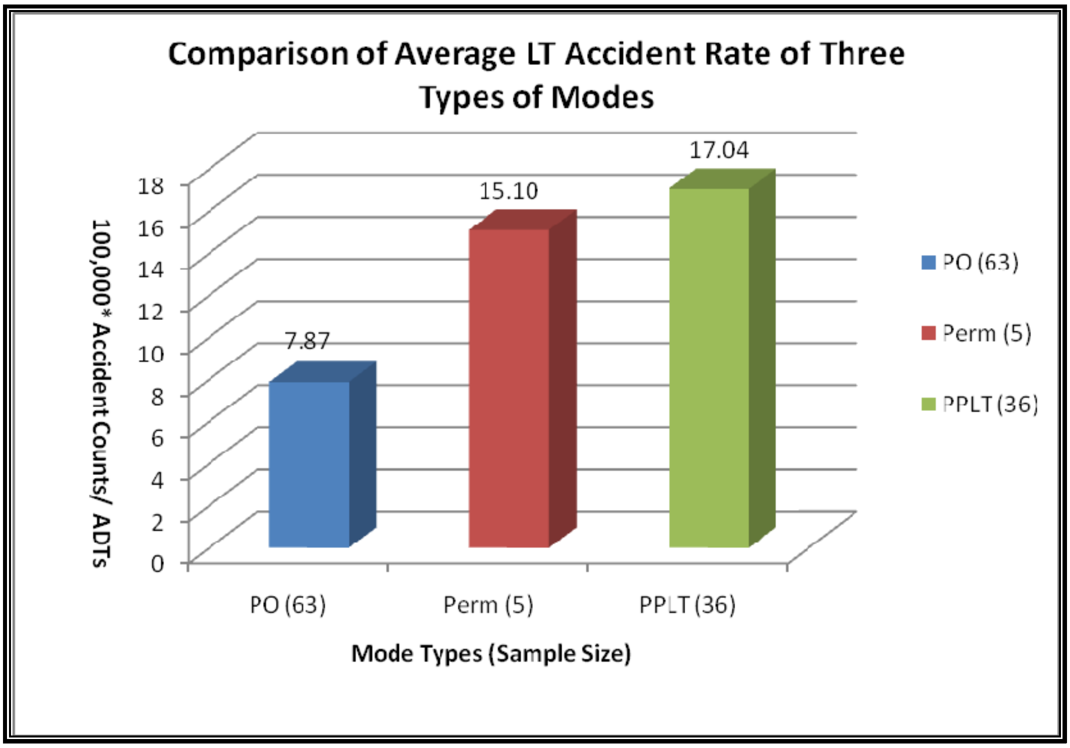


Figure 40: Comparison of Average LT-Related Accident Rates between Three Modes

Accident Frequency Modeling Results. In this model, the dependent variable is the frequency of left-turn–related accidents, and the independent variables include all the independent variables except the following three: (1) left-turn signal sequence, (2) split phasing, and (3) signal display. This is because left-turn signal sequence is not applicable for permissive-only intersections, and split phasing and signal display information is only available for a subset of intersections. First, the appropriate model was selected according to the model's goodness of fit measures estimated based on the data for this study (data for all 104 pairs of study intersection approaches). Table 46 provides the goodness of fit measures for both Poisson and negative binomial regression models derived from SAS.

Table 46: Goodness of Fit Measures for Selection between Poisson and Negative Binomial Regression Model

Criterion	Poisson	Negative Binomial (NB)	Model Selection
	Value	Value	
Deviance	3.8342	1.0555	NB is better than Poisson
Pearson Chi-Square	5.4915	1.4705	NB is better than Poisson
Log Likelihood	182.8294	265.3017	NB is better than Poisson

From Table 46, it can be seen that the negative binomial model fits the data much better than the Poisson regression model because its value of deviance and Pearson chi-square divided by the degrees of freedom is much closer to 1 and its log likelihood value is significantly higher than that of the Poisson model. The model selection for the following cross-sectional studies is omitted because all the testing results indicate that the NB regression model fits the accident data much better than the Poisson regression model, which is also consistent with the findings in the literature (Hadi et al. 1995, Poch and Mannering 1996). Therefore, in this study, the NB regression model was used for developing all the accident frequency models. The results of the developed model for analyzing the safety impacts of left-turn control mode are presented in Table 47.

Table 47: Results of LT Accident Frequency Model for Assessing the Impacts of LT Signal Control Mode

Model			Negative Binomial-Dependent Variable: Left-Turn–Related Accidents	
	Variable		Estimated Coefficients	Wald Chi-Square Test p-Value
Regression Results	Constant		–0.6057	0.2976
	Mode	Permissive-only	0.4403	0.3987
		PPLT*	0.5816	0.007
		PO (Reference)*	0	/
	No. of Lanes		0.1313	0.0003
	ADTPL**		0.0002	0.0355
	Sample Size		104	
	Log Likelihood		265.3017	

*PPLT means protected/permissive left-turn; PO means protected-only.
**ADTPL means average daily traffic volume per lane.

In Table 47, the positive parameters for permissive-only and PPLT modes means that the accident risk at the intersections with permissive or PPLT left-turn control mode is higher than that with the reference PO mode. If a confidence level of 95 percent is selected, the results of the Wald chi-square test indicate that the difference between permissive-only and PO mode is not statistically significant (p-value = 0.3987), but the difference between PPLT and PO mode is significant (p-value = 0.007). Positive parameters for number of lanes and ADTPL indicate that more lanes and more traffic per lane will result in more accident risks at intersections. The results of the Wald chi-square tests also show that the impacts of these two variables are statistically significant (p-value = 0.0003 and p-value = 0.0355). *In sum, this result indicates that PPLT mode is significantly safer than PO mode.*

Note that, according to Equation (14), the frequency of accidents that occurred at a particular intersection can be estimated based on the type of left-turn control mode, the number of lanes, and the traffic volume conditions at that intersection. For example, for a pair of intersection approaches with PPLT left-turn mode, a total of 10 lanes, and an average daily traffic volume per lane of 3000 vpl, the estimated accident rate (number of left-turn accidents per 4 years) is *exp (0.5816 + 0.1313 * 10 + 0.0002 * 3000) = 12.12.*

5.2.2.2 Safety Impacts of Signal Phasing Sequence

The data include 99 pairs of intersection approaches with PO and control modes. For the intersection approaches using permissive-only control mode, all the traffic is released in one signal phase. Therefore, phasing sequence is not applicable for these intersections.

Simple Comparison of Accident Rates. As discussed previously, signal phasing sequences, i.e., lead-lead, lag-lag, and lead-lag, are only applicable for intersection approaches with PO and PPLT signal control modes. In this study, there is no intersection with lag-lag signal phasing sequence and PPLT control mode. Therefore, for intersections with PPLT signal control mode, the comparison of accident rates is only between the lead-lead and lead-lag sequences. Figures 41 and 42 illustrate the comparison of left-turn–related accident rates between different types of sequences for the intersection approaches with PO and PPLT control modes, respectively.

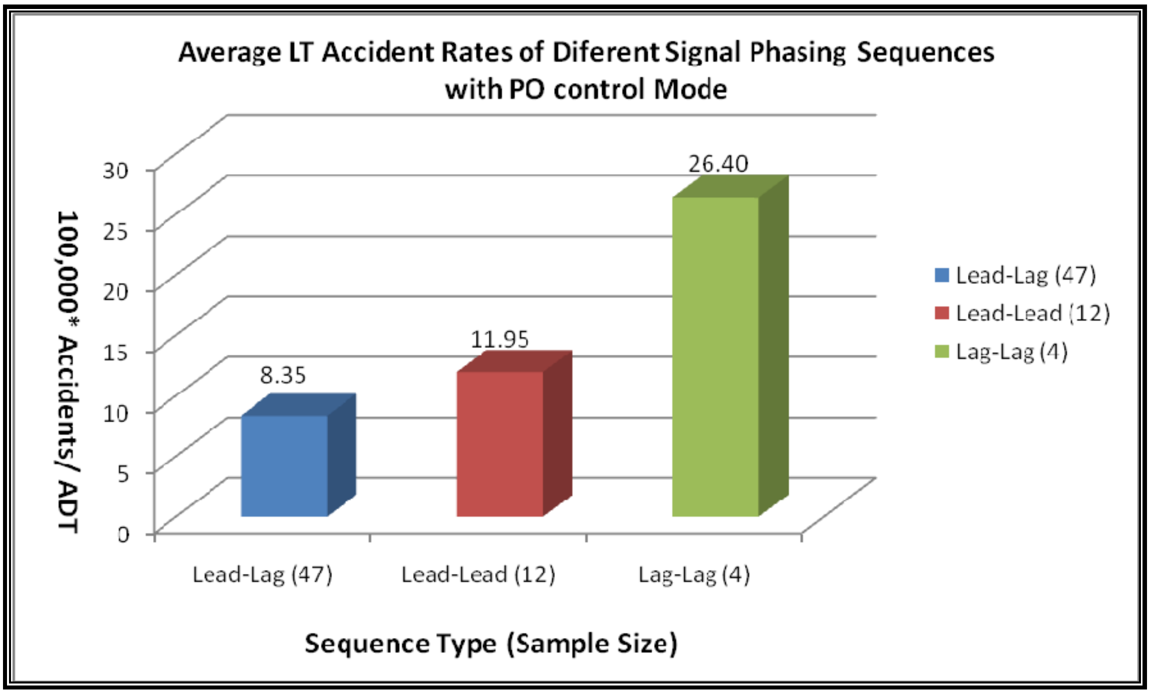


Figure 41: Comparisons of Average LT Accident Rates among Different Signal Phasing Sequences for Protected-Only Control Mode

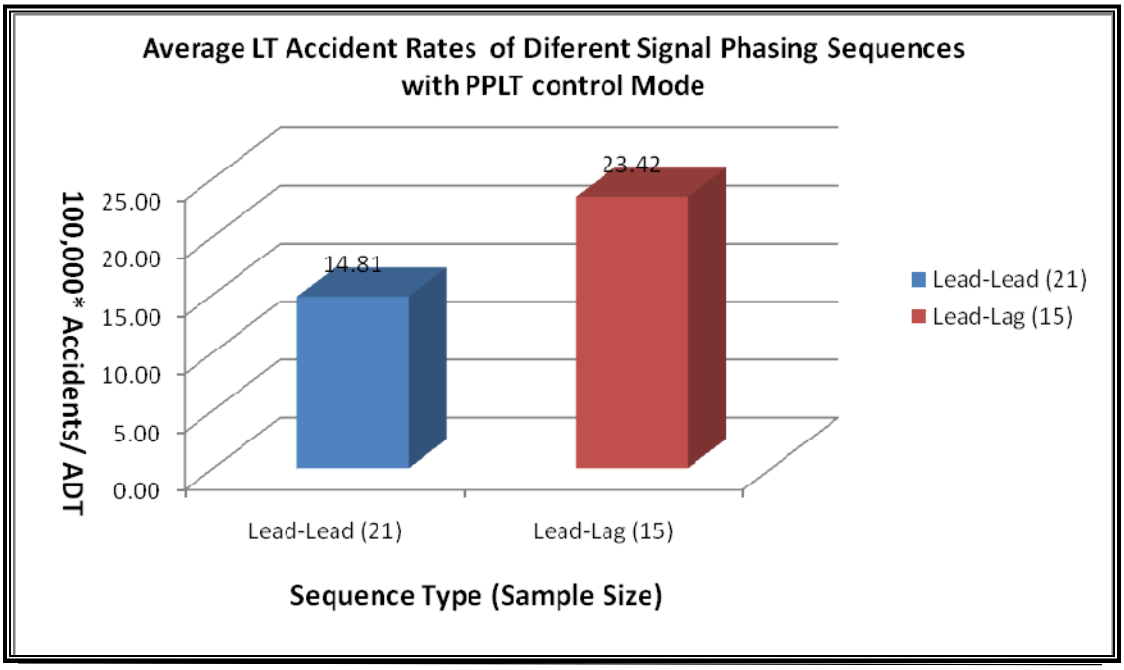


Figure 42: Comparisons of Average LT Accident Rates among Different Signal Phasing Sequences for PPLT Control Mode

Based on the simple comparison of accident rates presented in Figures 41 and 42, it can be seen that, under PO mode, lead-lag sequence is safer than lead-lead sequence. However, under PPLT mode, lead-lead sequence is safer than lead-lag sequence.

Accident Frequency Modeling Results. Table 48 presents the coefficient estimation results of negative binomial regression for this study. The negative parameter for PO mode with p-value < 0.05 shows that PO is safer than PPLT, which agrees with the modeling results of the first study (see Table 47). For the sequence, the negative parameters for lead-lag and lead-lead with both of their p-values < 0.05 indicate that the accident risk of intersections with lead-lag or lead-lead sequence is significantly lower than that of intersections with lag-lag sequence (the reference sequence). By changing the reference sequence, it is found that there is no significant difference between lead-lag and lead-lead sequence.

Table 48: Results of Left-Turn Accident Frequency Model for Assessing the Impacts of Left-Turn Signal Phasing Sequences

Model			Negative Binomial-Dependent Variable: Left-Turn–Related Accidents	
	Variables		Estimated Coefficients	p-Value
Regression Results	Constant		–0.3627	0.4642
	Mode	PO*	–0.6969	0.0013
		PPLT* (Reference)	0	.
	Sequence	Lead-Lag	–1.099	0.0064
		Lead-Lead	–1.1559	0.0079
		Lag-Lag (Reference)	0	.
	No. of Lanes		0.1263	0.0004
	ADTPL**		0.0001	0.0684
	Sample Size		99	
	Log Likelihood		272.0502	

* PO means protected-only; PPLT means protected/permissive left turn.
**ADTPL means average daily traffic volume per lane.

To further examine the difference in safety impacts between the lead-lag and lead-lead sequences, accident frequency models were developed individually for the intersections under two different signal control modes, i.e., PO and PPLT modes. Tables 49 and 50 show the modeling results for the intersections with PO and PPLT modes, respectively.

Table 49: Results of LT Accident Frequency Model for Intersections with PO Mode

Model			Negative Binomial-Dependent Variable: Left-Turn–Related Accidents	
	Variables		Estimated Coefficients	p-Value
Regression Results	Constant		–1.2716	0.064
	Sequence	Lag-Lag	0.7701	0.0702
		Lead-Lag	–0.3751	0.103
		Lead-Lead (Reference)	0	.
	No. of Lanes		0.13	0.0008
	ADTPL		0.0003	0.0024
	Sample Size		63	
	Log Likelihood		137.3673	

Table 50: Results of LT Accident Frequency Model for Intersections with PPLT Mode

Model			Negative Binomial-Dependent Variable: Left-Turn–Related Accidents	
	Variables		Estimated Coefficients	p-Value
Regression Results	Constant		–0.0429	0.9604
	Sequence	Lead-Lag	0.4509	0.2003
		Lead-Lead (Reference)	0	.
	No. of Lanes		0.1182	0.1443
	Sample Size		36	
	Log Likelihood		137.8485	

From Table 49, it can be seen that, *lead-lag is safer than lead-lead under PO mode at a confidence level of approximately 90 percent.* This can be explained by the fact that the intersections warranted for PO mode generally have more left-turn traffic or opposing through traffic. Under this situation, left-turn lane overflow or blockage problems may occur. Using lead-lag could allow vehicles in both the left-turn lane and through lanes to move simultaneously so that the accident risk caused by left-turn lane overflow or blockage problems is reduced.

Table 50 presents the accident frequency model developed for intersections with PPLT mode. The positive coefficient of lead-lag phasing indicates that lead-lag sequence is more risky than lead-lead sequence under PPLT mode. This result is consistent with the results of the conflicts study presented in section 5.1. The result may be due to the following facts:

1. Yellow trap problem: This problem arises when lead-lag phasing is implemented with PPLT control mode. Typically, a left-turn driver in the direction of the leading phase will expect to complete the turn during the yellow or all-red phase if necessary. However, with the lead-lag phasing, traffic in the direction of the lagging phase will not stop at the end of this driver's permissive phase. Thus, the vehicle that makes a left turn during the yellow phase may crash into the through traffic in the direction of the lagging protected phase (see Figure 43). Arlington phasing is used in some of the intersections in Austin to eliminate the yellow trap situation by allowing a continued permissive left turn during the opposite approach's lagging protected left-turn phase (see Figure 43). However, for intersections without Arlington phasing, this problem may still exit.
2. Lagging phase in PPLT mode causes confusion: By carefully examining accident reports (the detailed accident causes might be documented in some of the reports, even though there are very few), it is found that there are some drivers in the lagging approach of intersections with PPLT control mode and lead-lag sequence that run the permissive green ball without yielding to opposing traffic. In the records, three of them defended their behavior saying that they saw the adjacent through traffic was moving; by default they thought that they could move without any red light. This finding further showed that the lagging phase in PPLT control mode could cause driver confusion, thereby increasing the accident risk at the intersections.
3. More permissive left turns during the lagging phase: Under lead-lead sequence, a bigger portion of the left-turn vehicles make left turns during the protected phase, which reduces the accident risk associated with making permissive left turns. A study conducted by Hummer et al. (1991) shows that, for PPLT intersections, the lagging phase had significantly more left-turn movements completed under the permissive phase, compared to the leading phase (56 percent versus 44 percent).
4. Driver acceptance: According to a survey conducted by Hummer et al. (1991), leading sequence was preferred by 248 respondents, lagging sequence was preferred by 59

respondents, and 95 respondents expressed no preference for either of them. Therefore, leading sequence is preferred by most drivers.

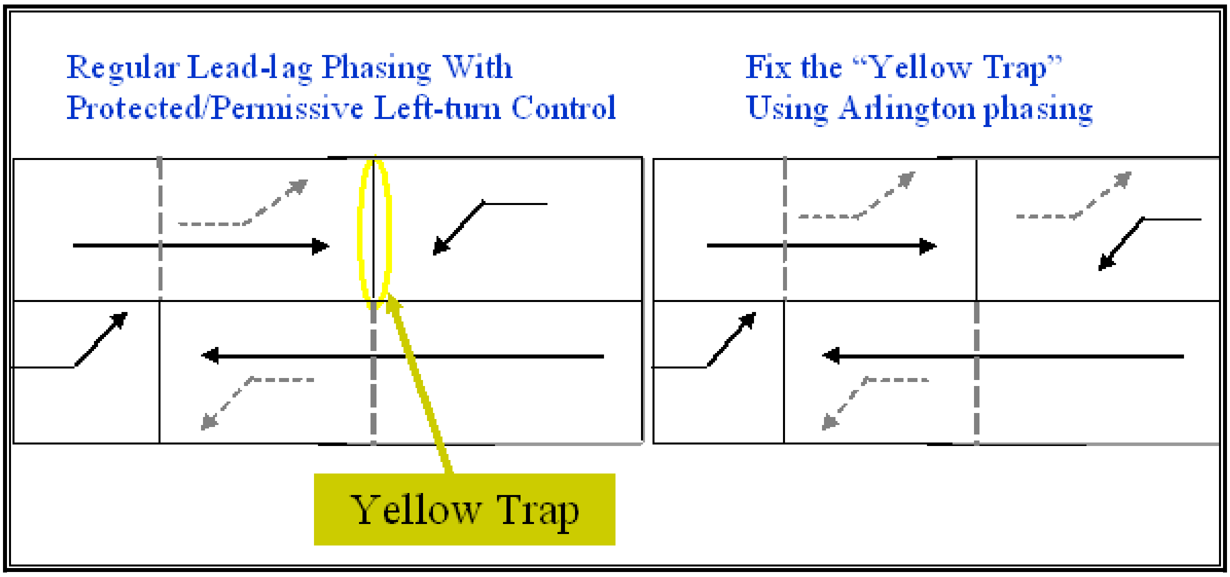


Figure 43: Yellow Trap Problem and Arlington Phasing

However, since the confidence level for the difference between lead-lead and lead-lag is relative low (around 80 percent), further investigation of the effects of left-turn sequence on intersection safety under different left-turn volume conditions is needed. For this purpose, 13 Houston and Austin intersections with PPLT control mode were selected for further investigation because detailed left-turn volume information at these intersections was available. Left-turn–related accident frequency versus left-turn volume for lead-lead and lead-lag sequences are plotted in Figure 44. The left-turn volume is the maximum left-turn volume of the pair of approaches to an intersection. Based on the plots in Figure 44, the performance of the lead-lead and lead-lag sequence can be compared to determine whether the signal phasing sequence had different impacts on intersection safety at different left-turn volume conditions. It was found that: (1) at low left-turn volume levels (less than about 150 vehicles/hr), lead-lead sequence results in lower left-turn accident frequency than lead-lag sequence; and (2) at high left-turn volume levels (more than 150 vehicles/hr), lead-lag sequence becomes safer than lead-lead sequence. This result can be explained by the following possible reasons:

- When the left-turn volume is high, not all the left-turn vehicles in the queue can be served during the protected phase. Thus, under the lead-lead sequence, the remaining left-turn vehicles at the leading approach tend to enter the intersection immediately after the yellow arrow signal has ceased as if they still have the right-of-way. These “time stealers” then risk conflicting with oncoming vehicles that have just received the green ball signal (Hummer et al. 1991). Therefore, when the left-turn volume reaches a certain level, leading phasing is associated with higher accident risk than lagging phasing.

- When the volume is high, left-turn lane overflow problems may occur (see Figure 45), which will also contribute to the increase in left-turn–related accidents. This problem can be mitigated by using lead-lag sequence since it allows the left-turn vehicles and the adjacent through vehicles to move together (Qi et al. 2008).

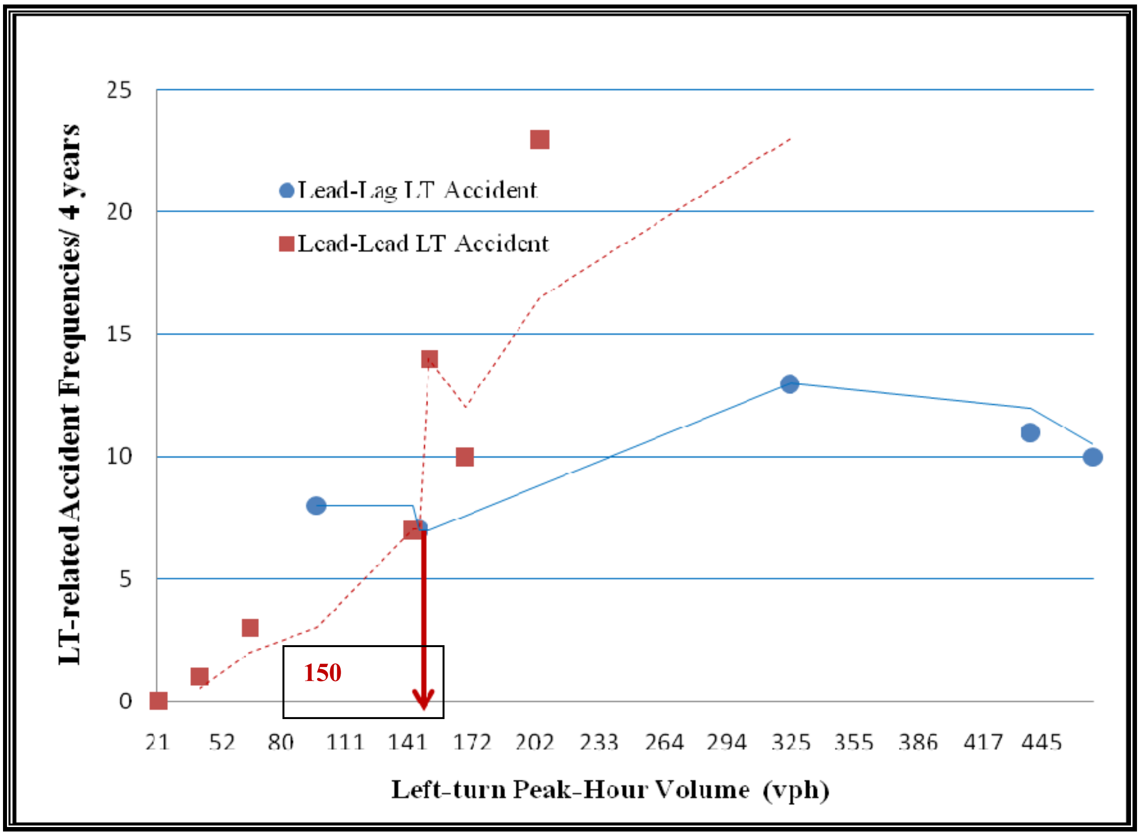


Figure 44: Left-Turn Accident Frequency versus Left-Turn Volume

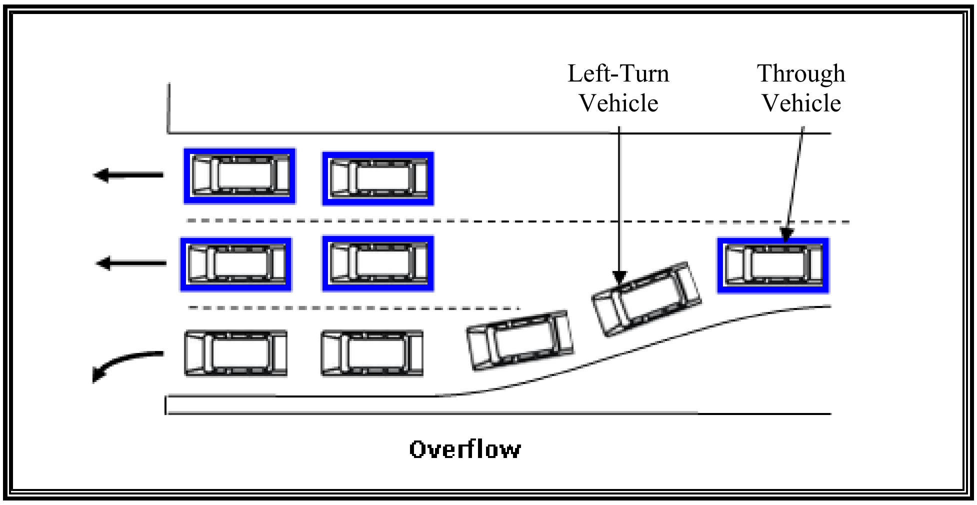


Figure 45: Left-Turn Overflow Due to High Left-Turn Volume

In summary, the results of signal sequence analysis indicate that (1) at low left-turn volume levels (less than about 150 vehicles/hr), lead-lead sequence is safer than lead-lag sequence; (2) at high left-turn volume levels (above about 150 vehicles/hr), lead-lag sequence becomes safer than lead-lead sequence.

5.2.2.3 Safety Impacts of Split Phasing

The data include 37 pairs of approaches to intersections in Austin with lead-lag phase sequence. Only the intersections in Austin have detailed signal timing information for identifying the split phasing, and split phasing must use lead-lag sequence.

Split phasing separates vehicle conflicts by assigning the right-of-way sequentially to the two opposing approaches. It is often used when the intersection geometric layout does not allow two left-turn movements on the opposing approaches to move simultaneously, or on an approach with a shared left/through lane.

Simple Comparison of Accident Rate. Split phasing information is only available for 37 samples with lead-lag sequence, of which only four are split phasing. The small sample size does not allow the regression modeling approach to produce valid results. Therefore, only a simple comparison of accident rates between intersections with and without split phasing was conducted. The comparison results are presented in Figure 46, which shows that the study directions with split phasing have lower LT accident rates and lower total accident rates. Therefore, split phasing improves intersection safety.

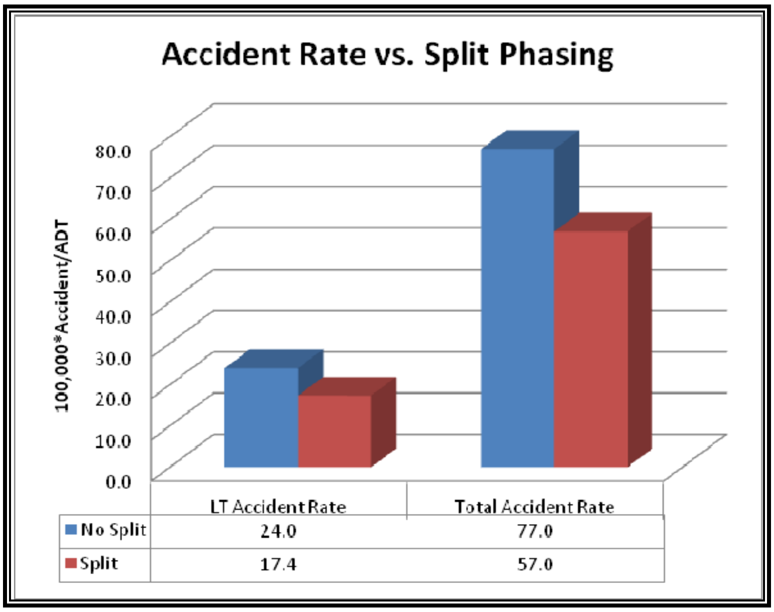


Figure 46: Comparisons of Accident Rates between Intersections with/without Split Phasing

5.2.2.4 Safety Impacts of Left-Turn Signal Display

The data include 44 pairs of approaches to intersections in Houston. The detailed signal display information was collected for Houston intersections through the field survey, and the studied intersections in Austin use very consistent signal display (all studied intersections used horizontal signal face arrangement, and all PO intersections used exclusive signal heads and green arrow indications).

Simple Comparison of Accident Rate. Since the indication for left-turn permissive phase is a green ball for all the study intersections, the only feature that can be studied is left-turn signal arrangement. The arrangement of the signal display is generally categorized as horizontal, vertical, and doghouse. In this study, only two types of arrangements are observed for the studied intersections: horizontal (H) and doghouse (D). Figure 47 illustrates the average LT and total accident rates for these two types of display arrangements. It was found that "D," i.e., doghouse arrangement, is related to much fewer accidents than "H," i.e., horizontal arrangement.

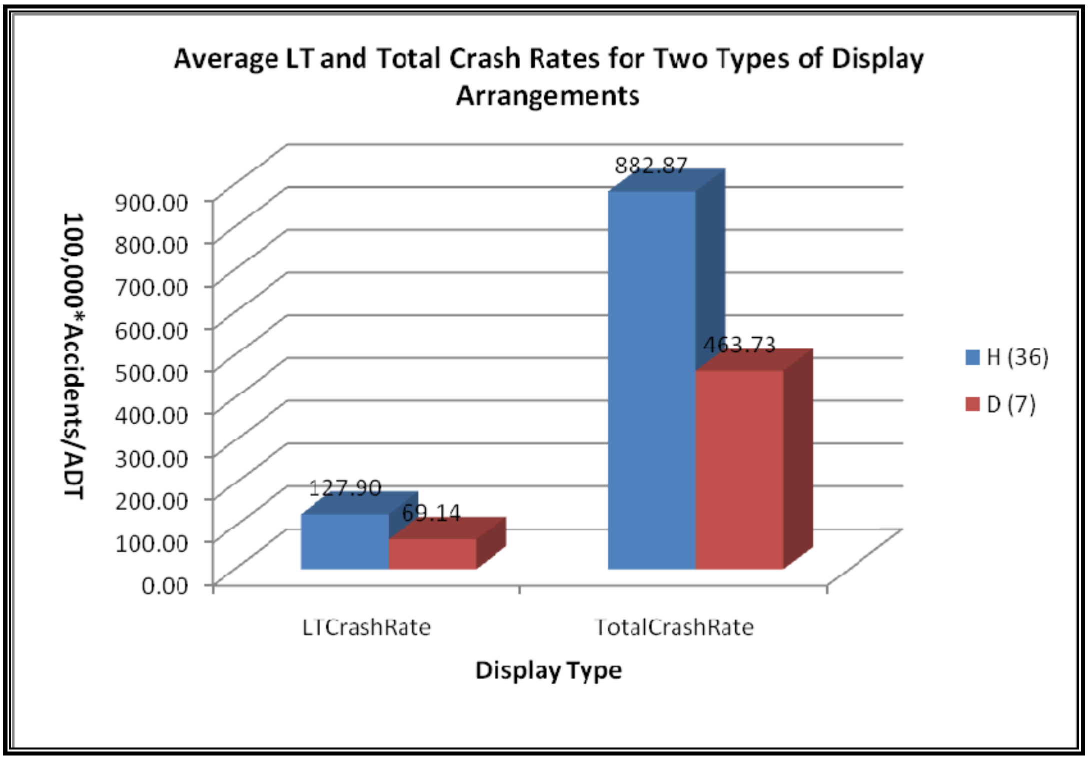


Figure 47: Comparisons of Accident Rates between Horizontal and Doghouse Arrangements

Accident Frequency Modeling Results. Table 51 presents the modeling results and also shows that the doghouse arrangement outperforms horizontal arrangement significantly (a positive parameter of D with p-value approximately equal to 0.05) in terms of safety.

Table 51: Results of LT Accident Frequency Model for Assessing the Impacts of LT Signal Display

Model			Negative Binomial-Dependent Variable: Left-Turn–Related Accidents	
	Variables		Estimated Coefficients	p-Value
Regression Result	Constant		–1.5566	0.0354
	Display	Doghouse	–0.8294	0.0508
		Horizontal (Reference)	0	.
	ADTPL		0.0095	<0.0001
	Sample Size		44	
	Log Likelihood		357.8439	

5.3 BEFORE-AND-AFTER STUDY

Seven intersections that have experienced changes in left-turn signal phasing (treatments) during the past 3 to 4 years were selected for the before-and-after study. The empirical Bayes (EB) method was applied in this study. This method was formulated by Hauer (1997) and is the approach for before-and-after evaluation that directly addresses the regression to the mean problem (Hauer et al. 2002). The theory of the EB method is well developed and is now used in the Interactive Highway Safety Design Model (IHSDM) and the Comprehensive Highway Safety Improvement Model (CHSIM). The distinct features of the EB method are as follows:

- The EB method attempts to account for the effects of time trends.
- The EB method attempts to account for the selection bias in the choice of the treatment intersections.
- The EB method increases the precision of estimates beyond what is possible when one is limited to the use of a 2- to 3-year history of accidents.
- The EB method corrects for the regression-to-mean bias.

The EB method is described below, followed by the evaluation results.

5.3.1 Methodology

The basic idea of the EB method is that the changes in accident rate may be due to random factors or contributing factors other than the treatments (the changes in signal phasing in this study). Therefore, in order to assess the true effects of the treatments, the expected number of accidents that occurred during the after treatment period in the absence of treatment will be estimated and compared with the actually observed number of accidents that occurred during the after treatment period. If the expected accident number is less than the actually observed number, the treatment is effective; otherwise, it is ineffective or even adversely affects the intersection safety.

To conduct the EB method, a reference group of samples should be selected to model the relationship between accident frequency and explanatory variables (intersection signal control, geometric, and traffic volume conditions). The reference group selected in this study consists of the samples for sequence impact analysis (99 pairs of intersection approaches) used in the cross-sectional study. The accident frequency model has been developed, and the estimated modeling results are presented in Table 47.

The developed model is then used to predict the number of accidents that would have occurred at the intersections in the after treatment period if no treatment had been made, which is denoted by π_i in Table 52. The equation to estimate π_i is expressed as:

$$\pi_i = E\{k|K\}_i = \alpha E\{k\}_i + (1-\alpha)K_i \tag{17}$$

where K_i represents the observed number of accidents during the before treatment period for a particular intersection approach pair *i*. $E\{k\}_i$ is the expected accident rate from regression modeling. α denotes the weight of $E\{k\}_i$, which can be estimated by the following equation:

$$\alpha = \frac{1}{1+d \times E\{k\}_i \times Y} \tag{18}$$

where d is the overdispersion parameter of the negative binomial regression model and Y is the number of years of available accident records before the treatment implemented for the study intersection.

From Equations (17) and (18), it can seen that, as more years of before treatment data are used, more weight is given to the actual accident rate and less weight is given to the expected accident rate from regression modeling.

The odds ratio θ_{ci} in Table 52, which is used to indicate the accident reduction effectiveness, could then be obtained by the equation:

$$\theta_i = L_i / \pi_i \tag{19}$$

where L_i is the observed accident counts during the after treatment period.

- When θ_i < 1, the accident frequency has decreased, and the treatment appears to be effective.
- When θ_i > 1, the accident frequency has increased, and the treatment appears to be adverse to safety.

To understand the whole procedure of using the EB method for the before-and-after study, a worksheet was developed and is presented in Table 52.

Table 52: Worksheet for Before-and-After Study Using Empirical Bayes Method

Site Number	Treatment Directions of Study Intersections			Observed Reduction Effectiveness
	Number of Accidents during Before Treatment Period	Expected Number of Accidents during After Treatment Period in the Absence of Treatment	Observed Number of Accidents during After Treatment Period	Odds Ratio
1	K_1	π_1	L_1	θ_1
2	K_2	π_2	L_2	θ_2
3	K_3	π_3	L_3	θ_3
4	K_4	π_4	L_4	θ_4
:	⋮	⋮	⋮	⋮
:	⋮	⋮	⋮	⋮
:	⋮	⋮	⋮	⋮
n	K_n	π_n	L_n	θ_n

5.3.2 Evaluation Results

The seven intersections used in this before-and-after study are listed in Table 53. Among them, the left-turn signal modes of five intersections in Lufkin were changed from PO to PPLT, and the signal sequences of another two intersections with PO mode in Austin were changed from lag-lag to lead-lead.

Table 53 presents the before-and-after evaluation results for these seven intersections by using the EB method. Based on the value of overall treatment effectiveness (overall odds ratio) for each type of treatment, *it can be concluded that the treatment change from PO to PPLT is adverse to safety (overall odds ratio > 1) and the treatment from lag-lag to lead-lead is effective* *in terms of safety (overall odds ratio < 1).* These conclusions agree with the ones drawn from the cross-sectional study.

Table 53: Before-and-After Study Intersections

Intersections	City	No. of Lanes (Direction)	No. of Lanes (Intersection)	Speed	Average ADT	ADTPL
Loop 287 and SH 103	Lufkin	8	16	50	16715	2089.4
Timberland and Akinson	Lufkin	6	12	37.5	17070	2845.0
Timberland and Paul	Lufkin	6	10	35	17070	2845.0
Timberland and Lufkin	Lufkin	7	13	37.5	23000	3285.7
Timberland and Denman	Lufkin	8	14	40	20070	2508.8
US 183 and Park	Austin	8	12	45	47290	5911.3
US 183 and Walton Way	Austin	8	12	40	35660	4457.5

Table 54: Evaluation Results from the Empirical Bayes Method in Before-and-After Study

Treatment Type	Intersection Name	Before Period Duration (Year)	After Period Duration (Year)	Observed LT Accident Frequency during Before Period	Expected LT Accident Frequency from Regression Model	Weight	Expected LT Accident Frequency during After Period in the Absence of Treatment	Observed LT Accident Frequency during After Period	Odds Ratio
PO changed to PPLT	Loop 287 and SH 103, Lufkin	3.35	0.39	0.6	0.84	0.38	0.69	0.30	***0.43***
	Timberland and Atkinson, Lufkin	1.82	1.90	0	2.35	0.29	0.68	1.10	***1.62***
	Timberland and Paul, Lufkin	1.82	1.90	0	2.43	0.28	0.68	1.10	***1.61***
	Timberland and Lufkin, Lufkin	1.82	1.90	0	3.77	0.20	0.76	1.10	***1.45***
	Timberland and Denman, Lufkin	1.82	1.90	0.55	3.06	0.24	1.14	1.64	***1.44***
	Overall Treatment Effectiveness	**1.32**							
Lag-lag changed to lead-lead	US 183 at Park, Austin	0.54	2.63	0	4.18	0.53	2.22	1.9	***0.86***
	US 183 at Walton Way, Austin	1.84	1.32	0.54	9.83	0.12	1.68	0.00	***0***
	Overall Treatment Effectiveness	**0.49**							

5.4 SUMMARY

Table 55 summarizes the findings from the three types of safety studies introduced in the previous sections. The level of safety performance is ranked by the numbers 1 to 3, with "1" representing the safest signal phasing/display treatment and "3" representing the most dangerous one.

Table 55: Summary of the Findings from the Safety Impacts Studies

Left-Turn Signal Design Elements	Safety Performance Levels (High →Low)		
	1st	**2nd**	**3rd**
Mode	PO	Permissive	PPLT
Sequence	***Under PO Mode***		
	Lead-lag	Lead-lead	Lag-lag
	Under PPLT Mode (LT Volume < 150)		
	Lead-lead	Lag-lag	Lead-lag
	Under PPLT Mode (LT Volume >150)		
	Lead-lag	Lead-lead	
Display	Doghouse	Horizontal	
Split Phasing	With split phasing	Without split Phasing	

CHAPTER 6: OPERATIONAL IMPACT ANALYSIS

The purpose of this chapter is to analyze the operational impacts of different left-turn signal phasing treatments at signalized intersections. Two critical issues are investigated: (1) the operational impacts of left-turn signal control modes, with emphasis on the selection between protected-only and protected/permissive left-turn control modes; and (2) the operational impacts of left-turn signal phasing sequences, i.e., lead-lead, lead-lag, lag-lead, and lag-lag. For the impacts of signal phasing sequences, the performance of an intersection using different signal phasing sequences and under different left-turn volume conditions was analyzed by traffic simulation. Then, recommendations on the selection of signal control modes and phasing sequences were provided based on the analysis results.

In the following sections, after describing how the study intersections were selected, this report presents the details of model development in the traffic simulation model, VISSIM®[2]. Then, the operational performances of different types of signal control modes and phasing sequences are analyzed based on the simulation results. Finally, conclusions are drawn.

6.1 SELECTION OF STUDY INTERSECTIONS

As mentioned in Chapter 4, field data were collected at 17 intersections with PPLT control mode and 8 intersections with PO control mode. Various data were collected at each study intersection, including traffic video data, intersection geometric layout, signal timing plan, and GPS data collected by probe vehicles. These data were used for simulating the operations of the study intersections. However, since traffic simulation takes a great deal of time and effort in model development, calibration, and multiple simulation runs, it is unaffordable to simulate the operations of all 25 studied intersections. Therefore, only a subset of studied intersections, including six intersections with PPLT control mode and three intersections with PO control mode, were selected for conducting the operational impacts study.

To select the study intersections with PPLT control mode, the following criteria were used; information about the selected intersections is presented in Table 56:

- cover different sequences of left-turn signal phasing,
- have a detailed signal-timing plan,

[2] PTV AG

- observe significant left-turn delays at the subject direction, and
- observe a high number of potential conflicts or "difficult-to-make-turn" events at the intersection.

Table 56: Six Selected Study Intersections with PPLT Control Mode

ID	Name	Location	Subject Direction	Sequence	LT Delay (s/Mile)	Number of Potential Conflicts	Difficult-to-Turn Events
1	Loop 360 @ Stonelake	Austin	EB	Lead-lead	346.05	46	22
5	Lamar @ Koenig	Austin	NB	Lead-lag	347.28	8	16
7	51st @ Airport	Austin	NB	Lead-lag	1002.27	1	0
8	Braker @ Metric	Austin	NB	Lag-lead	327.84	25	5
9	Lamar @ 29th	Austin	WB	Lead-lead	720.06	19	0
14	FM 528 @ San Joaquin	Houston	SB	Lead-lead	57.92	15	2

To select study intersections with PO control mode, the following criteria were used; information about the selected intersections is presented in Table 57:

- cover different sequences of left-turn signal phasing,
- have a detailed signal-timing plan,
- observe significant left-turn delays at the subject direction, and
- observe a high number of sneakers (vehicles that make turns when the yellow light is on).

Table 57: Three Study Intersections with PO

ID	Name	Location	Subject Direction	Sequence	LT Delay (s/Mile)	Number of Sneakers
3	Congress @ William Cannon	Austin	SB	Lag-lead	454.51	7
15	FM 518 @ Reid	Houston	WB	Lead-lag	328.33	7
16	FM 518 @ Dixle Farm	Houston	EB	Lead-lead	319.35	6

6.2 MODEL DEVELOPMENT IN VISSIM

A microscopic simulation model, VISSIM (version 4.2), was used for simulating the operations of the study intersections under different signal phasing control conditions. For each selected study intersection, a three-intersection network was developed in a VISSIM simulation model to estimate the operational impacts at both the intersection level and the network level. The developed network included the study intersection (at the middle of the network), an upstream intersection, and a downstream intersection (at the signal coordination direction or the major road direction).

6.2.1 Coding and Inputs

VISSIM is a microscopic, time-step, and behavior-based simulation model developed to model urban traffic and public transit operations. Unlike other typical simulation models that are based on link-node structures, VISSIM uses link-connector topology to code the network, which provides users more flexibility in modeling various geometric and traffic conditions, such as setting vehicle paths within an intersection. However, coding in VISSIM takes more time and effort than other simulation models.

Modeling Procedure

The first step is to develop geometric components on the background graphic of the study intersection, which should be done by importing a background map with specified scaling. This step needs to draw "links" (the roads), set up "connectors" (the turn movement paths at the middle of the intersection area), and define "speed distribution" (control of the speed range of vehicles running in the network). The next step is to use one type of signal state generators (SSG) in VISSIM, i.e., National Electrical Manufacturers Association (NEMA) standard editor, to code signal timing for each intersection in the network. After signal control is coded, the placement of a signal head needs to be set on every link. The final step is to input traffic information for the whole network, including the volume of each link, volume of each route, percentage of heavy vehicles, speed of each type of vehicle, etc. The whole procedure of coding and inputs in VISSIM can be summarized as follows:

- Geometric components:
    - scaling
    - links
    - connectors
    - speed distribution
- Traffic signal:
    - NEMA standard editor to code signal timing plan
    - placement of each signal head
- Traffic information:
    - volume of each link
    - volume of each route
    - percentage of heavy vehicles
    - speed of each type of vehicle

6.2.2 Model Calibration

After inputting and coding the study intersections in the VISSIM simulation model, model calibration was necessary to ensure that the baseline scenario correctly represented the real-world traffic conditions in the field. In fact, model calibration was the most critical step in the simulation-based study, and it provided the basis for modeling the alternative mode scenarios and for further analyzing the simulation.

The VISSIM model provided a comprehensive set of measures for model calibration, such as average speed, queue length, and travel times/delays. In this study, travel time was selected as the calibration measure because intersection delay is a main measure of effectiveness for evaluating the intersection's operational performance, and it is can be derived from travel time. In the calibration, the average travel time of the subject left-turn movement and its opposing through movement derived from the traffic simulation was compared with travel times collected by the probe vehicles in the field. If significant discrepancies were observed, the values of some driver behavior parameters and other default input parameters were adjusted to bring the simulation results close to the data collected in the field. The calibration was done mainly by adjusting the following two settings of the VISSIM model: "reduced speed areas" and "priority rules."

The term "reduced speed areas" refers to a short section of the road where the vehicle's speed is reduced temporarily. Due to complicated traffic situations and the turning movements at intersections, vehicles decelerate to a speed lower than the free-flow speed or the posted speed limit when they pass through the intersection. Therefore, "reduced speed areas" was set on the connectors in the intersection area, and a desired speed reduction range was defined. The real speed data of probe vehicles collected by GPS devices were used for setting the reduced speed area. The length of the reduced speed areas and the desired speed distribution were adjusted by observing the recorded traffic video from the study sites.

The effect of "priority rules" in VISSIM is similar to a yield sign in the real world. "Priority rules" must be set for intersections using PPLT signal control mode, which forces left-turn vehicles to yield to opposing through vehicles in the permissive left-turn phase. A priority rule consists of two components: (1) a stop line at the left-turn path; and (2) a conflict distance at the opposing through path, which is the distance to the conflict point. If an opposing through vehicle is within the conflict distance, the left-turn vehicle cannot make a turn and must yield to the through vehicle. To set the priority rule, two parameters must be set: minimum distance headway and minimum gap time. Both parameters specify when the left-turn vehicle can find an appropriate gap in the opposing traffic and safely make a permissive left turn. The minimum distance headway is set up according to the width of the intersection and the average speed of the opposing through vehicles that pass through the intersection. As a rule of thumb, a wide intersection and a high speed of opposing through movement require a long minimum headway. Calibrating the minimum gap time at an intersection is a time-consuming procedure, which consists of the following steps: First, observe the recorded traffic video to examine the behavior of the left-turn vehicles at the study site. Then, set an initial value of minimum gap time. Observe the simulation animation using different random seeds to check for the following two types of events: (1) observable "conflicts" between the left-turn vehicle and opposing through vehicles, and (2) left-turn vehicles not making the turn even if a large gap is available in the opposing traffic. If the first event is observed, increase the value of the minimum gap; if the second event is observed, decrease the value of the minimum gap. Otherwise, the minimum gap is appropriately set. This procedure may go through several iterations for model calibration. The calibration results of these nine intersections are summarized in Table 58.

From the results in Table 58, it can be seen that the travel times derived from the traffic simulation models (for both the subject left-turn movements and the opposing through movements) are very close to the travel time data collected from the field for all study intersections, which indicates that the simulation models are well calibrated and ready for analyzing the operational performance of these intersections.

Table 58: Model Calibration Comparison Results

ID	Name	Location	Subject Direction	Mode and Sequence	Travel Times (s)			
					Left-Turn Movement		Opposing Through Movement	
					VISSIM	GPS	VISSIM	GPS
1	Loop 360 @ Stonelake	Austin	EB	PPLT lead-lead	50.90	52.89	85.00	83.19
7	51st @ Airport	Austin	NB	PPLT lead-lag	54.40	58.88	73.00	75.54
8	Braker @ Metric	Austin	NB	PPLT lag-lead	115.90	115.18	131.20	129.45
14	FM 528 @ San Joaquin	Houston	SB	PPLT lead-lead	36.90	35.33	56.20	56.41
3	Congress @ William Cannon	Austin	SB	PO lag-lead	95.50	98.90	60.20	63.40
5	Lamar @ Koenig	Austin	NB	PPLT lead-lag	82.90	87.80	67.00	67.80
9	Lamar @ 29th	Austin	WB	PPLT lead-lead	60.50	61.10	81.30	84.70
15	FM 518 @ Reid	Houston	WB	PO lead-lag	119.5	123.6	49.80	51.60
16	FM 518 @ Dixle Farm	Houston	EB	PO lead-lead	121.5	122.1	151.60	154.80

6.2.3 Model Runs and Outputs

Since VISSIM is a microscopic simulation model, once the model calibration was completed, the traffic simulation needed to be run multiple times to take into account randomness in the simulation results. In this study, 30 runs with 30 different random seeds were conducted. Each simulation lasted 5400 s, and simulation results from 1800 s to 5400 s were used for the analysis. For analyzing the operational performance of the study intersections, the average traffic delays of the subject left-turn movements and its opposing through movements were derived from the simulation outputs. For analyzing network-wide performance, the following MOE was derived: network throughputs (total number of vehicles that finished their trip during the simulation time period), average vehicle speed, and average delay.

6.3 ANALYSIS OF THE OPERATIONAL IMPACTS OF SIGNAL CONTROL MODE

According to the literature review in Chapter 2, traffic volume is a critical criterion in the determination of the signal control mode for an intersection. Most of the existing warrants for PO or PPLT mode are based on left-turn volume or the cross product of left turns and its opposing through volumes (Agent and Deen 1979, City of San Diego 2006, Cottrell 1986, ITE 1991, Lalani et al. 1986, Roess et al. 2004, Stamatiadis et al. 1997, Upchurch 1986). In this study, emphasis is put on selection between PO and PPLT signal control modes. Therefore, the operational performance of the same intersection under PO and PPLT control modes was compared, and the delay difference between these two signal control modes under different traffic volume conditions was analyzed.

For this purpose, two traffic simulation scenarios were developed: (1) baseline scenario, using the existing signal control mode for the study intersection; and (2) alternative scenario, changing the signal control mode of the study intersection from PPLT to PO, or from PO to PPLT. Note that, for the baseline scenario, the signal control mode and signal phasing sequence are the same as the existing conditions. However, considering that the existing signal time plan was developed before this study and the traffic condition has changed since then, the phase splits (the amount of green time allocated to different phases) needed to be updated. Therefore, the signal timing optimization software, SYNCHRO, was used for optimizing the signal phase splits based on the intersection traffic volume data collected in the field studies. For the alternative scenario, after changing the signal control mode, the signal phase splits were also updated using SYNCHRO.

6.3.1 Information about the Study Intersection Approaches

For each study intersection, the performance of two left-turn movements at the subject direction and its opposing direction was evaluated based on the VISSIM simulation results. The geometric condition and traffic volume information of these approaches to the study intersections are summarized in Table 59. Note that, in Table 59, "(s)" indicates the subject direction and "(o)" indicates the opposing direction. For example, "16(s)" is the subject direction of intersection number 16. The distributions of the left-turn volume and CPOV of these intersections are presented in Figure 48. From Figure 48, it can be seen that the traffic volumes at these intersections are not evenly distributed, and there are some ranges (especially the high-volume parts) that were not covered by the traffic volumes at these study intersections. Since this study was designed to analyze the operational impacts of the signal control mode under different traffic volume conditions and since one major advantage of the simulation-based method is having control of the simulation network, five supplemental intersections were added to this study. These five new intersections were developed based on study intersection numbers 8 and 9. For intersection number 8, the volume of all approaches was multiplied by 1.2 and 1.5 to become two new intersections whose identifications are 8_1.2 and 8_1.5, respectively. For intersection number 9, the volume of all approaches was multiplied by 1.2, 2.1, and 2.2 to create three new intersections whose identifications are 9_1.2, 9_2.1, and 9_2.2, respectively. The information for these five supplemental intersections is also listed in Table 59. There are 13 total intersections used for this study, of which 9 are original intersections and 5 are supplemental intersections. The volume distributions of these 13 intersections are presented in Figure 48 as well. From Figure 48, it can see that the holes in the original data are filled by the supplemental intersections.

Table 59: Basic Information of Study Intersection Approaches

ID (Direction)		Number of Lanes		Volume		
		Left Turn	Opposing Through	Left Turn	Opposing Through	CPOV
Original Intersections	14(o)	1	2	20	1175	11750
	14(s)	1	2	114	870	49590
	15(o)	1	2	33	669	11039
	15(s)	1	2	135	639	43133
	16(o)	1	2	118	405	23895
	16(s)	1	2	153	737	56381
	3(s)	1	1	98	313	30674
	5(o)	1	2	45	530	11925
	5(s)	1	2	111	717	39794
	7(o)	1	2	74	765	28305
	7(s)	1	2	90	990	44550
	8(o)	1	2	195	260	25350
	8(s)	1	2	40	315	6300
	9(o)	1	2	84	130	10920
	9(s)	1	2	70	176	12320
Supplemental Intersections	8_1.3(o)	1	2	254	338	42842
	8_1.3(s)	1	2	52	410	10647
	8_1.5(o)	1	2	293	390	57038
	8_1.5(s)	1	2	60	473	14175
	9_1.2(o)	1	1	101	156	15725
	9_1.2(s)	1	1	84	211	17741
	9_2.1(o)	1	1	176	273	48157
	9_2.1(s)	1	1	147	370	54331
	9_2.2(o)	1	1	185	286	52853
	9_2.2(s)	1	1	154	387	59629

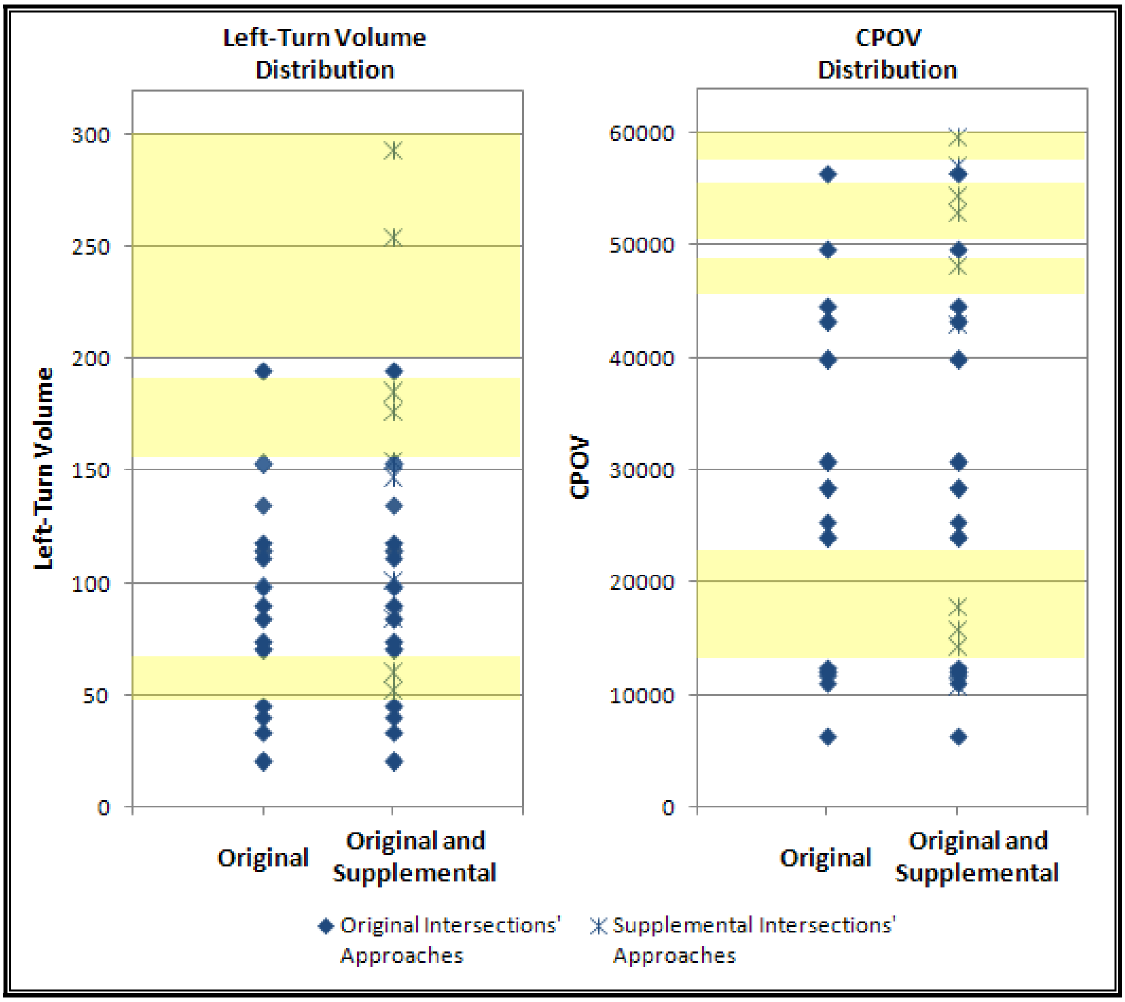


Figure 48: Volume Distribution of Study Intersections' Approaches

6.3.2 Intersection-Level Operational Analysis

In this study, left-turn delay is the major MOE used for assessing the operational performance of the intersections with different left-turn signal control modes, i.e., PO and PPLT modes. This is because the operation of the through movements is not significantly affected by the left-turn signal control modes according to the simulation results. The average left-turn delay for intersections with PO and PPLT modes are derived from the simulation results and are summarized in Table 60.

Table 60: Comparison of Study Intersection Performance between PO and PPLT

ID (Direction)		Volume		Left-Turn Delay		
		Left Turn	CPOV	PO	PPLT	Reduction %
Original Intersections	14(o)	20	11750	40.58	28.37	**30.09%**
	14(s)	114	49590	36.88	18.79	**49.04%**
	15(o)	33	11039	20.93	14.57	**30.38%**
	15(s)	135	43133	31.02	17.15	**44.71%**
	16(o)	118	23895	30.69	15.40	**49.80%**
	16(s)	153	56381	32.32	19.29	**40.31%**
	3(s)	98	30674	49.75	31.30	**37.08%**
	5(o)	45	11925	57.33	36.37	**36.57%**
	5(s)	111	39794	57.53	32.73	**43.11%**
	7(o)	74	28305	70.64	35.91	**49.16%**
	7(s)	90	44550	72.23	38.92	**46.12%**
	8(o)	195	25350	159.61	82.24	**48.47%**
	8(s)	40	6300	27.33	16.92	**38.07%**
	9(o)	84	10920	60.72	36.50	**39.88%**
	9(s)	70	12320	62.22	40.71	**34.57%**
Supplemental Intersections	8_1.3(o)	254	42842	31.72	16.07	**49.33%**
	8_1.3(s)	52	10647	384.73	220.61	**42.66%**
	8_1.5(o)	293	57038	381.93	194.76	**49.01%**
	8_1.5(s)	60	14175	28.42	16.82	**40.84%**
	9_1.2(o)	101	15725	63.66	37.58	**40.97%**
	9_1.2(s)	84	17741	61.74	39.86	**35.44%**
	9_2.1(o)	176	48157	73.34	37.11	**49.40%**
	9_2.1(s)	147	54331	67.83	37.77	**44.31%**
	9_2.2(o)	185	52853	80.97	40.84	**49.56%**
	9_2.2(s)	154	59629	64.71	37.16	**42.58%**

In Table 60, for all intersection approaches, left-turn delay was reduced significantly (from 30 percent to 50 percent). "The Delay Reduction %" in Table 60 was calculated by the following equation:

$$Reduction\ (\%) = (D_{PO} - D_{PPLT}) / D_{PO} * 100\% \qquad (20)$$

where D_{PO} is the left-turn delay of PO mode and D_{PPLT} is the left-turn delay of PPLT mode.

Left-Turn Delay Reduction versus Left-Turn Volume

According to the results listed in Table 60, the left-turn delay reduction and left-turn volume of the approaches to study intersections are plotted in Figure 49 and fitted by a tendency curve.

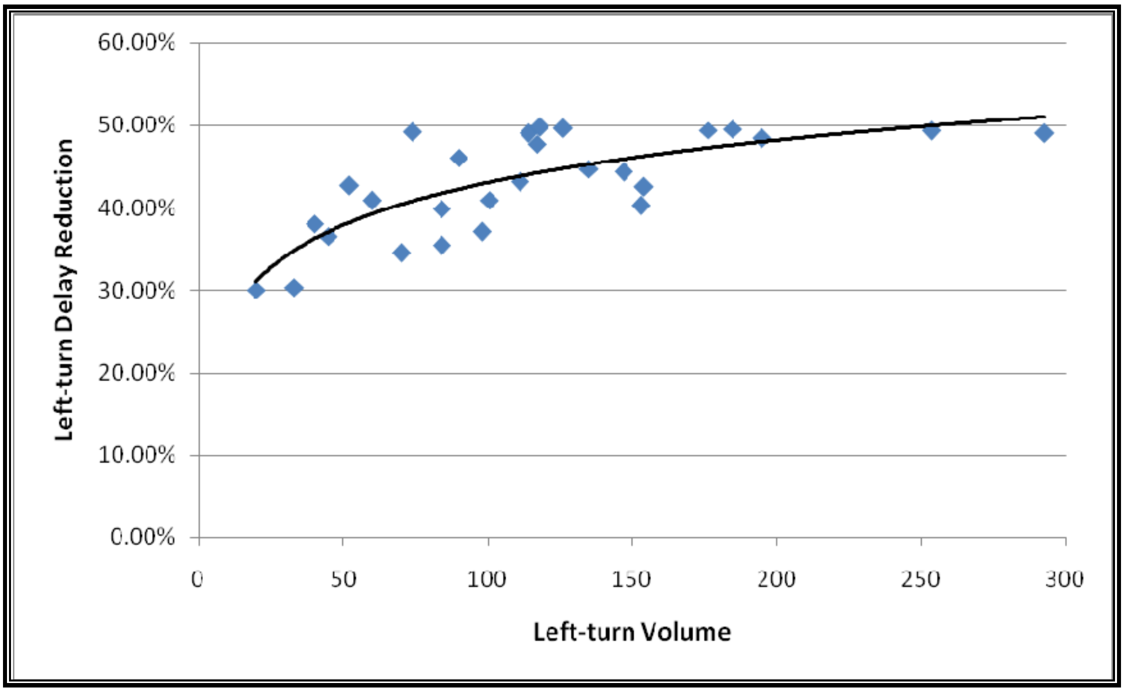


Figure 49: Plot of Left-Turn Delay Reduction versus Left-Turn Volume

From Figure 49, it can be seen that left-turn delay reduction increases with the increase of left-turn volume. The left-turn delay reduction increases rapidly when the left-turn volume is relative low and will stop increasing after the left-turn volume reaches a certain level. This is a reasonable result and can be explained as follows. Generally, PPLT mode increases the intersection's left-turn capacity by allowing vehicles make left turns during the permissive phase. As a result, the average left-turn delay is reduced under PPLT control mode, compared to that under PO mode. In addition, the more left-turn vehicles that use the permissive phase, the more left-turn delay reduction can be achieved. However, the additional capacity provided by the permissive phase is limited and is determined by the available "large" gaps in the opposing traffic. When all the available large gaps (additional capacity) are used by left-turn vehicles, left-turn delay will stop reducing. Therefore, left-turn delay reduction will stop increasing after left-turn volume reaches a certain level.

Left-Turn Delay Reduction versus Volume Cross Product

Based on the simulation results, the relationship between left-turn delay reduction and the cross product of left-turn volume and its opposing volume per lane was investigated. Since the number of lanes in the opposing direction affects vehicles making permissive left turns, the relationships between left-turn delay reductions and CPOVs under the conditions of one opposing lane and two opposing lanes were investigated individually. Based on the simulation results listed in Table 60, the scatter plots of the relationships between left-turn delay reduction and CPOV under both conditions were developed, and they are presented in Figures 50 and 51.

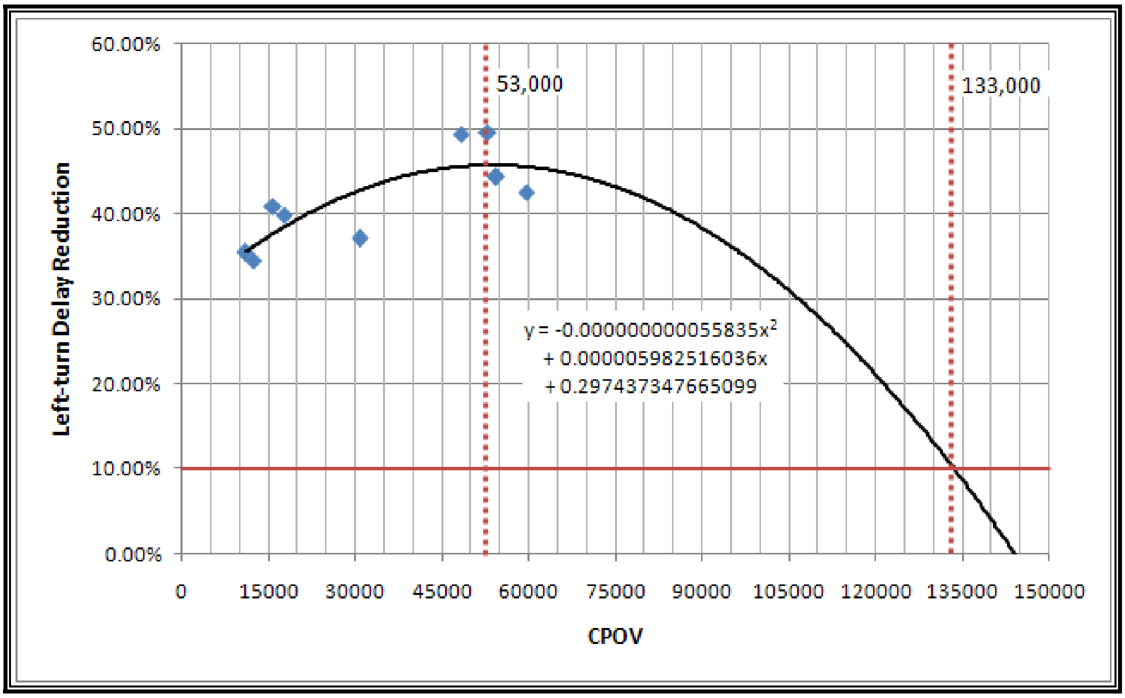


Figure 50: Plot of Left-Turn Delay Reduction versus Volume Cross Product for One Opposing Lane

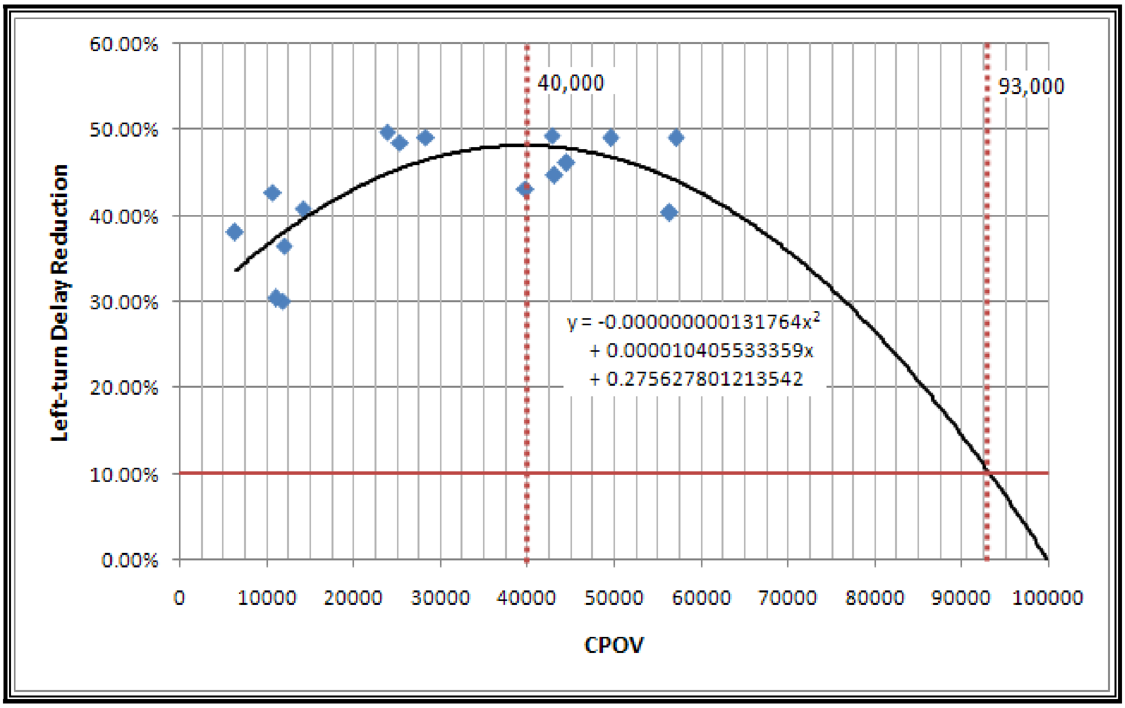


Figure 51: Plot of Left-Turn Delay Reduction versus Volume Cross Product for Two Opposing Lanes

In both Figures 50 and 51, a curve is fitted to the scatter plots, and the same tangency is shown. When CPOV is low, the left-turn delay reduction is low. The left-turn delay reduction increases with the increase of CPOV until it reaches a maximum point. After that, it will decrease with the increase of CPOV. In the one-opposing-lane condition, the maximum left-turn delay reduction occurs when the value of CPOV is about 53,000, and in the two-opposing-lane condition, the left-turn delay reduction reaches its maximum value when the value of CPOV is around 40,000.

These results are reasonable because when CPOV is low, both left-turn and opposing through volumes are low. In this case, under the PPLT control mode, most left-turn vehicles can be served during the protected phase, and the benefit of using PPLT mode, i.e., left-turn delay reduction, is relatively low. With the increase of left-turn volume, more vehicles make left turns during the permissive phase, and the benefits gained by using PPLT mode increase. However, with the increase of opposing traffic volume, the available safe gaps in the opposing traffic decrease, which reduces the capacity provided by the permissive phase. As a result, left-turn delay reduction under PPLT mode is reduced. Therefore, with the increase of CPOV, the benefit of PPLT mode reaches its maximum at a certain CPOV value (referred to as the critical CPOV value), and it decreases afterwards. This result indicates that if the CPOV of an intersection is great than a critical CPOV value, PO mode instead of PPLT mode should be provided, because the operational benefits gained by PPLT mode will become very small, and PPLT mode is more risky than PO mode. To find these critical CPOV values, it is assumed that when the left-turn delay reduction is less than 10 percent, the operational benefits gained by PPLT mode cannot overcome its safety cost. Based on this assumption, the critical CPOVs can be found according to the fitted curves in Figures 50 and 51. It is found that, for the one-opposing-lane condition, the critical CPOV value is 133,000 (Figure 50), and for the two-opposing-lanes condition, the critical CPOV value is 93,000 (Figure 51). This result seems very reasonable for the following two reasons. First, the critical CPOV value for the one-opposing-lane condition (133,000) is greater than that for the two-opposing-lanes condition (93,000). This is because when the volume per opposing through lane is at the same level, it is more difficult to make permissive left turns under the two-opposing-lanes condition compared to doing so under the one-opposing-lane condition. Therefore, for intersections with two opposing lanes, PO mode should be warranted at a lower CPOV level. Second, both critical CPOV values are within a reasonable range. According to the literature, a protected left-turn phase (either PO or PPLT mode) should be provided when the value of CPOV is greater than 50,000 (Agent and Deen 1979, Roess et al. 2004, Stamatiadis et al. 1997, Upchurch 1986). In addition, PPLT mode should not be used when the left-turn volume is more than 300 vph (Stamatiadis et al. 1997) or the opposing volume per lane is greater than 500 vphpl (Cohen and Mekemson 1985). Therefore, the critical value for the selection between PO and PPLT modes should be higher than 50,000 and lower than 150,000. Both of the recommended critical CPOV values are within this range.

6.3.3 Network-Wide Operational Analysis

The network-level performance of the intersections under PO and PPLT control modes was evaluated based on three MOEs derived from simulation outputs: (1) network throughput, the total number of vehicles that finished their trips in 1800 s to 5400 s during the simulation period; (2) average speed; and (3) average delay. The comparison results are listed in Table 61.

Table 61: Comparison of Network-Level Performance between PO and PPLT

ID	Network Throughput			Average Speed (km/hr)			Average Delay (s)		
	PO	PPLT	Diff.	PO	PPLT	Diff.	PO	PPLT	Diff. %
1	3466	3467	0.04%	26.28	27.63	5.13%	66.75	60.53	–9.33%
3	3058	3056	–0.06%	26.87	27.11	0.89%	42.23	41.48	–1.79%
5	3244	3236	–0.22%	31.15	31.82	2.15%	53.37	49.85	–6.59%
7	3000	3011	0.36%	10.40	10.93	5.07%	316.96	300.48	–5.20%
8	3089	3294	6.65%	5.00	6.74	34.84%	613.93	464.58	–24.33%
8_1.3	3193	3627	13.59%	3.80	5.26	38.39%	809.92	623.61	–23.00%
8_1.5	3172	3641	14.79%	3.69	4.91	33.03%	833.79	664.04	–20.36%
9	2739	2768	1.07%	33.94	34.46	1.52%	52.85	50.22	–4.97%
9_1.2	3134	3171	1.19%	33.32	33.96	1.90%	57.33	53.99	–5.83%
9_2.1	4503	4602	2.20%	17.96	18.30	1.89%	216.29	211.47	–2.23%
9_2.2	4579	4715	2.97%	16.90	18.19	7.61%	236.42	212.21	–10.24%
14	2848	2846	–0.06%	47.50	49.45	4.12%	20.90	17.12	–18.11%
15	2363	2367	0.15%	36.21	36.53	0.88%	31.59	29.36	–7.07%
16	2894	2892	–0.05%	34.96	35.53	1.63%	27.87	25.05	–10.12%

"Diff." in Table 61 is the difference of MOE between PPLT and PO modes and is calculated by the following equation:

$$Diff.\ (\%) = (MOE_{PPLT} - MOE_{PO}) / MOE_{PO} * 100\% \quad (21)$$

where MOE_{PO} is the MOE of PO mode and MOE_{PPLT} is the MOE of PPLT mode.

From the simulation results listed in Table 61, it is found that at three study intersections (highlighted), PPLT mode outperforms PO mode significantly in terms of these three MOEs. Actually, two of these three intersections, numbers 8_1.2 and 8_1.3, were developed based on intersection number 8. Therefore, these three intersections have similar traffic characteristics. The westbound and eastbound directions of intersection number 8 have very heavy traffic demand and a total of five lanes in each direction. Using PPLT control mode in the subject directions (northbound and southbound) increases the capacity in these two directions and cause more green time to be allocated to the westbound and eastbound directions. As a result, the average delay in westbound and eastbound directions decreases, which significantly improves the overall network-wide performance because of the heavy traffic volume on these two approaches. For other intersections, the performance of the network under PPLT mode is also better than that under PO mode. However, the improvements are not very significant. The range of average speed increase is from 0.88 percent to 5.13 percent, and the range of average delay reduction is from 1.79 percent to 10.12 percent. In terms of network throughput, in some study intersections, PO mode even shows better performance than PPLT mode. However, the difference is very minor (less than 0.3 percent) and can be ignored. Overall, it can be concluded that changing the left-turn signal mode from PO mode to PPLT mode at the study intersections will result in improvements in the operation of the whole network. However, network-wide improvements are mainly caused by improvement at the study intersections.

6.4 ANALYSIS OF THE OPERATIONAL IMPACTS OF PHASING SEQUENCE

Generally, regarding one subject direction, there are four different types of signal phasing sequences, i.e., lead-lead, lead-lag, lag-lead, and lag-lag (see Figure 52).

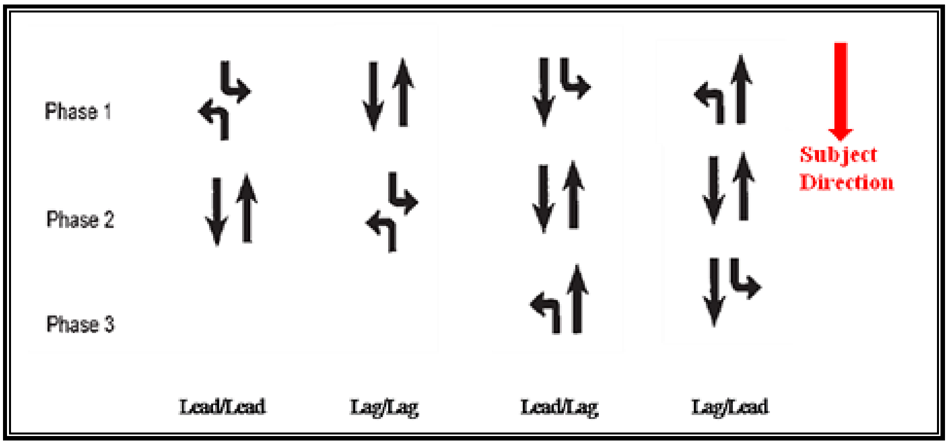


Figure 52: Phasing Diagrams of Four Types of Signal Phasing Sequences

For intersections without left-turn lane overflow or blockage problems, signal phasing sequence affects the operation of intersections mainly through its impact on the signal coordination of the network. According to the literature (Cohen and Mekemson 1985), appropriate signal phasing sequences can be selected to maximize the two-way through bandwidth of a study arterial. Thus, as proposed by Hummer et al. (1991), for an intersection in a two-way coordinated arterial, the signal phasing sequence that maximizes through bandwidth should be selected. Computer analysis tools for signal coordination, such as Passer IV, can be utilized for bandwidth optimization (Cohen and Mekemson 1985, Sheffer and Janson 1999). In addition, for a particular intersection, signal optimization software, such as SYNCHRO, can be used to analyze the signal bandwidth under four different types of signal phasing sequences and select the one that will provide the widest bandwidth.

However, if the intersection is on a one-way coordinated network, since the signal sequence will not affect the one-way bandwidth, the impact of signal phasing sequence on left-turn operation is an important factor to be considered in the selection of signal phasing sequence. Thus, this chapter investigates the impacts of signal phasing sequence on left-turn operation under the assumption that traffic signals are well coordinated in one direction during peak hour periods.

6.4.1 Methodology Description

A traffic simulation–based method was employed to analyze the operational performance of a study intersection under different types of signal phasing sequences. The study was conducted based on the following assumption about one-direction coordination.

It is assumed that directional peak hour traffic flow exists, and traffic signals along the arterial are coordinated only for one direction that has heavier traffic volume (subject direction) during the peak hour periods. Under this assumption, the impacts of signal phasing sequence on the through movements are controlled because the signals for the through movement are already perfectly coordinated in one direction, and the one-way bandwidth will not be affected by signal phasing sequences.

6.4.2 Selected Study Intersection

One study intersection in Houston (FM 518 at Dixle Farm) was selected for this study. This is because traffic flow on FM 518 is directional during the peak hour period. Its traffic flow condition during the PM peak hour is presented in Figure 53, and this intersection uses PPLT signal control mode.

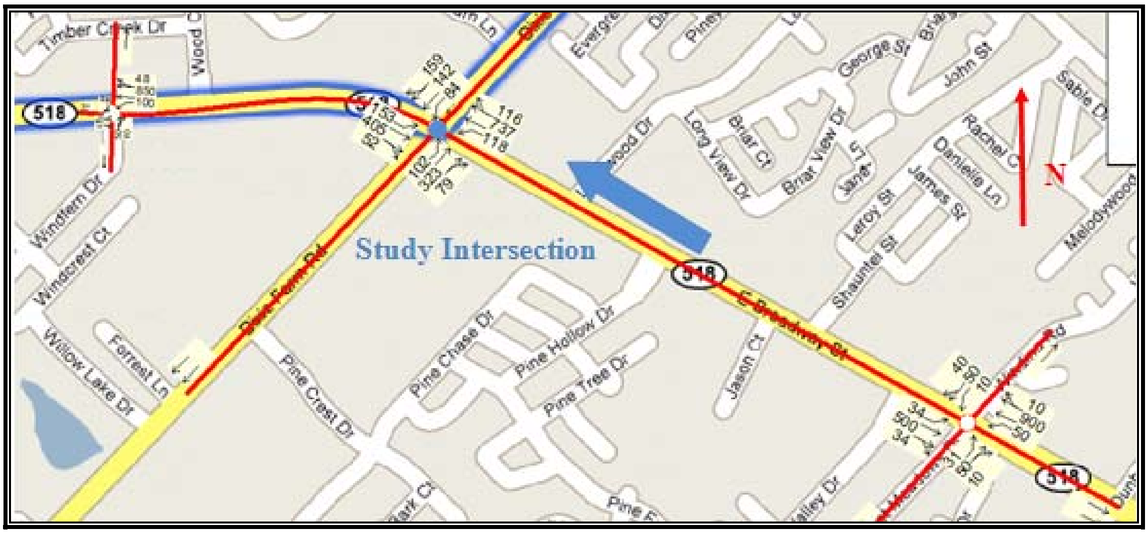


Figure 53: Map of Study Arterial

From Figure 53, it can be seen that the study intersection has much heavier traffic flow in the westbound direction during the PM peak hour period, and therefore this direction was selected as the subject direction for signal coordination. A three-intersection network was developed in the VISSIM simulation model, which included the study intersection (at the middle of the network), an upstream intersection, and a downstream intersection (at the signal-coordinated or major-road direction of the study intersection). The signal cycle length for the coordinated intersections was 130 seconds. The green time splits were obtained from signal timing optimization software, SYNCHRO. To ensure perfect coordination along the subject direction of the test arterial, the signal offsets were set according to the average travel time between the two intersections. To investigate the operational efficiency of different signal phasing sequences under left-turn volume conditions, the subject left-turn traffic volumes were increased from half of the existing left-turn volume to three times the existing volume. For every level of left-turn volume, multiple simulation runs were performed, and the average traffic delays for both through movement and left-turn movement were calculated based on the simulation results.

6.4.3 Analysis of Results

The overall intersection average delay under different left-turn signal phasing sequences at different levels of traffic congestion levels are presented in Table 62. The average traffic delays for the subject left-turn and through movements are presented in Figure 54.

Table 62: Overall Intersection Average Delay

Congestion Levels		Signal Phasing Sequence			
Current Volume / Existing Volume	Traffic Volume	Lead-Lead	Lead-Lag	Lag-Lead	Lag-Lag
0.5	59	21.18	19.95	22.61	19.52
1	118	21.81	20.11	23.35	20.45
1.5	177	23.07	20.31	25.01	21.77
2	236	24.00	20.82	28.01	23.22
2.5	295	25.43	22.87	33.26	25.77
3	354	27.98	26.73	40.40	29.56

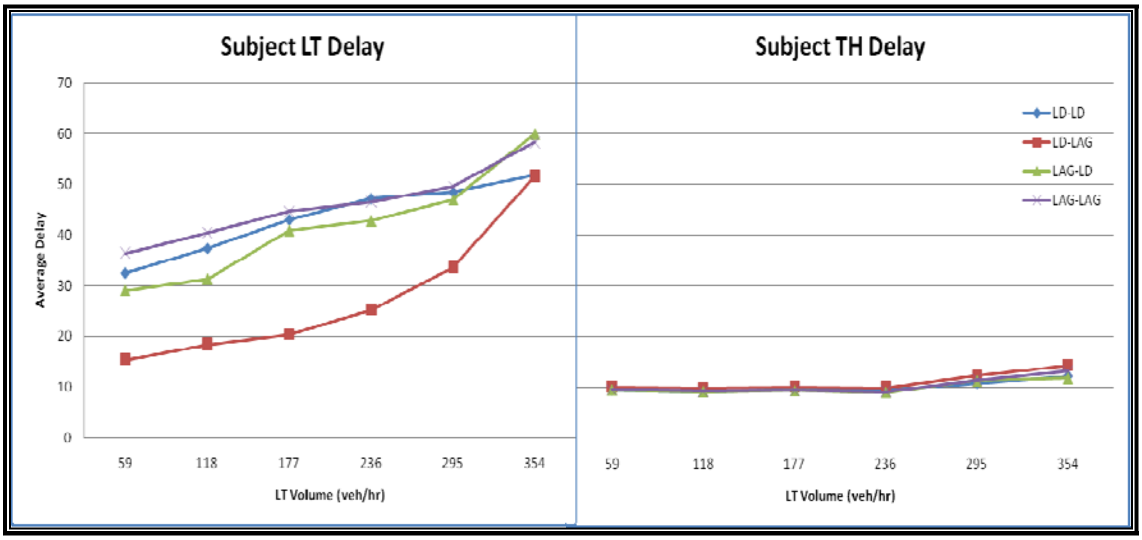


Figure 54: Average Delay for Subject LT and TH Movements

From the results above, the following findings can be obtained:

1. Signal phasing sequence does have significant impacts on the delay of the subject left-turn movement. These impacts are listed as follows:
   a. Lead-lag sequence has the lowest left-turn delay at all the tested traffic congestion levels.

b. Lead-lead sequence has higher left-turn delay when the traffic volume is low. But when the traffic volume increases, the left-turn delay for lead-lead sequence is close to that for lead-lag sequence.
c. Lag-lead sequence has lower left-turn delay than lag-lag sequence.

2. Signal phasing sequence does not have a significant impact on the delay of the subject through movement according to the results presented in Figure 54.
3. According to the results presented in Table 62, signal phasing sequence does not have a significant impact on the average delay of the overall intersection except that lag-lag sequence has a little worse performance when the left-turn volume is high.

To understand the underlying mechanism that leads to finding 1, time-spacing diagrams (Figures 55 to 58) for analyzing the left-turn traffic operations under different signal phasing sequences were developed. Since the majority of left-turn vehicles in the subject direction arriving at the study intersections comes from the upstream intersection, the signal coordination between the upstream through movement and the downstream (study intersection) left-turn movement needs to be analyzed. Therefore, in these time-spacing diagrams (Figures 55 to 58), the signal timing bar at the upstream intersection is for the through movement, and the signal timing bar at the study intersection is for the left-turn movement (along with the whole signal diagram). From these time-spacing diagrams, it can be seen that the major contributing factor for the difference in left-turn delay under different signal phasing sequences is platoon progression. Due to the assumption of perfect coordination for the subject through movement, the left-turn vehicles in the upstream platoon arrive at the study intersection at the beginning of the through green. However, as shown in Figures 55 to 58, the location of the start points of the protected left-turn phase relative to the start points of the through green phase are different under different signal phasing sequences. This difference causes the bandwidths for the left-turn movement to be different, which in turn affects left-turn operational efficiency. Based on these time-spacing diagrams, findings 1a and 1b can be explained as follows:

1. Lead-lag has the lowest left-turn delay because its protected left-turn phase begins at the same time as the through movement phase, and it has the widest left-turn bandwidths for both protected and permissive left-turn movements. As soon as the upstream vehicle platoon arrives at the intersection, the green arrow for the protected left-turn phase turns on, and the majority of the vehicles can be served during the protected phase (pass in

protected LT bandwidth). Vehicles that arrive after the protected left-turn phase still have a chance to pass the intersection during the permissive left-turn phase (pass in permissive LT bandwidth). Therefore, the average delay for left-turn vehicles under lead-lag sequence is low.

2. Lead-lead left-turn control sequence has higher delay when the traffic volume is low. This is because the protected left-turn phase begins before the upstream platoon arrives at the study intersection (see Figure 55). As a result, part of the protected green time for left-turn movement is wasted and the bandwidth for protected left-turn movement becomes narrow. Thus, left-turn vehicles experience high delay. However, with the increase of left-turn traffic volume, there are more and more left-turn vehicles waiting in the queue before the start of the protected left-turn phase. These could be vehicles leftover from the previous cycle. In this case, the green time for the protected phase is not wasted. Thus, the left-turn delay under lead-lead sequence becomes close to that under lead-lag.
3. Lag-lead sequence has lower left-turn delay than lag-lag sequence. By examining the animation of the traffic simulation, it is found that the progression of the opposing through traffic under lag-lag sequence is not very good, and the majority of the opposing traffic arrives at the study intersection during the red phase. Therefore, when the permissive left-turn phase begins, the initial opposing queue starts to discharge, which causes no vehicles to be able to make a permissive left turn until the opposing queue is cleared from the intersection. Under lag-lead left-turn sequence, the opposing initial queue is discharged before the permissive left-turn phase and is almost cleared when the permissive phase begins. Thus, it does not affect the left-turn vehicles in the subject direction to make permissive left turns. Note that since the coordination is set up according to the subjective direction, the progression of the opposing traffic is determined by the distance between the downstream intersection and the study intersection. Therefore, the poor progression in the opposing direction is only for this intersection and may not be true for other intersections that have different distances from the downstream intersections. Therefore, the result of the performance comparison between the lag-lead and lag-lag sequences is different for different locations. Overall, these two sequences have very similar performance.

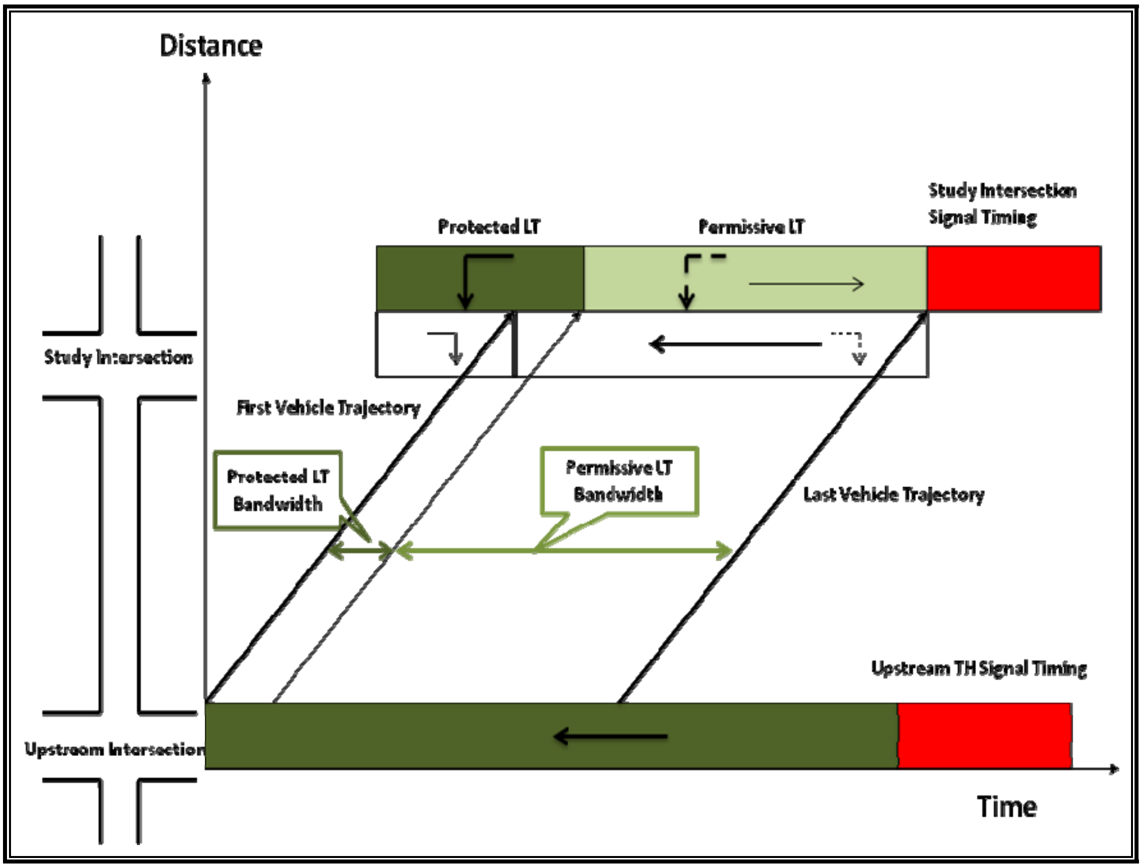


Figure 55: Time-Spacing Diagram for Lead-Lead Left-Turn Control Sequence

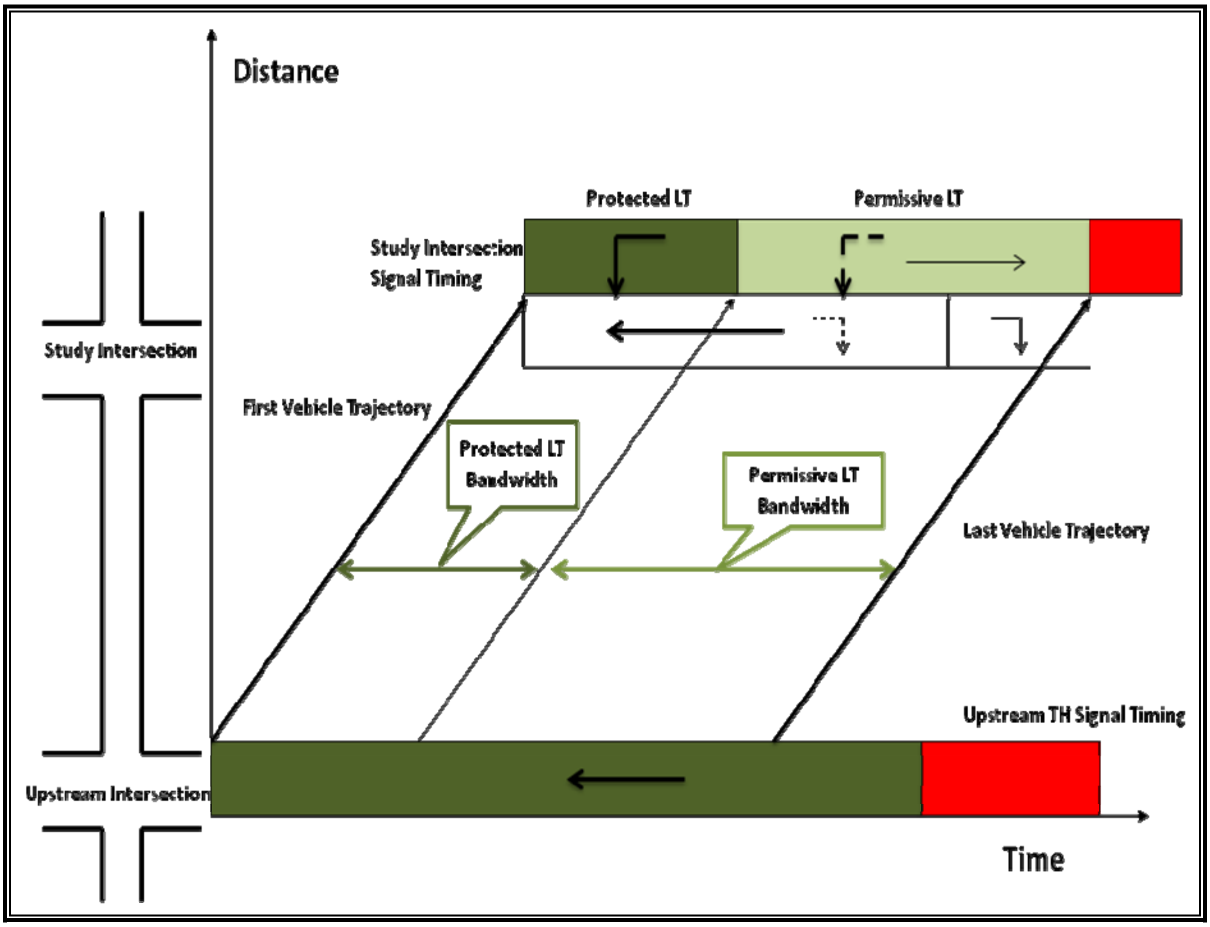


Figure 56: Time-Spacing Diagram for Lead-Lag Left-Turn Control Sequence

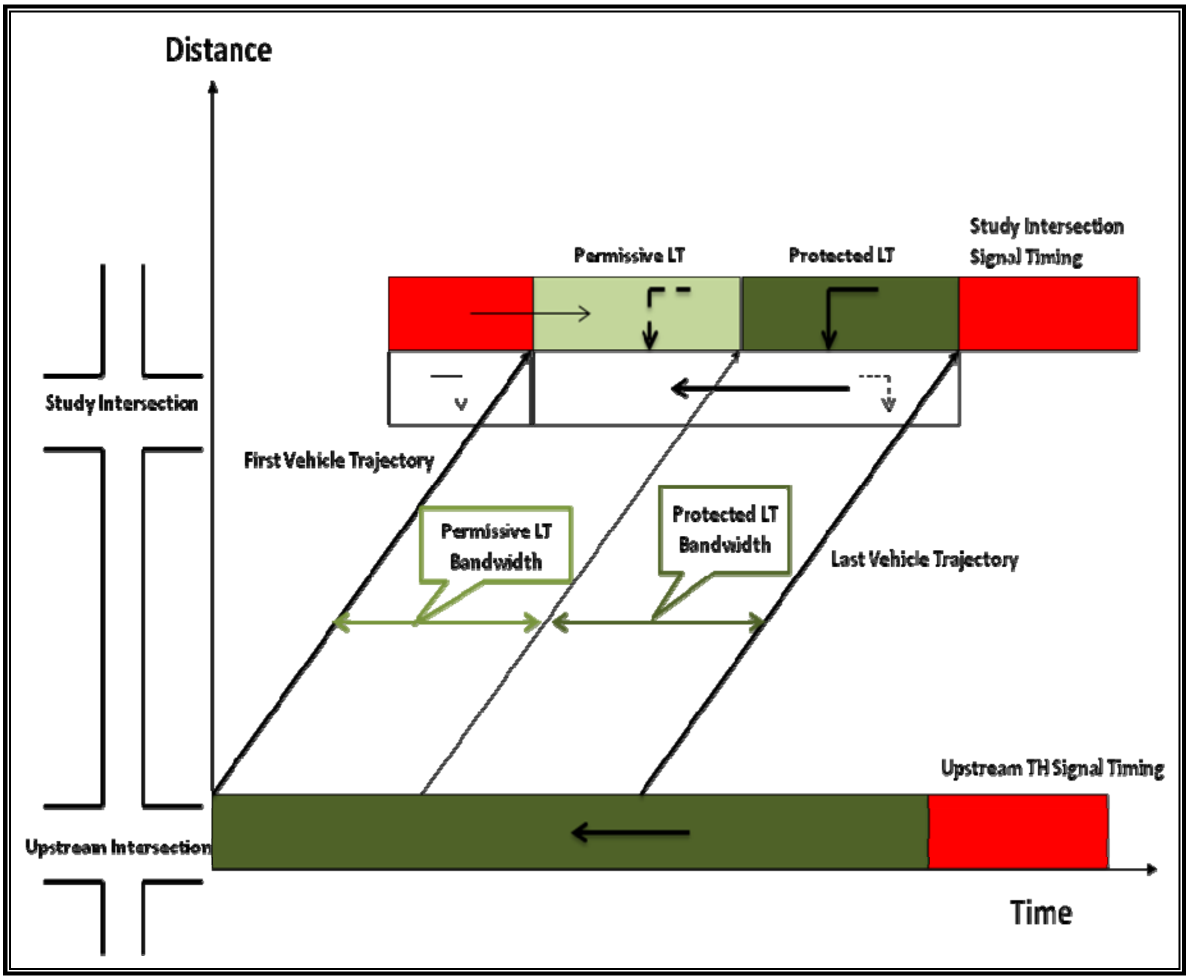


Figure 57: Time-Spacing Diagram for Lag-Lead Left-Turn Control Sequence

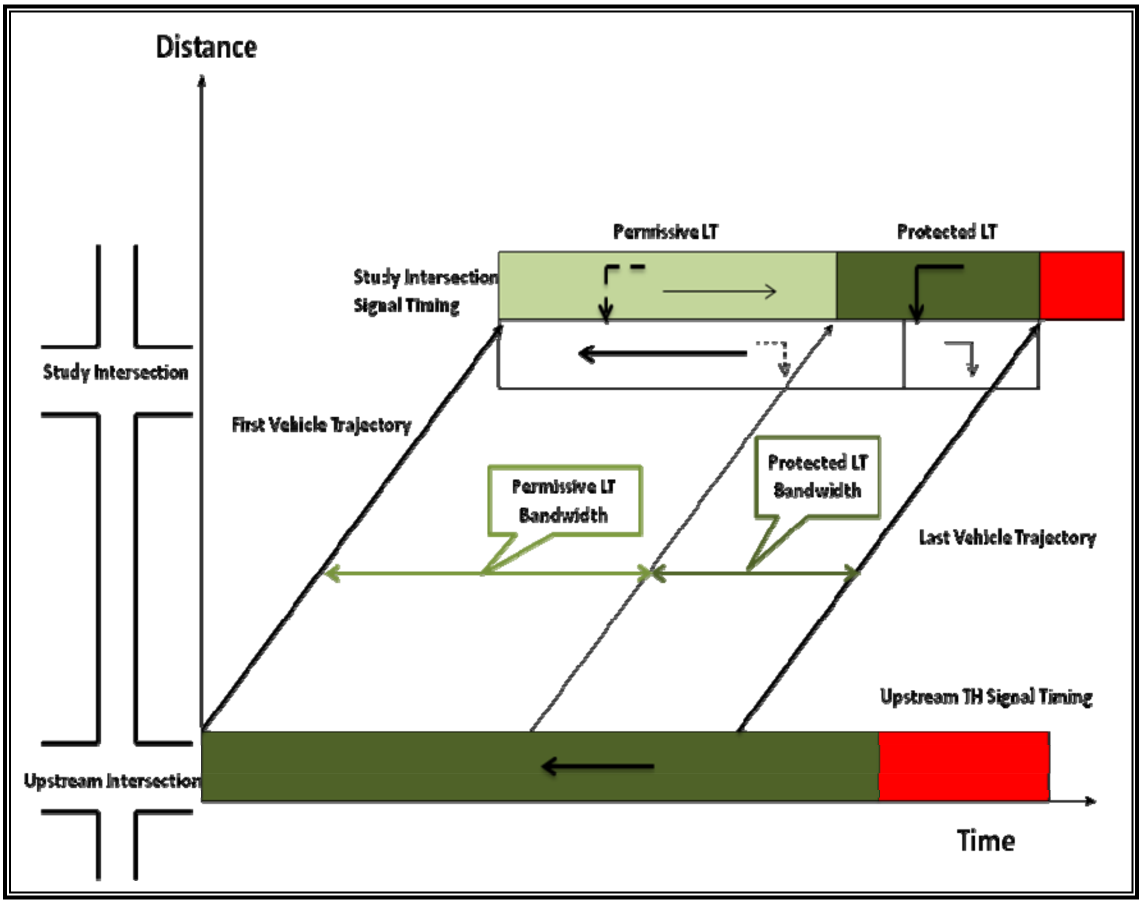


Figure 58: Time-Spacing Diagram for Lag-Lag Left-Turn Control Sequence

Findings 2 and 3 are easy to understand. First, since the traffic signals are coordinated in one direction, the operation of the subject through movement is not affected by the signal sequence. Then, since the total through volume is much higher than the left-turn volume, the overall intersection delay does not change significantly if the delay for the through movement does not have obvious changes.

6.5 CONCLUSION

In this chapter, a traffic simulation–based method was used for analyzing the impacts of different left-turn signal control modes and phasing sequences on the operation of signalized intersections. Based on the simulation results, CPOV-based criteria for selecting between PO and PPLT modes were developed, which recommend that:

- For intersections that have one opposing through lane, PPLT mode should be selected when the CPOV value is equal to or less than the threshold of 133,000.

- For intersections with two opposing through lanes, PPLT mode should be used when the CPOV value is equal to or less than the threshold of 93,000.

In terms of signal phasing sequence, it affects the operation of intersections mainly through its impacts on the signal coordination of the network. From the literature review and the results of traffic simulation, the following recommendations are provided:

- For an intersection in a two-way coordinated arterial, the signal phasing sequence that maximizes through bandwidth should be selected.
- For an intersection in a one-directional coordinated arterial during the peak hour periods, lead-lag sequence should be considered because it can cause much less delay for the subject left-turn movements than other signal phasing sequences at all left-turn volume levels.

CHAPTER 7: EVALUATION OF THE BENEFITS OF REGIONAL STANDARDIZATION

This chapter evaluates the benefits of regional standardization of left-turn operation. The objective of this chapter is to investigate the benefits of regional standardization of left-turn signal operation, including both signal phasing treatments and displays. In other words, this study answers the following question: would the use of consistent left-turn operation in a region improve the safety or operational efficiency of intersections?

7.1 STUDY SCOPE

The results of Chapter 6 show that the operational efficiency of intersections in an arterial is primarily determined by their signal control modes (protected/permissive are always better than protected-only) and the bandwidth of the signal progression, and is not related very much to the regional standardization of left-turn operation. Therefore, the major impacts of regional standardization of left-turn operation are on intersection safety.

The approach used for the safety benefits analysis compares the accident rates at four different roadway sections in Houston, i.e., FM 1960, SH 6 North, SH 6 South, and FM 518. The left-turn signal operations on these four roadway sections have different levels of mixtures in terms of left-turn signal control mode, phasing sequence, and signal display. Detailed information about the data collected for these four roadway sections is in Chapter 4. By comparing the accident rates at these four roadway sections, the safety impacts of using standardized/consistent left-turn operation can be evaluated. The following sections are detailed descriptions of the methodology used for this study and the results obtained from this task.

7.2 METHODOLOGY

To evaluate the safety benefits of using consistent left-turn signal operation in a region, this study compared the accident rates at four selected roadway sections with different levels of mixed signal operations in terms of left-turn signal control mode, phasing sequence, and signal display.

The first step was to determine the mix levels of left-turn signal operations for these four roadway sections. For this purpose, three different measures were used: (1) percentage of mode change, (2) percentage of sequence change, and (3) percentage of display change. To derive these measures, first the number of times that the two adjacent intersections have different types of signal control modes, phasing sequences, and displays are counted. Then, these three measures can be calculated for each roadway section according to the following equation:

$$Change\ \% = \frac{\#\ of\ changes}{\#\ of\ intersections} \times 100\% \quad (22)$$

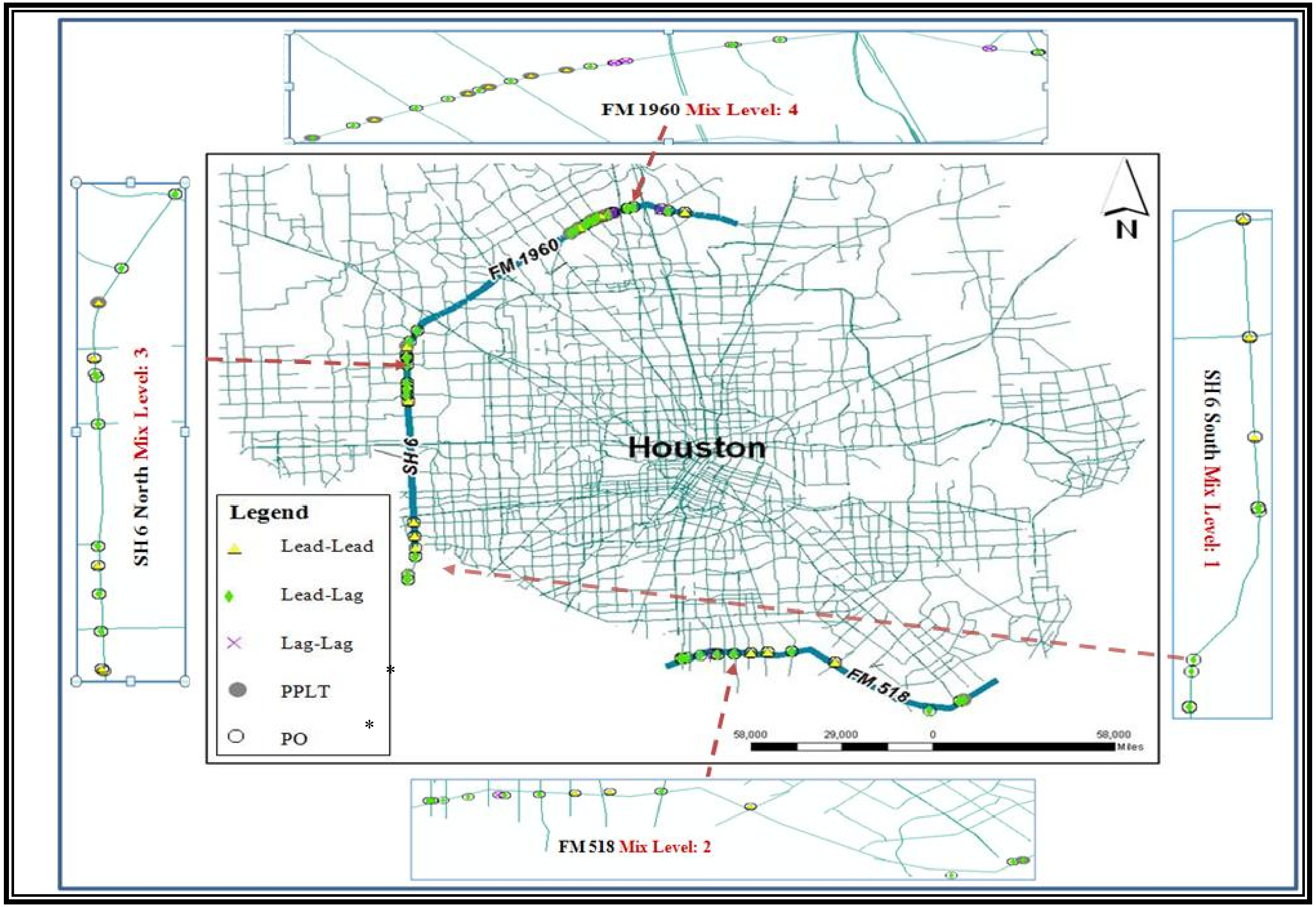
where $\#\ of\ intersetions$ is the total number of intersections in a roadway section and $\#\ of\ changes$ is the number of times that the two adjacent intersections have a different signal control mode/sequence/display.

Then, the mix level of each study roadway was ranked according to the values of the measures listed in Table 63. It was found that for these three measures, FM 1960 had the highest mix level, followed by SH 6 North, FM 518, and SH 6 South. Therefore, the overall mix level score was given to the four roadway sections according to this order. In addition, intersections with different phasing sequences (lead-lead, lead-lag, and lag-lag) and different types of signal control modes (protected-only and protected/permissive) were marked with different symbols and colors on a GIS map, as shown in Figure 59. For signal display, since both the left-turn signal head placement and indications are consistent on the four selected roadway sections, only the signal head arrangement was used to determine the mix levels of signal display on roadway sections. Figure 60 demonstrates the mix level of usage of different types of display arrangements (4H, 5H, and 5D[3]) on these four roadways. Based on Figures 59 and 60, the mix levels of these four roadway sections can also be determined visually.

[3] 4H means four-section horizontal signal head; 5H means five-section horizontal signal head; 5D means five-section doghouse signal head.

Table 63: Mix Levels of Left-Turn Signal Operation for Study Roadway Sections

Regions	Total No. of Intersections	Mode		Sequence		Display		Overall Mix Level
		No. of Changes/ No. of Intersections	Mix Level	No. of Changes/ No. of Intersections	Mix Level	No. of Changes/ No. of Intersections	Mix Level	
			Score		Score		Score	
FM 1960	21	45.00%	4	61.90%	4	45.00%	4	4
SH 6 North	19	11.11%	3	31.60%	3	11.11%	3	3
FM 518	22	4.76%	2	27.30%	2	4.76%	2	2
SH 6 South	11	0.00%	1	9.10%	1	0.00%	1	1



Note: PPLT means protected/permissive left-turn signal control mode; PO means protected-only left-turn signal control mode.

Figure 59: Left-Turn Signal Phasing Mix Levels on the Study Roadway Sections

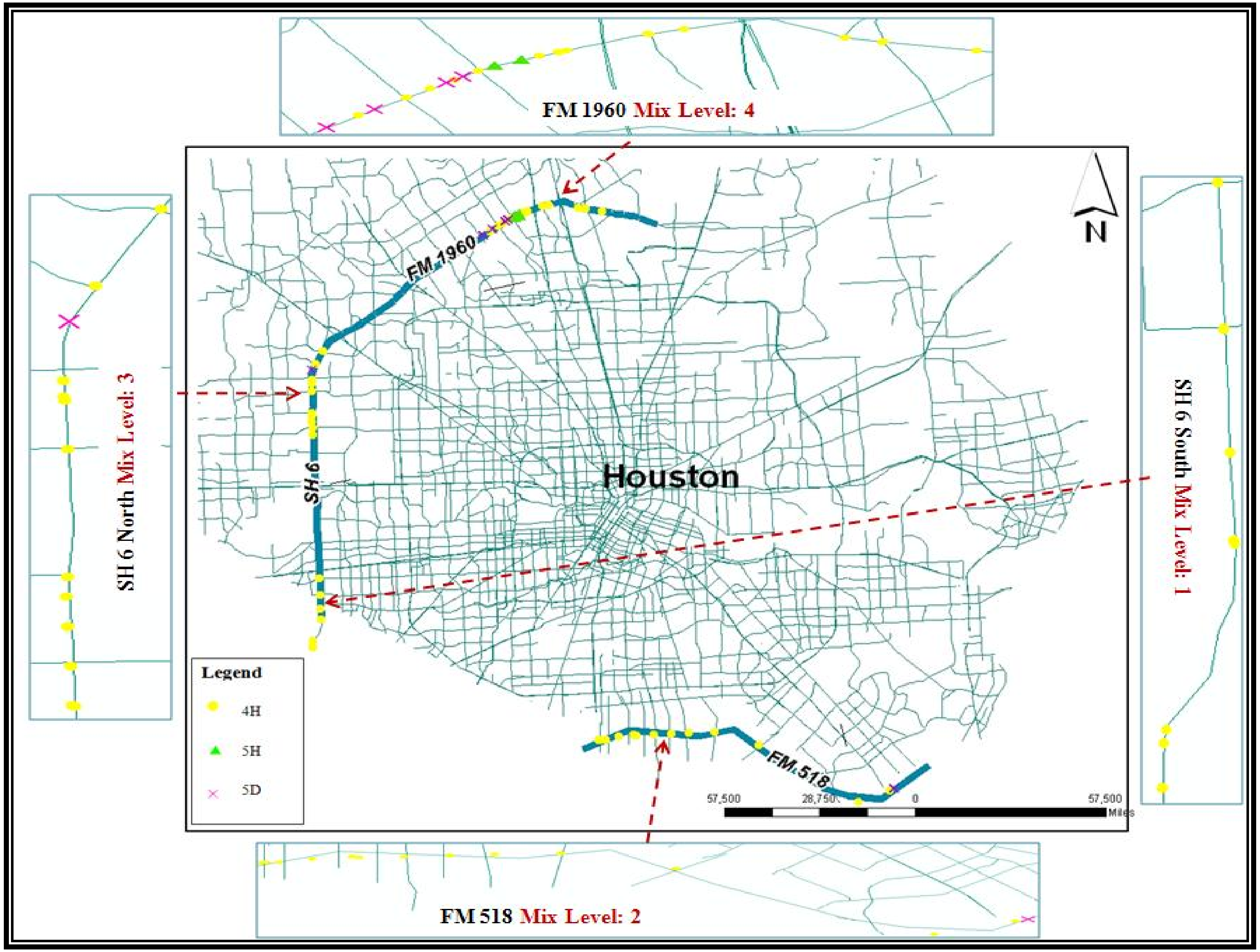


Figure 60: Left-Turn Signal Display Mix Levels on the Study Roadway Sections

After the mix levels of different roadway section are determined, the average accident rate per intersection for each study roadway section is calculated according to the following equation:

$$Average\,accident\,rate\,per\,intersection = 100{,}000 \times \frac{Accident\,counts\,on\,the\,roadway\,section}{Average\,ADT \times Total\,number\,of\,intersections} \quad (23)$$

where ADT is the average daily traffic on these roadway sections. It was estimated by multiplying average peak hour volume by 10 (Kimley-Horn and Associates, Inc 2003).

7.3 RESULTS

Table 64 summarizes the roadway information and the calculated average accident rates. Based on these results, the relationship between the average accident rate and the mix level of left-turn signal operation is developed and presented in Figure 61. It was found that the total accident rate increases significantly as the mix level increases, especially when the overall mix level increases from 3 to 4. From Table 64 it can be seen that for all three measures, the percentage of change increased more than 30 percent from mix level 3 to level 4. Thus, the results in Figure 61 show that higher mixture level in left-turn signal operation results in more accidents at intersections. It was also found that the left-turn–related accident rate increases as the mix level increases, even though the increase is not as significant as the total accident rate.

Overall, the results of this study indicate that the mixed application of left-turn signal phasing treatments and displays has adverse impacts on intersection safety. Such mixed applications should not be recommended even though they may be helpful for achieving better traffic operation (by maximizing the signal bandwidth). The results suggest that regional standardization of left-turn signal operation is needed for increasing the consistency in left-turn operation in urban areas with multiple jurisdictions.

Table 64: Results of Average Accident Rate per Intersection on Study Roadways

Regions	Overall Mix Level	Total No. of Intersections	Total Accident Counts*	LT-Related Accident Counts*	Average ADT	100,000 Accident Rate per Intersection*	100,000 LT-Accident Rate per Intersection*
FM 1960	4	21	810	164	37680	102.37	20.73
SH 6 North	3	19	521	98	38740	70.78	13.31
FM 518	2	22	352	71	24530	65.23	13.16
SH 6 South	1	11	357	69	50960	63.69	12.31

*Accident counts are from a 3-year study period.

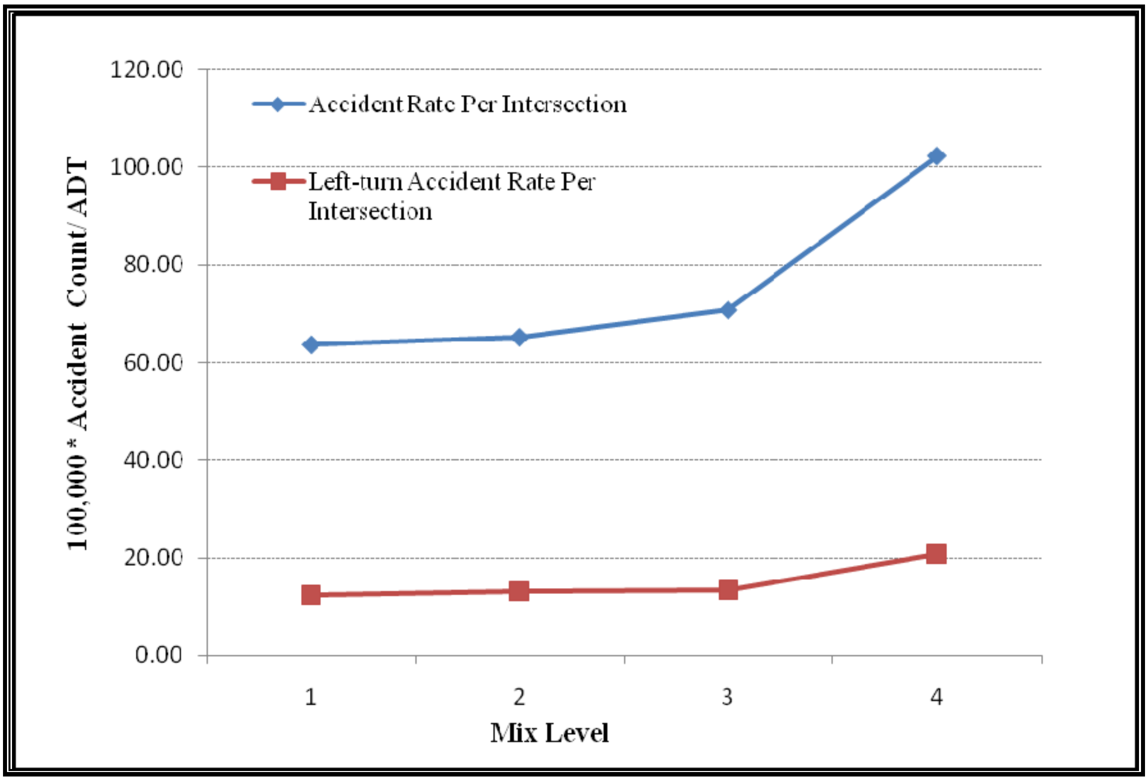


Figure 61: Accident Rate versus Mix Level of Left-Turn Operation

7.4 SUMMARY

This research explored the safety impacts of regional standardization of left-turn operation on intersection safety. The key finding from this study is that mixed application of left-turn signal operation, including signal control modes, phasing sequences, and displays, increases the risk of accidents at intersections. It is suggested that regional standardization of left-turn signal operation is needed for increasing the consistency of left-turn operation in a region.

CHAPTER 8: GUIDELINES FOR LEFT-TURN SIGNAL PHASING

The purpose of this chapter is to develop guidelines/flowcharts for determining the mode and sequence of left-turn signal phasing at a signalized intersection. The guidelines were developed based on the results from the previous chapters, as shown in the following:

- preliminary guidelines developed based on the literature review (Chapter 2),
- analysis results of the safety impacts of different left-turn phasing treatments (different modes and sequences of left-turn signal phasing) at signalized intersections (Chapter 5),
- analysis results of the operational impacts of different left-turn phasing treatments (different modes and sequences of left-turn signal phasing) at signalized intersections (Chapter 6), and
- evaluation of the benefits of regional standardization of left-turn operation (Chapter 7).

8.1 DEVELOPMENT OF GUIDELINES FOR SELECTING LEFT-TURN SIGNAL CONTROL MODE

As mentioned previously, there are three major modes for left-turn signal control: permissive-only, protected-only, and protected/permissive left turn. The guidelines for determining the most appropriate mode of left-turn signal phasing at an intersection were developed by synthesizing, comparing, and analyzing existing criteria, warrants, and guidelines on left-turn signal phasing, which were studied in Chapter 2, and by incorporating the newly developed traffic volume–based criteria for selection between PO and PPLT modes, which is one of the results of Chapter 6.

8.1.1 Results of Literature Review

Numerous studies have been conducted for developing criteria or guidelines for left-turn signal phasing. In general, the existing criteria can be categorized as being traffic volume based, accident experience based, geometric features based, speed based, left-turn delay based, and other. These existing criteria are summarized in Tables 65 and 66 by categories.

Table 65: Summary of Existing Traffic Volume–Based Criteria for Left-Turn Signal Phasing

Criterion	Warrant		Reference	Recommendation
Volume	LT Volume	≥ 2 vehicles/cycle	Agent and Deen 1979, Cottrell 1986, Lalani et al. 1986, Upchurch 1986, ITE 1991	PPLT and PO
		≥ 50 vph		
		≥ 50 vph & VCP > 100,000	City of San Diego 2006	PPLT and PO
		> 200 vph	Roess et al. 2004	PPLT and PO
		> 300 vph	Stamatiadis et al. 1997	PO
	Opposing Through Volume	>1000 vph (two opposing lanes)	Agent 1981	PO
	Volume Cross Product (VCP)	> 50,000 (one opposing lane)	Agent and Deen 1979, ITE 1991, Stamatiadis et al. 1997	PPLT and PO
		> 100,000 (two opposing lanes)		
		> 50,000 (per opposing lane)	Roess et al. 2004	PPLT and PO
		> 144,000 (two opposing lanes and opposing speed > 45 mph)	Upchurch 1986	PPLT and PO
		> 100,000 (three opposing lanes)		
		> 100,000 (LT volume ≥ 50 vph)	City of San Diego 2006	PPLT and PO
		200,000 ≥ VCP per lane ≥ 50,000	Cottrell 1986	PPLT

Table 66: Summary of Other Types of Criteria for Left-Turn Signal Phasing

Criterion	Warrant		Reference
Accident Experience	LT-Related Accidents	≥ 4 in any 1 year, or ≥ 6 in any 2 consecutive years, or ≥ 8 in any 3 consecutive years	Agent and Deen 1979, Agent 1987, ITE 1991, Stamatiadis et al. 1997
		≥ 5 in any 12-month period in 3 years	City of San Diego 2006
	LT Conflicts	≥ 10 basic conflicts in a peak hour	Agent and Deen 1979
		≥ 14 total conflicts in a peak hour	
		≥ 4 per 100 left-turn vehicles	Cottrell 1986
Geometric Features	Sight Distance	≤ 250 ft (opposing speed ≤ 35 mph)	ITE 1982, Upchurch 1986, City of San Diego 2006
		≤ 400 ft (opposing speed > 35 mph)	
	Number of Opposing Through Lanes	≥ 3	Cottrell 1986, Agent 1987, City of San Diego 2006
	Number of Left-Turn Lanes	≥ 2	ITE 1982, Agent 1987, City of San Diego 2006
Speed	Opposing Speed	≥ 45 mph	Agent and Deen 1979, Agent 1987, Upchurch 1986
Other	Left-Turn Delay		Agent and Deen 1979, Cottrell 1986, Lalani et al. 1986
	Number of Failed Cycles		Fisher 1998
	Benefit/Cost Analysis		Agent and Deen 1979, Cottrell 1986
	Vehicle Queue		Lalani et al. 1986
	LT Storage Length		
	Percent of Heavy Vehicles		
	Political Motivation		
	Public Demand		
	High Truck or Pedestrian Volume		City of San Diego 2006
	50 or More School-Age Pedestrians Crossing the Lane per Hour		
	Access Management Condition		Cottrell 1986
	Angle of the Two Approaches		

Note: This table was developed based on Zhang (2005).

Traffic Volume–Based Criteria

Traffic volume–based criteria are used widely for determining when a protected left-turn signal phase should be provided. In these criteria, if the left-turn volume (Agent and Deen 1979, City of San Diego 2006, Cottrell 1986, ITE 1991, Lalani et al. 1986, Roess et al. 2004, Stamatiadis et al. 1997, Upchurch 1986), opposing through volume (Cohen and Mekemson 1985), or cross product of left-turn volume and opposing volume (Agent and Deen 1979, City of San Diego 2006, Cottrell 1986, Lalani et al. 1986, Roess et al. 2004, Stamatiadis et al. 1997, Upchurch 1986) exceed a certain threshold, protected left-turn phasing (either PO or PPLT) should be installed. From the summary in Table 65, it can be seen that these existing criteria proposed by different studies are not very consistent. For example, for intersections with two approaching lanes, Agent and Deen (1979) suggested installing a protected left-turn phase when the volume cross product exceeded 100,000, while Upchurch (1986) proposed 144,000 as the critical value of the volume cross product for providing a protected left-turn phase. The inconsistency in the existing criteria complicates the decision-making process on mode selection for traffic engineers.

In addition, few traffic volume–based criteria have been developed for use in selecting between PPLT and PO modes. Cottrell (1986) found that for most of the intersections with PPLT control mode where the cross products of left-turn volume and opposing volume (per lane) were greater than 200,000, safety problems existed. Therefore, if the volume cross product is greater than 200,000, PO mode should be used. However, the 200,000 threshold seems to be too high. This is because, according to Agent (1981), for an intersection with two opposing lanes, it is difficult to make permissive left turns if the total opposing volume is greater than 1000 (or the opposing volume per lane is greater than 500). In this case, the left-turn volume must be at least 400 vph to exceed the 200,000 volume cross product threshold for using PO mode. However, when the left-turn volume is greater than 300 vph, double left-turn lanes are warranted (Courage et al. 2002, Qureshi et al. 2003, Stokes 1995) and PPLT mode should not be provided at all (Agent 1987, City of San Diego 2006, ITE 1982). Therefore, the 200,000 volume cross product threshold is too high, and research is needed to find more reasonable traffic volume–based criteria for selecting between PPLT and PO modes.

Other Types of Criteria

Accident experience–based criteria are most important for the selection of left-turn signal control mode. Some studies developed warrants based on the number of left-turn–related accidents (Agent and Deen 1979, Agent 1987, City of San Diego 2006, Stamatiadis et al. 1997, Upchurch 1986), and some others used the number of left-turn conflicts as criteria (Agent and Deen 1979, Cottrell 1986). There is no doubt that both a high number of left-turn–related accidents and a high number of left-turn conflicts require a protected left-turn signal phase.

Geometric features–based criteria consist of three types of warrants: (1) sight distance (Courage 2002, Lalani et al. 1986, City of San Diego 2006), (2) the number of left-turn lanes (Agent 1987, City of San Diego 2006, ITE 1982), and (3) the number of opposing through lanes (Agent 1987, Cottrell 1986, City of San Diego 2006). Sight distance and opposing speed could be considered together to determine the feasibility of using the permissive mode. PO mode is the appropriate choice for intersections that have multiple left-turn lanes or more than three opposing through lanes because it is not safe to make permissive left turns when such complicated geometric conditions exist.

Speed-based criteria are also very important for determining the correct signal control mode for an intersection. Previous research (Agent 1987, Agent and Deen 1979, Lalani et al. 1986) found that PO mode should be provided when opposing speed is greater than 45 mph to avoid collisions between left-turn vehicles and opposing through vehicles that are approaching the intersection at a high rate of speed.

Other types of criteria, such as left-turn delay, benefit/cost analysis, vehicle queue, high truck or pedestrian volume, and access management conditions, have also been proposed in several previous research studies. These criteria are listed in Table 66.

8.1.2 Results of Newly Developed Traffic Volume–Based Criteria

In Chapter 6, criteria based on the cross product of left-turn volume and its opposing volume per lane were developed for selecting between PO and PPLT modes by using traffic simulation–based methods. The developed criteria indicate the following:

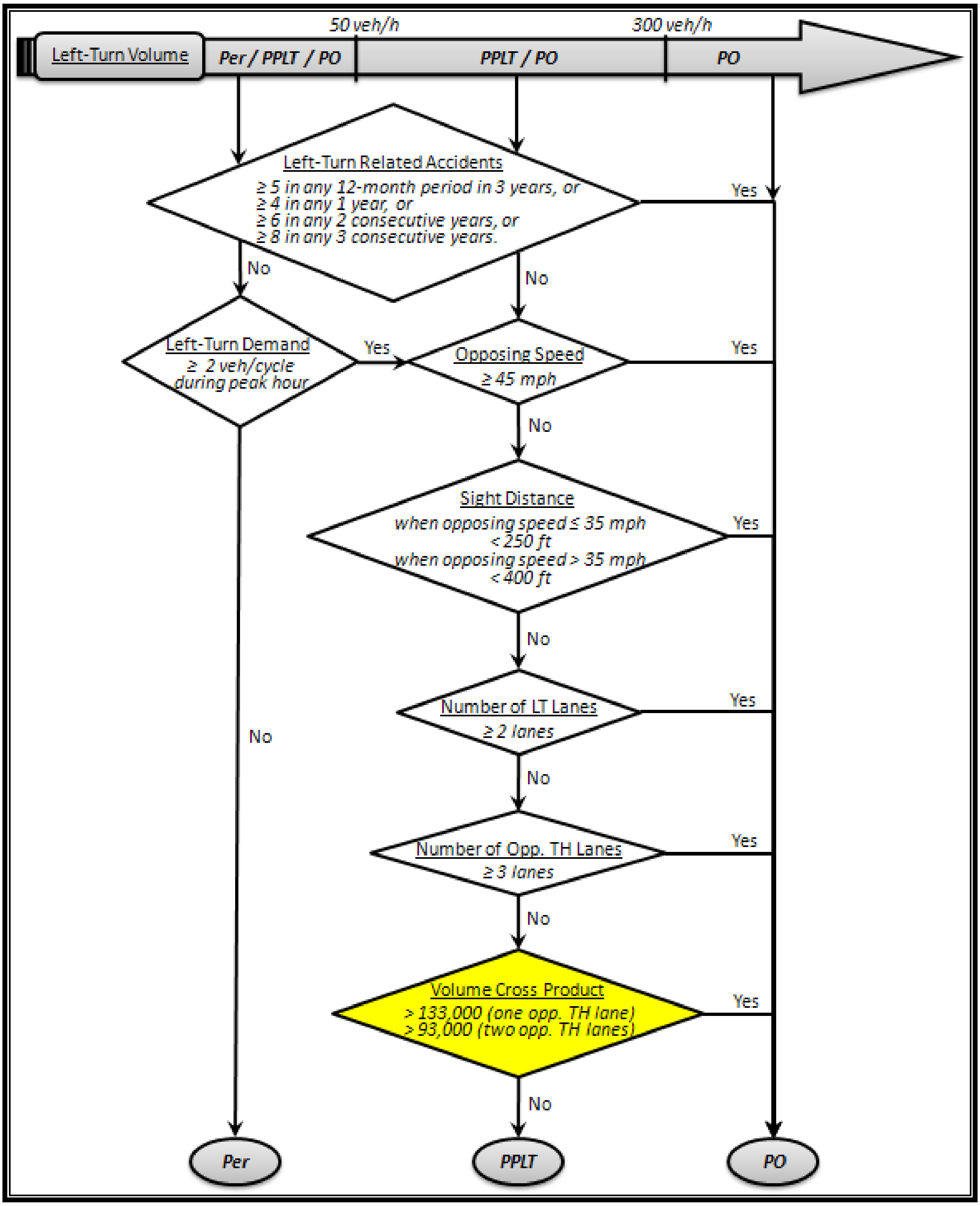
- For intersections that have one opposing through lane, PPLT mode should be selected when the CPOV value is equal to or less than the threshold of 133,000.
- For intersections with two opposing through lanes, PPLT mode should be used when the CPOV value is equal to or less than the threshold of 93,000.

8.1.3 Guidelines for Selecting Left-Turn Signal Control Mode

In this chapter, a flowchart for selecting the left-turn signal control mode was developed and is shown in Figure 62. This flowchart was developed by synthesizing the existing criteria, warrants, and guidelines on left-turn signal phasing (Tables 65 and 66) and by incorporating the traffic volume–based criteria developed in Chapter 6 (see the highlighted part in Figure 62).

In this flowchart, the first step is to make a decision based on the left-turn volume. Since protected left-turn phasing is warranted when left-turn volume is higher than 50 vph during the peak hours (Agent and Deen 1979, City of San Diego 2006, Cottrell 1986, ITE 1991, Lalani et al. 1986, Upchurch 1986), all three modes can be used when left-turn volume is lower than this critical value. When left-turn volume is between 50 vph and 300 vph, since a protected left-turn phase must be provided, the appropriate left-turn signal control mode will be selected between PO and PPLT modes. When left-turn volume is over 300 vph, PO mode is the only choice because dual left-turn lanes should be provided under such heavy left-turn volume conditions (Courage et al. 2002, Qureshi et al. 2003, Stokes 1995), and only PO mode can be used at an intersection with multiple left-turn lanes (Agent 1987, City of San Diego 2006, ITE 1982).

The next step is to check the criteria based on accident experience. In the literature, both warrants based on left-turn–related accidents and on left-turn conflicts have been proposed. However, in real-world implementation, it is difficult to collect traffic conflict data because traffic conflicts are observed in the field, and different people may count traffic conflicts differently, based on their differing judgments. Therefore, only warrants based on left-turn–related accidents were considered in the development of this flowchart. From the existing warrants summarized in Table 66, the following recommendations were made: PO mode should be selected when any one of the following conditions is met: (1) five or more accidents in any 12-month period in 3 years (City of San Diego 2006), (2) four or more accidents in any 1 year, (3) six or more accidents in any consecutive 2 years, or (4) eight or more accidents in any consecutive 3 years (Agent 1987, Agent and Deen 1979, Lalani et al. 1986, Upchurch 1986).



Note: "Per" means permissive mode; "PPLT" means protected/permissive mode; "PO" means protected-only mode.

Figure 62: Decision-Making Flowchart for Selecting Left-Turn Signal Control Mode

Then, for intersections where the left-turn volume is below 50 vph during the peak hour, if the left-turn volume is less than two left-turn vehicles/cycle during the peak hour, permissive-only mode should be used. This is because under such low left-turn volume conditions, left-turn vehicles can make turns during the yellow interval (sneakers), and the protected left-turn phase is not needed (Agent and Deen 1979, Cottrell 1986, ITE 1991, Stamatiadis et al. 1997, Upchurch 1986).

For intersections where the left-turn volume is between 50 vph and 300 vph, after checking the criteria based on accident experience, the speed of the opposing traffic should be checked. If the average speed of the opposing traffic is equal to or greater than 45 mph, PO mode should be used (Agent 1987, Agent and Deen 1979, Lalani et al. 1986).

In terms of intersection sight distance, previous studies (Lalani et al. 1986, City of San Diego 2006, ITE 1982) recommended that PO mode be installed if any one of the following conditions exists: (1) sight distance is less than 250 ft when the average opposing speed is 35 mph or less, or (2) sight distance is less than 400 ft when the average opposing speed is greater than 35 mph.

The next step is to check the number of left-turn lanes. As mentioned before, only PO mode can be used at intersections with multiple left-turn lanes (Agent 1987, City of San Diego 2006, ITE 1982).

For the opposing through lanes, previous studies (Agent 1987, City of San Diego 2006, Cottrell 1986) have shown that it is unsafe to make permissive left turns when there are more than three through lanes in the opposing direction. Therefore, PO mode should be used when this circumstance exists.

Finally, the CPOV-based criteria developed in Chapter 6 can be used for selecting between PO mode and PPLT mode. For intersections that have one opposing through lane, PPLT mode should be selected when the CPOV value is equal to or less than the threshold of 133,000. Otherwise, PO mode should be selected. For intersections with two opposing through lanes, PPLT mode should be used when the CPOV value is equal to or less than the threshold of 93,000. Otherwise, PO mode should be selected.

In summary, the appropriate signal control mode can be selected by the decision-making flowchart presented in Figure 62. This flowchart synthesizes the existing criteria for selecting left-turn signal control mode, including criteria based on traffic volume, criteria based on accident experience, and criteria based on speed and geometric conditions, combined with the criteria developed in Chapter 6 based on the CPOV value.

8.2 DEVELOPMENT OF GUIDELINES FOR SELECTING SIGNAL PHASING SEQUENCE

Left-turn phasing sequence is the order and combination of movements that make up signal phasing. Generally, there are three types of sequence arrangements: (1) lead-lead sequence, which moves both the opposing left turns before the through movements; (2) lag-lag sequence, which moves both the opposing left turns after the through movements; and (3) lead-lag sequence, which moves the opposing left turns separately from each other but simultaneously with their associated through phase. The guidelines for determining the most appropriate signal phasing sequence at an intersection were developed by synthesizing the safety impacts findings from Chapter 5, the operational impacts findings from Chapter 6, and other findings from Chapter 2. The following is a summary of the major findings about the impacts of signal phasing sequences from these three chapters.

8.2.1 Major Findings on the Impacts of Signal Phasing Sequences

General Findings for Both PO and PPLT Signal Control Modes

1. Operational impacts:

   Signal phasing sequence affects the operation of intersections mainly through its impacts on the signal coordination of the network. It affects the two-way through bandwidth but not the one-way through bandwidth (Cohen and Mekemson 1985). From the results of Chapter 6, the following recommendations are provided:

   a. For an intersection in a two-way coordinated arterial, the signal phasing sequence that maximizes through bandwidth should be selected.
   b. For an intersection in a one-directional coordinated arterial during the peak hour periods, lead-lag sequence should be considered because it can cause much less delay for the subject left-turn movements than other signal phasing sequences at all left-turn volume levels.
2. Safety impacts:
   a. The consistent usage of left-turn signal phasing treatments, both control mode and sequence, on a roadway section or in a region will have positive impacts on intersection safety. In other words, the use of mixed left-turn signal designs jeopardizes the safety of intersections (see the results of Chapter 7).
   b. At intersections with heavy pedestrian volume (e.g., intersections in the downtown area), approaches with leading sequence cause greater vehicle-

pedestrian accident risk than lagging sequence. This is because upon seeing the traffic on the cross street stop at the stop line, some pedestrians ignore the "Don't Walk" sign and assume that they can walk across the approach to which the left-turning vehicles are destined (see Figure 63) (Hummer et al. 1991).

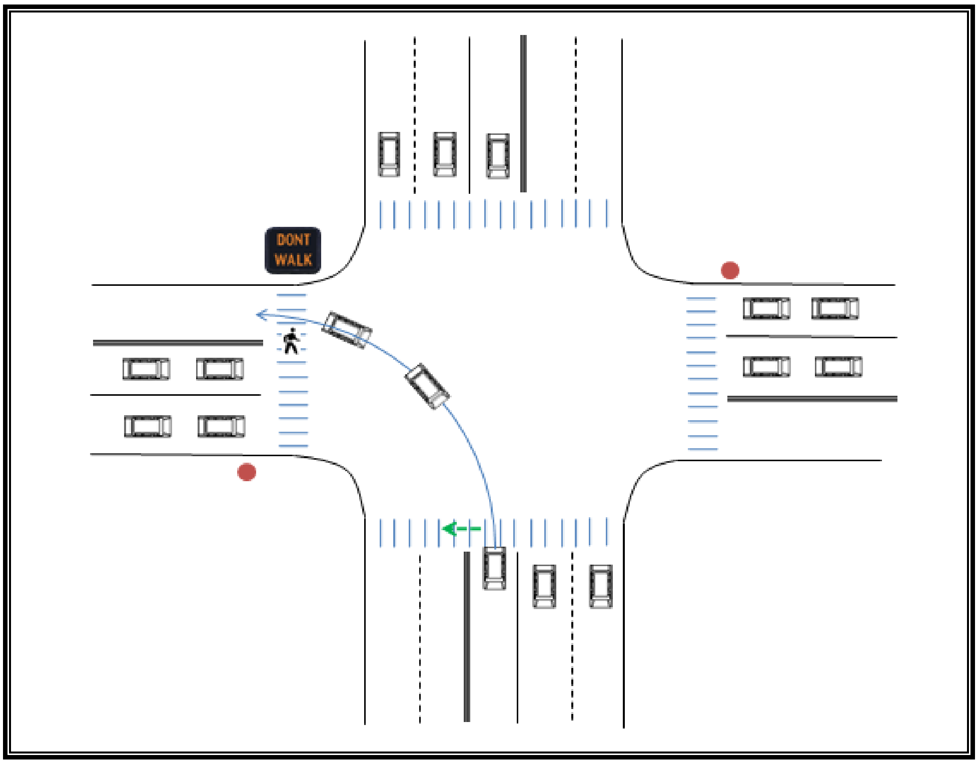


Figure 63: Conflicts between Vehicle and Pedestrian Caused by Leading Left-Turn Phase

3. Driver acceptance:

   According to the survey conducted by Hummer et al. (1991), leading sequence was preferred by 248 respondents, lagging sequence was preferred by 59 respondents, and 95 respondents expressed no preference for either of them. Therefore, leading sequence is preferred by most of the drivers.

Findings Only for PO Control Mode

1. Safety impacts:

   According to the analysis of historical accident records, the safest signal phasing sequence is lead-lag, followed by lead-lead and lag-lag. The difference in the safety impacts between these three signal phasing sequences is significant at a confidence level of 90 percent (see Chapter 5).

Findings Only for PPLT Control Mode

1. Safety impacts:
   a. Overall, lead-lag is the highest risk sequence. First, lead-lead sequence is safer than lead-lag sequence at a confidence level of 80 percent. This result is obtained from the safety impact analysis in Chapter 5 and is consistent with the results of the traffic conflicts study presented in Chapter 4. Second, according to the results of the traffic conflicts study, lag-lag sequence is also safer than the lead-lag phase.
   b. When both left-turn volume and pedestrian volume are low, lead-lead sequence should be safer than lag-lag sequence because the leading phase is safer than the lagging phase under these conditions (see the analysis in Chapter 5).
   c. When use lead-lag sequence, Dallas display/Arlington display should be used for preventing the yellow trap problem while maintaining operational efficiency and minimizing delay (Brookes et al. 1990, Camp and Denney 1992).
   d. The safety impacts of signal phasing sequence are different at different left-turn volume levels (see Figure 64 and the analysis in Chapter 5).
      i. When left-turn volume is less than about 150 vehicles/hr, lead-lead sequence is safer than lead-lag sequence.
      ii. When left-turn volume is greater than about 150 vehicles/hr, lead-lag sequence is associated with less accident risk than lead-lead sequence.

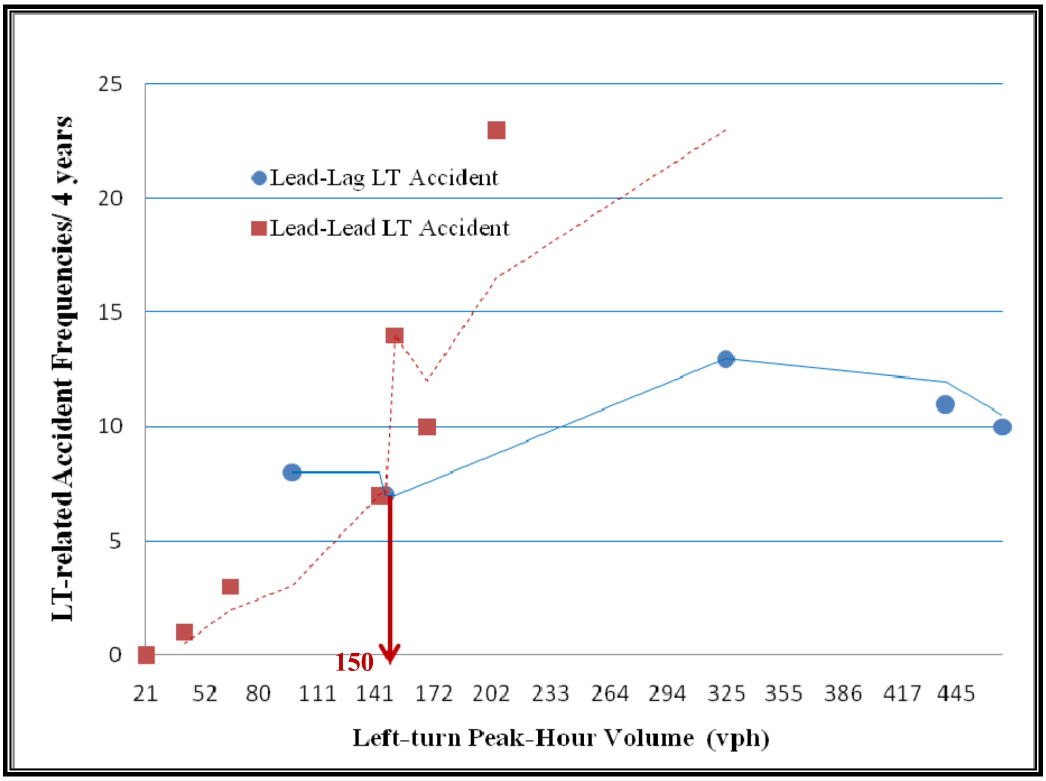


Figure 64: Left-Turn Accident Frequency versus Left-Turn Volume

8.2.2 Guidelines for Selecting Signal Phasing Sequence

Based on the key findings described above, different sets of recommendations on selecting the appropriate left-turn signal phasing sequences for intersections with two different types of signal control modes (PO and PPLT) were provided. Note that these recommendations are listed according to their importance. The most important one is listed first, followed by the less important ones. Therefore, when applying these guidelines, if two recommendations lead to different results, the first recommended signal phasing sequence should be weighted more in the final phasing sequence selection.

Recommendations for PO Control Mode

1. If the intersection has heavy pedestrian volume (e.g., intersections in the downtown area), the lead-lead sequence or lead-lag sequence should be avoided, unless there are other measures that could effectively prevent conflicts between left-turn vehicles and pedestrians. Reason: pedestrian safety considerations according to finding 1b in the section "General Findings for Both PO and PPLT Signal Control Modes."
2. Lead-lag sequence should be considered before lag-lag or lead-lead sequences, especially when left-turn volume is high. The approach with higher left-turn volume

should use the leading phase. Reason: safety considerations according to finding 1 in the section “Findings Only for PO Control Mode.”

3. Use the phasing sequence that is most common along the arterial and in a region. Reason: safety impacts of left-turn signal consistency according to finding 2a in the section “General Findings for Both PO and PPLT Signal Control Modes.”
4. When the signals in an arterial are two-way coordinated, choose the signal phasing sequence that will provide the widest two-way through bandwidth to achieve better signal progression. When the signals in an arterial are one-way coordinated (e.g., during the peak hour period), the lead-lag sequence should be considered and the approach in the coordinated direction should use the leading phase. Reason: operational efficiency considerations according to finding 1 in the section “General Findings for Both PO and PPLT Signal Control Modes.”

Recommendations for PPLT Control Mode

1. If the intersection has heavy pedestrian volume (e.g., intersections in the downtown area), the lead-lead sequence or lead-lag sequence should be avoided, unless there are other measures that could effectively prevent conflicts between left-turn vehicles and pedestrians. Reason: pedestrian safety considerations according to finding 1b in the section “General Findings for Both PO and PPLT Signal Control Modes.”
2. If the left-turn volume level is below 150 vehicles/hr, lead-lead sequence is recommended. If the left-turn volume is higher than 150 vehicles/hr, lead-lag sequence should be considered. The approach with higher left-turn volume should use leading sequence. Reason: safety considerations according to finding 1d in the section “Findings Only for PPLT Signal Control Mode.”
3. If lead-lag sequence is selected, Arlington or Dallas phasing should be considered to prevent the yellow trap problem. Reason: safety considerations according to finding 1c in the section “Findings Only for PPLT Signal Control Mode.”
4. Use the phasing sequence that is most common along the arterial and in a region. Reason: safety impacts of left-turn signal consistency according to finding 2a in the section “General Findings for Both PO and PPLT Signal Control Modes.”
5. When the signals in an arterials are two-way coordinated, choose the signal phasing sequence that will provide the widest two-way through bandwidth to achieve better signal progression. When the signals in an arterial are one-way coordinated (e.g., during the peak hour period), the lead-lag sequence should be considered and the

approach in the coordinated direction should use the leading phase. Reason: operational efficiency considerations according to finding 1 in the section "General Findings for Both PO and PPLT Signal Control Modes."

CHAPTER 9: GUIDELINES FOR LEFT-TURN SIGNAL DISPLAY

The objective of this chapter is to develop guidelines for determining left-turn signal display. The results from this chapter, combined with the results of Chapter 8, provide overall guidelines for determining left-turn signal design and will be used for the case studies in Chapter 10.

The guidelines are mainly based on the current standards for left-turn signal placement and display provided by the *Manual on Uniform Traffic Control Devices*. Findings from the literature review (Chapter 2), survey results (Chapter 3), safety evaluation (Chapter 5), and regional standardization benefits evaluation (Chapter 7) are also used to derive these comprehensive guidelines. By synthesizing all the findings, the guidelines provide recommendations for (1) selecting left-turn signal indication, (2) selecting left-turn signal arrangement, and (3) determining placement of left-turn signal heads. The developed guidelines are compared to the current standards of the MUTCD, and explanations are provided for recommendations that differ from MUTCD standards.

9.1 SELECTION OF LEFT-TURN SIGNAL INDICATION

Signal indication is the illumination of a signal lens that conveys a particular traffic control message to drivers. Typical left-turn signal indications are presented in Figure 65.

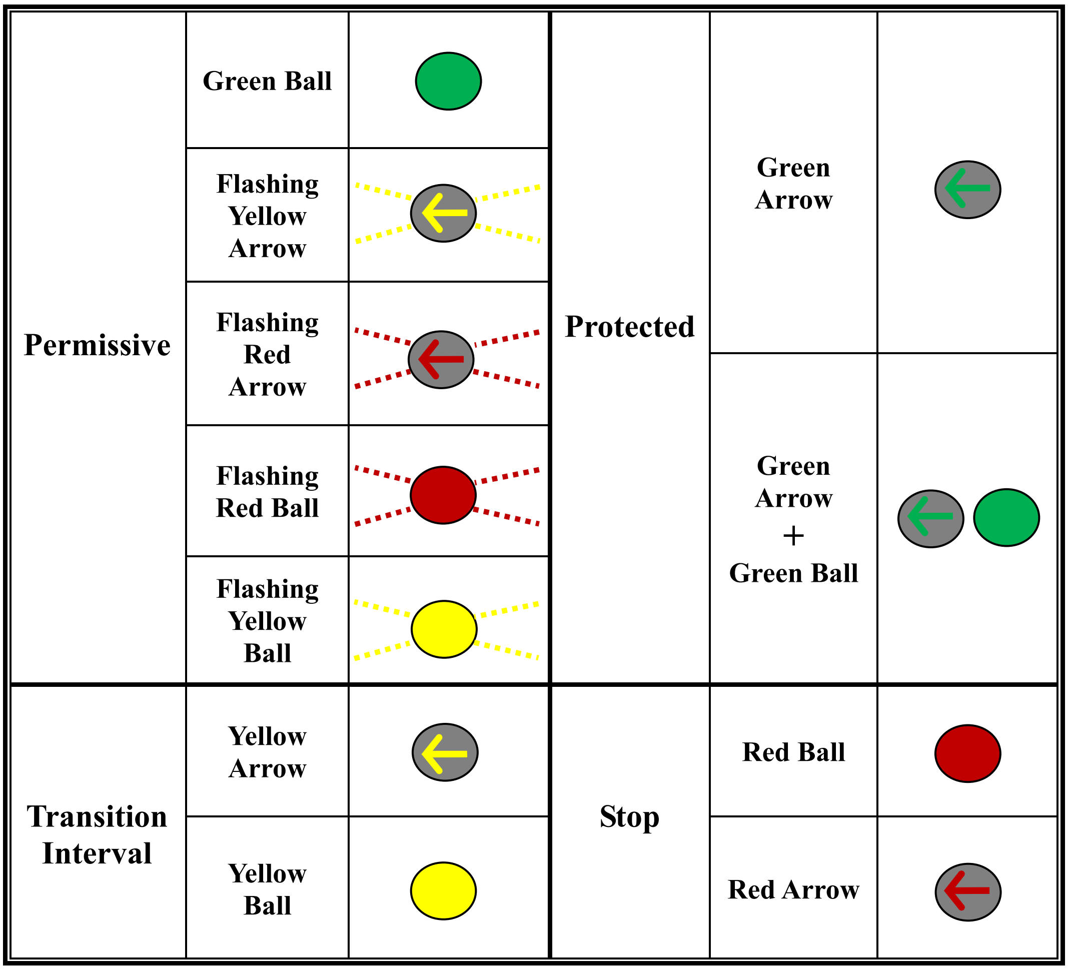


Figure 65: Typical Indications for Left-Turn Signal Display

For different left-turn signal control modes, guidelines regarding signal indication are provided as follows:

1. For protected-only mode: A left-turn green arrow signal face or a combination of left-turn green arrow and circular green ball signal face is required in the protected phase.
2. For permissive-only mode: During the permissive phase, the left-turn signal face shall display a circular green signal indication.
3. For PPLT mode: During the protected phase, a left-turn green arrow is required, while a circular green indication is required during the permissive phase. A flashing yellow arrow is recommended as an allowable indication to replace the green ball for the permissive phase on the following conditions:
   a. If FYA is implemented in one intersection, the whole arterial or the whole region should also be installed with FYA in order to maintain the consistency of signal indications.

b. A sign shall be placed with the left-turn signal head for PPLT mode, such as a LEFT TURN YIELD ON (plus a symbolic FYA) sign.

Difference with MUTCD Standards

A flashing yellow arrow is included as an allowable indication for the permissive phase in PPLT signal control mode.

Explanation of This Revision

A flashing yellow arrow has long been considered as a replacement for the "green ball" as the indication for the permissive phase for PPLT mode. It is recommended in these guidelines but not required to replace the GB for the following reasons:

1. If the intersection operates with PPLT lead-lag phasing, FYA eliminates the yellow trap problem and extends the permissive phase during the opposing protected lead and lag left-turn phase (Chapter 2).
2. A recent Federal Highway Administration (FHWA) project (Noyce et al. 2000) conducted a before-and-after accident analysis for FYA implementation and revealed that safety was improved at intersections that operated with PPLT phasing after the replacement of the GB indication with an FYA indication for the permissive left-turn phase.
3. A field conflict study was conducted (Kacir et al. 2003) at PPLT intersections installed with FYA and GB, which concluded that there is no significant difference in conflicts caused by FYA and GB.
4. Kacir et al. 2003 used simulator technology and a follow-up computer-based photographic survey to evaluate drivers' understanding of FYA. The results showed that people could understand FYA as well as they understood GB.
5. Although all the current studies demonstrated a positive effect of FYA in either safety or operational aspects, there are the following concerns about FYA permissive indications:
   a. Even though the report mentioned above (Noyce et al. 2007) showed that FYA operation results in a reduction in the accident rate as compared to the GB indication, the sample size may not be large enough to validate this conclusion (a total of 21 study sites with most of them having FYA implemented for less than 2 years).

b. If the FYA permissive indication is used for PPLT mode, there will be two permissive indications, i.e., GB for permissive-only mode and FYA for the permissive phase in PPLT mode. Since these two indications convey the same message to drivers, i.e., they should yield to the opposing through vehicles, it might cause driver confusion.
c. During this project, some traffic engineers were interviewed for their opinion on using FYA instead of GB as the indication for the permissive phase during PPLT control mode. There is a concern that drivers might mistake FYA for a steady yellow arrow (e.g., by a glance at the signal) and assume that they can sneak into the intersection, which may actually increase the risk of a crash between the left-turn and opposing through vehicles.

9.2 SELECTION OF LEFT-TURN SIGNAL ARRANGEMENT

Signal indications are arranged in different ways, including different orientations (horizontal, vertical, and cluster arrangements) and different numbers of signal lenses in a signal head (three-section, four-section, and five-section arrangements). Typical arrangements are presented in Figure 66.

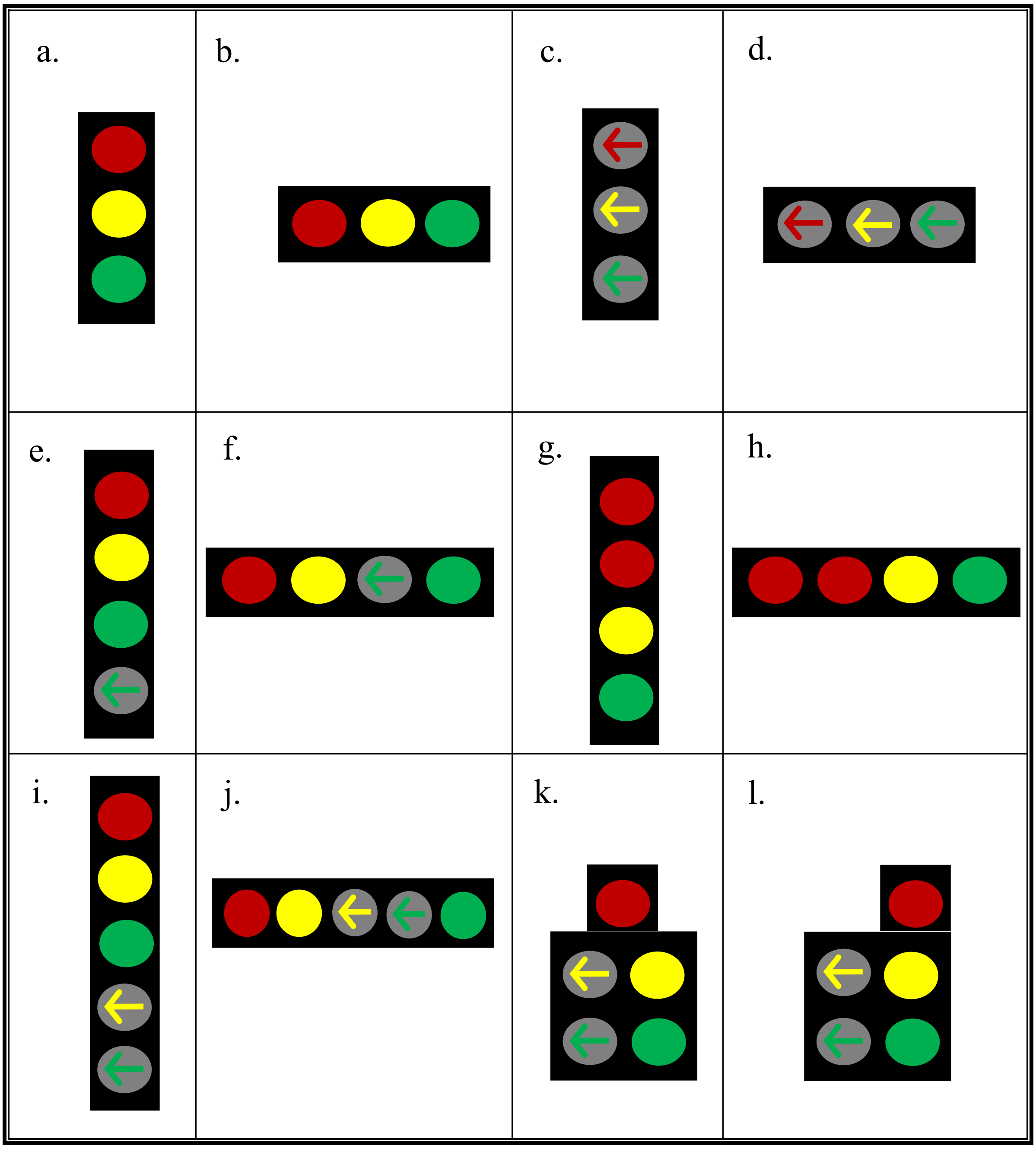


Figure 66: Variations of Signal Arrangements

For different left-turn signal control modes, different guidelines regarding the signal arrangement are provided as follows:

1. For protected-only mode: it is required that at least one exclusive left-turn signal head be provided for protected-only mode. Three- or four-section horizontal or vertical signal arrangement is recommended to be used, as shown in Figure 67.

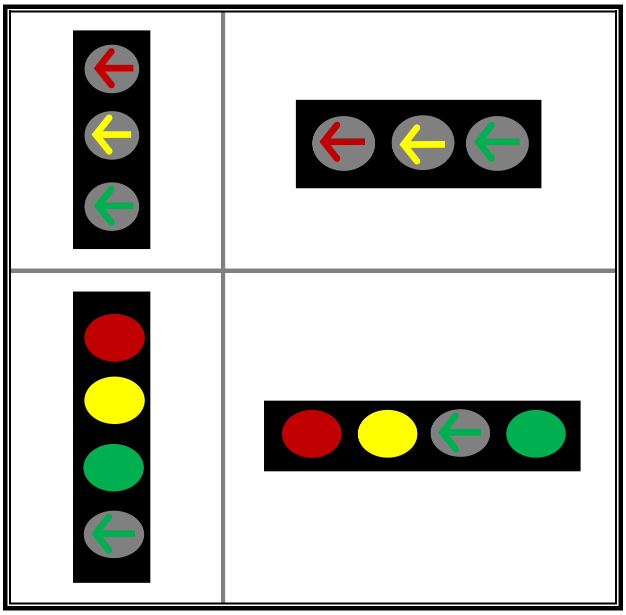


Figure 67: Recommended Left-Turn Signal Arrangement for PO Mode

2. For permissive-only mode: A three-section horizontal or vertical signal head is suggested to be used for permissive mode. It is better to use an exclusive signal for left-turn movement.
3. For PPLT mode: It is strongly recommended but not required that an exclusive signal head be used rather than a signal head shared with the through movement. Four-section signal arrangement is suggested if an exclusive signal head is used, of which the four-section vertical type is better. If a shared signal head has to be used, a five-section signal head should be used, of which the five-section cluster is preferred over the five-section horizontal arrangement (Figure 68). A sign shall be used for the shared signal head, such as LEFT TURN SIGNAL or LEFT TURN YIELD ON GREEN (plus a symbolic circular green indication). In addition, if the signal phasing sequence is lead-lag, Dallas or Arlington signal phasing can be considered to prevent the "yellow trap" problem.

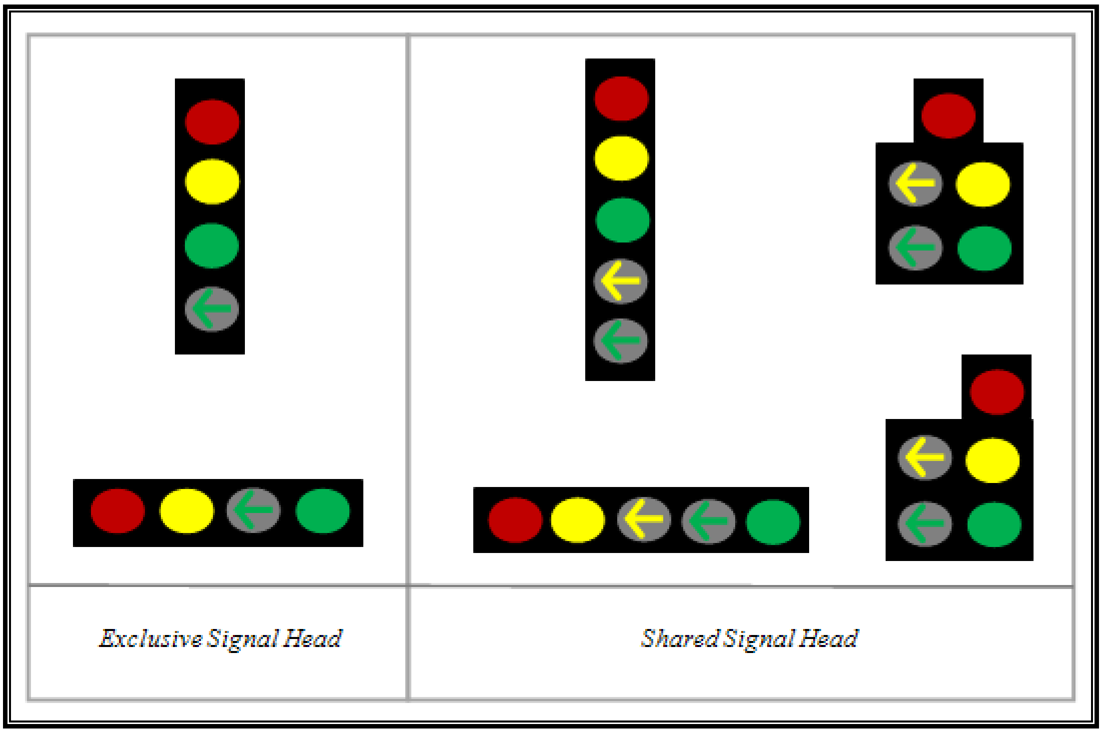


Figure 68: Recommended Left-Turn Signal Arrangement for PPLT Mode

In addition, it is recommended that a consistent signal arrangement be used within the area or along the corridor.

Difference with MUTCD Standards

The MUTCD does not recommend use of an exclusive signal head or give any suggestions on how to select among different signal arrangement types.

Explanation of These Revisions

1. Survey results in Chapter 2 indicate that it would improve safety at intersections if an individual signal display is provided for each movement. Therefore, an exclusive left-turn signal head is recommended for each signal control type.
2. The simultaneous signal indication of conflicting color (green arrow and red ball) in one left-turn signal head occurs when using a shared signal head for PPLT signal control mode (i.e., five-section horizontal/vertical/cluster signal arrangement). It is found in the literature (Asante et al. 1993, Bonneson and McCoy 1993, Kacir et al. 2003) that simultaneously displaying the green arrow and red ball indication in the same signal display confuses many drivers (see Chapter 2 for details). Therefore, an exclusive signal display is strongly recommended for PPLT mode.

3. It is also found in the literature (Kacir et al. 2003) that exclusive four-section vertical signal heads for PPLT mode are associated with the least driver confusion.
4. Results presented in Chapter 5 showed that a five-section cluster is comparatively safer than a five-section horizontal signal arrangement.
5. Dallas or Arlington signal operation would mitigate the yellow trap problem caused by PPLT lead-lag signal phasing (see Chapter 2 for details).
6. Results from Chapter 7 showed that the consistent usage of signal display would improve intersection safety.

9.3 DETERMINATION OF THE PLACEMENT OF LEFT-TURN SIGNAL HEADS

9.3.1 Determination of the Horizontal Location of Signal Heads

The determination of the horizontal placement of signal heads should be based on the size of the signal lens and the use of a supplemental signal face. As illustrated in Figure 69, if no supplemental signal face is installed, the distance of the signal heads from the stop line should be in a range of (1) not less than 40 ft nor more than 120 ft for a 200 mm (8 in) signal lens and (2) not less than 40 ft nor more than 150 ft for a 300 mm (12 in) signal lens. If a supplemental signal face is installed, the distance of the signal heads from the stop line should be in a range of (1) not less than 40 ft nor more than 150 ft for a 200 mm (8 in) signal lens and (2) not less than 40 ft nor more than 180 ft for a 300 mm (12 in) signal lens.

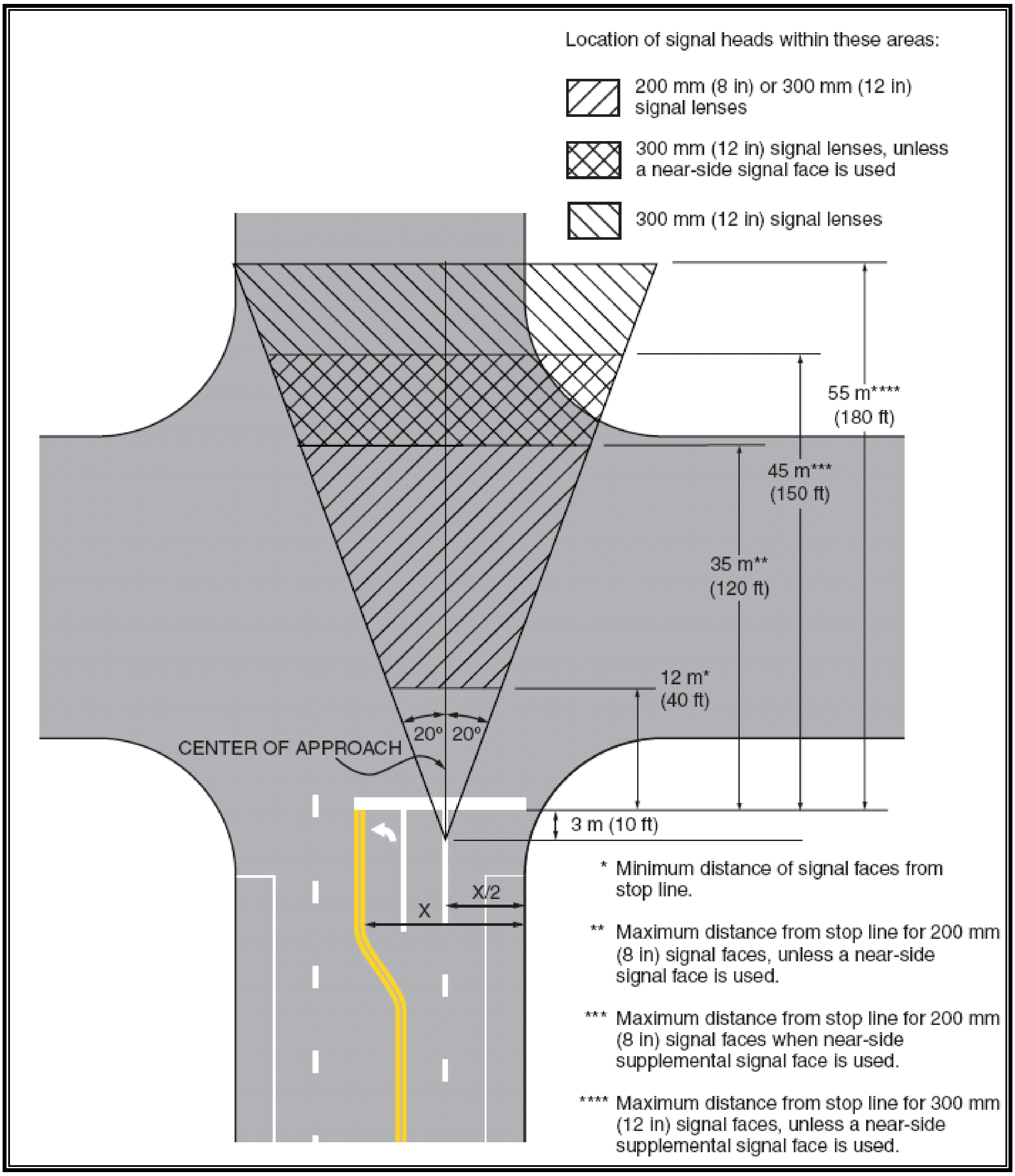
In addition, as shown in Figure 69, the signal shall be located between two lines intersecting with the center of the approach lanes at the stop line, one making an angle of approximately 20 degrees to the right of center of the approach and the other making an angle of approximately 20 degrees to the left of the center of the approach (MUTCD). If more conspicuity is desired, it is suggested that this 20-degree “cone of vision” be reduced to 10 degrees (King 1977).

Difference with MUTCD Standards

There is a minor revision in the degrees of the “cone of vision.”

Explanation of This Revision

The literature, i.e., King (1977), suggests use of a 10-degree “cone of vision” to achieve better conspicuity for drivers.



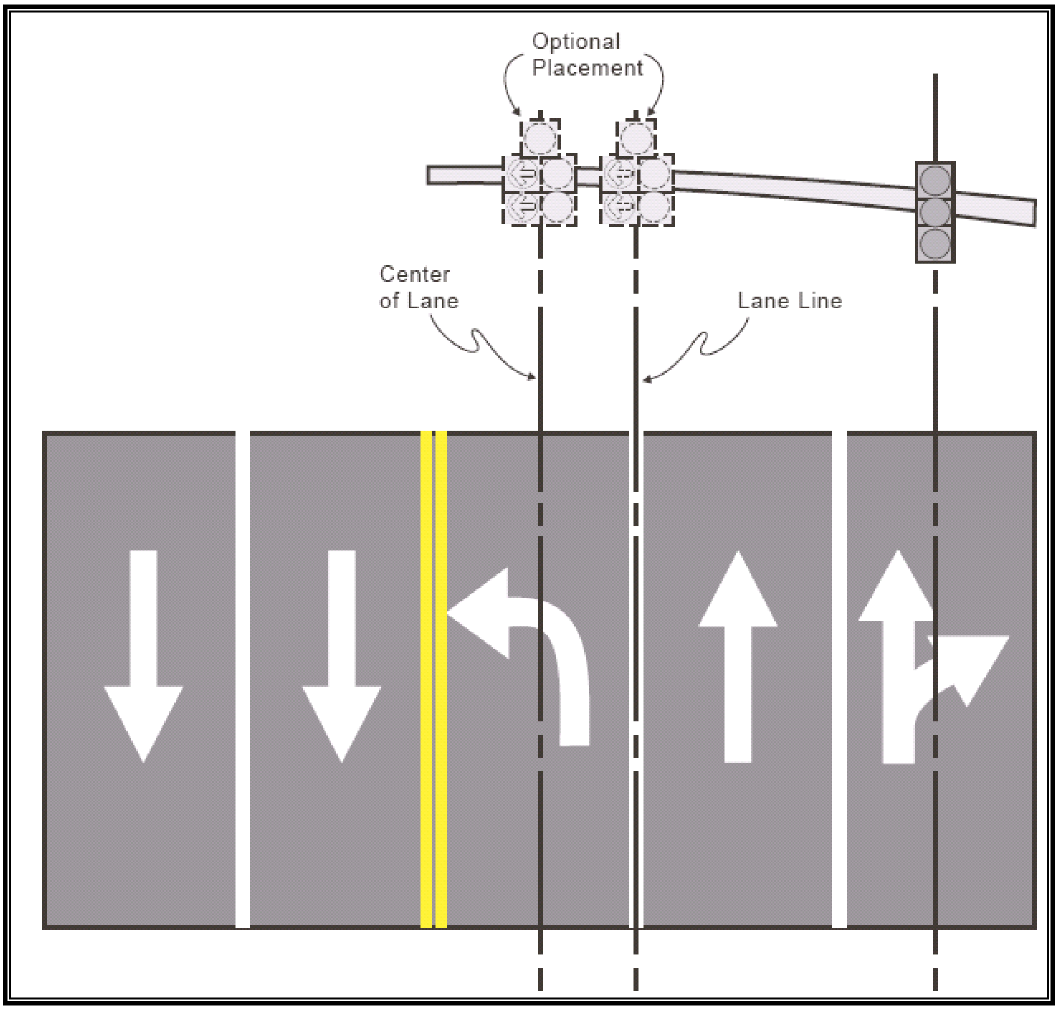
Source: MUTCD 2003 Revision Version

Figure 69: Criteria for Horizontal Location of Signal Face

9.3.2 Specific Placement Criteria for Left-Turn Signal Head

For different types of left-turn signal control modes, specific placement criteria for the left-turn signal head are recommended as follows:

1. For permissive-only mode: The signal head for permissive mode should be located in line with the lane line or with the center of the left-turn lane. If an exclusive signal head is used, it should be located in the center of the left-turn lane.
2. For protected-only mode: The signal head should be located in line with the center of the left-turn lane, overhead on the far side of the intersection, or ground mounted in the median.
3. For PPLT mode: The signal head can be located either in line with the center of the left-turn lane or the lane line (see Figure 70). If an exclusive signal head is used, it should be located in line with the center of the left-turn lane or ground mounted in the median.



Source: Kacir et al. 2003

Figure 70: Overhead PPLT Display Placement Options

Difference with MUTCD Standards

There is a minor revision in that the signal head is recommended to be in line with the center of the left-turn lane for PPLT and permissive-only signal control modes.

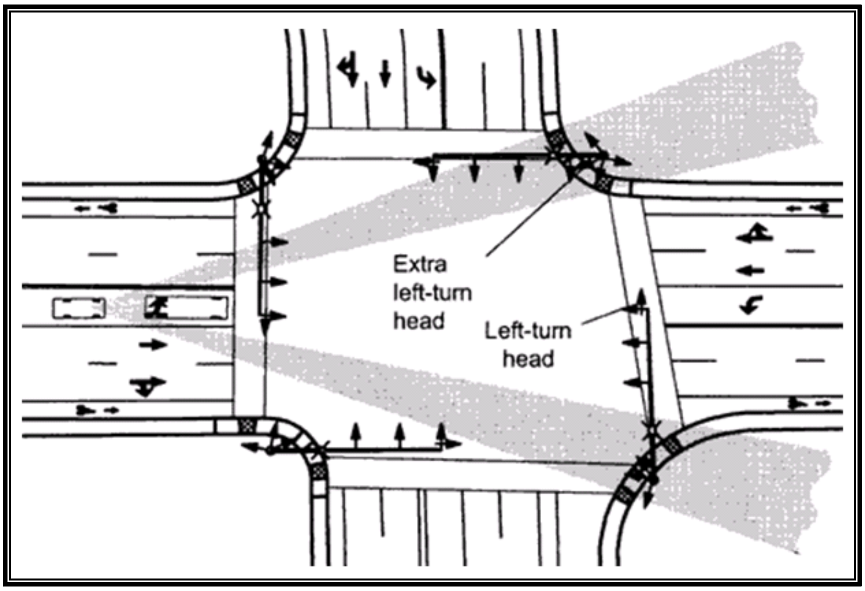
Explanation of This Revision

Survey results from Chapter 3 suggested that the signal heads should be placed in the center of each lane.

9.3.3 Determination of the Use of Supplemental Left-Turn Signal Heads

To achieve intersection visibility both in advance and immediately before the signalized location, supplemental left-turn signal heads should be used under some conditions based on engineering judgment. These guidelines recommend two types of supplemental signal heads under certain circumstances mentioned below; however, the decision to use these supplemental signal heads should not be limited to these circumstances and should be based on engineering judgment according to the intersection features:

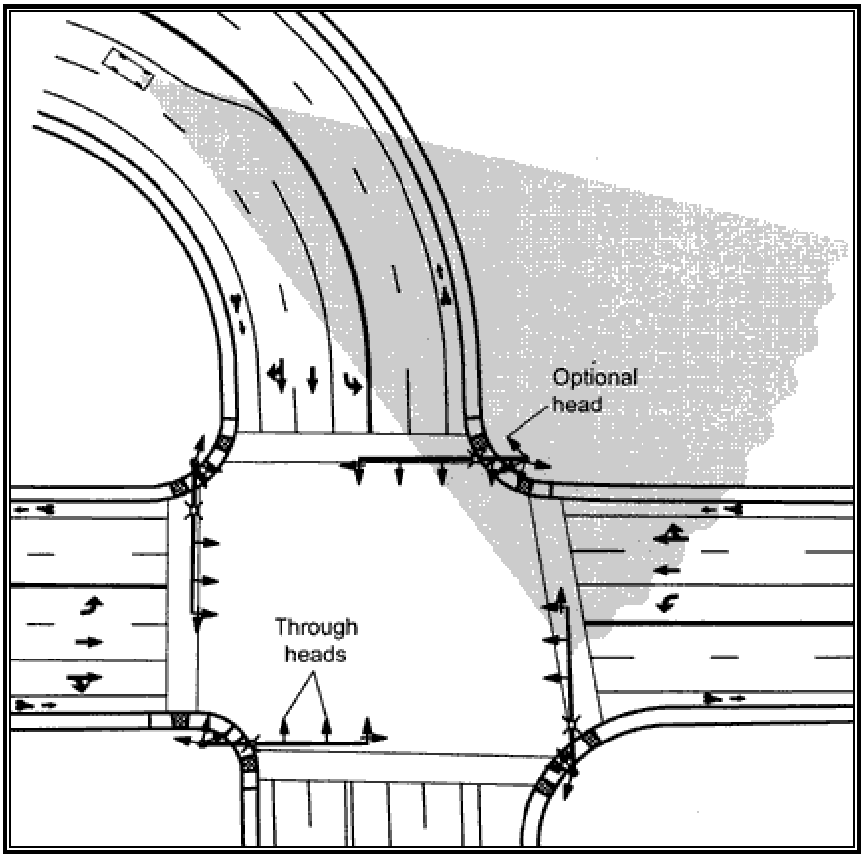
1. Far-side supplemental left-turn signal head: As shown in Figure 71, this is an extra left-turn signal head that is located in the far-side corner of the intersection. It should be considered under the following conditions:
    a. The intersection is comparatively large. The supplemental signal head can better guide left-turning vehicles across a wide intersection as they make their turn.
    b. The intersection may have relatively more heavy or large vehicles. The supplemental signal head helps improve visibility for vehicles behind large vehicles.
    c. The visibility of signal indications (color) is affected by sun glare during certain time periods of the day when the sun is near the horizon (e.g., the pair of approaches is in the west-east direction). The supplemental signal head can mitigate the risk caused by sun glare.



Source: Rodegerdts (2004)

Figure 71: Far-Side Supplemental Left-Turn Signal Head

2. Near-side supplemental left-turn signal head: A near-side supplemental signal head can be mounted in the median of the study approach (if the intersection has a median) or in the near-side corner of the intersection as shown in Figure 72. It should be considered under the following conditions:
   a. When visibility is hampered by a curve in the roadway upstream of the intersection, a near-side signal head can be used to provide an advance indication for vehicles coming from the curve.
   b. If the alignment of the intersection is not good, i.e., the two directions are not perpendicular to each other, the use of a near-side supplemental signal head might improve visibility for drivers.



Source: Rodegerdts (2004)

Figure 72: Near-Side Supplemental Left-Turn Signal Head

Difference with MUTCD Standards

The MUTCD does not provide information about under what conditions supplemental signal heads should be used.

Explanation of This Revision

These guidelines combine recommendations on the use of supplemental signal heads from the Federal Highway Administration (*Traffic Design and Illumination*).

CHAPTER 10: CASE STUDIES

This chapter demonstrates the application of the developed guidelines by using case studies. It consists of two parts. In the first part, the guidelines developed in Chapter 8 for left-turn signal phasing are applied to four study intersections selected in Chapter 4. In the second part, the guidelines for signal display developed in Chapter 9 are applied to two selected study intersections and one newly selected intersection in Houston, Texas.

10.1 CASE STUDIES FOR APPLICATION OF GUIDELINES ON LEFT-TURN SIGNAL PHASING

10.1.1 Case 1 — Intersection at Airport Boulevard and 51st Street in Austin, Texas

10.1.1.1 Intersection Description

The study intersection, Airport Boulevard and 51st Street, is located in northern Austin, Texas. The northbound approach of the intersection was selected as the subject approach. For the northbound (NB) and southbound (SB) approaches, the current signal control mode is protected/permissive left turn, and the current signal phasing sequence is lead-lag with the NB approach using the leading phase. Both the NB and SB approaches have one left-turn lane and two through lanes, and the speed limit of both approaches is 40 mph. During the AM peak hour period, the NB left-turn traffic volume is 90 veh/h, the NB through traffic volume is 765 veh/h, the SB left-turn traffic volume is 74 veh/h, and the SB through traffic volume is 990 veh/h. The intersection's geometric conditions, current traffic signal controls, and traffic volume information are presented in Figure 72.

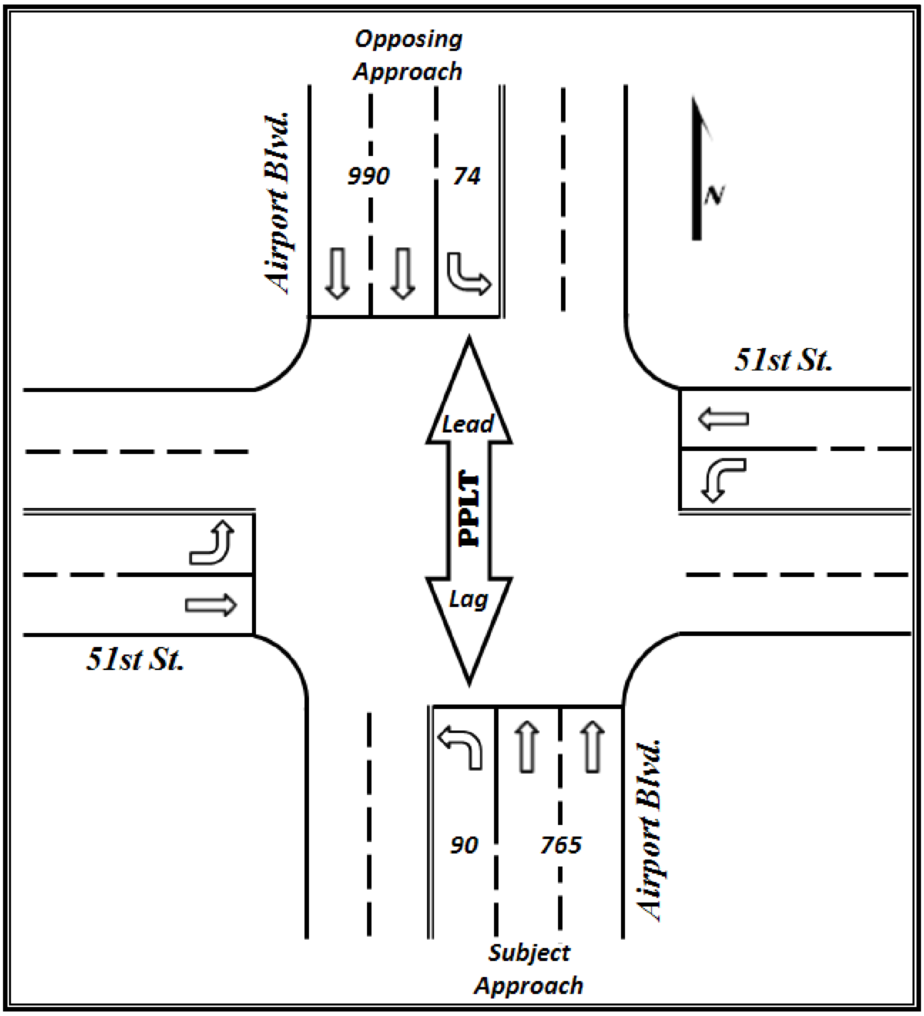


Figure 73: Basic Information for the Intersection at Airport Boulevard and 51st Street

10.1.1.2 Application of Guidelines for Selecting Signal Control Mode

According to the decision-making flowchart developed in Chapter 8, the appropriate signal control mode can be selected for this study intersection by following these steps:

Step 1. Check the Left-Turn Traffic Volume. Both left-turn volumes of northbound and southbound approaches are between 50 veh/h and 300 veh/h. Therefore, the signal control mode of the north-south (NS) directions of this study intersection should choose between protected-only and PPLT.

Step 2. Check the Number of Left-Turn–Related Accidents. The accident record of this study intersection from January 1, 2005, to February 2, 2008, shows that there were five left-turn–related accidents between May 2005 and December 2006, which does not satisfy any criteria listed for choosing PO mode. Therefore, the selection procedure continues.

Step 3. Check the Speed Limit of Opposing Through Traffic. The speed limit of both the northbound and southbound approaches is 40 mph, which is lower than 45 mph (the criterion for selecting PO mode). Thus, go to the next selection step.

Step 4. Check the Sight Distance for Left-Turn Movements. The sight distances for both the northbound and southbound movements are measured by using a Google map (see Figure 74). From Figure 74, it can be seen that both sight distances are just over 400 ft. Therefore, under the condition that the opposing through traffic speed is 40 mph (higher than 35 mph), PO mode cannot be warranted for this location at this step. Thus, go to the next selection step.

Step 5. Check the Number of Lanes. If an approach has two or more left-turn lanes, or three or more opposing through lanes, PO mode must be installed for this intersection. However, both the northbound and southbound approaches of this study intersection have only one left-turn lane and two opposing through lanes. Thus, go to the next selection step.

Step 6. Check the Cross Product of Volume per Lane. The northbound CPOV is 44,550, and the southbound CPOV is 28,305. For the two opposing through lanes, the threshold for selection between PO and PPLT modes is 93,000. Since both the NB and SB CPOVs at this intersection are lower than this threshold, PPLT mode should be used for the NB and SB approaches of this intersection.

Summary. By following the decision-making flowchart developed in Chapter 8, it is found that PPLT mode is the most appropriate signal control mode for the NB and SB approaches of this study intersection. Since the current signal control mode is also PPLT, no change is recommended for this location.

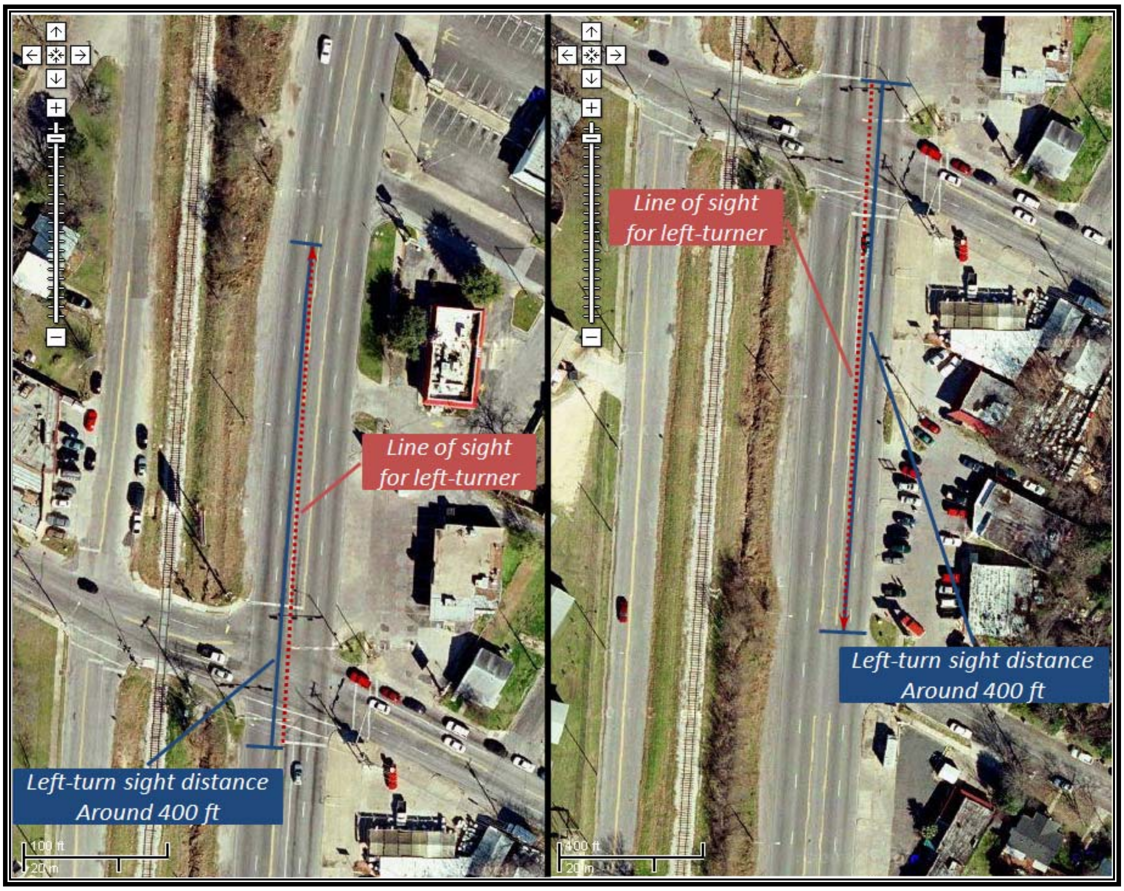


Figure 74: Sight Distances for the Left-Turn Movements at NB and SB Approaches of the Intersection at Airport Boulevard and 51st Street

10.1.1.3 Application of Guidelines for Selecting Signal Phasing Sequence

Since PPLT mode is selected for the subject approaches (NB and SB), signal phasing sequence guidelines for PPLT mode (see Chapter 8) could be applied to this intersection using the following steps:

Step 1: Pedestrian Volume Check. This intersection is not located in a downtown area. There is almost no pedestrian volume. Therefore, both the leading phase and lagging phase can be used for this intersection.

Step 2: Left-Turn Volume Check. Left-turn volume in the subject direction is 90 veh/h, which is below 150 veh/h. Therefore, lead-lead sequence is recommended.

Step 3: Arlington or Dallas Phasing Check. Since lead-lead phasing sequence is recommended, Arlington or Dallas phasing is not applicable for this intersection.

Step 4: Signal Phasing Consistency Check. Left-turn phasing information for the other intersections along Airport Boulevard is not available. Therefore, this step is skipped for this case study.

Step 5: Bandwidth Check. From Figure 73, it can be seen that traffic flow on the major street Airport Boulevard is not directional. Thus, signals on this arterial are two-way coordinated. In this study, the signal optimization software SYNCHRO is used to set up the signal splits under different types of signal phasing sequences. By comparing the two-way bandwidth under different types of signal phasing sequences (see Figures 75 through 78), it is found that lead-lag phasing with NB being the leading phase provides the widest two-way bandwidth. Actually, in this intersection, the bandwidths under different sequences are very close.

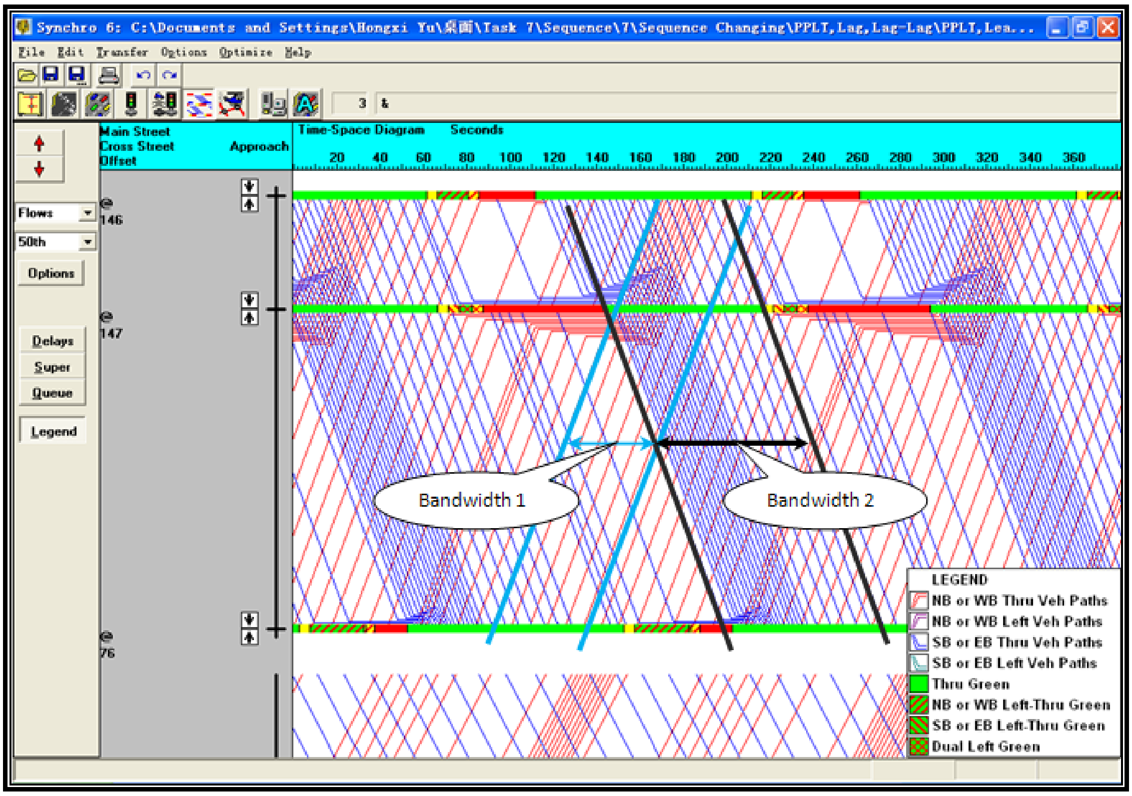


Figure 75: SYNCHRO Time-Spacing Diagram under Lag-Lag Phasing

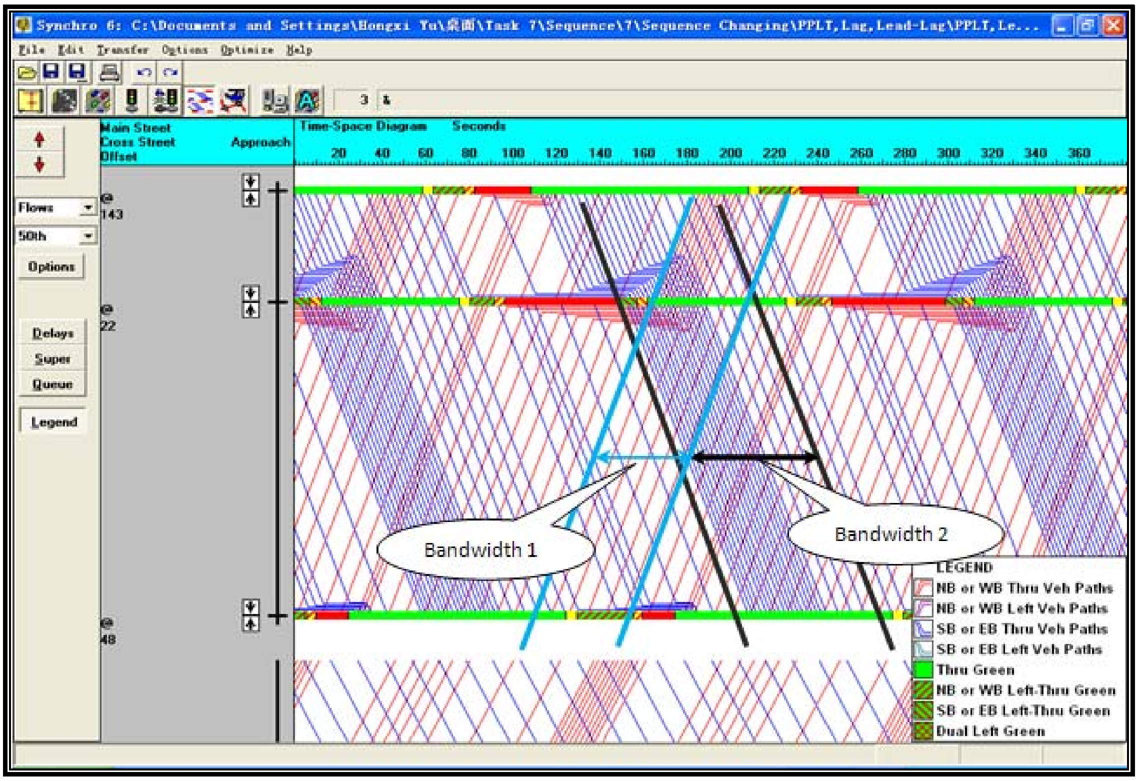


Figure 76: SYNCHRO Time-Spacing Diagram under Lead-Lag Phasing with NB Being the Leading Phase

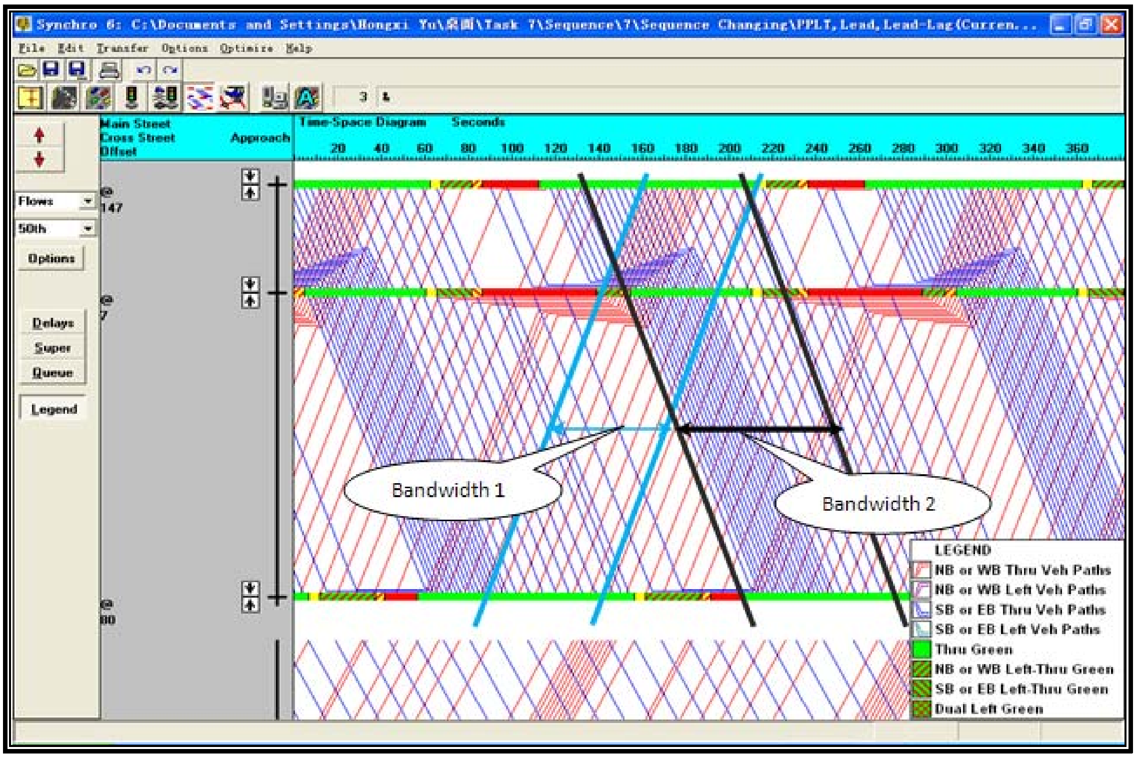


Figure 77: SYNCHRO Time-Spacing Diagram under Lead-Lag Phasing with NB Being the Leading Phase

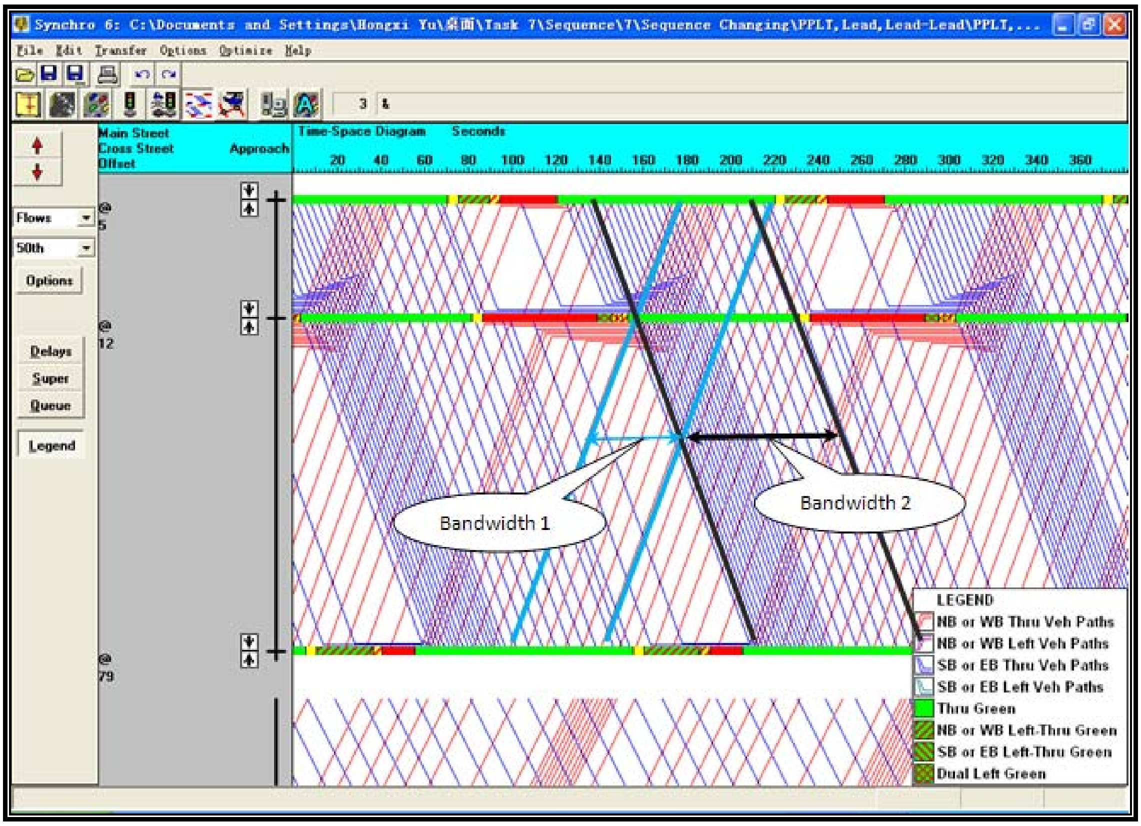


Figure 78: SYNCHRO Time-Spacing Diagram under Lead-Lead Phasing

Summary. Combining the results from step 1 to step 5, it is found that step 2 recommends lead-lead phasing sequence and step 5 recommends lead-lag phasing sequence with NB being the leading phase. Since the criteria for step 2 have higher priority than that for step 5 and the two-way through bandwidths under these two sequences are quite close, lead-lead phasing sequence is recommended for this intersection.

10.1.2 Case 2 — Intersection at 29th Street and Lamar Boulevard in Austin, Texas

10.1.2.1 Intersection Description

The study intersection, 29th Street and Lamar Boulevard, is located in Austin, Texas. The westbound approach (WB) of the intersection was selected as the subject approach, and the eastbound (EB) approach was the opposing approach. The current signal control mode for this pair of approaches is PPLT, and the current phasing sequence is lead-lead. The WB approach has one left-turn lane and one through lane, and the EB approach has one left-turn lane, one through lane, and one right-turn lane. The speed limit of both approaches is 30 mph. During the peak hour period, the WB left-turn traffic volume is 70 veh/h, the WB through traffic volume is 130 veh/h, the EB left-turn traffic volume is 84 veh/h, and the EB through traffic volume is 176 veh/h. The intersection's geometric conditions, current traffic signal controls, and traffic volume information are presented in Figure 79.

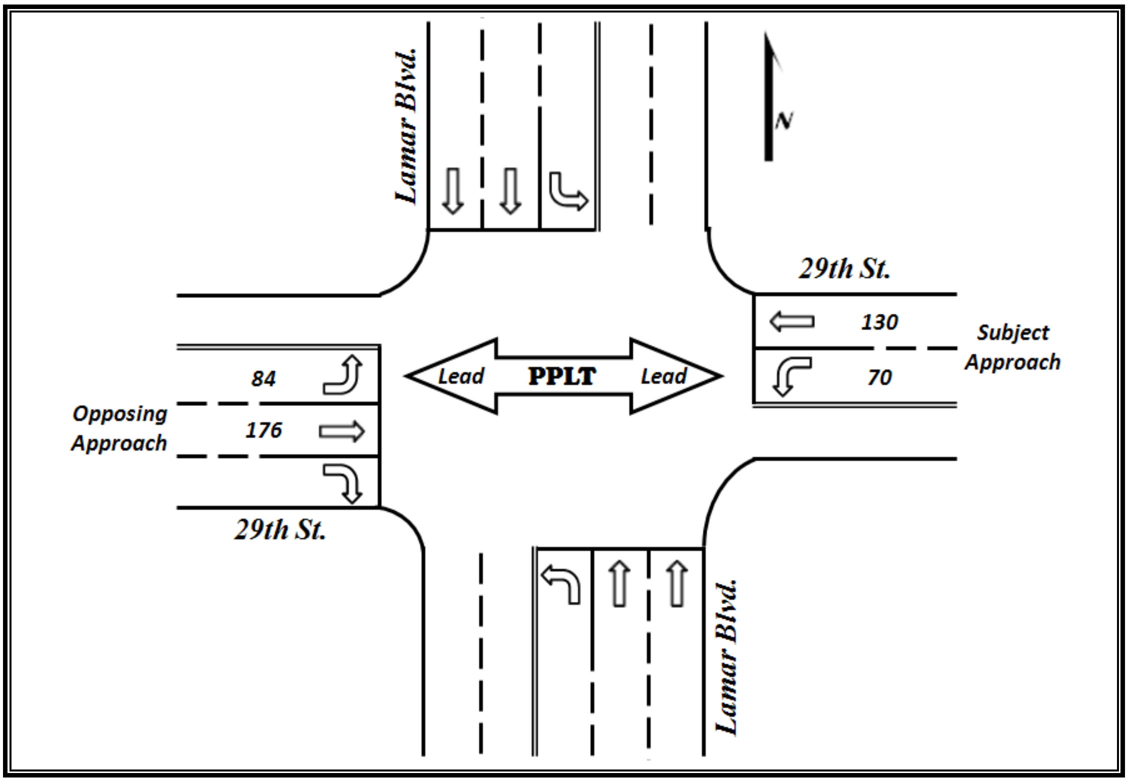


Figure 79: Basic Information for the Intersection at 29th Street and Lamar Boulevard

10.1.2.2 Application of Guidelines for Selecting Signal Control Mode

According to the decision-making flowchart developed in Chapter 8, the appropriate signal control mode can be selected for this study intersection by following these steps:

Step 1. Check the Left-Turn Traffic Volume. Both left-turn volumes of the WB and EB approaches are between 50 veh/h and 300 veh/h. Therefore, the signal control mode of the west-east (WE) directions of this study intersection should choose between PO and PPLT.

Step 2. Check the Number of Left-Turn–Related Accidents. The accident record of this study intersection shows that there has been only one left-turn–related accident in the past 4 years. Since it does not satisfy any criteria listed for choosing PO mode, the selection procedure continues.

Step 3. Check the Speed Limit of Opposing Through Traffic. The speed limit for both WB and EB approaches is 30 mph, which is lower than 45 mph (the criterion for selecting PO mode). Thus, go to the next selection step.

Step 4. Check the Sight Distance for Left-Turn Movements. The sight distances for both WB and EB left-turn movements are measured by using a Google map (see Figure 80). From Figure 80, it can be seen that the sight distance for EB is 270 ft and for WB is 160 ft. Since, the WB sight distance is less than 250 ft when the opposing through traffic speed is less than 35 mph, PO mode should be installed for the WB approach. For the EB approach, the selection procedure continues.

Step 5. Check the Number of Lanes. If an approach has two or more left-turn lanes, or three or more opposing through lanes, PO mode must be installed for this intersection. The EB approach of this study intersection has only one left-turn lane and one opposing through lane. Thus, go to the next selection step.

Step 6. Check the Volume Cross Product per Lane. The CPOV of the EB approach is 10,920, which is below the threshold of one opposing through lane for the selection of PO or PPLT mode (133,000). Therefore, PPLT could be installed for the EB direction of this intersection.

Summary. By following the decision-making flowchart in Chapter 8, it is found that PO mode is the most appropriate signal control mode for the WB direction due to the limited sight distance at this approach. It is also found that PPLT mode is the most appropriate signal control mode for the EB direction of the study intersection. However, in order to keep the consistency of signal control in this intersection, PO mode is selected for the WE directions of this intersection, which is different from the current signal control mode, i.e., PPLT.

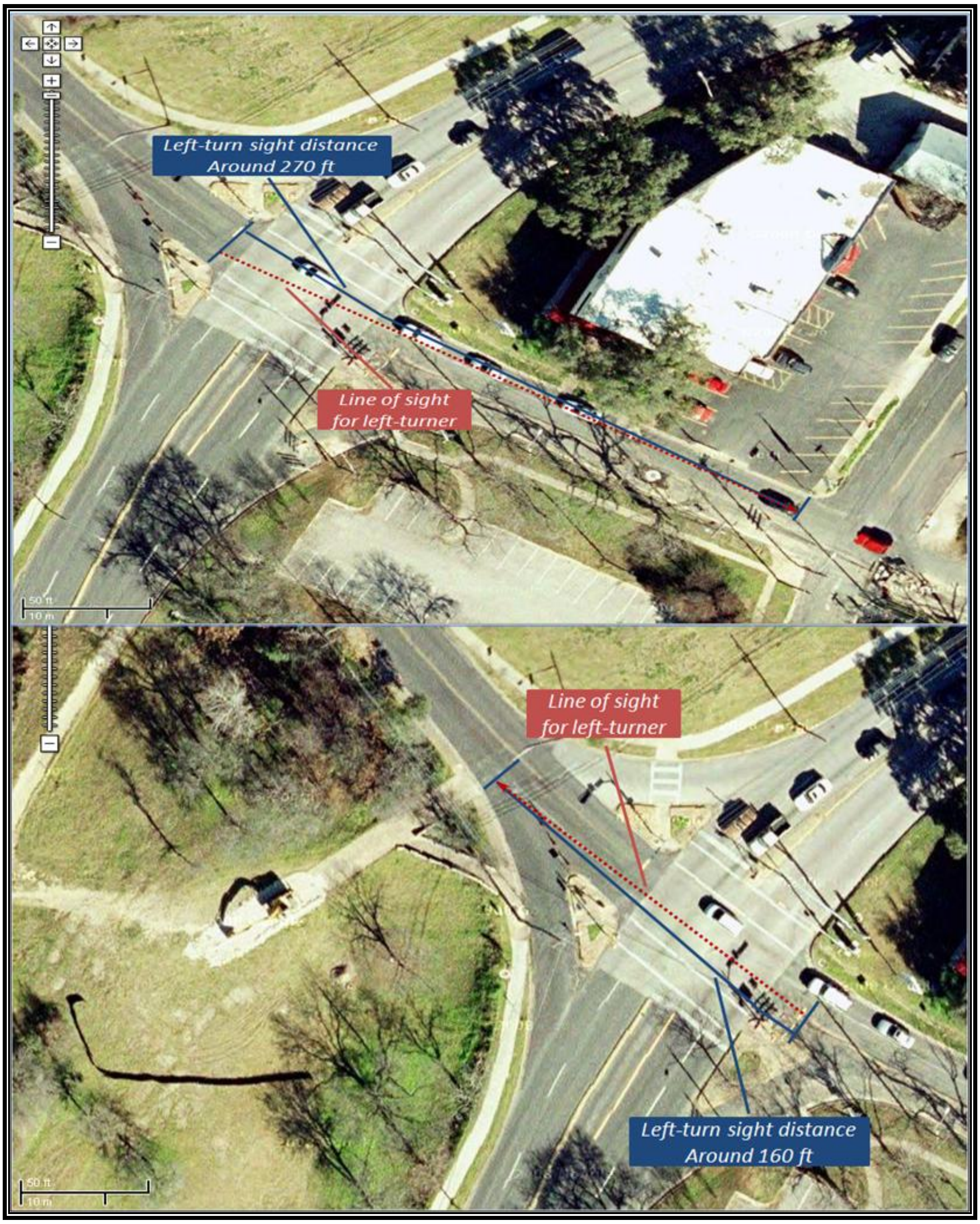


Figure 80: Sight Distances for the Left-Turn Movements at WB and EB Approaches of the Intersection at 29th Street and Lamar Boulevard

10.1.2.3 Application of Guidelines for Selecting Signal Phasing Sequence

Since PO mode is selected for the WB and EB approaches of this intersection, signal phasing sequence guidelines for PO mode (see Chapter 8) could be applied to this intersection by following these steps:

Step 1: Pedestrian Volume Check. This intersection is not located in a downtown area. There is very low pedestrian volume. Therefore, both the leading phase and lagging phase can be used for this intersection.

Step 2: Left-Turn Volume Check. Lead-lag sequence is recommended for this intersection because PO mode is selected. In addition, since the WB left-turn volume is 70 veh/h and the EB left-turn volume is 84 veh/h, EB should use the leading phase.

Step 3: Signal Phasing Consistency Check. Left-turn phasing information for the intersections along 29th Street is not available. Therefore, this step is skipped for this case study.

Step 4: Bandwidth Check. In this intersection, the signal is coordinated in the NS directions. Therefore, this step is not applicable for the WE direction signal phasing sequence selection.

Summary. Combining the results from step 1 to step 4, the lead-lag phase with EB being the leading phase is recommended for this intersection.

10.1.3 Case 3 — Intersection at Lamar Boulevard and 38th Street in Austin, Texas

10.1.3.1 Intersection Description

The study intersection, Lamar Boulevard and 38th Street, is located in Austin, Texas. The NB approach of the intersection was selected as the subject approach, and the SB approach was the opposing approach. The current signal control mode for this pair of approaches is PPLT, and the current phasing sequence is lead-lag with the NB approach being the leading phase. The NB approach has one left-turn lane, two through lanes, and one right-turn lane, and the SB approach has one left-turn lane and two through lanes. The speed limit of both approaches is 40 mph. During the peak hour period, the NB left-turn traffic volume is 151 veh/h, the NB through traffic volume is 591 veh/h, the SB left-turn traffic volume is 143 veh/h, and the EB through traffic volume is 742 veh/h. The intersection's geometric conditions, current traffic signal controls, and traffic volume information are presented in Figure 81.

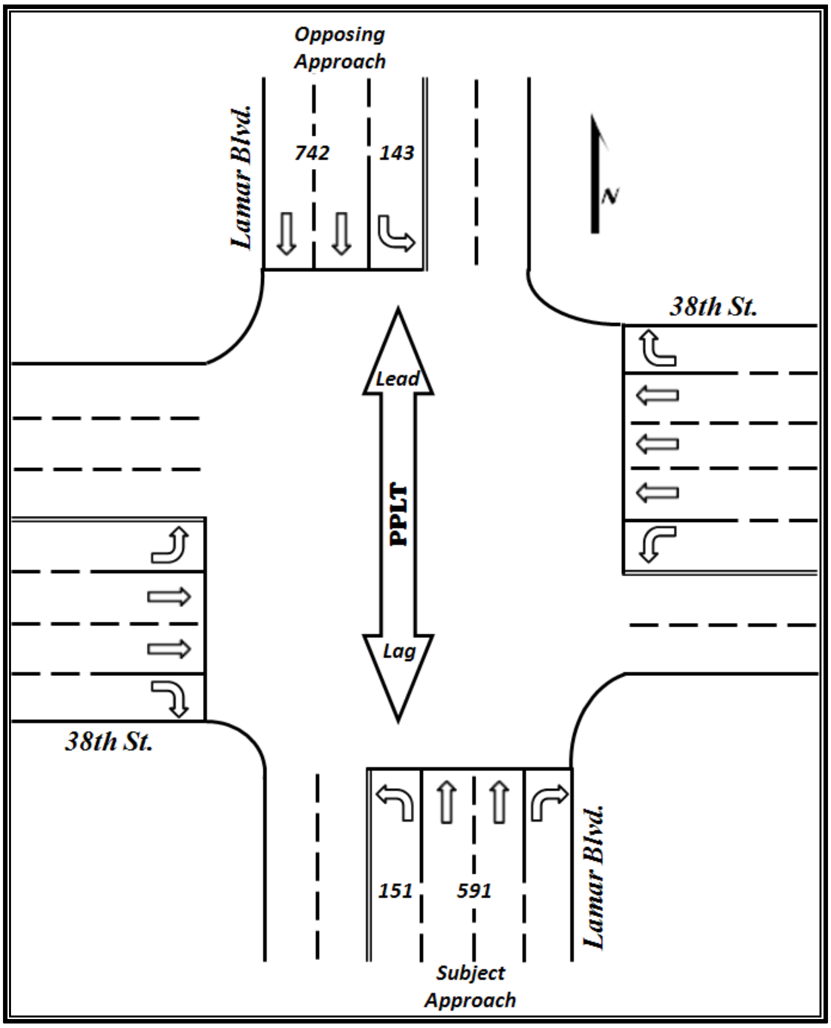


Figure 81: Basic Information for the Intersection at Lamar Boulevard and 38th Street

10.1.3.2 Application of Guidelines for Selecting Signal Control Mode

According to the decision-making flowchart developed in Chapter 8, the appropriate signal control mode can be selected for this study intersection by following these steps:

Step 1. Check the Left-Turn Traffic Volume. Both NB and SB left-turn volumes are between 50 veh/h and 300 veh/h. Therefore, the signal control mode of the NS directions of this study intersection should be chosen between PO and PPLT.

Step 2. Check the Number of Left-Turn–Related Accidents. The accident record of this study intersection shows that seven left-turn–related accidents occurred between October 2004 and June 2007. And five of these accidents happened in a 12-month period between July 2006 and June 2007 for NB. Since one listed criteria for choosing PO mode is satisfied, which is five or more left-turn–related accidents per approach during any 12-month period in the past 3 years, PO mode should be used for the NS directions of this study intersection. Thus, the selection procedure stops at this step.

Summary. By following the decision-making flowchart developed in Chapter 8, PO mode is the most appropriate signal control mode for the NS directions of this study intersection, which is different from the current signal control mode, i.e., PPLT.

10.1.3.3 Application of Guidelines for Selecting Signal Phasing Sequence

Since PO mode is selected for the NB and SB approaches of this intersection, signal phasing sequence guidelines for PO mode (see Chapter 8) could be applied for this intersection by following these steps:

Step 1: Pedestrian Volume Check. This intersection is located in a downtown area. However, there is very low pedestrian volume (30 pedestrians/hr). Therefore, both the leading phase and lagging phase can be used for this intersection.

Step 2: Left-Turn Volume Check. Lead-lag sequence is recommended for this intersection because PO mode is selected. In addition, since SB left-turn volume is 143 veh/h and NB left-turn volume is 151 veh/h, NB should use the leading phase.

Step 3: Signal Phasing Consistency Check. Left-turn phasing information for the other intersections along Lamar Boulevard is not available. Therefore, this step is skipped for this case study.

Step 4: Bandwidth Check. From Figure 81, it can be seen that the traffic flow on Lamar Boulevard is not very directional. Thus, signals on this arterial should be two-way coordinated. Like case study 1, the signal optimization software SYNCHRO was used to set up the signal splits under different types of signal phasing sequences. By comparing the two-way bandwidth under different types of signal phasing sequences, it was found that lead-lag phasing with NB being the leading phase provides the widest two-way bandwidth. Therefore, this phasing sequence is recommended in this step.

Summary. Combining the results from step 1 and step 4, it is found that both step 2 and step 4 recommend the lead-lag phase with NB being the leading phase. Therefore, this phasing sequence is recommended for this intersection.

10.1.4 Case 4 — FM 518 and Calder Drive in Houston, Texas

10.1.4.1 Intersection Description

The study intersection, FM 518 and Calder Drive, is located in the southeast of Houston, Texas. The WB approach of the intersection was selected as the subject approach, and the EB approach was the opposing approach. The current signal control mode for these pairs of approaches is PPLT, and the current phasing sequence is lead-lag with EB being the lagging phase. Both the WB and EB approaches have one left-turn lane and one through lane, and the speed limit of both approaches is 40 mph. During the peak hour period, the WB left-turn traffic volume is 225 veh/h, the WB through traffic volume is 1100 veh/h, the EB left-turn traffic volume is 106 veh/h, and the EB through traffic volume is 1410 veh/h. The intersection's geometric conditions, current traffic signal controls, and traffic volume information are presented in Figure 82.

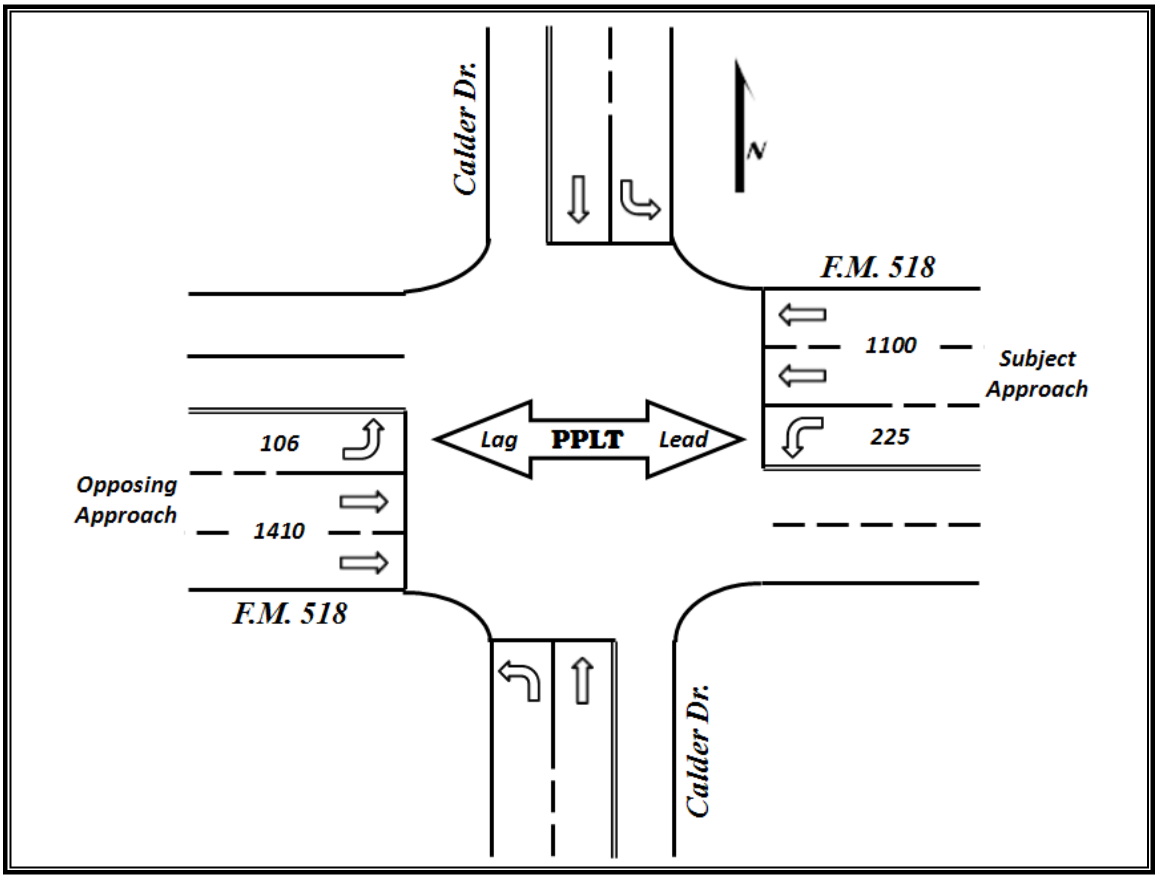


Figure 82: Basic Information for the Intersection at FM 518 and Calder Drive

10.1.4.2 Application of Guidelines for Selecting Signal Control Mode

According to the decision-making flowchart developed in Chapter 8, the appropriate signal control mode can be selected for this study intersection by following these steps:

Step 1. Check the Left-Turn Traffic Volume. Both left-turn volumes of WB and EB approaches are between 50 veh/h and 300 veh/h. Therefore, the signal control mode for the WE directions of this study intersection should be chosen between PO and PPLT.

Step 2. Check the Number of Left-Turn–Related Accidents. The accident record of this study intersection shows that there were five left-turn–related accidents: one accident in 1999, one accident in 2000, and three accidents in 2001. Since the left-turn–related accident records do not satisfy any criteria listed for choosing PO mode, the selection procedure continues.

Step 3. Check the Speed Limit of Opposing Through Traffic. The speed limit of both the northbound and southbound approaches is 40 mph, which is lower than 45 mph (the criterion for selecting PO mode). Thus, go to the next selection step.

Step 4. Check the Sight Distance for Left-Turn Movements. The sight distances for both the WB and EB movements are measured by using a Google map (see Figure 83). From Figure 83, it can be seen that both sight distances are about 420 ft. Therefore, under the condition that the opposing through traffic speed is 40 mph (higher than 35 mph), PO mode cannot be warranted for this location at this step. Thus, go to the next selection step.

Step 5. Check the Number of Lanes. If an approach has two or more left-turn lanes, or three or more opposing through lanes, PO mode must be installed for this intersection. However, both the WB and EB approaches of this study intersection only have one left-turn lane and two opposing though lanes. Thus, go to the next selection step.

Step 6. Check the Cross Product of Volume per Lane. The westbound CPOV is 158,625, and the eastbound CPOV is 58,300. For two opposing through lanes, the threshold for selection between PO and PPLT modes is 93,000. Since the westbound CPOV is over this threshold, PO mode should be used for the westbound direction of this study intersection. For the eastbound approach, PPLT mode could be used. However, to keep the consistency of signal control at this intersection, it is recommended to use PO mode for both WB and EB approaches.

Summary. By following the decision-making flowchart developed in Chapter 8, it is found that PO mode is the most appropriate signal control mode for the WB approach of this study intersection, which is different from the current signal control mode, i.e., PPLT.

Therefore, it is recommended the signal control mode for the WE directions of this intersection be converted from PPLT to PO.

Figure 83: Sight Distances for the Left-Turn Movements at WB and EB Approaches of the Intersection at FM 518 and Calder Drive

10.1.4.3 Application of Guidelines for Selecting Signal Phasing Sequence

Since PO mode is selected for the WB and EB approaches of this intersection, signal phasing sequence guidelines for PO mode (see Chapter 8) could be applied to this intersection by following these steps:

Step 1: Pedestrian Volume Check. This intersection is not located in a downtown area. There is very low pedestrian volume. Therefore, both the leading phase and lagging phase can be used for this intersection.

Step 2: Left-Turn Volume Check. Lead-lag sequence is recommended for this intersection because PO mode is selected. In addition, since left-turn volume in the WB direction is 225 veh/h and in the EB direction is 106 veh/h, WB should use the leading phase.

Step 3: Signal Phasing Consistency Check. For the intersections along FM 518, 59.1 percent of them use lead-lag phasing sequence and 40.9 percent use lead-lead phasing sequence. Therefore, lead-lag phasing sequence is recommended by this step.

Step 4: Bandwidth Check. It is an isolated intersection, and its signal is not coordinated with other intersections. Therefore, this step is not applicable for this intersection.

Summary. Combining the results from step 1 to step 4, it is found that step 2 recommends lead-lag phasing sequence with WB being the leading phase and step 3 recommends lead-lag phasing sequence too. Therefore, it is recommended to use lead-lag phasing sequence with WB being the leading phase for this intersection.

10.2 CASE STUDY FOR APPLICATION OF GUIDELINES ON LEFT-TURN SIGNAL DISPLAY

10.2.1 Case 1 — Intersection at Airport Boulevard and 51st Street in Austin, Texas

According to case study 1 in section 10.1.1.2, the recommended left-turn signal control mode for the NS directions of this intersection is PPLT. In the following part, guidelines for PPLT signal display developed in Chapter 9 are applied to determine the left-turn signal display for the NB left-turn movement.

Select Left-Turn Signal Indication

Based on the developed guidelines, a left-turn green arrow is used for the protected left-turn phase. Since a flashing yellow arrow indication has not been applied in this area, a circular green indication is recommended for the permissive left-turn phase.

Select Left-Turn Signal Arrangement

An exclusive four-section left-turn signal head is recommended as shown in Figure 84. This recommendation is made because:

1. Survey results in Chapter 3 indicate that it would improve safety at intersections if individual signal display is provided for each movement. Therefore, an exclusive left-turn signal head is recommended for each signal control type.
2. The simultaneous signal indication of conflicting colors (green arrow and red ball) in one left-turn signal head would occur when using a shared signal head for PPLT signal control mode (i.e., five-section horizontal/vertical/cluster signal arrangement). The literature (Asante et al. 1993, Bonneson and McCoy 1993, Kacir et al. 2003) found that simultaneously displaying the green arrow and red ball indication in the same signal display confuses many drivers. Therefore, an exclusive signal display is strongly recommended for PPLT mode.
3. The literature (Kacir et al. 2003) found that exclusive four-section vertical signal heads for PPLT mode are associated with the least driver confusion.

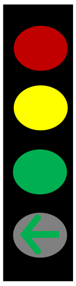


Figure 84: Recommended Left-Turn Signal Arrangement

Determine the Placement of Left-Turn Signal Head

First, in this intersection, no supplemental signal face is recommended to be installed because it is not a very big intersection and there are no curves that hamper the visibility of this intersection.

Second, a 20-degree "cone of vision" was drawn on the vertical view picture of this intersection (see Figure 85). According to the width of this intersection, 8-in signal lenses should be enough for this intersection, and the signal head should be placed in the trapezoid area in a range of not less than 40 ft and no more than 120 ft (see Figure 85).

Finally, a left-turn signal head is recommended to be located in line with the center of the left-turn lane on the far side of the intersection. The recommended location for the exclusive signal head for the NB left-turn movement is indicated in Figure 85, which is very close to the location of the current left-turn signal head.

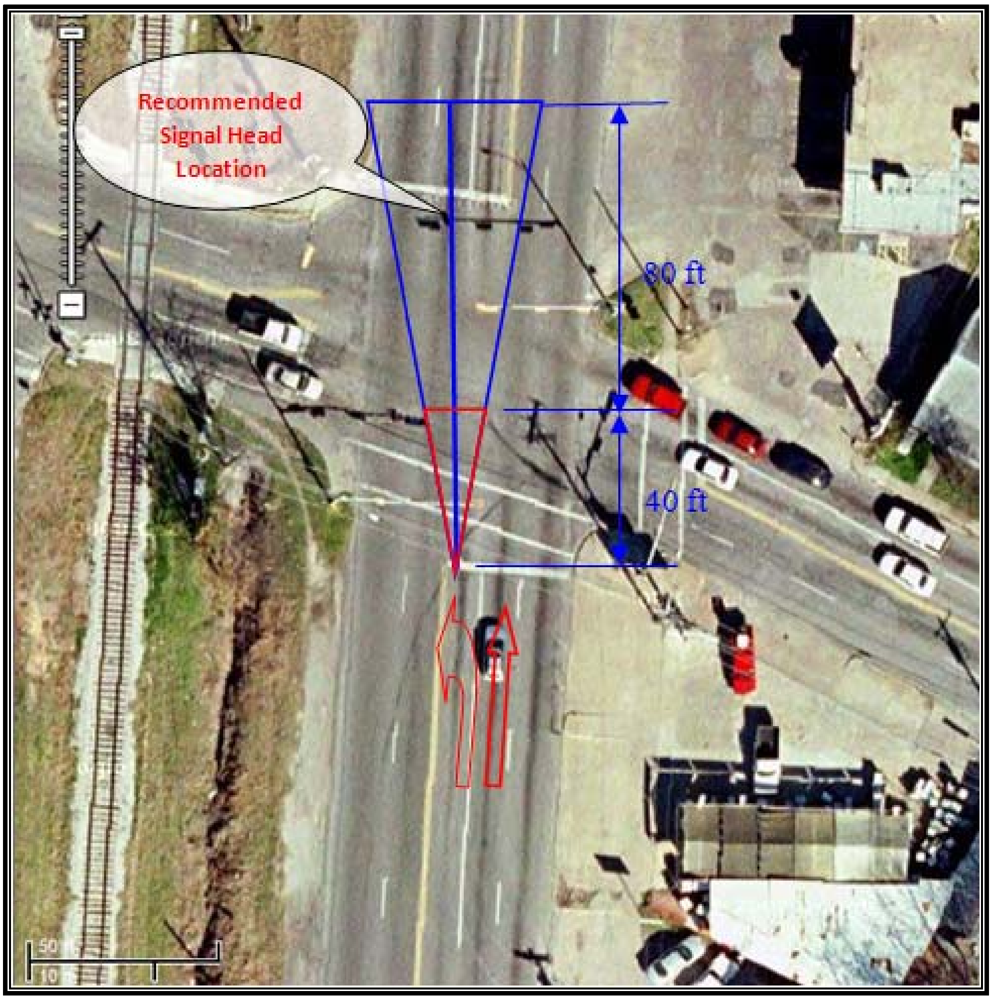


Figure 85: Recommended Signal Head Horizontal Location for the Intersection at Airport Boulevard and 51st Street in Austin, Texas

10.2.2 Case 2 — Intersection at FM 518 and Calder Drive in Houston, Texas

According to section 10.1.4.2 in this chapter, the recommended left-turn signal control mode for the NS directions of this intersection is protected-only. In the following part, guidelines for protected-only signal display developed in Chapter 9 are applied to determine the left-turn signal display for the NB left-turn movement.

Select Left-Turn Signal Indication

A left-turn green arrow signal face or a combination of left-turn green arrow and circular green ball signal face could be used in the protected phase.

Select Left-Turn Signal Arrangement

For protected-only mode, it is required that at least one exclusive left-turn signal head be provided. Three- or four-section horizontal or vertical signal arrangement is recommended, as shown in Figure 86.

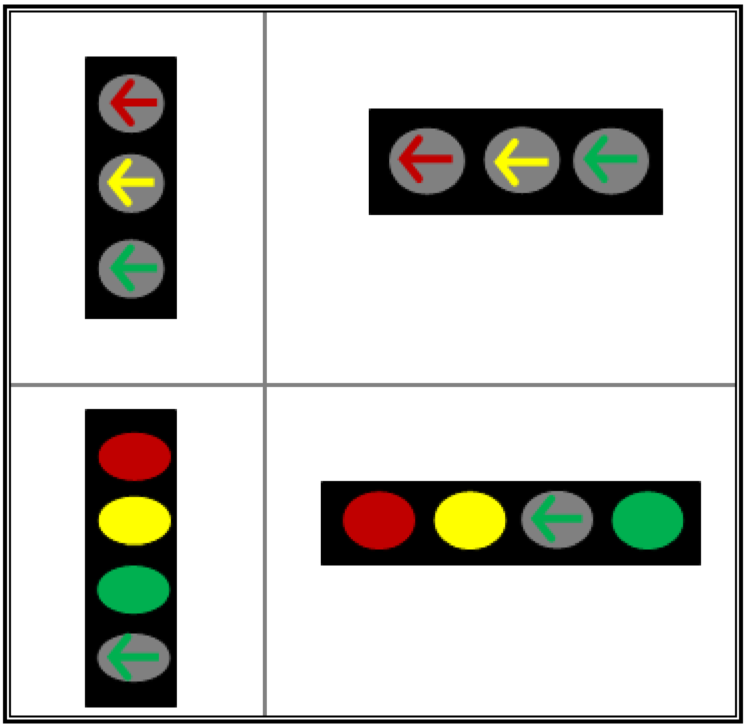


Figure 86: Recommended Left-Turn Signal Arrangement for PO Mode

Determine the Placement of Left-Turn Signal Head

First, in this intersection, no supplemental signal face is recommended to be installed because it is not a very big intersection and there are no curves that hamper the visibility of the intersection for the NB or SB approach.

Second, a 20-degree "cone of vision" was drawn on the vertical view picture of this intersection (see Figure 87). According to the width of this intersection, 8-in signal lenses should be enough for this intersection, and the signal head should be placed in the trapezoid area in a range of not less than 40 ft and no more than 120 ft (see Figure 87).

Finally, a left-turn signal head is recommended to be located in line with the center of the left-turn lane on the far side of the intersection. The recommended location for the exclusive signal head for the NB left-turn movement is indicated in Figure 87.

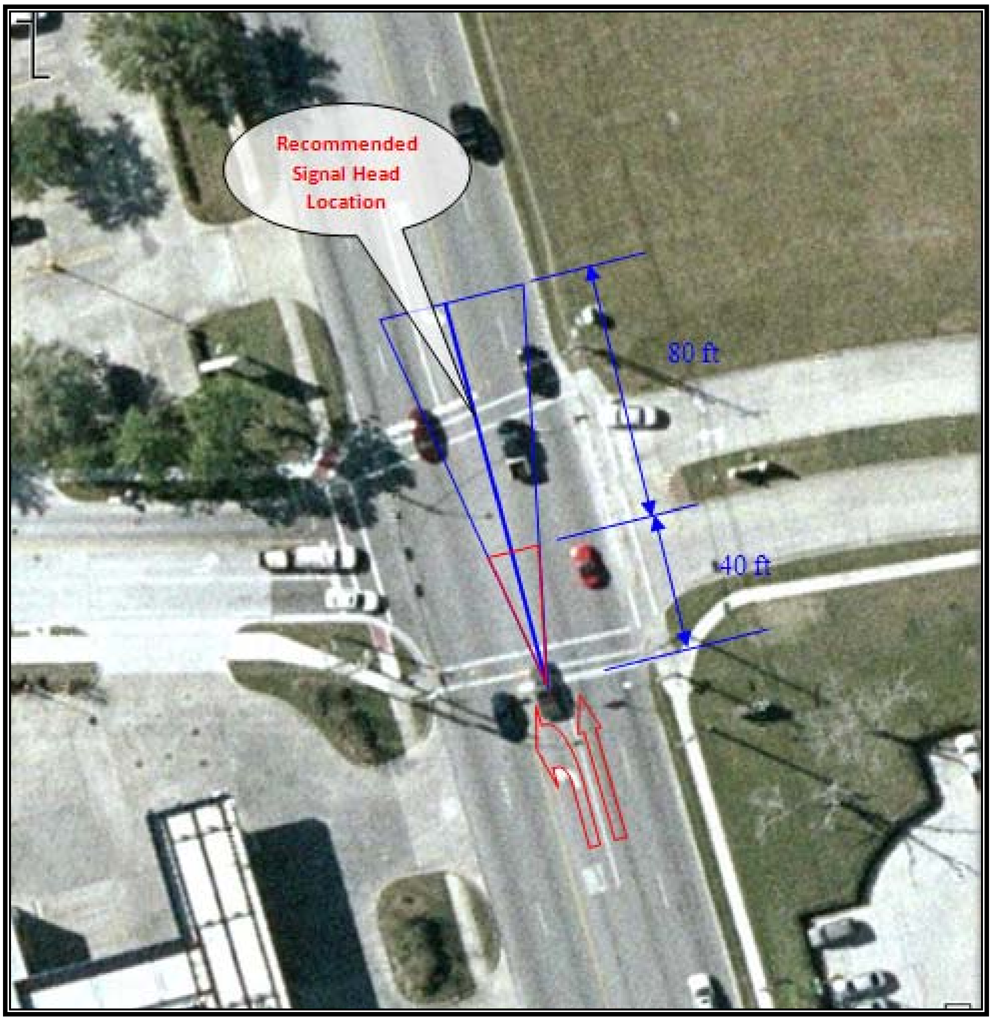


Figure 87: Recommended Signal Head Horizontal Location for Case 2

10.2.3 Case 3 — Intersection at Bellaire Boulevard and South Gessner Road in Houston, Texas (for Placement of Supplemental Left-Turn Signal Head)

As shown in Figure 88, the subject direction of this intersection is eastbound. For this intersection, a far-side supplemental left-turn signal head is recommended because of following reasons:

1. The intersection is comparatively large. The supplemental signal head can better guide left-turning vehicles across a wide intersection as they make their turn.
2. The intersection has relatively more heavy or large vehicles (see Figure 89). The supplemental signal head helps improve visibility for vehicles behind large vehicles.
3. Because the subject approach is EB, the visibility of signal indications (color) is affected by sun glare during the morning peak hour when the sun is near the horizon. The supplemental signal head can mitigate the risk caused by sun glare.

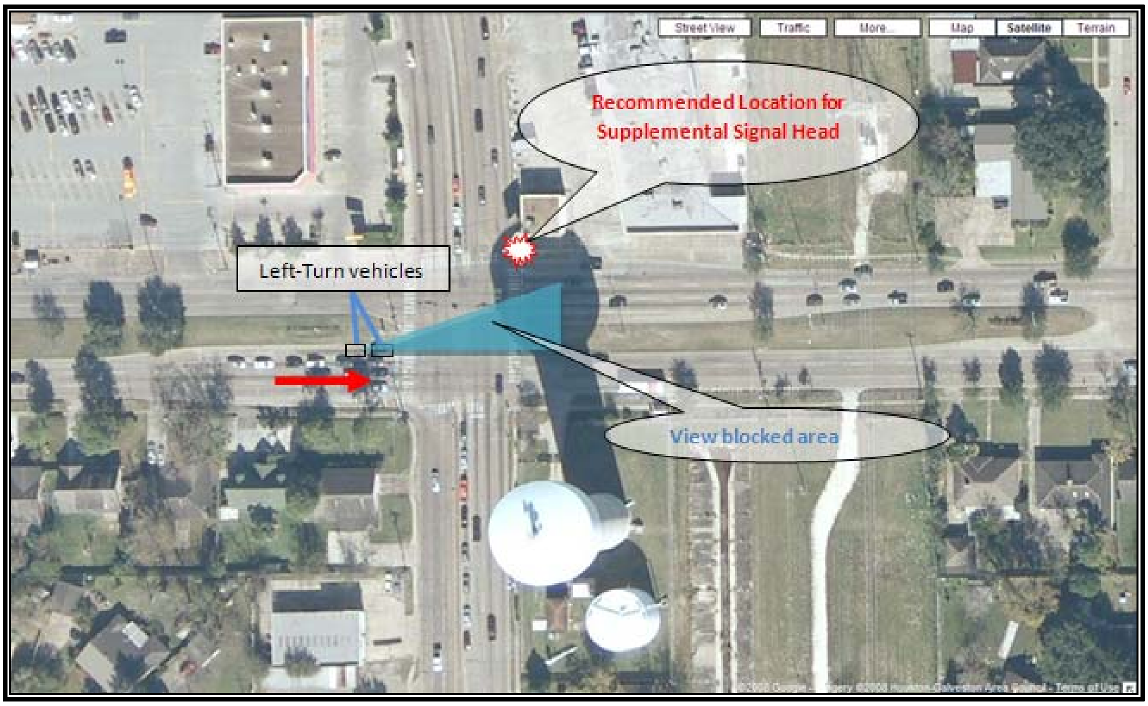


Figure 88: Layout of the Intersection at Bellaire Boulevard and South Gessner Road in Houston, Texas

Figure 89: Current Supplemental Left-Turn Signal Head for the Intersection at Bellaire Boulevard and South Gessner Road in Houston, Texas

As shown in Figure 89, currently there is an extra left-turn signal head that was ground mounted in the median of the far side of the intersection. However, by analyzing the sight of view of the second vehicle in the left-turn lane, it is found that the median is within the area that could be blocked by the first left-turn vehicle in the queue. In other words, if the first vehicle in the left-turn lane is a large vehicle, the second left-turn vehicle may not be able to see the supplemental left-turn signal head installed on the median. Therefore, it is recommended to install the supplemental left-turn signal head at the northeast corner of the intersection as shown in Figure 88. Then, all the vehicles in the NB left-turn lane are able to see the supplemental left-turn signal head.

CHAPTER 11: CONCLUSIONS AND RECOMMENDATION

11.1 CONCLUSIONS

This research examined important issues related to left-turn operations at signalized intersections. The results of this research provide answers to the following critical questions in left-turn signal design:

1. How do you select the most appropriate type of left-turn signal phasing for a signalized intersection?
2. How do you display the left-turn signal appropriately?
3. Will the regional standardization of left-turn signal operation bring benefits?

For the first question, guidelines for determining the left-turn signal phasing, i.e., signal control mode and phasing sequence, were developed. To develop these guidelines, both operational and safety impacts of left-turn signal phasing were analyzed.

In the operational impact analysis, traffic simulation–based methods were used for analyzing the impacts of different left-turn signal phasing treatments (including left-turn signal control mode and phasing sequence) on the operation of signalized intersections. Based on the simulation results, CPOV-based criteria for selecting between PO and PPLT modes were developed, which recommends that:

- At intersections with one opposing through lane, PPLT mode should be selected when the CPOV value is equal to or less than the threshold of 133,000.
- At intersections with two opposing through lanes, PPLT mode should be used when the CPOV value is equal to or less than the threshold of 93,000.

In terms of the signal phasing sequence, it was found that the sequence affects intersection operations mainly through its impacts on the signal coordination of the network. From the literature review and the results of traffic simulation, the following recommendations are provided:

- For an intersection in a two-way coordinated arterial, the signal phasing sequence that maximizes through bandwidth should be selected.
- For an intersection in a one-directional coordinated arterial during peak hour periods, lead-lag sequence should be considered because it can cause less delay for the subject left-turn movements than other signal phasing sequences.

For the safety impact analysis, both simple comparison methods and advanced statistic modeling methods were employed for analyzing the historical accident data collected from more than 100 intersections. The major findings are summarized as follows:

- Protected-only is the safest signal control mode.
- Under PO mode, lead-lag is the safest, followed by lead-lead and lag-lag.
- Under PPLT mode, lead-lead and lag-lag are safer than lead-lag when left-turn volume is low, and lead-lag is safer than lead-lead when left-turn volume is high.

Based on the findings of operational and safety impact analysis, the results of the literature review, and the survey results, guidelines for determining left-turn signal phasing, i.e., left-turn signal control mode and sequence, were developed.

For the second question, the safety impacts of different PPLT signal display arrangements were analyzed. It was found that the five-section cluster signal display is associated with less accident risk than the five-section horizontal signal display. Based on the findings of the safety impact analysis and the results of the literature review, guidelines on how to select different types of signal displays for different types of left-turn signal phasing and on how to place the signal heads appropriately have been developed.

For the third question, the safety benefits of regional standardization of left-turn signal phasing and signal display were analyzed by comparing the accident rates at four different corridors with different mix levels of left-turn signal operations. It was concluded that regional standardization of left-turn signal operations will benefit intersection safety.

Finally, case studies were conducted to demonstrate the application of the developed guidelines. The guidelines for left-turn signal phasing were applied to four selected study intersections, and the guidelines for signal display were applied to three intersections including two study intersections and one newly selected intersection in Houston, Texas.

In addition, this study also developed training strategies and materials for providing training sessions to TxDOT and TMC personnel (see Yu et al. 2008 for details).

11.2 RECOMMENDATIONS

Based on the results of the research conducted in this project, it is recommended that regional standardized guidelines be used for left-turn operations at signalized intersections. The appropriate left-turn phasing treatments and signal displays can be determined by using the guidelines developed by this study. To facilitate the implementation of the developed guidelines, providing a training session to TxDOT and TMC personnel based on the developed training strategies and materials is proposed (see Yu et al. 2008).

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APPENDIX A: SURVEY FORM

Survey for Texas Department of Transportation (TxDOT) Research Project 0-5840: Development of Left-Turn Operations Guidelines at Signalized Intersections

Dear traffic engineers and transportation professionals,

We need your help to complete a very important survey on left-turn signal design and operation. Texas Southern University (TSU) is conducting a research project for TxDOT to examine important issues related to guidelines for left-turn operations at signalized intersections. The primary objectives of this research are:

1. to develop guidelines for recommending the most appropriate left-turn phasing treatments at signalized intersections by investigating all aspects of left-turn operations, including the mode of left-turn signal control, the sequence of left-turn phasing, and signal displays; and
2. to estimate the benefits of regional standardization of left-turn operations.

To achieve these goals, this survey is designed to solicit information regarding the current practices of left-turn operation in your jurisdiction and your suggestions on left-turn signal design and operation for the following aspects:

1. the modes of left-turn controls: the permissive, protected, protected/permissive (PPLT), and variable left-turn control modes;
2. the sequence of left-turn phasing: lead-lead sequence, lag-lag sequence, and lead-lag sequence; and
3. signal displays and signal head placement.

The survey consists of two major parts. The first part is for left-turn signal mode and sequence, and the second part is for left-turn signal displays and placement. Each part consists of four sections. Please complete the following forms and then submit the survey by clicking the “submit” button at the end of the web page.

You can also e-mail your response to yu_lx@tsu.edu or fax to (713) 313-1856 ***before June 1, 2007*.** We appreciate your assistance with this survey.

Part I: Determination of the Mode and Sequence of Left-Turn Phasing

Part 1.1. Prioritize Parameters for Determining the Mode and Sequence of Left-Turn Phasing

Each parameter listed in the following table is given numbers from 1 to 5, with 1 indicating the lowest priority and 5 indicating the highest priority. Please grade each parameter by checking one box that represents the level of importance of the parameters (rows) in different aspects of left-turn signal design (columns).

Parameters		*For Determining Mode of Left-Turn Signal Phasing*	*For Determining Sequence of Left-Turn Signal Phasing*
Vol.	Left-Turn Traffic Volume	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	Opposing Traffic Volume	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
Traffic Condition	Vehicle Type/Fleet Composition (Percent of Heavy Vehicles)	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	Pedestrian and/or Bicycle Crossings	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	Intersection Congestion Level (V/C Ratio)	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	Platoon Progression and Bandwidth	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	Posted Speed Limit	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
Geometric Condition	Sight Distance	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	Median Width	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	Number of Left-Turn Lanes	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	Number of Opposing Lanes	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	Intersection Alignment	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	Left-Turn Storage Length	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
Delay	Left-Turn Delay	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	Intersection Delay	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	Number of Failed Cycles	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
Safety	Historical Rate of Total Accidents at Intersection	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	Historical Rate of Left-Turn–Related Accidents at Intersection	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
Others	Driver Acceptance	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	____	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	____	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	____	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
	____	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐

Part 1.2. Identify Practices in Your Jurisdiction

1. How many signalized intersections are currently operated and maintained by your jurisdiction? _______

2. The approximate percentage of different left-turn control modes in your jurisdiction:
   a) Permissive-only: ____________________
   b) Protected-only: ____________________
   c) Protected/permissive: ____________________
   d) Others (please specify): ____________________
   TOTAL 100%

3. The approximate percentage of different sequences of left-turn phasing in your jurisdiction:
   a) lead-lead sequence: ____________________
   b) Lag-lag sequence: ____________________
   c) Lead-lag sequence: ____________________
   d) Others (please specify): ____________________
   TOTAL 100%

4. Is there any special mode or sequence used in your jurisdiction? If yes, please explain.

____

____

5. In your opinion, which combination of mode and sequence has the lowest crash rate?

____

____

6. Are there any intersections in your jurisdictions that have ever experienced changes in left-turn signal mode and/or sequence in the past 5 years?

____

____

If yes, please specify the name of the intersection, the before and after left-turn signal phasing, the reason for the change, and your opinion whether this change brought any benefits in terms of safety and operation efficiency.

____

____

7. Can you provide the contact information for the person who is in charge of signal timing plans/signal installation in your jurisdiction?

____

____

8. Can you provide the contact information for the person who is in charge of the accident database in your jurisdiction?

____

____

Part 1.3. Provide Your Existing Guidelines

1. What are the existing guidelines for determining the mode of left-turn signal control in your jurisdiction?

____

____

2. What are the existing guidelines for determining the sequence of left-turn signal phasing in your jurisdiction?

____

____

3. Have regional standardized guidelines for selecting left-turn phasing treatments been implemented in your jurisdiction?

____

____

Part 1.4. Provide Your Suggestions

1. Do you have any suggestions/good experiences about the determination of the mode of left-turn signal control that can be shared with us?

____

____

2. Do you have any suggestions/good experiences about the determination of the sequence of left-turn signal phasing that can be shared with us?

____

____

3. In your opinion, what are the benefits of the regional standardization of left-turn phasing?

____

____

4. To evaluate the performance of an intersection, we would like to integrate the safety cost with the operational cost (delay). Therefore, we would like to know, in your opinion, how much delay (in seconds per vehicle) is equivalent to a 1 percent chance that the vehicle will be involved in a potential conflict (the vehicle takes a permissive left turn in a gap less than the critical gap).

____

____

5. In terms of safety, which signal phasing sequence do you think is better for PPLT control, lead-lead PPLT or lag-lag PPLT? Can you specify the reason for your opinion?

____

____

6. If the traffic signal control at an intersection was converted from leading PPLT to lagging PPLT, what do you think are the possible reasons for this type of conversion?

____
____

Part II: Left-Turn Signal Display and Placement

Part 2.1. Prioritize Parameters for Determining Signal Display and Placement

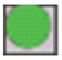
Each parameter listed in the following table is given numbers from 1 to 5, with 1 indicating the lowest priority and 5 indicating the highest priority. Please grade each parameter by checking one box that represents the level of importance of the parameters (rows) in different aspects of left-turn signal display design (columns).

Parameters	Different Aspects of Left-Turn Signal Display & Signal Head Placement		
	Indication	Arrangement	Placement
Intersection Alignments	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
Number of Left-Turn Lanes	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
Number of Through Lanes	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
Roadway Functional Class (Interstate, Local Arterial, Etc.)	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
Median Width	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
Type of Left-Turn Phasing	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
Left-Turn Volume	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
Accident Rate	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐	1☐ 2☐ 3☐ 4☐ 5☐
Others* ________			
________			
________			
________			

Part 2.2. Identify Practices in Your Jurisdiction

1. What type of signal indication is used for the permitted left-turn phase? (Check all that apply.)

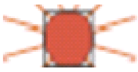
☐ Green Ball



☐ Flashing Yellow Arrow

☐ Flashing Red Arrow

☐ Flashing Red Ball



☐ Flashing Yellow Ball

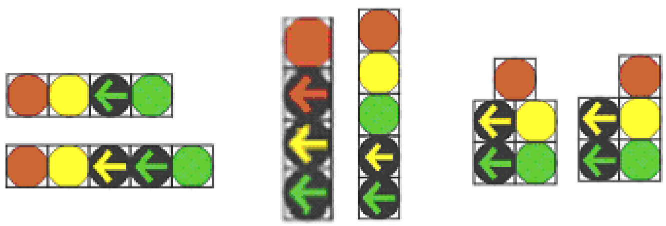
☐ Others (please specify)

____

2. In your jurisdiction, what is the percentage of left-turn signal display arrangements for different left-turn control modes (or you can give the exact number)?

	Protected-only	***PPLT***
5-section horizontal?	_________	_________
5-section vertical?	_________	_________
5-section cluster?	_________	_________
4-section horizontal?	_________	_________
4-section vertical?	_________	_________
4-section cluster?	_________	_________
3-section vertical?	_________	_________
Other (*please specify*)	_________	_________
TOTAL	**100%**	**100%**

Left-turn signal display example arrangements



Horizontal ***Vertical*** ***Cluster***

3. If you identified multiple signal display arrangements in Question 2, are there any criteria that your agency used for selecting one left-turn signal display arrangement over another?
   - ☐ No
   - ☐ Yes (*please explain*)

____

____

____

____

4. Do you use the left-turn signal display as one of the two required signal displays for through traffic (use shared left-turn display)?
   - ☐ Never
   - ☐ Yes
   - ☐ Sometimes (*explain the criteria for using shared left-turn display*)

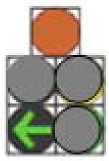
____

____

____

____

5. If you identified "yes" in Question 4, does the simultaneous display of red ball (to through traffic) and green arrow (to left-turn traffic) occur in the protected left-turn phasing (see the following figure as an example)?
   - ☐ No
   - ☐ Yes



6. Do you use special left-turn phasing or techniques to avoid the yellow trap problem in PPLT mode?
   - ☐ No
   - ☐ Yes — Dallas/Arlington phasing
   - ☐ Yes — Lead-lead/lag-lag phasing
   - ☐ Yes — Other (*please specify*) ____________________________________

7. Please give your opinions on Dallas/Arlington phasing. What are your concerns in using it?

____

____

8. Do you use secondary left-turn signal display?
   - ☐ Never (*go to Question 12)*
   - ☐ Always
   - ☐ Sometimes (*please explain the reason*)

____

____

9. If a secondary left-turn signal display(s) is used, where is it mounted? (Check all that apply.)

____

____

10. In your opinion, which types of left-turn signal displays (indication/arrangement/ placement) are related to high crash rates? Please explain the reason.

____

____

11. Are there any intersections in your jurisdictions that have ever experienced changes in signal display type in the past 5 years?

☐ No

☐ Yes

If yes, please specify the name of the intersection, the before and after left-turn signal displays, the reason for the change, and your opinion whether this change has brought any benefits in terms of safety and operation efficiency.

____

____

Part 2.3. Provide Your Existing Guidelines

1. What are the current guidelines used for determining left-turn signal display and signal head placement in your jurisdiction?

____

____

____

____

2. Have regional standardized guidelines for left-turn signal display and signal head placement been implemented in your jurisdiction?

____

____

____

____

Part 2.4. Provide Your Suggestions

1. Do you have any suggestions/good experiences about the determination of left-turn signal display and signal head placement that can be shared with us?

____

____

____

____

2. In your opinion, what are the benefits of the regional standardization of left-turn signal displays and signal head placement?

____

Part III: Acknowledgments

We appreciate your valuable time taken to participate in this survey. Please fill in the following information for further contact.

Name of the person who filled out this survey:__________

Title: __________

Name of organization: ________________

Address: ____

Telephone: (_____) __________ Fax: (_____) __________

E-mail: _____

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APPENDIX B: ACCIDENT DATA AND INTERSECTION INFORMATION FOR SAFETY STUDIES

Table A-1: Austin Accident Data for Cross-Sectional Study

Intersection	Direction	Mode	Sequence	Split	No. of Lanes (Direction)	No. of Lanes (Inter-section)	ADT Direction	ADTPL	Speed	LT Accident Count*	Total Accident Count*
51st at Airport	NS	PPLT	Lead-lead	NA	6	10	28624	4770.7	45	5	15
Airport and MLK	NS	PO	Lead-lag	0	6	12	30290	5048.3	45	3	16
Anderson and Burnet	NS	PO	Lead-lag	0	8	16	26960	3369.9	45	1	2
Anderson Mill at Pond Springs	NS	PO	Lead-lag	1	4	8	14161	3540.3	40	2	2
Braker and Burnet	NS	PO	Lead-lag	0	7	15	33936	4848.0	45	1	3
Braker W. and Metric Blvd.	NS	PPLT	Lead-lag	0	6	14	27525	4587.5	40	7	16
Brodie and Slaughter	NS	PO	Lead-lag	0	5	11	22384	4476.8	45	1	11
Burnet and Justin	NS	Permissive	NA	NA	6	9	26731	4455.2	40	3	8
Cameron at Coronado Hills	NS	PPLT	Lead-lag	0	8	10	15597	1949.6	40	1	10
Howard at Dessau	NS	PPLT	Lead-lead	NA	6	12	29002	4833.7	50	5	20
Lamar and 45th	NS	PO	Lead-lag	0	8	14	31865	3983.1	40	3	8

Intersection	Direction	Mode	Sequence	Split	No. of Lanes (Direction)	No. of Lanes (Inter-section)	ADT Direction	ADTPL	Speed	LT Accident Count*	Total Accident Count*
Lamar and Rundberg	NS	PO	Lead-lag	0	8	16	32854	4106.8	45	11	24
Lamar and 29th	NS	Permissive	NA	NA	6	10	29583	4930.5	35	2	15
Lamar and 38th	NS	PPLT	Lead-lag	0	6	14	30163	5027.2	40	7	18
Manchaca and Slaughter	NS	PO	Lead-lag	0	8	16	20516	2564.4	45	1	12
Manchaca and Redd	NS	PPLT	Lead-lag	0	6	10	17575	2929.2	20	1	5
Parmer and McNeil	NS	PO	Lead-lag	1	12	20	40994	3416.2	60	5	19
Parmer at Scofield Farms	NS	PPLT	Lead-lead	NA	5	15	2579	515.8	25	5	10
Pleasant Valley and Wm. Cannon	NS	PPLT	Lead-lag	0	7	12	26564	3794.9	35	1	8
Pleasant Valley at 7th	NS	PPLT	Lead-lag	0	4	12	5733	1433.3	35	8	21
Pond Springs at Hunter's Chase	NS	PO	Lead-lead	NA	6	14	11634	1939.0	40	1	3
Wm. Cannon and Brodie	NS	PPLT	Lead-lag	0	8	12	22384	2798.0	40	37	43
51st at Airport	WE	PPLT	Lead-lag	0	4	10	10077	2519.3	20	3	13

Intersection	Direction	Mode	Sequence	Split	No. of Lanes (Direction)	No. of Lanes (Inter-section)	ADT Direction	ADTPL	Speed	LT Accident Count*	Total Accident Count*
Airport and MLK	WE	PPLT	Lead-lag	0	6	12	13455	2242.5	30	8	32
Anderson and Burnet	WE	PO	Lead-lag	0	8	16	28422	3552.7	20	3	3
Anderson Mill at Pond Springs	WE	PO	Lead-lead	NA	4	8	18207	4551.8	40	1	1
Braker and Burnet	WE	PO	Lead-lag	0	8	15	26706	3338.3	45	3	11
Braker W. and Metric Blvd.	WE	PO	Lead-lag	0	8	14	26888	3361.0	45	5	14
Brodie and Slaughter	WE	PO	Lead-lag	0	6	11	21365	3560.8	45	1	12
Burnet and Justin	WE	Permissive	NA	NA	3	9	6114	2038.0	20	1	3
Cameron at Coronado Hills	WE	Permissive	NA	NA	2	10	3250	1625.0	25	9	18
Howard at Dessau	WE	PO	Lead-lag	1	6	12	18158	3026.3	50	1	16
Lamar and 45th	WE	PPLT	Lead-lag	0	6	14	20414	3402.3	35	5	8
Lamar and Rundberg	WE	PO	Lead-lag	0	8	16	14110	1763.8	35	3	19
Lamar and 29th	WE	PPLT	Lead-lead	NA	4	10	4735	1183.8	25	1	7

Intersection	Direction	Mode	Sequence	Split	No. of Lanes (Direction)	No. of Lanes (Inter-section)	ADT Direction	ADTPL	Speed	LT Accident Count*	Total Accident Count*
Lamar and 38th	WE	PPLT	Lead-lag	0	8	14	24632	3079.0	35	3	15
Manchaca and Slaughter	WE	PO	Lead-lag	0	8	16	40234	5029.3	45	1	7
Manchaca and Redd	WE	PPLT	Lead-lead	NA	4	10	4430	1107.5	20	3	5
Parmer and McNeil	WE	PO	Lead-lag	1	8	20	30150	3768.8	45	11	24
Parmer at Scofield Farms	WE	PPLT	Lead-lag	0	10	15	57846	5784.6	50	1	6
Pleasant Valley and Wm. Cannon	WE	PPLT	Lead-lead	0	5	12	18539	3707.8	45	3	11
Pleasant Valley at 7th	WE	PPLT	Lead-lag	0	8	12	19607	2450.9	40	9	23
Wm Cannon and Brodie	WE	PO	Lead-lag	0	8	14	35275	4409.4	40	7	8
Pond Springs at Hunter's Chase	WE	PO	Lead-lag	0	4	12	4013	1003.2	40	1	3
FM 1431 at Lakeline Blvd.	WE	PPLT	Lead-lead	NA	6	12	22344	3724.0	50	15	48
FM 1431 at Sam Bass	WE	PPLT	Lead-lead	NA	6	11	26358	4393.0	60	5	8
SH 29 at DB Woods	WE	PPLT	Lead-lead	NA	4	6	14680	3670.0	65	1	4
US 281 B15 at Mission Hills	NS	PPLT	Lead-lead	NA	4	8	5540	1385.0	40	4	37

Intersection	Direction	Mode	Sequence	Split	No. of Lanes (Direction)	No. of Lanes (Inter-section)	ADT Direction	ADTPL	Speed	LT Accident Count*	Total Accident Count*
Bus. 35 at FM 2338	NS	PO	Lead-lag	NA	4	8	16980	4245.0	45	5	16
FM 2244 and Westbank	WE	PO	Lead-lag	NA	5	11	23000	4600.0	35	1	11
FM 620 and Anderson Mill/ FM 2786	NS	PO	Lead-lag	0	6	10	31594	5265.7	55	1	7
FM 971 and Inner Loop	WE	PO	Lead-lag	NA	4	8	6870	1717.5	45	1	4
US 183 at FM 812	NS	PO	Lead-lead	NA	4	8	19260	4815.0	55	0.1	40
US 183 at Discovery	NS	PO	Lead-lag	0	6	8	44916	7486.0	40	2	6
US 281 at Green Mile	NS	PO	Lead-lag	0	4	6	6714	1678.5	63	2	6
US 290 at LP 212	NS	PO	Lead-lag	0	4	10	35544	8886.0	55	8	102
FM 1100 at SH 95	WE	Permissive	NA	NA	2	6	3184	1592.0	45	1	15
SH 95 at FM 1100	NS	Permissive	NA	NA	4	8	6710	1677.5	65	4	19
US 290 at SH 95	WE	Permissive	NA	NA	6	12	17460	2910.0	53	3	30
US 290 at 11th	NS	Permissive	NA	NA	4	8	8634	2158.5	60	3	47

*Accident counts are standardized to a 4-year period.

Table A-2: Houston Accident Data for Cross-Sectional Study

Intersection	Direction	Mode	Sequence	Display	No. of Lanes (Direction)	No. of Lanes (Inter-section)	ADT Direction	ADTPL	Speed	LT-related Accident Counts*	Total Accident Counts*
FM 1960 and Aldine-Westfield	WE	PO	Lead-lag	4H	8	15	18509	2314	40	4	9
FM 1960 and Bammel Westfield	WE	PO	Lag-lag	4H	10	13	37381	3738	40	27	45
FM 1960 and Beaver Spring	WE	PO	Lead-lag	4H	8	10	26990	3374	40	5	18
FM 1960 and Butte Creek	WE	PPLT	Lead-lead	5D	8	11	26903	3363	40	5	21
FM 1960 and Cypress Station	WE	PO	Lag-lag	4H	8	14	42846	5356	40	25	80
FM 1960 and Ella Blvd.	WE	PO	Lead-lag	4H	8	14	28520	3565	40	8	30
FM 1960 and Fritz Oaks	WE	PPLT	Lead-lead	5D	8	10	34539	4317	40	2	5
FM 1960 and Greenbrook	WE	PO	Lead-lag	4H	8	12	9416	1177	40	0	23
FM 1960 and Hafer	WE	PO	Lead-lag	4H	8	11	33400	4175	40	6	24
FM 1960 and Imperial Valley	WE	PO	Lead-lag	4H	8	14	21522	2690	40	2	3
FM 1960 and Kuykendahl	WE	PO	Lead-lag	4H	8	14	35809	4476	40	12	67
FM 1960 and Nanes	WE	PPLT	Lead-lead	5H	8	10	31304	3913	40	14	26

Intersection	Direction	Mode	Sequence	Display	No. of Lanes (Direction)	No. of Lanes (Inter-section)	ADT Direction	ADTPL	Speed	LT-related Accident Counts*	Total Accident Counts*
FM 1960 and Northgate Forest	WE	PO	Lead-lag	4H	8	14	22183	2773	40	6	20
FM 1960 and Rayford	WE	PO	Lead-lead	4H	8	13	14116	1765	40	2	16
FM 1960 and Red Oak	WE	PPLT	Lead-lead	5H	8	11	35127	4391	40	3	8
FM 1960 and Rolling Creek	WE	PPLT	Lead-lead	5D	8	11	32726	4091	40	7	25
FM 1960 and Sugar Pine	WE	PO	Lead-lag	4H	8	12	28526	3566	40	9	31
FM 1960 and Terrace Oaks	WE	PPLT	Lead-lag	5D	8	11	31749	3969	40	7	23
FM 1960 and Treaschwig	WE	PO	Lag-lag	4H	10	14	26830	2683	40	5	25
FM 518 @ Barry Rose	WE	PO	Lead-lag	4H	6	11	13209	2202	35	4	9
FM 518 @ Calder	WE	PPLT	Lead-lag	5D	6	10	17710	2952	35	5	16
FM 518 @ CO Rd. 94	WE	PO	Lead-lag	4H	6	12	14619	2437	35	0	1
FM 518 @ Cullen	WE	PO	Lag-lag	4H	6	14	17915	2986	35	1	4
FM 528 @ San Joaquin	WE	PPLT	Lead-lead	5D	6	8	10230	1705	50	1	1

Intersection	Direction	Mode	Sequence	Display	No. of Lanes (Direction)	No. of Lanes (Inter-section)	ADT Direction	ADTPL	Speed	LT-related Accident Counts*	Total Accident Counts*
SH 6 @ FM 519	WE	Per-missive	NA	5H	8	10	8625	1078	45	1	4
SH 6 and Beechnut	NS	PO	Lead-lead	4H	8	14	29101	3638	45	15	48
SH 6 and Bellaire	NS	PO	Lead-lead	4H	8	16	28899	3612	45	28	93
SH 6 and Bissonnet	NS	PO	Lead-lead	4H	8	12	27649	3456	45	0	1
SH 6 and Clay Road	NS	PO	Lead-lag	4H	8	15	28612	3576	45	8	46
SH 6 and Empanada	NS	PO	Lead-lead	4H	8	12	27658	3457	45	10	44
SH 6 and FM 529	NS	PO	Lead-lead	4H	8	16	28173	3522	45	20	57
SH 6 and Home Depot	NS	PO	Lead-lead	4H	8	11	27173	3397	45	13	28
SH 6 and Keith Harrow	NS	PO	Lead-lag	4H	8	13	23367	2921	45	11	43
SH 6 and Loch Katrine	NS	PO	Lead-lead	4H	8	10	34637	4330	45	3	19
SH 6 and Longenbaugh	NS	PO	Lead-lag	4H	8	12	26088	3261	45	0	3
SH 6 and Old Richmond	NS	PO	Lead-lag	4H	8	10	27334	3417	45	9	29

Intersection	Direction	Mode	Sequence	Display	No. of Lanes (Direction)	No. of Lanes (Inter-section)	ADT Direction	ADTPL	Speed	LT-related Accident Counts*	Total Accident Counts*
SH 6 and Pine Forest	NS	PO	Lead-lead	4H	8	12	20880	2610	45	2	10
SH 6 and Ridge Park	WE	PPLT	Lead-lead	5D	8	12	13753	1719	45	0	3
SH 6 and Smithstone	NS	PO	Lead-lag	4H	8	12	32063	4008	45	3	7
SH 6 and Voss	NS	PO	Lead-lag	4H	8	10	23834	2979	45	8	27
SH 6 and W. Airport	NS	PO	Lead-lag	4H	8	12	18374	2297	45	1	1
SH 6 and West Little York	NS	PO	Lead-lag	4H	8	16	31053	3882	45	3	33
SH 6 and West Rd.	NS	PO	Lead-lag	4H	8	14	29787	3723	45	14	41

*Accident counts are standardized to a 4-year period.

Table A-3: Before-After Study Intersection Basic Information

Intersection	City	No. of Lanes (Direction)	No. of Lanes (Intersection)	Speed	ADT for Year 2005	ADT for Year 2006	Average ADT	ADTPL
Loop 287 and SH 103	Lufkin	8	16	50	17330	16100	16715	2089.4
Timberland and Akinson	Lufkin	6	12	37.5	17940	16200	17070	2845.0
Timberland and Paul	Lufkin	6	10	35	17940	16200	17070	2845.0
Timberland and Lufkin	Lufkin	7	13	37.5	24000	22000	23000	3285.7
Timberland and Denman	Lufkin	8	14	40	18140	22000	20070	2508.8
US 183 and Park	Austin	8	12	45	47000	47580	47290	5911.3
US 183 and Walton Way	Austin	8	12	40	35000	36320	35660	4457.5

Table A-4: Before-After Study Intersection Comparison of Before and After Change

Intersection	Before Change				After Change				Date of Change
	Mode	Sequence Pair	LT-Related Accidents/ Year	Total Accidents/ Year	Mode	Sequence Pair	LT-Related Accidents/ Year	Total Accidents/ Year	
Loop 287 and SH 103	PO	Lead-lead	0.60	6.88	PPLT	Lead-lead	0.30	0.90	4/4/2007
Timberland and Akinson	PO	Lag-lag	0.00	7.12	PPLT	Lag-lag	1.10	7.67	9/26/2005
Timberland and Paul	PO	Lag-lag	0.00	6.03	PPLT	Lag-lag	1.10	6.58	9/26/2005
Timberland and Lufkin	PO	Lag-lag	0.00	14.80	PPLT	Lag-lag	1.10	10.41	9/26/2005
Timberland and Denman	PO	Lag-lag	0.55	11.51	PPLT	Lag-lag	1.64	7.12	9/26/2005
US 183 and Park	PO	Lag-lag	0.00	18.62	PO	Lead-lead	1.90	17.89	7/12/2005
US 183 and Walton Way	PO	Lag-lag	0.54	4.90	PO	Lead-lead	0.00	0.76	11/2/2006