Texas Department of Transportation

Research Product 0-5840-P1

Training Strategies and Materials

August 2008

For TxDOT Project 0-5840:
Development of Left-Turn Operations Guidelines
at Signalized Intersections

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16. Abstract

TxDOT project 0-5840 “Development of Left-Turn Operations Guidelines at Signalized Intersections” has developed 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 the signal displays. To facilitate the implementation of the guidelines developed by this project, training strategies and materials have been developed to provide a training session for TxDOT signal operations and TMC personnel. “Training Strategies” provides details on the purpose, method, scheduling and location for the training. “Training Materials” provides a list of the developed training materials along with the printouts of these training materials. Workshop Section I contains a PowerPoint presentation and workbook materials for Guidelines on Left-Turn Signal Control Mode and Phasing Sequence Selection. Workshop Section II consists of a PowerPoint presentation and workbook materials for Guidelines on Left-Turn Signal Display.

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INTRODUCTION

TxDOT project 0-5840 "Development of Left-Turn Operations Guidelines at Signalized Intersections" has developed 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 the signal displays. To facilitate the implementation of the guidelines developed by this project, training strategies and materials have been developed for providing a training session for TxDOT signal operations and TMC personnel.

This document consists of two parts. Part I "Training Strategies" provides details on the purpose, method, scheduling and location for the training. Part II "Training Materials" provides a list of the developed training materials along with the printouts of these training materials.

TRAINING STRATEGIES

Training Objectives and Contents

The goals of the proposed training section are to introduce to traffic engineers the developed guidelines and the use of these guidelines for selecting the most appropriate left-turn phasing treatments at signalized intersections. The training session will cover the following topics:

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, which include the following aspects:
    - Signal indication,
    - Signal face arrangement,
    - Signal head placement, and
    - Supplemental left-turn signal head.

For each topic, the developed guidelines will be introduced and the case studies will be used for demonstrating the application of the developed guidelines.

Training Audience

The potential audience for the workshop will be the engineers who are in charge of traffic signal design and installations. It will include the personnel in TxDOT traffic operations sections in different districts and traffic engineers in local Transportation Management Centers (TMCs).

Training Method

Researchers suggest a half-day, four-hour workshop for the proposed training. It is our belief that a half-day course at a TxDOT host district will encourage better participation considering the busy schedules of those individuals targeted to attend.

The workshop will consist of two sections: 1) Guidelines on Left-Turn Signal Control Mode and Phasing Sequence Selection, and 2) Guidelines on Left-Turn Signal Display. At the end of each section, workshop evaluation forms will be distributed to all attendees and will be reviewed after each workshop. The workshop agenda and materials will be refined, as appropriate, to capitalize on comments and suggestions that will improve the workshop in the future.

Training Scheduling and Coordination

The scheduling of workshops will be coordinated between the university workshop team leader, TxDOT project director from the Traffic Operations Division and TxDOT project advisor from the Human Resources Division. The project director will be responsible for coordinating workshops scheduling with TxDOT district training coordinators to ensure that district training facilities will be available for conducting workshops.

Training Location

The workshops are planned to be held in a TxDOT facility within selected host district. Location selection will be coordinated between the workshop team leader, project director and project advisors.

TRAINING MATERIALS

PowerPoint materials include:

- A presentation for introducing the Guidelines on Left-Turn Signal Control Mode and Phasing Sequence Selection.
- A presentation for introducing the Guidelines on Left-Turn Signal Display.

Workbook materials include:

- Workshop Section I, including 1.) Guidelines on Selecting Left-Turn Signal Control Mode, 2.) Guidelines on Selecting Signal Phasing Sequence, and 3.) Case Studies for Signal Control Mode and Phasing Sequence Selection.
- Workshop Section II, including 1.) Guidelines on the Placement of Left-Turn Signal Heads and Signal Displays, and 2.) Case Studies.

Guidelines on Left-Turn Signal Control Mode and Phasing Sequence Selection

PowerPoint Presentation and Workbook Materials for Workshop Section I

Guidelines on Left-Turn Signal Control Mode and Phasing Sequence Selection

For Workshop Section I

Texas Southern University

Outline

- Guidelines for Selecting Left-Turn (LT) Signal Control Mode
- Guidelines for Selecting LT Signal Phasing Sequence
- Case Studies

Guidelines for Selecting LT Signal Control Mode

- Introduction
- Existing Criteria
  - Traffic volume based criteria
  - Other types of criteria
- Newly-Developed CPOV Based Criteria
- A Decision-Making Flowchart

Introduction

- Three major modes for left-turn signal control:
  - Permissive only (Per)
  - Protected only (PO)
  - Protected/Permissive left-turn (PPLT)
- Guidelines are developed based on
  - Existing criteria
  - Newly-developed criteria
    - Based on the cross product of LT and opposing through volumes (CPOV)
    - For selecting between the PO and PPLT modes

Existing Criteria

- Traffic Volume Based Criteria
  - Left-turn volume
  - Opposing through volume
  - CPOV
- Other Types of Criteria
  - Accident experience-based
  - Geometric features-based
  - Speed-based

Traffic Volume Based Criteria

Criterion	Warrant		Reference	Recommendation
Volume	Left-Turn Volume	≥ 2 Veh/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 B. 1986	PPLT

Other Types of Criteria

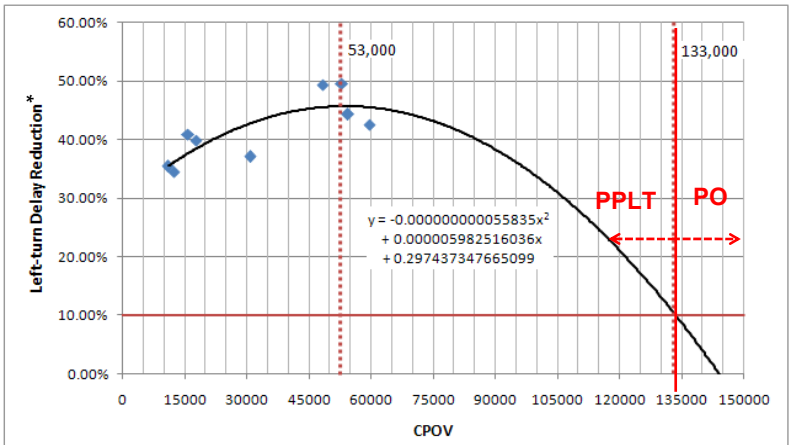
Criterion	Warrant		Reference
Accident Experience	LT-Related Accidents	≥ 4 in any one year, or ≥ 6 in any two consecutive years, or ≥ 8 in any three consecutive years	Agent and Deen 1979, Agent 1987, ITE 1991, Stamatiadis et al. 1997
		≥ 5 in any 12-month period in 3 years	City of San Diego 2006
	LT Conflicts	≥ 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 Florida Section 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 Florida Section 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 pedestrian crossing the lane per hour		
	Access Management Condition		Cottrell 1986
	Angle of the two approaches		

Newly-Developed CPOV Based Criteria

- Developed by using traffic simulation-based methods
- To select between the PO and PPLT modes based on the value of the cross product of left-turn volume and its opposing volume per lane (CPOV) for one hour of the day

Newly-Developed CPOV Based Criteria

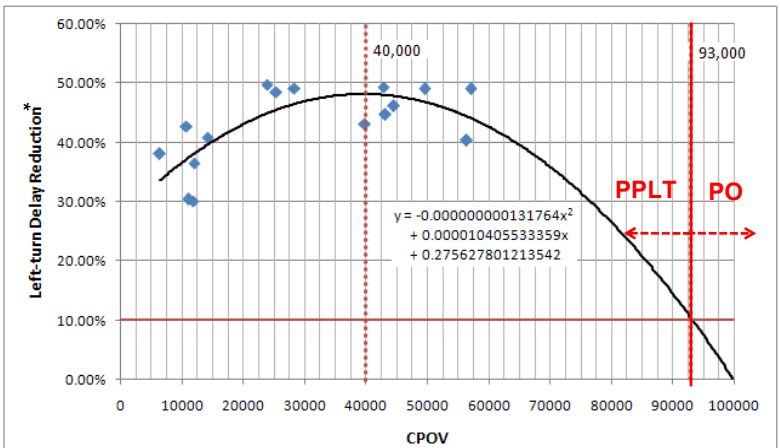
- For intersections with one opposing through lane



*Expected delay reduction when PPLT phase is used instead of PO phase

Newly-Developed CPOV Based Criteria

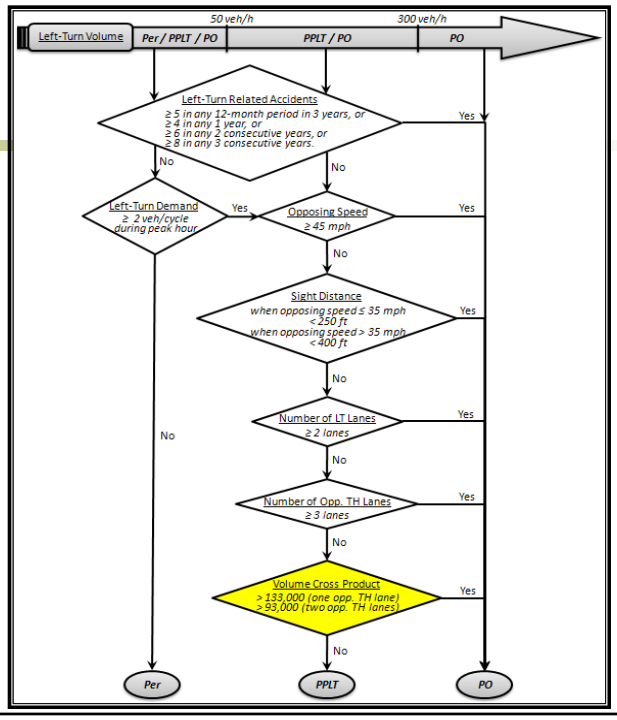
- For intersections with two opposing through lanes



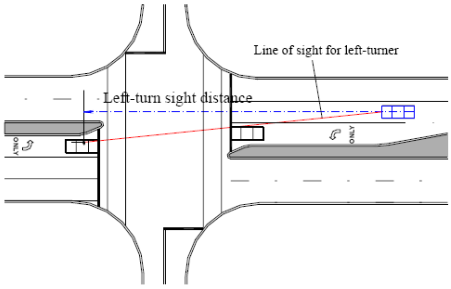
*Expected delay reduction when PPLT phase is used instead of PO phase

Guidelines in the Decision-Making Flowchart

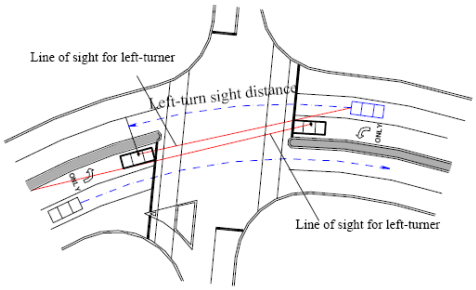
- The decision-making flowchart was developed by
  - Synthesizing, comparing and analyzing the existing criteria, and
  - Incorporating the newly-developed CPOV based criteria for selecting between the PO and PPLT modes



Measures of Sight Distance

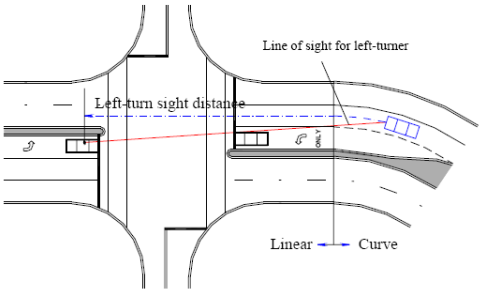


a. Linear approach

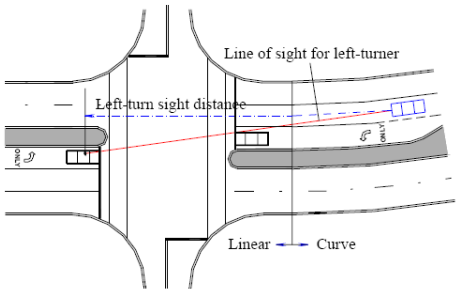


b. Curve approach

Measures of Sight Distance

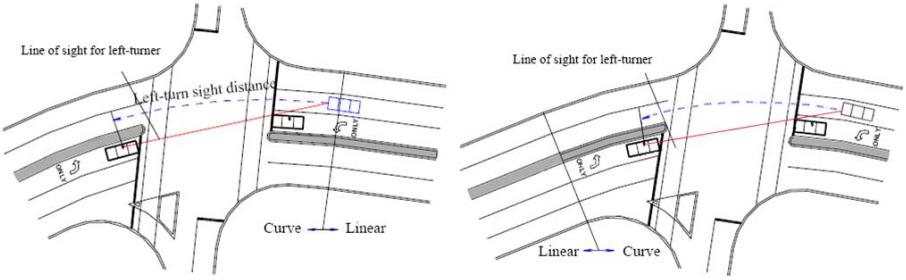


c. Linear approach leading to a curve (left-turn toward outside)



d. Linear approach leading to a curve (left-turn toward inside)

Measures of Sight Distance



e. Curve approach leading to a linear segment (left-turn toward outside) f. Curve approach leading to a linear segment (left-turn toward inside)

Guidelines for Selecting LT Signal Phasing Sequence

- Introduction
- General Findings
- Findings for PO Mode
- Findings for PPLT Mode
- Guidelines for Selecting LT Signal Phasing Sequence

Introduction

- Three major left-turn signal phasing sequences:
  - Lead-Lead
  - Lag-Lag
  - Lead-Lag
- Guidelines were developed based on
  - Findings from previous studies
  - Findings from operational impact analysis
  - Findings from safety impact analysis

General Findings

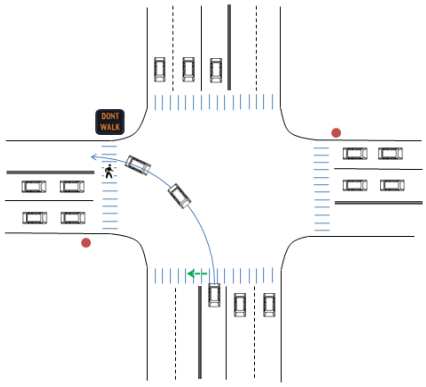
- Operational Impacts
- Safety Impacts
- Driver Acceptance

Operational Impacts

- For an intersection in a two-way coordinated arterial
  - Signal phasing sequence that maximized through bandwidth should be selected.
- For an intersection in a one-directional coordinated arterial during the peak hour periods
  - Lead-Lag phasing sequence should be considered and the approach in the coordinated direction should use leading phase

Safety Impacts

- The use of mixed left-turn signal designs jeopardizes the safety of the intersections
  - At the intersections with heavy pedestrian volume, approach with leading sequence causes higher vehicle-pedestrian accident risk than lagging sequence



Driver Acceptance

- Leading sequence is preferred by most drivers
  - Survey conducted by Hummer et al, 1991
    - 248 respondents preferred leading sequence
    - 59 respondents preferred lagging sequence
    - 95 respondents expressed no preference

Findings for PO Mode

- Safety Impacts
  - Based on the analysis of historical accidents records collected at 114 pairs of intersection approaches, the following safety ranking is derived:
    1. Lead-Lag (safest)
    2. Lead-Lead
    3. Lag-Lag (riskiest)

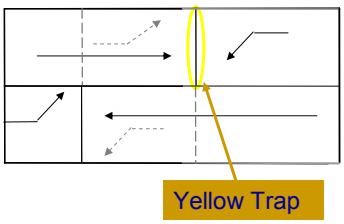
Findings for PPLT Mode

- Safety Impacts
  - Overall, lead-lag phasing has the highest risk sequence
  - When both left-turn volume and pedestrian volume is low, lead-lead sequence should be safer than the lag-lag sequence

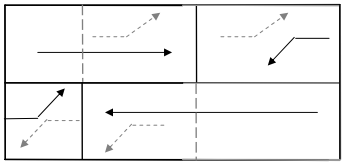
Findings for PPLT Mode

- When using lead-lag sequence, use Dallas Display or Arlington Display for preventing yellow trap problem

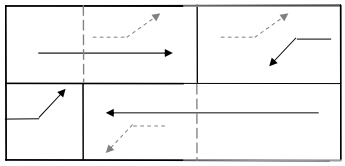
Regular Lead-Lag Phasing with PPLT Control Mode



Fix the Yellow Trap



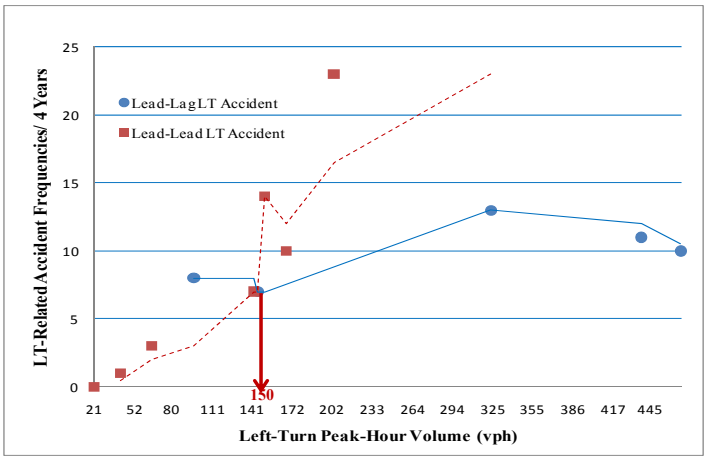
Dallas Phasing



Arlington Phasing

Findings for PPLT Mode

- The safety impacts of signal phasing sequence are different at different left-turn volume levels



Guidelines for Selecting Sequence

- Recommendations for PO Mode
  1. If the intersection has heavy pedestrian volume, the lead-lead or lead-lag sequence should be avoided to prevent conflicts between left-turn vehicles and pedestrians.
  2. Lead-lag sequence should be considered when the left-turn volume is high. The approach with a higher left-turn volume should use the leading phase.

Guidelines for Selecting Sequence

- Recommendations for PO Mode
  3. Use the phasing sequence which is most common along the arterial and in a region.
  4. In a two-way coordinated arterial, choose a signal phasing sequence that will provide widest two-way through bandwidth.
  5. In an one-way coordinated arterial, a lead-lag sequence should be considered and the approach in the coordinated direction should use the leading phase.

Guidelines for Selecting Sequence

- Recommendations for PPLT Mode
  1. If the intersection has heavy pedestrian volumes, lead-lead or lead-lag sequence should be avoided to prevent conflicts between left-turning vehicles and pedestrians.
  2. If LT volume < 150 vph, use a lead-lead sequence; if LT volume >=150 vph, use a lead-lag sequence, and the approach with the higher left-turn volume should use a leading sequence.
  3. If a lead-lag sequence is selected, Arlington or Dallas Phasing should be considered.

Guidelines for Selecting Sequence

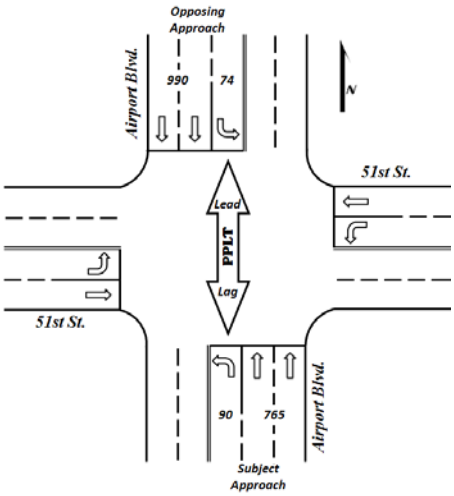
- Recommendations for PPLT Mode
  4. Use the phasing sequence which is most common along the arterial and in a region.
  5. In a two-way coordinated arterial, choose a signal phasing sequence that will provide the widest two-way through bandwidth.
  6. In a one-way coordinated arterial, the lead-lag sequence should be considered and the approach in the coordinated direction should use the leading phase.

Case Studies

- Four intersections were selected to apply guidelines for selecting LT signal control mode and sequence
  - Case 1 – Airport Blvd. & 51st St., Austin, Texas
  - Case 2 – 29th St. & Lamar Blvd., Austin, Texas
  - Case 3 – Lamar Blvd. & 38th St., Austin, Texas
  - Case 4 – FM 518 & Calder Rd., League City, Texas

Airport Blvd. & 51st St.

— *Intersection Description*



Airport Blvd. & 51st St.

— *Selection of Signal Control Mode*

- Step 1. Check the left-turn traffic volume
  - Subject Approach (NB): 90 vph
  - Opposing Approach (SB): 74 vph

Both NS left-turn approach volumes are between 50 vph and 300 vph. The signal control mode in the NS directions should choose between the PO and PPLT modes.

Airport Blvd. & 51st St.
— *Selection of Signal Control Mode*

- Step 2. Check the number of left-turn related accidents
  - 5 left-turn related accidents happened between May 2005 and December 2006

It does not satisfy any criteria listed for choosing the PO mode. Go to next selection step.

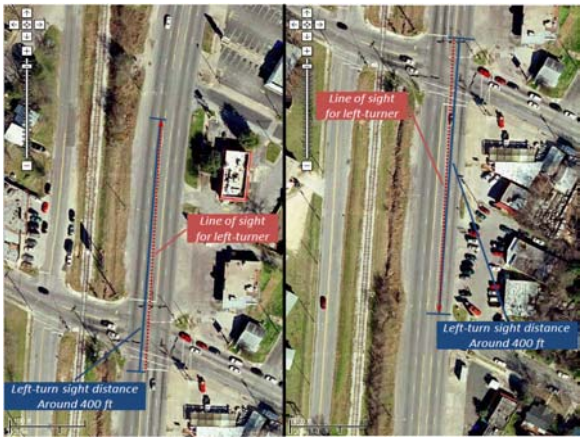
Airport Blvd. & 51st St.
— *Selection of Signal Control Mode*

- Step 3. Check the speed limit of opposing through traffic
  - Subject Approach (NB): 40 mph
  - Opposing Approach (SB): 40 mph

Both approach speed limits are lower than 45 mph (if ≥ 45 mph, install PO mode). Go to the next selection step.

Airport Blvd. & 51st St.
— *Selection of Signal Control Mode*

- Step 4. Check the sight distance for left-turn movements



Airport Blvd. & 51st St.
— *Selection of Signal Control Mode*

- Step 4. Check the sight distance for left-turn movements
  - Subject Approach (NB): approx. 400 ft
  - Opposing Approach (SB): approx. 400 ft

Both approaches have sight distances just over 400 ft (if < 400 ft, when opposing speed > 35 mph, install PO mode). Go to next selection step.

Airport Blvd. & 51st St.
— *Selection of Signal Control Mode*

- Step 5. Check number of lanes
  - Subject Approach (NB): 1 left-turn lane; 2 opposing through lanes
  - Opposing Approach (SB): 1 left-turn lane; 2 opposing through lanes

Both approaches do not satisfy the criteria for choosing the PO mode (2 or more left-turn lanes, or 3 or more opposing through lanes, install PO mode). Go to next selection step.

Airport Blvd. & 51st St.
— *Selection of Signal Control Mode*

- Step 6. Check cross product of volume per lane (CPOV)
  - Subject Approach (NB): 44,550
  - Opposing Approach (SB): 28,305

Both approaches are lower than 93,000 which is the threshold for selection between the PO and PPLT modes (when the approach has 2 opposing through lanes). Therefore, the signal control mode of the NS directions should be the PPLT mode.

Airport Blvd. & 51st St.
— *Selection of Signal Control Mode*

- Summary
  - By following the decision-making flowchart, it has been determined that the PPLT mode is the appropriate signal control mode for NB and SB approaches of this study intersection.

Airport Blvd. & 51st St.
— *Selection of Signal Phasing Sequence*

- Step 1. Check pedestrian volume
  - This intersection is not located in downtown area
  - There is very low pedestrian volume

Therefore, both the leading phase and lagging phase can be used for this intersection.

Airport Blvd. & 51st St.
— *Selection of Signal Phasing Sequence*

- Step 2. Check the left-turn traffic volume
  - Left-turn volume in the subject direction is 90 vph, which is below 150 vph

Therefore, the lead-lead sequence is recommended.

Airport Blvd. & 51st St.
— *Selection of Signal Phasing Sequence*

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

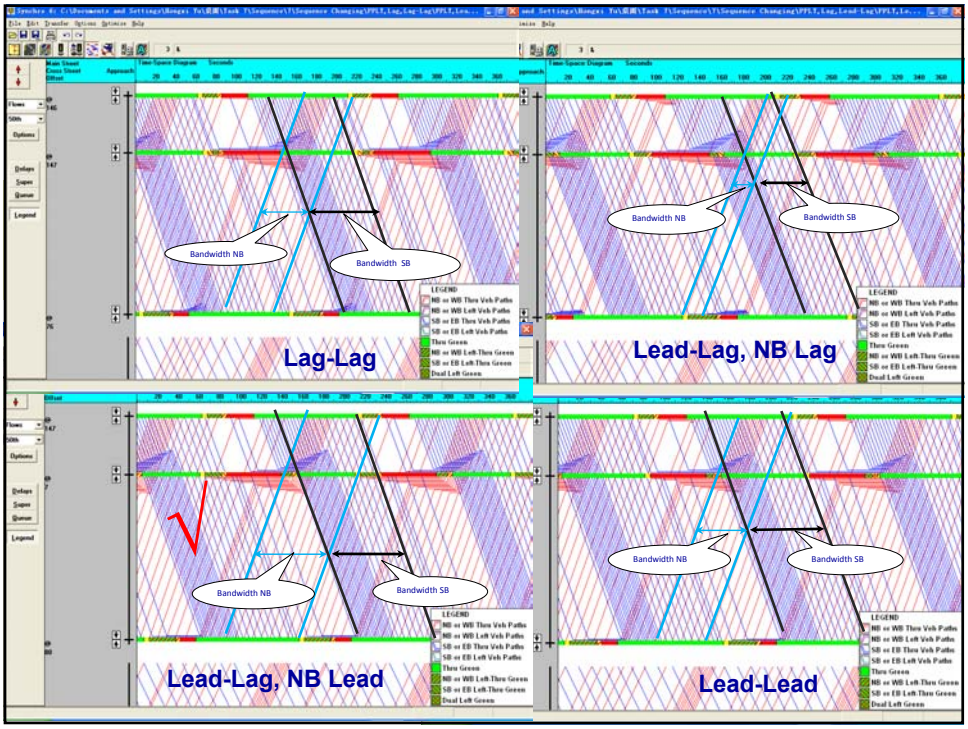
Airport Blvd. & 51st St.
— *Selection of Signal Phasing Sequence*

- Step 4. Check signal phasing consistency
  - Left-turn phasing information for the other intersections on Airport Blvd. is not available. Therefore, this step is skipped for this case study.

Airport Blvd. & 51st St.
— *Selection of Signal Phasing Sequence*

- Step 5. Check bandwidth
  - NB approach is the subject approach
  - Signals along NS direction are two-way coordinated
  - SYNCHRO is used to represent the two-way bandwidth under different types of signal phasing sequences (see next slide)

Lead-lag phasing with NB being leading phase provides the widest two-way bandwidth. In this case, the bandwidths under different sequences are very close.



Case Studies

Case 1

Airport Blvd. & 51st St.

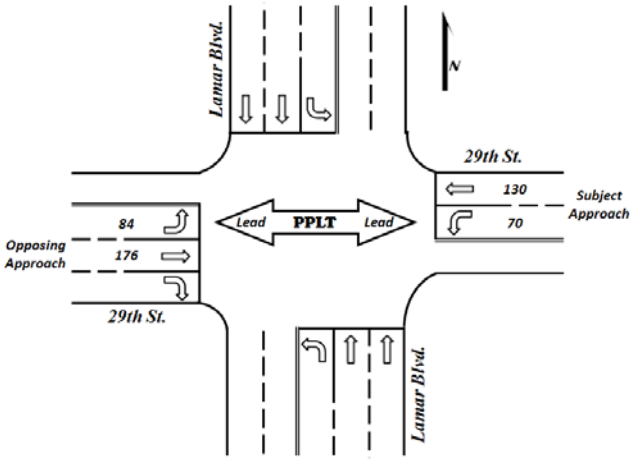
— *Selection of Signal Phasing Sequence*

- Summary
  - Step 2 recommended lead-lead phasing
  - Step 5 recommended lead-lag phasing
  - The criteria for Step 2 have higher priority than that for Step 5 and the two-way through bandwidth under these two sequences are quite close

Lead-lead phasing sequence is recommended for this intersection

29th St. & Lamar Blvd.

— *Intersection Description*



29th St. & Lamar Blvd.

— *Selection of Signal Control Mode*

- Step 1. Check the left-turn traffic volume
  - Subject Approach (WB): 70 vph
  - Opposing Approach (EB): 84 vph

Both approach volumes are between 50 vph and 300 vph. Therefore, the signal control mode of the WE directions should choose between the PO and PPLT modes.

29th St. & Lamar Blvd.
— *Selection of Signal Control Mode*

- Step 2. Check the number of left-turn related accidents
  - Only one left-turn related accident, which occurred in the past four years

None of the criteria listed are satisfied for choosing the PO mode. Go to the next selection step.

29th St. & Lamar Blvd.
— *Selection of Signal Control Mode*

- Step 3. Check the speed limit of opposing through traffic
  - Subject Approach (WB): 30 mph
  - Opposing Approach (EB): 30 mph

Both approach speeds are lower than 45 mph (if ≥ 45 mph, install PO mode). Go to the next selection step.

29th St. & Lamar Blvd.
— *Selection of Signal Control Mode*

- Step 4. Check the sight distance for left-turn movements

29th St. & Lamar Blvd.
— *Selection of Signal Control Mode*

- Step 4. Check the sight distance for left-turn movements
  - Subject Approach (WB): approx. 160 ft
  - Opposing Approach (EB): approx. 270 ft

The sight distance of the WB approach is less than 250 ft and the sight distance of EB is over 250 ft. (if < 250 ft, when opposing speed ≤ 35 mph, install PO mode). For the WB approach, PO mode should be installed.

29th St. & Lamar Blvd.
— *Selection of Signal Control Mode*

- Summary
  - By following the decision-making flowchart, it is found that PO mode is the appropriate signal control mode for WB approach
  - To keep the consistency of signal control in this intersection, PO mode is selected for both WE directions of this intersection

29th St. & Lamar Blvd.
— *Selection of Signal Phasing Sequence*

- Step 1. Check pedestrian volume
  - This intersection is not located in downtown area
  - There is very low pedestrian volume

Therefore, both leading phase and lagging phase can be used for this intersection.

29th St. & Lamar Blvd.
— *Selection of Signal Phasing Sequence*

- Step 2. Check the left-turn traffic volume
  - Subject Approach (WB): 70 vph
  - Opposing Approach (EB): 84 vph

A lead-lag sequence is recommended for this intersection because the PO mode is selected. The EB approach should use the leading phase.

29th St. & Lamar Blvd.
— *Selection of Signal Phasing Sequence*

- Step 3. Check signal phasing consistency
  - Left turn phasing information for the other intersections along 29th St. is not available. This step is skipped for this case study.

29th St. & Lamar Blvd.
— *Selection of Signal Phasing Sequence*

- Step 4. Check bandwidth
  - The WB approach is the subject approach. The signal is coordinated in the NS direction. This step is not applicable.

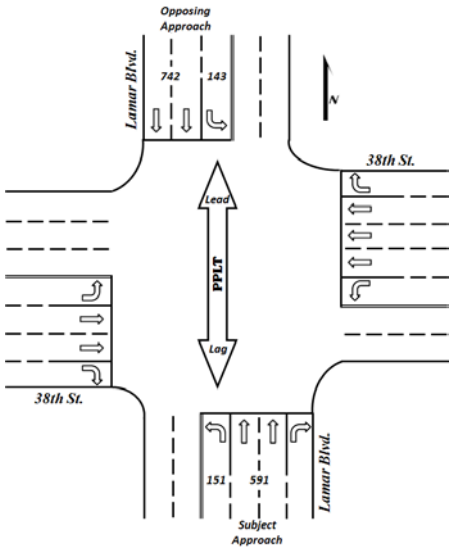
29th St. & Lamar Blvd.
— *Selection of Signal Phasing Sequence*

- Summary
  - Step 2 recommended lead-lag phasing with EB being leading phase
  - Step 4 recommended lag-lag phasing
  - The criteria for Step 2 have higher priority than criteria for Step 4

Lead-lag phasing sequence with EB being the leading phase is recommended for this intersection.

Lamar Blvd. & 38th St.

— *Intersection Description*



Lamar Blvd. & 38th St.

— *Selection of Signal Control Mode*

- Step 1. Check the left-turn traffic volume
  - Subject Approach (NB): 151 vph
  - Opposing Approach (SB): 143 vph

Both approach volumes are between 50 vph and 300 vph. Therefore, the signal control mode of the NS directions should choose between the PO and PPLT modes.

Lamar Blvd. & 38th St.
— *Selection of Signal Control Mode*

- Step 2. Check the number of left-turn related accidents
  - 5 of the 7 accidents happened between July 2006 and June 2007 on the NB approach

The PO mode should be installed for the NS direction of this study intersection. This satisfies the criterion that five or more left-turn related accidents occurred in any 12-month period in the most recent 3 years.

Lamar Blvd. & 38th St.
— *Selection of Signal Control Mode*

- Summary
  - By following the decision-making flowchart, it is determined that the PO mode is the most appropriate signal control mode for the NS directions of this study intersection.

Lamar Blvd. & 38th St.
— *Selection of Signal Phasing Sequence*

- Step 1. Check pedestrian volume
  - This intersection is not located in downtown area
  - There is very low pedestrian volume

Therefore, both the leading phase and lagging phase can be used for this intersection.

Lamar Blvd. & 38th St.
— *Selection of Signal Phasing Sequence*

- Step 2. Check the left-turn traffic volume
  - Subject Approach (NB): 151 vph
  - Opposing Approach (SB): 143 vph

The lead-lag sequence is recommended for this intersection because the PO mode is selected. The NB approach should the use leading phase.

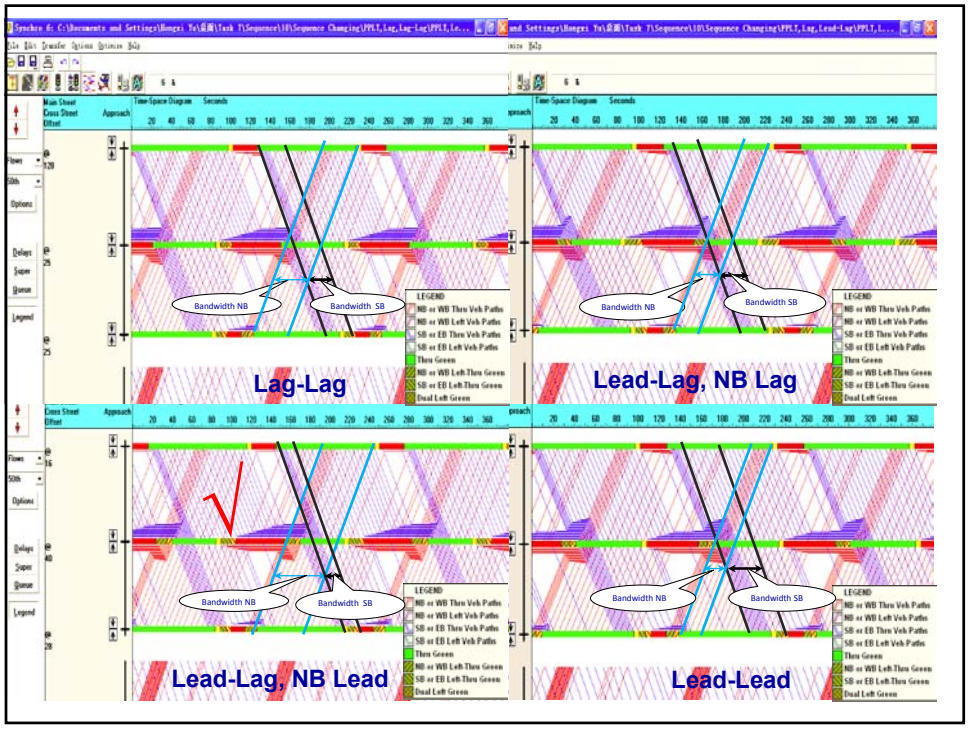
Lamar Blvd. & 38th St.
— *Selection of Signal Phasing Sequence*

- Step 3. Check signal phasing consistency
  - Left turn phasing information for the other intersections along Lamar Blvd. is not available. This step is skipped for this case study.

Lamar Blvd. & 38th St.
— *Selection of Signal Phasing Sequence*

- Step 4. Check bandwidth
  - Signals along NS direction are two-way coordinated
  - SYNCHRO is used to represent the two-way bandwidth under different types of signal phasing sequences (see next slide)

Lead-lag phasing with NB being leading phase provides the widest two-way bandwidth.



Case Studies

Case 3

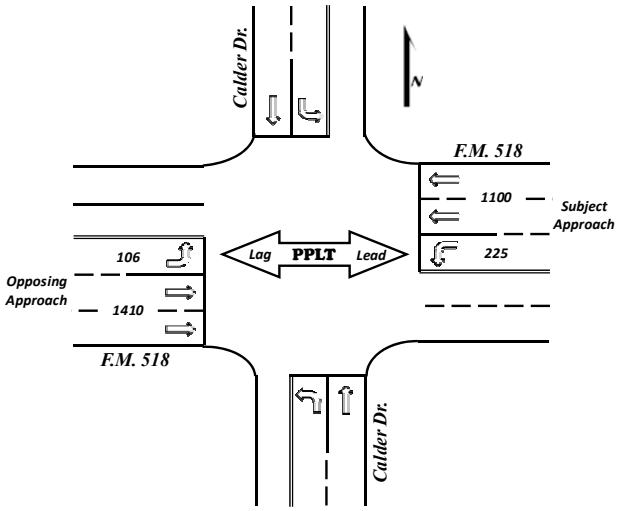
Lamar Blvd. & 38th St.

— *Selection of Signal Control Sequence*

- Summary
  - Both Step 2 and Step 4 recommended lead-lag phasing with NB being the leading phase. Therefore, the lead-lag phasing sequence is recommended for this intersection.

FM 518 & Calder Rd.

— *Intersection Description*



FM 518 & Calder Rd.

— *Selection of Signal Control Mode*

- Step 1. Check the left-turn traffic volume
  - Subject Approach (WB): 225 vph
  - Opposing Approach (EB): 106 vph

Both approaches are between 50 vph and 300 vph. Therefore, the signal control mode of the WE directions should choose between the PO and PPLT modes.

FM 518 & Calder Rd.
— *Selection of Signal Control Mode*

- Step 2. Check the number of left-turn related accidents
  - 5 left-turn related accidents, which were 1 accident in 1999, 1 accident in 2000, and 3 accidents in 2001.

It does not satisfy any criteria listed for choosing PO mode. Thus, go to next selection step.

FM 518 & Calder Rd.
— *Selection of Signal Control Mode*

- Step 3. Check the speed limit of opposing through traffic
  - Subject Approach (WB): 40 mph
  - Opposing Approach (EB): 40 mph

Both approach speeds are lower than 45 mph (if ≥ 45 mph, install PO mode). Go to next selection step.

FM 518 & Calder Rd.

— *Selection of Signal Control Mode*

- Step 4. Check the sight distance for left-turn movements

Case Studies
Case 4

FM 518 & Calder Rd.

— *Selection of Signal Control Mode*

- Step 4. Check the sight distance for left-turn movements

FM 518 & Calder Rd.
— *Selection of Signal Control Mode*

- Step 4. Check the sight distance for left-turn movements
  - Subject Approach (WB): approx. 420 ft
  - Opposing Approach (EB): approx. 420 ft

Both approaches have sight distances just over 400 ft (if < 400 ft, when opposing speed > 35 mph, install PO mode). Go to next selection step.

FM 518 & Calder Rd.
— *Selection of Signal Control Mode*

- Step 5. Check number of lanes
  - Subject Approach (WB): 1 left-turn lane; 2 opposing through lanes
  - Opposing Approach (EB): 1 left-turn lane; 2 opposing through lanes

Both approaches do not satisfy the criteria for choosing the PO mode (2 or more left-turn lanes, or 3 or more opposing through lanes, install PO mode). Go to next selection step.

FM 518 & Calder Rd.
— *Selection of Signal Control Mode*

- Step 6. Check cross product of volume per lane (CPOV)
  - Subject Approach (WB): 158,625
  - Opposing Approach (EB): 58,300

The CPOV of the WB approach is over 93,000, which is the threshold for selection between the PO and PPLT modes. The WB approach should use the PO mode.

FM 518 & Calder Rd.
— *Selection of Signal Control Mode*

- Summary
  - By following the decision-making flowchart, it is determined that the PO mode is the appropriate signal control mode for the WB approach. To keep the consistency of signal control in this intersection, the PO mode is selected for both WE directions of this intersection.

FM 518 & Calder Rd.
— *Selection of Signal Phasing Sequence*

- Step 1. Check pedestrian volume
  - This intersection is not located in downtown area
  - There is very low pedestrian volume

Both the leading phase and lagging phase can be used for this intersection.

FM 518 & Calder Rd.
— *Selection of Signal Phasing Sequence*

- Step 2. Check the left-turn traffic volume
  - Subject Approach (WB): 225 vph
  - Opposing Approach (EB): 106 vph

The lead-lag sequence is recommended for this intersection because the PO mode is selected. The WB approach should use the leading phase.

FM 518 & Calder Rd.
— *Selection of Signal Phasing Sequence*

- Step 3. Check signal phasing consistency
  - For the intersections along FM 518, 59.1% use lead-lag phasing sequence and 40.9% use lead-lead phasing sequence

The lead-lag phasing sequence is recommended by this step.

FM 518 & Calder Rd.
— *Selection of Signal Phasing Sequence*

- Step 4. Check bandwidth
  - This is an isolated intersection and the signal is not coordinated with other intersections. Therefore, this step is not applicable.

FM 518 & Calder Rd.

— *Selection of Signal Phasing Sequence*

- Summary
  - Both Step 2 and Step 3 recommended lead-lag phasing with the WB approach being the leading phase. The lead-lag phasing sequence is recommended for the WE approaches of this intersection.

Summary

- This section introduced:
  - Guidelines for selecting left-turn (LT) signal control mode
  - Guidelines for selecting LT signal phasing sequence
- Presented 4 case studies for applying both guidelines

Questions/Comments?

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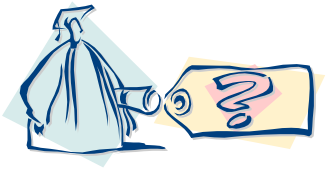

TxDOT Project 0-5840

Guidelines on Left-Turn Signal Control Mode And Phasing Sequence Selection

Workbook Materials for Workshop Section I

Prepared By Texas Southern University
2008

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1. Introduction

Left-turn signal phasing is a critical component for the safe operation of a signalized intersection. The appropriate type of left-turn signal phasing will result in reduced traffic delay, improved traffic progress, and decreased accident rates. The selection of an appropriate left-turn signal phasing for a signalized intersection is a complicated process in which trade-offs between safety and operational efficiency may be required. This training material introduces the guidelines for left-turn signal phasing treatment developed by TxDOT project 0-5840 "Development of Left-Turn Operations Guidelines at Signalized Intersections." It consists of: 1) guidelines on selecting left-turn signal control mode, 2) guidelines on selecting signal phasing sequence, and 3) case studies for signal control mode and phasing sequence selection. To demonstrate the application of the developed guidelines step by step, case studies were conducted at four selected signalized intersections in Texas.

2. Guidelines on Selecting Left-Turn Signal Control Mode

Generally, there are three major modes for left-turn signal control: 1) permissive only (Per), protected only (PO) and protected/permissive left-turn (PPLT). The guidelines on 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, and by incorporating the newly-developed criteria based on the values of the cross product of left-turn volume and the opposing volume (CPOV) for selecting between the PO and PPLT modes.

2.1 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 1 and 2 by categories.

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 (1, 2, 3, 4, 5, 6, 7, 8),

opposing through volume (9) or the cross product of left-turn volume and opposing volume (1, 2, 4, 5, 6, 7, 8) exceeds a certain threshold, protected left-turn phasing (either PO or PPLT) should be installed. From the summarization in Table 1, 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 the 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, the 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 the PO mode. However, when the left-turn volume is greater than 300 vph, double left-turn lanes are warranted (10, 11, 12), and the PPLT mode should not be provided at all (6, 13, 14). 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 the PPLT and PO modes.

Other Types of Criteria

Accident experience-based criteria are the most important for the selection of the left-turn signal control mode. Some studies developed warrants based on the number of left-turn related accidents (1, 5, 6, 8, 14), and some others used the number of left-turn conflicts as criteria (1, 2). There is no doubt that both a high number of left-turn related accidents and of left-turn conflicts require a protected left-turn signal phase.

Geometric features-based criteria consist of three types of warrants: 1) sight distance (4, 6, 13); 2) the number of left-turn lanes (6, 13, 14); and 3) the number of opposing through lanes (2, 6, 14). Sight distance and opposing speed could be considered together to determine the feasibility of using the permissive mode. The 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 (1, 4, 14) found that the PO mode should be provided when opposing speed is greater than 45 mph to avoid collisions between the 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 2.

TABLE 1. Summary of the Existing Traffic Volume Based Criteria for Left-Turn Signal Phasing

Criterion	Warrant		Reference	Recommendation
Volume	LT Volume	≥ 2 Veh/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 B. 1986	PPLT

TABLE 2. Summary of Other Types of Criteria for Left-Turn Signal Phasing

Criterion	Warrant		Reference
Accident Experience	LT-Related Accidents	≥ 4 in any one year, or ≥ 6 in any two consecutive years, or ≥ 8 in any three 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 Florida Section 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 Florida Section 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		[3]Lalani et al. 1986
	LT Storage Length		
	Percent of Heavy Vehicles		
	Political Motivation		
	Public Demand		
	High truck or pedestrian volume		[6]City of San Diego 2006
	50 or more school age pedestrian crossing the lane per hour		
	Access Management Condition		[2]Cottrell 1986
	Angle of the two approaches		

2.2 Results of Newly-Developed Criteria Based on CPOV

The criteria based on the cross product of left-turn volume and its opposing volume per lane (CPOV) were developed for selecting between the PO and PPLT modes by using a traffic simulation-based method (see Yu et al, 2008 for the details). The developed criteria indicate that

- For intersections that have one opposing through lane, the PPLT mode should be selected when the CPOV value is equal to or less than the threshold of 133,000 (see Figure 1).
- For intersections with two opposing through lanes, the PPLT mode should be used when the CPOV value is equal to or less than the threshold of 93,000 (see Figure 2).

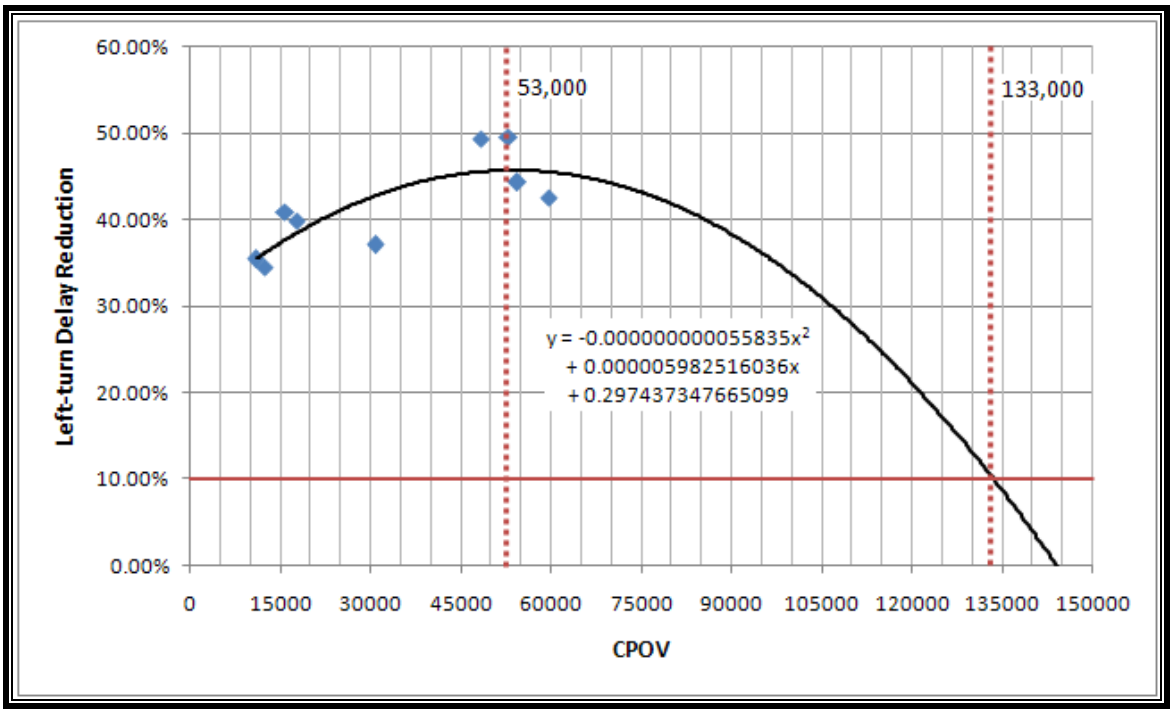


FIGURE 1. Plot of Left-Turn Delay Reduction versus Volume Cross Product for One Opposing Lane

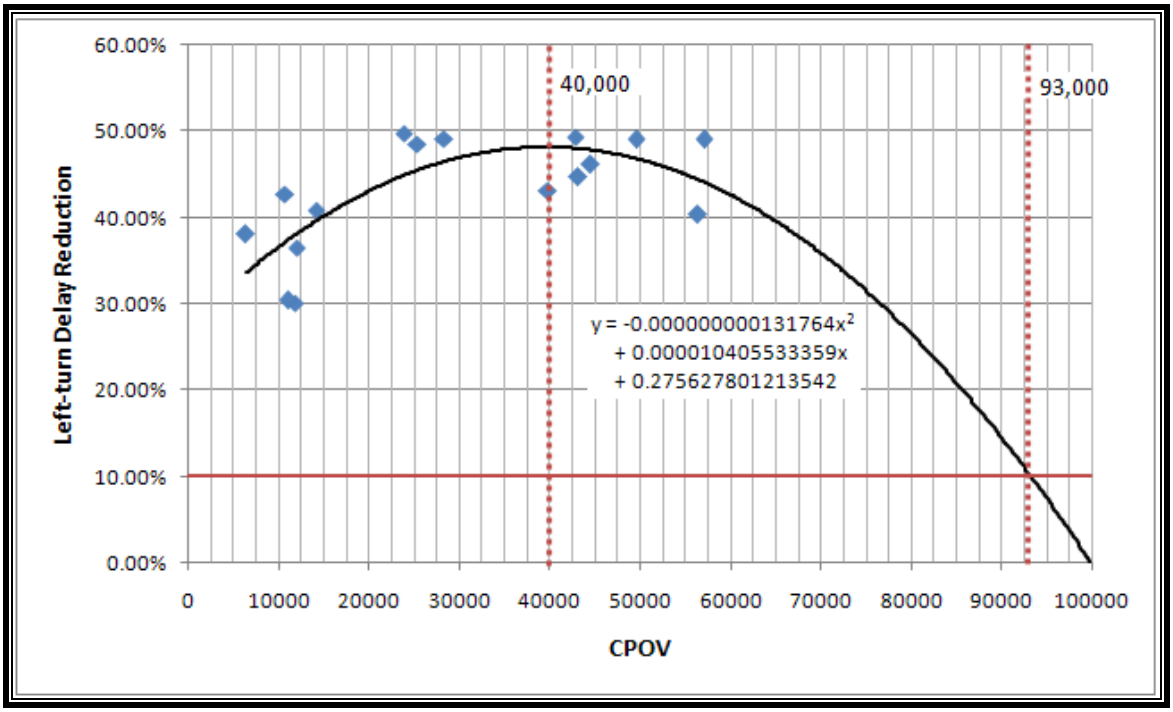
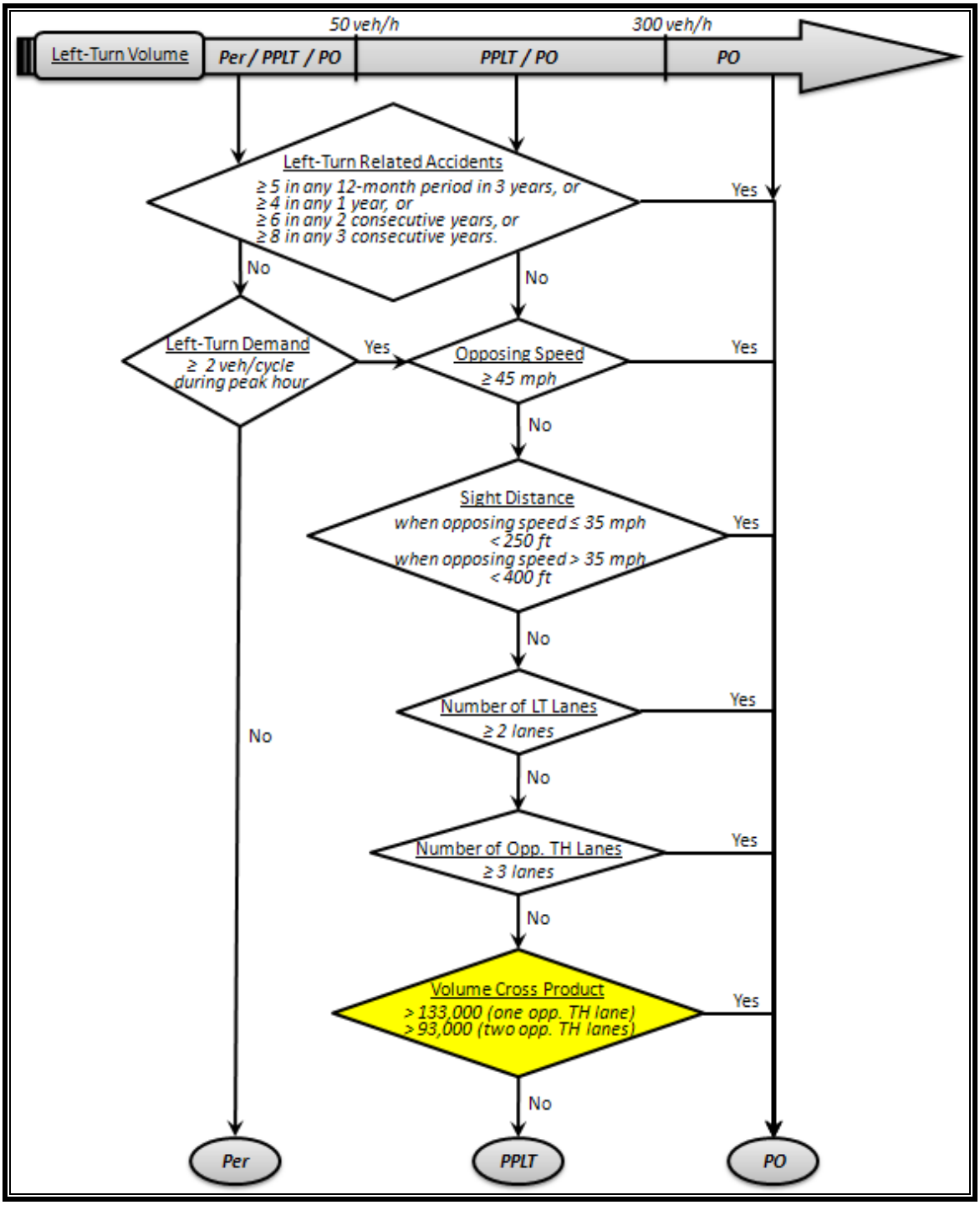


FIGURE 2. Plot of Left-Turn Delay Reduction versus Volume Cross Product for Two Opposing Lanes

2.3 Guidelines on Selecting Left-Turn Signal Control Mode

A flowchart for use in selecting the left-turn signal control mode was developed and is shown in Figure 3. This flowchart was developed by synthesizing the existing criteria, warrants, and guidelines on left-turn signal phasing (Tables 1 and 2) and by incorporating the newly-developed criteria based on the values of CPOV for selecting between the PO and PPLT modes (See the highlighted part in Figure 3).



Note: "Per" is Permissive mode;
"PPLT" is Protected/Permissive mode;
"PO" is Protected-Only mode.

FIGURE 3. Decision-Making Flowchart for Selecting Left-Turn Signal Control Mode

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 the left-turn volume is higher than 50 vph during the peak hours (1, 2, 3, 4, 5, 6), all three modes can be used when the left-turn volume is lower than this critical value. When the 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 the PO and PPLT modes. When the left-turn volume is over 300 vph, the PO mode is the only choice, because dual left-turn lanes should be provided under such heavy left-turn volume conditions (10, 11, 12), and only the PO mode can be used at an intersection with multiple left-turn lanes (6, 13, 14).

The next step is to check the criteria based on accident experience. In the literature, both warrants based on left-turn-related accidents and 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 differing judgments. Therefore, only warrants based on left-turn related accidents were considered in the development of this flowchart. According to the existing warrants summarized in Table 2, the following recommendations were made. The PO mode should be selected when any one of following conditions is met: 1) 5 or more accidents in any 12-month period in three years (6); 2) 4 or more accidents in any one year; 3) 6 or more accidents in any consecutive two years; or 4) 8 or more accidents in any consecutive three years (1, 5, 8, 14).

After that, for intersections at which the left-turn volume is below 50 vph during the peak hour, if the left-turn volume is less than 2 left-turn veh/cycle during the peak hour, permissive-only (Per) mode should be used. This is because, under such low left-turn volume conditions, left-turn vehicles can make turns during the yellow intervals (sneakers), and the protected left-turn phase is not needed (1, 2, 3, 4, 5).

For intersections at which 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, the PO mode should be used (1, 4, 14).

In terms of the intersection sight distance, previous studies (4, 6, 13) recommended that the 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 the PO mode can be used at intersections with multiple left-turn lanes (6, 13, 14).

For the opposing through lanes, previous studies (2, 6, 14) have shown that it is unsafe to make permissive left-turns when there is more than three through lanes in the opposing direction. Therefore, the PO mode should be used when this circumstance exists.

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

In summary, the appropriate signal control mode can be selected by the decision- making flowchart presented in Figure 3. This flowchart synthesized the existing criteria for selecting the 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 newly-developed criteria based on the CPOV value.

3. Guidelines on 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: it moves both the opposing left-turns before the through movements, 2) lag-lag sequence: it moves both the opposing left-turns after the through movements, and 3) lead-lag sequence: it 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 operational impacts findings, the safety impacts findings and other findings literature review. The following is a summarization of the major findings on the impacts of signal phasing sequences.

3.1 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 will affect the two-way through bandwidth but not one-way through bandwidth *(17)*. Considering its impacts on the left-turn movements under one-way coordination condition, the following recommendations are provided:

   1.1) For an intersection in a two-way coordinated arterial, the signal phasing sequence that maximized through bandwidth should be selected.

   1.2) 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 much less delay for the subject left-turn movements than other signal phasing sequences at all left-turn volume levels.

2. Safety impacts:

   2.1) 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 the intersections.

   2.2) At intersections with heavy pedestrian volumes (for example, the intersections in a downtown area), an approach with a leading sequence causes higher vehicle-pedestrian accident risk than a lagging sequence. In some cases, when pedestrians see traffic on the cross street stop at the stop

line, some pedestrians will 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 4) *(18)*.

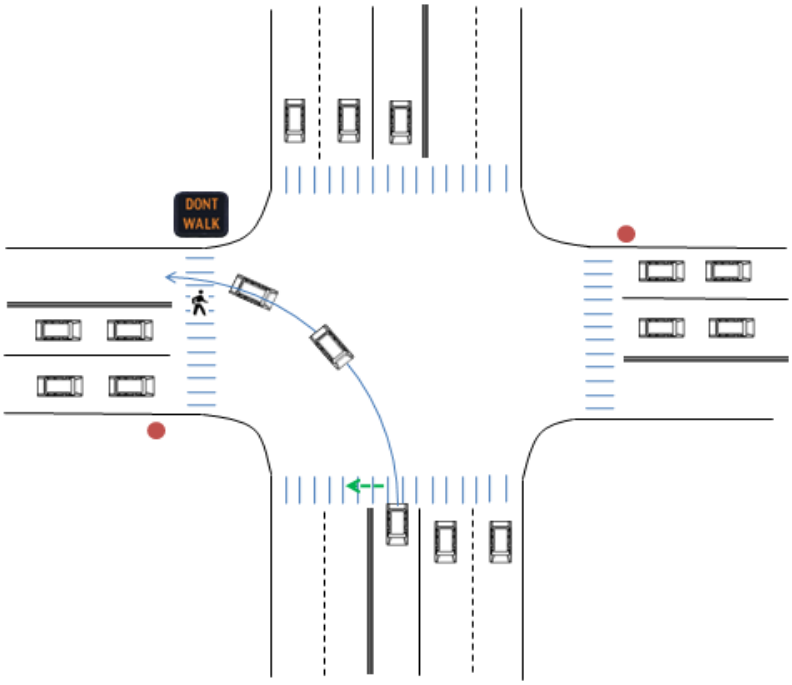


FIGURE 4. Conflict Between Vehicle and Pedestrian Caused by Leading Left-Turn Phase

3. Driver acceptance:

According to a survey conducted by Hummer et al, the1991, 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, the leading sequence is preferred by most of the drivers.

Findings for PO Signal Control Mode:

1. Safety impacts:

According to the analysis of historical accident records, the safest signal phasing sequence is the lead-lag followed by lead-lead, and lag-lag. The difference in the

safety impacts between these three signal phasing sequences is significant at the confidence level 90 percent.

Findings for PPLT Signal Control Mode:

1. Safety impacts:

   1.1) Overall, the lead-lag sequence is the highest risk sequence. First, the lead-lead sequence is safer than lead-lag sequence at the 80 percent confidence level. This result is obtained from the safety impact analysis and is consistent with the results of the traffic conflict study presented. Second, according to the results of traffic conflict study, the lag-lag sequence is also safer than the lead-lag phase (note that, no accident data is available for intersections with the PPLT lag-lag sequence).

   1.2) When both left-turn volume and pedestrian volume is low, the lead-lead sequence should be safer than the lag-lag sequence because the leading phase is safer than the lagging phase under these conditions.

   1.3) When using the lead-lag sequence, the Dallas Display/ Arlington Display can prevent a yellow trap problem while maintaining operational efficiency and minimum delay *(19, 20)*.

   1.4) The safety impacts of signal phasing sequence are different at different left-turn volume levels (see Figure 5.).

      i. When the left turn volume is less than about 150 vph, the lead-lead sequence is safer than the lead-lag sequence.

      ii. When the left-turn volume is greater than about 150 vph, the lead-lag sequence is associated with less accident risk than the lead-lead sequence.

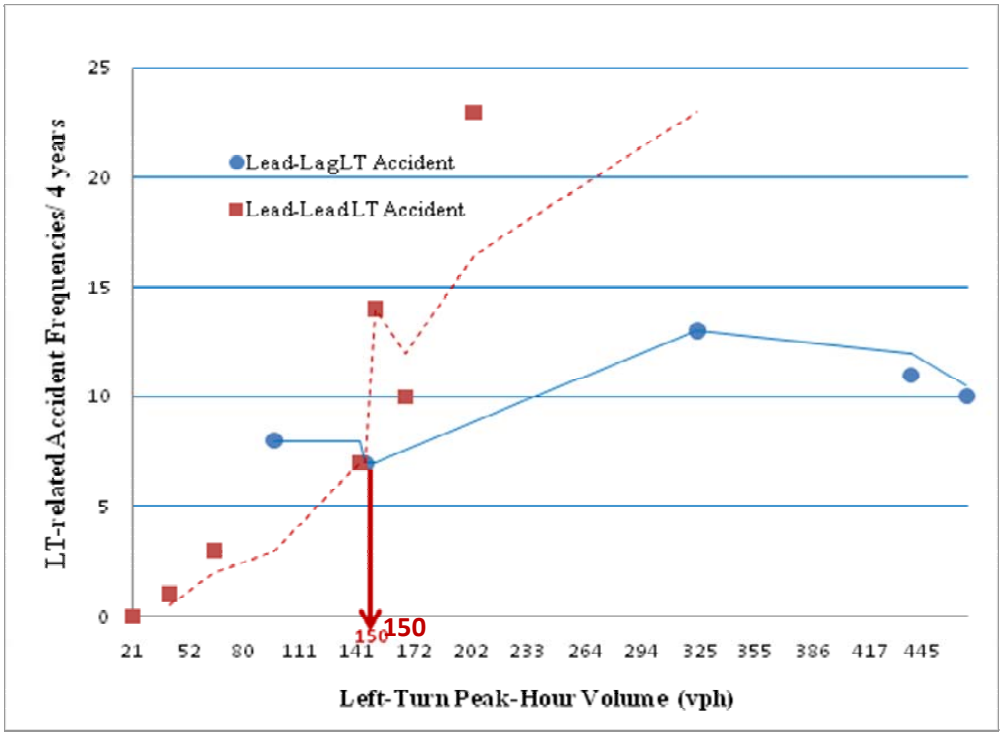


FIGURE 5. Left-Turn Accident Frequency versus Left-Turn Volume

3.2 Guidelines on 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 the intersections with two different types 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 the different results, the first recommended signal phasing sequence should be weighted more in the final phasing sequence selection.

Recommendations for PO Signal Control Mode:

1. If the intersection has heavy pedestrian volume (for example, the intersections in downtown area), the lead-lead sequence or lead–lag sequence should be avoided, unless there are other measures that could effectively prevent the conflicts between left-turn vehicles and pedestrians.

Reason: pedestrian safety consideration according to finding 1.2 in the section "general findings for both PO or PPLT signal control modes."

2. Lead-lag sequence should be considered before lag-lag or lead-lead sequences, especially when the left-turn volume is high. The approach with the higher left-turn volume should use leading phase.

   Reason: safety consideration according to finding 1 in the section "findings for PO signal control mode"

3. Use the phasing sequence which is most common along the arterial and in a region.

   Reason: safety impacts of left-turn signal consistency according to finding 2.1 in the section "general findings for both PO or PPLT signal control modes."

4. When the signals in an arterial are two-way coordinated, choose a 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 (for example 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 consideration according to finding 1 in the section "general findings for both PO or PPLT signal control modes."

Recommendations for PPLT Signal Control Mode:

1. If the intersection has heavy pedestrian volume (for example, intersections in a downtown area), the lead-lead sequence or lead–lag sequence should be avoided, unless there are other measures that could effectively prevent the conflicts between left-turn vehicles and pedestrians.

   Reason: pedestrian safety consideration according to the finding 1.2 in the section "general findings for both PO or PPLT signal control modes."

2. If the left-turn volume level is below 150 vph, the lead-lead sequence is recommended. If the left-turn volume is higher than 150 vph, the lead-lag sequence should be considered. The approach with the higher left-turn volume should use the leading sequence.

Reason: Safety consideration according to finding 1.4 in the section "findings for PPLT signal control mode"

3. If the lead-lag sequence is selected, Arlington or Dallas phasing should be considered to prevent the yellow trap problem.

   Reason: Safety consideration according to finding 1.3 in the section "findings for PPLT signal control mode"

4. Use the phasing sequence which is most common along the arterial and in a region.

   Reason: safety impacts of left-turn signal consistency according to finding 2.1 in the section "general findings for both PO or PPLT signal control modes."

5. When signals in 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 signals in an arterial are one-way coordinated (for example during the peak hour period), the lead-lag sequence should be considered and the approach in the coordinated direction should use leading phase.

   Reason: operational efficiency consideration according to finding 1 in the section "general findings for both PO and PPLT signal control modes."

4. Case Studies for Signal Control Mode and Phasing Sequence Selection

To demonstrate the application of the developed guidelines step by step, case studies were conducted at the following four intersections:

- Airport Blvd. & 51st St. in Austin, Texas
- 29th St. & Lamar Blvd in Austin, Texas
- Lamar Blvd. & 38th St. in Austin, Texas
- F.M. 518 & Calder Rd. in League City, Texas

4.1 Case 1 –Airport Blvd. & 51st St. in Austin, Texas.

- ***Intersection Description***

The study intersection, Airport Blvd. & 51st St., is located in north-central 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 PPLT 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 vph, the NB through traffic volume is 765 vph, the SB left-turn traffic volume is 74 vph, and the SB through traffic volume is 990 vph. The intersection's geometric conditions, current traffic signal controls and traffic volume information are presented in Figure 6.

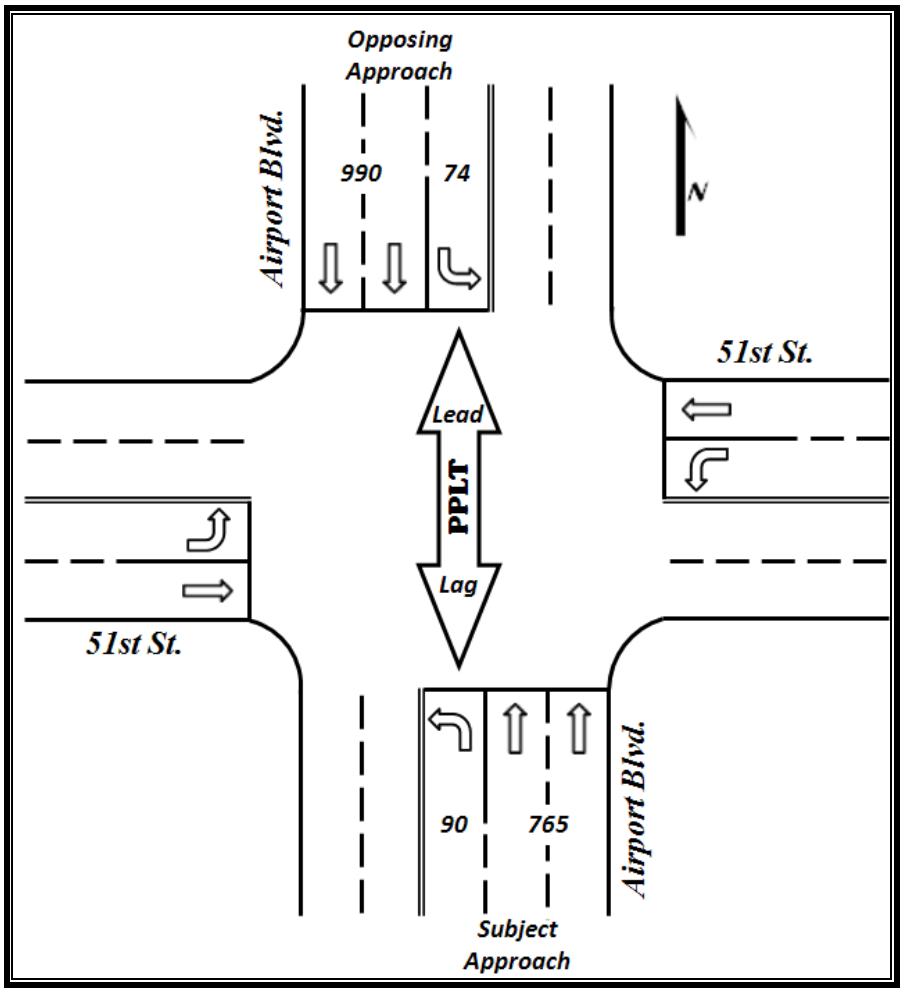


FIGURE 6. Basic Information for Intersection at Airport Blvd. & 51st St.

- ***<u>Application of Guidelines on Selecting Signal Control Mode</u>***

According to the decision-making flowchart developed (see Figure 3), the appropriate signal control mode can be selected for this study intersection by the following steps:

- Step 1. Check the left-turn traffic volume. Both left-turn volumes of the NB and SB approaches are between 50 and 300 vph. Therefore, the signal control mode of the north-south direction for 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 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 the PO mode. Therefore, the selection procedure continues.

- Step 3. Check the speed limit of opposing through traffic. The speed limit of both the NB and SB approaches is 40 mph which is lower than 45 mph (the criterion for selecting PO mode). Thus, go to next selection step.

- Step 4. Check the sight distance for left-turn movements. The sight distances for both the NB and SB left-turn movements are measured by using Google maps (see Figure 7). From Figure 7, it is can be see that both sight distances are just over 400 ft. Therefore, under the condition that the opposing through traffic speed is 40 mph (higher than 35mph), the PO mode cannot be warranted for this location at this step. Thus, go to next selection step.

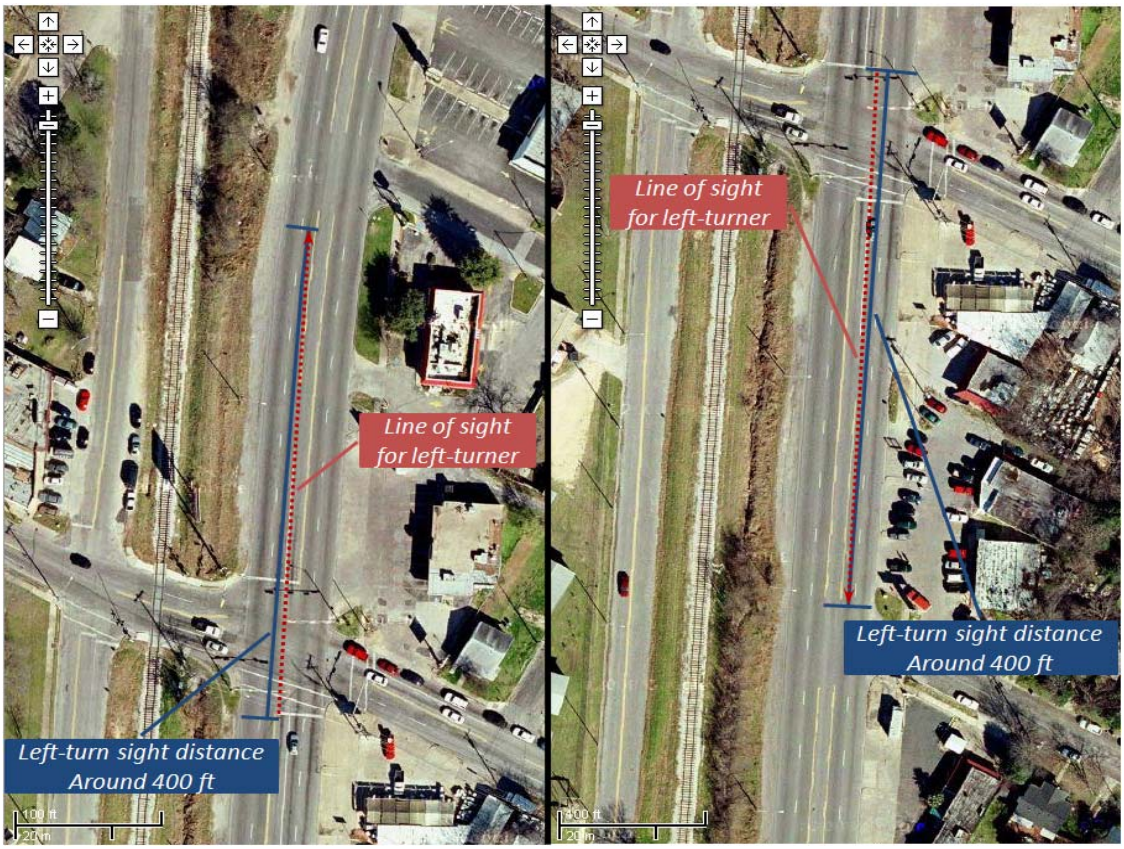


FIGURE 7. Sight Distances for the Left-Turn Movements at NB and SB Approaches of the Intersection at Airport Blvd. & 51st St

- <u>Step 5. Check number of lanes.</u> If an approach has two or more left-turn lanes, or three or more opposing through lanes, the PO mode must be installed for this intersection. However, both the NB and SB approaches of this study intersection have one left-turn lane and two opposing through lanes. Thus, go to next selection step.

- <u>Step 6. Check cross product of volume per lane (CPOV).</u> The NB CPOV is 44,550, and the SB CPOV is 28,305. For 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, the PPLT mode should be used for the NB and SB approaches of this intersection.

In summary, by following the decision-making flowchart in Figure 3, it is found that the PPLT mode is the appropriate signal control mode for NB and SB approaches of this study intersection. Since the current signal control mode is PPLT, no change is recommended for this location.

- ***Application of Guidelines on Selecting Signal Phasing Sequence***

Since the PPLT mode is selected for the subject approaches (NB and SB), the signal phasing sequence guideline for the PPLT mode should be applied for this intersection by using following steps:

- Step 1: Pedestrian Volume Check. This intersection is not located in a downtown area. Pedestrian volume is minimal. Therefore, both leading phase and lag phasing can be used for this intersection.
- Step 2: Left Turn Volume Check. *The* left turn volume in the subject direction is 90vph, which is below 150vph. Therefore, a lead-lead sequence is recommended.
- Step 3: Arlington or Dallas Phasing Check. Since a lead-lead left-turn 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 Blvd is not available. Therefore, this step is skipped for this case study.
- Step 5: Bandwidth Check. From Figure 6, it can be seen that the traffic flows on the major street (Airport Blvd) are not directional. Thus, signals in this arterial are two-way coordinated. In this study, 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 8-11), it is found that lead-lag phasing with the NB approach having the leading phase provides the widest two-way bandwidth. Actually, in this intersection, the bandwidths under different sequences are very close.

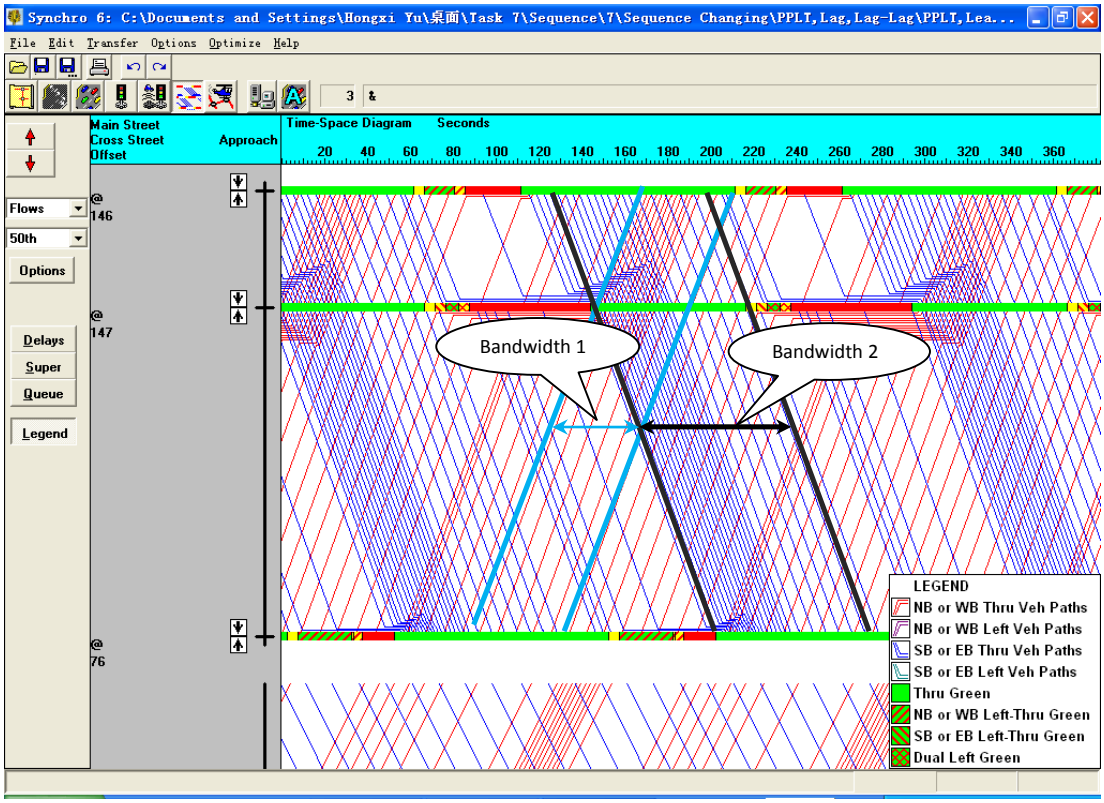


FIGURE 8. SYNCHRO Time-Space Diagram under Lag-Lag Phasing

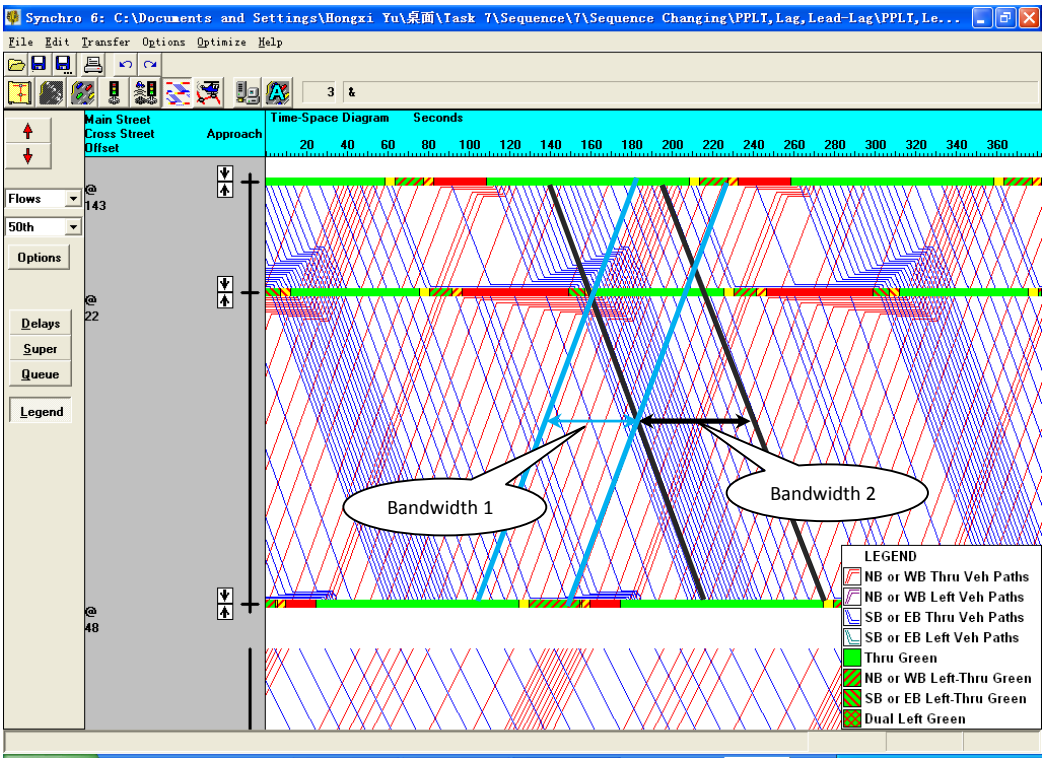


FIGURE 9. SYNCHRO Time-Space Diagram under Lead-Lag Phasing with NB Approach Having Leading Phase

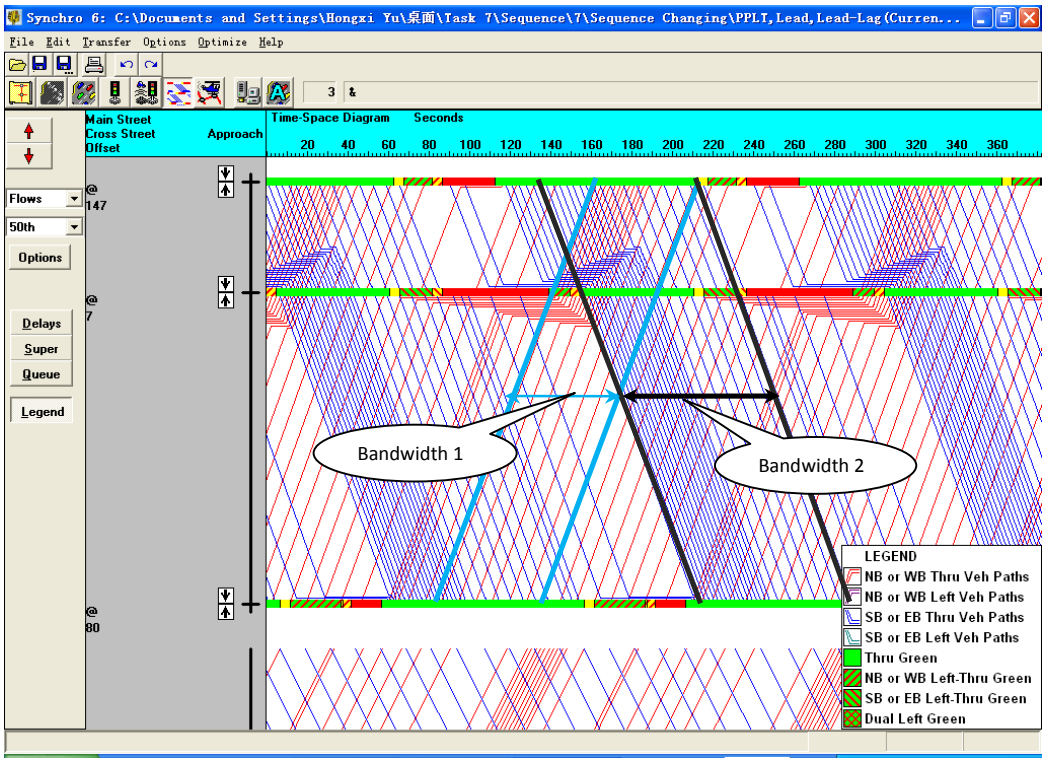


FIGURE 10. SYNCHRO Time-Space Diagram under Lead-Lag Phasing with NB Approach Having Leading Phase

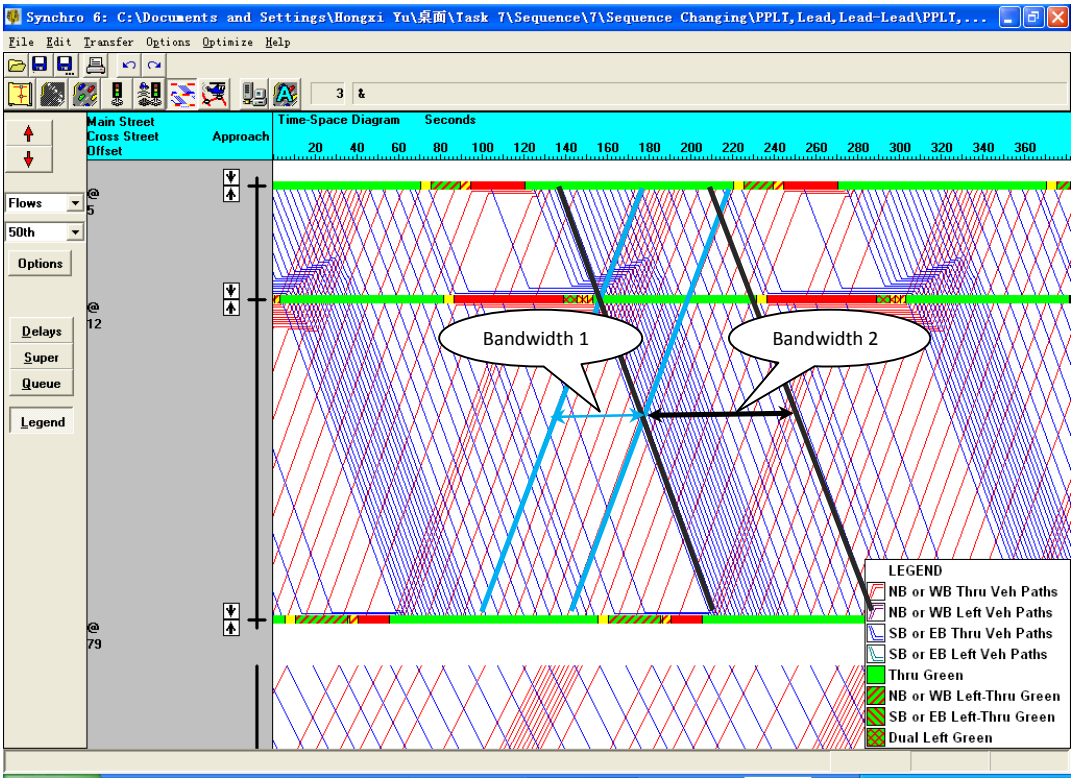


FIGURE 11. SYNCHRO Time-Space Diagram under Lead-Lead Phasing

In summary, by combining the results from Step 1 to Step 5, it is found that both the step 2 recommended lead-lead phase and the step 5 recommended lead-lag phasing sequences with NB the approach having the leading phase. Since the criteria for Step 2 have higher priority than that for Step 5 and the two-way through bandwidth under these two sequences are quite close, the lead-lead phasing sequence is recommended for this intersection.

4.2 Case 2 –29th St. & Lamar Blvd in Austin, Texas

- ***Intersection Description***

The study intersection, 29th St. & Lamar Blvd., is located in Austin, Texas. The westbound (WB) approach 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 vph, the WB through traffic volume is 130 vph, the EB left-turn traffic volume is 84 vph, and the EB through traffic volume is 176 vph. The intersection's geometric conditions, current traffic signal controls and traffic volume information are presented in Figure 12.

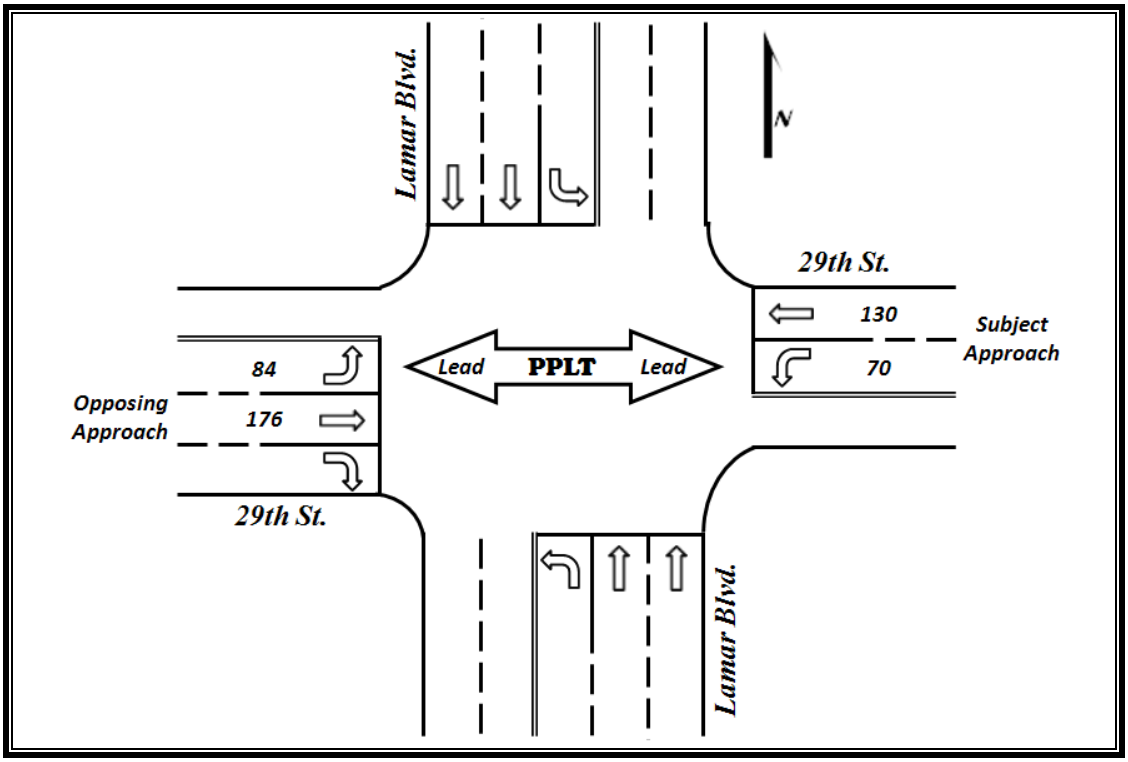


FIGURE 12. Basic Information for Intersection at 29th St. & Lamar Blvd.

- ***Application of Guidelines on Selecting Signal Control Mode***

According to the decision-making flowchart (see Figure 3), the appropriate signal control mode can be selected for this study intersection by the following steps:

- Step 1. Check the Left-Turn Traffic Volume. Both left-turn volumes of WB and EB approaches are between 50 and 300 vph. Therefore, the signal control mode of the east-west direction for 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 was only one left-turn related accident which happened in the past four years. Since it does not satisfy any criteria listed for choosing the PO mode, the selection procedure continues.

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

- Step 4. Check the Sight Distance for Left-Turn Movements. The sight distances for both the WB and EB left-turn movements are measured by using Google maps (see Figure 13). From Figure 13, it is 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 35mph, the PO mode should be installed for the WB approach. For the EB approach, the selection procedure continues.

- Step 5. Check 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 next selection step.

- Step 6. Check volume cross product per lane (CPOV). 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 should be installed for the EB direction of this intersection.

In summary, by following the decision-making flowchart, it is found that the PO mode is the most appropriate signal control mode for the WB direction due to the limited sight distance in this approach. It is also found that the PPLT mode is the most appropriate signal control mode for the EB direction of the study intersection. In order to keep the consistency of signal control in this intersection, the PO mode is selected for both east-west directions of this intersection, which is different from the current signal control mode, i.e. PPLT.

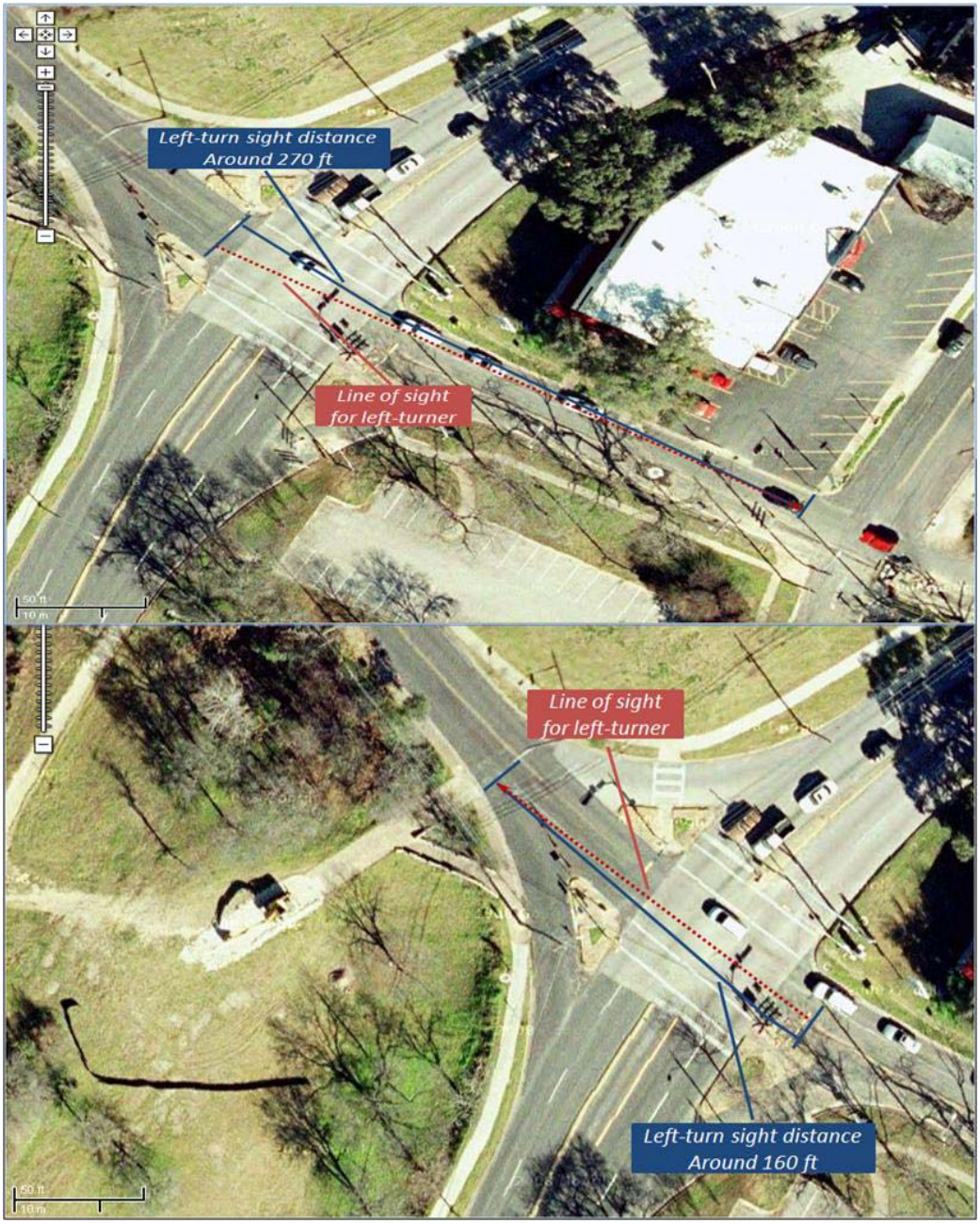


FIGURE 13. Sight Distances for the Left-Turn Movements at WB and EB Approaches of the Intersection at 29th St. & Lamar Blvd.

- ***<u>Application of Guidelines on Selecting Signal Phasing Sequence</u>***

Since the PO mode is selected for the WB and EB approaches of this intersection, the signal phasing sequence guideline for the PO mode should be applied for this intersection by the following steps:

- Step 1: Pedestrian Volume Check. This intersection is not located in a downtown area. There is very low pedestrian volume. Therefore, both leading phase and lag phasing can be used for this intersection.
- Step 2: Left Turn Volume Check. The lead-lag sequence is recommended for this intersection because the PO mode is selected. In addition, since the left turn volume in the WB direction is 70vph and in the EB direction is 84 vph, the EB approach should use 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 north-south direction. Therefore, this step is not applicable for the east-west direction signal phasing sequence selection.

In summary, by combining the results from Step 1 to Step 4, both the step 2 recommended lead-lag phase with the EB approach being the leading phase and the step 4 recommended lag-lag phasing sequence should be used. Since the criteria for Step 2 have higher priority than that for Step 4, the lead-lag phase with the EB approach being the leading phase is recommended for this intersection.

4.3 Case 3 –Lamar Blvd. & 38th St. in Austin, Texas.

- ***Intersection Description***

The study intersection, Lamar Blvd. & 38th St., 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 these pair of approaches is PPLT, and the current phasing sequence is a lead-lag with the NB approach being 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 vph, the NB through traffic volume is 591vph, the SB left-turn traffic volume is 143vph, and the EB through traffic volume is 742 vph. The intersection's geometric conditions, current traffic signal controls and traffic volume information are presented in Figure 14.

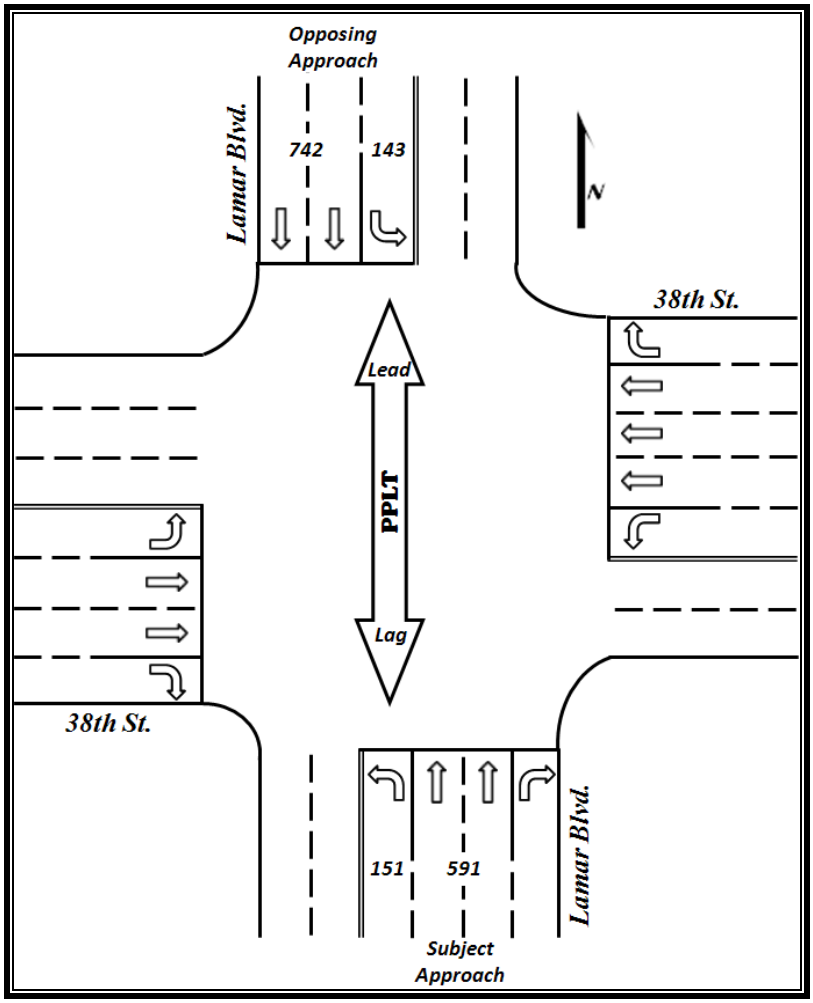


FIGURE 14. Basic Information for Intersection at Lamar Blvd. & 38th St.

- ***Application of Guidelines on Selecting Signal Control Mode***

According to the decision-making flowchart developed (see Figure 3), appropriate signal control mode can be selected for this study intersection by following steps:

- Step 1. Check the left-turn traffic volume. Both NB and SB left-turn volumes are between 50 and 300 veh/h. Therefore, the signal control mode of the north-south direction for 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 happened between October 2004 and June 2007. Five of these accidents happened in a 12-month period between July 2006 and June 2007. Since one listed criteria for

choosing the PO mode is satisfied, which is five or more left-turn related accidents in any 12-month period in the most recent 3 years, the PO mode should be installed for the north-south direction of this study intersection. Thus, the selection procedure stops at this step.

In summary, by following the decision-making flowchart, the PO mode is the most appropriate signal control mode for the north-south directions of this study intersection, which is different from the current signal control mode, i.e. PPLT.

- ***Application of Guidelines on Selecting Signal Phasing Sequence***

Since the PO mode is selected for the NB and SB approaches of this intersection, the signal phasing sequence guideline for the PO mode should be applied for this intersection by following steps:

- Step 1: Pedestrian Volume Check. This intersection is located in a downtown area. However, there is a low pedestrian volume (30 peds/h). Therefore, both leading phase and lag phasing can be used for this intersection.
- Step 2: Left Turn Volume Check. The lead-lag sequence is recommended for this intersection because PO mode is selected. In addition, since the left-turn volume in the SB direction is 143 vph and in the NB direction is 151 vph, the NB approach should use leading phase.
- Step 3: Signal Phasing Consistency Check. Left turn phasing information for the other intersections along Lamar Blvd is not available. Therefore, this step is skipped for this case study.
- Step 4: Bandwidth Check. From Figure 14, it can be seen that the traffic flow on Lamar Blvd is not very directional. Thus, signals in this arterial should be two-way coordinated. Similar to case study 1, signal optimization software SYNCHRO is used to setup the signal splits under different types of signal phasing sequences. By comparing the two-way bandwidth under different types of signal phasing sequences, it is found that lead-lag phasing with the NB approach being the leading phase provides the widest two-way bandwidth. Therefore, this phasing sequence is recommended in this step.

In summary, by combining the results from Step 1 to Step 4, it is found that both Step 2 and Step 4 recommend a lead-lag phase with the NB approach being the leading phase. Therefore, this phasing sequence is recommended for this intersection.

4.4 Case 4 –F.M. 518 & Calder Rd. in League City, Texas.

- ***Intersection Description***

The study intersection, F.M. 518 & Calder Rd., is located in League City, Texas southeast of Houston. The WB approach of the intersection was selected as the subject approach, while the EB approach was the opposing approach. The current signal control mode for these pair of approaches is PPLT, and the current phasing sequence is lead-lag with the EB approach being the lagging phase. Both the WB and EB approaches have one left-turn lane and two through lanes, and the speed limit of both approaches is 40 mph. During the peak hour period, the WB left-turn traffic volume is 225 vph, the WB through traffic volume is 1,100 vph, the EB left-turn traffic volume is 106 vph, and the EB through traffic volume is 1410 vph. The intersection's geometric conditions, current traffic signal controls and traffic volume information are presented in Figure 15.

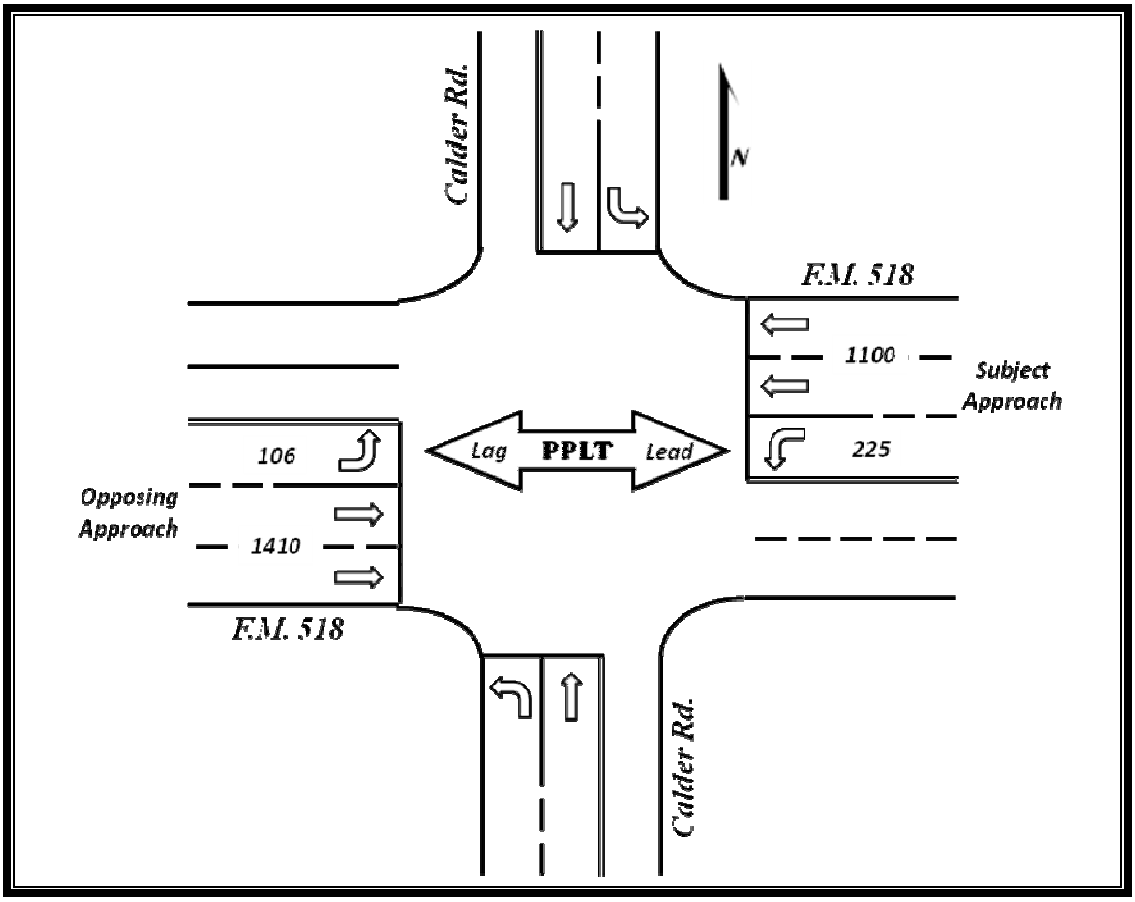


FIGURE 15. Basic Information for Intersection at F.M. 518 & Calder Rd.

- ***Application of Guidelines on Selecting Signal Control Mode***

According to the guidelines on selecting a signal control mode in a decision-making flowchart (see Figure 3), the procedure for selecting the appropriate signal control mode for this study intersection should apply the following steps:

- Step 1. Check the left-turn traffic volume. Both left-turn volumes of the WB and EB approaches are between 50 and 300 vph. Therefore, the signal control mode of the east-west direction for 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. There was one accident in 1999, one accident in 2000, and three accidents in 2001, which does not satisfy any of the criteria listed for choosing the PO mode. Therefore, the selection procedure continues.

- Step 3. Check the speed limit of opposing through traffic. The speed limit of both the EB and WB approaches is 40 mph which is lower than 45 mph (the criterion for selecting the 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 Google maps (see Figure 16). From Figure 16, 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 35mph), the PO mode cannot be warranted for this location at this step. Thus, go to the next selection step.

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

- Step 6. Check cross product of volume per lane (CPOV). The WB CPOV is 158,625, and the EB CPOV is 58,300. For two opposing through lanes, the threshold for selection between the PO and PPLT modes is 93,000. Since the westbound CPOV is over this threshold, the PO mode should be used for the WB direction of this study intersection. For the EB approach, the PPLT mode could be used. However, to keep the consistency of the signal control at this intersection, it is recommended to use the PO mode for the EB approach too.

In summary, by following the decision-making flowchart in Figure 3, it is found that the 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 to convert the signal control mode for the east-west directions of this intersection from PPLT to PO.

FIGURE 16. Sight Distances for the Left-Turn Movements at WB and EB Approaches of the Intersection at F.M. 518 & Calder Rd.

- ***<u>Application of Guidelines on Selecting Signal Phasing Sequence</u>***

Since the PO mode is selected for the WB and EB approaches of this intersection, the signal phasing sequence guideline for the PO mode should be applied for this intersection by the following 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 lag phase can be used for this intersection.

- Step 2: Left Turn Volume Check. The lead-lag sequence is recommended for this intersection because the PO mode is selected. In addition, since the left turn volume in the WB direction is 225 vph and in the EB direction is 106 vph, the WB approach should use leading phase.

- Step 3: Signal Phasing Consistency Check. For the intersections along FM 518, 59.1 percent of them use the lead-lag phasing sequence and 40.9 percent use the lead-lead phasing sequence. Therefore, the lead-lag phasing sequence is recommended by this step.

- Step 4: Bandwidth Check. This is an isolated intersection and is not coordinated with other intersections. Therefore, this step is not applicable for this intersection.

In summary, by combining the results from Step 1 to Step 4, it is found that step 2 recommended the lead-lag phasing sequence with the WB approach being the leading phase and step 3 recommended the lead-lag phasing sequence too. Therefore, it is recommended to use the lead-lag phasing sequence with the WB approach being the leading phase for this intersection.

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Guidelines on Left-Turn Signal Display

PowerPoint Presentation and Workbook Materials for Workshop Section II

Guidelines for Left-Turn Signal Display

For Workshop Section II

Texas Southern University

Outline

- Introductions
- Guidelines on Signal Displays
- Case Studies

Introduction

- The guidelines are mostly based on the MUTCD
- Findings from literature review, survey results, safety evaluation and regional standardization benefits evaluation are also incorporated

Guidelines on Signal Displays

- Left-turn signal indication
- Left-turn signal head arrangement
- Placement of left-turn signal heads

Guidelines on Left-Turn Signal Indication

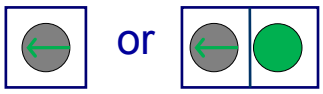
Typical Indications for Left-Turn Signal Displays

Permissive	Green Ball		Protected	Green Arrow	
	Flashing Yellow Arrow				
	Flashing Red Arrow			Green Arrow + Green Ball	
	Flashing Red Ball				
	Flashing Yellow Ball				
Transition Interval	Yellow Arrow		Stop	Red Ball	
	Yellow Ball			Red Arrow	

Guidelines on Left-Turn Signal Indication

- 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 for the protected phase



Guidelines on Left-Turn Signal Indication

- For Permissive-Only Mode:

  During the permissive phase, the left-turn signal face shall display a circular green signal indication

Guidelines on Left-Turn Signal Indication

- 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.

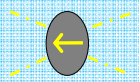
Protected phase in PPLT	Permissive phase in PPLT

Guidelines on Left-Turn Signal Indication

- Flashing Yellow Arrow (FYA) is recommended as an allowable indication to replace Green Ball (GB) for the permissive phase.

Advantages:

- Eliminates the yellow trap problem and extends the permissive phase
- Studies shows that it improves safety and people understand FYA as correctly as GB

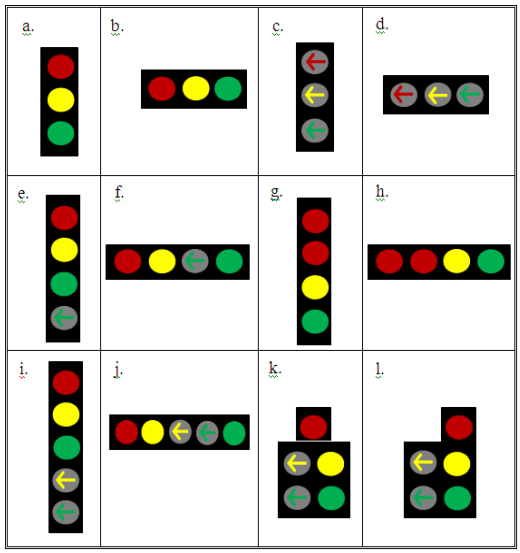


Disadvantages:

- Using two different indications to convey the same message to the drivers (GB for permissive-only; FYA for permissive phase in PPLT)
- Drivers might mistake FYA for a steady yellow arrow and cause conflicts

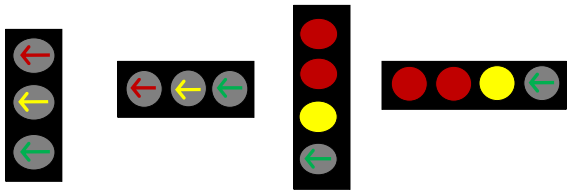
Guidelines on Left-Turn Signal Arrangement

- Variations of Signal Arrangement



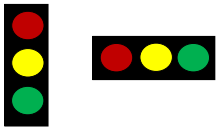
Guidelines on Left-Turn Signal Arrangement

- For Protected-Only Mode:
  - Required that at least one exclusive left-turn signal head should be provided
  - Three or four-section horizontal or vertical signal arrangement is recommended



Guidelines on Left-Turn Signal Arrangement

- For Permissive-Only Mode:
  - Use a three-section horizontal or vertical signal head
  - Preferred to use an exclusive signal head for left-turn movement



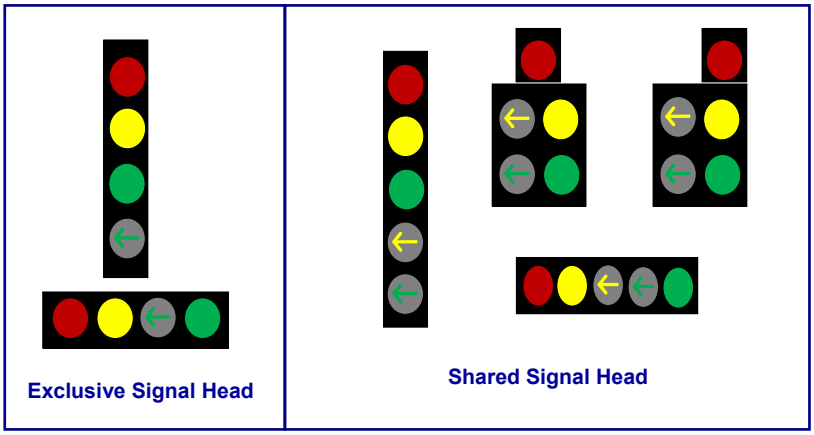
Task 2 survey results show improved intersection safety if individual signal display is provided for each movement

Guidelines on Left-Turn Signal Arrangement

- For PPLT Mode: Strongly recommended to use an exclusive signal head rather than shared signal head, but not required
  - Survey results indicated that it would improve safety at intersections if individual signal head is provided for each movement.
  - Simultaneous display of conflicting color (green arrow and red ball) in one left-turn signal head would occur when using shared signal head for PPLT

Guidelines on Left-Turn Signal Arrangement

Recommendations for PPLT mode arrangement



Guidelines on Left-Turn Signal Arrangement

- Four-section signal arrangement is suggested if an exclusive signal head is used

Literature showed that exclusive 4-section vertical signal head for PPLT mode is less confusing

Guidelines on Left-Turn Signal Arrangement

For PPLT Mode:

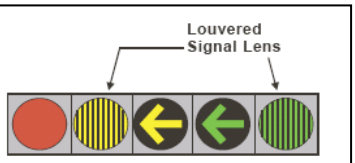
- If a shared signal head has to be used, five-section signal head should be used
- Five-section cluster is preferred to five-section horizontal arrangement

Results of accident data analysis showed 5-section cluster is comparatively safer than 5-section horizontal arrangement

Guidelines on Left-Turn Signal Arrangement

- For PPLT mode, if signal phasing sequence is lead-lag, Dallas or Arlington signal phase could be considered in following conditions:
  - Use rigid mast arm
  - Intersection well-aligned
  - Overhead mounted signal

Dallas or Arlington signal operation would mitigate the yellow trap problem caused by PPLT lead-lag signal phasing



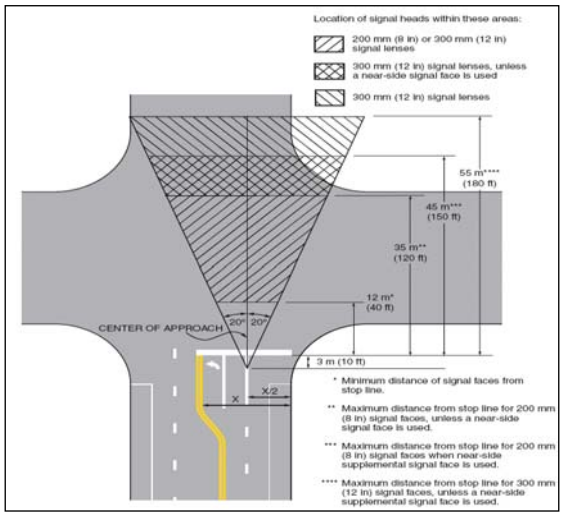
5-SECTION "DALLAS DISPLAY" PPLT with "Dallas Phasing" eliminating yellow trap

Left-Turn Signal Head Placement Guidelines

- Horizontal Location of Signal Heads
- Specific Criteria for Different Modes
- Supplemental Left-Turn Signal Heads

Left-Turn Signal Head Placement Guidelines

Determine Horizontal Location of Signal Heads



Left-Turn Signal Head Placement Guidelines

- For Permissive-Only Mode:
  - Signal head for permissive mode should be located in line with lane line or with center of left-turn lane
  - If exclusive signal head is used, it should be located in center of the left-turn lane

Left-Turn Signal Head Placement Guidelines

- For Protected-Only Mode:

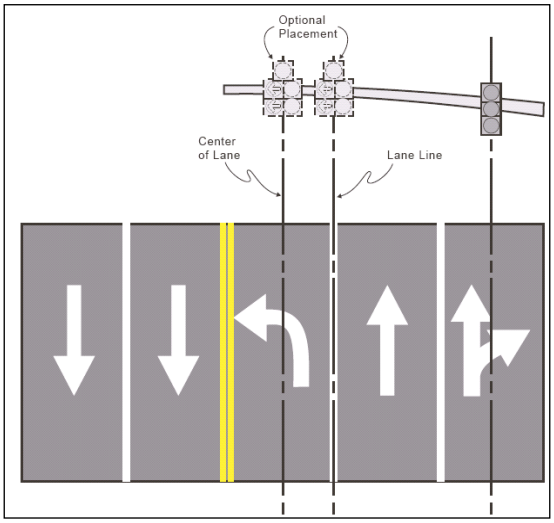
  Signal head should be located in line with center of left-turn lane, overhead on far side of intersection, or it could be ground mounted in median

Left-Turn Signal Head Placement Guidelines

- For PPLT Mode:
  - It can be located either in line with center of left-turn lane or lane line
  - If an exclusive signal head is used, it is recommended to be located in line with center of left-turn lane, or ground mounted in median

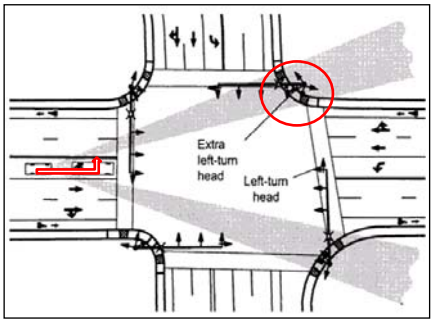
Left-Turn Signal Head Placement Guidelines

Example of PPLT Signal Head Placement



Left-Turn Signal Head Placement Guidelines

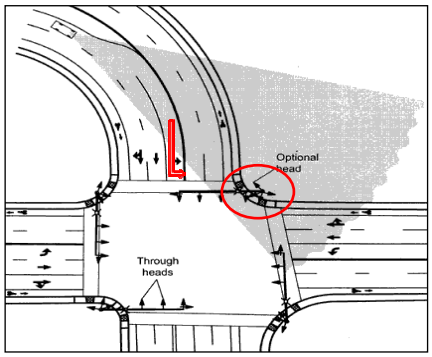
- Supplemental Signal Heads
  - Far-Side Supplemental Left-Turn Signal Head



- Large intersection
- Relatively more large size vehicles
- Sun glare problem

Left-Turn Signal Head Placement Guidelines

- Supplemental Signal Heads
  - Near-Side Supplemental Left-Turn Signal Head



- Curved approach
- Intersection alignment not good

Case Studies

Three intersections were selected:

- Case 1 - Airport Blvd. & 51st St. in Austin, Texas
- Case 2 - FM 518 & Calder in League City, Texas
- Case 3 - Bellaire Blvd & S. Gessner Rd. in Houston, Texas (newly selected intersection study for placement)

Case 1 - Airport Blvd. & 51st St. in Austin, Texas

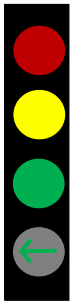
- Study approach: Northbound
- Recommended left-turn signal control mode for PPLT (according to Case Studies in Workshop Section I, Left-Turn Signal Control Mode and Phasing Sequence Selection)

Select Left-Turn Signal Indication

- For protected phase, a left-turn green arrow is used
- For permissive phase, a circular green indication is recommended
  - Since flashing yellow arrow indication has not been applied in this area, it is not recommended to be installed

Select Left-Turn Signal Arrangement

- An exclusive four-section vehicle left-turn signal head is recommended

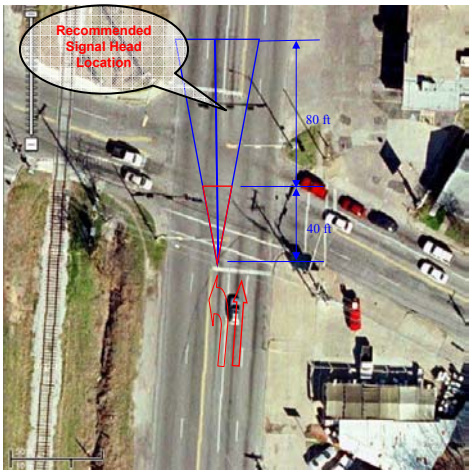


Determine Placement of Left-Turn Signal Head

- No supplemental signal head is recommended to be installed
  - Not a very big intersection
  - No curve hampers intersection visibility

Determine Placement of Left-Turn Signal Head

- Horizontal Location
  - 20 degree “cone of vision”
  - Range: 40 ft - 120 ft
- In line with the center of left-turn lane
- Recommended signal head location is very close to the existing signal head location



Case 2 - FM 518 & Calder Rd. in League City, Texas

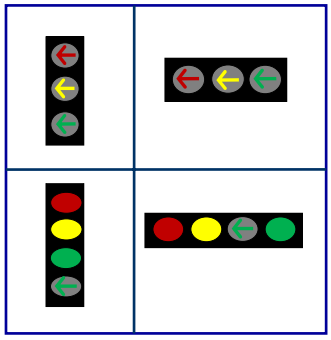
- Study approach: Northbound
- The recommended left-turn signal control mode for is Protected-Only (according to Case Studies in Workshop Section I, Left-Turn Signal Control Mode and Phasing Sequence Selection)

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

- At least one exclusive left-turn signal head should be provided
- Three or four-section horizontal or vertical signal arrangement is recommended

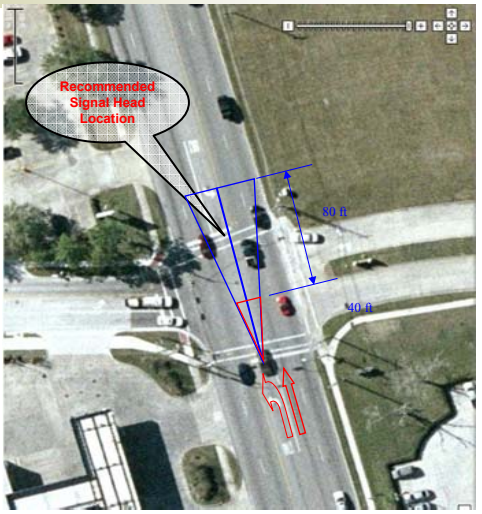


Determine Placement of Left-Turn Signal Head

- No supplemental signal face is recommended to be installed
  - Not a very big intersection
  - No curve hampers intersection visibility

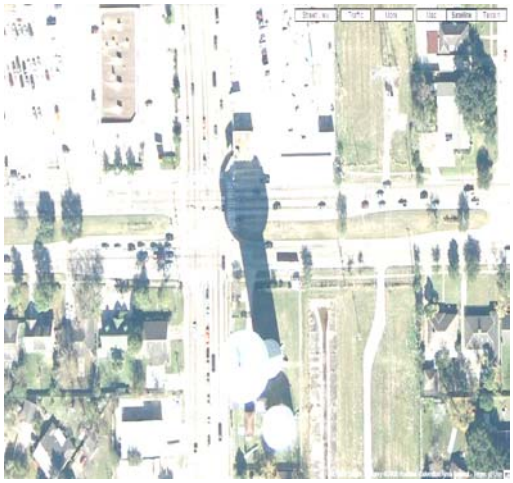
Determine Placement of Left-Turn Signal Head

- Horizontal Location
  - 20 degree cone of vision
  - Range: 40 ft - 120 ft
- In line with the center of left-turn lane



Case 3 - Bellaire Blvd & S. Gessner Rd. in Houston, Texas

- Demonstrating the use of supplemental left-turn signal head
- Subject direction: Eastbound



Supplemental Left-Turn Signal Head

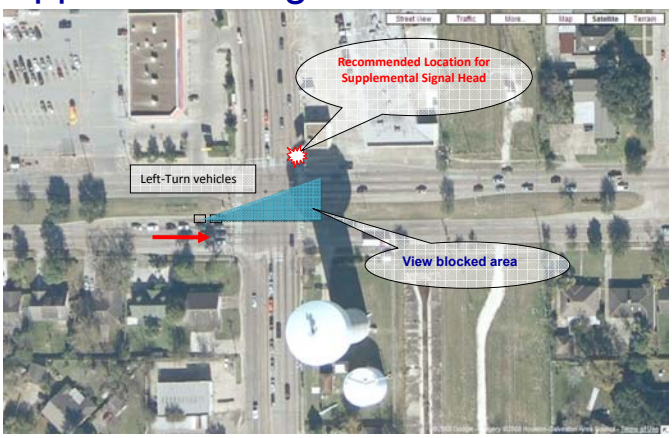
- A far-side supplemental left-turn signal head is recommended
  - Intersection is comparatively large: total of 18 lanes
  - Subject approach is EB, visibility of signal indications (color) is affected by sun glare during PM peak hour
  - Intersection has relatively more large size vehicles

Supplemental Left-Turn Signal Head

- Current location of supplemental signal head

Supplemental Left-Turn Signal Head

- The recommended location of supplemental signal head



Summary

- Introduced guidelines on signal displays
  - Guidelines on left-turn signal indication
  - Guidelines on left-turn signal arrangement
  - Guidelines on the placement of left-turn signal heads
- Conduct case studies at three selected intersections

Questions/Comments?

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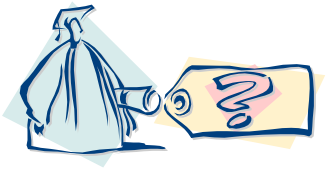

TxDOT Project 0-5840

Guidelines on Left-Turn Signal Display

Workbook Materials for Workshop Section II

Prepared By Texas Southern University
2008

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1. Introduction

This training material is to introduce the guidelines on left-turn signal display developed by TxDOT project 0-5840 "Development of Left-Turn Operations Guidelines at Signalized Intersections." The guideline provides the recommendations in 1) selecting a left-turn signal indication, 2) selecting a left-turn signal arrangement and 3) determining the placement of left-turn signal heads. First, the developed guideline is introduced and the differences from the current standards will be explained in detail. Three case studies are provided to demonstrate the application of the developed guidelines.

2. Guidelines on the Placement of Left-Turn Signal Heads and Signal Displays

The guideline is mainly based on the current standards for left-turn signal placement and display provided by the *Manual of Uniform Traffic Control Devices (MUTCD) (1)*. Findings from the results produced in Project 0-5840 are also used to derive this comprehensive guideline. The developed guideline will be compared to the current standards of the MUTCD. Explanations will be provided for the recommendations that are different from the MUTCD standards.

2.1 Select Left-turn Signal Indication

A signal indication is the illumination of a signal lens that conveys a particular traffic control message to the drivers. Typical left-turn signal indications are presented in Figure 1.

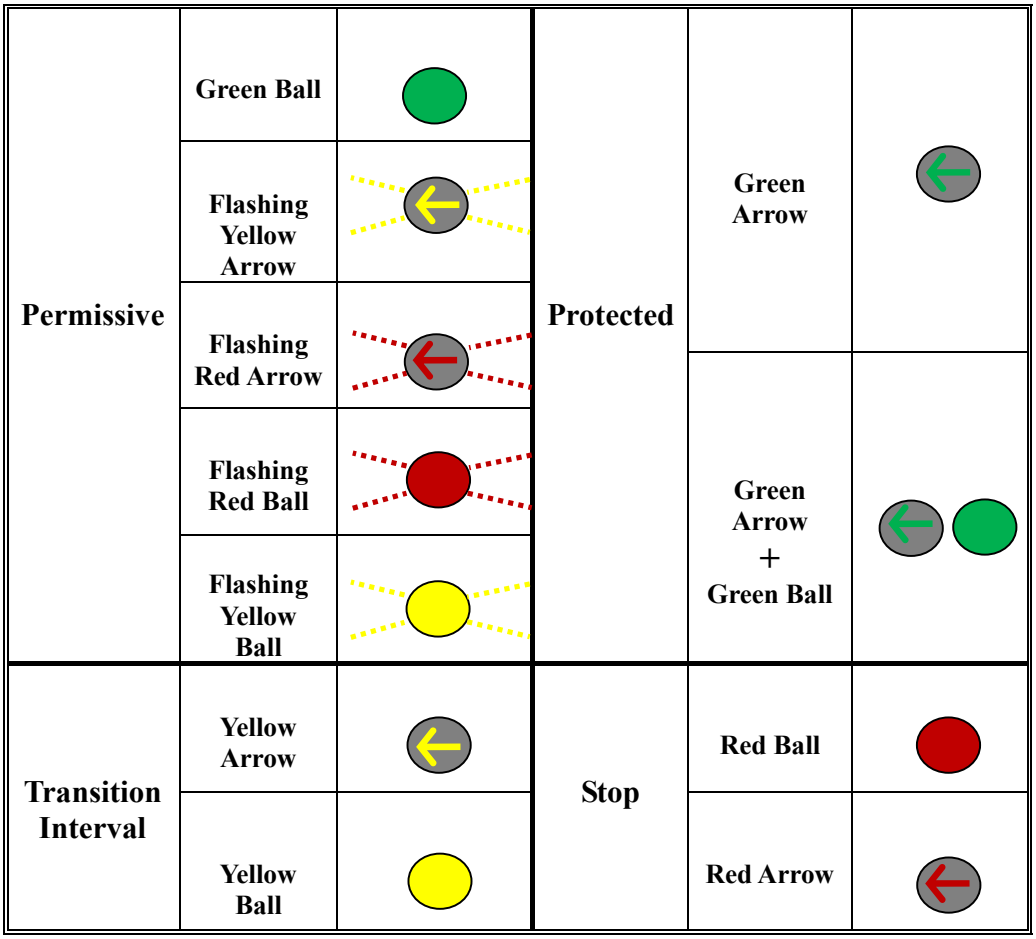

Figure 1 Typical Indications for Left-Turn Signal Display

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

1) <u>For Protected-Only Mode:</u> 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) <u>For Permissive-Only Mode:</u> During the permissive phase, the left-turn signal face shall display a circular green signal indication.
3) <u>For PPLT Mode:</u> 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 (FYA) is recommended as an allowable indication to replace the Green Ball (GB) for the permissive phase in the following conditions:

a. If the FYA is implemented in one intersection, the whole arterial or the whole region should also be installed with FYAs in order to maintain the consistency of signal indication;

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

<u>The difference with MUTCD standards:</u> A Flashing Yellow Arrow is included as an allowable indication for the permissive phase in the PPLT signal control mode.

<u>Explanation on this revision:</u> The Flashing Yellow Arrow (FYA) has been discussed at length as a replacement for the Green Ball (GB) as the indication for the permissive phase for the PPLT mode. It is recommended in this guideline but not required to replace the GB for the following reasons:

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

b. If the FYA permissive indication is used for the PPLT mode, there will be two permissive indications, i.e. GB for permissive-only mode while FYA for the permissive phase in PPLT mode. Since these two indications convey the same message to the 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 the FYA instead of the GB as the indication for the permissive phase during the PPLT control mode. There is a concern that drivers might mistake the FYA for a steady yellow arrow (for example, by a glance at the signal) and assume that they could sneak into the intersection, which may actually increase the risk of a crash between the left-turn and opposing through vehicles.

2.2 Select Left-Turn Signal Arrangement

Signal indications are arranged in different ways, including orientation (horizontal, vertical and cluster arrangements) and number of signal lenses in a signal head (3-section, 4-section and 5-section arrangements). The typical arrangements are presented in Figure 2.

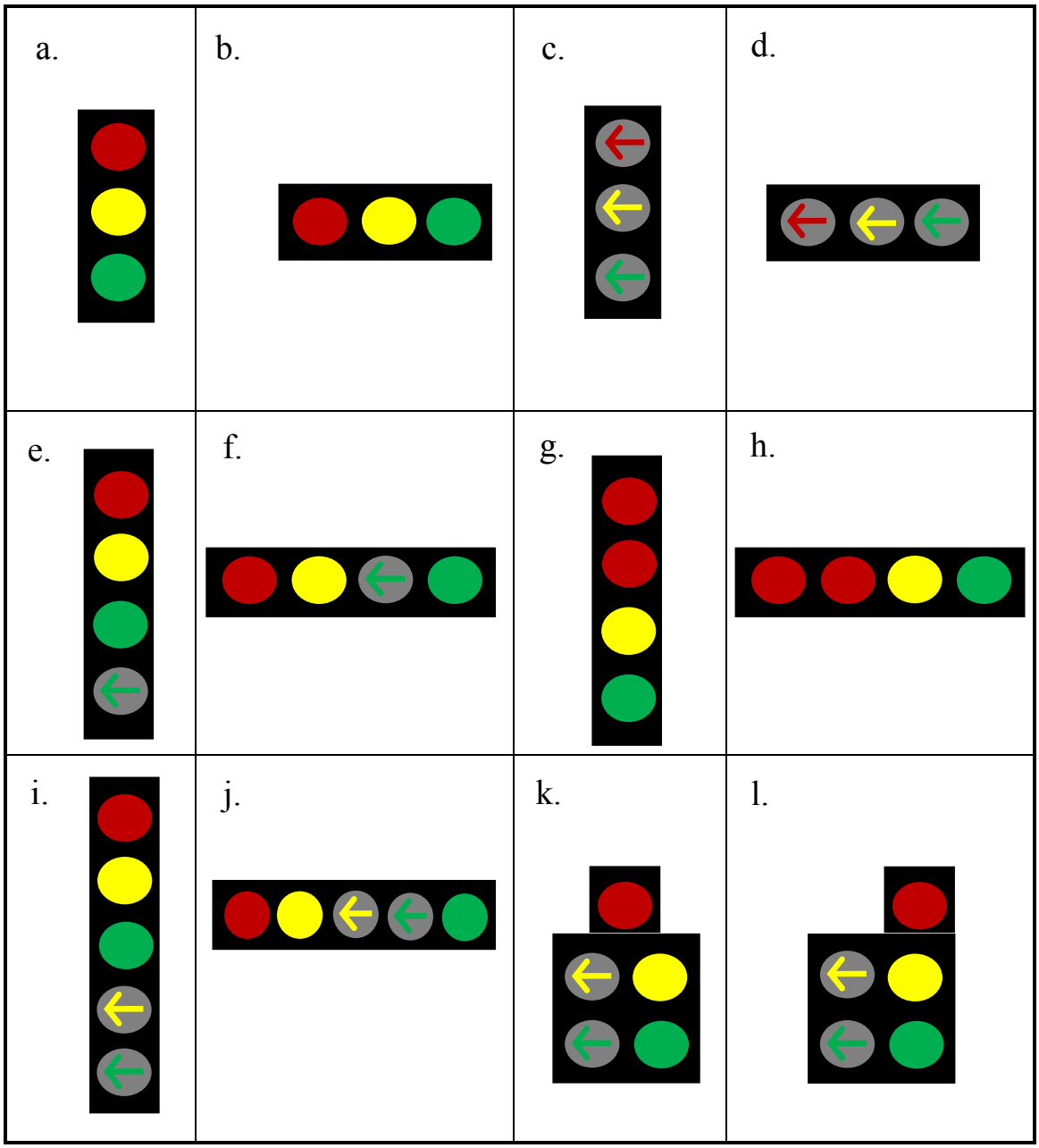

Figure 2 Variations of Signal Arrangements

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 should be provided for the protected-only mode. A three or four-section horizontal or vertical signal arrangement is recommended to be used, as shown in Figure 3.

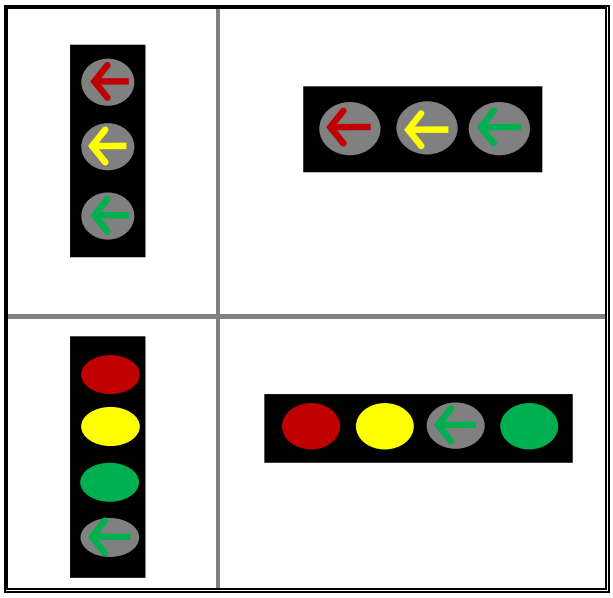

Figure 3 Recommended Left-Turn Signal Arrangement for PO Mode

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 to use an exclusive signal head rather than signal head shared with through movements. A four-section signal arrangement is suggested if an exclusive signal head is used, of which a 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 a five-section cluster is preferred to a five-section horizontal arrangement (Figure 4). A sign shall be used for the shared signal head, such as LEFT TURN SIGNAL sign or a LEFT TURN YIELD ON GREEN (plus a symbolic circular green indication) sign.

In addition, if the signal phasing sequence is lead-lag, a Dallas or Arlington signal phase

(Figure 5) could be considered to prevent the "yellow trap" problem under the following conditions:

a. There is the availability to use rigid mast arm mounted signal heads rather than span wire or a free-swinging mast arm, so that it can ensure that the left-turn signal face be mounted securely enough to provide proper aim of the louvered indications at all times.
b. The intersection must be aligned well, which means the study approach should not be curved or angled.
c. The signal head should be mounted overhead of the left-turn lane rather than placed far-side in customary locations or used for the shared left-turn lane.

Only in the above cases (b and c) should the louvered indications be aimed so as to be readily visible only to left-turn traffic.

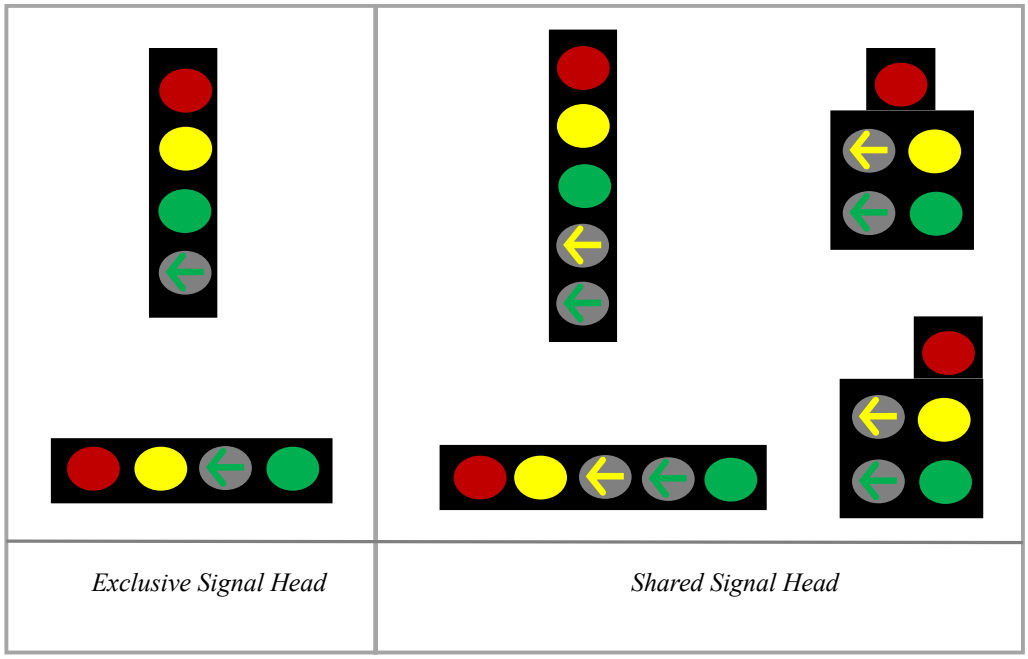

Figure 4 Recommended Left-Turn Signal Arrangement for PPLT Mode

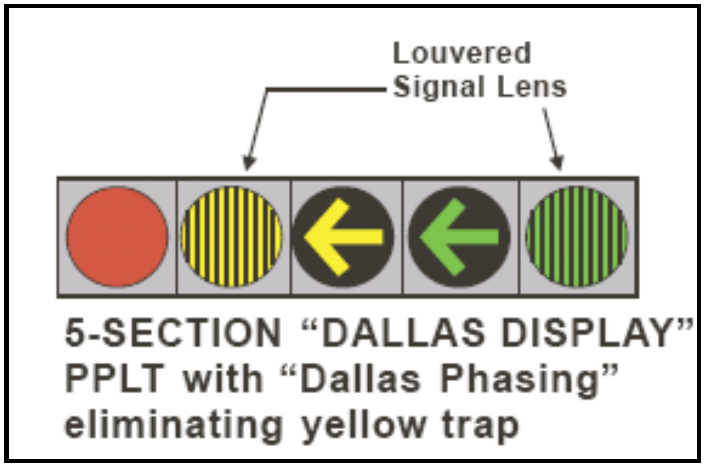

Figure 5 Signal Faces of Dallas Display

Note that it is recommended to use a consistent signal arrangement within the area or along the corridor.

<u>The difference with MUTCD standards:</u> The MUTCD does not recommend exclusive signal head use or suggest how to select among the different signal arrangement types.

<u>Explanation on these revisions:</u>

1) Survey results in Project 0-5840 indicated 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 would occur when using a shared signal head for the PPLT signal control mode (i.e. 5-section horizontal/vertical/cluster signal arrangement). A review of the literature *(3) (4) (5)* finds that simultaneously displaying the green arrow and red ball indication in the same signal display would confuse many drivers. Therefore, an exclusive signal display is strongly recommended for PPLT mode.
3) A review of the literature *(3)* indicates that exclusive 4-section vertical signal heads for the PPLT mode are associated with the least driver confusion.
4) A safety impacts study conducted in Project 0-5840 showed that a 5-section cluster is comparatively safer than a 5-section horizontal signal arrangement.
5) A Dallas or Arlington signal operation would mitigate the yellow trap problem caused by the PPLT lead-lag signal phasing.

6) A regional standardization benefits study conducted in Project 0-5840 showed that the consistent usage of signal displays would improve intersection safety.

2.3 Determine the Placement of Left-turn Signal Heads

2.3.1 Determine 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 6, 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 an 8 in signal lens and 2) not less than 40 ft nor more than 150 ft for a 12 in signal lens. If a supplemental signal face is installed, the distance of the signal heads from stop line should be in a range of 1) not less than 40 ft nor more than 150 ft for an 8 in signal lens and 2) not less than 40 ft nor more than 180 ft for a 12 in signal lens.

In addition, as shown in Figure 6, the signal shall be located between the 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 the approach extended and the other making an angle of approximately 20 degrees to the left of the center of the approach extended. If more conspicuity is desired, it is suggested that this 20-degree "cone of vision" be reduced to 10 degrees.

The difference with MUTCD standards: There is a minor revision on the degrees of "cone of vision".

Explanation on this revision: In the literature review, King *(6)* suggested the use of a 10 degree "cone of vision" to achieve better conspicuity for the drivers.

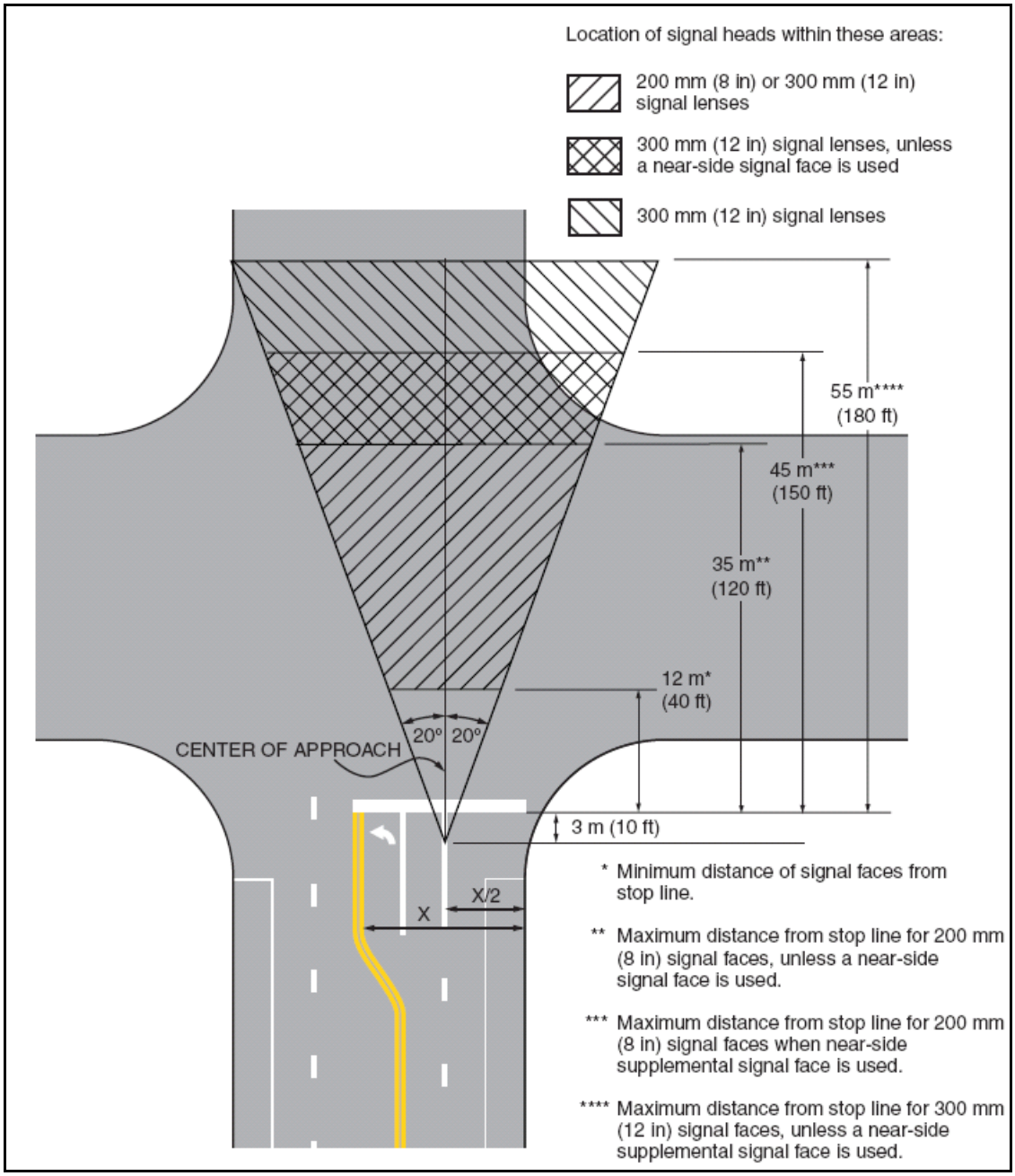

Figure 6 Criteria for Horizontal Location of Signal Face

Source: MUTCD 2003 Revision Version

2.3.2 Specific Placement Criteria for Left-Turn Signal Head

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

1) For Permissive-Only Mode: A signal head for the 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 7). If an exclusive signal head is used, it is recommended to be located in line with the center of the left-turn lane, or be ground mounted in the median.

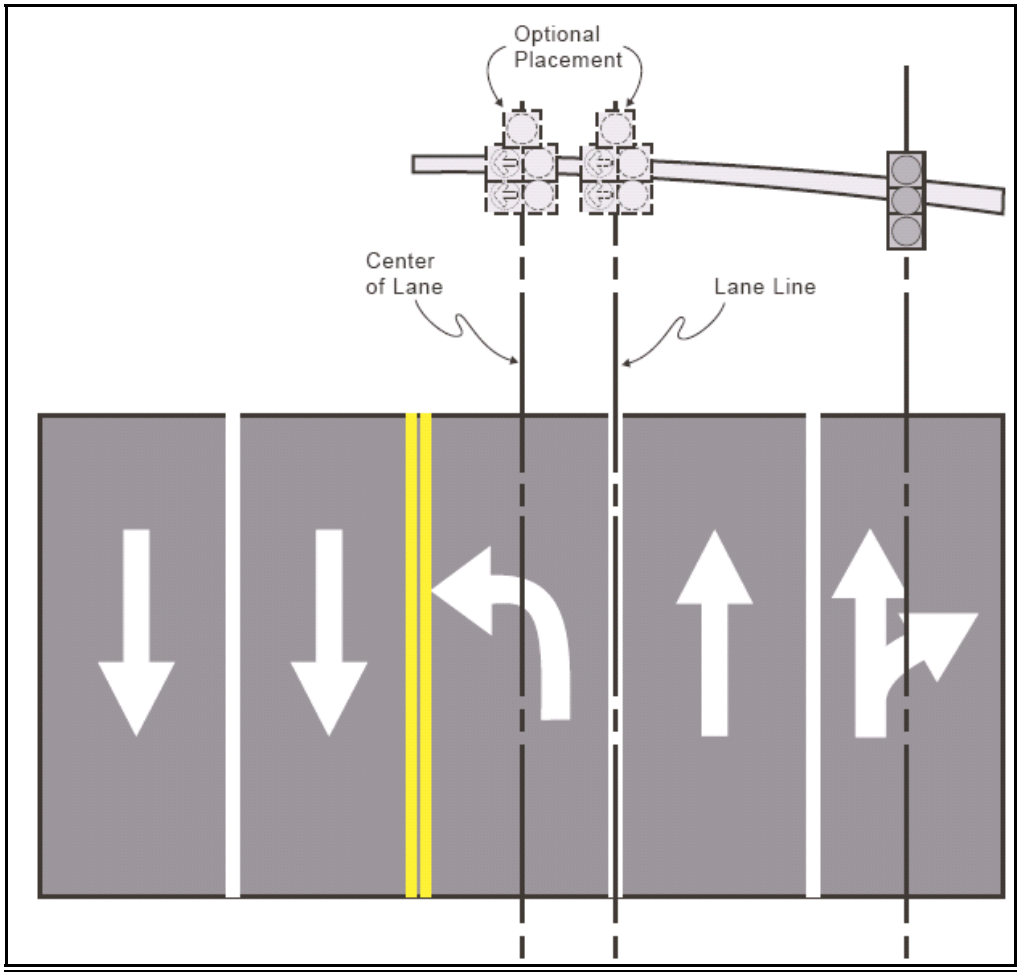

Figure 7 Overhead PPLT Display Placement Options

Source: NCHRP Report 493

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

Explanation on this revision: Survey results from Project 0-5840 suggested that the signal heads should be placed in the center of each lane.

2.3.3 Determine If Supplemental Left-Turn Signal Heads Should be Used

To achieve intersection visibility both in advance and immediately before the signalized location, the supplemental left-turn signal head should be used in some conditions based on engineering judgment. This guideline will recommend two types of supplemental signal heads under some specific circumstances. However, the decision to use these supplemental signal heads should not be limited to those circumstances mentioned and should be based on engineering judgment according to the intersection features.

1) Far-Side Supplemental Left-Turn Signal Head: As shown in Figure 8, this is an extra left-turn signal head that is located in the far-side corner of the intersection. It should be considered under 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 the visibility for vehicles behind large vehicles.
    c. The visibility of signal indications (color) is affected by the sun glare during certain time periods of day when the sun is near the horizon. The supplemental signal head can mitigate the risk caused by sun glare.

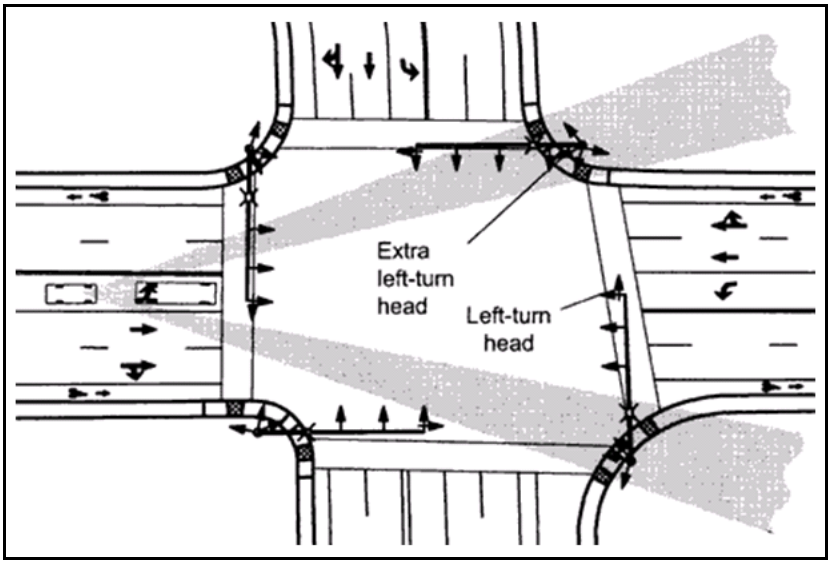

Figure 8 Far-Side Supplemental Left-Turn Signal Head

Source: FHWA

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 median) or in the near-side corner of the intersection as shown in Figure 9. It should be considered under following conditions:

   a. When the visibility is hampered by a curve in the roadway upstream of the intersection. In this condition, a near-side signal head can be used to provide an advance indication for the vehicles coming from the curve.

   b. If the alignment of the intersection is not good, i.e. the two directions are not perpendicular with each other, the use of a near-side supplemental signal head might improve the visibility for the drivers.

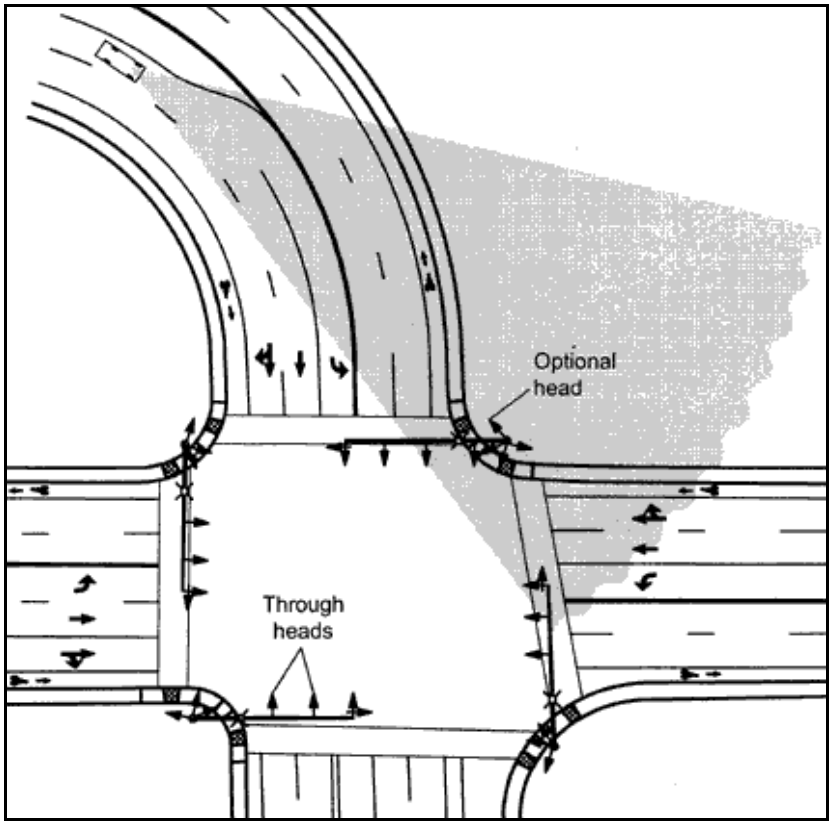

Figure 9 Near-side Supplemental Left-Turn Signal Head

Source: FHWA

The difference with MUTCD standards: The MUTCD does not provide information under what conditions the supplemental signal heads should be used.

Explanation on this revision: This guideline combines the recommendations on the use of supplemental signal heads from the *Federal Highway Administration (7)*.

3. Case Studies

The guidelines introduced above are applied to following three selected intersections:

- Airport Blvd. & 51st St. in Austin, Texas
- FM 518 & Calder Rd in League City, Texas
- Bellaire Blvd & S Gessner Rd in Houston, Texas.

The first two intersections are also used in the case studies for the training materials regarding left-turn mode and sequence guidelines. The third intersection was selected

only for demonstrating the application of the developed guidelines for using a supplemental left-turn signal head.

Case 1 – Airport Blvd. & 51st St. in Austin, Texas.

The study intersection, Airport Blvd. & 51st St., is located in northern Austin, Texas. The northbound (NB) approach of the intersection was selected as the subject approach. For the NB approach, the recommended signal control mode in the case study for mode and sequence guideline is Protected/Permissive Left-Turn (PPLT). In the following part, guidelines for the PPLT signal display are applied to determine the left-turn signal display for the NB left-turn movement.

- <u>Select left-turn signal indication</u>

  Based on the developed guidelines, a left-turn green arrow is used for the protected left-turn phase. Since the flashing yellow arrow indication has not been applied at this location, a circular green indication is recommended for the permissive left-turn phase.

- <u>Select left-turn signal arrangement</u>

  An exclusive four-section left-turn signal head is recommended as shown in Figure 10. This recommendation is made because:

  1) Survey results in Project 0-5840 indicated 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 would occur when using a shared signal head for the PPLT signal control mode (i.e. 5-section horizontal/vertical/cluster signal arrangement). In the literature review (3) (4) (5), it was found that simultaneous display of the green arrow and red ball indication in the same signal display would confuse many drivers. Therefore, an exclusive signal display is strongly recommended for the PPLT mode.
  3) It is found in the literature (3) that an exclusive 4-section vertical signal head for the PPLT mode is associated with the least driver confusion.

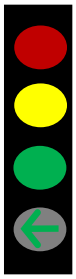

Figure 10 Recommended Left-Turn Signal Arrangements

- Determine the placement of left-turn signal head

For this intersection, no supplemental signal head is recommended to be installed because it is a not a large intersection and there are no curves that hamper the visibility of this intersection.

A 20-degree "cone of vision" was drawn on the vertical view picture of this intersection (see Figure 11). According to the width of this intersection, an 8-inch signal lens should be adequate 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 Figure11).

Finally, the exclusive 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 the Figure 11, which is very close to the location of the current left-turn signal head.

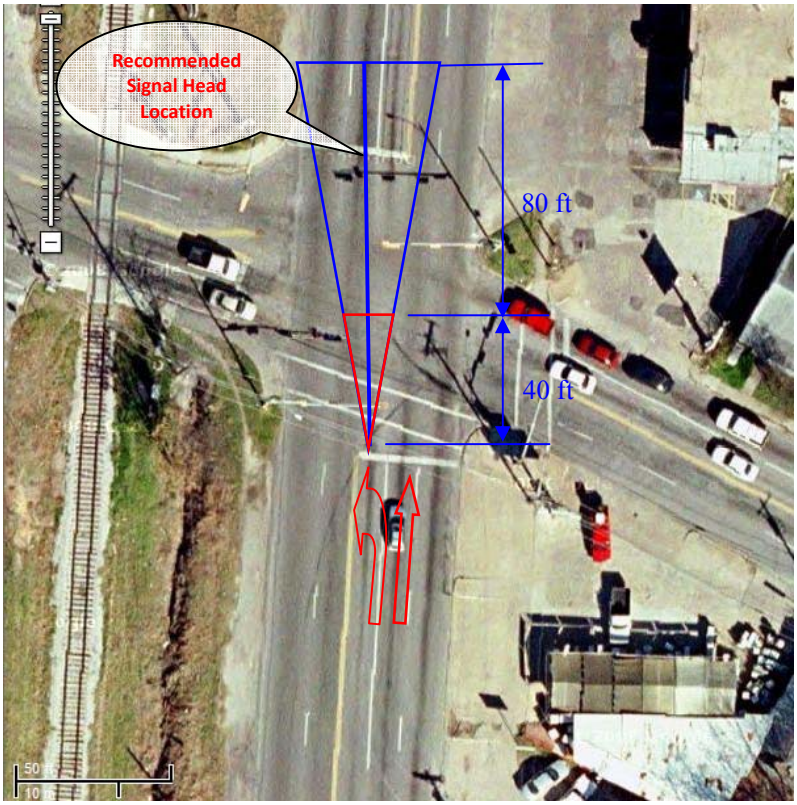

Figure 11 Recommended Signal Head Horizontal Location for Intersection at Airport Blvd. & 51st St. in Austin, Texas.

Case 2 –FM 518 & Calder Rd. in League City, Texas.

The study intersection, F.M. 518 & Calder Rd., is located in League City, Texas, southeast of Houston. The northbound (NB) approach of the intersection was selected as the subject approach. The recommended signal control mode for this direction is Protected-Only. In the following part, guidelines for the Protected-Only signal display are applied to determine the left-turn signal display for the NB left-turn movement.

- <u>Select left-turn signal indication</u>

  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.

- <u>Select left-turn signal arrangement</u>

  For the Protected-Only mode, it is required that at least one exclusive left-turn signal head should be provided. A three or four-section horizontal or vertical signal arrangement

is recommended to be used, as shown in Figure 12.

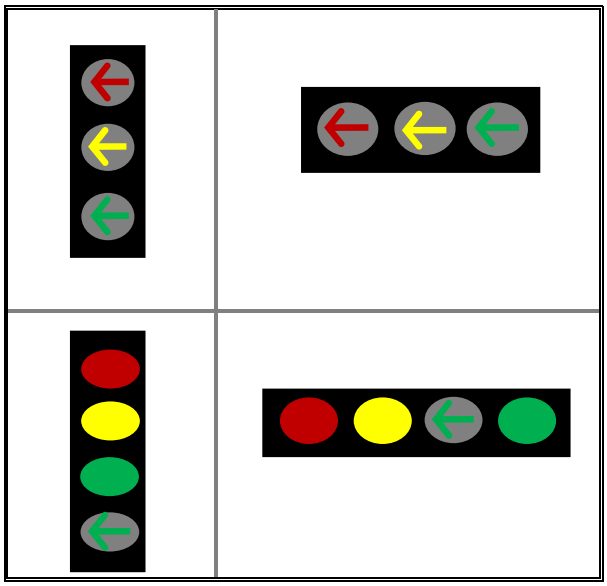

Figure 12 Recommended Left-Turn Signal Arrangement for PO mode

- <u>Determine the placement of left-turn signal head</u>

For this intersection, no supplemental signal face is recommended to be installed because it is not a large intersection and there is no curve that hampers the visibility of the intersection for the NB approach.

A 20-degree "cone of vision" was drawn on the vertical view picture of this intersection (see Figure 13), according to the width of this intersection, an 8-inch signal lens 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 Figure13).

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 the Figure 13.

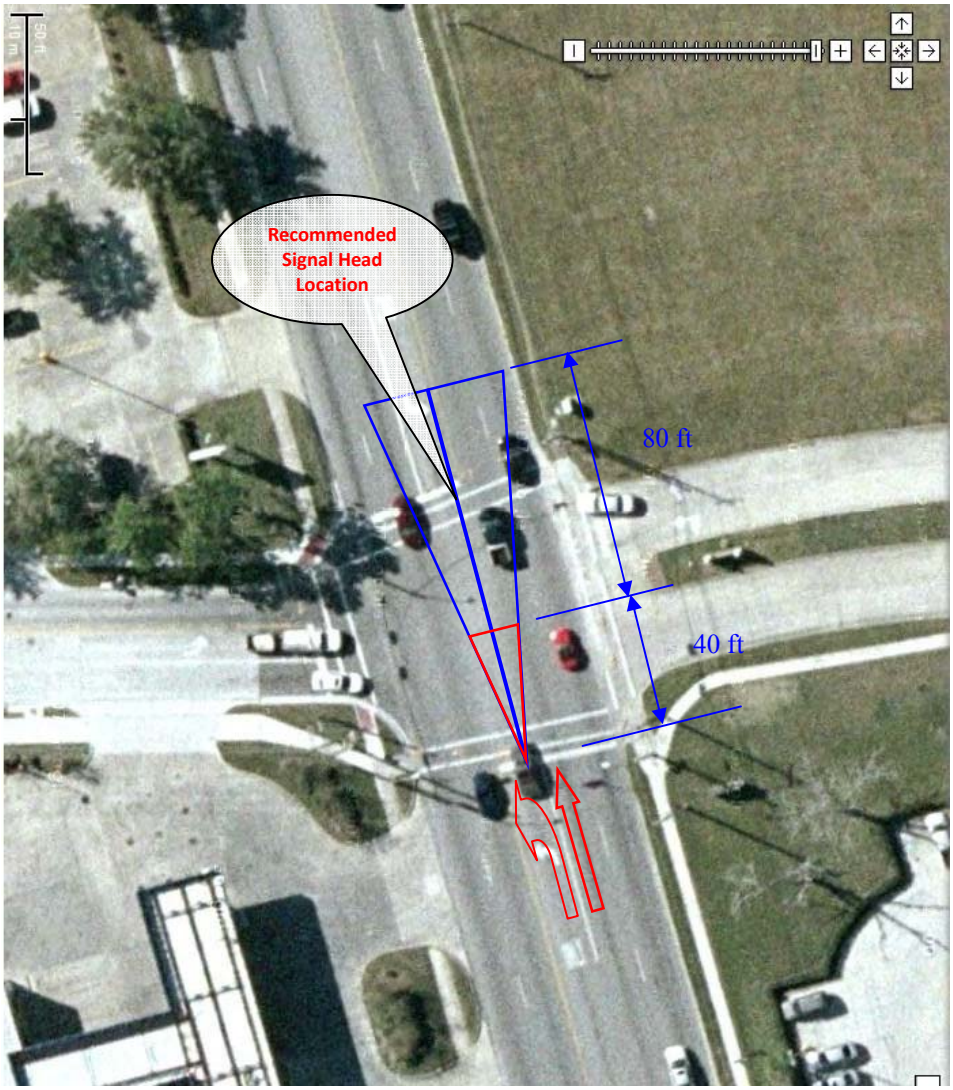

Figure 13 Recommended Signal Head Horizontal Location for Intersection at FM 518 & Calder Rd., League City, Texas.

Case 3 –Bellaire Blvd & S Gessner Rd in Houston, Texas.

As mentioned earlier, this intersection was selected only for the guideline application of selection and placement of a supplemental left-turn signal head. As shown in Figure 14, the subject direction of this intersection is eastbound (EB). 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 15). The supplemental signal head helps improve the visibility for vehicles behind large vehicles.
3) Because the subject approach is EB, the visibility of signal indications (color) is affected by the sun glare during morning peak hour when the sun is near the horizon. The supplemental signal head can mitigate the risk caused by sun glare.

As shown in Figure 15, currently, there is an extra left-turn signal head that was ground mounted in the median on the far side of the intersection. However, by analyzing the line of sight 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 size vehicle, the second left-turn vehicle may be not able to see the supplemental left-turn signal head installed in the median. Therefore, it is recommended to install the supplemental left-turn signal head on the northeast corner of the intersection as shown in Figure 14 so that, all the vehicles in the NB left-turn lane are able to see the supplemental left-turn signal head.

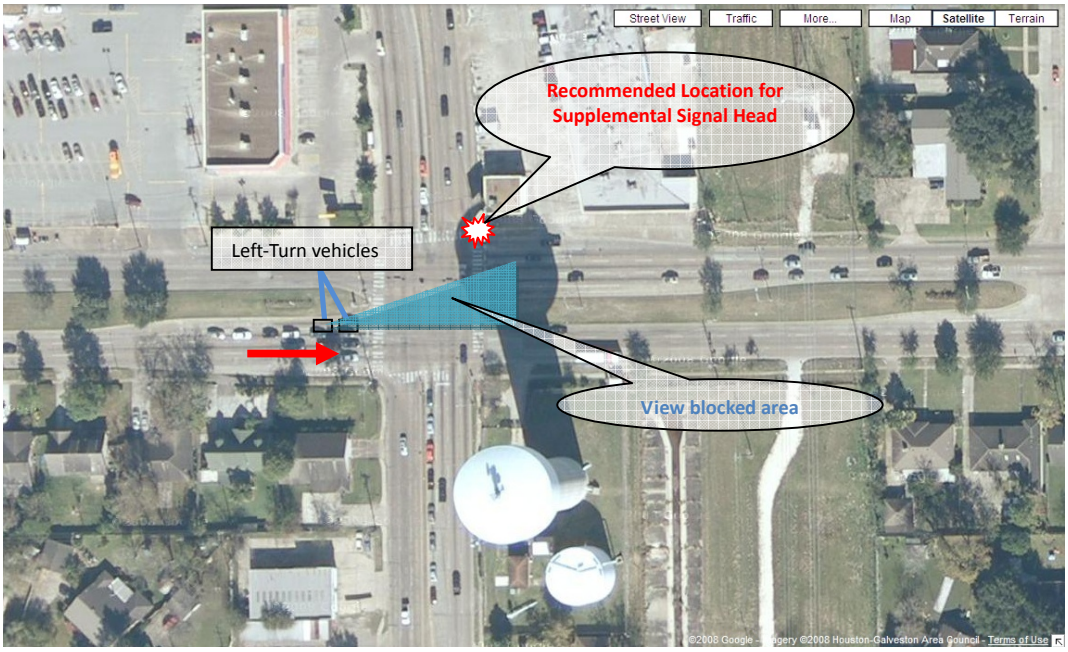

Figure 14 Layout of Intersection at Bellaire Blvd & S Gessner Rd in Houston, Texas.

Figure 15 Current Supplemental Left-Turn Signal Head for Intersection at Bellaire Blvd & S Gessner Rd in Houston, Texas.

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