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16. Abstract

MUTCD 2009 Edition suggests the use of Flashing Yellow Arrow (FYA) indication in replacement of green ball indication for permissive left-turn signal in presence of separate signal heads. Currently, there is no clear guidance on how to implement flashing yellow operations with PPLT in Texas. The objective of this research project is to developed guidelines for FYA with PPLT operations. To fulfill this goal, the researchers (1) reviewed and synthesized national and peer state practices on FYA PPLT; (2) surveyed traffic engineers and drivers ; (3) deployed FYA PPLT operation at five selected intersections in Texas cities; (4) identified software and hardware issues associated with the deployment of FYA PPLT; and (5) evaluated the safety performance of FYA PPLT based on the historical crash data analysis and field traffic conflict studies. According to the findings of this research, it is recommended that FYA signal indication can be used at most of signals with PPLT operations to improve intersection safety and to comply with the requirements of the MUTCD. However, FYA PPLT operation is not recommended at busy intersections that have high left-turn volumes and opposing volumes, and it should be implemented with great cautions at intersections where lead-lead left-turn phasing is used.

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USE OF FLASHING YELLOW OPERATIONS TO IMPROVE SAFETY AT SIGNALS WITH PROTECTED-PERMISSIVE LEFT TURN (PPLT) OPERATIONS

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DISCLAIMER

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

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SUMMARY

Traffic engineers have used protected-permissive left-turn (PPLT) phasing for years to improve operational performance and progression along roadways. However, as a safety concern associated with PPLT operations, "yellow trap" has been received extensive attention. In response, MUTCD 2009 Edition suggests the use of Flashing Yellow Arrow (FYA) indication in replacement of green ball indication for permissive left-turn signal in presence of separate signal heads. Currently, there is lack of detailed guidelines on the implementation of FYA. The objective of this research project is to develop guidelines for FYA with PPLT operations. To fulfill this goal, following key tasks have been performed: (1) national and peer state practices on FYA PPLT were reviewed and synthesized; (2) survey of traffic engineers and survey of drivers were conducted; (3) FYA PPLT operations were deployed at five selected intersections in a two-stage field test; (4) software and hardware issues were identified associated with the deployment of FYA PPLT; (5) historical crash data were analyzed and field traffic conflict study was conducted to evaluate safety performance of FYA PPLT.

In this study, the researchers have reviewed manuals and guidelines for PPLT signal indication, and existing studies on FYA PPLT indication. Most of the studies showed that drivers have a good understanding of an FYA permissive left-turn indication and FYA signals can improve safety of intersections.

Both the survey of traffic engineers and the survey of general drivers received good responses. Among the participating traffic engineers who had experience with FYA PPLT operations, 42% of them thought that the implementation achieved "satisfactory" results, 35% of them rated their implementation as "acceptable," and 10% redeemed it "risky" to use FYA. The 124 responses from the survey of drivers showed that the FYA indication was correctly understood by 92% of the subject drivers, and only 3.2% of them had incorrect understanding that may lead to a "fail critical" situation.

In the field tests in Waco and Austin Districts, FYA signals were successfully set up at five selected intersections with an average of 3 hours of signal work for a pair of opposing approaches. Technical issues, such as controller programming mode and method, and wiring problems, have been identified and documented. In addition, based on the experiences of the field tests, a general installation procedure and a checklist have been developed for setting up FYA PPLT.

For evaluating the safety performance of FYA PPLT operations, researchers collected historical crash data before and after FYA implementation at 51 intersections located in Tyler, TX, Federal Way, WA, and Kennewick, WA. In addition, before-and-after traffic conflict studies were conducted at the five intersections selected for the field test in this study. The safety performance analysis led to following key findings:

- Majority of drivers had a good understanding of FYA indications.
- Overall, FYA PPLT improved intersection safety at most study intersections by reducing traffic crashes or conflict rates.
- Given high traffic volumes and the use of lead-lag protected left-turn phases, a safety issue associated with "steady-yellow-arrow confusion" was identified as directly related to the use of FYA indication.
- Given high traffic volumes, left-turn drivers in the leading left-turn direction may be insensitive to the signal change from an FYA to a steady yellow arrow, which will increase the risk of crashes. The field traffic conflict study showed that this problem caused increased the frequency of "running red lights" and "backing into the left-turn lane" events
- Converting signal operation from protected-only mode to FYA PPLT mode may cause safety problems at some intersections, since permissive left-turn phasing may not be safe due to some traffic (e.g., high traffic volumes), operational (e.g., high design speed), and/or geometric conditions (e.g., limited sight distance, whether turning paths conflict with each other).

Based on the results of this research, it is recommended that FYA signal indication can be used at most of signals with PPLT operations to improve intersection safety and to comply with the requirements of the MUTCD. However, FYA PPLT is not appropriate for all situations. It is not recommended for busy intersections that have high left-turn volumes and high opposing volumes, and it should be implemented with great caution at intersections with lead-lead left-turn phasing. In addition, before the installation of FYA signals at an intersection previously operated under protected-only mode, it is necessary to assess whether it is safe to allow permissive left-turns/U-turn at that intersection at first. Traffic engineers should contact equipment manufacturers before field implementation regarding the programming method of controller and MMU, since the preferred methods are commonly quite different among various makes.

CHAPTER 1: INTRODUCTION

1.1 BACKGROUND

Protected/permissive left-turn (PPLT) phasing has been considered as the most efficient left-turn operation mode, because it increases left-turn capacity by providing a protected turn phase as well as a permissive phase during which left turns can be made as opposing traffic will allow. Traditionally, a Circular Green (CG) is used in the United States for permissive left-turn indication. However, several studies had found that the CG indication could cause drivers' confusion and then put drivers in a risky situation. To avoid the safety issues caused by the CG left-turn signal indication, National Cooperative Highway Research Program (NCHRP) project 3-54 recommended the use of a flashing yellow arrow (FYA) signal indication for permissive left-turns. Following sections will firstly introduce the safety issues caused by the CG indication and then provide an overview for the FYA indication and FYA PPLT operation.

Safety Issues Caused by CG Indication

Previous studies found that a CG indication could cause drivers' misunderstanding, and it may be interpreted by drivers as a cue for right-of-way. An "LEFT TURN MUST YIELD ON GREEN BALL" sign makes drivers feel hard to decide whether to proceed or to yield when left-turns has a green arrow and the adjacent through movement has a green ball meanwhile.

In addition to the drivers' confusion when facing traditional CG indications, there is also a "yellow trap" problem associated with the use of lead-lag PPLT operations, which will leaves drivers exposed to a risky situation. The yellow trap problem can be illustrated by the signal timing diagram shown in Figure 1-1. In Figure 1-1, the circular green/red and green arrow symbols indicate different phases for different directions. At the end of Phase 2 (in the yellow or all-red phase), the left-turn vehicles in the leading direction may turn left as a 'sneaker' based on the assumption that the opposing traffic is also having a yellow signal indication as they see the

signal for the adjacent through traffic turns yellow at this moment. Actually, the signal display for the opposing through movement is still green, and the opposing through vehicles will not stop or slow down. In this case, the vehicle that makes a left turn during the yellow phase may crash into the opposing through traffic.

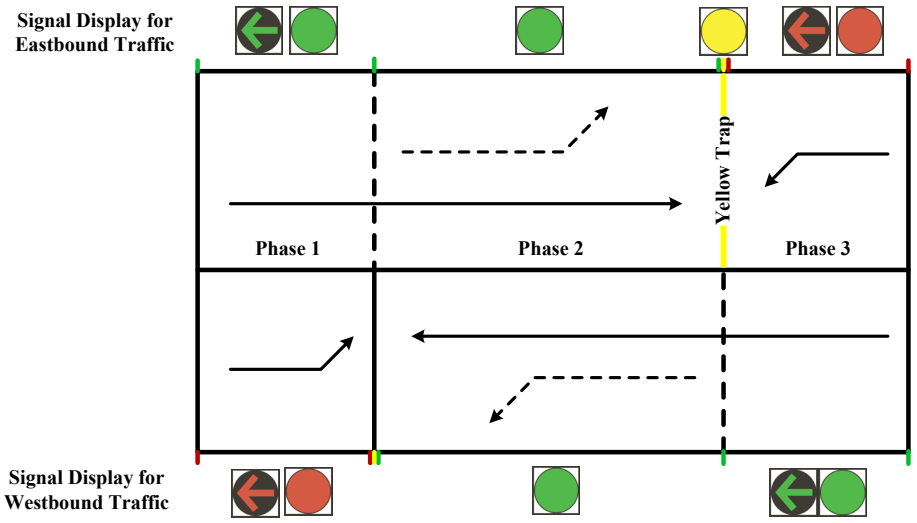
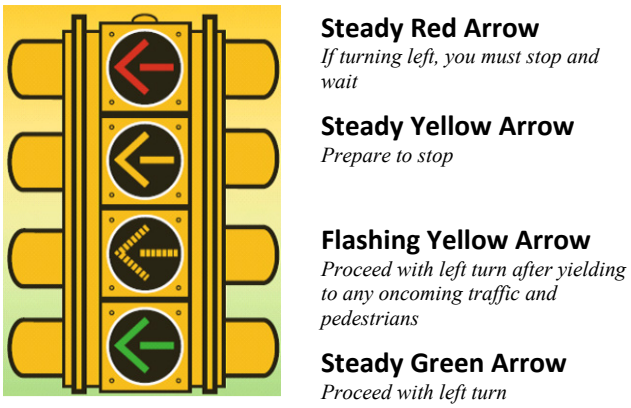


Figure 1-1: Yellow Trap Illustration in Phasing Graph

To fix this problem, many traffic engineers have tried to identify alternative indications for permissive left turns, such as flashing yellow arrow (FYA), flashing red arrow (FRA), flashing red ball (FRB) and flashing yellow ball (FYB). Several existing studies have concluded that the FYA has a high level of driver understanding, and the current version Manual on Uniform Traffic Control Devices (MUTCD, 2009) recommended the use of FYA displays as permissive left-turn indications in presence of a separate left-turn signal face to avoid the "yellow traps".

Overview of FYA Indication and FYA PPLT Operations

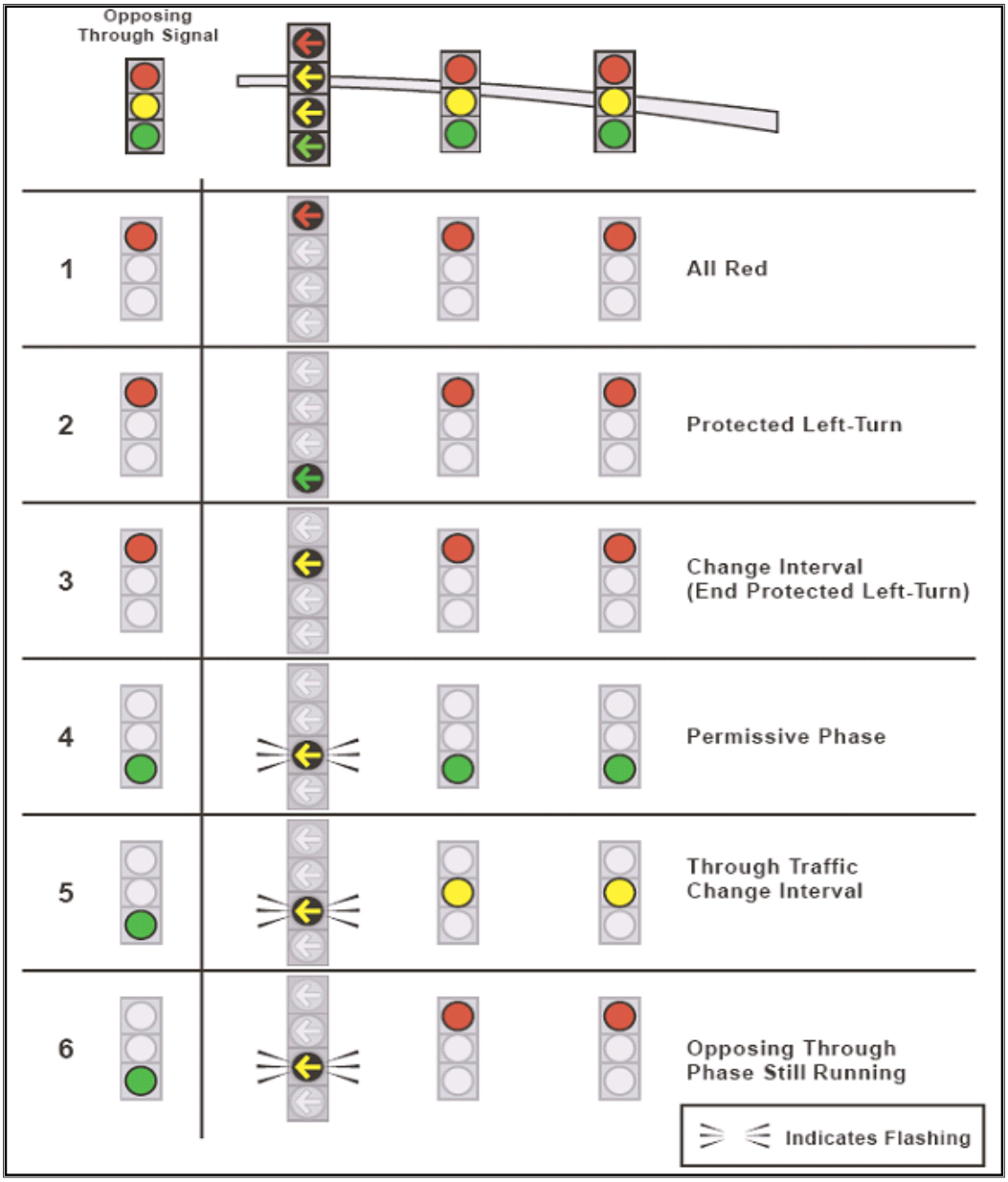
A typical signal head for the FYA signal indication includes an FYA, as well as a steady green arrow, a steady yellow arrow, and a steady red arrow, as is shown in Figure 1-2.



Source: Michigan Department of Transportation (2008)

Figure 1-2: Left-Turn Signal with Four-Arrow Display

The operational logic of this new four-section signal display with FYA PPLT control mode is illustrated in Figure 1-3.

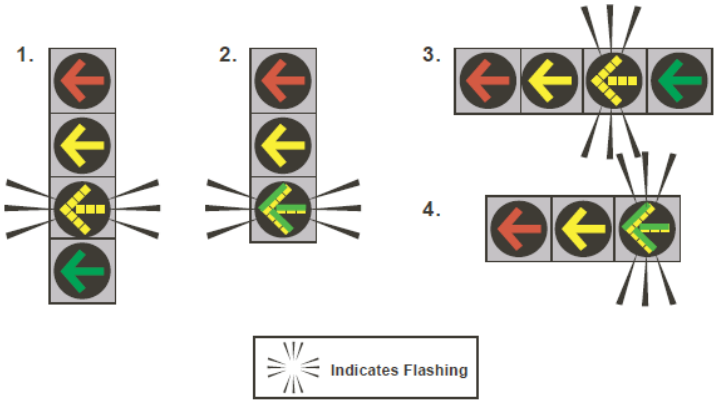


Source: NCHRP Report 493

Figure 1-3: FYA Logic Link

NCHRP Report 493 recommended four types of signal face arrangements to incorporate the FYA indication at locations where there is an exclusive left-turn lane, and the display is exclusive for left turns, not shared by the adjacent through movements. These signal face arrangements are shown in Figure 1-4 with different configurations in terms of section (three-section or four-section) and/or alignment (vertically or horizontally). Generally, the four-section

display face is more widely used for FYA PPLT display as opposing to the three-section signal face with a bi-modal section enabling steady green arrow and FYA indications.



Source: NCHRP Report 493 (2003)

Figure 1-4: Excusive FYA Display Faces

Figure 1-5 illustrates the mechanism how FYA indications eliminate "yellow trap" in PPLT control mode. The FYA indication will be on whenever the opposing traffic has a green indication. When facing the FYA indication, the left-turn drivers know that they need to yield to the opposing traffic with necessary cautions. In addition, both eastbound and westbound permissive left-turn phase can be extended, e.g., the eastbound permissive left-turn phase is extended to the end of Phase 3, which may gain additional capacities by allowing more vehicles to make permissive left turns.

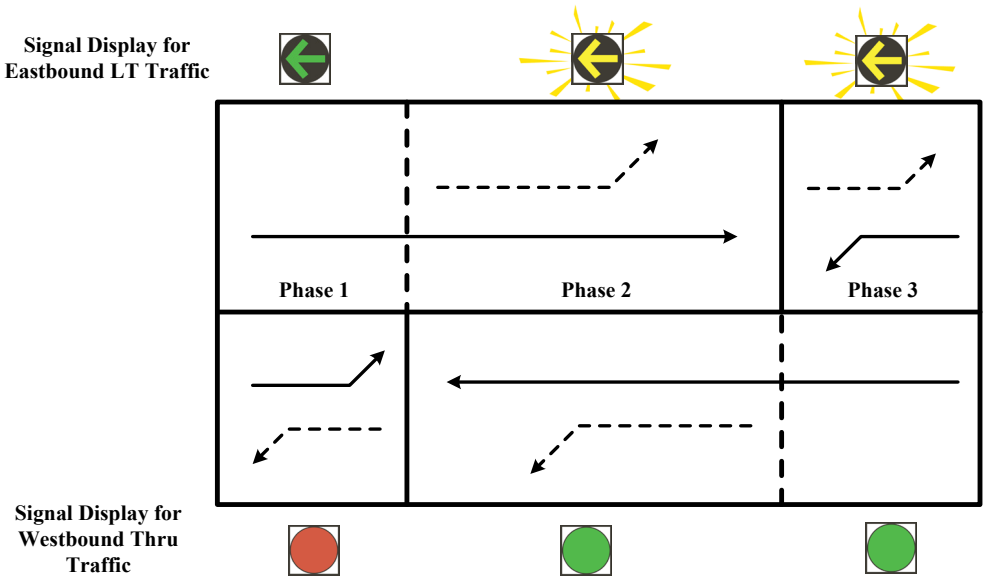


Figure 1-5: Fixed the "Yellow Trap" with FYA

1.2 RESEARCH GOALS AND OBJECTIVE

This primary goal of this research project is to develop guidelines for the implementation of FYA with PPLT operations in Texas. To fulfill this goal, this research accomplished following major tasks:

- Reviewed and synthesized the state or national practices on the FYA PPLT display,
- Conducted surveys of traffic engineers and general motorists to solicit their opinions on the implementation of the FYA PPLT operation
- Deployed the FYA PPLT display at five selected intersections in a two-stage field test
- Identified the software and hardware issues with the deployment of the FYA PPLT display,
- Conducted historical crash data analysis and traffic conflict study to evaluate the safety performance of the FYA PPLT display,
- Developed guidelines for the implementation of the FYA PPLT display,

1.3 OUTLINE OF THIS REPORT

This report covers all the tasks conducted during the span of the research project. In Chapter 2, national and peer state practices on FYA PPLT are reviewed and synthesized. In Chapter 3, a survey of traffic engineers and a survey of general motorists are introduced, and the survey responses are analyzed. Field tests and the software/hardware issues encountered are described in Chapter 4. In Chapter 5, the safety performance of FYA PPLT is analyzed, which is followed by a description of guidelines developed for implementation of FYA PPLT in Chapter 6. Finally, key findings and recommendations are provided in Chapter 7.

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Brehmer, C. L., Kacir, K. C., Noyce, D. A., and Manser, M. P. *NCHRP Report 493: Evaluation of Traffic Signal Displays for PPLT Control.* Transportation Research Board, National Research Council, Washington, D.C., 2003.

CHAPTER 2: LITERATURE REVIEW

In literature, numerous studies have been conducted regarding PPLT signal indications and the implementation of FYA signal indication for the PPLT operation. To develop a full context for this research project, this chapter will first introduce the FYA-related standards established in MUTCD, and then summarize the major research findings from 1) general studies on PPLT signal displays, 2) in-laboratory based studies on FYA indications, and 3) field-test based studies on FYA PPLT operation.

2.1 MUTCD STANDARDS FOR FYA PPLT SIGNAL INDICATION

The MUTCD defines the standards used by road managers nationwide to install and maintain traffic control devices on all streets and highways, and it is published by the Federal Highway Administration (FHWA) under 23 Code of Federal Regulations (CFR), Part 655, Sub-Part F.

2.1.1 Evolution of MUTCD Regarding Permissive Left-Turn Indication

The 2003 Edition MUTCD recommended that a CG signal indication should be displayed during permissive left-turn phases. Guidelines for FYA signal indications are not included in the 2003 Edition MUTCD, and an interim approval (IA-10) was issued in March 2006 for optional use of FYA. It allows related agencies to install FYA signal indications at signalized intersections for interim use. IA-10 also provided design and optional requirements of FYA in terms of left-turn operation mode, signal face arrangement, signal face placement, and signal display. This interim approval recommended that under PPLT mode, a four-section signal face is needed, while a three section signal face containing a dual arrow signal section (capable of alternating between the display of a steady green arrow and an FYA) may be used where signal head height or wind loading limit the use of a four-section signal face.

On January 2, 2008, FHWA published a Notice of Proposed Amendment in the Federal Register including a proposal for a new version of MUTCD. Also, a revised draft on the MUTCD was published on the FHWA website for public review and comments.

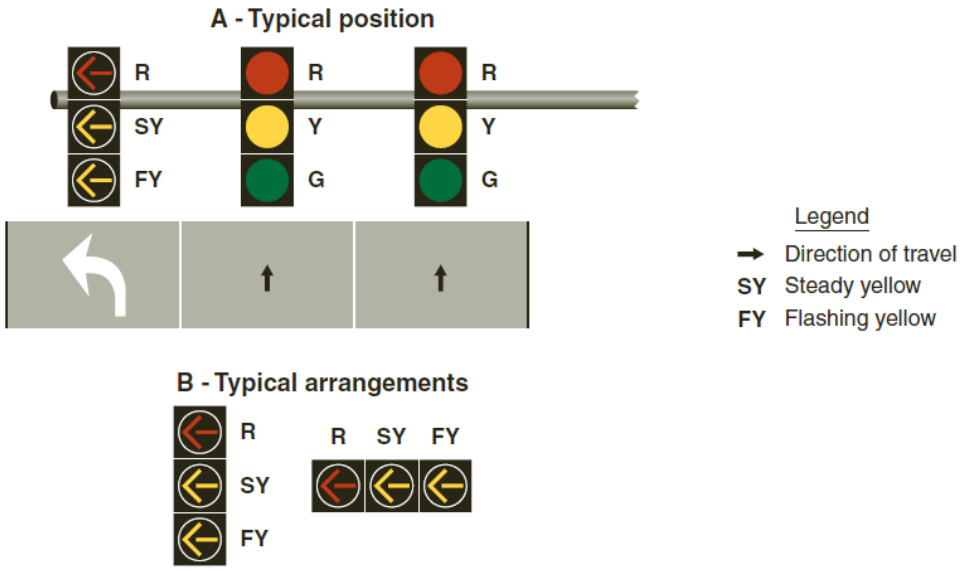
2.1.2 MUTCD Enhancements Regarding FYA Permissive Left-Turn Indication

The 2009 Edition MUTCD is the most current version available on the MUTCD website during the span of this project. The final rule adopting the 2009 Edition MUTCD was published on December 16, 2009. In this version, there are four sections (4D.17 - 4D.20) focusing on left-turn signal indication.

In general, the 2009 Edition MUTCD eliminates the use of CG signal indication for permissive left turns in a separate left-turn signal face. The major differences for permissive left-turn signal indications between the 2003 and 2009 Edition MUTCD are summarized for both permissive-only and PPLT modes as follows:

Permissive-Only Mode: For permissive-only operation mode, the 2009 Edition MUTCD provides guidelines in terms of arrangement, placement and signal sequence. The most significant change is that CG signal indications are no longer allowed in a separated signal face to indicate permissive left turns. Instead, an FYA signal indication (see Figure 2-1) is required for permissive left-turn movements if a separate left-turn signal face is provided.

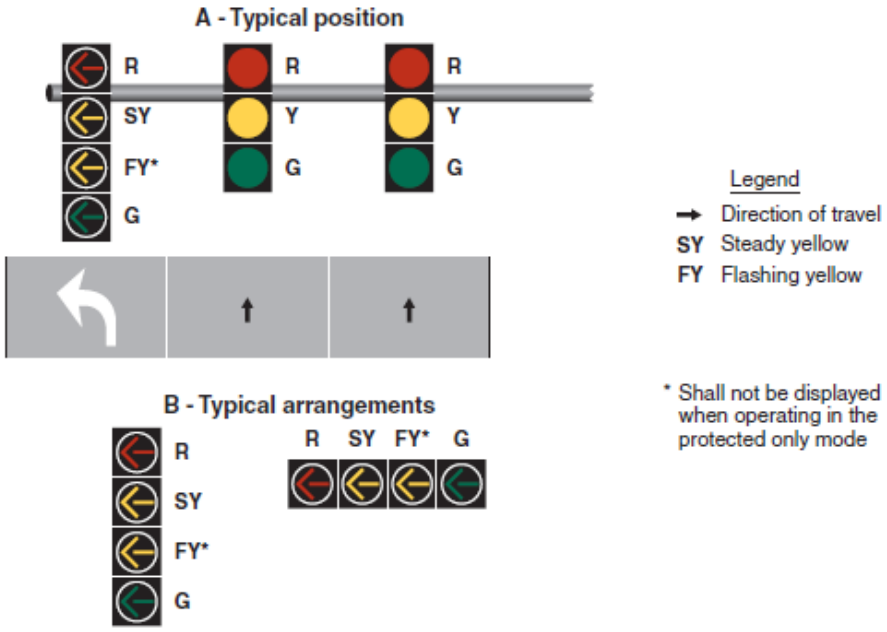
In addition, the 2009 Edition MUTCD also suggests that for unusual geometric conditions, such as wide medians with offset left-turn lanes, a flashing red arrow (FRA) signal indication instead of FYA should be used in a separate left-turn signal face to indicate that each and every vehicle must successively come to a full stop before a permissive left-turn maneuver. Note that, the use of FRA should be determined based on the results of engineering studies.



Source: MUTCD (2009)

Figure 2-1: Typical Position and Arrangement of Separate Signal Faces with FYA for Permissive-Only Mode

PPLT Mode: For PPLT operation mode, the 2009 Edition MUTCD also eliminates the use of CG signal indications for permissive left turns in presence of a separate signal face. The typical position and arrangement of separate signal faces with FYA for PPLT is shown in Figure 2-2. Besides this change, the 2009 Edition MUTCD also specifies particular requirements in terms of signal phasing sequences and change intervals under PPLT mode. Between an FYA indication (permissive left-turn phase) and a steady left-turn red arrow indication (clearance phase), a steady yellow arrow (change interval) is required; while between an FYA indication (permissive left-turn phase) and a steady green arrow indication (protected left-turn movement), a steady yellow arrow (change interval) should not be displayed.



Source: MUTCD (2009)

Figure 2-2: Typical Position and Arrangement of Separate Signal Faces with FYA for PPLT Mode

2.2 GENERAL STUDIES ON PPLT SIGNAL DISPLAY

Since this project focuses on the use of FYA under PPLT control mode, this section will present a summary of the existing studies on PPLT signal displays.

Noyce (1999)

This paper conducted a comprehensive agency survey on the use of PPLT control mode in the United States. This survey quantified the attributes of more than 107,000 of the estimated 300,000 signalized intersections in the United States. It presented the following major results related to PPLT signal display:

- Percentage of PPLT signal phasing: Approximately 29 percent of these signalized intersections use PPLT signal phasing.
- Arrangement of signal head of PPLT: A five-section cluster display with a CG permissive indication is used as the primary display accounting for 63 percent of PPLT

intersections. In addition, the five-section cluster display is predominantly used in 34 states. The second most commonly used PPLT signal display is a five-section vertical with a CG permissive indication.

- Permissive indication: More than 98 percent of all PPLT signal displays use a CG permissive indication. The flashing red ball, flashing red arrow, flashing yellow ball, and FYA permitted indications are also used in a limited number of locations.

Noyce (1999)

This paper provided an in-depth review of the impacts of human factors on selecting traffic signal operations, with a focus primarily on PPLT control and the corresponding PPLT signal displays.

In this study, three issues were discussed in the selection of a uniform PPLT signal display as following: (1) general concepts related to human factors aspects of traffic signal displays, (2) detailed overview of color vision of humans regarding the red, yellow, and green traffic signal indications, and (3) older driver issues. The research concluded that uniform and consistent PPLT signal displays can reduce the level of informational complexity placed on drivers. It is also pointed out that there is a need for the standardization and uniformity of PPLT signal displays to improve left-turn drivers' safety. Ultimately, the selection of a uniform traffic signal displays will significantly rely on the human factors issues.

NCHRP Report 493 (2003)

NCHRP Project 3-54, "Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control" comprehensively evaluated a wide variety of alternative displays for permissive left-turn signals in terms of safety and effectiveness of displays and phasing for PPLT operation. Eight different types of studies were involved: (1) agency studies: the research team administered an agency survey to traffic engineers at 50 State DOTs and in 275 large city and county transportation agencies in the United Stated and Canada, so as to identify the breakdown

of different PPLT signal displays in use; (2) photographic driver study: the photographic driver survey evaluated driver understanding of the signal indications under various conditions; (3) field traffic operations study: the field operations study was to quantify the effects of PPLT signal displays and indications currently used in the United States on capacity and delay; (4) field traffic conflict study: the traffic conflict study quantified left-turn conflict rates and event rates (unusual, dangerous, or illegal non-conflict maneuvers) for various PPLT signal displays and indications; (5) crash data analysis: the crash data analysis compared left-turn crash rates associated with various PPLT signal displays; (6) driver confirmation study: the driver confirmation study was conducted using fully-interactive dynamic full-scale driving simulators to evaluate drivers comprehension of the most promising types of PPLT signal displays; (7) field implementation study: real-world applications of FYA PPLT display was conducted. The technical and non-technical issues associated with the implementation of the FYA display and its safety and cost implications were documented; (8) engineering assessment: the engineering assessment considered scientific and non-scientific implementation issues in the following areas: safety, operations, implementability, human factors, and versatility. The updated engineering assessment identified objective and subjective information needed for evaluating the signal displays/indications.

The major findings of this study included:

- Among all the candidate permissive left-turn displays, the laboratory-based research supported the conclusion that the FYA indication represents the best alternative to the CG indication.
- The field implementation study showed the following results: (1) the FYA displays was successfully implemented in the field with relatively little or no technical issues. Post-implementation public testimony almost unanimously supported use of the experimental display; (2) most participating traffic engineers endorse FYA displays; and (3) the field data support that drivers had a good understanding of the FYA display.

- The confirmation study also showed that (1) FYA display was understood as well as CG indication; (2) drivers' understanding of the FYA display became better with exposure; (3) the FYA display showed a higher fail-safe response compared with CG indication.
- The traffic conflict studies demonstrated that drivers can correctly interpret FYA displays.

Based on the findings of this study, FYA was identified and recommended as the most appropriate signal display for PPLT control, and as the best alternative to CG indications for permissive left turns.

Yu et al. (2009)

This study developed guidelines for left-turn phasing treatments at signalized intersections. Multiple research approaches was used to investigate the safety and operational issues related with PPLT left-tune signal control, including literature review, survey of traffic engineers, and field studies.

Following guidelines were developed regarding the signal face arrangement for PPLT operations:

- An exclusive signal head is recommended but not required,
- If an exclusive signal head is used, the four-section vertical signal arrangement is suggested,
- If shared signal has to be used, the five-section signal face should be used, and the five-section horizontal arrangement is preferable,
- A supplemental sign shall be used for shared signal head, such as LEFT TURN SIGNAL or LEFT TURN YIELD ON GREEN (plus a symbolic CG indication)
- Lead-lag sequence with PPLT operation may lead to yellow trap problem. Dallas or Arlington signal phasing can be considered as alternative to solve this problem.

The results of this study also indicated that an FYA is an allowable indication to replace the CG for permissive left-turn phase if the following conditions are met:

- If FYA is implemented in one intersection, the whole arterial or the whole region should also be installed with FYA in order to maintain the consistency of signal indications.
- A sign should be placed with the left-turn signal head for PPLT mode, such as a "LEFT TRUN YIELD ON (plus a symbolic FYA)" sign.

Summary

This section focuses on existing research related to PPLT signal displays. The research clarifies important issues associated with PPLT displays, and reaches some very useful conclusions related to this project. For example, uniform and consistency of PPLT signal display is important, that is, if the FYA is installed in one intersection, it should be installed in the whole arterial or the whole region in order to maintain the consistency of signal indications.

2.3 IN-LABORATORY BASED STUDIES ON FYA INDICATIONS

Before the field implementation of FYA left-turn signal indication, numerous studies have been conducted on safety performance of FYA signal indication comparing with other types of permissive left-turn indications.

Smith and Noyce (2000)

This research was conducted to evaluate drivers' understanding of CG, FYA, Flashing Yellow Ball (FYB), Flashing Red Ball (FRB), and Flashing Red Arrow (FRA) permissive left-turn indications in various five-section PPLT signal displays.

A set of 15 unique PPLT signal displays was created in a driving simulator based experimental platform. These 15 displays are the combinations of the three different signal display

arrangements (horizontal, vertical, or cluster) and the five different types of permissive left-turn indications.

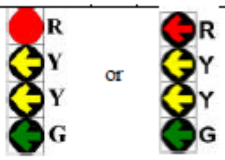
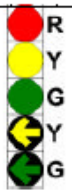
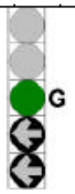
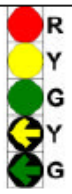
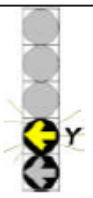
Driver's responses to various signal indications were collected during the driving simulator tests. In total, 991 responses from 34 drivers were collected. The results reveal that the CG, FYB and FYA left-turn permissive indications are all easy to be understood by drivers (with correct response rates of 92.9%, 92.9%, and 91.9%, respectively). The FRB and FRA permissive indication had a relative low correct response rate (69.3% and 59.6%, respectively).

Knodler et al. (2002)

This study investigated driver comprehension of CG and FYA permissive left-turn indications using a full-scale dynamic driving simulator.

A total of 12 driving simulator scenarios were designed based on combinations of (1) FYA and/or CG, (2) signal arrangements, and (3) concurrent signal phases displayed for the adjacent through traffic. These scenarios can be illustrated as Figure 2-3.

A total of 316 drivers participated in the driving simulator experiment. Drivers' responses to each PPLT signal display were manually recorded as "correct" or "incorrect." The incorrect responses were further categorized as "fail safe" and "fail critical." Fail safe means the drivers did not correctly respond to the PPLT signal display, but did not infringe on the right-of-way of the opposing traffic. Fail critical means a type of incorrect responses to PPLT signal displays, as a result of which drivers impeded the opposing traffic, and were exposed to the potential of crashes. Table 2-1 shows the six categories of possible drivers' responses in the simulator experiments.

Scenario[a]	Lens Color and Arrangement	Left-Turn Indication[b]	
		Protected Mode	Permitted Mode
1,2			
3, 4			
5,6			
7, 8			
9, 10			
11, 12			

R=RED G=GREEN Y=FLASHING YELLOW

[a] 1,3,5,7,9,11-CG through indication;2,4,6,8,10,12-RB through indication

[b] The indication illuminated for the given mode is identified by the color letter

Figure 2-3: PPLT Displays Evaluated in Knodler et al. (2002)

Table 2-1: Possible Driving Simulator Responses to PPLT Signal Displays

Response Type	Category	Driver Actions
1	Correct	Yield, go if an acceptable gap in opposing traffic allows
2	Fail safe	Stop, instead of yielding before proceeding Through the intersection
3		Stop and remain stopped (must be directed to proceed)
4		Stop, wait for all opposing traffic to pass before proceeding (drivers did not accept several large gaps)
5	Fail critical	No visible stop or yield before attempting to proceed through the intersection
6		Go through the intersection incorrectly taking the right-of-way from opposing traffic (created crash potential or crashed with opposing traffic)

Given the abovementioned Type 1 as correct responses, the percentage of correct responses is presented in Table 2-2.

Table 2-2: Correct Response Percentages by Left-turn Permissive Indications

Left-Turn Permissive Indications	Observations	Correct Response Rate	Statistical P-value
CG	1136	91 **%**	0.433
FYA	1701	90 **%**	
CG/FYA	565	92 **%**	

The results indicate that there were no statistically significant differences in drivers' correct response rates to different types of permissive left-turn signal indications. In addition, other

signal display-related factors, such as signal face arrangement, placement, and adjacent through indications, also have no significant impacts on drivers' understanding of PPLT signals.

Noyce (2003)

This research evaluated the safety and effectiveness of selected PPLT signal displays through a driver behavior analysis and a comprehension evaluation. The study was conducted using two full-scale fixed-base driving simulators at the University of Massachusetts, Amherst (UMass) and at the Texas Transportation Institute (TTI).

Twelve different PPLT signal displays (the same as those in *Knodler et al., 2002* as shown in Figure 2-3) were evaluated. After completing the driving simulator experiments, participating drivers were asked to participate in a video-based static evaluation for PPLT signal displays. The static evaluation used screen snapshots containing the PPLT displays, and presented them sequentially using videocassette records. Each signal display was shown for 30 seconds, during which the driver verbally indicated how they would react. Data were recorded and combined with the driving simulator data for a comprehensive analysis.

The results of the driving simulator experiments showed that drivers had high correct response rates (from 90% to 92%) for all types of PPLT signal displays. No statistically significant difference in driver comprehension was found between the 12 PPLT displays. The results indicate that an FYA indication is a viable alternative to a CG permissive indication.

The in-laboratory experiments and field implementation studies have identified following benefits of FYA permissive left-turn indications in a setting of a four-section vertical all-arrow display:

- Left-turn confusion is significantly reduced, especially that related to shared signal heads;
- Neither louvers nor precise head placement is required;
- The "yellow trap" problem is eliminated, as the FYA display is logically coordinated with the opposing through movement green indication.

Knodler et al. (2005)

This research evaluated driver comprehension of FYA permissive left-turn indications in shared five-section signal heads at the intersections with PPLT signal phasing. Two different approaches were used: a dynamic driving simulator experiment and a computer-based static evaluation.

In the dynamic driving simulator experiments, seven scenarios with various permissive left-turn signal displays were created. Among them, there was a baseline scenario with CG indications for permissive left turns, and other six scenarios using FYA as permissive left-turn indications (see Figure 2-5 for details of PPLT signal display design).

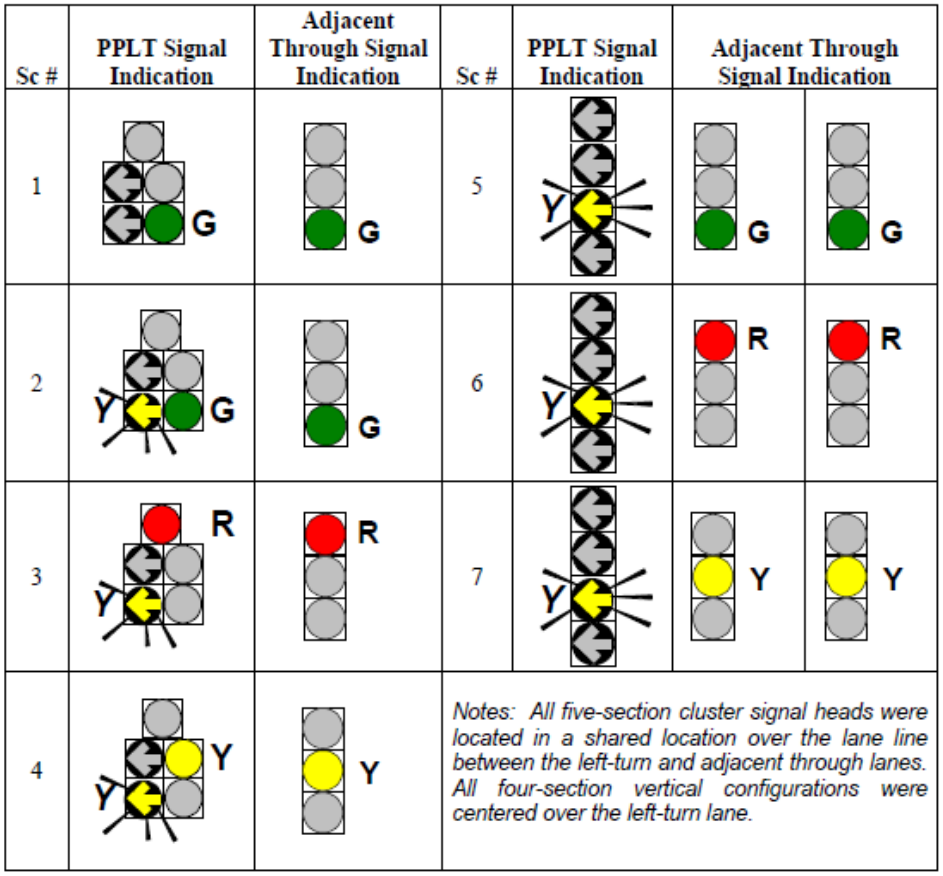


Figure 2-4: Permissive Left-Turn Signal Displays Evaluated with Dual Displays

The computer-based static evaluation was conducted in two different ways: 1) a follow-up evaluation that was followed by the driving simulator experiments, and 2) an independent static evaluation.

In the computer-based static evaluation, an auxiliary survey instrument was used to present drivers with various traffic signal displays in realistic background photos, which allows the signal indications to flash as required. For each signal display, drivers were asked to respond with one of four options to the following question: "if you want to turn left and you see the traffic signals shown, you would?" (see Figure 2-5 for an example scenario).

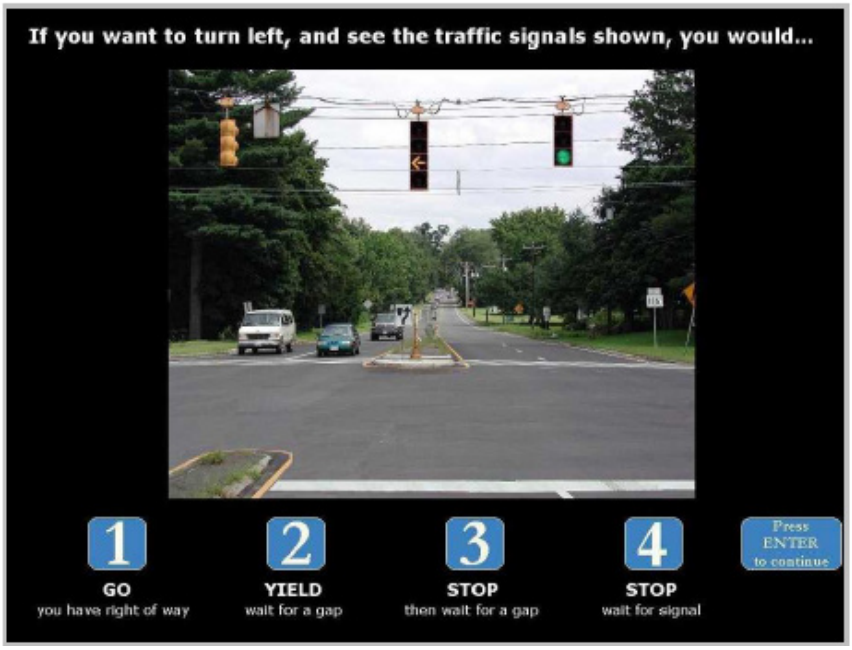


Figure 2-5: Sample of Computer-Based Static Evaluation

A total of 54 drivers participated in the dynamic driving simulator experiments and follow-up static evaluation; while 210 drivers participated in the independent static evaluation.

These results reached the following conclusions:

1. The follow-up static evaluation revealed that drivers have a statistically significant higher correct response rate for an FYA than a CG permissive indication. The evidence suggested FYA displays may improve driver comprehension of a permissive indication.

2. Given both "yield" and "stop first" as correct responses, the driving simulator experiments and the follow-up static evaluation indicated that the drivers have high correct response rates to all the seven PPLT signal displays including both CG and FYA displays. The difference between various scenarios was not statistically significant. It can be concluded that drivers have high level of comprehension for both CG and FYA.

Note that the 2009 Edition MUTCD has set new standards for shared signal faces. It requires that, for the permissive left-turn phases, only CG signal indications should be displayed for shared signal faces; while an FYA indication is exclusive for separate signal faces. In this case, the PPLT signal displays 2, 3 and 4 in Figure 2-4 will not be allowed according to the 2009 Edition MUTCD.

Knodler et al. (2006)

This research aimed to quantify driver comprehension of FYA as permissive left-turn indications compared to FRA indications at intersections with exclusive left-turn lanes and wide medians.

In total, four permissive left-turn displays featured by either FYA or FRA indications (see Figure 2-6) were evaluated at wide median intersections in a driving simulator environment.

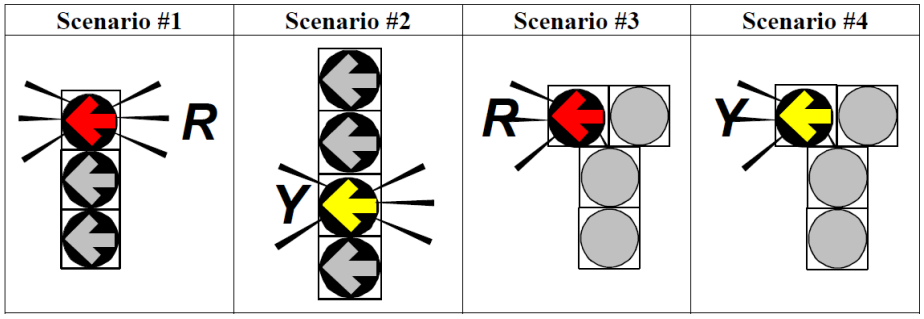


Figure 2-6: Permissive Displays Evaluated at Wide-Median Applications

In this study, both driving simulator experiments and computer-based static evaluation were applied as in *Knodler et al. (2005)*. The driver responses are classified into four categories:

1) Go, you have the right-of-way − fail critical (see Section 2.4.2 for definition)

2) Yield, wait for a gap − right reaction for FYA

3) Stop first, then wait for a gap − right reaction for FRA

4) Stop, wait for the signal − fail safe (see Section 2.4.2 for definition).

The results of the simulator experiments, the follow-up computer-based static evaluation, and the independent static evaluation are essentially consistent, which show that

- FYA scenarios have a higher 'yield' response rate (more than 70%) than FRA (less than 40 %);
- FRA scenarios have statistically a higher percentage of 'stop first' responses than FYA;
- FYA scenarios have a statistically significant higher percentage of 'go' responses (fail critical) than the FRA scenarios;
- FRA scenarios have a higher percentage of 'stop and wait' responses than the FYA scenarios.

Based on these results, it was concluded that FYA can be understood by most of drivers. However, the relative high percentage of fail critical responses with FYA may indicate a need for supplemental treatments, such as providing signage at wide median intersections or providing driver trainings.

Knodler et al. (2007)

This study aimed to investigate drivers' responses to CG indications after having been exposed to FYA indications. The hypothesis of this research was that "after FYA displays are implemented and drivers comprehend the FYA indication, drivers are more likely to interpret CG indications as a right-of-way situation."

Both static evaluation and dynamic driving simulator experiments were used. The static evaluation was administered to two different groups: a follow-up static evaluation was completed by all drivers participating in the simulator experiments, and a separate pool of drivers completed the static evaluation, independently of the driving simulator experiments. Before the driving simulator experiments, drivers were trained to learn about FYA indications using a computer-

based training tool. The simulation included 14 intersections, half of which involved left-turn maneuvers with an FYA indication, a protected green arrow indication, or a CG indication. Drivers were first exposed to the FYAs, and then encountered an intersection display with the CG indication that was used for evaluation. The same approach was adopted in both the follow-up static evaluation and the independent static evaluation.

A total of 25 drivers participated in both the driving simulator experiments and the follow-up static evaluation. A total of 100 drivers participated in the independent static evaluation.

In the driving simulator experiments, driver comprehension of CG permissive indications following exposure to FYA indications did not differ significantly from the comprehension of the CG before the exposure to the FYA. The separate independent static evaluation showed a result consistent with the driving simulator experiments. In the follow-up static evaluation, drivers exposed to FYA indications were more likely to give a yield (correct) response to CG permissive indications. These results provided statistical evidence that the implementation of the FYA may not impact drivers understanding of CG indications during a short time period after implementation.

Henery and Geyer (2008)

This study was to identify driver comprehension of permissive left-turn indications. The survey consisted of several visualized survey questions, which presented respondents with various driving situations. The results of the survey showed that CG indications with "LEFT TURN YIELD ON GREEN' supplemental sign" (R10-12, see Figure 2-7) is better understood than FYA indications. The average correct response rate to FYA indications was 72.4%, while the average correct response rate to CG indications with the sign was 94%.

Figure 2-7: Supplemental Sign (R10-21): LEFT TURN YIELD ON GREEN

The results implied that a supplemental sign may help drivers understand permissive left-turn indications; while the authors recommended that the installation of FYA should be preceded with more cautions.

Summary of In-Laboratory Based Studies

Most of the existing studies verified that an FYA indication performs as good as or better than a CG indication in term of driver comprehension. It was also noted that CG indications together with a "LEFT TURN YIELD ON GREEN" supplemental sign have even better understandability than FYA indications (*Henery and Geyer, 2008),* which means traffic engineers may be able to further improve driver comprehension by the use of supplemental sign. Note that the use of supplemental traffic signs is recommended for intersections with wide medians (*Knodler et al., 2006*). The major results of the laboratory- and survey-based studies are summarized in Table 2-3.

Table 2-3: Summary of Laboratory- and Survey-Based Studies

Reference	Objective	Methodology	Sample Size (Drivers)	Major Conclusions
Smith and Noyce (2000)	Compare CG, FYA, FYB and FRA for Permissive Left-turn indication	Driving simulator experiment	34	FYA has no significant difference from other permissive left-turn indications
Knodler et al. (2002)	Compare FYA and CG for Permissive Left-turn indication	Driving simulator experiment	316	FYA and CG have no significant difference in term of driver comprehension
Noyce (2003)	Compare FYA and CG for Permissive Left-turn indication	Driving simulator experiment & static evaluation	316	FYA and CG have no significant difference
Knodler et al. (2005)	Compare FYA and CG for Permissive Left-turn indication	Driving simulator experiment & static evaluation	264	FYA may be better than CG in term of driver comprehension of the permissive indication
Knodler et al. (2006)	Compare FYA and FRA for Permissive Left-turn indication	Driving simulator experiment & static evaluation	264	FYA can be widely understood while signage or training is suggested for wide median intersections
Knodler et al. (2007)	Determine drivers' response to CG indication after exposed to FYA indication	Driving simulator experiment & static evaluation	100 (static evaluation) 25 (driving simulator)	FYA implementation may not impact drivers understanding of the CG indication
Henery and Geyer (2008)	Compare FYA and CG (with supplemental signs) for Permissive Left-turn indication	Survey	204	CG indication with supplemental sign is better than FYA

2.4 FIELD-TEST BASED STUDIES ON FYA PPLT OPERATION

While lab-based studies have shown that an FYA performs as well as or better than a CG for permissive left turns in term of driver comprehension, field studies are still needed to further verify its effectiveness, safety performance, and the associated technical issues in implementation of FYA PPLT. This section will focus on existing research based on field tests. Major findings in the following fields will be summarized as: (1) technical issues, (2) timing and phasing issues, (3) safety concerns related to FYA PPLT, (4) safety performance of FYA PPLT, and (5) supplemental signs for FYA PPLT.

2.4.1 Technical Issues

Based on previous studies, most FYA displays were installed by converting traditional five-section PPLT signal displays to four-section all-arrow FYA display. So, the most important issue in the implementation of FYA PPLT is the existing equipment conditions for a successful and cost-effective conversion to FYA PPLT displays. Based on literature review, there are two major types of equipment issues associated with (1) signal head/display and (2) controller and malfunction monitor unit (MMU).

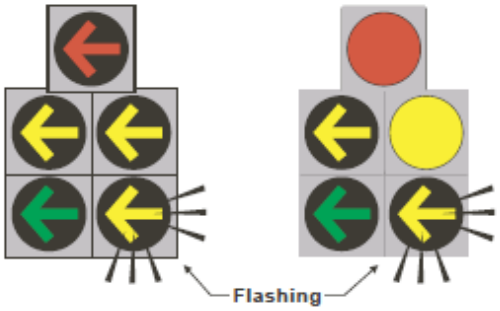
1) Signal Head/Display

In the literature reviewed, the field study results associated with FYA signal heads/displays are introduced. Signal heads/displays for FYA Installation are summarized in Tables 2-4.

NCHRP Report 493 (2003)

As the most comprehensive evaluation of PPLT indication that has been conducted, NCHRP Report 493 (2003) recommended that four-section, all-arrow displays should be the only display allowed for FYA signal face. However, three-section and five-section displays may be used for FYA signal face under special conditions:

- A three-section display with bi-modal lenses is justified as exception because it operates in the same way as the four-section display face does by incorporating FYA and green arrow into one section. Only one indication shall be illuminated at any time.
- A five-section display may only be allowed under the condition when it is used as the left-turn signal and must be shielded from the adjacent through movement. NCHRP Report 493 (2003) demonstrated two potential options for converting a five-section signal face to the FYA signal faces as shown in Figure 2-8.



(1) **(2)**

Source: NCHRP Report 493(2003)

Figure 2-8: Potential FYA Retrofit to Five-Section Cluster Displays (Exclusive Left-Turn Displays)

This report also represented the following allowed variations:

- The agency may use a circular red indication in lieu of the red arrow;
- A three-section all-arrow display using the center section for the change interval (with steady yellow arrow indication) and the permissive interval (with FYA indication) is allowed, provided that all yellow change intervals for the approach are initiated simultaneously.

Deskins (2006)

This study compared three-section and four-section left-turn signal heads for FYA displays. The advantages of each type of signal heads were summarized as follows:

- Three-section head: 1) both "go" phases occur in the bottom head as expected, which can work well for color blinds, 2) all signal sections were utilized even when phases are omitted, 3) progression of indications does not skip over heads, 4) wind loading is reduced, so it's easier to retrofit and more stable for video detection platform.
- Four-section head: 1) provides drivers with expectation of "something different," 2) provides additional clues to drivers, such as a positional shift between FYA and green arrow in Lagging Case, 3) Interim Approval strongly suggests use of four-section heads unless there are physical constrains.

Deskins (2009)

Four FYA PPLT displays were installed in Kennewick, WA with three-section signal heads with green/yellow bi-modal lenses. By observing driver behaviors, this study found that three-section configuration was feasible at these intersections.

McCarroll (2009)

From the experience of FYA installation in Oregon, McCarroll (2009) suggested that FYA signal heads should comply with the following requirements:

- Separate signal face for the left-turn movement,
- Standard FYA head with four sections, all arrows, and
- A three-section signal face with bimodal sections (green arrow and FYA) may be used where impractical to use four-section signal faces.

Installation of FYA also required one more conductor than that of protected-only head.

Table 2-4: Summary of Signal Head/Display Face for FYA Installations

Signal Head/Display Face		Reference
Four-section FYA signal head	Four -section, all arrow display face (standard FYA head , strongly suggested by Interim Approval)	NCHRP Report 493
		Deskins (2006)
		Deskins (2009)
		McCarroll (2009)
Three-section FYA signal head	Three -section display face with bi-modal lenses (exception)	NCHRP Report 493
		Deskins (2006)
		Deskins (2009)
		McCarroll (2009)
Five-section FYA signal head	Five-section display face(conditional variation)	NCHRP Report 493

2) Controller and Malfunction Monitor Unit (MMU)

NCHRP Web-only Document 123 (2007)

In this study, the controller and MMU conditions were summarized in Table 2-5 for 50 intersections where FYA PPLT signal displays had been successfully installed. As shown in this table, successful FYA installations can work with a wide range of controller types (different models, different manufacturers, and different types of conflict monitors/MMUs).

Table 2-5: Summary of Successful FYA Installations by Controllers

Reference	Controller Type	Controller Manufacturer/ Model/Firmware	External Logic Used(Y/N)	Conflict Monitor
NCHRP Web-Only Document 123	170	BITrans 233	N	EDI 210E
	170	BITrans 233	N(5 outputs to 3 section head)	EDI 210ECL
	170	Wapiti	Y(flasher in head)	
	170E	McCain-BITrans 233NC2	N	EDI 210ECL(remove jumpers and switches as shown)
	170E	Wapiti	Y(flasher in head)	EDI 210+modified diode card
	170E	Wapiti	N	EDI 210(via unused overlap channel)
	2070L	AECOM-Econolite Oasis	N	EDI 2010
	2070L	Eagle-Econolite Oasis	N	EDI 2010ECL(remove jumpers and switches as shown)
	NEMA	Eagle EPAC 300	N	EDI MMU 16-LE
	NEMA	Peek 3000	N	Peek LMD
	NEMA TS-1	Eagle EPIC	N	EDI custom 6&12 channel
	NEMA TS-1	ECPI-KMC 8000	Y	
	NEMA TS-1	LMD 8000	N	Peek LNM 12E
	NEMA TS-1	Traconex TMP-390	N	NEMA TS-1(install jumpers as shown)
	NEMA TS-2	Eagle EPAC M52	N	EDI
	NEMA TS-2, Type 1	Eagle Econolite ASC/3	N	EDI MMU 16-LE
	NEMA TS-2, Type 1	Eagle Econolite 2070 – Northwest Signal Supply IDTS2	N	EDI 16E
	NEMA TS-2, Type 2	Eagle EPAC M50	N	

Reference	Controller Type	Controller Manufacturer/ Model/Firmware	External Logic Used(Y/N)	Conflict Monitor
	NEMA TS-2, Type 2	Eagle EPAC M50-Econolite Oasis	N	NEMA TS-1
NCHRP Web-Only Document 123	NEMA TS-2, Type 2	Eagle EPAC M52-EPAC v3.33b+	N	EDI SSMLE-FYA(12channel)
	NEMA TS-2, Type 2	Eagle EPAC M52-SCATS v.s15	N	EDI SSMLE-FYA(12channel)

In this report, special emphasis was put on two types of controllers that have been successfully used for installation of FYA: (1) 170E controller running BITrans 233 software and (2) NEMA TS-2, Type 2 Eagle M50 series controller running Econolite Oasis. The authors pointed out:

- For 170E controller (McCain Traffic) running BITrans 233 software, its installation required the addition of an EDI model 210ECL conflict monitor, programmed in a specific manner.
- For NEMA TS-2, Type 2 Eagle M50 series controller running Econolite Oasis, its installation required the addition of a NEMA TS-1 MMU. Despite being designed for a 2070, Oasis will also run on an Eagle controller. The Oasis firmware allows for the creation of flashing outputs directly in the controller which eliminates the need for any external flasher circuits. Oasis also allows these outputs to be assigned in the controller to the appropriate pins on the MS-A, B AND C. The FYAs were driven off the unused load switch positions on the pedestrian load switches, which required the installation of several sets of jumpers in the cabinet. To allow the intersection to run properly, the yellow monitoring on the MMU had to be disabled.

Overall, these successful FYA installations presented in this study provide valuable experiences and agency information for future installation of FYA for our research project.

Deskins (2006)

The following suggestions regarding controller, wiring, software and MMU issues were summarized.

Controllers for installing FYA PPLT:

- City's Econolite ASC/2 controllers wouldn't run FYA. But, Econolite company now has the ASC/3 controller
- Controllers should be compatible with existing Aries system
- There is a new controller named 2070N&Northwest Signal's WA03 to be recommended

MMUs for installing FYA PPLT:

It's necessary to use the Conflict Monitor (CM) or MMU in FYA PPLT operations. Channel limitation may exist in some cases.

Deskins (2009)

Northwest Signal Supply's Voyage software provides multiple setup options for FYA and makes it easy to set protected-only or permitted-only by time of day as necessary. It was also found that an EDI Smart Monitor MMU has special settings that allow the pairing of channels to detect faults of FYA signals which were driven by two load switches.

McCarroll (2009)

Based on the FYA installation experience in Oregon, McCarroll (2009) showed that the controller software/firmware used by Oregon Department of Transportation (ODOT), such as Wapiti's W4IKS, W4HC11, or Voyage, had different features:

- W41KS requires command-box logic of approximately 200 lines of code. Necessitates use of laptop to download timing to controller;
- W4HC11 has new tables for FYA without command box;

- Voyage software for 2070L controllers can run FYA without command box.

3) Other issues

Wiring issue

A common installation of PPLT phasing using a CG indication for the permissive left-turn phases is connected to a CG signal head for adjacent through traffic. Due to the flashing indication, additional cabling may be needed in order for the flashing display to be controlled by its own circuits.

Controller logic link issue

In a typical PPLT operation, it is possible for the CG display and green arrow display to illuminate simultaneously. However, by converting to the FYA display, the FYA and green arrow displays cannot illuminate simultaneously.

Under unusual situations, additional or different phases could serve as parent phases to drive the FYA overlap. The same overlap logic can also be used to drive right-turn arrows where appropriate.

If existing controller software/firmware cannot be modified to provide this functionality, the same effect can be achieved by using external logic, although with less flexibility. It is assumed that new controller software/firmware and any significant upgrade of existing controller software/firmware will include this functionality, so that over time, external logic will no longer be needed.

4) Summary

According to the literature aforementioned, Table 2-6 summarizes the equipment used for the intersections where FYA PPLT displays have been successfully installed.

Table 2-6: Equipment Employed for FYA Installation

Reference	Signal Head/Display	Controller/Software/Firmware	Conflict Monitor (CM/MMU)
NCHRP Report 493	1) 4-section, all-arrow display face (only display for FYA) 2) 3-section display face with bi-modal lenses (exception) 3) 5-section display face (conditional variation)	Not specified	Not specified
NCHRP Web-only Document123	Not specified	1) 170E controller (with BITrans233 software) 2) NEMA TS-2, Type 2 Eagle M50 series controller (with Econolite Oasis software) 3) Others see Table 2-5	1) EDI model 210ECL 2) NEMA TS-1 3) Others see Table 2-5
Deskins (2006)	1) 3-section head (good for color blind) 2) 4-section head (strongly suggested by Interim Approval)	1) Econolite ASC/2 controllers wouldn't run FYA, But Econolite now has the ASC/3 controller 2) Controllers should be compatible with existing Aries system 3) New controller--2070N&Northwest Signal's WA03 to be recommended	Not specified
Deskins (2009)	1) 3-section signal head with green/yellow bi-modal section (feasible in their first four intersections) 2) 4-section signal head (suggested by Interim Approval)	Northwest Signal Supply's Voyage software provides multiple setup options for FYA and makes it easy to set protected-only or permitted-only by time of day as necessary	EDI Smart Monitor
McCarroll (2009)	1) 4-section, all arrows left turn signal face (standard FYA head) 2) 3-section signal face with bimodal section (GA, YFA)	1) W4IKS (need command-box logic of about 200 lines of code) 2) W4HC11 (without command box) 3) 2070L controller (with Voyage software and without command box)	Not specified

2.4.2 Timing and Phasing Issue

Based on the experience of field installation, Deskins (2009) proposed the following suggestions related to timing and phasing:

- Don't provide a yellow and/or red clearance interval between an FYA and a lagging green arrow because there are no benefits but more lost time.
- Provide both yellow and red clearance between a green arrow and the start of an FYA. A minimum of 1.5 to 2.5 seconds of red is desirable. It is because the left-turns will fail to yield after the steady yellow in absence of an all-red interval.

2.4.3 Safety Concerns Related to the FYA PPLT Operation

Deskins (2009) pointed out the following safety concerns related to the signal timing for FYA PPLT operations.

- Two different meanings of steady yellow arrow. In FYA PPLT operation, steady yellow arrow will be displayed at two different times in one signal cycle (as shown in the Figure 2-9), having two different meanings as follows: 1) when steady yellow arrow follows a green arrow, it means that the left-turn drivers still have the right-of-way over opposing traffic when finishing their left turn; on the other hand, 2) when steady yellow arrow follows FYA, it means that left-turn drivers have to yield to the opposing traffic. These two different meanings may cause drivers' confusion. However, according to field observations, there is no evidence that left-turn drivers could not distinguish these two meanings of the steady yellow arrow indications.
- High traffic volume. According to Deskins (2009), at one of the FYA PPLT implementation locations, there were five fail-to-yield crashes during the first five weeks. This location had a left-turn volume of 280 vph, higher than the average. The signal sequence is lead-lag and all the crashes involved the leading left-turn approach. According to field observation, it has been found that in about one in every 5-10 cycles,

the drivers in the sneaker position for the left turn would become panic as they saw the adjacent signals go yellow and then red (to allow the opposing green arrow to come on). This problem was not found at the other implementation locations with left-turn volumes less than 150 vph.

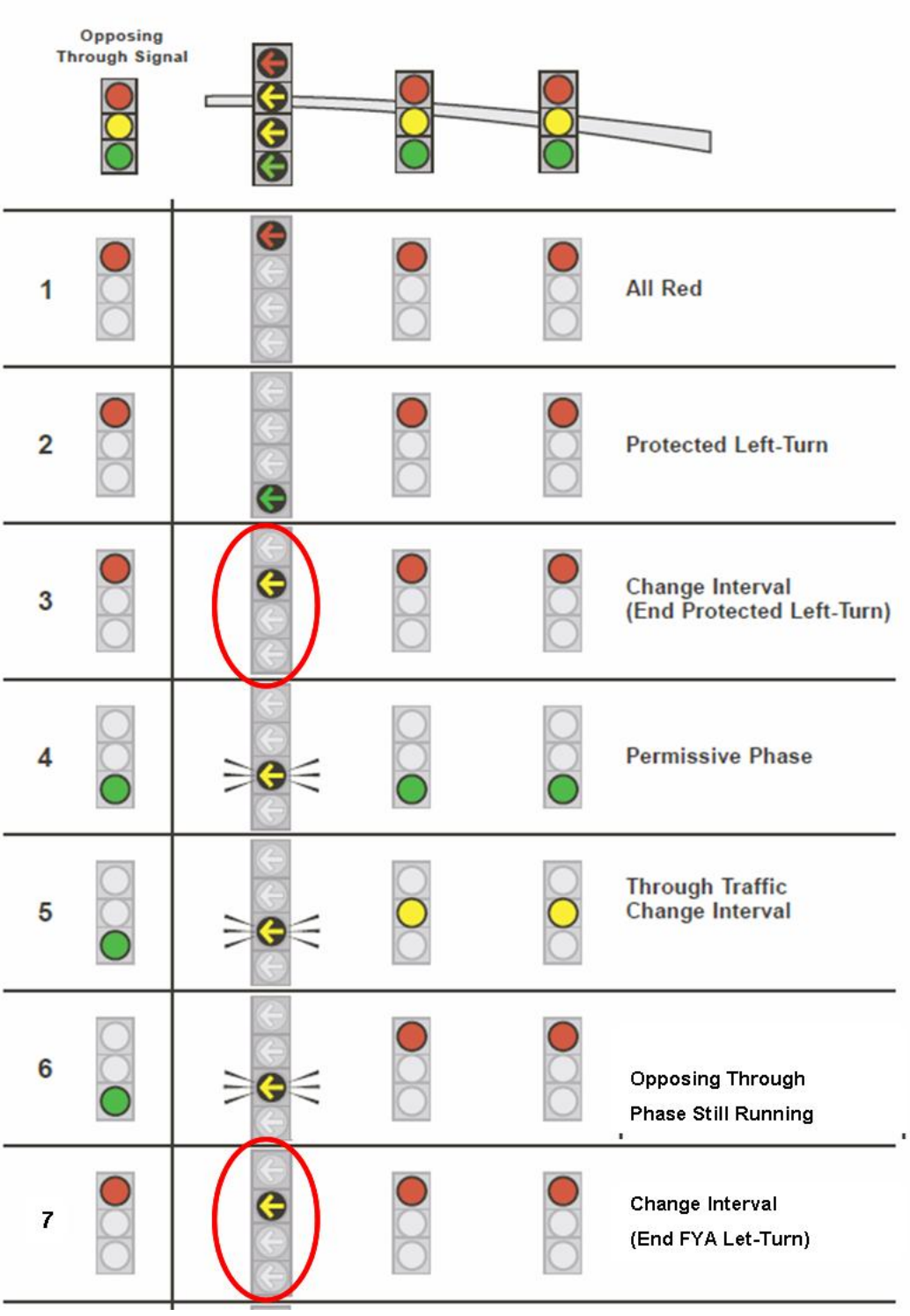


Figure 2-9: Two Meanings of Steady Yellow Arrows

2.4.4 Safety Performance of FYA PPLT Observed Through Field Study

A limited number of field studies have been conducted for assessing the safety performance of FYA PPLT. The major results and findings of these existing researches are summarized as follows.

NCHRP Report 3-54 (2003)

The objective of the field implementation study in NCHRP 3-54 was to document the implementation of the FYA PPLT operation, and the associated safety implications and cost.

Several agencies participated in this field implementation study. The participated agencies and the numbers of study sites are listed in Table 2-7. The intersections selected for evaluation were operated with PPLT signal phasing, and were considered typical intersections with no special geometric or operational features.

Table 2-7: Summary of Implementation Study Sites in NCHRP Report 493

Agency	Implementation Date	Number of Implementation Sites
Montgomery County, Maryland	September 2000	3
Tucson, Arizona	May 2001	3
Jackson County, Oregon	May 2001	1
Oregon Department of Transportation	June 2001	2
Beaverton, Oregon	April 2002	3
Broward County, Florida	June 2002	3

During the field implementation, some agencies reported the FYA safety performance as follows:

- Jackson County, Oregon converted five protected-only left-turn operations to PPLT with FYA displays. The county received very positive feedback from the local police department and citizens.
- The City of Beaverton, Oregon implemented FYA at three locations and no problems had been experienced or reported at those intersections.
- Montgomery County, Maryland, and the Oregon Department of Transportation (ODOT) reported that they received minimal public feedback regarding FYA display.

As part of the field implementation, before and after traffic conflict studies were conducted at each of the FYA implementation sites. The local jurisdiction and/or research team members videotaped 16 hours of traffic video before/after implementation FYA PPLT at those intersections. Then, the videotapes were reviewed to conduct a conflict rate analysis with a focus on those conflicts related to the left-turn signal displays.

Overall, left-turn related conflict rates were low for all PPLT displays evaluated, and few left-turn conflicts were associated with the PPLT display. The results of this field traffic conflict study revealed little notable difference in the before and after conflict rates, and no difference that could be attributed to the change in the PPLT display.

Traffic events involving non-conflict maneuvers (but illegal or dangerous) were also observed in this field study. The events such as red indication violations, backing, hesitation on signal change, and slowing considerably in a traffic lane were counted. A total of 242 traffic events were observed, including 147 "hesitate on protected," 53 "hesitate on permitted," 5 "red signal violation," and 37 "backing." Most of the events were related to hesitation at the onset of the green indications, which were not very critical safety events.

NCHRP Web-Only Document 123 (2007)

This study conducted a field evaluation on the safety performance of FYA permissive left-turn indications. The study analyzed the data collected at over 50 intersections using PPLT phasing with FYA indications. Before implementation of the FYA PPLT operation, these study intersections were operated with various types of left-turn phasing, including, permissive-only, protected-only, and PPLT phasing. Safety performance of FYA indication was evaluated based on the crash experience observed before and after the implementation of FYA PPLT.

Besides 'before' and 'after' crash data, the data collected for the field evaluation included supporting information about the intersections, such as traffic volume, signal timing, geometry, and adjacent land use. A minimum of three years of crash data were obtained for the time period prior to implementation of the FYA PPLT operation. Crash data available 'after' implementation were obtained from the date of installation to the most recent date for which data were available. Data from similar intersections which were not implemented with the FYA were requested as 'comparison sites' to allow for more robust statistical analysis of safety performance.

The major findings in this field study can be summarized as follows:

- Safety was improved at the intersections that were previously operated with PPLT phasing.
- Safety was not improved at the intersections that were operated with protected-only left-turn phasing prior to field implementation.

- No conclusions were reached at intersections that were operated with permissive-only left-turn phasing prior to the implementation of FYA PPLT operation. It is a result of the limited number of implementation sites and data sample size.

Collectively, this research concluded that the installation of FYA indications will result in safety improvement at intersections previously operated with PPLT phasing.

Deskins (2006 and 2009)

These two literatures documented the field observations and lessons learned in the implementation of FYA displays at 33 locations throughout Kennewick, WA. The major findings are summarized as follows:

- Crash experience was reported for the 33 FYA locations around 2006. After the field implementation of FYA displays, crashes occurred at the following four intersections only, three of which presented a high fail-to-yield left-turn crashes rates (one reached up to 10 crashes in 7 months).

Table 2-8: Crash Experience after Installation of FYA in Kennewick, WA

Intersection	27th & Quillan	10th & Kellogg	CCB & Deschutes	CCB & Grandridge
Time in Service	17 months	14 months	7 months	6.5 months
Total # of Crashes	18	12	14	7
Fail-to-Yield Left-turn Crashes	6	4	10*	1**

* Five northbound left-turn Fail-to-Yield crashes in first five weeks, then converted to protected-only phasing for northbound approach

** One additional crash caused by driver failing to yield under icy conditions

- The City of Kennewick tried to apply FYA to dual left-turn lanes, which turned out working well; another dual left-turn intersection converting a protected-only signal operation into a FYA PPLT operation did not encounter problems. Note that, lots of the researchers (the City of San Diego, 2006; ITE, 1982; Asante et al., 1993) did not recommend permissive left-turn phasing for dual left-turn lanes sites.

- FYA showed some minor limitations with emergency vehicles, but there was still significant improvement over previous PPLT operation in preemption.
- This study conducted a field test of driver responses to FYA indications during the middle of the day utilizing both leading and lagging sequences. The results showed that the drivers tempted to stay behind the stop bar on the red arrow, and responded in the appropriate manner to pick up immediately on the change from red to FYA. The results of this study showed that an FYA has higher level of understandability than traditional standard PPLT displays. In addition, before and after comparisons showed that lower rate of fail-critical responses after conversion; and thus the conclusion was reached that the safety performance was improved by the use of FYA against traditional left-turn signal indications.

McCarroll (2009)

This research presentation documented the ODOT's efforts to perform a field evaluation on safety implications of FYA. Field data were collected from five study sites where the left-turn signal indications were converted from traditional Doghouses to FYA before 2008. The results of the field evaluation indicated that:

- Annual average number of left-turn related crashes has been reduced by 67%, from 1.1 to 0.35 crashes/yr/intersection.
- Benefit/cost ratio due to crash reduction is approximately 8:1.
- Significant safety improvement can be achieved over the traditional doghouse display.

Summary

There is a limited number of existing field studies on assessing the safety performance of FYA PPLT operations. Collectively, the results of these studies verified that the use of FYA PPLT will enable safety improvements at most of studied intersections comparing with the traditional PPLT indications. The summary is shown in Table 2-9.

Table 2-9: Comparison of Previous Field Studies on Safety Implications of FYA PPLT

Reference	Sample Size	Comparison Method	Study Duration	Before Conversion (Head/Phase)	After Conversion (Head/Phase)	Results	Overall Safety performance
NCHRP Report 493	15 intersections	Before and after traffic conflict analysis	16 hours of before and after traffic videos	Standard PPLT displays	FYA PPLT	1) Little notable difference in the before and after conflict rate 2)No difference that could be attributed to the change in PPLT display	Neutral
NCHRP Web-Only Document 123	Over 50 intersections	Before and after crash data analysis	Before:22-72 months After:12-60 months	1) Standard PPLT displays 2) Protected-only LT displays 3) Permissive-only LT displays	FYA PPLT	1) Safety was improved for PPLT locations 2) Safety was not improved Protected only LT 3) No conclusions for Permissive only LT	Positive
Deskins (2006) & Deskins (2009)	33 intersections	Crash data analysis	Five years	1) Standard PPLT displays (a vast majority) 2) Protected-only LT displays 3) Permissive-only LT displays	FYA PPLT	Encountered specific crash problems at two locations	Mixed
McCarroll (2009)	5 intersections	1) Before and after crash data analysis 2) Benefit/cost analysis	Before crash data: before 2008 After crash data: 2009, 2010	Doghouses left turn heads (most conversion involved 2 doghouse heads)	FYA PPLT	1) Annul average Left turn related crashes reduced from 1.1 crashes/yr/intersection to 0.35. (Reduction of 67%) 2) Calculated Benefits/Cost Ratio from crash reductions is approximately 8:1	Positive

2.4.5 Supplemental Signs for FYA PPLT

Some researchers believe that there is no need to use supplemental signs for FYA PLLT, since drivers can understand FYA well. However, some research results supported the use of supplemental signs.

1) Proposed Supplemental Sign for FYA by Existing Studies

NCHRP Report 493 (2003)

In NCHRP Report 493, supplemental signing was an optional treatment. Furthermore, this report suggested that the most promising sign as follows: YEILD ON FLASHING YELLOW ARROW or YIELD ON FLASHING YELLOW [Symbolic Arrow] (see Figure 2-10).

Deskins (2009)

In this study, it was found that drivers who saw FYA permissive left-turn indications for the first time might not be able to understand FYA very well, which resulted in left-turn accidents at some of the FYA implementation sites. The potential solution to this problem was to use the supplemental sign "LEFT-TURN YIELD ON FLASHING YELLOW" with a symbolic arrow, as shown in the Figure 2-10.

Source: Deskins (2009)

Figure 2-10: An Option of Supplemental Sign

Hawkins (2005)

Hawkins (2005) proposed an Extinguishable Message Sign (EMS) as shown in Figure 2-11, to replace the existing "LEFT TURN YIELD ON GREEN BALL" sign. The EMS was attached

above the signal heads directing the left-turn movement, and was synchronized with the signal indications. The EMS would illuminate when the yellow arrow or green ball indications were illuminated on the signal head. Figure 2-12 shows the use of the EMS during the green arrow, yellow arrow, and CG signal indications.

Source: Hawkins (2005)

Figure 2-11: "LEFT TURN YIELD" EMS Sign

Source: Hawkins (2005)

Figure 2-12: Operation of "LEFT TURN YIELD" EMS

2) Supplemental Sign for FYA Recommended by the Research Team

While the MUTCD has no specific guidance for the supplemental sign for FYA permissive left-turn indications, it offered the detailed Size Regulatory for the Yield Sign as follows.

Table 2-10: Regulatory Sign Size for Yield Signs

Sign	MUTCD Code	Section	Conventional Road	Expressway	Freeway	Minimum
Yield	R1-2	2B.08	900 × 900 × 900 (36 × 36 × 36)	1200 × 1200 × 1200 (48 × 48 × 48)	1500 × 1500 × 1500 (60 × 60 × 60)	750 × 750 × 750 (30 × 30 × 30)

2.5 SUMMARY

Based on the literature reviewed, the benefits, concerns, and findings associated with FYA permissive left-turn indications are summarized as follows:

2.5.1 Benefits of FYA Permissive Left-Turn Indications

1. An FYA permissive left-turn indication has a good driver comprehension. Most existing studies (e.g., *Smith and Noyce, 2000; Knodler et al., 2006*; *Kacir et al., 2003*) have concluded that an FYA permissive left-turn indication has a higher understandability than a CG indication, based on driving simulator experiments and/or a static survey. Recognizing "yellow traps" are a result of driver misunderstanding of permissive signal, FYA permissive left-turn indications is thus considered as a universe and effective alternative to CG indications (*NCHRP Report 493*).
2. Existing research (e.g,. *Noyce, 2000; Niemeyer, 2005; Deskins, 2006*) indicated that FYA permissive left-turn indications can improve intersection safety.
3. FYA permissive left-turn indications showed a higher fail-safe response rate as opposing to CG indications (*Kacir et al., 2003*). Recall that a fail-safe response was that drivers did not correctly respond to the PPLT signal display, but did not infringe on the right-of-way of the opposing traffic.
4. FYA permissive left-turn indications were successfully implemented in the field with relatively little or no technical issues. The display can be mounted by pole, span wire, or median mount. Neither louvers nor precise head placement is required (*Kacir et al., 2003; Noyce, 2003*).
5. FYA displays provide a flexible option to handle various traffic volume levels, as different left-turn phasing (protected-only, permissive-only, or PPLT) can be alternatively used at different time of day (*Idaho DOT, 2009*).

2.5.2 Safety Concerns Related to the Use of FYA Permissive Left-Turn Indications

Despite the benefits aforementioned, some concerns have also been reported:

1. Experimental results showed that FYA displays have no significant impacts on driver understanding of CG permissive indications a short period after implementation. However, its long-term effects are still unknown. Related concerns were raised that in a long run CG indications might be misinterpreted as a protected left-turn in presence of FYA displays (*Knodler et al., 2007*).
2. Geometric features have significant effects on driver comprehension of FYA permissive left-turn indications. For example, at wide-median intersections, there was a statistically significant higher percentage of 'go' responses (fail critical) for the FYA scenarios than the FRA scenarios (*Knodler et al., 2006*), which indicated a need for supplemental treatments, such as providing proper signage or driver training.
3. There are concerns that drivers may mistake an FYA indication for a steady yellow arrow (for example, by a glance at the signal) and assume that they can sneak into the intersection, which may actually increase the risk of a crash between the left-turning and opposing through vehicles (*Yu et al, 2009*).
4. In FYA PPLT operation modes, steady yellow arrows will be displayed at two different times in one signal cycle having two different meanings as shown in Figure 2-9, which may confuse drivers (*Deskins, 2009*).
5. The sample sizes involved in the existing studies are relatively small. For example, even in the FHWA study (*Noyce, 2000*), only 21 study sites were evaluated for less than 2 years. This sample size may not be enough to validate the conclusion that FYA indications result in a reduction of accident rates compared to CG indications.

2.5.3 Findings Associated with Field Implementation of FYAs

Some findings from the existing studies on the field implementation of FYAs were summarized as follows:

1. Technical and Hardware: Most FYA displays were installed by converting traditional five-section displays to four-section all-arrow FYA displays. A wide range of controllers

(various makes and models, various conflict monitors/MMU, etc) can enable a successful FYA installation (*Deskins, 2009*).

2. Timing and Phasing: (1) don't provide a yellow and/or red clearance interval between the FYA and a lagging green arrow because there are no benefits but merely more lost time; (2) provide yellow and red clearance between a green and the start of the FYA. A minimum of 1.5 to 2.5 seconds of red is desirable. The reason is that left-turn drivers will fail to yield after the steady yellow in absence of an all-red interval (*Deskins, 2009*).

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CHAPTER 3: SURVEY

To collect information about current practices and implementation of FYA signal displays with PPLT operation, two surveys were developed and conducted in this chapter: 1) survey of traffic engineers and 2) survey of general motorists.

The organization of this chapter is as follows: First, the results of the survey of traffic engineers are presented, which aims to collect information from nationwide professional community for future implementation of FYA in Texas. Then, the results of the survey of drivers were described, which gathered information about driver understanding of FYA indications.

3.1. SURVEY OF TRAFFIC ENGINEERS

3.1.1 Survey Design

The survey of traffic engineers was designed to solicit information about current practices on the implementation of FYA PPLT displays from nationwide professional community. The survey includes three groups of questions:

I) Current practices regarding installation of FYA (for engineers who have FYA displays implemented in their jurisdictions)

II) General questions for permissive left-turn signal indications (for engineers who do not have FYA displays implemented in their jurisdictions)

III) General questions for FYA indications (for all the participating engineers)

Traffic engineers who have experienced installation of FYA displays were required to finish the questions in Part I and Part III; while the traffic engineers who do not have any experience in installation of FYA, were required to finish Part II and Part III.

Part I includes questions on (a) current problems with PPLT operations, (b) the best signal sequence and signal control mode compatible with FYA displays, (c) supplementary sign installed with FYA displays, (d) criteria in use for warranting FYA displays, and (e) hardware and software issues on deployment of FYA displays.

Part II aims to identify (a) left-turn signal indication in use, (b) opinions of traffic engineers regarding FYA displays, and (c) the current problems with left-turn operations.

Part III includes three questions covering issues on FYA safety performance, and current practices to improve driver understanding of this relatively new left-turn signal indication.

The survey results will be summarized in the following Section 3.1.2.

3.1.2 Results of Survey of Traffic Engineers

A web-based survey was conducted from May 25 to June 7, 2010. The survey was sent to the traffic engineers working at peer state Departments of Transportation (DOTs). In addition, the survey was also sent to TxDOT district engineers through emails by Project Director, Mr. Henry Wickes, P.E.

Finally, a total of 37 survey responses were received, among which 33 respondents completed all the questions. Based on the responses received, the research team presents the summarized results as follows.

PART I: Current Practices Regarding Installation of FYA

A total of 11 questions are included in Part I.

Question 1: Approximately how many locations in your jurisdiction have been installed FYA?

In all, 13 responses were received as summarized in Table 3-1.

Table 3-1: Number of FYA Displays Installed in Responding Agencies

Locations	Number of locations with FYA installed
Scottsdale, Arizona	2
Charlotte, NC	28
Beaverton, OR	20+
Coeur d'Alene, ID	10
Yakima, WA	2
Frankfort, KY	21
Salem, OR	150
Salt Lake City, UT	2
Colorado (city unspecified)	10
Carson City, NV	10
Clearwater, FL	1
Total	**256+**

Question 2: What are the existing guidelines used for designing and installing FYA in your jurisdiction?

In all, 19 respondents stated that they had or referenced existing guidelines for designing and installing FYA. Some representative guidelines or "rules-of-thumb" are listed as follows:

- Follow the provisions in the MUTCD *(Charlotte, NC; Colorado).*
- All new installations of PPLT and single-lane protected-only left-turn phases shall receive an FYA, if the controller at the intersection can operate it (*Charlotte, NC*).
- Use FYA to replace old five-section PPLT signal heads. Note that the PPLT operation is used during certain times of day for the selected locations *(Charlotte, NC).*

Question 3: What is your overall opinion on FYA display?

This is a multiple-choice question. Figure 3-1 presents the survey results.

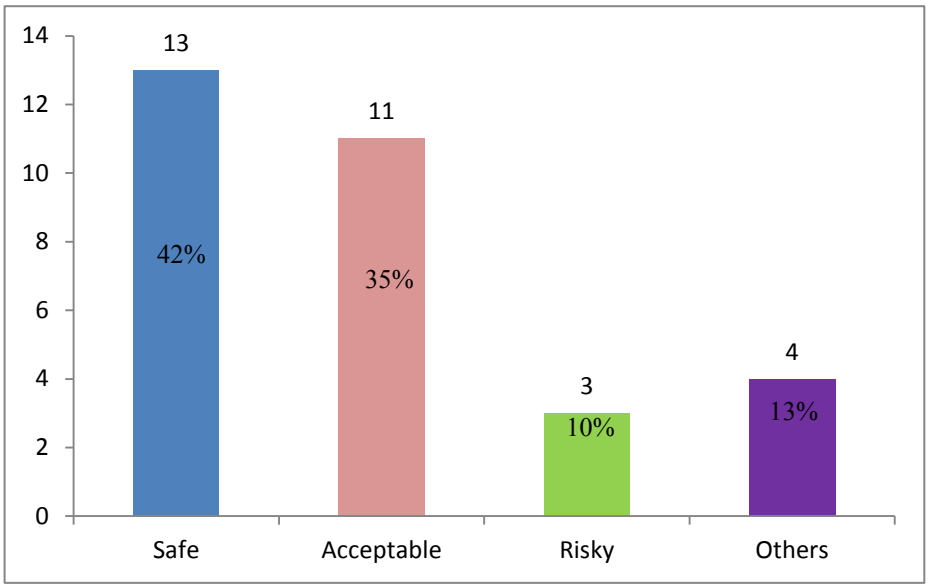


Figure 3-1: Overall Opinions on FYA Displays

Note that for the option "Others," some traffic engineers (*Beaverton, OR; Clearwater, FL*) specified that an FYA display is safe only if drivers can understand the operation.

Question 4: In your opinion, what are the major advantages and disadvantages of using FYA left-turn signal display?

Totally, 17 responses were received for this question, and the major comments are summarized below:

Advantages:

- FYA can be well understood by motorists. The use of FYA can make it additionally clear for drivers that the left turn is acceptable but to use caution.
- FYA can improve intersection operational efficiency. Use of FYA can increase intersection capacity due to the extended permissive left-turn phases. Thus, it can reduce signal cycle length and intersection delay.
- FYA can improve intersection safety. FYA indications eliminate confusion associated with CG indications and left-turn yellow traps. Four respondents stated that FYA indications reduced crashes compared to a five-section "doghouse" signal head. In addition, one respondent reported that, at locations that have left turns crossing Railroad

(RR) track or Light Rail Transit (LRT) tracks, FYA displays show a good performance to eliminate left-turn yellow trap *(Charlotte, NC)*.

- FYA can provide more flexibility in signal timing. It can provide protected left-turn movement during peak hours and permissive during off-peak hours if desired.

Disadvantages:

- Drivers' confusion. FYA is new to drivers, and anything new is a little confusing to motorists. Drivers have to be well educated before use.
- Equipment requirements. It will require some equipment replacement and modification to implement FYA. For example, it requires longer mast arm centered over left-turn lanes.
- Pedestrian safety. One respondent reported that it imposes hazards on pedestrian movement if an FYA display for permissive left-turn movement is turned on shortly after the pedestrian signal turns green.

Question 5: What is the best signal sequence for using FYA displays?

A total of 15 respondents answered this question, and 8 of them believe the signal sequence is irrelevant to the use of FYA display, as presented in Figure 3-2.

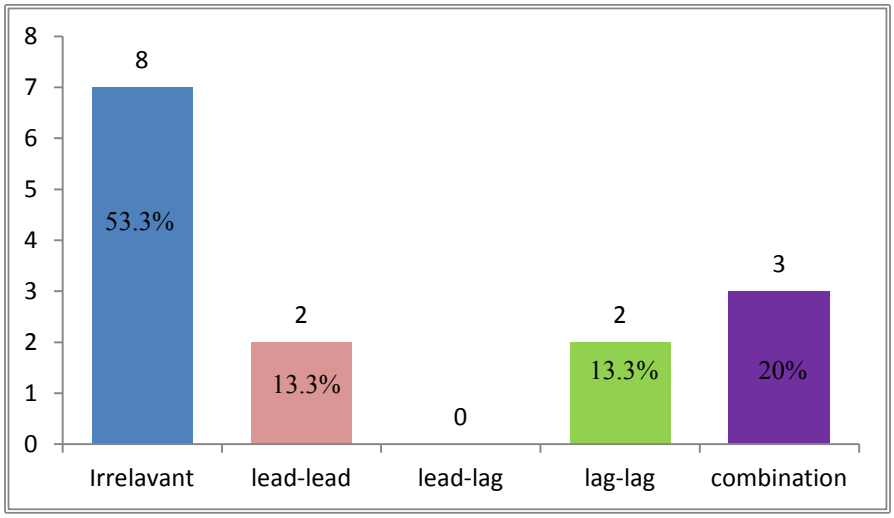


Figure 3-2: Survey Results for Signal Sequence Best Compatible with FYA Displays

Question 6: What is the best left-turn control mode for using FYA display?

This question received 15 responses and 53% of respondents believed that PPLT is the best mode for using FYA displays. The results are presented in Figure 3-3.

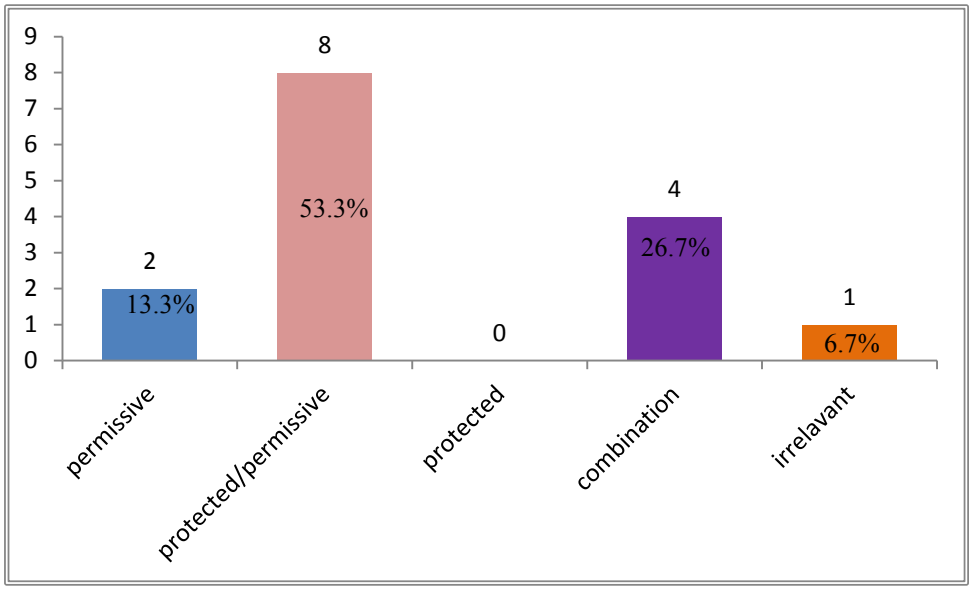


Figure 3-3: Results for Left Turn Control Mode Best Compatible with FYA Display

Question 7: Were there any studies performed to evaluate the safety of the intersections after installing FYA? If yes, please provide a brief description of the major results?

A total of 17 respondents answered this question, and 8 respondents indicated that related studies had been performed in their jurisdictions. However, FYA displays were newly installed at most locations, and most of the studies were still ongoing. Two agencies (*City of Scottsdale, Arizona; Colorado*) reported that after the FYA installations, accidents involving left turns were significantly reduced based on crash data.

Question 8: Is there any supplementary sign installed at the intersection with FYA indication? Do you think a supplementary sign is necesssary or not?

In all, 16 respondents answered this question. Ten respondents claimed that they did not have any supplementary sign installed at the intersections with FYA indication, as six of the ten respondents thought that signs are confusing to most drivers. Two agencies did not use any sign because the FYA installations were at FHWA testing phase, and they were not allowed to install a sign at that stage. As presented in Figure 3-4, six respondents stated that sign installation is a good idea for first implementation.

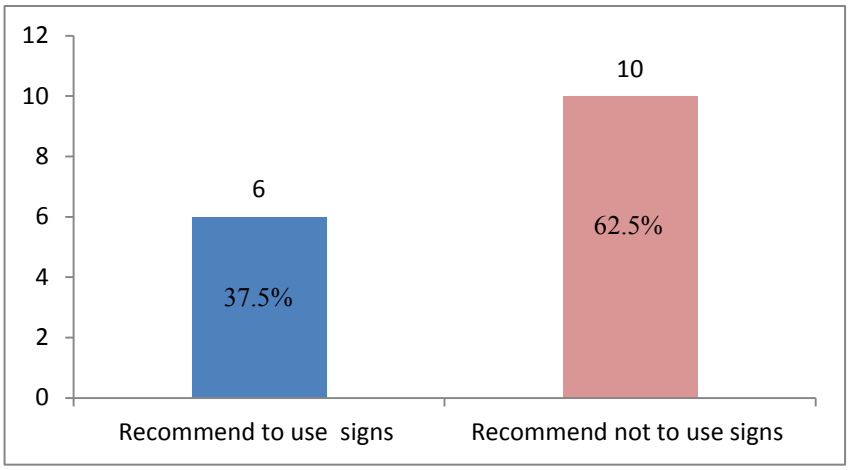


Figure 3-4: Traffic Engineer Opinions on Use of Supplementary Signs

Question 9: What are the criteria used for selecting intersections to install FYA signal display in your jurisdiction?

This is a multiple-choice question, and sixteen respondents answered this question. The survey lists the following five options. The results are presented in Figure 3-5.

A: The existing hardware conditions are good for installing FYA

(Please specify _____)

B: There is a high rate of permissive left-turn related accidents

C: High left-turn volume/traffic volume at the intersection

D: Random selection

E: Others (please specify_____)

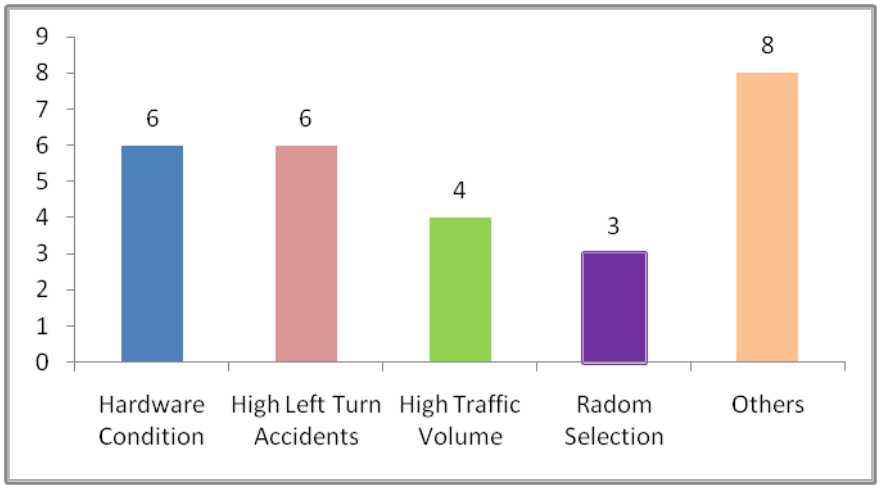


Figure 3-5: Criteria in Use for Selecting Intersections to Install FYA Displays

There is no consensus among the responding agencies, as they are motivated by various reasons to install FYA displays. The main reasons for using FYA include the existing hardware conditions and left-turn related safety concerns. The respondents also provided following concerns in selecting intersections to install FYA signal display:

- Existing mast arm length and conduit condition are factors that need to be considered when selecting intersections.
- Speed limit is also a key factor that affects the intersection selection, for example, the City of Beaverton, OR chooses to install FYA display at intersections with a speed limit below 40 mph.

Question 10: Which kind of problems do you have in implementation of FYA indication?

This question is to identify related hardware and software issues on installing FYA. Eleven responses were received, and the results are summarized as follows:

Controller:

- New types of controller, such as a 2070 controller, can work with FYA display very well.
- A 170 controller with wapiti (firmware for the traffic controller) works with FYA display.

- Old controllers (Eagle M40 and Econolite ASC/2) cannot work with FYA display easily, and the agencies in Salt Lake City, UT, upgraded controller to Eagle M50 and Econolite ASC/3 to install FYA.

Conflict monitor/MMU:

- MMUs need to have enough channels; otherwise it will become a problem when there are lots of signal phases.
- Old MMUs may have problems with the use of FYA. One agency (*Salt Lake City, Utah*) has upgraded their MMUs to smart MMU in order to drive FYA.
- MMU 16 Eip can work well with FYA display.

Signal head:

- Installation of four-section signal heads (to replace five-section dog house) may need to raise wire spans.
- FYA signal heads need to be centered over the left-turn lane, thus, it requires a long mast arm.
- Additional conductor might be needed.

Software:

- Old W4IKS software (for 170 controller) does not easily run FYA display. The new W4IKS for 170-HC-11 controller is able to drive FYA.

Question 11: Are there any valuable experiences or suggestions on installation of FYA can be shared with us?

Nine responses were received for this question, which were summarized as follows:

- Public awareness and education is important for successful implementation of FYA signal display.
- Do not install any of the three-section FYA head that contains a dual-arrow signal section, because of the inability of certain color blind males (2% of male population) to

distinguish between green arrow and FYA in the same section of a three-section FYA head (please see Figure 3-6).

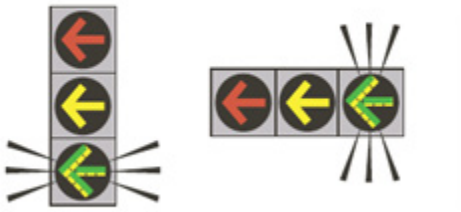


Figure 3-6: Three-Section FYA Signal Heads for PPLT

Additionally, some suggestions for FYA indications were received as follows:

- Install the four-section signal head at first and operate it as three-section RYG signal head to let people know it is going to be implemented soon.
- Test MMU and signal timing on a test signal head before install them in the field for the FYA displays.

PART II: General Questions for Permissive Left-Turn Operation

This part aims to survey traffic engineers who do not have FYA installed in their jurisdictions. Totally, four questions are presented in this part to identify problems regarding left-turn operations, and to collect these traffic engineers' opinions on FYA indications.

Question 1: What do you currently use for indicating a permissive left-turn in protected-permissive left turn (PPLT) control mode?

This is a multiple-choice question. A total of 27 traffic engineers responded to this question. A vast majority of permissive left-turn signal indications in use is "circular green (CG)," while flashing yellow ball has also been reported in use for permissive left turns, as shown in Figure 3-7.

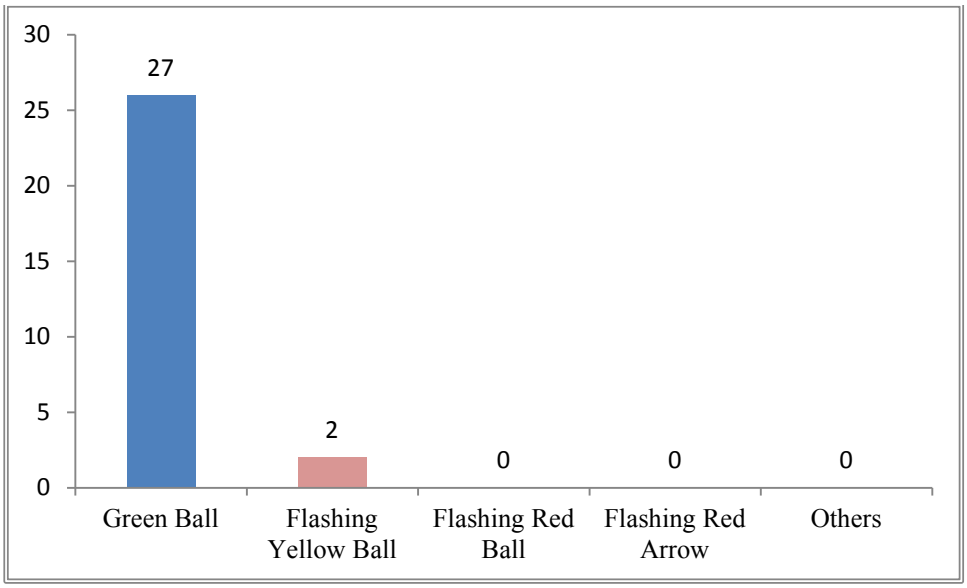


Figure 3-7: Permissive Left-Turn Indications in Use Other Than FYA for PPLT

Question 2: Have you ever considered installing FYA for the intersections with PPLT signal control mode in your jurisdiction?

A total of 15 out of 23 (65%) respondents answered "No" to this question.

Question 3: If no, what's your major concern?

The question is designed to collect the reasons why the traffic engineers "choose to be conservative" in using the new signal display. This multiple-choice question is provided in conjunction to Question 2, and all the options are listed as follows:

A: Unfamiliar with FYA indication

B: FYA can cause drivers' confusion and other risks

C: Expensive to install FYA

D: Other (please specify_____)

Totally, 15 respondents answered this question, and the results are presented in Figure 3-8.

About 43% of the traffic engineers who have not ever considered FYA display are unfamiliar with FYA displays. Another main reason is that 32% of them believe that FYA may cause confusion to motorists.

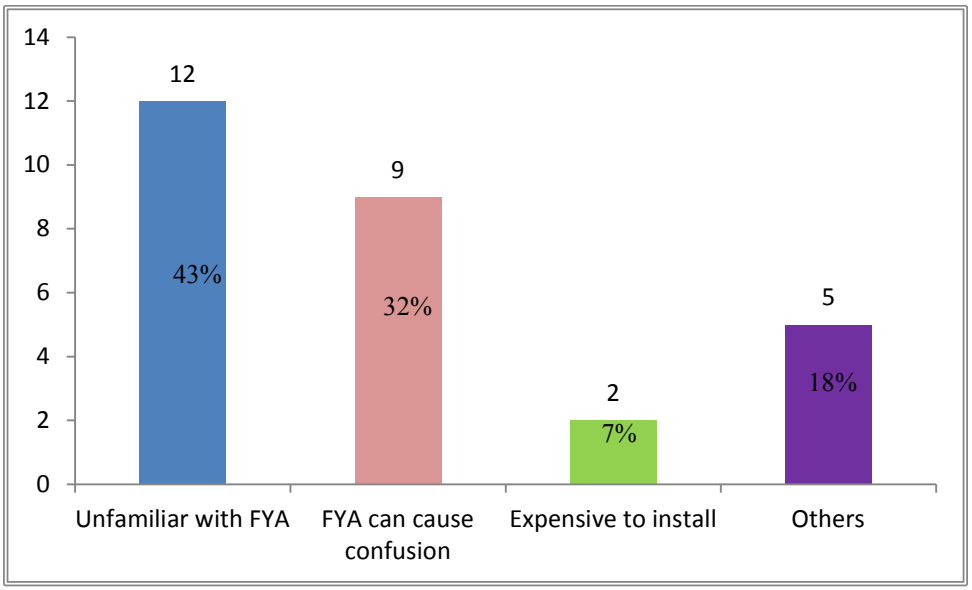


Figure 3-8: Reasons for Not Using FYA Permissive Left-Turn Indications

Question 4: Do you find any problems in left-turn operations at the signalized intersections in your jurisdiction? If yes, please specify.

A total of 27 respondents answered this question. The major problems are reported as follows:

- The five-section signal seems to still confuse some drivers.
- Drivers tend to misjudge gaps for permissive left-turn maneuvers.
- Permissive left-turn capacity is significantly reduced during periods of high through volumes. Left-turn queue spillback may block adjacent through traffic.

PART III: General Questions for FYA Permissive Left-turn Indications

This part of survey is designed for all the engineers surveyed. The purpose is to collect information from traffic engineers on expected safety performance of FYA display, and on how to improve driver understanding of FYA indications.

Question 1: Do you think FYA indications for permissive left-turn movement can improve intersection safety? Do you have any evidence to support your opinion?

Totally, 32 respondents answered this question. As shown in Figure 3-9, majority of respondents thought FYA indications can improve traffic safety; while 3 respondents hold negative viewpoint on safety impacts of FYA. There are also 9 respondents being neutral on this issue.

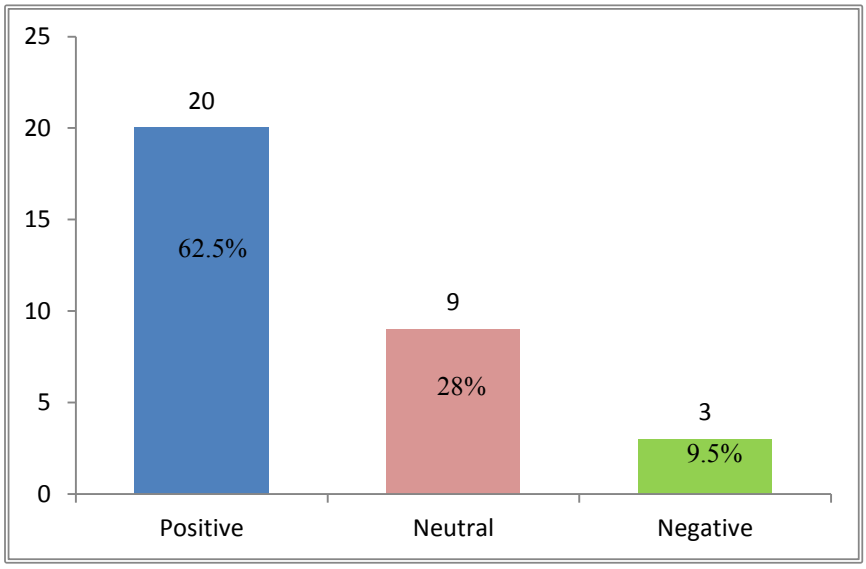


Figure 3-9: Impacts of FYA Indications on Intersection Traffic Safety

The major evidences provided to support that FYA display can improve intersection safety are summarized as follows:

- FYA indications may cause people to pay more attention, and are even more distinctive than a 'dog house' signal.
- There was a significant reduction in collisions involving left turns at the two intersections at Scottsdale, AZ, installed with FYA displays.

Those respondents who had a neutral opinion on FYA also provided their concerns with FYA display:

- Any time when something new is implemented to traffic control, there is a large learning curve. So education of the traveling public is critical.

One respondent, who do not believe that FYA will improve intersection safety, stated that the current study on the safety performance of FYA have limited sample sizes and did not fully take into account of all the influencing factors, including:

- Changing traffic volumes,
- Maturing drivers in an area,
- Nearby traffic generators,
- Roadway improvements,
- Traffic signal equipment and timing improvements,
- Lighting improvements,
- Red-light runner enforcement cameras, and
- Other factors that can be affecting the intersection safety.

Question 2: FYA is a relatively new type of signal indication, and is unfamiliar to many drivers; how to improve driver understanding of FYA indications?

Totally, 36 respondents answered this multi-choice question, and the results are shown in Figure 3-10. The respondents also provided many other ways to improve driver understanding of FYA indications, which includes:

- Media, including television, newspaper, webpage, and radio.
- Drivers' license handbook, public education training, and public service announcements.
- Electronic blank-out sign/extinguishable message sign.

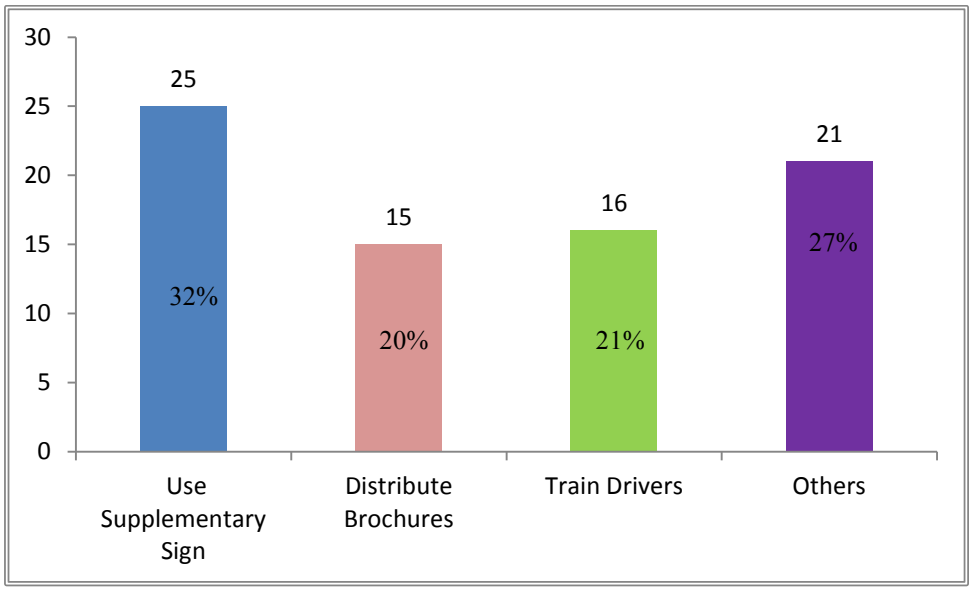


Figure 3-10: Suggested Ways to Improve Driver Understanding of FYA Indications

Question 3: If a supplementary sign will be used with the FYA, which one do you prefer?

A

B

C

This question is also presented in the survey of drivers. Figure 3-11 shows the survey results. No consensus was reached among the 28 responding traffic engineers on this issue.

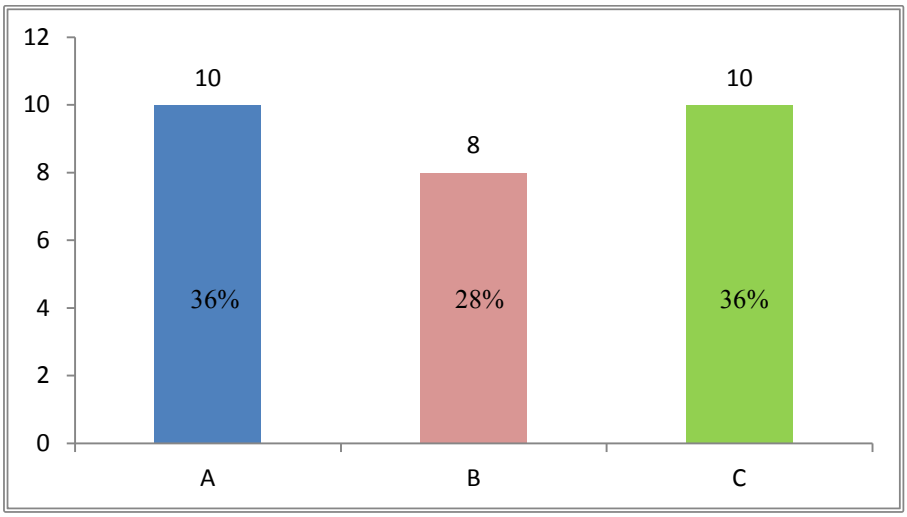


Figure 3-11: Preference of Traffic Engineers on Candidate Supplementary Signs

3.2. SURVEY OF GENERAL MOTORISTS

In addition to the survey of traffic engineers, the research team designed a survey for drivers. The survey aimed to evaluate driver understanding of the new permissive left-turn indication - FYA. The draft survey got the approval from the PMC prior to finalizing a version for distribution. After the PMC reviewed and approved the contents of the survey, the research group distributed it to randomly selected, local drivers in Houston, Texas.

3.2.1 Survey Structure

The survey of drivers includes two parts. The first part is to collect demographic information of the participating drivers, including driving experience and driver age range; while the second part is to evaluate driver understanding of FYA permissive left-turn indication.

3.2.2 Results of Survey of General Motorists

The survey was conducted during May 10-22, 2010. The research group distributed the survey forms to randomly selected drivers at the parking lots around Texas Southern University and Medical Center Area in Houston. Finally, 126 survey responses were received. Based on the survey responses received, the research team summarized the survey results as follows.

PART I: Driver Basic Information

The drivers are divided into four age groups according to the method used in *Mason-Dixon Polling & Research, Inc (2005*) and *Battelle (2004)*. The age distribution of drivers involved in this survey (Figure 3-12) is also compared with the U.S. licensed driver age distribution released in *infoplease.com* (Figure 3-13).

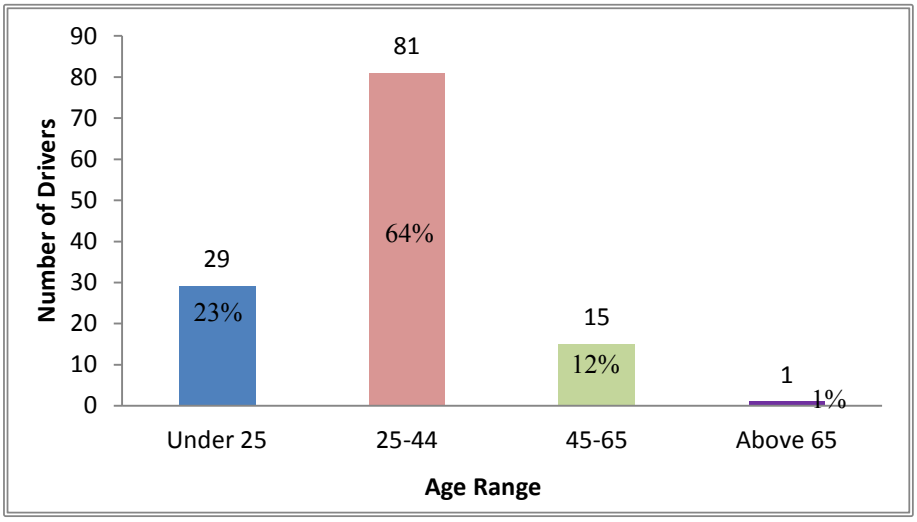


Figure 3-12: Age Distribution of Participating Drivers

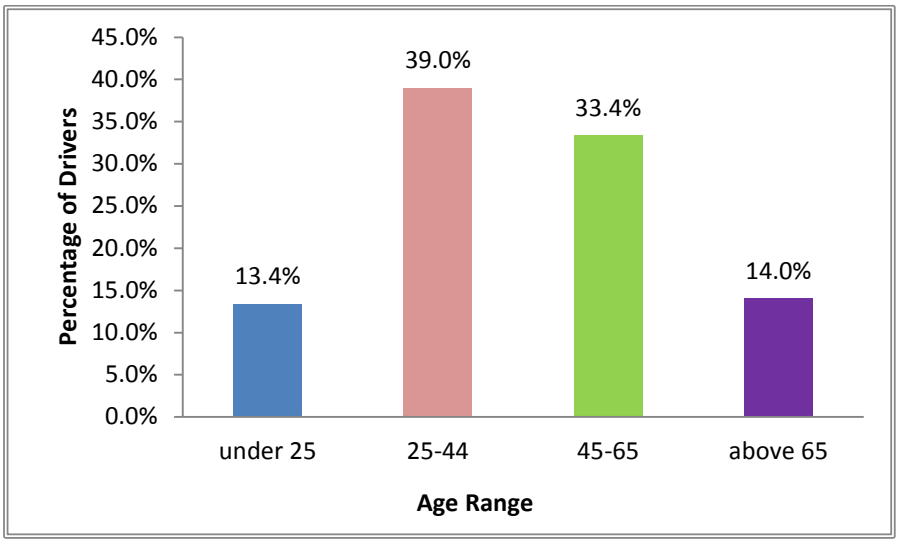


Figure 3-13: Age Distribution of U.S. Licensed Drivers

The driving experience distribution of participating drivers is shown in Figure 3-14.

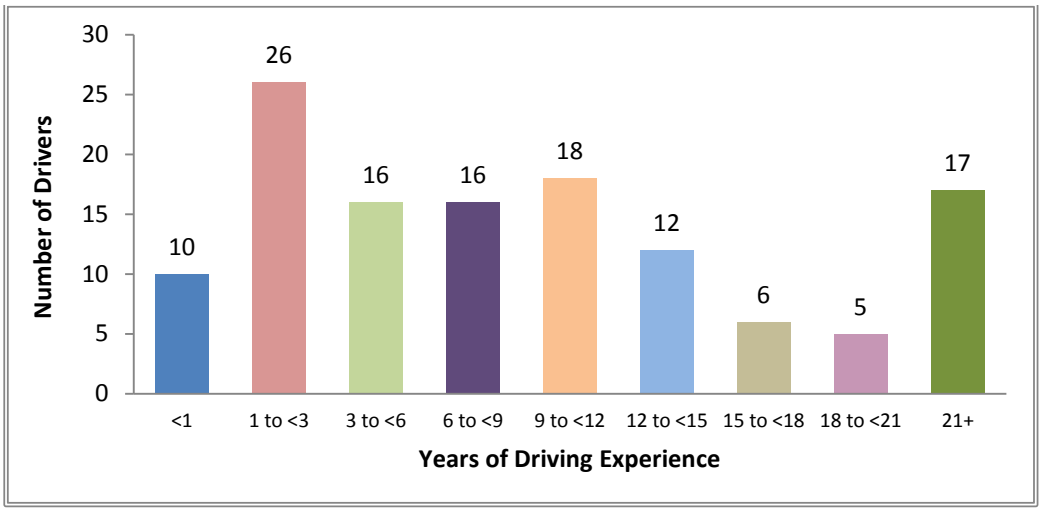


Figure 3-14: Driving Experience Distribution of Participating Drivers

PART II: Driver Understanding of FYA Permissive Left-Turn Indications

Three questions are included in this part.

Question 1: Select the most appropriate meaning for each of the following traffic signal indications?

A. *Stop*

B. *Prepare to stop*

C. *Left turn after yielding to any oncoming traffic and pedestrians*

D. *Go (you have the right-of-way)*

E. *Others*

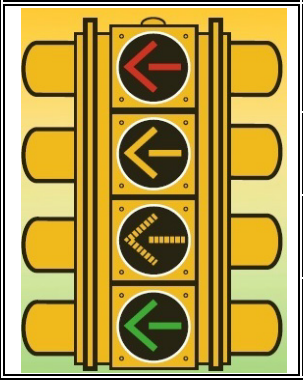
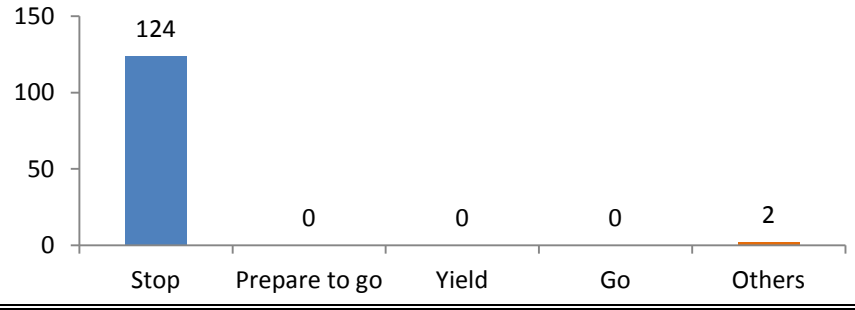
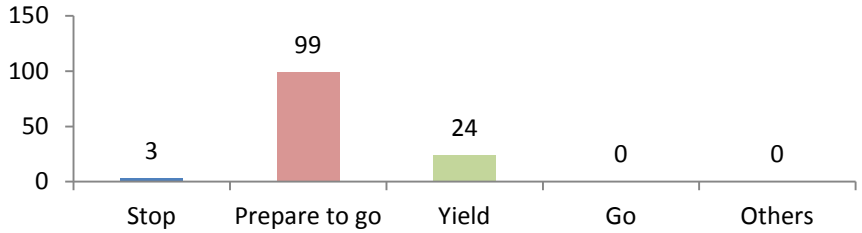
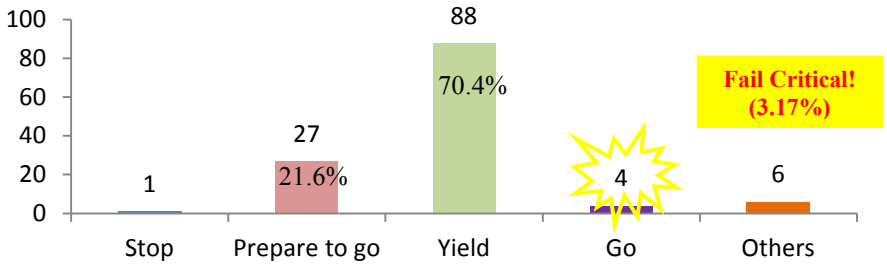
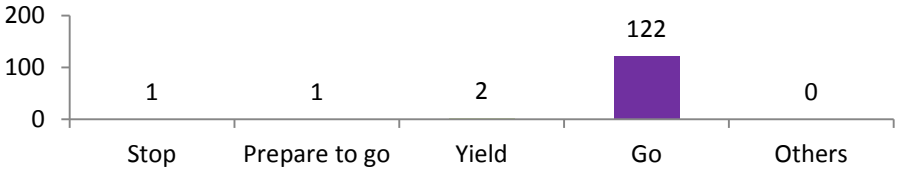
Ilustration	Traffic Signal	Meaning
	Steady Red Arrow	_____
	Steady Yellow Arrow	_____
	Flashing Yellow Arrow	_____
	Steady Green Arrow	_____

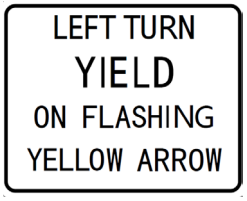
Table 3-2 shows the survey responses of the participating drivers. The FYA indication is well understood by most of drivers with a high correct response rate up to 92%. Only 3.17% of the drivers had "fail critical" responses, which may result in crashes due to mistaking the signal indicating "Yield" for "Go," As defined by *Knodler et al. (2002)*, the "fail critical" event means a type of incorrect responses to permissive indication, as a result of which drivers impede the opposing traffic, and are exposed to the potential of a crash. The results generally demonstrate that traveling public are quite knowledgeable on this new type of permissive left-turn indication.

Table 3-2: Driver Understanding of Left-Turn Signal Indications

Item	Traffic Signal	Distribution of Responses
A	Steady Red Arrow	
B	Steady Yellow Arrow	
C	**Flashing Yellow Arrow**	
D	Steady Green Arrow	

Question 2: In your opinion, which sign best explains the Flashing Yellow Arrow, and will most likely help you understand?

A



B

C

Totally, we got 124 responses from surveyed drivers for this question. Figure 3-15 shows the results of their preference on supplementary signs to FYA indications.

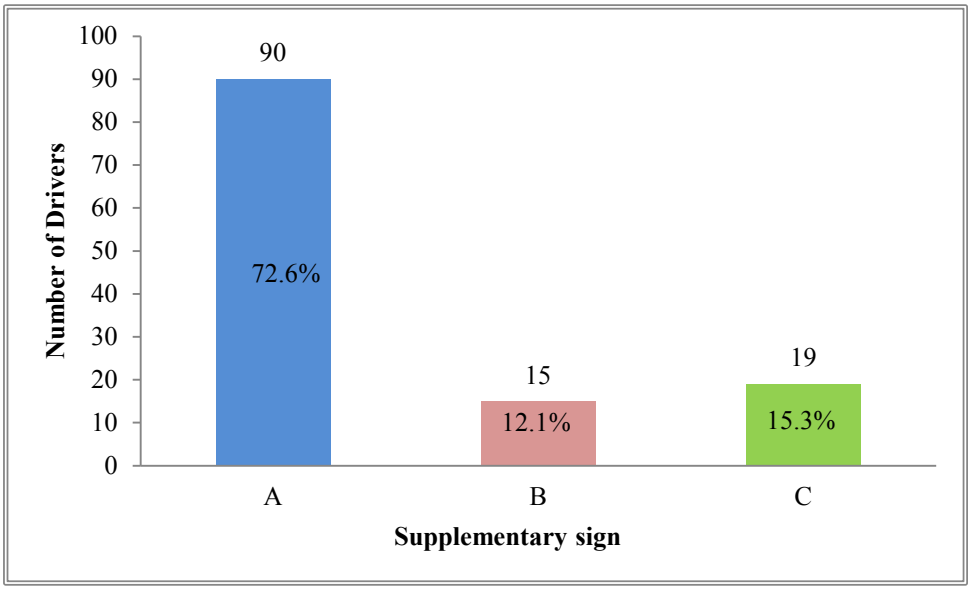
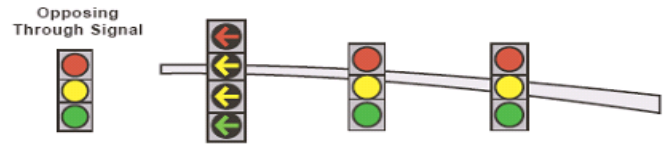
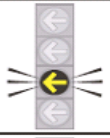
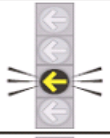
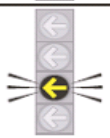
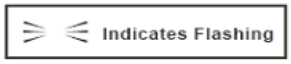


Figure 3-15: Preference of general motorist on candidate supplementary signs

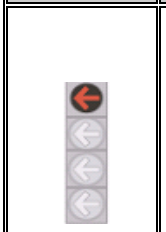
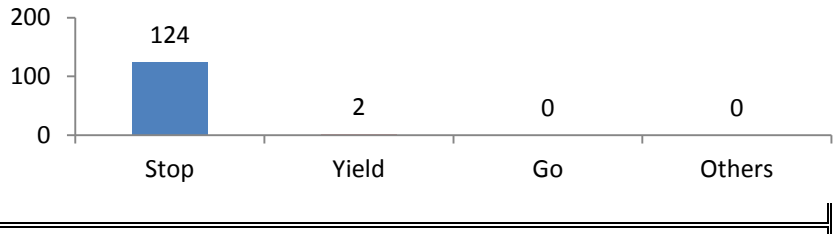
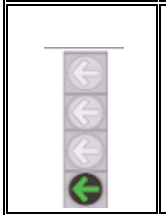
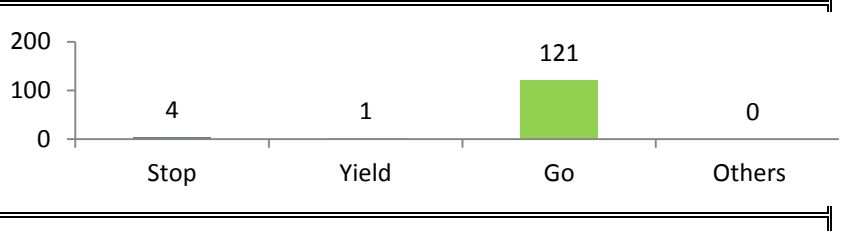
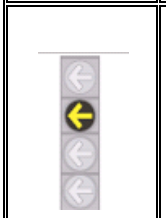
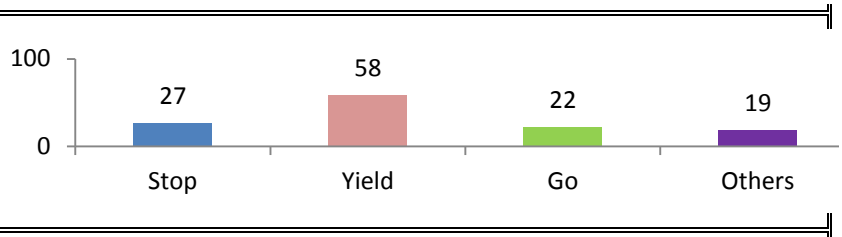
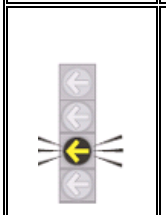
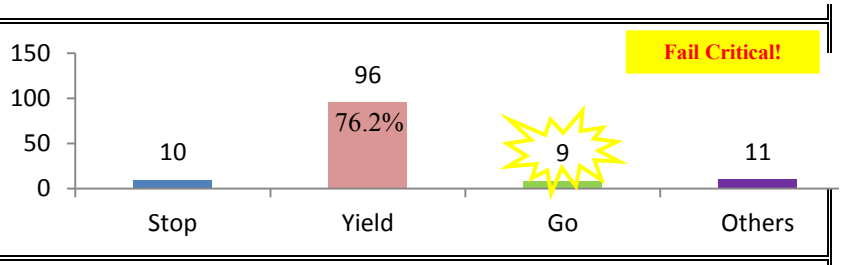
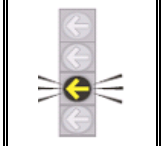
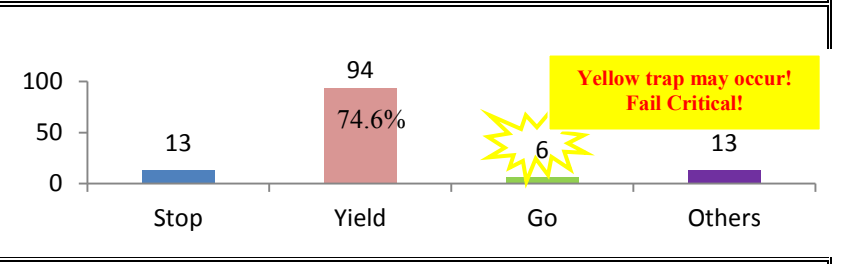
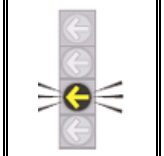
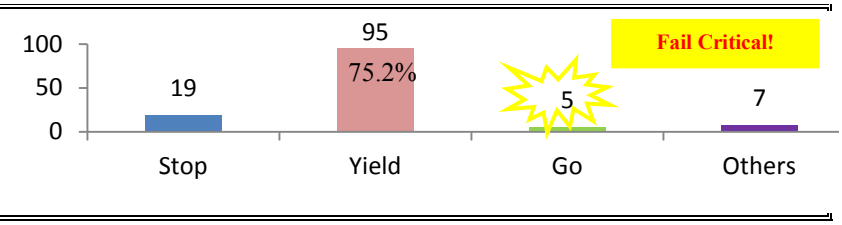
Question 3: Please mark your response to the various situations assuming you are making a left-turn maneuver:

Opposing Trough Signal	Left-Turn Traffic Light	Adjacent Traffic Light	<u>Your Response</u> Assuming You Are Making a Left Turn
			
1		 All Red	Stop __Yield___ Go___ Others_____
2		 Protected Left-Turn	Stop __Yield___ Go___ Others_____
3		 Change Interval (End Protected Left-Turn)	Stop __Yield___ Go___ Others_____
4		 Permissive Phase	Stop __Yield___ Go___ Others_____
5		 Through Traffic Change Interval	Stop __Yield___ Go___ Others_____
6		 Opposing Through Phase Still Running	Stop __Yield___ Go___ Others_____
			

Question 3 provides FYA signal indications on a complete signal cycle basis, and also displayed the signal indications for adjacent through traffic. If any response to Sections 4-6 in the table belongs to fail-critical response, the respondent will be counted. Finally, the fail-critical response rate of FYA in Question 3 is 11.9%. Compared with the fail-critical response rate of 3.17% in Question 1, the higher fail-critical rate in Question 3 indicated that drivers might be more confused about FYA in a more realistic experimental setting where they can see the left-turn signal head and the through signal head at the same time. Thus, this result indicated that the adjacent through traffic signal light may have negative effects on driver understanding of left-turn FYA signal display.

According to the survey, 7.14% of the drivers stated that they would "go" with a circular-green indication for the adjacent through traffic; 3.97% would "go" with a red-ball on for the adjacent through traffic; and 4.76% choose to "go" with a yellow-ball indication for adjacent through. Thus, more drivers will give fail-critical responses when the adjacent through light is green. This may be due to the fact that some drivers are not familiar with the FYA indication, and chose the incorrect responses when first exposed to the FYA indication.

Table 3-3: Driver Responses to Various Left-Turn Signal Displays

Left-Turn Indication	Adjacent Traffic Indication	Distribution of Responses
		
		
		
		
		
		

3.3 SUMMARY

3.3.1 Major Findings from Nationwide Survey of Traffic Engineers

The major findings from the survey are summarized as follows:

- Of all the participating traffic engineers, about 62.5% expect positive impacts of FYA permissive left-turn indications on intersection traffic safety.
- For the surveyed traffic engineers who have experience in installation of FYA, 42% think that their implementation achieved satisfied results, while 35% of them rate their implementation as "acceptable," Only 10% of the engineers think it risky to use FYA display.
- The major concerns regarding the use of FYA displays include drivers' confusion, equipment requirements and pedestrian safety issues.
- More than half of the traffic engineers believe that signal sequence is irrelevant to the application of FYA displays. 53.3% of the experienced traffic engineers maintain that PPLT is the best mode for deploying FYA displays.
- The criteria selecting installation of FYA displays are quite diverse among different responding agencies. The major considerations center on existing hardware conditions and high left-turn crash rates.
- Valuable information has been collected associated with controller, conflict monitor/MMU, signal head, and software. The lessons learned have also been reported; for example, three-section FYA signal heads should not be used.
- For the traffic engineers who have not ever considered installation of FYA, 43% are unfamiliar with FYA displays, while 35% of them believe that FYA may cause confusion to drivers.

3.3.2 Major Findings from Survey of General Motorists

Overall, an FYA display has a good performance in term of driver comprehension. What follows are the key findings from the survey:

- FYA indications are well understood by most of the drivers, and presented a high correct response rate up to 92%.
- Drivers can understand FYA indications, as only 3.17% of the drivers had "fail critical" responses, which may result in crashes due to mistaking the signal indicating "Yield" for "Go."
- If a supplementary sign is need, most drivers like a sign including an FYA symbol more than a sign with word message only.
- The adjacent through traffic signal may have impacts on drivers' understanding of FYA indication, as the fail-critical response rate was up to 11.9% where they can see both the left-turn signal head and the through signal head at the same time. It indicates that visibility-limited signal head (such as louvered signal head) may be needed for the adjacent through-movement lens at the intersection with FYA left-turn displays. In addition, the public awareness and education is an vital part of the installation process of FYA signals.

CHAPTER 4: FIELD TESTS

In this project, field tests were conducted for two purposes: (1) to collect field traffic conflict data for evaluating the safety performance of FYA PPLT (as presented in Chapter 5), and (2) to identify software and hardware issues that may possibly be experienced during future implementation of FYA PPLT. The field tests were phased to two stages. Stage I field test was performed at three signalized intersections in Waco District, and Stage II field test was performed at two signalized intersections in Austin District.

This chapter is organized as follows: first, a field study plan was presented, which was followed by a description of the field data collection. Then, the implementation of FYA at the five intersections was summarized. Finally, software and hardware issues encountered and the solutions used during the field tests were elaborated.

4.1 PLANS FOR FIELD TESTS

4.1.1 Criteria for Selecting Study Sites

A total of 5 intersections were selected for Stages I and II field tests. The criteria for candidate study locations included:

- The left-turn signal timing is in PPLT mode with various phasing sequences (lead-lead, lead-lag, or lag-lag);
- The left-turn related accident rates are relatively high;
- No FYA has been installed in any nearby intersections so far; and
- The 5 intersections cover a spectrum of geometric and traffic conditions.

4.1.2 Selected Study Sites

Based on these criteria, three intersections in Bellmead, TX (Waco District), were selected for Stage I field test, and two intersections in Austin, TX (Austin District), were selected for Stage II field test. Detailed information regarding these intersections is summarized in Tables 4-1.

Table 4-1: Five Intersections in Stages I and II Field Tests

Intersection	Direction	Left-Turn Control Mode	Left-Turn Phase Sequence	Average Left-Turn Volume* (vph)	Average Through Volume* (vph)	Posted Speed Limit (mph)
US 84 & Maxfield, Bellmead	US 84	PPLT	Lead/Lag	10	893	30
US 84 & Hogan, Bellmead	US 84	PPLT	Lag/Lag (Lead/Lead)	26	1036	30
US 84 & Ashleman, Bellmead	US 84	PPLT	Lead/Lag	23	897	30
FM 620 & Great Oaks, Austin	FM 620	PPLT	Lead-lag	152	1594	60
FM 2244 & Walsh Tarleton, Austin	FM 2244	PPLT	Lead-lag	216	1422	40
	Walsh Tarleton NB	PPLT	Lead/Lead	192**	72**	40

* The values are the sum of two opposing left turn approaches or two opposing through approaches for the first 4 intersections on US84 and FM620, and the FM2244 direction at the last intersection (FM 2244 & Walsh Tarleton, Austin)

** For Walsh Tarleton direction at the intersection (FM 2244 & Walsh Tarleton, Austin), only NB left-turn and SB through movement on Walsh Tarleton street were collected because only NB installed with FYA signal head.

The detailed conditions of these five locations are summarized and depicted as follows. The related crash history were also compiled and listed below.

Stage I - Intersection 1: US 84 & Hogan Ln., Bellmead, TX

- **Left-turn control mode before FYA installed:** Lag-lag PPLT
- **Left-turn control mode after FYA installed:** Lead-lead PPLT
- **Current left-turn signal head:** Five-section signal heads with a green-ball for permissive left-turns and a "LEFT TURN YIELD ON GREEN" sign
- **FYA left-turn signal head:** Five-section FYA signal heads on both legs of US 84 (with 2 red arrows, equivalent to four-section FYA signal heads)
- **Posted speed limit:** 30 mph
- **Current hardware:** Naztec 900 Series TS 2 controller, EDI-16 MMU
- **Hardware after FYA installed:** Naztec 900 Series TS 2 controller, Naztec 516L MMU
- **Left-turn related crash history:** 9 crashes during 2003-2009 (entire intersection: 57 crashes)

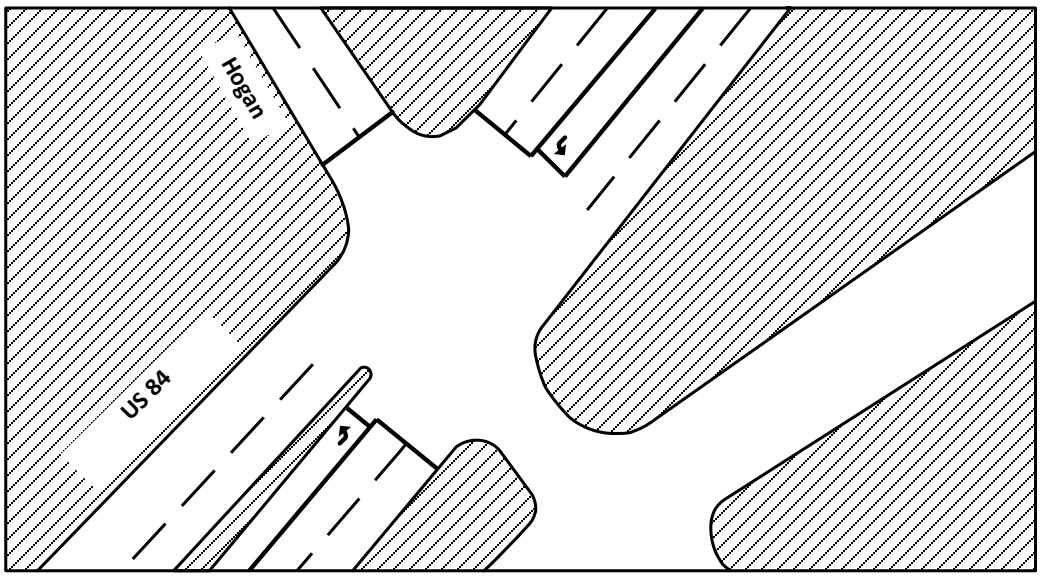


Figure 4-1: US 84 & Hogan, Bellmead, TX

Stage I - Intersection 2: US 84 & Ashleman St., Bellmead, TX

- **Left-turn control mode before FYA installed:** Lead-lag PPLT

- **Left-turn control mode after FYA installed:** Lead-lag PPLT
- **Current left-turn signal head:** Five-section signal heads with a green-ball for permissive left-turns and a "LEFT TURN YIELD ON GREEN" sign
- **FYA left-turn signal head:** Five-section FYA signal heads on both legs of US 84 (with 2 red arrows, equivalent to four-section FYA signal heads)
- **Posted speed limit:** 30 mph
- **Current hardware:** Naztec 900 Series TS 2 controller, EDI-16 MMU
- **Hardware after FYA installed:** Naztec 900 Series TS 2 controller, Naztec 516L MMU
- **Left-turn related crash history:** 1 crash during 2003-2009 (entire intersection: 6 crashes)

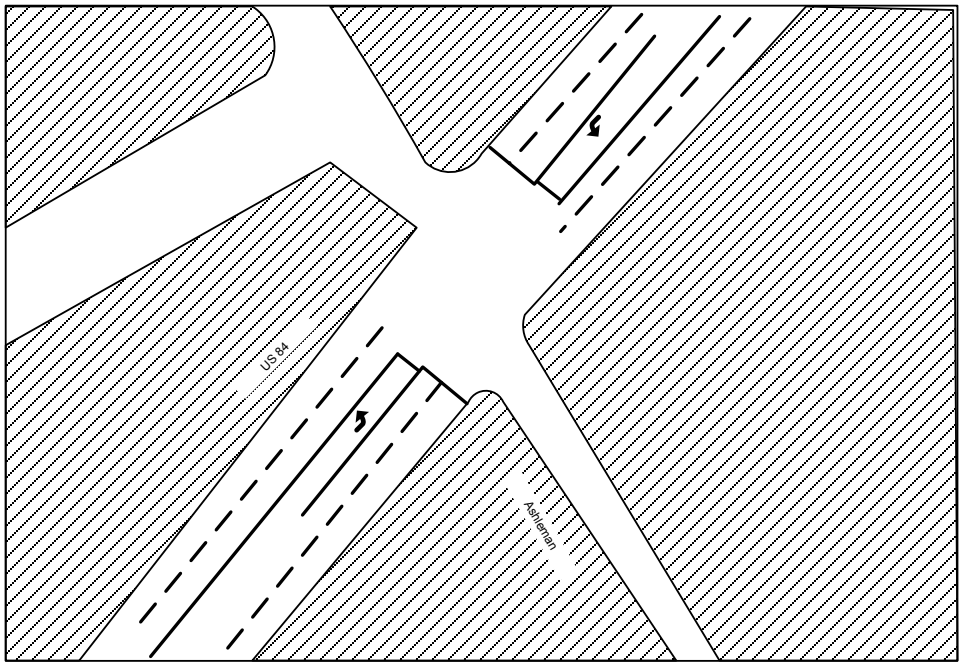


Figure 4-2: US 84 & Ashleman, Bellmead, TX

Stage I - Intersection 3: US 84 & Maxfield, Bellmead, TX

- **Current left-turn control mode:** Lead-lag PPLT
- **Left-turn control mode after FYA installed:** Lead-lag PPLT
- **Current left-turn signal head:** Five-section signal heads with a green-ball for permissive left-turns and a "LEFT TURN YIELD ON GREEN" sign

- **FYA left-turn signal head:** Five-section FYA signal heads on both legs of US 84 (with 2 red arrows, equivalent to four-section FYA signal heads)
- **Posted speed limit:** 30 mph
- **Current hardware:** Naztec 900 Series TS 2 controller, EDI-16 MMU
- **Hardware after FYA installed:** Naztec 900 Series TS 2 controller, Naztec 516L MMU
- **Left-turn related crash history:** 5 crashes during 2003-2009 (entire intersection: 14 crashes)

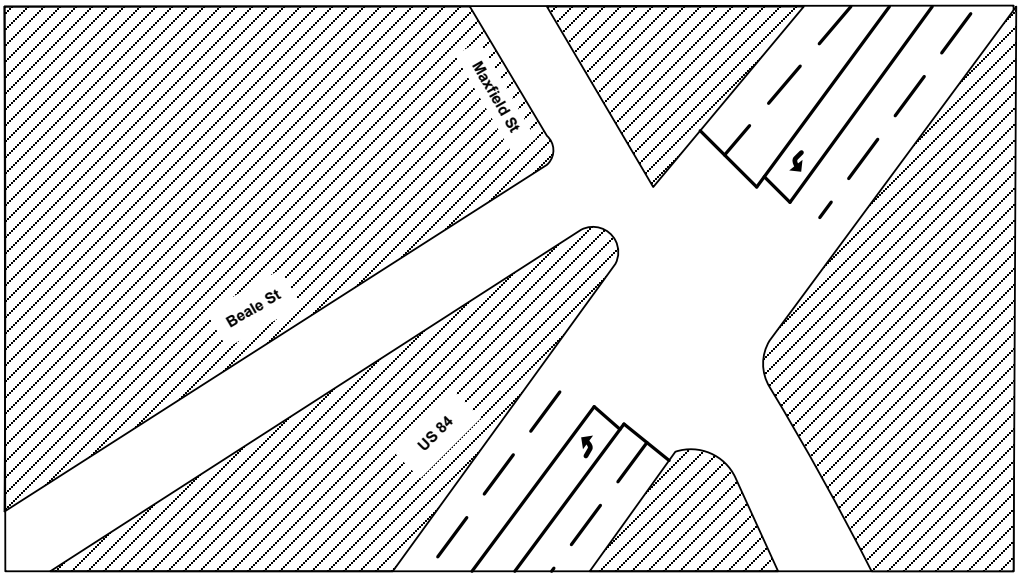


Figure 4-3: US 84 & Maxfield, Bellmead, TX

The three intersections in Bellmead, TX, are neighboring signalized intersections on US 84, since Le Clede St. and Kane St. are 2-way STOP sign controlled. This ensures the consistency of the signal display after the conversion.

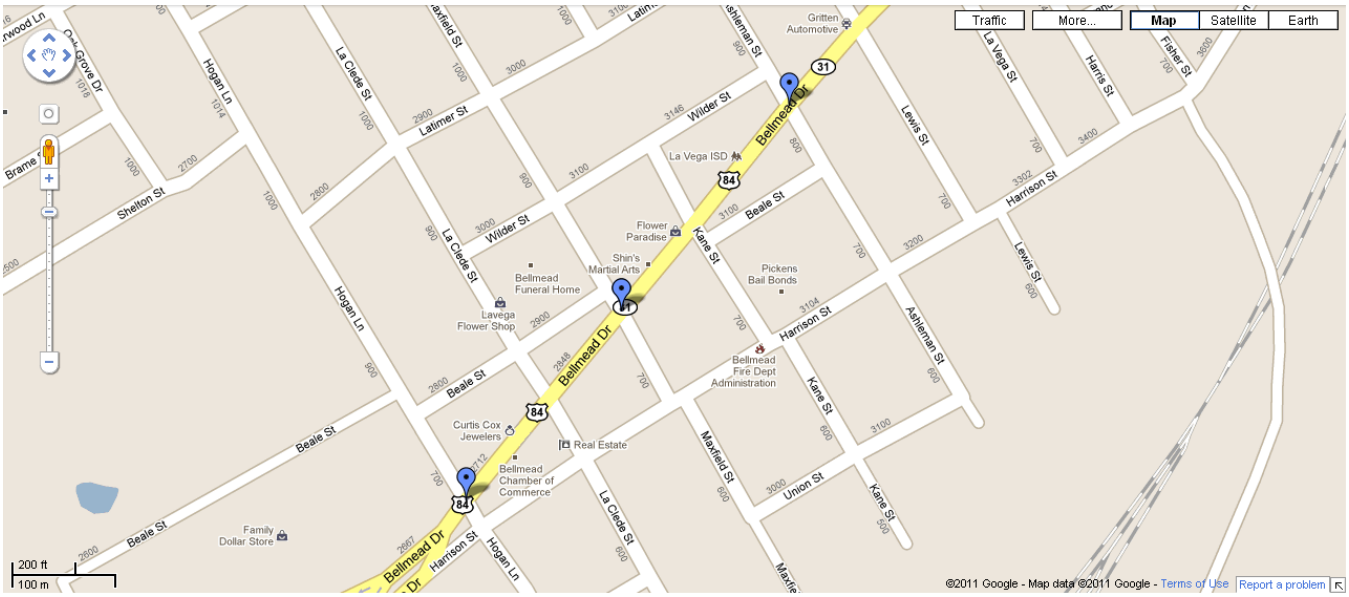


Figure 4-4: Spatial Distribution of Intersections in Stage II Field Test

Stage II - Intersection 1: FM 2244 &Walsh Tarlton Ln, Austin, TX

- **Left-turn control mode before FYA installed:** Lead-lead PPLT
- **Left-turn control mode after FYA installed:** Lead-lead PPLT
- **Current left-turn signal head**: Five-section signal heads with a green-ball for permissive left-turns and a "LEFT TURN YIELD ON GREEN" sign
- **FYA left-turn signal head:** Four-section FYA signal heads on each approach
- **Posted speed limit:** 40 mph
- **Current Hardware:** Econolite ASC-3 controller, EDI 16E MMU
- **Hardware after FYA installed:** Econolite ASC-3 controller, EDI 16LE SmartMonitor
- **Left-turn related crash history:** 2 crashes during 2003-2009 (entire intersection: 8 crashes)

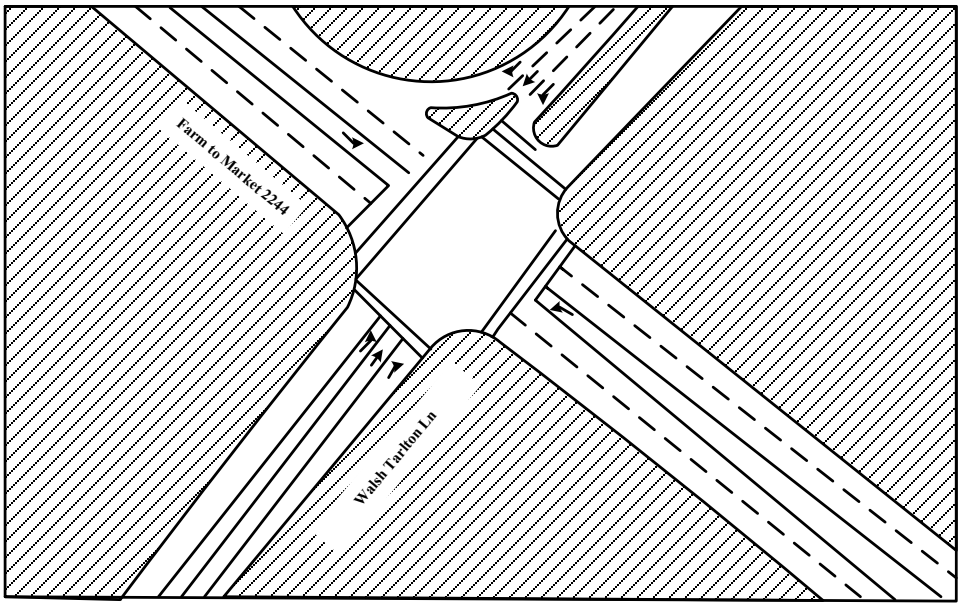


Figure 4-5: FM 2244 & Walsh Tarlton Ln, Austin, TX

Stage II - Intersection 2: FM 620 & Great Oaks, Austin, TX

- **Left-turn control mode before FYA installed:** Lead-lag PPLT
- **Left-turn control mode after FYA installed:** Lead-lag PPLT
- **Current left-turn signal head**: Five-section signal heads with a green-ball for permissive left-turns and a "left turn yield on green" sign
- **FYA left-turn signal head**: Four-section FYA signal heads on both legs of FM 620
- **Posted speed limit:** 60 mph
- **Current hardware:** Econolite ASC-3 controller, EDI 16E MMU
- **Hardware after FYA installed:** Econolite ASC-3 controller, EDI 16LE SmartMonitor
- **Left-turn related crash history:** N/A

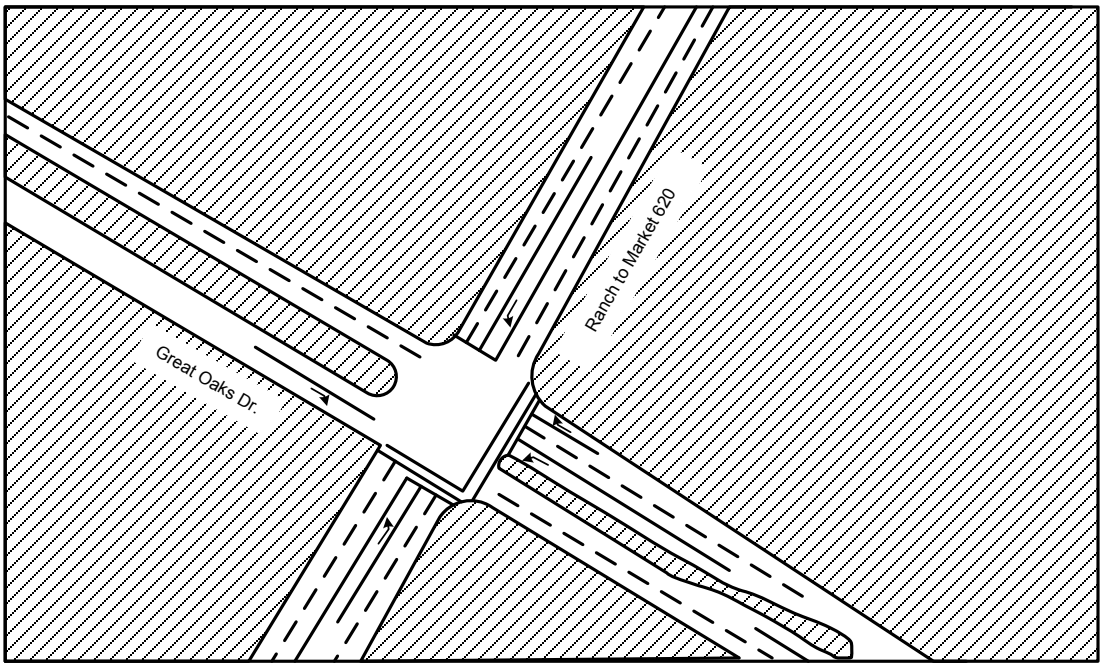


Figure 4-6: FM 620 & Great Oaks, Austin, TX

4.1.3 Plan for Field Traffic Conflict Study

Before-and-after field traffic conflict survey was conducted to investigate the issues in the implementation of FYA PPLT signal display, especially the safety performance of FYA PPLT display.

Periods for Observation

Five-day before FYA installation: The research team observed traffic conflicts and other critical safety events for 5 days before FYA installation. On each day, six-hour field traffic conflict data were collected during 6-9/7-10 AM and 3-6/4-7 PM.

FYA installation: TSU team assisted TxDOT staff to set up FYA signals, and recorded the problems encountered and corresponding solutions.

Five-day after FYA installation: The research team observed traffic conflicts and other critical safety events for 5 days after FYA installation. On each day, six-hour field traffic conflict data were collected during 6-9/7-10 AM and 3-6/4-7 PM.

The research team observed and manually recorded traffic conflicts and other critical safety events. The observers specified the type of the observed conflicts and the time stamps for each of the conflicts and events. The information collected included the following:

Before-and-After Intersection Conditions

- Digital photos of signal heads for each approach
- Lane configuration (e.g,. number of lanes, presence of exclusive left-turn lanes)
- Left-turn phasing (permissive-only, protected-only, or PPLT)
- Speed limit and roadside sign for each approach
- Signal timing
- Videotapes of the focused left-turn movements

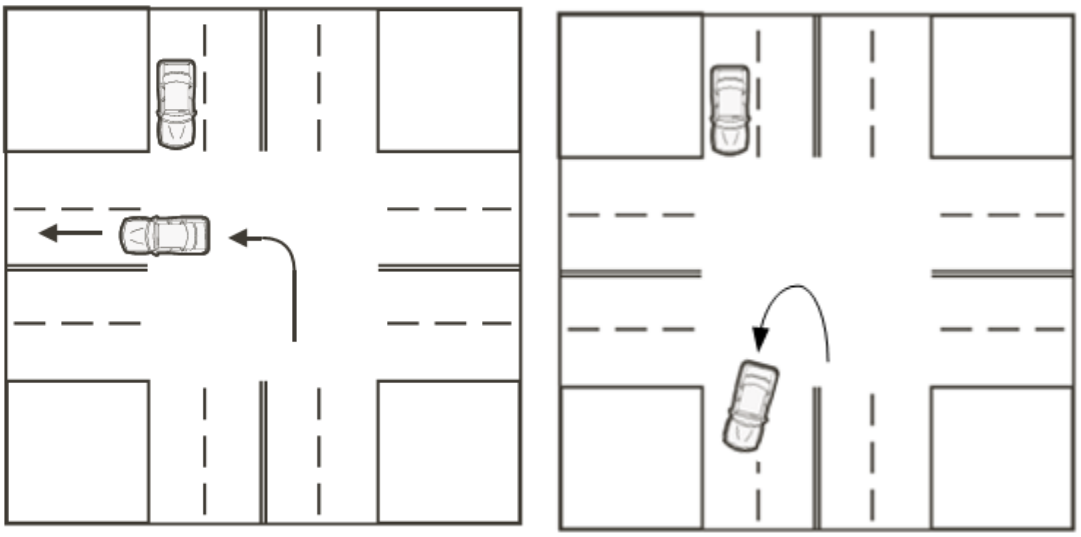
Before-and-After Traffic Conflict and Events

- **Traffic conflicts** are defined as the interaction of two or more road users (e.g., vehicles, pedestrians, and bicycles), where one or more users take evasive action to avoid a collision.
  - **Type 1 - conflicts between subject left turn (or U-turn) and opposing through,** occurs when an oncoming vehicle makes a left turn, placing a second vehicle, going in the opposite direction, in danger of a head-on or broadside collision. It applies only when the second vehicle has the right-of-way.
  - **Type 2 - conflicts between subject left turns in the same direction,** occurs when the first vehicle slows to make a left turn, placing a follow-up vehicle in danger of a rear-end collision.
  - **Type 3 - conflicts between subject left turn and lane change,** occurs when the first vehicle changes from one lane to another, placing a follow-up vehicle in danger of a rear-end or sideswipe collision.
  - **Type 4 - conflicts between subject left turn and opposing right turn,** occurs when an opposing vehicle makes a right-turn while placing a left-turning vehicle in danger of a broadside or rear-end collision.

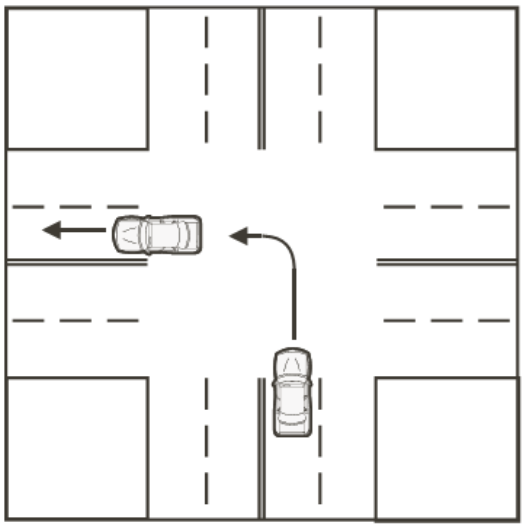
- **Type 5 - conflicts between subject left turn and pedestrians/bicycles,** occurs when a pedestrian or a bicycle crosses in front of a vehicle that has the right-of-way, causing the vehicle to brake or swerve to avoid a collision.
- **Type 6 - conflicts due to overflow of the subject left turn lane,** occurs when left-turn vehicle storage overflows the left-turn lane and blocks a through lane.
- **Type 7 - secondary conflicts,** occurs when a second vehicle makes a maneuver to avoid the first vehicle, placing a third vehicle in danger of a collision.

- **Traffic events** are non-conflict maneuvers but illegal or dangerous.
  - **Type 1** - subject left-turn drivers hesitating on protected left-turn indication
  - **Type 2** - subject left-turn driver hesitating on permissive left-turn indication
  - **Type 3** - subject left-turn driver running the red light
  - **Type 4** - subject left-turn driver backing to the stop bar (after entering the intersection but finding it impossible to complete a permissive left-turn in the current cycle)

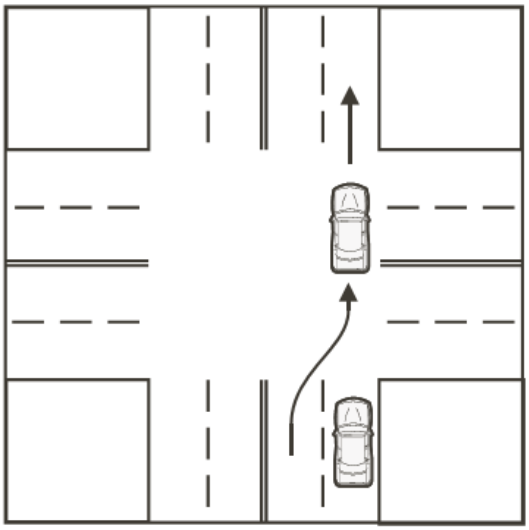
Illustrative examples of the conflict Types 1-6 are presented below:



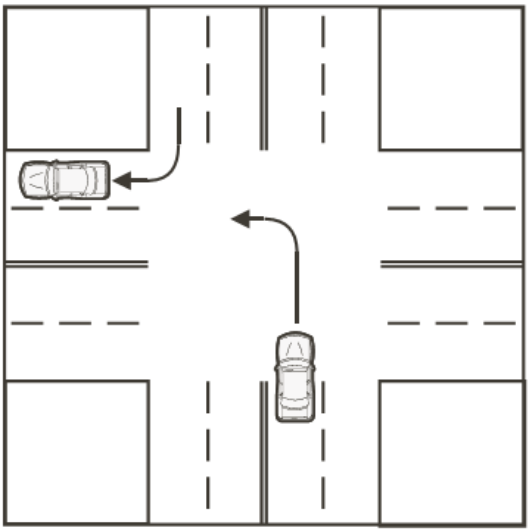
Type 1: Conflict with opposing through



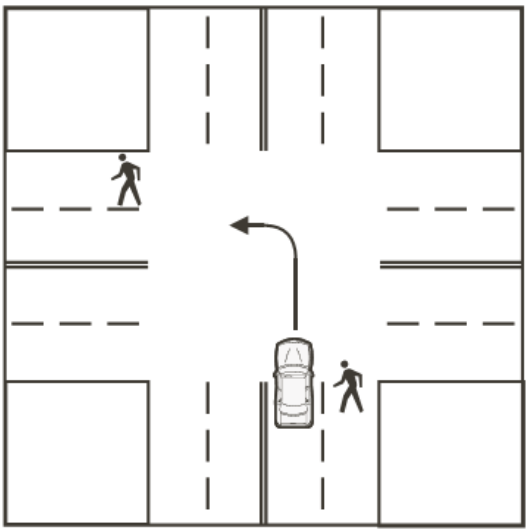
Type 2: Conflict with left-turn in same direction



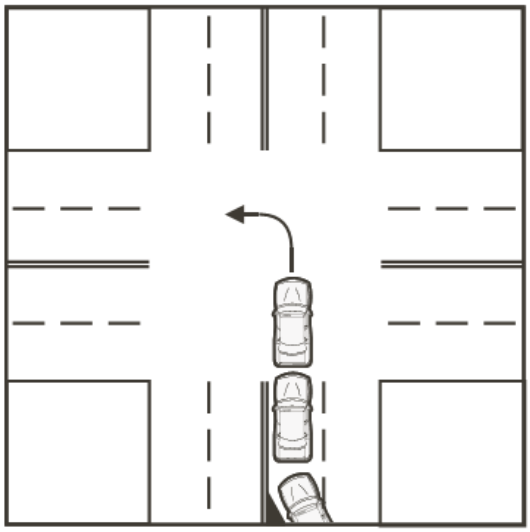
Type 3: Lane-change conflict



Type 4: Conflict with opposing right-turn



Type 5: Conflict with pedestrian/bicycle



Type 6: Conflict due to overflow of the subject left-turn lane

Source: NCHRP Report 493

Figure 4-7: Illustrations of Various Types of Traffic Conflicts Associated with Left Turns

4.2 FIELD DATA COLLECTION

4.2.1 Field Observation in Bellmead (Stage I Field Test)

During January 28 – February 10, 2011, the TSU team completed Stage I field test in Bellmead, TX with great assistance from the staff in TxDOT Waco District, including Mr. Larry Colclasure, Mr. David Pollard, and Mr. Tim Schulte. On Feb. 3, 2011, FYA signals were successfully installed at US 84 & Hogan Ln., and on Feb. 7, 2011, FYA signals were set up at US 84 & Maxfield St. and US 84 & Ashleman St. Before-and-after field traffic conflicts were collected at the three intersections by the team members, and an Autoscope Van was used for collecting traffic volume data, as shown in Figure 4-8.

Figure 4-8: Field Observation Work at Bellmead, TX

The observation time periods are listed as Table 4-2. Nearly 100 hours of traffic videos were recorded. Based on our field observation, motorists had a very good understanding of FYA indications.

Table 4-2: Hours of Field Observation at Bellmead, TX (Stage I Field Test)

Intersection	Traffic Conflicts (Before FYA installed, hrs/approach)	Traffic Conflicts (After FYA installed, hrs/approach)	Traffic Volume Videos (hrs/approach)
US 84 & Hogan, Bellmead	31	39	34
US 84 & Maxfield, Bellmead	36	18	35
US 84 & Ashleman, Bellmead	36	18	30
Total	102	75	99

4.2.2 Field Observation in Austin (Stage II Field Test)

During July 14 – 25, 2010, the UT/CTR team completed "before-FYA-installation" data collection at the two study intersections (FM 620 & Great Oaks, and FM 2244 & Walsh Tarlton Ln. in Austin, TX, as shown in Tables 4-1). Traffic conflicts were observed for 6 hours per day during 6:00-9:00 AM and 4:00-7:00 PM. A total of 30 hour traffic conflict data has been collected for each approach as shown in Table 4-3.

With great assistance from Mr. Robert Guydosh with Austin District, FYA signals were successfully set up at the two intersections on April 27 and 28, 2011. The signal timing plans remained the same before and after the implementation of FYA.

Table 4-3: Hours of Field Observation at Austin, TX (Stage II Field Test)

Intersection	Direction	Traffic Conflicts (Before FYA installed)	Traffic Conflicts (After FYA installed)	Traffic Volume Videos (hrs/approach)
FM 2244 & Walsh Tarlton	Westbound	30 hours/approach	32 hours/approach	21.5 hours/approach
	Eastbound			
	Northbound			
FM 620 & Great Oaks	Southbound	30 hours/approach	30 hours/approach	18.5 hours/approach
	Northbound			

After FYA signals were set up, traffic conflicts were observed for 6 hours per day. No less than 30 hours of traffic conflict data has been collected for each approach under study. Table 4-3 shows a summary of time period lengths of the "after" field observation. The field observation also revealed that motorists had a very good understanding of FYA indications.

FM 620 & Great Oaks, Austin FM 2244 & Walsh Tarlton, Rollingwood

Figure 4-9: Field Observation Work at Austin District, TX

4.3 IMPLEMENTATION OF FYA PPLT

4.3.1 Implementation of FYA PPLT during Stage I Field Test

FYA signals were set up at the three intersections in Bellmead, TX. At the study locations, left-turn signal heads were converted from conventional five-section signal heads to five-section FYA signal with a double-red-arrow arrangement (equivalent to conventional four-section FYA signal heads) as follows:

Before	red	yellow	steady yellow	green	green
After	red	red	flashing yellow	steady yellow	green

Figure 4-10: Before and After Arrangement of Left-Turn Signal Lens and Sign (Bellmead)

At the three intersections, the cabinets have 12 channels. The controllers were Naztec 900 Series TS 2 both before and after the implementation. The MMUs were upgraded from EDI-16 to Naztec 516.

Generally, there are two options to drive the controller outputs for load switches to accommodate FYA signal. They are "Overlap Mode" and "Ped Mode." Ped Mode means the use of unused "yellow" outputs of pedestrian load switches, which allows an FYA signal to be implemented without using a second full load switch socket or cumbersome cabinet re-wiring. Overlap Mode typically requires adding overlap load switches. During the FYA implementation in Bellmead, Ped Mode was used at the three intersections. The FYA was output through unused pedestrian yellow output of a pedestrian load switch. Before the implementation of FYA, no pedestrian channels or pedestrians signal heads were used at the three intersections. So, "virtual" pedestrian load switches were added in addition to the 6 load switches in use in the cabinet, as shown in Figure 4-11.

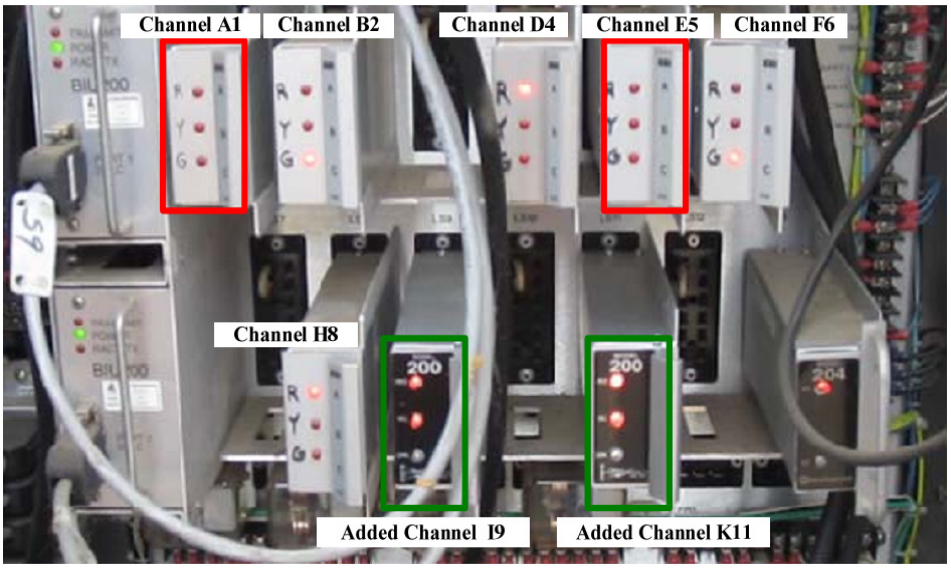


Figure 4-11: Cabinet and Load Switches for Implementation of FYA

4.3.2 Implementation of FYA PPLT during Stage II Field Test

FYA signals were set up at FM 2244 & Walsh Tarlton and at FM 620 & Great Oaks in Austin, TX. Left-turn signal heads were converted from conventional five-section signal heads to four-section FYA signal as follows:

Before	red	yellow	steady yellow	green	green
After	red		flashing yellow	steady yellow	green

Figure 4-12: Before and After Arrangement of Left-Turn Signal Lens and Sign (Austin)

At both of the field test intersections, the cabinets have 16 channels. At FM 620 & Great Oaks, the MMU were upgraded from EDI-16E to EDI-16LE SmartMonitor. Econolite ASC/3 1000 Controller was used to replace the Eagle NEMA EPAC 300 Controller. At FM 2244 & Walsh Tarlton, the MMU were upgraded from EDI-16E to EDI-16LE SmartMonitor. Econolite ASC/3 1000 Controllers were used before and after the implementation.

During the implementation of FYA in Austin, Overlap Mode was used at the two intersections. Additional load switches (overlap switches) were added to the cabinet to implement FYA indications.

At FM 620 & Great Oaks, two additional load switches were added onto Channels 13 and 15. FYA, steady yellow and red arrow for left-turn approaches on FM 620 were mapped onto these two load switches. The green arrows were mapped onto load switches 1 and 5 (protected left-turn phases on FM 620).

At FM 2244 & Walsh Tarlton Ln., three additional load switches were added onto Channels 13, 15 and 16 to enable FYA permissive left-turn indications on approaches to FM 2244 and the northbound approach on Walsh Tarlton Ln. FYA, steady yellow, and red arrow were mapped onto load switches 13, 15 and 16. The green arrows were mapped onto load switches 1, 5, and 7 (left-turn movements on FM 2244 approaches and the northbound approach).

4.4 HARDWARE AND SOFTWARE ISSUES EXPERIENCED

Problem Encountered #1 (in Bellmead):

The minor-street signals, which are operated by Phases 4 and 8, respectively, as shown in Figure 4-13. One three-section signal head was used for all movements on each approach, could not work properly to display either a red or green phases. The MMU detected a red-fail conflict.

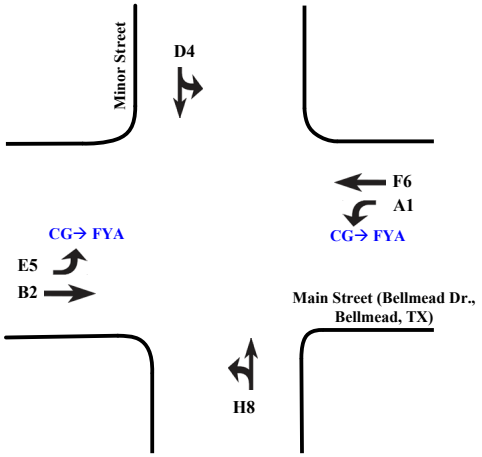


Figure 4-13: Signal Phase Assignment

Cause to the Red-Fail Conflict: No inputs for the unused Walk (Green) Field Terminals for the added Load Switches 9 and 11 since no pedestrian signals are installed.

Solution to the Red-Fail Conflict:

Method A - Added Jumpers

Originally, the MMU program card was programmed as follows:

	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
1		(2)			5	6			(9)		11					
2					5	6			9		11					
3				(4)			7	8		(10)		12				
4							7	8		10		12				
5						(6)			9		(11)					
6									9		11					
7								(8)		10		(12)				
8										10		12				
9											11					
10												12				
11																
12																
13																
14																
15																
16																

Figure 4-14: MMU program card programmed according to Naztec TecNote No. 1105

In the field, traffic engineers added 6 jumpers, as the MMU suggested, i.e., 4-9, 8-9, 1-9, 4-11, 8-11, and 5-11 to the MMU program card. These 6 additional jumpers dismissed the red-fail conflict and made the signals function properly. Accordingly, the controller "Permissive Matrix" was updated too. However, the added jumpers may raise some safety concerns.

Method B - Added Load Resistors or Capacitors

According to Naztec technical support, the manufacturer for the controller and MMU, the problem can be solved by installing Load Resistors on the unused Walk (Green) Field Terminals for Load Switches 9 and 11, without having to add incorrect jumpers to the program card. Method B is believed by the Naztec technical support as a better solution in terms of traffic safety. Therefore, we recommend load resistors be used for those intersections without pedestrian channels if Naztec equipment is used. A concern regarding the use load resistor is that they may be overheated. In these cases, the use of capacitors may be considered.

Problem Encountered #2 (in Bellmead):

The Phase E-5 (eastbound main-street left-turns) signal head turned black-out, when the adjacent through has red balls at Ashleman St. and it is expected to display a red arrow.

Solution: The load switch for Phase E-5 broke down. The engineers replaced the bad load switch and the signal worked properly.

Problem Encountered #3 (in Bellmead):

Green arrows were displayed concurrently with FYA on the same signal head at Maxfield St.

Solution: The wires were mistakenly connected, with Channels 9 and 11 interchanged.

Problem Encountered #4 (in Austin):

A problem was encountered during the implementation of FYA at FM 2244 & Walsh Tarlton, Austin. There were only 6 cables available for the signal lens for southbound approach on Walsh Tarlton Ln, as shown in the figure below. Before the installation of FYA, the signals for the side street (Walsh Tarlton Ln) were operated by split-phased PPLT. The permissive left-turn green ball had the same indication with the adjacent through movement. To enable FYA, one more cable was needed (7 in total).

Discussion: A common installation of PPLT phasing using a green ball for the permissive interval makes use of the green through phase to illuminate the green ball. Due to the flashing indication, additional cabling may be necessary in order for the flashing display to be controlled by its own circuit.

Figure 4-15: Signal head arrangement for southbound approach on Walsh Tarlton Ln.

Other Possible Problems:

Many of the MMUs and controllers that can enable FYA displays are produced to accommodate up to 16 channels. But the cabinet in use may be a 12-channel system. In these cases, the controller and MMU should be programmed to comply with the hardware condition with 12 channels. It is suggested to double check the cabinet before programming MMUs and controllers

4.5 SUMMARY

In this chapter, we presented the field study plan and described the field data collection. Then, we summarized the implementation of FYA at the five intersections as well as the field observation of traffic conflicts before and after the installation. Finally, we elaborated the software and hardware issues encountered and the solutions used during the field tests.

CHAPTER 5: SAFETY PERFORMANCE ANALYSIS

In this chapter, the safety performance of FYA PPLT displays is evaluated. Results from this chapter serve as the basis for developing the guidelines for implementing the FYA signal display.

For this purpose, the team conducted two types of safety studies: 1) historical crash data analysis, which analyzes the crash data collected from the intersections with the FYA PPLT signals installed, and 2) traffic conflict study, which analyzes the traffic conflicts data collected at the 5 intersections during Stages I and II field test. In these two studies, safety performances before and after the deployment of FYA PPLT were compared.

5.1 HISTORICAL CRASH ANALYSIS

5.1.1 Data Collection

The City of Kennewick, WA, is among the first cities that have documented research on FYA PPLT. As a pioneering, representative study, Deskins (2009) presented the five-year experience of FYA PPLT implementation at Kennewick, WA. The TSU research team interviewed Mr. John Deskins and collected crash data and other pertinent information regarding the 39 intersections that have been installed with FYA PPLT in the recent 7 years in Kennewick, WA, and Federal Way, WA.

The City of Tyler is one of the earliest cities in Texas that has employed FYA PPLT signal operations. In this study, the safety performance at 12 intersections operated with FYA PPLT in Tyler were investigated with great assistance from Mr. Justin Smith, Associate Traffic Engineer with the City of Tyler, TX, and from Ms. Debra Vermillion, Safety Construction Programs & Data Analysis Branch Manager with TxDOT.

For the historical crash data analysis, a total of fifty-one intersections were evaluated in the three cities: 1) Tyler, TX, 2) Federal Way, WA, and 3) Kennewick, WA. For these intersections, the team also collected a total of 97 police-reported crash records for the intersections in Tyler, TX, and Kennewick, WA. The researchers carefully examined each crash report to analyze and identify safety issues associated with FYA PPLT. In addition, the team contacted traffic engineers in these cities to collect other relevant information about these intersections. Table 5-1 summarizes the information that was collected.

Table 5-1: Information for the Study Intersections

City	Number of FYA intersections	Months of crash data before	Months of crash data after	Number of crash reports studied	Other information
Tyler, TX	12	60-72	8-24	52	• Average daily traffic (ADT) volume • Left-turn phasing • Posted speed limit
Kennewick, WA	32	36-60	22-65	45	• Average daily traffic (ADT) volume • Left-turn phasing • Posted speed limit • Signal timing plan • Geometry
Federal Way, WA	7	36	8- 36	NA	• Average daily traffic (ADT) volume • Left-turn phasing

5.1.2 Safety Analysis for FYA in Tyler, TX

We initially compared the left-turn related crash rates before and after FYA implementation at the 12 intersections located in Tyler, TX. All of these intersections were operated under lead-lead CG PPLT and have been operated under lead-lag FYA PPLT after the conversion. Table 5-2 exhibits that the average left-turn related crash rate decreased from 0.19 to 0.18 with the FYA signal indication, which indicated that collectively the implementation of FYA signals did not cause more crashes. To further compare the crash rates, a statistical method - a paired t-test was used to determine the statistical significance of the difference between the crash rates before and after FYA PPLT implementation. As shown in Table 5-2, the P-value for the paired t-test is 0.39 (greater than 0.05). Thus, there is no evidence of significant difference between the crash rates before and after the implementation of FYA PPLT.

Table 5-2: Crash Experience at FYA Intersections in Tyler, TX

Intersection	FYA approaches	FYA turn-on date	Months before/after FYA installation	ADT	Number of LT crash before/after	Crash rate[1] before/after	Change in crash rate[2]
Old Bullard & Loop 323	E & W	3/4/2008	62/22	71950	56/13	0.41/0.27	-34%
Heritage & Broadway	N & S	4/15/2008	64/21	33650	9/7	0.14/0.33	**141%**
Donnybrook & Loop 323	ALL 4	5/13/2008	64/20	49240	28/6	0.29/0.20	-30%
Kinsey & Loop 323	E & W	6/25/2008	66/18	54750	15/6	0.14/0.20	45%
Van Hwy & Loop 323	ALL 4	8/26/2008	68/16	35400	15/4	0.21/0.23	12%
R E Lee & Broadway	N & S	9/23/2008	69/15	49580	19/6	0.18/0.26	43%
Front & Broadway	ALL 4	10/21/2008	70/14	49500	23/2	0.22/0.09	-58%
Houston & Broadway	ALL 4	11/4/2008	70/14	32590	12/2	0.17/0.15	-16%
Troup & Broadway	N & S	3/10/2009	74/10	43260	14/0	0.14/0.00	-100%
Beckham & Hospital	N & S	4/21/2009	76/8	14860	5/1	0.15/0.27	**82%**
Broadway & Rieck	N & S	5/12/2009	76/8	66530	30/2	0.19/0.13	-33%
Chimney & Broadway	ALL 4	1/16/2008	60/24	50260	0/0	0.00/0.00	0%
Average						0.19/0.18	-5%
One-tailed paired T-test						P-value= 0.39	

[1] Crash Rate was calculated as crashes per million entering vehicles (MEV).

$$R = \frac{C * 1{,}000{,}000}{\sum ADT * 365 * Y}$$

Where R = crash rate per million entering vehicles, C=number of crashes, and Y=number of years analyzed (Green and Agent, 2003).

[2] Increase rate = (Left turn crash rate after - Left turn crash rate before)/ Left turn crash rate before

From Table 5-2, it was evident that the crash rates at two intersections (Heritage & Broadway and Beckham & Hospital) increased significantly (more than 50%) after the implementation of FYA PPLT. Therefore, further analysis was conducted for these two intersections.

Heritage & Broadway

Broadway St. is a 4-lane arterial with exclusive left-turn lanes and is the major-street direction of the intersection. A total of 7 left-/U-turn related crashes occurred in 21 months after FYA implementation. Before FYA installation, the crash rate at this location was 0.14 crashes/MEV. However, after FYA installation, the crash rate rose to 0.33 crashes/MEV, increasing by 141%.

After a careful analysis, we found that the crash rate increased with time at this intersection. Figure 5-1 describes the number of crashes that occurred each year at Heritage & Broadway. As shown in

Figure 5-1, FYA signal indication was installed on April 5, 2008. In 2007, the annual crash count had reached 4, indicating that the high crash rate had already been an existing problem for this location before FYA PPLT implementation. Compared with the crash rate in the year 2007, the crash rate in 2008 had not increased after the implementation of FYA PPLT at this location. Therefore, the evidence indicates that the high crash rate at Heritage & Broadway may not be directly related to the FYA operation.

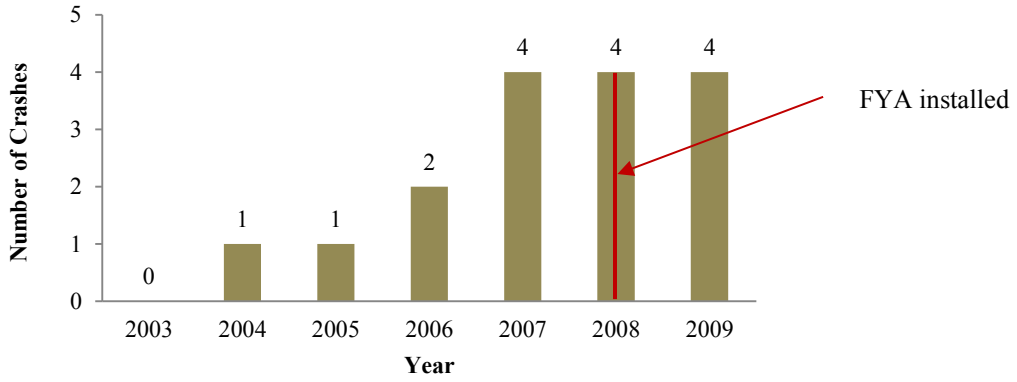


Figure 5-1 Number of Crashes by Year at Heritage & Broadway

Beckham & Hospital

The intersection at Beckham and Hospital had a moderate traffic-volume level (major street: 12,860 vpd and minor street: 2,000 vpd) and had 5 crashes during the 76 months before FYA PPLT. Only one left-turn related crash happened during the 8 months after FYA PPLT implementation. According to the police report, this crash was not related to the FYA signal indication. Therefore, the increased crash rate at this intersection is not related with the FYA signal indication too.

Furthermore, the team reviewed the police crash reports for other intersections with increased crash rates in Tyler and identified that the increases are generally not directly linked to the use of FYA PPLT.

Collectively, the implementation of FYA PPLT operations did not lead to more crashes in Tyler, TX.

5.1.3 Safety Analysis for FYA in Federal Way, WA

A total of 7 intersections with FYA signal indication in the City of Federal Way, WA, were available for the safety analysis. Crash data over a period of 3 years before and 3 years after the

FYA PPLT implementation are compared in Table 5-3. The average crash rate had decreased by 8% after the implementation of FYA PPLT. However, the result of paired T-test (P-value = 0.23>0.05) indicates that the decrease of the crash rate is not statistically significant.

All the intersections were further divided into three groups according to the left-turn signal phasing before installing FYA indications: protected-only (group A), protected/permissive (group B), and permissive-only (group C). The collected data revealed that the FYA signals can significantly reduce the crash rates in group B (by 39%) and group C (by 45%). The results indicated that FYA can improve the safety at intersections that operated with permissive-only or protected/permissive left turn prior to the implementation of the FYA PPLT operation. For the intersections that were operated under protected-only mode prior to FYA PPLT operation, previous studies (*Noyce, 2007; Qi, 2009*) have shown that the protected-only mode has better safety performance than the PPLT mode. Thus, the crash rate increased in group A as a result of the change from protected-only to PPLT mode, not as a direct result of the FYA indications.

Table 5-3: Crash Rate Before/After FYA Implementation in Federal Way, WA

Intersection	FYA turn-on Date	Crash rate		
		Before	After	% Change
9 & S 336	11/8/2006	0.49	0.64	31%
99 & S 312	1/24/2008	1.13	1.38	22%
Mil & S 288	6/10/2008	1.10	0.98	-11%
1 & S 312	12/2/2008	0.72	1.07	48%
1 & S 336	12/29/2008	0.93	0.63	-32%
21 & SW336	3/31/2009	1.84	1.08	-41%
16 & S344	12/29/2009	0.83	0.45	-45%
Totals		1.10	1.01	-8%
A: Protected only → FYA PPLT		1.02	1.17	15%
B: CG PPLT → FYA PPLT		1.47	0.90	-39%
C: CG Permissive → FYA PPLT		0.83	0.45	-45%
One tailed paired T-test		P-value=0.23		

5.1.4 Safety Analysis for FYA in Kennewick, WA

1) Crash Experience in Kennewick, WA

The City of Kennewick has implemented FYA PPLT in its intersections for over 6 years. In this study, the crash data of before and after the implementation of FYA PPLT at 32 intersections in Kennewick were analyzed. General information for the studied intersections is listed in Table 5-4.

Table 5-4: General Information for FYA Intersections in Kennewick, WA

Intersection	FYA turn-on date	Number of FYA approaches	Speed limit N/S	Speed limit E/W	Major ADT(after 2008)	Months before	Months after
1st & SR 397	5/15/2008	2	35/40	30	17797	60	27
1st & Washington	5/27/2008	2	30	30	11261	60	26
10th & Washington	9/3/2008	4	30/35	30	11358	60	23
10th & Garfield	8/11/2008	4	30	30	12525	60	24
10th & Olympia	8/13/2008	4	30/35	35/30	11913	60	24
10th & Vancouver	8/5/2008	4	30/35	35	12375	60	24
10th & Huntington	6/5/2008	2	35	25	12085	60	26
10th & Union	8/25/2008	4	35	35	12526	60	23
10th & Edison	8/27/2008	1	35	35	11392	60	23
10th & Kellogg	3/17/2005	4	35	35	11392	48	65
27th & Ely	7/14/2008	4	35	40	13793	60	25
27th & Quillan	12/16/2004	2	25	40	18973	36	67
Canal & Edison	7/29/2008	4	35	40/35	19161	60	24
Canal & Kellogg	9/11/2008	2	35	40	13232	60	23
Canal & Grandridge	9/17/2008	1	30	35/40	15018	60	22
Canal & Young	7/24/2008	2	25	35	15018	60	24
Clearwater & Morain	6/19/2008	4	30	35	21960	60	25
Clearwater & Union	6/23/2008	4	35	35	23469	60	25
Clearwater & Edison	6/25/2008	2	35	35	23758	60	25
Clearwater & Kellogg	6/3/2008	4	35	35	19993	60	26
Columbia Center & 10th	9/24/2008	2	40	40/35	5400	60	22
Columbia Center & Clearwater	11/16/2006	2	35	45/40	19753	60	44
Columbia Center & Deschutes	10/27/2005	4	35	35/25	26291	48	57
Columbia Center & Grandridge	11/17/2005	2	35/40	30	26630	48	56
Columbia Center & Okanogan	9/28/2006	2	35	25	26620	60	46
Columbia & SR 397	5/14/2008	2	35/40	30	21352	60	27
Columbia & Washington	5/20/2008	2	30	30	18995	60	26
Columbia & Fruitland	5/22/2008	2	30	30/35	25500	60	26
Gage & Grandridge	3/6/2008	2	30	40	19685	60	29
Gage & Steptoe	7/16/2008	2	40	40	25987	60	24
Quinault & Center Parkway	7/22/2008	4	35	30	9543	60	24
Vineyard & Garfield	5/29/2008	2	30/35	30	9004	60	26

At these 32 intersections, the "before" left-turn control modes include protected-only, PPLT, and permissive-only. The "after" left-turn control modes consist of PPLT only. As shown in Table 5-5, the study intersections were categorized into 3 groups according to different left-turn control modes operated before the implementation of FYA indications.

Table 5-5: Crash Rate Before/After FYA Implementation in Kennewick, WA

Before LT phasing	Intersection	Number of left-turn crashes before/after	Left-turn crash rates before/after	Change in crash rate
Protected	10th & Huntington	1/8	0.07/1.35	1829%
	Columbia & SR 397	1/4	0.04/0.32	700%
	1st & Washington	5/4	0.28/0.52	86%
	1st & SR 397	7/1	0.33/0.11	-67%
Protected only → FYA PPLT			0.18/0.58	222%
One tailed paired T-test		P-value=0.15		
Permitted	10th & Kellogg	4/8	0.31/0.46	48%
	Columbia & Fruitland	2/1	0.08/0.08	0%
	Gage& Grandridge	6/3	0.27/0.26	-4%
	27th & Quillan	11/19	0.95/0.77	-19%
	27th & Ely	3/1	0.18/0.14	-22%
	Columbia Center & 10th	5/0	0.61/0	-100%
Permitted only → FYA PPLT			0.4/0.29	-27.5%
One tailed paired T-test		P-value=0.17		
PPLT	Canal & Edison	14/21	0.49/1.8	267%
	Gage & Steptoe	6/8	0.18/0.52	189%
	Clearwater & Edison	7/6	0.22/0.44	100%
	Columbia Center & Deschutes	8/20	0.36/0.69	92%
	10th & Olympia	5/3	0.26/0.4	54%
	10th & Edison	2/1	0.14/0.2	43%
	Clearwater & Kellogg	10/2	0.37/0.48	30%
	10th & Garfield	4/2	0.23/0.27	17%
	Columbia & Washington	6/3	0.28/0.3	7%
	Canal & Young	0/0	0/0	0
	Canal & Grandridge	6/2	0.29/0.26	-8%
	Columbia Center & Clearwater	20/15	0.78/0.66	-15%
	Clearwater & Union	19/6	0.66/0.47	-29%
	10th & Vancouver	7/2	0.38/0.27	-29%
	10th & Union	8/2	0.38/0.26	-32%
	Columbia Center & Okanogan	39/24	1.77/1.18	-33%

Before LT phasing	Intersection	Number of left-turn crashes before/after	Left-turn crash rates before/after	Change in crash rate
	Columbia Center & Grandridge	10/9	0.52/0.33	-37%
	Vineyard & Garfield	8/2	0.45/0.26	-42%
	Canal & Kellogg	8/1	0.47/0.16	-66%
	Clearwater & Morain	8/1	0.33/0.1	-70%
	10th & Washington	11/1	0.6/0.13	-78%
	Quinault & Center Parkway	14/0	0.92/0	-100%
CG PPLT → FYA PPLT			0.46/0.42	-9%
One tailed paired T-test		P-value=0.33		
Total average			0.42/0.41	-2%

As shown in Table 5-5, the crash rates decreased after implementation of FYA at the intersections that were operated under permitted-only or CG PPLT mode prior to the FYA PPLT operation. The crash rates increased at the intersections that were operated under protected-only mode prior to FYA PPLT operation. The paired t-test results indicated that none of these differences is statistically significant.

Table 5-5 also shows that the crash rates at eight of the 32 intersections (highlighted with different colors increased significantly (crash rate increase >50%) after the installation of FYA signal displays. Among these intersections, the signal operations of five intersections were converted from CG PPLT to FYA PPLT, and the signal operations of three intersections were converted from protected-only to FYA PPLT. For both types of intersections, the possible causes to the crash increase are discussed in the following sections.

2) Safety Analysis for Intersections Converted from CG PPLT to FYA PPLT

For the five intersections in this category, we analyzed the detailed police reports along with other intersection information including geometric design, signal timing plan, ADT, and environment changes. We found that two intersections (Columbia Center & Deschutes; Gage & Steptoe) had safety issues that were directly related to the use of FYA signal display. For the other three intersections, the major causes for the increased crash rates were not directly related to FYA PPLT operation.

"Steady-Yellow-Arrow Confusion" Problem - Safety Issues Related to the Use of FYA

Problematic Intersection - Columbia Center & Deschutes: This intersection was converted from a lead-lead PPLT to a lead-lag PPLT after the FYA installation. Based on the study of the detailed police reports for crashes at this intersection, we found that the FYA PPLT operation caused "Steady-Yellow-Arrow confusion" problem at this location.

Figure 5-2 illustrates the signal timing for typical lead-lag PPLT phasing with key signal indications. The arrows represent traffic signal indications for left-turn movements, and the balls indicate traffic signals for through movement. The red and yellow lines between two phases indicate the change intervals between different signal phases. C1 stands for the crashes due to "steady-yellow-arrow confusion" occurred at this intersection, which will be discussed later.

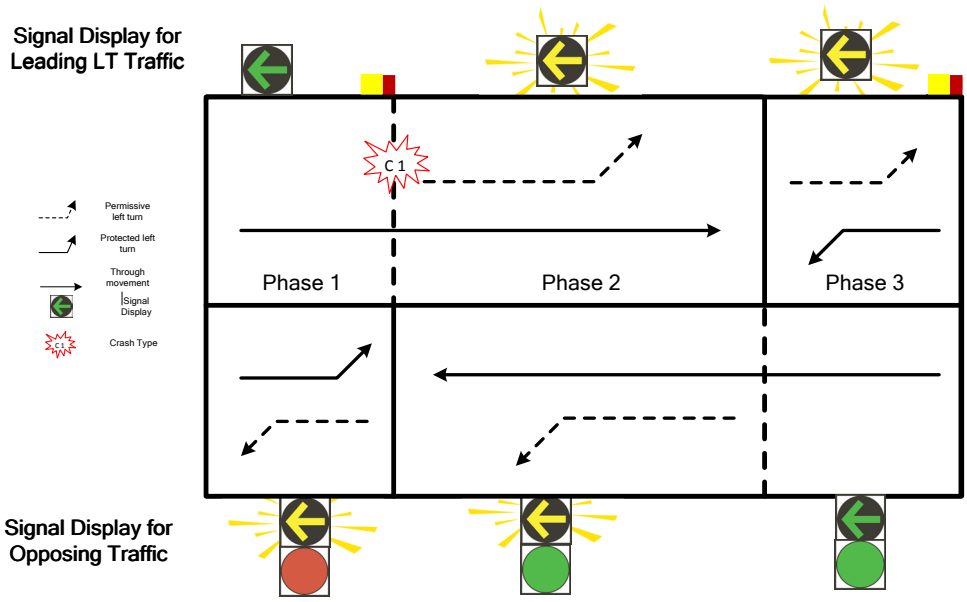


Figure 5-2: Signal Phase of Lead-Lag PPLT Operation

At this location, during the first two years after FYA installation, twenty left-turn related crashes occurred. Eighteen of the police reports just indicated that the crashes were caused by left-turn vehicle failing to yield to the through vehicle with no further description. According to the two police reports with detailed descriptions, it was indicated that the left-turn vehicles arrived at the intersection during the short steady yellow intervals at the end of Phase 1 (C1 in Figure 1-2) and became confused and less sensitive about the steady yellow arrow due to the use of FYA PPLT operation. As a result, instead of making a quick turn, the left-turn vehicles stopped in the middle of

intersection to yield to the opposing vehicles that will be released soon. However, as the left-turn signal turned into a red arrow, the drivers, who had already pulled into the middle of the intersection, mistakenly thought that the next movement would be the cross-street movement instead of the opposing through movement. Thus, these vehicles, in making a left turn in a rush, collided with the opposing through vehicles that had already started up. This problem is referred to as the "steady yellow arrow confusion" problem in this study.

This problem occurred at this intersection for the following reasons:

1. Steady-yellow-arrow confusion: During the steady yellow arrow interval, some left-turn drivers, instead of making a quick turn, chose to stop at the middle of the intersection to yield to the opposing traffic due to following two reasons:
    a. They mistook the steady yellow arrow for the FYA,
    b. They confused about the meaning of steady yellow arrow in the FYA PPLT operation. It is because in the FYA PPLT operation, steady yellow arrow will be displayed at two different times in one signal cycle, having two different meanings as follows: 1) when steady yellow arrow follows a green arrow, it means that the left-turn drivers still have the right-of-way over opposing traffic when finishing their left turn; on the other hand, 2) when steady yellow arrow follows FYA, it means that left-turn drivers have to yield to the opposing traffic (Figure 2-9). These two different meanings caused drivers' confusion.
2. Heavy left-turn volume: the intersection was busy with a high left-turn V/C ratio. According to the traffic count during the morning peak hour, it was found that the Columbia Center & Deschutes intersection has a very high left-turn volume (270 vph) and the left-turn V/C ratio is 0.97. As a result, at this intersection, not all left-turn vehicles will be able to pass through the intersection during the leading protected phase, allowing left-turn vehicles a great chance to enter the intersection during the steady yellow arrow interval.

    Due to the high left-turn volume, at this location, the leading protected left-turn phase is very likely to end at the same time as the approaching through phase (very similar to split phasing). In this case, drivers will easily make a mistake that the next movement would be

the cross-street movement instead of the opposing through movement if they see both the left-turn arrow and the through green ball signal indications are turning red at the same time.

Recommendation Concerning "Steady-Yellow-Arrow Confusion"

For the leading phased left-turns, MUTCD 2009 suggests that a steady-yellow-arrow signal indication should be displayed following the left-turn green arrow. The manual does not provide recommendations about whether a steady red arrow should be displayed after the steady yellow arrow. According to the findings of this study, it is suggested the use of a relatively long red arrow (3-4 s) between the steady yellow arrow and FYA, because this red clearance interval can better warn the left-turn drivers of the end of the protected left-turn phase and make sure the confused left-turn drivers can clear from the intersection.

Safety Issues Not Directly Related to FYA

At other three intersections, the researchers found that the increases of crash rates were not directly caused by the use of FYA. The following are the major causes of the increased crash rates at these intersections.

- Increased left-turn and through volume after FYA installation (at Clearwater & Edison)
- Signal timing for the intersection changed after FYA implementation (at Canal & Edison, signal phasing changed from split phase to lead-lag PPLT phase)
- The intersection geometric design changed after FYA implementation (at Canal & Edison, the intersection lane configuration changed. The middle lane is changed from shared left-turn to exclusive left-turn lane)
- Improved signal coordination led to better traffic progression and less gaps for permissive left turns (at Canal & Edison)

3) Safety Analysis for Intersections Converted from Protected-Only to FYA PPLT

Among the 51 studied intersections, seven intersections were converted directly from traditional 4-section protected-only to 4-section FYA PPLT operation. Among these seven intersections, the left-turn crash rates at 5 intersections have increased. Through the analysis of the crash data at these intersections, it was found that the major causes for the increases is that the locations themselves are not very safe or suitable to run PPLT signal control mode or to allow making permissive left turns.

For example, the increased traffic volume at the intersection 10th & Huntington is a result of a lack of gaps for making safe left-turns during the permissive phase. Therefore, extra cautions should be given when implementing the FYA PPLT operations at the intersections previously operated under protected-only left-turn signal mode. Before installing FYA PPLT at such an intersection, the traffic engineer should evaluate whether it is safe to allow permissive left-turns/U-turn at the intersection. The factors need to be considered include:

- Left-turn demand
- Opposing traffic volume
- Speed limit
- Sight distance
- Number of left turn lanes and opposing through lanes
- U-turn demand
- Left-turn accident history

5.1.5 Summary of Historical Crash Analysis

Overall, after implementing FYA PPLT operation, the average left-turn crash rate decreased for all the three cities involved in the study (i.e., Tyler, TX, Federal Way, WA, and Kennewick, WA), as shown in Table 5-6. The use of FYA signal indication generally had no negative effects on traffic safety of the intersections.

Table 5-6: Summary of Crash Rate Analysis for Studied Intersections

City	Left Turn Phase Before/ After	Number of FYA Intersections	Crash Rate Before	Crash Rate After	% Change
Tyler, TX	CG PPLT→FYA PPLT	12	0.19	0.18	-5%
Federal Way , WA	Protected → FYA PPLT	4	1.02	1.17	15%
	CG PPLT → FYA PPLT	2	1.47	0.09	-39%
	CG Permissive→ FYA PPLT	1	0.83	0.45	-45%
	Total	7	1.10	1.01	-8%
Kennewick, WA	Protected → FYA PPLT	4	0.18	0.58	222%
	CG PPLT → FYA PPLT	6	0.40	0.29	-27.5%
	CG Permissive→ FYA PPLT	22	0.46	0.42	-9%
	Total	32	0.42	0.41	-2%

However, a portion of intersections (11 out 51) presented significant increases in left-turn crash rates (2 in Tyler and 8 in Kennewick). The reasons resulting in the crash increases can be summarized as: 1) "steady-yellow-arrow confusion" problem, 2) conversion from protected-only phase to PPLT, and 3) other factors.

Among these causes, the "steady-yellow-arrow confusion" problem was directly related to the use of FYA, and the problem only became significant at the intersections with certain conditions (e.g., high V/C or lead-lag protected left-turn phases). The possible solutions for solving or mitigating the problems can be as follows: at the locations with high left-turn V/C ratio, longer clearance interval (red arrow) should be provided between protected left-turn phase (leading green arrow) and permissive left-turn phase (FYA).

5.2 TRAFFIC CONFLICT STUDY

The TSU team has completed the field traffic conflict study at five intersections through two stages. From January 28 - February 10, 2011, the team conducted Stage I field study at three intersections in Bellmead, Texas. From April 27 - May 3, 2011, the team conducted Stage II field study at two intersections in Austin, Texas. The detailed intersection information is shown in Table 5-7.

5.2.1 Field Observation of Traffic Conflicts and Events

The collected traffic conflict data have been analyzed and the major results are shown in Table 5-8 to Table 5-12.

Table 5-7: Detailed Information about Five Study Intersections in Austin and Bellmead, TX, for Stage I and II Field Test

Intersection	Direction	Left Turn control Mode*	Sequence	No. of LT Lanes	No. of Opposing Lanes	Avg. LT Volume (vph)	Avg. Thru Volume (vph)	Speed(mph)
FM 2244 & Walsh Tarlton, Austin	Northbound	PPLT	Lead-Lead	1	2	192	72	40
	Eastbound			1	1	216	1422	
	Westbound			1	1			
FM 620 & Great Oaks, Austin	Northbound	PPLT	Lead-Lag	1	2	152	1594	60
	Southbound			1	2			
US 84 & Hogan, Bellmead	Westbound	PPLT	Lag/Lag** (Lead-Lead)	1	2	26	1036	30
	Eastbound			1	2			
US 84 & Ashleman, Bellmead	Westbound	PPLT	Lead/Lag	1	2	23	897	30
	Eastbound			1	2			
US 84 & Maxfield, Bellmead	Westbound	PPLT	Lead/Lag	1	2	10	893	30
	Eastbound			1	2			

* All the intersections are operated with PPLT mode before and after the use of FYA indication.

** The left-turn phasing sequences at these intersections remained the same except at US 84 & Hogan, Bellmead (lag-lag to lead-lead).

Table 5-8: Results of Traffic Conflict Study at US 84 & Hogan, Bellmead, TX

US 84 & Hogan																	
	Traffic Conflicts									Traffic Events					Volumes	
	Hours of Obsv.	Type 1		Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Conflict Total	Type 1	Type 2	Type 3	Type 4	Event Total	Avg. LT (vph)	Avg. Thru (vph)
		Opposing Left-Turn	Opposing U-Turn	LT Same Direction	Lane Change	RT*-	LT, Ped*/Bike conflict	LT Lane Overflow	Secondary Conflict		Hesitating on LT* Pro*	Hesitating on LT Per*	Running red lights	Backing into LT Lane			
Before Total #	Before 31	14	4	0	2	1	0	0	2	23	1	11	2	1	15	26	1036
Before Conflict Rate ##		**0.452**	**0.129**	**0**	**0.065**	**0.032**	**0**	**0**	**0.065**	**0.742**	**0.032**	**0.355**	**0.065**	**0.032**	**0.484**		
After Total#	After 39	4	5	0	0	1	0	0	0	10	1	6	14	12	33		
After Conflict Rate ##		**0.103**	**0.128**	**0**	**0**	**0.026**	**0**	**0**	**0**	**0.256**	**0.026**	**0.154**	**0.359**	**0.308**	**0.846**		
Increase Rate (%) **		**-77**	**-1**	**0**	**-100**	**-21**	**0**	**0**	**-100**	**-65**	**-21**	**-57**	**456**	**854**	**75**		
P-value**	w/ U-turn conflicts	**.007**	**N.A.**	**1**	**.254**	**.849**	**1**	**1**	**.254**	**.029**	**.849**	**.464**	**.032**	**.012**	**.090**		
	w/o U-turn conflicts	**.031**		**1**	**.254**	**.849**	**1**	**1**	**.254**	**.029**	**.849**	**.464**	**.032**	**.012**	**.090**		

*LT= left turn; RT=right turn; Pro=protected indication; Per=permissive indication; Ped=pedestrian;

** Increase rate (%) = (After Conflict Rate – Before Conflict Rate)/ Before Conflict Rate; P-value of independent non-parametric test;

Before/After Total= Sum of before/after FYA installation observed conflicts within three peak hours;

Before/After Conflict Rate = Hourly conflict rate before/after FYA installation.

Table 5-9: Results of Traffic Conflict Study at US 84 & Maxfield, Bellmead, TX

US 84 & Maxfield																
	Traffic Conflicts									Traffic Events					Volumes	
	Hours of Obsv.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Conflict Total	Type 1	Type 2	Type 3	Type 4	Event Total	Avg. LT (vph)	Avg. Thru (vph)
		Opposing Left-Turn 	LT Same Direction 	Lane Change	RT*- 	LT, Ped*/Bike conflict	LT Lane Overflow	Secondary Conflict		Hesitating on LT* Pro*	Hesitating on LT Per*	Running red lights	Backing into LT Lane			
Before Total #	Before 36	3	0	1	1	1	0	0	6	0	3	1	0	4	10	893
Before Conflict Rate ##		**0.082**	**0**	**0.027**	**0.027**	**0.027**	**0**	**0**	**0.164**	**0**	**0.082**	**0.027**	**0**	**0.110**		
After Total#	After 18	0	0	0	0	0	0	0	0	0	1	0	0	1		
After Conflict Rate ##		**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0**	**0.056**	**0**	**0**	**0.056**		
Increase Rate (%) **		**-100**	**0**	**-100**	**-100**	**-100**	**0**	**0**	**-100**	**0**	**-32**	**-100**	**0**	**-49**		
P-value**		**.150**	**1**	**.439**	**.439**	**.439**	**1**	**1**	**.046**	**1**	**.564**	**.439**	**1**	**.519**		

*LT= left turn; RT=right turn; Pro=protected indication; Per=permissive indication; Ped=pedestrian;

** Increase rate (%) = (After Conflict Rate – Before Conflict Rate)/ Before Conflict Rate; P-value of independent non- parametric test;

Before/After Total= Sum of before/after FYA installation observed conflicts within three peak hours;

Before/After Conflict Rate = Hourly conflict rate before/after FYA installation.

Table 5-10: Results of Traffic Conflict Study at US 84 & Ashleman, Bellmead, TX

US 84 & Ashleman																
	Traffic Conflicts								**Traffic Events**					**Volumes**	
	Hours of Obsv.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Conflict Total	Type 1	Type 2	Type 3	Type 4	Event Total	Avg. LT (vph)	Avg. Thru (vph)
		Opposing Left-Turn 	LT Same Direction 	Lane Change	RT*- 	LT, Ped*/Bike conflict	LT Lane Overflow	Secondary Conflict		Hesitating on LT* Pro*	Hesitating on LT Per*	Running red lights	Backing into LT Lane			
Before Total #	Before 36	3	1	1	0	1	0	0	6	0	2	0	0	2	23	897
Before Conflict Rate ##		**0.083**	**0.028**	**0.028**	**0**	**0.028**	**0**	**0**	**0.167**	**0**	**0.056**	**0**	**0**	**0.056**		
After Total#	After 18	0	1	0	0	0	0	2	5	0	0	0	0	0		
After Conflict Rate ##		**0**	**0.056**	**0**	**0**	**0**	**0**	**0.111**	**0.278**	**0**	**0**	**0**	**0**	**0**		
Increase Rate (%) **		**-100**	**100**	**-100**	**0**	**-100**	**0**	**NA**	**67**	**0**	**-100**	**0**	**0**	**-100**		
P-value**		**.192**	**.606**	**.480**	**1**	**.480**	**1**	**.039**	**.872**	**1**	**.480**	**1**	**1**	**.480**		

*LT= left turn; RT=right turn; Pro=protected indication; Per=permissive indication; Ped=pedestrian;

** Increase rate (%) = (After Conflict Rate – Before Conflict Rate)/ Before Conflict Rate; P-value of independent non-parametric test;

Before/After Total= Sum of before/after FYA installation observed conflicts within three peak hours;

Before/After Conflict Rate = Hourly conflict rate before/after FYA installation.

Table 5-11: Results of Traffic Conflict Study at FM 2244 & Walsh Tarlton, Austin, TX

FM 2244 & Walsh Tarlton																
	Traffic Conflicts									Traffic Events					Volumes	
	Hours of Obsv.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Conflict Total	Type 1	Type 2	Type 3	Type 4	Event Total	Avg. LT (vph)	Avg. Thru (vph)
		Opposing Left-Turn 	LT Same Direction 	Lane Change	RT*- 	LT, Ped*/Bike conflict	LT Lane Overflow	Secondary Conflict		Hesitating on LT* Pro*	Hesitating on LT Per*	Running red lights	Backing into LT Lane			
Before Total #	Before 30	3	0	0	4	1	0	0	8	11	46	12	0	69	407	1494
Before Conflict Rate ##		**0.100**	**0**	**0**	**0.133**	**0.033**	**0**	**0.000**	**0.267**	**0.367**	**1.533**	**0.400**	**0**	**2.300**		
After Total#	After 33	18	0	0	1	2	0	1	22	4	32	68	21	126		
After Conflict Rate ##		**0.545**	**0**	**0**	**0.030**	**0.061**	**0**	**0.030**	**0.667**	**0.121**	**0.970**	**2.061**	**0.636**	**3.818**		
Increase Rate (%) **		**445**	**0**	**0**	**-77**	**82**	**0**	**0**	**150**	**-67**	**-37**	**415**	**+∞**	**66**		
P-value**		**.012**	**1**	**1**	**.134**	**.615**	**1**	**.333**	**.189**	**.041**	**.081**	**.013**	**.000**	**.591**		

*LT= left turn; RT=right turn; Pro=protected indication; Per=permissive indication; Ped=pedestrian;

** Increase rate (%) = (After Conflict Rate – Before Conflict Rate)/ Before Conflict Rate; P-value of independent non-parametric test;

Before/After Total= Sum of before/after FYA installation observed conflicts within three peak hours;

Before/After Conflict Rate = Hourly conflict rate before/after FYA installation.

Table 5-12: Traffic Results of Traffic Conflict Study at FM 620 & Great Oaks, Austin, TX

FM 620 & Great Oaks																
	Traffic Conflicts									Traffic Events					Volumes	
	Hours of Obsv.	Type 1	Type 2	Type 3	Type 4	Type 5	Type 6	Type 7	Conflict Total	Type 1	Type 2	Type 3	Type 4	Event Total	Avg. LT (vph)	Avg. Thru (vph)
		Opposing Left-Turn 	LT Same Direction 	Lane Change	RT*- 	LT, Ped*/Bike conflict	LT Lane Overflow	Secondary Conflict		Hesitating on LT* Pro*	Hesitating on LT Per*	Running red lights	Backing into LT Lane			
Before Total #	Before 30	11	1	5	3	0	0	0	20	3	91	3	2	100	153	1593
Before Conflict Rate ##		**0.367**	**0.033**	**0.167**	**0.100**	**0.000**	**0.000**	**0.000**	**0.667**	**0.100**	**3.033**	**0.100**	**0.067**	**3.333**		
After Total#	After 30	0	0	0	2	0	0	0	2	2	4	0	5	11		
After Conflict Rate ##		**0**	**0**	**0**	**0.067**	**0**	**0**	**0**	**0.067**	**0.067**	**0.133**	**0.000**	**0.167**	**0.367**		
Increase Rate (%) **		**-100**	**-100**	**-100**	**-33**	**0**	**0**	**0**	**-90**	**-33**	**-96**	**-100**	**150**	**-89**		
P-value**		**.008**	**.403**	**.135**	**.748**	**1**	**1**	**1**	**.004**	**.230**	**.000**	**.230**	**.617**	**.000**		

*LT= left turn; RT=right turn; Pro=protected indication; Per=permissive indication; Ped=pedestrian;

** Increase rate (%) = (After Conflict Rate – Before Conflict Rate)/ Before Conflict Rate; P-value of independent non-parametric test;

Before/After Total= Sum of before/after FYA installation observed conflicts within three peak hours;

Before/After Conflict Rate = Hourly conflict rate before/after FYA installation.

5.2.2 Results of Field Traffic Conflict Study

Based on the field observation, the results can be summarized as follows:

1. Most drivers had a good understanding of the FYA indication, even during the first several days after implementation. After FYA was implemented, the rate of Type 2 traffic events (subject left-turn driver hesitating on permissive left-turn indication) decreased at all the five locations.
2. After FYA was implemented, the rate of Type 1 traffic conflicts (between subject left-/U-turn and opposing through traffic) was reduced at four out of the five intersections. FM 2244 & Walsh Tarlton was the only location that had an increased rate of Type 1 conflicts. The causes for the increased conflict rates can be described as follows:
    1) Cause 1: the FM 2244 & Walsh Tarlton intersection, as the busiest intersection among the five locations, had a significantly higher left-turning volume and a higher V/C ratio (Volume/Capacity Raito) than the other four locations. The situation created a very stressful driving condition for the left-turn drivers since there is a limited amount of acceptable gaps in the opposing traffic flow. As a result, left-turning drivers were more likely to make risky turns during the permissive phase.
    2) Cause 2: based on the field observation and interviews of drivers, it was found that, compared to CG indication, the FYA indication may encourage more drivers psychologically to make aggressive left turns under such stressful driving conditions.
3. A significant number of U-turns were observed at the intersection of US 84 & Hogan at Bellmead, TX. Since a U-turn maneuver typically takes longer time to cross the intersection than a left-turn maneuver, traffic conflicts involving U-turns and opposing traffic accounted for a significant proportion of the Type 1 conflicts (i.e., 4 out of 18 before FYA and 5 out of 9 after FYA). Although the implementation of FYA PPLT had reduced the conflicts between left-turn and opposing vehicles significantly, it had little impact on traffic conflicts involving U-turn vehicles.
4. Among the five field study intersections, US 84 & Hogan and FM 2244 & Walsh Tarlton showed increased rates of Type 3 traffic events (left-turn drivers running the red lights) and Type 4 traffic events (left-turn drivers backing up to the stop bar) after implementation of

FYA. According to the field observations, these two types of traffic events are closely related. The increased rates of these two types of events can be explained by the following flowchart:

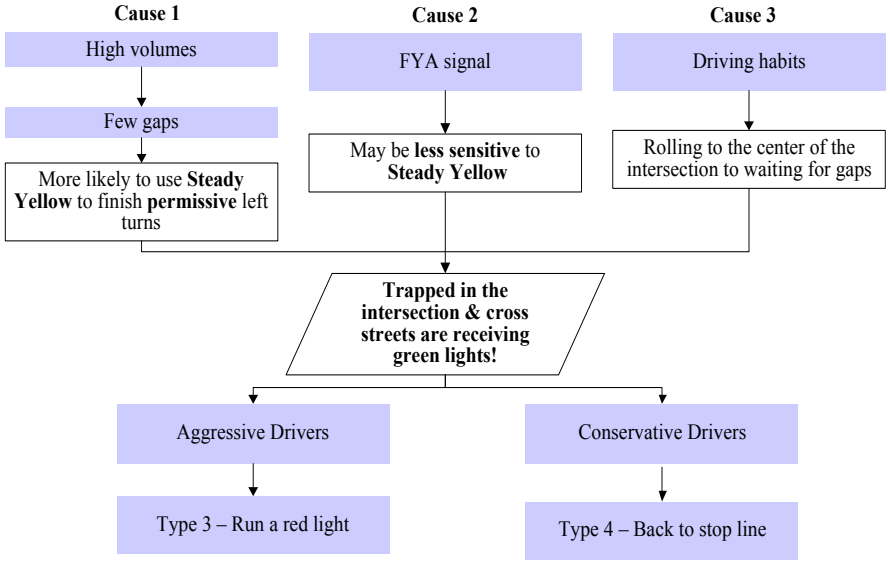


Figure 5-3: Explanation on the Increased Rates of Type 3 and Type 4 Traffic Events after the Use of FYA

According to the field observations, Type 3 and Type 4 traffic events, "running the red lights" and "backing to the left-turn lane," respectively, increased at the intersections with the following two features:

- High traffic volumes
- Use of lead-lead left-turn phasing

Among the five study intersections, FM 2244 & Walsh Tarlton was the busiest, while US 84 & Hogan is the busiest intersection among the three field study intersections in Bellmead, TX. Both of the intersections use lead-lead left-turn phasing with FYA PPLT. Because of high opposing traffic volume at these intersections, left-turn drivers were very likely unable to find safe gaps to make turns during the permissive phase. In this case, if left-turn vehicles already proceeded into the intersection during the permissive phase, they must use the steady yellow arrow interval to finish their permissive turns. However, with the use of FYA indication, drivers may be less sensitive to the steady yellow arrow indications because they might mistake it for an FYA. As a result, they may miss the opportunity to make left turns during the steady yellow arrow signal

interval and be “trapped” in the middle of intersection when the red arrow indication was turned on. In addition, with the use of leading left-turn phasing, the permissive phases will be followed by the signal phases for cross-street movements. Thus, the “trapped” drivers must either run the red light (Type 3 Event) or back up to the stop line (Type 4 Event).

According to the field observation and the analysis presented above, it can be found that, in general, drivers showed very good understanding of FYA indications, and FYA did not present safety issues at most of the field test locations. However, FYA signals may result in more traffic conflicts between left-turn and opposing vehicles at intersections with high left-turn and opposing volumes. In addition, FYA implementation will cause more “red-light runners” at busy intersections with lead-lead left-turn phasing. Therefore, FYA indication is not recommended for very busy intersections with high left-turn and opposing volumes, and should be implemented with great caution at intersections that use lead-lead left-turn phasing.

5.3 SUMMARY

In this task, two types of safety studies, historical crash data analysis and traffic conflict study, were conducted to evaluate the safety performance of the FYA PPLT display. The results of these studies show that:

- Majority of drivers showed a very good understanding of the FYA display
- Engineers should be very cautious when implementing FYA at intersections with following conditions:
    - Busy intersections (high opposing and left-turn volumes)
    - Leading protected left-turn phase (especially lead-lead phase)
    - High posted speed limit
    - Previously operated under protected-only mode

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CHAPTER 6: GUIDELINES FOR IMPLEMENTATION OF FYA PPLT

The purpose of this document is to present general guidelines for future implementation of the FYA PPLT display in Texas. These guidelines were developed based on the results of a thorough literature review, a nationwide survey of traffic engineers, field tests in Waco and Austin Districts, crash data analysis and field conflict studies conducted throughout the research project.

6.1 FRAMEWORK OF DEVELOPED GUIDELINES

The proposed guidelines include two parts: 1) general guidelines on the FYA PPLT operation, and 2) guidelines on the installation of FYA signals. The recommended guidelines were highlighted in shaded text boxes for easy reference.

6.2 GENERAL GUIDELINES ON THE FYA PPLT OPERATION

This part of guidelines aims to provide general guidelines regarding the situations under which the use of FYA indications should be suggested. The guidelines also aim to address other issues that need to be considered during the implementation of FYA signals.

Guideline 1 – When FYA Should Be Considered:

FYA signal indication is suggested for the permissive-only or permissive-protected left-turn operations if a separate left-turn signal face is being operated.

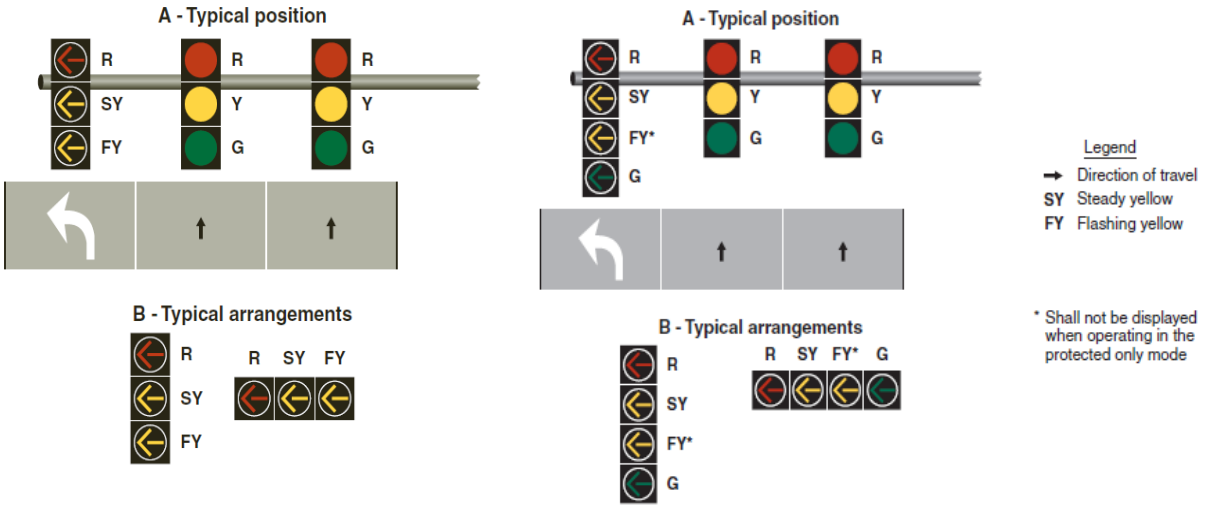
This guideline is based on the provision in Section 4D.18 and Section 4D.20, the 2009 Edition MUTCD. According to this manual, circular green signal indications shall not be used in a separate left-turn signal face to indicate permissive left turns. According to a highway engineer with the MUTCD Team, all new design work shall comply with this guideline. The existing signalized locations that don't comply can retain the non-compliant display until the end of the service life of the signal heads, signal reconstruction, or other major modifications.

In addition, the 2009 Edition MUTCD also suggests that for unusual geometric conditions, such as wide medians with offset left-turn lanes, a flashing left-turn red arrow signal indication instead of an FYA should be used in a separate left-turn signal face to indicate that each vehicle

must successively come to a full stop before making a permissive left turn. Note that, this option is used only when it is proven by engineering studies.

Guideline 2 - Typical Positions and Arrangements for FYA Signal Head:

- Figure 6-1 (a) is for permissive-only mode
- Figure 6-1 (b) is for PPLT mode



(a) Permissive-Only Mode Left Turns (b) PPLT Mode Left Turns

Source: MUTCD (2009)

Figure 6-1: Typical Position and Arrangement for Separate Signal Faces with FYAs

This guideline is based on the provision in 4D.18 and Section 4D.20, the MUTCD (2009).

Furthermore, according to the 2009 Edition MUTCD, a three-section signal face (shown in Figure 6-2) containing a dual-arrow signal section is also permitted where signal head height or wind loading limit the use of a four-section signal face. However, based on the nationwide survey of traffic engineers conducted during this research, the three-section signal face is not recommended for implementing FYA signals because dual-arrow signal section which is used to display both green arrow and FYA may confuse drivers especially who are green-yellow color blind.

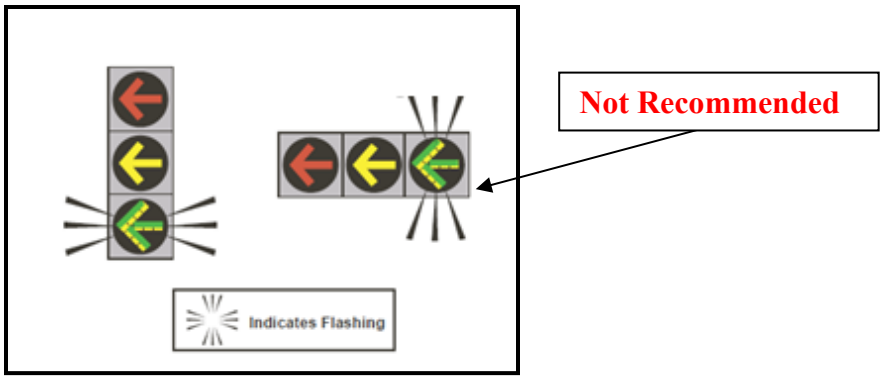


Figure 6-2: Three-Section Signal Face

Guideline 3 – Signal Display Sequence:

The suggested FYA display sequences for different types of signal left-turn phasing (lead-lead, lead-lag, lag-lag) are illustrated in Figures 6-3, 6-4 and 6-5.

This guideline is suggested based on NCHRP Report 493, the MUTCD, and the results of this research.

	Opposing Left Turn (lead)	Opposing Through	**Subject Left Turn (lead)**	Subject Through	Description
1					All-red
2					Green arrow for subject approach
3					Steady yellow at the end of the protected subject LT phase
4					Red clearance at the end of the protected subject LT phase
5					Delay the start of subject FYA (Optional)
6					FYA permissive
7					Steady yellow arrow at the end of the permissive LT phase

Figure 6-3: FYA Displays for Lead-Lead PPLT Operations

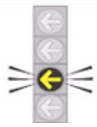
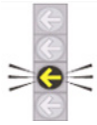
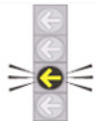
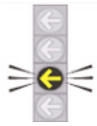
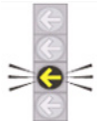
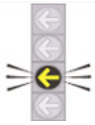
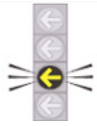
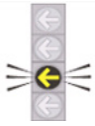
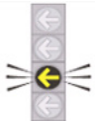
	Opposing Left Turn (lag)	Opposing Through	**Subject Left Turn (lead)**	Subject Through	Description
1					All-red
2					Green arrow for subject LT approach
3					Steady yellow at the end of the protected subject LT phase
4					Red clearance at the end of the protected subject LT phase
5					Delay the start of subject FYA (Optional)
6					FYA permissive
7					Yellow clearance for subject through
8					Red clearance for subject through
9					Steady yellow arrow at the end of the permissive LT phase

Figure 6-4: FYA Displays for Lead-Lag PPLT Operations

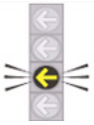
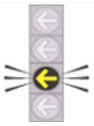
	Opposing Left Turn (lag)	Opposing Through	**Subject Left Turn (lag)**	Subject Through	Description
1					All-red
2					FYA permissive
3					Yellow clearance for through traffic
4					Red clearance for through traffic
5					Lag-lag protected phase for left-turns
6					Steady yellow clearance for left turns

Figure 6-5: FYA Displays for Lag-Lag PPLT Operations

For leading-phased left turns, the MUTCD suggests that a steady left-turn yellow arrow signal indication should be displayed following the left-turn green arrow signal display, as shown in interval 3 in Figures 6-3 and 6-4. The MUTCD does not provide recommendations about whether a steady red arrow should be displayed after the steady yellow arrow, as shown in interval 4 in Figure 6-3. According to the literature reviewed, a steady red arrow is recommended to clearly indicate the end of the protected left-turn interval. In addition, in the field study, a delay of the start of FYA (interval 5 in Figures 6-3 and 6-4) has been set to prevent the left-turn vehicles from failing to yield to the opposing vehicles at the beginning of permissive left-turn interval, which worked well from the observation by the researchers.

The crash analysis in this research also showed that issues that may result in crashes were associated with leading protected left-turn interval, i.e., "steady yellow arrow confusion." To address the issue, we suggest the use of a little longer red arrow (e.g. 3-4 seconds for interval 4 in Figures 6-3 and 6-4) between the steady yellow arrow and FYA, because this red clearance interval can better warn the left-turn drivers of the end of the protected left-turn, and better clear the confused left-turn drivers who have already entered the intersection.

For lagging phased left-turns, the MUTCD suggests that FYA should be followed directly by the steady green arrow signal indication, as shown in Figure 6-4 (the lagging left-turn movement in the blue box) and Figure 6-5. A steady yellow arrow should not be displayed in between (provision G in section 4D.20).

Guideline 4 – Safety Assessment for Converting Signal Operation from Protected-Only Mode to FYA PPLT Mode:

Before implementation of the FYA PPLT operations at intersections that were previously operated under protected-only mode, following factors need to be checked to evaluate whether it is safe to allow permissive left-turns/U-turn at the intersection:

- Left-turn volume
- Opposing traffic volume
- Speed limit
- Sight distance
- Number of left-turn lanes and opposing through lanes
- U-turn volume
- Crash history
- Geometry (i.e., whether turning paths conflict with each other)

This guideline is based on the results of this research project. Among the 51 intersections under study, 7 intersections were converted directly from traditional four-section protected-only signal operation to four-section FYA PPLT operation. The left-turn related crash rates at 5 intersections out of the 7 intersections increased. By analyzing the crash data at these intersections, it was found that the major causes for the increased crash rates is that the locations are not safe to allow permissive left turns due to some traffic and geometric conditions, such as heavy traffic volume, high speed, and presence of multiple turning lanes.

Guideline 5 – Supplementary Signs

An optional supplementary sign for FYA indications may be used where necessary.

"LEFT-TURN YIELD ON FLASHING YELLOW" without graphic

Source: Deskins (2009) and NCHRP Report 493 (2003)

Figure 6-6: Optional Supplementary Sign for FYA PPLT

Guideline 6 – Unfavorable/Adverse Conditions for FYA PPLT Operation:

Special cautions are needed to install FYA signal indication at intersections with following traffic conditions:

- Heavy traffic volume
- High speed limit

If the installation of FYA is required at such intersections, the use of lead-lead signal phasing sequence should be avoided.

This guideline is based on the results of this study. The "steady yellow confusion" problems related to the use of FYA may occur and the number of "red-light runners" may increase at intersections with high traffic volumes and/or high speed limit, especially when the subject left-turn movements are operated under leading left-turn phases. Therefore, if the installation of the FYA display is used at such intersections, for example, to comply with the requirement of

Sections 4D.18 and 4D.20 of the 2009 Edition MUTCD, a lag-lag signal phasing sequence would be preferable to minimize the occurrence of the above issues.

6.3 GUIDELINES ON THE INSTALLATION OF FYA SIGNALS

This part of guidelines is focused on providing guidelines on hardware and software issues associated with installing FYA signals. These guidelines were developed based on the literature review, the survey of equipment manufacturers/vendors, and the field tests conducted in Waco and Austin Districts.

Guideline 7 – General Installation Procedure:

The installation procedure can be generalized as the following steps:

Step 1 Set up traffic control plan determined by the engineer. To include warning signs, reflective cones, vehicle mounted arrow boards, temporary stop signs or police for controlling the intersection if needed, etc.

Step 2 Modify or replace left-turn signal heads and install supplemental signs;

Step 3 Transmit signal timing plans to the controller replacement, replace the existing controller and MMU with the replacements which has been programmed, modify MMU program card, load switches may be added;

Step 4 Re-wire and check every signal lens for proper display;

Step 5 Confirm proper signal operations.

This procedure is generalized based on the practices of TxDOT district traffic engineers during the field tests conducted in Bellmead and Austin, TX.

Guideline 8 – Load Switch Output Options:

Generally, there are two optional modes for driving the controller and load switch outputs for displaying FYA indications:

- Ped Mode – use the unused "yellow" outputs of pedestrian load switches

  Generally, Ped Mode allows an FYA signal to be implemented without using a second full load switch socket or cumbersome cabinet re-wiring.

- Overlap Mode – add overlap load switches

This guideline is based on information collected from signal equipment manufacturers/vendors and the experiences of the field tests. During Stage I field test in Waco District, Ped Mode was used to drive controller and load switch outputs; while during Stage II field test in Austin District, Overlap Mode was used.

The decisions associated with which mode should be used largely depend on the existing hardware conditions and preferred level of system flexibility, e.g., availability of unused load switch sockets and presence of pedestrian load switches. It is critically important to refer to relevant instructions from the equipment providers, since the internal controller programming may vary with different manufacturers.

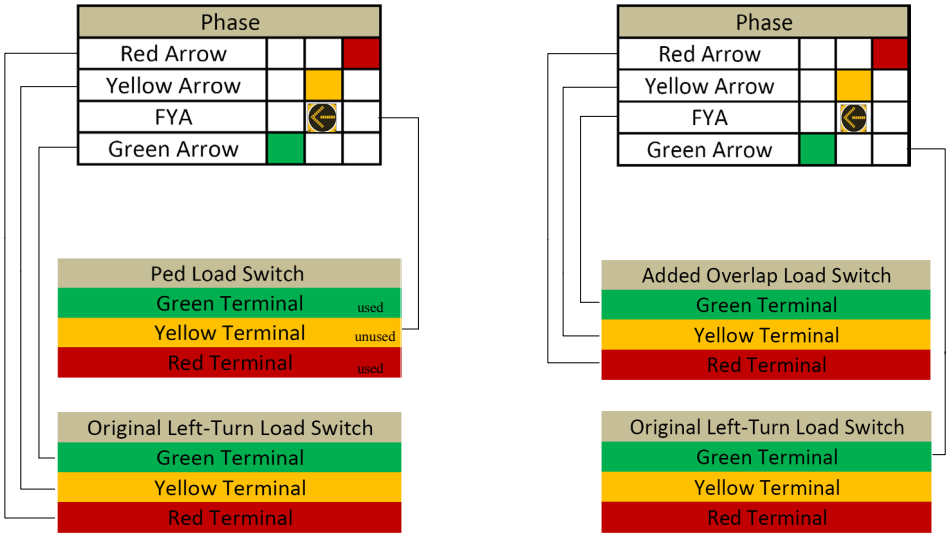
Guideline 9 – Typical Overlap Programming Method for FYA PPLT:

Typically, different overlap programming methods are used for Ped Mode and Overlap Mode:

- Under Ped Mode, the output of FYA should be mapped to the pedestrian yellow output on the pedestrian load switches. The green arrow, steady yellow arrow, and red arrow outputs are commonly mapped to the load switch driving the corresponding protected left-turn phases (Figure 6-7 (a)).
- Under Overlap Mode, the output of FYA, steady yellow arrow, and red arrow are commonly mapped to the added load switches. The FYA should be outputted through the green field terminals. The green arrow should be mapped to the load switch driving the corresponding protected left-turn phases (Figure 6-7 (b)).

This guideline is based on information collected from signal equipment manufacturers/vendors and has been verified through the field tests conducted in Waco District and Austin District. It should be noted that the choice of programming method for FYA outputs may also be restricted by the internal programs of controllers and MMUs.

Based on the experience in the field test in Waco District, a Red-Fail problem will occur with the Ped Mode if the Green (or Walk) field terminals for a load switch is unused. This problem can be resolved by installing load resistors or capacitors on the unused Green (Walk) field terminals for the load switches.



(a) Ped Mode (b) Overlap Mode

Figure 6-7: Typical Overlap Programming Methods for FYA PPLT

Guideline 10 – Checklist for Setting up FYA PPLT:

Before FYA signal is set up in the field, the proposed checklist can be used to examine the existing hardware conditions at the intersections.

This guideline is based on the literature review and field tests. Full awareness of the existing hardware conditions can facilitate a smooth implementation of FYA PPLT. The following checklist can be used before FYA PPLT is set up in the field.

☑ Check replacement head size/mounting

The implementation of the FYA indication typically requires a 12-inch lens. If the current green ball display has an 8-inch lens, replacement of the complete head will likely be necessary. Sometimes, installation of four-section vertical signal head (to replace five-section doghouse) may need to raise wire spans.

☑ Check the number of cabinet channels and unoccupied load switch sockets

The number of cabinet channels has effects on how to program the controller and MMU (e.g., MMU program card), and the number of unoccupied load switch sockets

may determine which option, Ped Mode or Overlap Mode, will be more suitable.

☑ Check if the number of available cables is sufficient to enable FYA signals

A common installation of PPLT phasing using a green ball for the permissive interval makes use of the green through phase to illuminate the green ball. Due to the flashing indication, additional cabling may be necessary in order for the flashing display to be controlled by its own circuit.

For example, at FM 2244 & Walsh Tarlton, Austin, TX, there were only 6 cables available for the signal lens for southbound approach on Walsh Tarlton Ln. Before the installation of FYA, the signals for the side street (Walsh Tarlton Ln) were operated by PPLT. The permissive left-turn green ball had the same indication with the adjacent through movement. To enable FYA, one more cable was needed (7 in total).

☑ Check if the mast arm is long enough to center the FYA signal head over the exclusive left-turn lane

☑ Check status of signal equipment

Before implementing FYA signals, the equipment to be used should be checked, e.g., a malfunctioned load switch or a bad load switch socket may lead to problems during the implementation of FYA.

☑ Confirm with signal equipment manufacturers about the applicability and programming method of the controller and MMU

Most leading signal equipment manufacturers have developed new models of controllers and MMUs that support FYA signal operations. Controllers must have the correct firmware to enable FYA operations.

TSU research team has contacted major signal equipment manufacturers. The team has collected information about the types of controllers that support FYA operations, the minimum firmware requirement, as well as the user manuals collected, as summarized in Table 6-1 and Table 6-2.

While manufacturers and users will often devise different solutions that may result in inter-changeability and inter-operability problems, according to the interview with a member of NEMA Standards Approval Associate, the recent development of the NEMA TS-2 amendment

No. 4 for FYA will provide an equipment based standard that will ensure compatibility between the controller and MMU that are conformant to the new standard. The Standard will provide a way for these issues to be mitigated.

Table 6-1: Some Controllers and Firmware Supporting FYA Displays

Vendor	Controller Type	Model of Controllers Enabling FYA	Min. Firmware Requirement	User Manual Collected*
Econolite	NEMA TS 2	ASC3-2100	Version 2.48.00	• Econolite controller programming method
		ASC3-1000		
Naztec	NEMA TS 2	TS2 Type 1	Version 61.x	• Naztec controller programming method
		TS2 Type 2		
McCain	170	All McCain 170 controllers	Version 233MC1	• 2070 controller programming method
	2070	All McCain 2070 controllers	Version 2033RV	
Peek	NEMA TS1 and TS 2	3000E	Version 3.7.3 BD420	• 3000E controller programming method
Northwest Signal	NEMA TS1 and TS 2	M1 Controller	NWSCentral**	• M1 controller programming method

* Documents are available at the website for the research project: http://itri.tsu.edu/TXDOT6568/d.htm

** Version unspecified

Table 6-2: Some MMUs Supporting FYA Displays

Make	MMU	Type of Standard
EDI	SSM-6LE, SSM-12LE, 16LE SmartMonitor	NEMA TS-1
	MMU-16LE SmartMonitor	NEMA TS-2
	2010ECL, 2018KCL, 2018ECL	170/2070
Naztec	516 MMU LCD w/Ethernet	NEMA TS2
Reno A&E	MMU-1600D Series	NEMA TS-1 and TS-2
	MMU-1600G Series	NEMA TS-1 and TS-2
	2018 Series	170/2070
Econolite	MMU-16LE	NEMA TS-1 and TS-2

REFERENCES

Manual on Uniform Traffic Control Devices (MUTCD). Federal Highway Administration, 2009. Available at http://mutcd.fhwa.dot.gov/pdfs/2009/pdf_index.htm

Kacir, K.C., Brehmer, C.L., Noyce, D.A., and Manser, M.P. *NCHRP Report 493: Evaluation of Traffic Signal Displays for PPLT Control*. Transportation Research Board, National Research Council, Washington, D.C., 2003.

Deskins, J. *Five Years of Observations of the Flashing Yellow Arrow Display*. ITE Meeting, 2009.

CHAPTER 7: KEY FINDINGS AND RECOMMENDATIONS

This research project achieved its primary goal, i.e., to develop guidelines for the implementation of the FYA PPLT operations. To fulfill this goal, following key tasks have been performed:

- Reviewed and synthesized national and peer state practices on the FYA PPLT.
- Conducted survey of traffic engineers to solicit professional opinions regarding the use of the FYA PPLT and conducted survey of general drivers to evaluate their understanding of the FYA display.
- Deployed the FYA PPLT operations at five selected intersections in a two-stage field test.
- Identified the software and hardware issues associated with the deployment of the FYA PPLT.
- Analyzed historical crash data and conducted field traffic conflict study to evaluate the safety performance of the FYA PPLT.
- Developed guidelines for the FYA PPLT implementation in Texas.

7.1 SUMMARY OF KEY FINDINGS

While the current version of MUTCD (2009) recommended the use of FYA as permissive left-turn indications in presence of a separate signal face, there is lack of detailed guidelines on the implementation of FYA. In this study, the researchers have reviewed manuals and guidelines for PPLT signal indication, and existing studies on FYA PPLT indication. Most of the studies showed that drivers have a good comprehension of FYA permissive left-turn indications and FYA signals can improve safety of intersections.

Both the survey of traffic engineers and the survey of general drivers received good responses. For the participating traffic engineers who had experience with FYA PPLT operations, 42% of them thought that the implementation achieved “satisfactory” results, 35% of them rated their implementation as “acceptable”, and 10% redeemed it “risky” to use FYA. The 124 responses from the survey of drivers showed that the FYA indication was correctly understood by 92% of

the subject drivers, and only 3.2% of them had incorrect understanding that may lead to a "fail critical" situation.

In the field tests in Waco and Austin Districts, FYA signals were successfully set up at five selected intersections with an average of 3 hours of signal work for a pair of opposing approaches. Technical issues, such as controller programming mode and method, and wiring problems, have been identified and documented. In addition, based on the experiences of field test, a general installation procedure and a checklist have been developed for setting up FYA PPLT.

For evaluating the safety performance of FYA PPLT operation, researchers collected historical crash data before and after FYA implementation at 51 intersections located in Tyler, TX, Federal Way, WA, and Kennewick, WA. In addition, before-and-after traffic conflict studies were conducted at the five intersections selected for field test in this study. The safety performance analysis led to following key findings:

- Majority of drivers had a good understanding of the FYA indication.
- Overall, FYA PPLT improved intersection safety at most study intersections by reducing traffic crash or conflict rates.
- Drivers may become insensitive to the signal change from an FYA to a steady yellow arrow at the leading left-turn direction, and this could increase the risk of a crash. The field traffic conflict study showed that this problem caused increased number of "Running Red Lights" and "Backing into the Left-Turn Lane" events at intersections with high traffic volumes and lead-lead left-turn phasing.
- A safety issue that was directly related to the use of FYA PPLT signal operation were identified, i.e., the "steady-yellow-arrow confusion" problem. The problem was only significant at intersections with certain conditions, e.g., high traffic volume and lead-lag left-turn phasing.
- Converting signal operation from protected-only mode to FYA PPLT mode may cause safety problems at some intersections, since permissive left-turn phasing may not be not safe due to some traffic (e.g. high traffic volumes), operational (e.g. high design speed), and/or geometric conditions (e.g. limited sight distance).

7.2 RECOMMENDATIONS OF THE PROJECT

Based on the results of this research, it is recommended that FYA signal indication should be used at most of signals with PPLT operations to improve intersection safety and to comply with the requirements of 2009 MUTCD. However, FYA PPLT is not appropriate for all situations. It is not recommended for very busy intersections that have high left-turn volumes and high opposing volumes, and it should be implemented with great caution at intersections that use lead-lead left-turn phasing. In addition, before the installation of FYA signals at an intersection that were previously operated under protected-only mode, it is necessary to assess whether it is safe to allow permissive left-turns/U-turn at that intersection at first. Finally, traffic engineers can refer to the developed guidelines for the implementation of FYA PPLT operation. Particularly, they can use the developed checklist to examine the existing hardware conditions to facilitate a smooth implementation, and they should contact equipment vendors before field implementation regarding the programming method of controller and MMU since the preferred method are commonly quite different among various makes.