SAFETY AND OPERATIONS ASSESSMENT OF VARIOUS LEFT-TURN PHASING STRATEGIES

FINAL PROJECT REPORT

by

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16. Abstract

This research evaluated the safety and operational impacts of different left turn movement treatments at signalized intersections. The project (1) compared the safety and operational impacts of protected-only left-turn (POLT) phasing with those of protected-permissive left-turn (PPLT) phasing with a flashing yellow arrow (FYA) indication, (2) compared the safety and operational impacts of doghouse displays with those of four-section vertical displays for PPLT with an FYA, and (3) identified whether time-of-day (TOD) variable left-turn control mode with an FYA produces confusion among left-turning drivers. The literature showed that converting a POLT to a PPLT control mode is associated with an increase in crash rates while reducing intersection delay. Previous research has recommended selecting the control mode on the basis of traffic volumes, speed limit, sight distance, number of lanes, and crash history. Previous research has shown that doghouse displays are associated with larger crash modification factors, more confusion among drivers, and higher delays than a four-section vertical display with an FYA. The results of our driver comprehension survey showed that half of the drivers who had encountered intersections with a left-turn control mode variable by TOD felt confused by that phasing strategy. On the other hand, the simulation-based analysis showed that changing the left-turn control mode by TOD yields more efficient traffic operations and lower average delays.

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List of Abbreviations

CFR: Circular flashing red

CFY: Circular flashing yellow

CG: Circular green

CMF: Crash modification factors

FCY: Flashing circular yellow

FRA: Flashing red arrow

EB: Empirical Bayes

FYA: Flashing yellow arrow

LT: Left-turn

POLT: Protected-only left-turn mode

PPLT: Protected-permissive left-turn mode

PRLT: Permissive-only left-turn mode

TH: Through

TOD: Time-of-day

USDOT: United States Department of Transportation

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Executive Summary

The objectives of this research were as follows:

1) Compare the safety and operational impacts of protected-only left-turn (POLT) phasing with those of protected-permissive left-yurn (PPLT) phasing with a flashing yellow arrow (FYA) indication.
2) Compare the safety and operational impacts of doghouse displays with those of four-section vertical displays for PPLT with an FYA.
3) Verify whether the time-of-day (TOD) variable left-turn control mode with an FYA (i.e., switching between permissive, protected-only, and protected-permissive left-turn phases throughout the day at one location) produces confusion among left-turning drivers. Also, investigate the operational impacts of such a strategy.

This research developed a framework to evaluate the operational effects of a time-of-day left-turn control mode. Historical findings on safety and operational impacts were investigated through a comprehensive literature search to achieve the objectives of this project. Also, an online driver comprehension survey was designed primarily for Washington state drivers to evaluate their understanding of left-turn signals (excluding red signals) conveyed by doghouse displays and four-section vertical displays with an FYA. The survey also evaluated whether drivers who encountered time-of-day variable left-turn phasing with an FYA at signalized intersections were confused by that signal strategy. For the TOD left-turn control model selection, 270 simulation scenarios were designed and run 15 times with different seeds to identify which of the left-turn control modes—protected-only, protected-permissive, and permissive-only—resulted in the most efficient intersection operation. The simulation scenarios were a combination of five geometries, six through-demand volumes, three left-turning percentages (5, 10, and 25 percent), and three left-turn control modes a (total of 5×6×3×3=270 scenarios). Each simulation scenario's signal timing plan was optimized by using the 2016 Highway Capacity Manual methodologies in Vistro.

Selected results are presented below.

Objective 1: POLT vs. PPLT Phasing

Safety

Most studies indicated that overall crash rates increased when the phase plan changed from POLT to PPLT. They recommended verifying the suitability of allowing permissive left-turn movements on signalized intersections on the basis of left turn and opposing traffic volumes, speed limit, sight distance, number of left turn and opposing through-traffic lanes, U-turn volumes, and crash history involving left turning vehicles.

Operations

A study indicated that PPLT phasing may reduce intersection delay more than POLT phasing.

Objective 2: Doghouse Displays vs. Four-Section Vertical Displays with an FYA

Safety

Under the lead-lag phasing sequence, doghouse displays are prone to yellow traps. Doghouse displays indicate the permissive LT phase with a green ball signal and a yield sign, which may confuse some drivers, as green signals indicate the right of way. The FYA is an effective remedy for yellow traps. The FYA reduces confusion among left-turning drivers, as it conveys solely permissive left-turn phases. However, the FYA dilutes the meaning of steady yellow arrow for the change of the interval. When a steady yellow arrow follows a green arrow, left turning drivers clearing the intersection have the right of way. On the other hand, if it follows an FYA, then left turning drivers must yield to oncoming traffic. Four-section vertical displays have shown safety benefits in comparison to doghouse displays, as they are associated with lower crash modification factors.

Operations

One study suggested that four-section displays with an FYA reduce the delay of left turning vehicles and increase left-turn throughput in comparison to doghouse displays. Under the engineering assessment task of NCHRP project 3-54, an FYA indication scored higher in categories of operations and versatility than the circular green ball indication in five-section displays.

Objective 3: TOD Variable Left-Turn Phasing with an FYA

Confusion among Drivers

This research performed a driver comprehension survey, and the results showed that almost 70 percent of 142 respondents believed they had encountered intersections whose left - turn phases changed throughout the day. Almost half of those believed that they were confused by that phasing strategy. Further research is necessary to evaluate driver confusion caused by TOD varying left-turn phasing. It will be necessary to select the drivers from those areas of Washington state where such TOD varying signalized intersections operate and to conduct interviews to identify the causes of that confusion.

Operations

By definition, time varying left-turn phasing strategies are designed to select the most suitable control modes to improve the operation of signalized intersections while ensuring safety. Two studies were found that developed statistical models for selecting suitable left-turn control modes during a day using mainly operational factors. The results of this research also indicated that a time varying left-turn control mode has positive effects on intersection operations.

Developed a Framework to Evaluate the Operational Effects of Time-of-Day Left-Turn Control Mode

The designed simulation experiment yielded 4,050 observations (270 scenarios × 15 runs = 4050 total observations). The statistical analysis of the observations showed that the number of left turning vehicles and the left-turn control mode were among the factors that most influenced intersection delay. A binary probit model was fitted to select the best left-turn control mode on the basis of intersection geometry and the cross-product of the left turn and the opposing through-movements.

Chapter 1: Introduction

Left-turn movements are predisposed to a higher crash risk, as vehicles cross the paths of opposing through-movements at intersections. Left-turn movements are subject to right angle crashes, which are often more severe. Furthermore, inappropriate selection of left-turn control modes (among protected-only, protected-permissive, and permissive-only) at signalized intersections increases overall intersection delay and yields inefficient operations. Therefore, it is vital to assess the safety and operations of various left-turn phasing strategies and control modes to improve both public safety and traffic operations at signalized intersections.

1.1. Background

Protected-permissive left-turn (PPLT) phases with a flashing yellow arrow (FYA) have the potential to improve traffic operations by allowing more vehicles to complete their left turns during permissive phases, especially in off-peak hours; however, their level of safety is perceived to be less than that of protected-only left-turn (POLT) phases. Therefore, it is necessary to evaluate the safety of protected-permissive left-turn phases with an FYA and protected-only left-turn phases. There are two prominent display types in Washington state: **doghouse** and **vertical** displays. Doghouse displays accommodate permissive left-turn movements during a circular green (CG) signal. As a result, doghouse displays may confuse some left-turning drivers, as circular green signals indicate the allocation of the right-of-way. Consequently, the safety of doghouse displays needs to be assessed and compared to that of vertical displays with an FYA. Finally, the left-turn control mode can switch among permissive-only, protected-permissive, and protected-only throughout the day on the basis of traffic conditions. However, the changes among control modes may produce confusion among drivers and need to be studied.

Selecting a suitable left-turn control mode at signalized intersections throughout a day is a complex process, as there are many traffic characteristics that influence the decision-making process. Shea et al. (2016) conducted a survey of state departments of transportation on their practices for selecting left-turn phases. Table 1-1 summarizes the findings of the survey.

Table 1-1. Left-turn phasing policies by state (Shea et al., 2016)

ITE/FHWA Flowchart (8 states)	**FHWA Guidelines (4 states)**	**State Adapted Criteria (14 states)**	**Formula-Based Approach (6 states)**	**No Statewide Guidelines (12 states)**
Alaska Delaware Louisiana North Dakota Rhode Island South Dakota Texas Wyoming	Hawaii Kentucky Nevada Vermont	Arizona Georgia Michigan Minnesota Mississippi Nebraska New York North Carolina Oregon Pennsylvania South Carolina Tennessee Utah Wisconsin	Alabama Idaho Illinois Indiana Missouri Montana	Arkansas Connecticut Florida Iowa Kansas Maine Massachusetts New Hampshire Ohio Oklahoma Virginia Washington

*Non-Responding States: California, Colorado, Maryland, New Jersey, New Mexico, and West Virginia

Table 1-1 shows that state policies vary, and there is no uniform approach for selecting the left-turn control mode. Moreover, twelve states, including the State of Washington, do not have official policies for selecting LT phases. To help facilitate the decision-making process, this project studied the operational effects of various left-turn control modes.

1.2. <u>Research Objectives</u>

This research had three main objectives, as follows:

1) Compare the safety and operational impacts of protected-only left-turn phasing with those of protected-permissive left-turn phasing with an FYA.

2) Compare the safety and operational impacts of doghouse displays with those of four-section vertical displays with an FYA.
3) Verify whether time-of-day variable left-turn phasing with an FYA produces confusion among left-turning drivers. Also, investigate the operational impacts of such a strategy.

Furthermore, the research developed a framework to evaluate the operational effects of the time-of-day left-turn control mode.

The research team conducted a comprehensive literature review to address the objectives of this project in terms of traffic safety and operations. Furthermore, an online survey was designed, and distributed primarily among Washington state drivers to test their knowledge of messages conveyed by doghouse displays and four-section vertical displays with an FYA, as well as to determine whether the TOD left-turn control mode had ever confused them. Finally, a simulation-based method was designed to select the most appropriate left-turn control modes throughout a day to minimize intersection delay.

1.3. Report Organization

This report includes five chapters. Chapter 2 provides a detailed review of the literature to identify the safety and operational characteristics of protected-only and protected-permissive left-turn control modes, as well as those of doghouse and four-section vertical displays. Chapter 3 describes the results of a driver comprehension survey aimed at identifying whether changing the TOD left-turn control mode caused any confusion among drivers. Chapter 4 details the operational effects of various left-turn control modes. Finally, Chapter 5 provides a summary of findings, concluding remarks, and trends for future research.

Chapter 2: Literature Review

Pline (1996) studied left-turning (LT) movements in the design of operationally efficient intersections. The study highlighted that making a left turn involves a complicated decision-making process, especially for elder drivers, as left turning vehicles need to find a gap in the oncoming traffic and to look for pedestrians and bicyclists during a permissive phase under dynamic conditions. Consequently, lane markings and traffic signals (mode of operation, phasing sequence, and signal display) should be designed on the basis of traffic volumes, traffic queues, crash history, vehicle delays, and sight distances. Lei et al. (2008) designed a survey for traffic engineers to use in collecting information on influencing factors, along with their priorities for selecting the type of left-turn (LT) treatments, including the mode of traffic signal operation and the phasing sequence. An analysis of 26 completed surveys showed that the number of LT lanes and the historical rate of LT-related crashes were the most important factors in selecting the mode of LT operations. For selecting a phasing sequence, the platoon progression and intersection congestion levels (v/c ratio) had the highest priority.

This literature review was conducted to identify historical findings relevant to research objectives 1, 2, and 3 in terms of safety and operational impacts.

2.1. Protected and Protected-Permitted Left Turns with an FYA

2.1.1. Safety

Noyce et al. (2007) evaluated the safety impacts of changing the LT operation mode of an intersection from POLT to PPLT with an FYA. The study collected the required data for a crash analysis from Oregon (22 locations), Washington (9 locations), and California (5 locations). After the data collection, the study performed a sign test and an Empirical Bayes (EB) analysis. Performing the sign test on 18 sites showed that when the intersection control mode had changed from protected-only to PPLT with an FYA, 12 locations had an increase in the number of total crashes, 14 had an increase in left-turn-related crashes, and 13 had more crashes, that occurred during the FYA illumination. Although the increase in LT-related crashes was statistically significant, the total number of crashes was not statistically different after implementation of PPLT with an FYA. In the EB analysis, 19 intersections had sufficient data for analyzing the LT-related crashes. The results showed a statistically significant reduction in left-turn-related crashes at 15 out of 19 intersections, but, four of 19 intersections showed an increase in LT crashes after implementation of PPLT with an FYA. Overall, the following conclusions were made in this study by considering several types of analyses for changes in intersection control mode from POLT to PPLT with an FYA:

- The average annual frequency of total crashes increased at 12 of 18 sites after implementation of an FYA indication.
- The average annual frequency of left-turn-related crashes increased at 14 of 18 sites after implementation of an FYA indication.
- The average annual frequency of left-turn crashes that occurred on an approach with the FYA indication increased at 13 of 18 sites after implementation of the FYA indication.
- An average increase in the crash frequency of between 0.7 to 1.3 crashes per year for total, left-turn, and FYA left-turn crashes was observed within an average period of 24 months after the implementation of an FYA.

Qi et al., (2012) selected 51 intersections in Tyler, Texas; Federal Way, Wash., and Kennewick, Wash. They collected crash data, which are summarized in table 2-1. For each intersection, individual crash rates for before and after periods were calculated by the following formula:

$$R = C * \frac{1{,}000{,}000}{(\Sigma ADT * 365 * Y)} \quad (2\text{-}1)$$

where: R is the crash rate per million entering vehicles,

C is the number of crashes in the study period, and

Y is the number of years analyzed.

Table 2-1. Data on study intersections (Qi et al., 2012)

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

Next, the percentage changes in the before-and-after crash rates were determined. Then, average crash rates for the before-and-after periods at each location were tested for statistical significance by using the one-tailed paired T-test. In Kennewick, intersections were grouped by LT control modes operated in the *before* period, and their LT control group average crash rates were tested for significance as well. Table 2-2 shows a summary of the results.

As can be seen in table 2-2, the crash rates decreased when a permissive control mode was converted to a protected-permissive control mode with an FYA. However, the intersections that were converted from POLT to PPLT with a FYA experienced an increase in crash rates (in

Federal Way and Kennewick). This trend was experienced at se intersections. Upon a closer analysis, the study concluded that these intersections were not suitable for a PPLT control mode.

Table 2-2. Summary of crash rate analysis for studied intersections (Qi et al., 2012)

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%

Before POLT approaches are converted to PPLT with an FYA, the study recommended evaluating the following traffic factors to assess whether it is safe to allowpermissive LT movements:

- LT demand
- Opposing traffic volume
- Speed limit
- Sight distance
- Number of LT lanes and opposing through-lanes
- U-turn demand
- LT crash history.

Agent (1985) evaluated the changes in the number of crashes resulting from converting the LT control mode from POLT to PPLT. This study was conducted in Kentucky using the data of 58 intersections (mostly “T” intersections). Speed limit, sight distance, and signal configuration data were collected at each intersection. A before-and-after analysis of crashes showed that the average number of left-turn crashes per year per approach increased from 1.1 to 2.1; however, the corresponding total number of intersection crashes decreased from 9.7 to 8.7. As mentioned in the study, part of this reduction was attributed to a reduction in the total number of rear-end accidents per year from 3.0 to 2.5.

Pulugurtha and Chittoor Khader (2014) performed a before-and-after analysis to evaluate the effects of using PPLT with an FYA on the number of LT-related and total intersection crashes. In this study, 18 candidate intersections in the City of Charlotte, North Carolina, were selected. The operating mode of the selected intersections was changed from protected-only or permissive-only to PPLT with an FYA. For each of the candidate intersections, the number of crashes, traffic volumes, and geometric characteristics were collected. Two negative binomial models for both the left-turn crashes and the total number of crashes were fitted by using the collected data for the before-change period. In these models, the dependent variable was the expected number of crashes, and the independent variables were the volumes of LT vehicles and the volumes of opposing traffic. The comparison of the number of crashes predicted by the models with those observed during the after-change period showed that the actual numbers of left-turn crashes were lower than the numbers of predicted crashes in 14 out of 18 case study intersections. Therefore, changing the LT control mode to PPLT with an FYA reduced the number of left-turn crashes. Furthermore, the actual total number of crashes at the intersections were lower than the estimated total number of crashes in 16 out of 18 intersections, which indicated the benefit of using PPLT with an FYA for reducing the total number of crashes at the case study intersections. Note that the study compared the **actual number** of crashes for the PPLT control mode with an FYA to the **predicted number** of crashes for the POLT or PRLT control modes. Therefore, the findings of this study should be interpreted with cautioun.

Simpson and Troy (2015) performed a before-and-after safety analysis of 222 North Carolina intersections by estimating safety performance functions to derive crash modification factors (CMFs). In this study, the change in the LT control mode from POLT and PRLT to PPLT with an FYA was considered. Crash data were categorized into total number of crashes, LT target crashes (left-turn crashes on the approaches that experienced the change), and injury crashes. Table 2-3 shows that the numbers of all types of crashes were reduced by changing from permissive-only to PPLT with an FYA. However, changing the control mode from protected-only to PPLT with an FYA increased the number of crashes, as shown by other studies.

Table 2-4. CMF due to the change from permissive-only or POLT to PPLT with an FYA (Simpson and Troy, 2015)

No	Mode of operation (before the change)	Sample size (number of intersections)	Crash Type	CMF
1	Permissive-only	13	Total	0.93
2	Permissive-only	13	Injury	0.65
3	Permissive-only	13	Target	0.74
4	Protected-only	20	Total	1.12
5	Protected-only	20	Injury	2.21
6	Protected-only	20	Target	3.44

Srinivasan (2011) investigated the impacts of converting permissive-only control mode to PPLT on left-turn and non-left-turn-related crashes. The data were collected from the City of Toronto, Canada, and urban areas of North Carolina. Data from 59 treated sites and 626 reference sites for the intersection-level analysis, as well as 46 treated sites and 552 reference sites for the approach-level analysis from Toronto were collected. The data from North Carolina were available just for the intersection-level analysis, including 12 treated sites and 49 reference sites. Utilizing the collected data, the Empirical Bayes approach was employed to develop crash modification factors (CMF) for several types of crashes: total, injury, rear-end, left-turn, and left-turn-opposing crashes. Table 2-4 shows the significant CMFs with a 95 percent significance level in this study. The CMFs show that changing from permissive to protected-permissive control mode reduced the left-turn opposing through-crashes for both approach-level and the intersection-level crashes. However, the total number of approach-level crashes increased.

Table 2-5. CMFs for the change in control mode from permissive to protected-permissive (Srinivasan, 2011)

No	Analysis Type	Crash type	Number of treated approaches	Data set	CMF
1	Intersection-level	Total	1 treated approach	Toronto and NC	1.081
2	Intersection-level	Left turn opposing through	All sites	Toronto and NC	0.862
3	Intersection-level	Left turn opposing through	>1 treated approach	Toronto and NC	0.787
4	Intersection-level	Rear-end	All sites	Toronto and NC	1.075
5	Intersection-level	Rear-end	1 treated approach	Toronto and NC	1.094
6	Approach-level	Total	-	Toronto	1.077
7	Approach-level	Injury and Fatal	-	Toronto	1.150
8	Approach-level	Left turn opposing through	-	Toronto	0.776

Maze, Henderson and Sankar (1994) fitted simple linear regression models to identify relationships between LT crashes at high-speed signalized intersections and associated geometrical characteristics of LT approaches, traffic volumes, signal phases, and approach speeds. Models were fitted with respect to two dependent variables: 1) the ratio of the number of LT crashes per approach to one million LT vehicles per approach and 2) the ratio of crashes per approach to one million traffic movements per approach. The linear regression models for each independent variable were fitted on the basis of three different LT volumes: low, medium, and high. The data for traffic and intersection characteristics were collected at 63 intersections in Iowa, which totaled 284 approaches. The collected crash records were dated before 1994. The models presented the following relevant findings:

- The POLT control mode had a lower likelihood for crashes than the PPLT or PRLT modes.

- Crash rates were lower for signal corridors than for isolated signals.
- Raised medians tended to increase the likelihood of crashes.

It is important to note that most parameter estimates in the models turned out to be statistically insignificant. The study suggested that this fact was related to the limited number of independent variables included in the modelling process.

Lee, Dittberner and Kweon (2012) compared the safety performance of intersections with dissimilar signal LT control modes on opposing LT approaches (namely POLT on one approach and PPLT on the other) with that of intersections with PPLT phases on both opposing LT approaches. LT crash data were acquired for the two types of intersections. The study group included the data from 18 intersections with LT opposing approaches operating as POLT/PPLT. The subject group included the data from 505 LT opposing approaches operating as PPLT/PPLT. The data were received from the Virginia Department of Transportation. First, average crash rates of the two groups were compared. Second, a negative binomial regression model for predicting the expected frequency of annual permissive crashes was fitted. The results showed that the average crash rate for the PPLT/PPLT group was higher, which was confirmed by the prediction model as well. The research team could not substantiate the results because of the limited data; they recommended increasing the sample size for the subject group for further evaluation.

2.1.2. Operations

Lei et al. (2008) investigated the required criteria for choosing an appropriate LT control mode from POLT and PPLT. They selected 26 intersections in Austin, Houston, and Lufkin, Texas. Three hours of videotaped traffic data, GPS data from two probe vehicles, signal timing parameters, and geometry were collected at each intersection. Six intersections with the PPLT control mode and three intersections with the POLT control mode were modeled in Vissim. The calibrated models in Vissim allowed scenarios to be compared with different combinations of control modes and phasing sequences. As a result, the following findings were identified:

- The PPLT mode should be selected for intersections with one opposing through-lane when the cross-product of the LT volumes and opposing through-volumes is equal to or less than 133,000.
- The PPLT mode should be selected for intersections with two opposing through-movement lanes when the cross-product of the LT volumes and opposing through-volumes is equal to or less than 93,000.
- The PPLT control mode has less delay than the POLT control mode

2.2. Four-Section and Doghouse Traffic Signal Displays

2.2.1. Safety

Fisher and Obery (2009) compared the number of crashes before and after changing the traffic signal display of five intersections from doghouse to four-section vertical displays with an FYA in Oregon. They claimed that the left-turn-related crashes decreased from 1.1 to 0.35 crashes per year per intersection. In fact, the benefit/cost ratio was 8:1. However, the results were not supported by any statistical techniques. Although this document did not provide the details of their data collection and their methodology, the simple comparison of crash rates showed the safety benefits of using four-section vertical displays with an FYA in Oregon.

Srinivasan (2011) used EB analysis to evaluate the safety impacts of installing the FYA as a permissive LT indication. In this report, CMFs were developed on the basis of a historical before-and-after crash analysis of the intersections where FYA had been installed. The required data were collected from the City of Kennewick, Oregon, and North Carolina. The study intersections were divided into two groups. Group one included intersections for which a doghouse signal display was changed to PPLT with an FYA at one leg and from permissive to PPLT with an FYA at another leg (five intersections). In group two, the change was from the doghouse signal display to PPLT with an FYA at two legs of the intersections (six intersections). In this group, the estimated CMFs showed that the total number of intersection crashes and LT crashes decreased with CMFs equal to 0.922 and 0.806, respectively. However, the reductions were not significant at a 95 percent confidence level.

Simpson and Troy (2015) performed a before-and-after crash analysis of 105 intersections in North Carolina to investigate the effects of changing the signal display of intersections from a doghouse to a four-section display with an FYA. In this study, crash data from three years before the change and data from two to three years after the change were used to estimate safety performance functions. The results showed that by changing the signal displays, the total number of crashes decreased by 7 percent, injury crashes by 15 percent, and LT-related crashes by 22 percent. The results were statistically significant.

Qi et al. (2012) studied the safety impacts of converting PPLT with a circular green (CG) to PPLT with an FYA (see table 2-2). The study identified safety issues directly related to the FYA phasing at two of the intersections. The safety issue is called **steady-yellow-arrow confusion**. This issue arises when some drivers mistakenly accept the steady yellow arrow indication for the FYA during the change of interval. Crashes/conflicts may be created if a driver who proceeds into the intersection during the steady yellow arrow signal decides to yield instead of clearing it immediately.

In addition, the study described how the steady-yellow-arrow confusion became problematic for one of the intersections operated under a lead-lag PPLT phasing sequence with high LT volumes (an LT V/C ratio of 0.97). In that case, during the leading-protected phase, LT drivers were likely to enter the intersection at the onset of the steady yellow arrow signal. Next, because of the high LT volumes, the leading-protected phase was most likely to be terminated at the same time as the adjacent through-movement signal phase. Then, if a driver had stopped in the intersection because of steady-yellow-arrow confusion, they may have mistakenly believed that a cross-street movement would begin because they could see that the indications for the LT and adjacent through-movements turned red.

The study recommended using an extended red clearance interval, about 3-4 seconds, between the steady yellow arrow and the FYA to improve the safety of confused LT drivers.

NCHRP project 3-54 analyzed LT crashes associated with the following permissive LT indications at 24 subject intersections located in eight states (Brehmer et al., 2003): green ball, flashing red arrow, flashing red ball, and flashing yellow ball.

Three years of crash data were collected, and the following four statistics were used to quantify crash rates: 1) average number of crashes per year per intersection, 2) the average number of crashes per year per 100 left-turning vehicles, 3) the average number of crashes per year per 100,000 left-turns multiplied by opposing through -vehicles, and 4) the average rate for the intersection based only on left-turn crashes. Table 2-6 to table 2-8 summarize the findings.

Table 2-6. Ranking of PPLT performance based on crashes per year (NCHRP Report 493)

City	PPLT Indication	Crash Rate
Seattle	Circular Flashing Yellow	0.75
Cupertino	Flashing Red Arrow	0.83
Dover	Flashing Red Arrow	0.85

Portland	Circular Green	1.04
Orlando	Circular Green	1.48
Dallas	Circular Green	2.06
College Station	Circular Green	2.53
Oakland County	Flashing Circular Red	2.92

Table 2-7. Ranking of PPLT performance based on crashes per 100 left-turning vehicles (NCHRP Report 493)

City	PPLT Indication	Crash Rate
Seattle	Circular Flashing Yellow	0.47
Portland	Circular Green	0.71
Orlando	Circular Green	0.73
Cupertino	Flashing Red Arrow	0.87
Dover	Flashing Red Arrow	0.96
Dallas	Circular Green	1.10
Oakland County	Flashing Circular Red	1.23
College Station	Circular Green	2.29

Table 2-8. Ranking of PPLT performance based on crashes per 100,000 left turns multiplied by the opposing through-vehicles (NCHRP Report 493)

City	PPLT Indication	Crash Rate
Seattle	Circular Flashing Yellow	0.87
Cupertino	Flashing Red Arrow	0.91
Orlando	Circular Green	0.92
Oakland County	Flashing Circular Red	1.18

Dover	Flashing Red Arrow	1.85
Portland	Circular Green	2.27
Dallas	Circular Green	4.56
College Station	Circular Green	6.75

Table 2-9. Ranking of PPLT performance based on average left-turn crash rate (NCHRP Report 493)

City	PPLT Indication	Crash Rate
Cupertino	Flashing Red Arrow	0.28
Dover	Flashing Red Arrow	0.29
Dallas	Circular Green	0.34
Seattle	Circular Flashing Yellow	0.34
Oakland County	Flashing Circular Red	0.44
Orlando	Circular Green	0.49
Portland	Circular Green	0.52
College Station	Circular Green	0.70

The study reported that the crash rate rankings of the LT permissive indications were not consistent among the four crash statistics. Moreover, no correlation was found with the findings of the conflict study conducted under this project.

NCHRP project 3-54 performed a field conflict/event study to evaluate LT traffic conflict rates and events associated with various PPLT signal displays and their permissive LT indications (Brehmer et al., 2003). The research team selected 24 intersections from eight states. The intersections contained the following PPLT signal displays: five-section (in cluster, vertical, and horizontal forms), four-section (in cluster and vertical forms), and three-section (in vertical form). The permissive LT indications included a green ball, flashing red arrow, flashing red ball, and flashing yellow ball. The FYA indication was not available for studying at the time of field data collection in 1999.

The study defined four types of traffic conflicts:

- Type 1 - opposing LT conflicts
- Type 2 - LT/same direction conflicts
- Type 3 - LT/lane change conflicts
- Type 4 - secondary conflicts, such as those involving a pedestrian or bicyclist or resulting from a lane overflow.

Also, the study defined four types of traffic events:

- Type 1 - driver hesitating on the LT protected indication
- Type 2 - driver hesitating on the LT permissive indication
- Type 3 - driver going through the circular red indication
- Type 4 - driver backing a vehicle out of the intersection, back into the LT lane.

Observers recorded defined traffic conflicts and events at each intersection. Additionally, each intersection was equipped with a video camera to videotape LT movements. Later, the videotapes were reviewed to verify recorded observations manually. This project recorded 11 hours of data at each of the 24 intersections.

The study found that the left-turn conflict rates were low for all PPLT displays evaluated. The PPLT display was associated with few LT conflicts, most of which were related to driver hesitation at the onset of the green indication. Furthermore, the cause of 146 of the 155 Type 1 conflicts appeared to be aggressive driving, and the cause of eight Type 1 conflicts appeared to be the driver’s assumption that the right-of way was granted when the left-turn permissive circular green indication was illuminated. Of those eight conflicts, two occurred at intersections with a five-section horizontal PPLT arrangement, and the remaining conflicts occurred at intersections with a five-section cluster PPLT arrangement. Another Type 1 conflict was observed when the driver assumed the right-of-way when a left-turn permissive flashing red arrow indication was illuminated on a four-section cluster arrangement. Furthermore, nine Type 2 conflicts were caused by driver hesitating to turn left on the left-turn permissive indication.

Overall, many drivers proceeded through the intersection during the all-red indication in Type 3 events. However, this occurrence was not shown to be influenced by the PPLT signal display, indication, or phasing. Another major finding of this study was that the five-section horizontal PPLT signal display arrangement caused most of the Type 1 traffic events because of an increase in driver workload cause by the simultaneous illumination of the green arrow and the circular red indications. Also, 33 of the 37 Type 4 events were associated with a flashing permissive indication. In those events, the driver entered the intersection during the permissive phase and did not have the opportunity to make a left-turn, so the driver chose to back up.

NCHRP project 3-54 evaluated the safety and operations effects of FYA displays that were installed at 15 test locations within four different states (Brehmer et al., 2003). In addition, technical/non-technical issues and implementation costs were documented. This study was conducted to fill the gap in field data available on FYA performance at the time of study in 2000. At the onset of the study, one of the participant states decided to withdraw from participation because of a crash unrelated to the FYA; that reduced the number of studied intersections to 12. In addition to study intersections, participating agencies were required to identify control intersections where the FYA would not be installed for comparison purposes.

LT traffic at intersections was videotaped for 16 hours during the before and after FYA installation periods to conduct conflict studies along with follow-up headway studies. The comparison of conflict rates for both periods showed a negligible difference. In addition, the implementation of the FYA had little impact on the follow-up headway in comparison to that of the *before* period. Being a relatively novel indication in 2000, the FYA received mostly positive feedback from the local public.

Qi et al. (2012) compared the safety performance of including an FYA in PPLT phasing by converting a five-section horizontal display to a four-section horizontal display with FYA at five intersections. They performed a before-after analysis and considered LT conflicts and events as their safety measures. The intersections shared the following initial features:

- Five-section horizontal displays with CG to indicatie permissive LT
- PPLT phasing sequences: Lead-Lead or Lead-Lag
- Exclusive LT lanes
- Relatively high LT crash rates
- No nearby FYA applications
- Various geometric and traffic conditions.

They collected data at five intersections over a period of five days before and five days after implementation of the FYA indication. The research team collected field counts for defined traffic conflicts and events and videotaped LT traffic volume. Before and after counts for each type of conflict/event at each intersection were normalized per total hours of observation during each period, respectively. Next, the change rates between the *before* and *after* periods of conflict/event rates were tested for statistical significance at a 95 percent confidence level by using an independent nonparametric test (not specified which test).

The inclusion of an FYA phase reduced LT conflicts at four intersections out of the five. Only at one intersection was the FYA associated with a higher number of LT conflicts between subject left-turn (or U-turn) and opposing through-movement traffic. Qi et al. (2012) reported the following reasons:

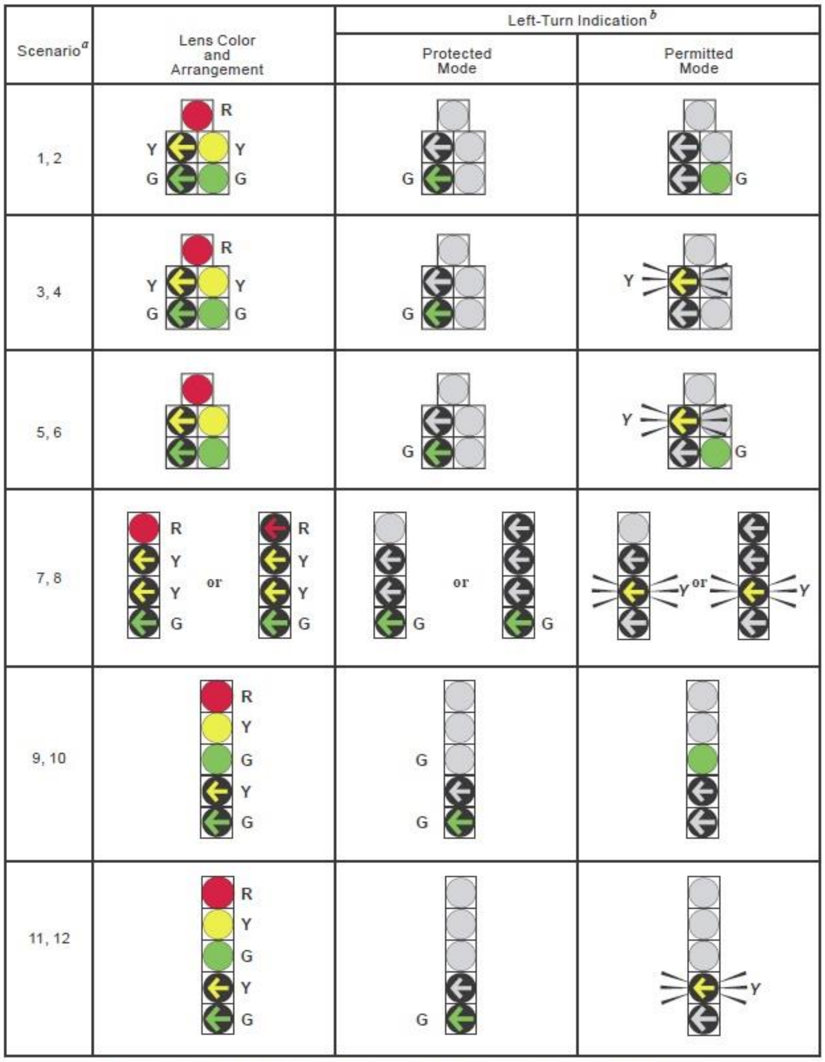
Awareness of this phenomenon was realized as a result of an increase in the opposing through-movement vs. LT movement conflict rate at one of the intersections. In fact, this conflict was the sole contributor to the overall increase in *after* period traffic conflicts for this intersection. The intersection had high LT volumes and the highest volume-to-capacity ratio of all intersections. Under such conditions, LT drivers experience uneasiness because of a lack of adequate gaps in opposing through-traffic to make permissive left turns. Therefore, LT drivers are inclined to make risky left turns during the permissive phase. In addition, the FYA may enforce this inducement more than the CG permissive indication, according to the interviewed drivers.

The inclusion of an FYA phase reduced the number of events in three out of five intersections. In the other two intersections, the inclusion of the FYA increased red-light running and rolling back to the stop bar events for left turning vehicles. Qi et al. (2012) attributed this increase to the following reasons:

- High LT and opposing through-traffic volumes
- Misrecognition of the steady yellow arrow for an FYA
- Drivers habitually proceeding to the middle of intersection to make permissive left turns.

NCHRP project 3-54 performed a driver confirmation study using a motion-based driving simulator to evaluate participants' understanding of 12 PPLT signal displays (Brehmer et al., 2003). In the virtual environment of the driving simulator, simulated traffic intersections were had LT protected-only and protected-permissive modes indicated on five-section cluster, five-section vertical, and four-section vertical traffic displays. The green arrow was selected to indicate protected left-turns. The green ball and the flashing yellow arrow were chosen to indicate a permissive left-turn (see figure 2-1). In addition to the driving simulator experiment, participants' understanding of the same 12 PPLT signal displays was tested by having them screen videotaped, still images of simulated intersections.

During the driving simulator test, as drivers drove in the simulated environment, they encountered each PPLT signal display at intersections sequentially. During permissive LT scenarios, drivers encountered opposing through-vehicles as well. Test drivers were required to act in response to the LT signal as left-turning drivers. Furthermore, they were to announce their observations. Two team members were present at each test to observe and record drivers' response actions and remarks manually. In addition, each test was videotaped to verify the manually recorded data. The driving simulation test took 15 to 20 minutes to complete. After the completion, the drivers were asked to complete the aforementioned video-based static test. Each of the 12 PPLT signal displays was shown for 30 seconds; after which, the participants answered how they would proceed as LT drivers.



R = RED Y = YELLOW G = GREEN *Y* = FLASHING YELLOW

[a] 1, 3, 5, 7, 9, 11 -GB 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 2-1. Twelve PPLT signal display scenarios (Brehmer et al. 2003)

The driver confirmation study was conducted at two locations. A total of 316 evaluations from the driving simulator and 436 evaluations from the video-based static tests were aggregated and analyzed for statistical significance using ANOVA methods. The results of the driving simulator and video-based static tests were analyzed individually and compared with each other. The following are selected findings from this study.

Driving simulator findings:

- Overall, drivers' responses showed a high level of understanding of the tested PPLT displays. 91percent of the drivers responded correctly with no statistical difference across the 12 PPLT displays.

Static evaluation findings:

- Overall, drivers' responses reflected a high level of understanding of the tested PPLT displays. 83 percent of the drivers responded correctly.
- Scenarios in which the left-turn indication was green and the adjacent through-movement indication was red resulted in a significantly lower percentage of correct responses. This finding was yet more proof that conflicting color indications between LT movements and the adjacent through-movements increase confusion among LT drivers.

Comparison of driving simulator and static evaluation findings:

- Overall, the correct response rate for the driving simulator test was significantly higher than that of the video-based static evaluation test.
- The research team identified that during the actual driving, LT drivers had more visual clues to compensate for their possible misunderstanding of the PPLT display instructions, such as following the lead vehicle, evaluating opposing traffic, and accepting adequate gaps.

Noyce and Smith (2003) evaluated drivers' comprehension of different five-section signal displays with different permissive LT indications. In this study, 15 signal scenarios were created out of three types of five-section displays: five-section horizontal, five-section vertical, and five-section clustered; and five different permissive indications: CG, circular flashing red

(CFR), circular flashing yellow (CFY), flashing red arrow (FRA), and FYA. These scenarios were featured in both a driver simulator test and a static survey. The analysis of 34 completed tests showed that the type of five-section display did not have a statistically significant influence on driver comprehension. However, the type of indication had a significant effect on explaining driver comprehension. The CG, CFY, and FYA displays were among the best understood indications. In considering combinations of signal displays and left-turn indications, the five-section horizontal signal display with CFY indication was rated highest for driver comprehension.

NCHRP Project 3-54 conducted a photographic driver study to test LT drivers' understanding of PPLT signals used in the U.S. as of 1999 (Brehmer et al., 2003). Specifically, the study tested the understanding of all-red, protected LT, and permissive LT indications of prevailing traffic displays encountered by LT drivers at typical signalized intersections.

A computer-based test was designed to administer the study. The design incorporated photo images of actual intersections taken from the viewpoint of a left-turning driver to enhance the fidelity of study. Each image contained displays for left-turn and adjacent through-movements. The images served as static background for traffic signals, whereas the signal indications were applied over images as computer graphics; flashing indications were animated. The intersection images were selected from three categories that were based on 1) the mounting type of a PPLT signal display, 2) the location of a PPLT signal display, and 3) the geometric configuration of an intersection. Two images from each category were selected—six intersection images in total. Two hundred scenarios were created that varied in display arrangement, location, mounting; permissive/protected LT indications, and through signal indications. The permissive LT indications included the following: green ball, flashing yellow ball, flashing yellow arrow, flashing red ball, and flashing red arrow. For each test, 30 different scenarios were selected randomly out of 200 scenarios. On the basis of these scenarios, the participants—licensed drivers—were asked to make their choices as left-turning drivers. Each scenario was followed by one typical question: "If you want to turn left, and you see the traffic signals shown, you would …" The participants had four options to answer the question: 1) Go; 2) Yield. Wait for a gap; 3) Stop, then wait for a gap; 4) Stop. Each answer was recorded along with the duration of time spent to make a choice. The response time was used to gain additional insight into a participant's understanding of a PPLT signal indication. In addition, demographic information was collected from participants using the same software.

Understanding of all-red, protected, and permissive indications was assessed by grouping the responses into various factors (such as display type, indication type, age etc.) and evaluating the percentages of correct responses within each factor. ANOVA methods were applied to evaluate the statistical significance of results at a 95 percent level of confidence.

The study was administered to licensed drivers in the following eight locations: Dallas, Texas; Dover, Delaware; Oakland County, Michigan; College Station, Texas; Seattle, Washington; Portland, Oregon; Cupertino, California; and Orlando, Florida. Most test sites were hosted in local departments of motor vehicles. The participants were asked to take the test on computer workstations; their responses were recorded on the hard drives of those computer workstations. Then, all the records from each workstation were aggregated into a spreadsheet.

According to the NCHRP 493 report, "A total of 2,465 drivers participated in the study, exceeding the target of 2,400 participants. At least 300 drivers completed the study at all but one of the eight locations. Because each study respondent was presented with 30 scenarios, a total of 73,950 responses were recorded. Of the 2,465 drivers, 58 percent were male, 41 percent were female, and the balance (1% percent) did not respond to the gender question." The following relevant findings are presented below:

- Flashing permissive LT indication is better understood than a solid permissive LT indication. Overall, the average response time for flashing permissive indications were lower.
- In scenarios with exclusive protected left-turns (exclusive display for LT), four-section and three-section PPLT displays had the highest number of correct survey responses.
- In scenarios with protected left-turns, the average survey response time related to the five-section PPLT displays was larger than the average of all response times for all PPLT displays.
- The permissive CG indications accounted for very low correct rates for drivers over the age of 65.
- The flashing yellow permissive indications accounted for higher correct response rates for drivers over the age of 65 than other age groups.

Drakopoulos and Lyles (2000) evaluated the driver comprehension associated with several LT permitted and protected signal displays. In this research, they surveyed a total of 191 subjects from Philadelphia, Penn.; Seattle, Wash.; Dallas, Texas; and Lansing, Michigan. Each of the subjects was presented with a combination of 81 LT signs and illuminated signal lenses in 17 different combinations of signal display and roadway configuration. Analysis results of the collected data indicated that permissive LT indications other than CG, including FRA, FYA, and flashing circular yellow (FCY) enhanced driver comprehension. They also identified that it was beneficial to complement the permissive LT phases, run by doghouse displays, with the sign -

"Left Turn Must Yield on Green Ball." However, the message of the sign was confusing when left-turning vehicles had a protected green indication and, at the same time, the signal of the adjacent through-movement was green.

The Missouri Department of Transportation administered a driver comprehension survey in Creve Coeur, Missouri to compare the comprehension of an FYA permissive indication in four-section-vertical signal displays with that of a CG permissive indication in doghouse signal displays with the sign "Yield on Green" (Henery, 2008). The survey participants/drivers were selected from the neighborhoods of Creve Coeur, Missouri, where an FYA signal was operational. A total of 204 drivers above the age of 15 were selected to participate in the survey. The questionnaire presented different traffic signals, and participants had to select the correct action as LT drivers (see figure 2-2). Also, questions about the age of the participant and whether this participant had seen FYA indications before were included.

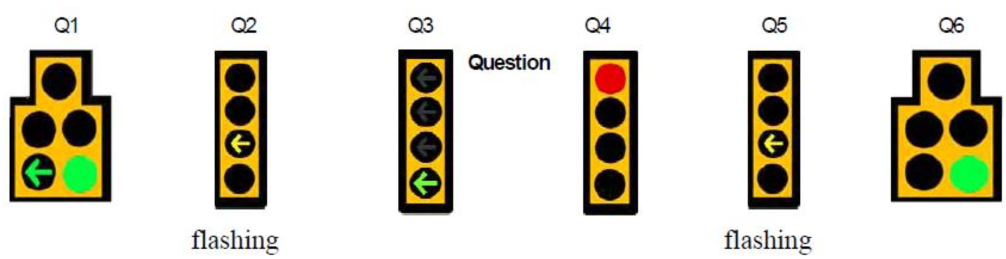


Figure 2-2. Different signal combinations in the study by Henery (2008)

This study compared correct response rates among the scenarios. The results showed that the CG permissive indication with the sign of "Yield on Green" was understood correctly by 94 percent of participants, but the FYA indication was understood correctly by 72.4 percent of participants. Furthermore, the analysis of correct response rates by driver age showed that experienced drivers in the age categories of 24 to 44 and 45 to 65 had higher rates of correct answers than those in the age category of under 24. Similarly, drivers who had been exposed to the FYA indication before had a higher number of correct answers in questions related to the FYA indication. However, this study did not perform any statistical tests to determine whether the correct answers were statistically different. Therefore, although the CG indication was understood better, comprehension might not have been statistically different from that of the FYA indication. As a result, the report recommended proceeding with caution when installing FYA phases at more locations within Missouri. In addition, it recommended launching a public information campaign to increase familiarity with the FYA among drivers during FYA installations.

Noyce et al. (2014) compared drivers' comprehension of bimodally retrofitted FYA indications in three-section and doghouse displays with that of the standard four-section display with FYA. Additionally, comprehension was evaluated with respect to the location of bimodally operated FYA indication within either green arrow or steady yellow arrow faces. To perform such evaluations, a static, computer-based survey and a full-scale driving simulator study were designed. The static survey tested the understanding of 12 different scenarios of LT signal indications shown within the three study displays. Over 440 local drivers of Madison, Wisconsin, and Amherst, Massachusetts, took the survey in three weeks. When the static survey results were compared with respect to the location of the FYA—whether the FYA indication was in the middle section or the bottom section of the displays—the results showed no statistically significant difference in the drivers' understanding. The comprehension of the FYA was the lowest for the scenario with the doghouse display in which LT movement and through-movement indications were illuminated simultaneously. However, the authors concluded that the signal display arrangement did not affect drivers' comprehension of the FYA indication overall. In the driver simulation study, 56 drivers participated, and for 16 of those, the eye tracking records were stored. The results showed no statistically significant difference in comprehension of the FYA when it operated bimodally at the bottom or the middle of a three-section signal display. However, driver comprehension was significantly lower when the bimodal FYA was illuminated in the doghouse display with the through-movement indication illuminated at the same time. The study suggested that the FYA could be retrofitted in three-section displays with steady yellow arrow or green arrow indications without negatively affecting drivers' comprehension. However, retrofitting the FYA in doghouse displays was not recommended.

Rescot et al. (2015) investigated some of the installation challenges of using four-section signal displays with an FYA at two intersections in Indiana. The study identified that the prevailing structures for holding the LT signal displays might not be appropriate for vertical mounting. Therefore, an LT display might need to be mounted horizontally. One of the study objectives was to compare drivers' comprehension of horizontally placed vs. vertically placed LT displays. A survey with 12 different signal scenarios was conducted in Vincennes and Richmond, Indiana; 53 individuals participated in the survey. The results of correct response rates showed no statistically significant difference between the signal display arrangements - vertical or horizontal. The only concerning scenario was the case in which the solid yellow arrow was displayed with the adjacent CG through-movement illuminated, which resulted in 11 percent of the incorrect answers. Also, they used a radar gun to record the speed, deceleration, and acceleration of 67 vehicles approaching the four-section with an FYA and the regular doghouse signal displays. By performing a t-test on the mean values of vehicle speeds and accelerations (decelerations), the authors concluded that there was no difference in the way vehicles performed.

Knodler Jr et al. (2006) investigated whether LT drivers were aware of the need to yield to pedestrians during the FYA phasing and whether the FYA indication influenced pedestrians to find walking opportunities when the pedestrian signal was not present. The study team designed a driving simulator test and a static computer-based survey for both drivers and pedestrians. In the simulated network, 36 drivers faced intersections with and without pedestrian activities while they were performing left-turn maneuvers. In the static survey, 136 drivers were tested on their comprehension of the right of way in the presence of pedestrians at the intersections. Additionally, 100 pedestrians were tested on their knowledge for utilizing opportunities to cross streets on the basis of the signal indications for conflicting left-turning movements when the pedestrian signal was not present. The analysis results suggested that the FYA indication could be used at intersections with pedestrian activities and that the FYA did not degrade operational conditions, since tested drivers and pedestrians comprehended the right-of-way rules and the opportunities for crossing the streets when a pedestrian signal was not present.

Hurwitz and Monsere (2013) studied how drivers visually process information while making permissive left-turns on an FYA indication when pedestrians impede the LT movement. It was noted that during protected LT phases, LT drivers are freed from having to visually evaluate the presence of pedestrians conflicting with their right of way.

The study was conducted with a driving simulator. Six intersections were simulated in the virtual environment, and 27 participants drove in the simulated environment. A total of 620 permissive LT movements were analyzed. The analysis evaluated eye-glance durations fixed on the following visual variables: LT pavement lane markings, the signal indication, the pedestrian and vehicle waiting area, and the pedestrian signal heads. The data collected were tested for statistical significance. The relevant findings are as follows.

According to the study, “1) the increased presence of pedestrians led drivers to pay more attention to the crossing pedestrians, 2) as the number of opposing vehicles increased, drivers spent less time fixating on pedestrians, 3) four to seven percent of drivers did not focus on pedestrians in the crosswalk.” The practical suggestion of the study was to consider limiting permissive LT phases when pedestrians are present.

Hurwitz et al. (2014) evaluated drivers’ comprehension of the FYA in three-section and four-section traffic signals in the permissive phase in the presence of pedestrians. This study utilized a driving simulator at Oregon State University equipped with an eye tracking system. In the simulated environment, drivers faced zero, three, or nine oncoming vehicles with one or two pedestrians walking from both sides simultaneously and two different signal displays. Data from 27 subjects with a total of 620 left-turns were analyzed to measure the average total eye fixations at specific locations, and the positions of pedestrians when the left-turning movements were initiated. The results of this analysis showed that the largest fixation duration was on the opposing traffic, and the fixations were not significantly different for the two signal displays. Moreover, the positions of pedestrians were significantly different for the three-section and four-section signal displays when a single pedestrian was walking away from the left-turning vehicle. However, overall, the performance of drivers was not influenced by the signal display configuration.

Appiah and Cottrell (2014) evaluated the impacts of FYA delay on safety and operations in the PPLT control mode. The FYA delay is defined as the duration of the red arrow that follows the protected LT indication and precedes the permissive LT indication. More precisely, the duration of the red arrow that is illuminated after the steady yellow arrow before the onset of the FYA is referred to as the FYA delay. This study surveyed state DOTs and consulted with practitioners to collect different opinions and practices regarding the FYA delay application. The responses in favor of using such a delay were based on the perceived safety benefits for left-turning drivers. The safety benefits were related to a reduction in confusion among drivers through employment of a set of distinct transitions between different phases and allowing the opposing through-traffic to establish the right of way through the intersection. However, other practitioners believed that it would increase the total delay of an intersection, since the duration of a red arrow indication is usually set up to be short (less than 2 seconds). In addition, the increased FYA delay can confuse LT drivers into thinking that the signal controller is malfunctioning, which would raise complaints about the signal's operation.

To evaluate the safety and operational impacts of using the FYA delay, this study performed a simulation study on an isolated intersection with PPLT control mode and lead-lead phasing sequence. The authors concluded that traffic conflicts could be reduced significantly by using the FYA delay except for a scenario with high LT volumes, low opposing traffic volumes, and a short FYA delay of 2.0 seconds; in that case a higher number of conflicts were observed than in the case of the same conditions but without the FYA delay. In addition, in all scenarios with FYA delays of 2, 4, and 8 seconds along with opposing through-traffic volumes of 800 and 1200 vph, the average LT conflict rates were significantly reduced, and the negative impacts on the average delay, average queue length, and average stopped delay were statistically insignificant.

2.2.2. Operations

Almoshaogeh (2014) evaluated the operational impacts of using four-section and five-section signal (doghouse) displays in Central Florida on delay and the number of processed left-turning vehicles. The research team collected data from 13 intersections located in Orlando, Florida, to conduct the analysis. Among the selected intersections, seven intersections were operating with a four-section signal display with an FYA, and the rest were operating with a doghouse signal display. For each intersection approach, seven hours of LT traffic were videotaped. After analysis of the video records, four different models were derived to estimate the delay of left-turning vehicles and the processed LT volumes due to the use of four-section and doghouse signal displays. Next, 109 hours of field observation data were fed into the developed models. Next, the authors performed a t-test analysis on the estimated values for the delay and the number of processed LT vehicles. The analysis results showed that the mean values for the delay of left-turning vehicles in the four-section FYA signal display were statistically lower than the delay of left-turning vehicles with the doghouse signal display. Furthermore, the number of processed left-turning vehicles was higher fir the four-section display with an FYA than for the doghouse signal display.

NCHRP project 3-54 conducted a field traffic operations study to evaluate the impacts of various PPLT signal displays and their LT permissive indications on LT-lane capacity and delay (Brehmer et al., 2003). A total of 26 study intersections were selected from eight states. The intersections included the following display arrangements: five-section (with cluster, vertical, and horizontal displays), four-section (with cluster and vertical displays), and three-section vertical. The permissive LT indications included green ball, flashing red arrow, flashing red ball, and flashing yellow ball. At the time of field data collection in 1999, the FYA indication was not available for studying.

The operational impacts on LT-lane capacity and delay were measured by collecting the following performance measures: saturation flow rate, start-up lost time, response time, and follow-up headway. The study observers collected data by using portable computers to record LT traffic headway data. Also, each intersection was equipped with a video camera to record LT traffic volumes. Once the headway data had been collected, they were converted to performance measures. Next, a statistical analysis was performed to evaluate whether the PPLT signal display, PPLT signal phasing, and the location significantly contributed to the variability of the saturation flow rate, start-up lost time, and response time between intersections. The variability in the follow-up headway data between the PPLT signal display and permitted LT indication factors was tested for statistical significance. The findings were as follows:

- The variance in average saturation flow rate data was significantly influenced by the location factor, but the PPLT signal display and phasing factors were not statistically significant.
- The variance in start-up lost time was significantly influenced by the PPLT signal phasing factor, but the PPLT signal display and location factors were not statistically significant.
- Most of the variability in response time data was influenced by the PPLT signal phasing factor. The PPLT signal display and location factors were statistically significant as well.
- There was no statistical difference in the variance of average follow-up headway for each PPLT signal display and permissive LT indication, except for the four-section cluster display with a flashing red arrow. The drivers at those locations were required to stop before proceeding with a permissive LT, which was noted by a supplemental sign.

Schattler et al. (2013) compared the operational and safety effects of converting CG permissive LT indications to an FYA. Sixteen PPLT study approaches were selected in Peoria, Illinois, for data collection. Sixty-four hours of *before* conversion and 64 hours of *after* conversion video data were recorded. To compare operational effects, a median gap-size accepted variable was chosen. For comparing safety effects, the following variables were considered: red-light running, yellow-light running, and LT traffic conflicts. Comparisons were tested for statistical significance at a 95 percent confidence level by using two-tailed t-test. The following comparison results were reported: 1) the difference in the median gap-size accepted was not statistically significant, 2) the difference in red light running and yellow light running rates were minimal 3) the difference in traffic conflicts was not significant.

Rietgraf and Schattler (2013) evaluated drivers' behavior at ten study approaches of "T" intersections in Peoria, Illinois. These intersections had conditions that were similar as possible except for the permissive LT indication: CG, FYA, and FRA. Each study approach was videotaped for four hours in two-hour intervals during the peak hour of the LT movements. To evaluate driver behavior, driver actions were divided into unsafe actions (accepting inadequate gaps, accepting an adequate gap but proceeding to the intersection without stopping or slowing down when opposing traffic was present), efficient actions (accepting the first available adequate gap), and inefficient actions (rejecting the first available gap and accepting the next either adequate or inadequate gap, or waiting for the next protected LT phase). The results of the analysis in the first phase showed that the intersections with the FRA had the highest rating for safe actions, but the percentage of efficient actions was lower for it than for the CG and FYA. In the second phase of this study, the authors planned to evaluate the comprehension of CG in a city where several types of LT indications were used and CG was the only permissive indication in use. Therefore, in this phase, two intersections in Peoria and two intersections in Bloomington, Illinois, were videotaped for four hours. The city of Peoria had different permissive LT indications, while in Bloomington, all permissive LT indications were CG. The analysis of drivers' behavior at the selected intersections showed that having different LT indications (as in Peoria) did not have a statistically significant impact on either drivers' behavior or traffic operations.

NCHRP project 3-54 designed an evaluation matrix to assist in evaluating qualities needed for choosing the "best" indication for the PPLT control (Brehmer et al., 2003). The research team identified questions to be answered for selected permissive LT indications and grouped them into the following categories: safety, operations, implementability, human factors, and versatility. Each answer to the question for a related indication was rated on a scale of 0 to 4. Sound engineering judgment governed the ratings where appropriate. In other cases, the evaluation matrix was updated on the basis of the findings of other tasks under this project.

Table 2-10 presents the evaluation assessment matrix, in which the five-section display with CG permissive indication was evaluated against an FYA. The five-section display was defined to include cluster, vertical, or horizontal arrangements, whereas, the FYA was defined to be included in four-section vertical or horizontal displays, as well as in three-section vertical or horizontal displays.

As can be seen from the evaluation matrix, the FYA was ranked higher in almost all categories than the traditional five-section display with CG. However, under the implementability category, it was ranked a little lower because the MUTCD did not include updated provisions for the FYA at the time of publication in 2002.

Table 2-10. Engineering assessment matrix (Brehmer et al. 2003)

#	Questions to be answered	Traditional 5-Section with CG indication	Flashing Yellow Arrow

	Safety		
S-1	Is it fail-safe? Is a misunderstanding of the indication likely to result in a safe action?	0	2
S-2	Can the indication eliminate the yellow trap under all operational and field conditions?	0	4
S-3	Can a red clearance be displayed after leading left?	0	4
S-4	Can the start of permissive indication be delayed?	0	4
S-5	Does it avoid dilution of the safety or meaning of other indications?	3	3
S-8	Are conflicts reduced?	0	1
	Total	3	18
	Operations		
O-1	Does the indication increase total delay to the driver due to indecision, increased start-up lost times, reduced travel speeds, and/or lower saturation flow rates?	3	4
O-2	Does the indication impact pedestrian movements?	2	2
O-3	Can the indication be used with lead/lag operation?	0	4
O-4	Does the indication impact the opposing left-turning traffic?	1	4
O-5	Does the indication allow the skipping of all side-street phases?	0	4
O-6	Is the indication consistent with flashing indications?	4	4
O-7	Does operating the intersection in flashing mode provide negative consequences?	4	4
O-8	Does the indication lead to false starts or related driver errors?	1	3
	Total	15	29
	Implementability		
I-1	Are there significant issues with installation? Can the indication be placed to meet with the current MUTCD requirements?	4	2
I-2	Are there issues with conversion of existing indications?		
	-Convert a signal currently using traditional 5-section indication?	4	1
	-Convert a signal currently using permissive-only?	2	2
	-Convert a signal currently using protected-only?	2	3
I-3	Are there legal issues to consider including the Uniform Vehicle Code and state and local laws?	4	3
I-4	Does the signal indication permit maximum number of signal phasing strategies?	0	4
	Total	16	15
	Human factors		
H-1	Is the indication universally understood? Does the indication meet both priori and ad hoc driver expectancies?	2	3
H-2	Do drivers respond correctly to the information presented?	2	2
H-3	Do drivers accept the indication? Does the indication increase driver workload, reduce conspicuity, or increase driver error?	2	2
H-4	Are supplemental signs required for understanding?	0	4
H-5	Do drivers exposed to the "new" indication easily learn the meaning?	2	3
H-6	Is the signal indication fail-safe? What are the consequences of a driver misinterpreting the signal indication message?	0	2
	Total	8	16
	Versatility		
V-1	Does it allow permissive-only operation?	4	4
V-2	Does it allow protected-only operation?	0	4
V-3	Does it allow change between modes of operation by time of day?	0	4
V-4	Can it be used on curved approaches?	4	4

V-5	Does it allow two far-side LT heads in customary locations?	4	4
V-6	Does it allow use of any phase sequence?	0	4
V-7	Is it applicable to right turns as well as left?	2	4
V-8	Can it be used with span wire-mounted signals?	4	4
V-9	Can heads be in same location as permanent protected- only heads for easy conversion?	2	4
V-10	Can heads be in same location as permanent permissive- only heads for easy conversion?	4	3
V-11	Does it allow use of all of the opposing through green time for permissive turns?	1	4
V-12	Can it be used when the left-turn lane is shared with through traffic?	4	4
V-13	Can permissive, turning traffic proceed legally without stopping?	4	4
V-14	Could it replace all current standard and non-standard PPLT indications?	1	4
V-15	Can it be used where there is no adjacent through movement?	2	4
V-16	Can it be used where the adjacent through movement is unsignalized?	0	4
V-17	Can it be used when the left-turn slot is physically separated or on different alignment than through lane (wide median, etc.)?	0	4
V-18	Can the signal indication be placed horizontally or vertically in the same arrangement?	2	4
V-19	Does it work under all preemption scenarios?	0	4
V-20	Does it avoid the yellow trap situation under all circumstances?	0	4
V-21	Can the permissive indication be easily applied to other than PPLT situations?	0	4
V-22	Will practitioners likely use the indication if made the standard, or allowed alternate?	4	4
	Total	42	87

2.3. Time Varying Control Mode of PPLT with an FYA

2.3.1. Safety

Davis et al. (2015) stated that using four-section or five-section signal heads with an FYA allows for the utilization of different LT control strategies throughout a day. Furthermore, the authors stated the necessity for developing a framework in which the safest LT control strategy could be found in different hours of a day. To develop such a framework, the authors used a matched case-control study. The data on 436 LT related crashes that occurred at intersections operated by Minnesota DOT were collected (subject cases). Additionally, for each subject case, five random hours of the same day without a crash were randomly selected (control cases). Then, for the subject and control cases, the left-turn hourly volumes, opposing hourly volumes, and the opposing LT hourly volumes were estimated, as the data were not available for all the cases. Next, the data were categorized on the basis of three factors: the opposing speed limit, type of the LT crash, and the sight distance (whether the sight distance was enough or not). Then, for each category, a logistic regression model was fitted for predicting the crash occurrence, given the approach traffic volumes and the signal control mode. The risk of changing from one control mode to another mode could be predicted in each hour of a day using the regression models. Consequently, in each hour of a day, one could evaluate the changes in the crash risk by changing the control mode of an intersection. As a result, a control mode with the least crash risk could be selected for the intersection within the desired hour.

Lei *et al.* (2008) studied four different roadway sections with different LT treatments to evaluate the effects of regional LT treatment uniformity on safety. For each road section, a measure of "section change" was defined by scoring the number of changes in the LT control mode of intersections, phasing sequence, and signal display type. Then, each road section was assigned a "mixed level" on a scale from zero to one, where zero indicated the lowest rate and one indicated the highest rate of changes. Moreover, the crash rates for each section were plotted against the assigned mixed levels. The plot showed that higher mixed levels of road sections were associated with crash rates. Therefore, the authors concluded that using uniform types of LT treatments in a region enhances safety.

2.3.2. Operations

Radwan et al. (2013) stated that there was no uniform and interactive decision-making system in Central Florida to help traffic engineers determine the mode of LT control throughout a day (as of the date of their study). This research project developed an interactive framework in which the data from a traffic management center could be used to determine modes of LT operation throughout a day to address this issue. They selected 13 intersections with various traffic conditions from Central Florida. The selected intersections were equipped with either doghouse or four-section with FYA signal displays. However, there were only two intersections with four-section vertical displays with an FYA, as it was new to Central Florida. After the candidate intersections had been selected, the traffic was recorded during different days of the week and times of day along with crash data for five years. The recorded traffic data were used to extract the following variables: traffic volumes (for different types of movements corresponding to different traffic signal phases), the travel time of vehicles, and vehicle gaps (during the permissive LT phase). After the independent variables had been extracted in the case study intersections, the authors fitted generalized linear regression models for predicting the number of processed LT vehicles. This model estimated the number of vehicles that could be processed during a permissive LT phase in a specified time of day, given traffic volumes, land use, and additional parameters in an hour. In the next part of this research, three indices were defined:

- PTLT index: The predicted LT volume during the peak hour multiplied by the total opposing volumes over the permitted LT green time during the hour.
- PTLT ratio: The predicted LT volume during the peak hour over the total LT volume.
- LT Crashes: Whether the LT-related crashes were over two or less than two over the past three years.

The suggested mode of LT operation in this framework is found by comparing the estimated number of processed LT vehicles with the defined indices.

Chalise et al. (2015) developed a model to predict the expected LT delay for POLT and PPLT control modes. In this study, 100 hours of data were recorded and analyzed from intersections that operated under the PPLT control mode in Central Florida. Then, the collected field data were used to model and calibrate an intersection in Vissim to derive the delay of LT vehicles given different intersection geometries, traffic volumes, and signal control modes. Then, the collected field data along with the average LT delay from Vissim were used to fit a regression model. The developed regression model predicts the average delay of LT vehicles given the traffic volumes, the speed limit, and the signal control mode. In addition, this paper defined a threshold referred to as %LT index—the normalized permitted left turn volume multiplied by the normalized permitted opposing volume over the normalized permitted green time. Accordingly, the average delay of different types of LT control mode can be compared to the LT index, and thus the suggested LT control mode can be found.

2.4. Transportation Agency Surveys

Qi et al. (2012) surveyed traffic engineers from state DOTs on their practices related to implementing the PPLT control mode with an FYA. In addition, the survey included questions for jurisdictions that had not implemented an FYA to assess their opinion on adopting an FYA.

The core objectives of the survey provided to the professional community was to summarize the following:

- Commonly adopted guidelines for implementing FYA PPLT operations
- Issues related to the implementation of an FYA
- Opinions on advantages and disadvantages of an FYA.

The survey questions were broken into the following three parts:

- Part I contained 11 questions on current practices for installing an FYA addressed to jurisdictions with FYA applications.

- Part II contained four questions on permissive LT signal indications addressed to jurisdictions without FYA applications.
- Part III contained three questions on the safety and comprehension of FYA indication addressed to all jurisdictions.

For the list of questions, please refer to Appendix 1.

The survey was administered electronically using a website and emails. Survey answers were summarized as percentages where applicable. Otherwise, common answers were presented as bullet-points. The survey was conducted from May 25 to June 7, 2010. Thirty-seven respondents replied to the survey, among which 33 respondents fully completed the survey. Selected relevant findings from the survey are presented below.

Part I: Current Practices Regarding Installation of FYA

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

- Single-lane POLT phases shall receive FYA indications as well as new installations of PPLT phases (Charlotte, NC)
- Change old five-section PPLT displays to displays with time-of-day FYA operation (Charlotte, NC)

Question 4: In your opinion, what are the major advantages and disadvantages of using FYA left-turn signal display? The main points were summarized from 17 responses.

Advantages:

- FYA displays reduced crashes in comparison to doghouse displays (four respondents).

- FYA indication can improve intersection operations because of the prolonged permissive LT phases.
- FYA indication allows for more flexibility as POLT/PPLT phases can be operated on the basis of peak/off-peak hours if desired.

Disadvantages:

- FYA permissive phase can conflict with pedestrian movement.

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?

- After installing FYA indications, LT crashes were significantly reduced (at those locations) (City of Scottsdale, Arizona; Colorado)

Question 10: Which kind of problems do you have in implementation of FYA indication? The main points were summarized from 11 responses.

- Wire spans may need to be raised while replacing doghouse displays with four-section (vertical) displays.

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

- Twenty out of 32 respondents replied that FYA has a positive impact on intersection safety. One of the main points was that the FYA indication may draw more attention from people and is more distinctive than (the permitted) signal of the doghouse display.

Under NCRHP Project 3-54, the second study task involved administering an agency survey for determining and quantifying types of PPLT control applications as of 1999. The survey solicited all 50 state DOTs along with 275 additional transportation agencies of the largest cities and counties in the U.S. and Canada. One of the survey objectives was to quantify the prevalence of various PPLT signal displays employed in the U.S. Another objective was to quantify PPLT phasing sequences in use, such as lead-lead, lag-lag, and lead-lag. In addition, the survey sought to identify whether any special measures were implemented to prevent the yellow trap.

The paper survey comprised 15 questions divided into three categories. The first category, "General Information," included two questions (Q1 and Q2) for identifying the total number of signalized intersections and PPLT signal phasing applications within a jurisdiction. The second category, "PPLT Signal Displays," involved nine questions (Q3 to Q11) related to types of PPLT displays and their types of mounting, permitted indication, and complementary signs in use. The third category, "Geometry and Phasing," involved four questions (Q12 to Q15) concerning intersection geometry, signal phasing, solutions to the yellow trap, and local laws/ordinances related to the use of PPLT. The survey questions are presented in Appendix 2.

Out of 325 distributed surveys, 180 surveys were received. Out of 180 completed surveys, the surveys from Canada and agencies that did not employ PPLT control were excluded. In total, 168 surveys were analyzed. The selected relevant findings are presented below:

- PPLT signal phasing was employed in 29 percent out of 107,219 signalized intersections.
- The five-section cluster display (doghouse) accounted for 63 percent of all PPLT signal displays.
- The four-section vertical PPLT signal displays were less common.
- The green ball permissive LT indication was used in 165 out of 168 agencies.

- The lead-lead phasing sequence was used in 83 percent of all signalized PPLT intersections.
- The lag-lag phasing sequence was used in 11 percent of all signalized PPLT intersections.
- The lead-lag phasing sequence was used in 6 percent of all signalized PPLT intersection.
- 53 percent of agencies did not implement any special measures to avoid the yellow trap.

2.5. Literature Review Summary

2.5.1. POLT and PPLT with an FYA – Safety Considerations

1. Overall, crash rates increase when an intersection is changed from POLT to PPLT phasing (Agent, 1985; Noyce, Bergh and Chapman, 2007; Qi *et al.*, 2012; Simpson and Troy, 2015).
2. Before converting POLT phases to PPLT with an FYA, it is recommended to evaluate the suitability of allowing permissive LT movements on the basis of the following: LT demand, opposing traffic volume, speed limit, sight distance, number of LT lanes and opposing through-lanes, U-turn demand, and LT crash history (Qi *et al.*, 2012).

2.5.2. POLT and PPLT with an FYA – Operational Considerations

PPLT phasing reduces intersection delay in comparison to POLT phasing (Lei *et al*., 2008).

2.5.3. Doghouse and Four-Section Vertical Displays with an FYA – Safety Considerations

2.5.3.1. Doghouse Displays – Safety Considerations

1. Under the lead-lag phasing sequence, doghouse displays are prone to yellow traps

(Brehmer *et al.*, 2003; Qi *et al.*, 2012).

2. Doghouse displays operate the permissive LT phase by indicating a green ball light with a yield sign. This set-up may confuse some drivers, as green lights indicate the right of way. Furthermore, simultaneous indication of a green arrow with a green ball may be confusing as well (Drakopoulos and Lyles, 2000; Brehmer *et al.*, 2003).
3. The average response time to LT driver comprehension questions related to doghouse displays and other five-section displays was longer for four- or three-section PPLT displays (Brehmer *et al.*, 2003).

2.5.3.2. Four-Section Vertical Displays with an YA– Safety Considerations

1. FYA is an effective remedy for yellow traps (Brehmer *et al.*, 2003).
2. Crash modification factors decreased as a result of changing from a doghouse display to a four-section vertical display with an FYA (Srinivasan, 2011; Simpson and Troy, 2015).
3. The FYA has no significant impact on the number of traffic conflicts in PPLT phasing. In some cases, it was associated with a reduction in LT traffic conflicts (Qi *et al.*, 2012; Schattler *et al.*, 2013).
4. The FYA reduces confusion among left-turning drivers, as it conveys solely permissive left-turn phases (Brehmer *et al.*, 2003).
5. The flashing indications draw more attention and are better understood than solid indications. Per MUTCD, no complementary signs are required for conveying the meaning of an FYA (Brehmer *et al.*, 2003).
6. The FYA dilutes the meaning of the steady yellow arrow for the change of interval. When a steady yellow arrow follows a green arrow, LT drivers clearing the

intersection have the right of way. On the other hand, if it follows an FYA, then LT drivers clearing the intersection must yield to oncoming traffic (Qi *et al.*, 2012).

7. Under heavy LT volume conditions, LT drivers may confuse a steady yellow arrow for an FYA and proceed to the center of intersection to make a permissive LT. Nevertheless, the PPLT control mode is not appropriate for intersections with heavy LT volumes (Qi *et al.*, 2012).
8. A dedicated compartment for an FYA in four-section vertical displays provides a redundant safety measure for drivers who have difficulty recognizing colors.
9. The FYA is a relatively fail-safe indication. Misunderstanding of the FYA may result in a safe action such as stopping completely before turning left (Brehmer *et al.*, 2003).
10. Four-section displays with an FYA have the capability to delay the start of the permissive indication. This strategy is employed to ensure LT permissive drivers are aware that the opposing through-traffic has the right of way (Brehmer *et al.*, 2003).
11. In four-section displays with an FYA, the red indication can be displayed after a leading LT. This is not convenient with doghouse displays, as their red indication is shared between LT movements and adjacent through-movements (Brehmer *et al.*, 2003).
12. A study indicated that a change in signal phasing has more significant impact on safety than a change in permissive LT indication. Overall, PPLT with an FYA is safer than PPLT (Noyce, Bergh and Chapman, 2007).

2.5.4. Doghouse and Four-Section Vertical with an FYA Display – Operational Considerations

1. One study suggested that four-section displays with an FYA reduce the delay of LT vehicles and increase LT throughput in comparison to doghouse displays (Almoshaogeh, 2014).
2. Under the engineering assessment task of NCHRP project 3-54, the FYA indication scored higher in categories of operations and versatility than the circular green ball indication in five-section displays (Brehmer *et al.*, 2003). Please see **Error! Reference source not found.**.

2.5.5. Time Varying LT Control Modes – Safety Impacts

1. Overall, the time of day LT traffic control strategy is a relatively novel approach for managing LT traffic. In this strategy, it is necessary to evaluate thresholds for changing from one LT control mode to another on the basis of many local factors.
2. A study developed a model for changing LT control modes throughout the day on the basis of historical crash rate experience (Davis, Hourdos and Moshtagh, 2015).
3. Uniformity of LT treatments in a region enhances safety (Qi, Ph and Chen, 2008).

2.5.6. Time Varying LT Control Modes – Operations Impacts

Two studies developed statistical models for selecting suitable LT control modes during a day by using mainly operational factors (Radwan *et al.*, 2013; Chalise, Radwan and Abou-Senna, 2015).

Chapter 3: Driver Comprehension Survey

This research project incorporated an online driver comprehension survey of left-turn signals (accessible at https://wsu.co1.qualtrics.com/jfe/form/SV_5hwlPuyG7hHNwdT). The survey sought to evaluate mainly representative populations of Washington state drivers' understanding of left-turn signals conveyed by doghouse displays and four-section vertical displays with an FYA. The drivers were asked whether they had ever encountered intersections with time-of-day alternating FYA left-turn phases, and if so, whether they were confused by them. The primary goals of the survey were to identify 1) which of the displays produced better understanding of left-turning signals (the red signal was excluded from testing), 2) which of the displays was preferred by respondents, and 3) if alternating the left-turn control mode between protected-only and protected-permissive with FYA by time-of-day confused the respondents.

3.1. Survey Structure

Survey questions were presented in the following order (see Appendix 3):

1) Display signals:
   - A short video sequence of all left-turn signals for one of the displays was played.
   - Next, each signal (excluding red signal) was presented in a picture, and participants were asked to select the correct action from three choices as left-turning drivers.
   - Finally, participants were asked whether they had ever been confused by the left-turn signals of one of the displays.
2) Intersections with time-of-day varying FYA left-turn phases:

- Participants were asked whether they had encountered such intersections, and if they had been confused by them.

3) Display preference:

   - Participants were asked which of the tested displays they preferred to see as left-turning drivers.

4) Color recognition:

   - Participants were asked whether they had difficulty recognizing colors.

5) Demographic information:

   - Participants were asked to select their driving experience (in years) category.
   - Participants were asked to select their age category.

6) Optional comments:

   - Participants were asked to provide additional comments about their experience with left-turning signals.

3.2. Survey Count Results

A total of 142 survey responses were received.

3.2.1. User Demographics and Display Preference

As can be seen in figure 3-1 and figure 3-2, the age of most of respondents fell in the category of less than 25 years, and the majority of the respondents had driving experience of up to 5 years. On the basis of the results of figure 3-3, the majority of respondents preferred to see vertical, four-section displays with anFYA to convey left-turning signals.

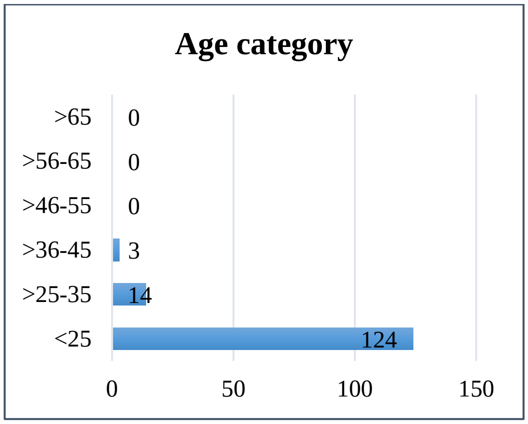


Figure 3-1. Age distribution of participants

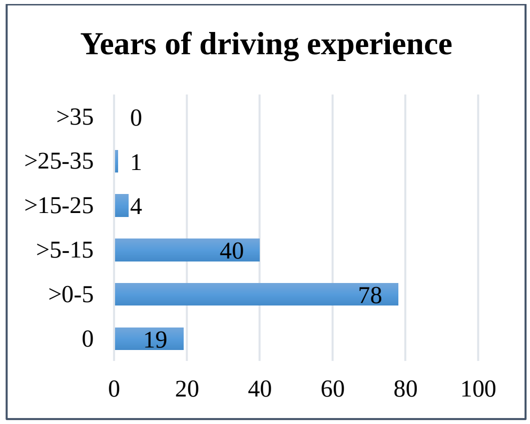


Figure 3-2. Distribution of driving experience

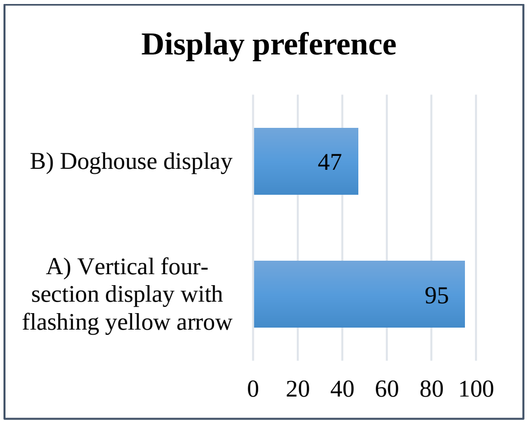


Figure 3-3. Display preference

3.2.2. Time-of-Day Flashing Yellow Arrow Left-Turn Phasing and Difficulty Recognizing Colors

Figure 3-4 shows that the majority of the respondents either had or may have experienced an intersection whose LT control mode changed by TOD. Among 99 respondents, 46 believed that a change in LT control mode was confusing to them (see figure 3-5). As shown in figure 3-6, a strong majority of the respondents did not have an issue with recognizing colors. Figure 3-7 shows which colors the respondents said were hard to recognize.

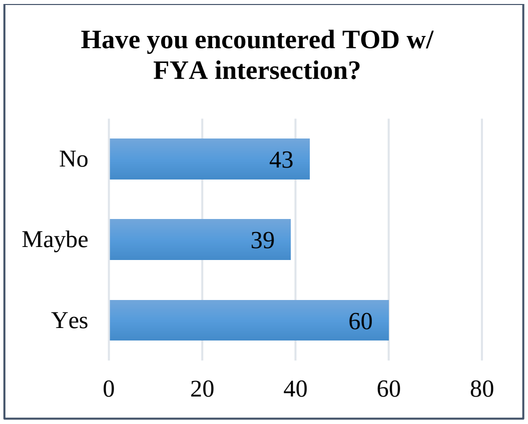


Figure 3-4. TOD with FYA intersection

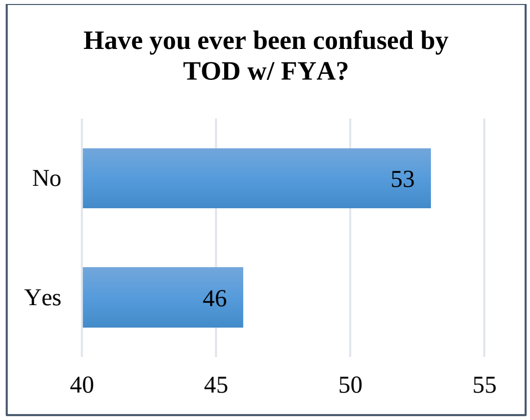


Figure 3-5. Confusion due to TOD with FYA

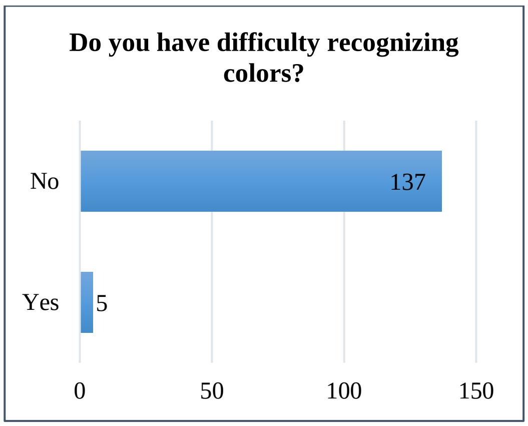


Figure 3-6. Difficulty recognizing colors

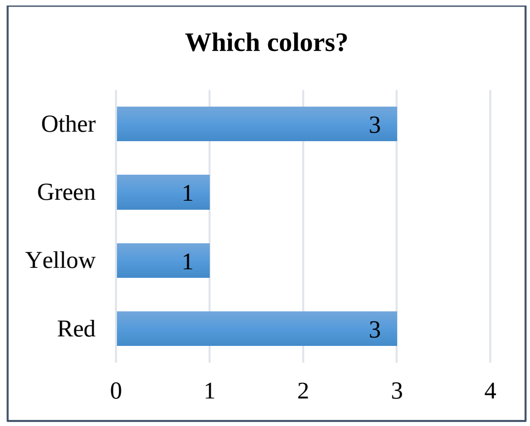


Figure 3-7. Colors of difficulty

3.2.3. Left-Turn signal comprehension - Paired comparison results

Figure 3-8 and figure 3-9 show the number of drivers that experienced confusion with doghouse and four-section vertical displays, respectively. The majority of drivers did not experience any confusion. Furthermore, the numbers of drivers that felt confused by these signal displays were identical. Figure 3-10 and figure 3-11 show that the majority of the respondents comprehended the green arrow correctly. However, a small proportion believed that even during a green arrow they must yield to opposing traffic. Similarly, the majority of the respondents selected one of the correct answers when facing a steady yellow arrow: either clear the intersection if they are within it, or stop if they are still approaching it. There was no significant difference between the doghouse and four-section with FYA vertical displays (see figure 3-12 and figure 3-13) Finally, the majority of the respondents selected the correct option during the permissive phase with both doghouse and four-section with FYA vertical displays (see figure 3-14 and figure 3-15).

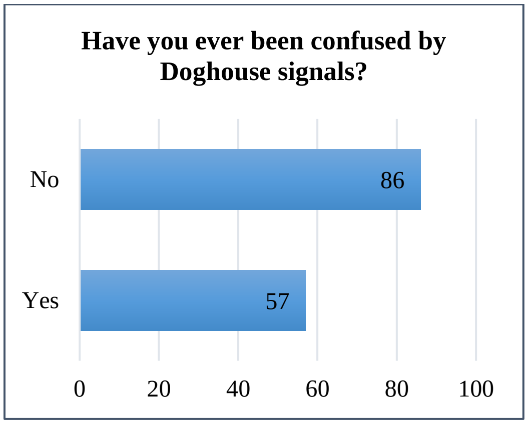


Figure 3-8. Confusion due to doghouse display signals

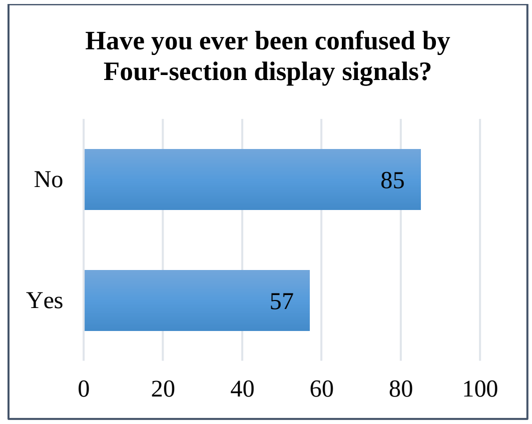


Figure 3-9. Confusion due to four-section display signals

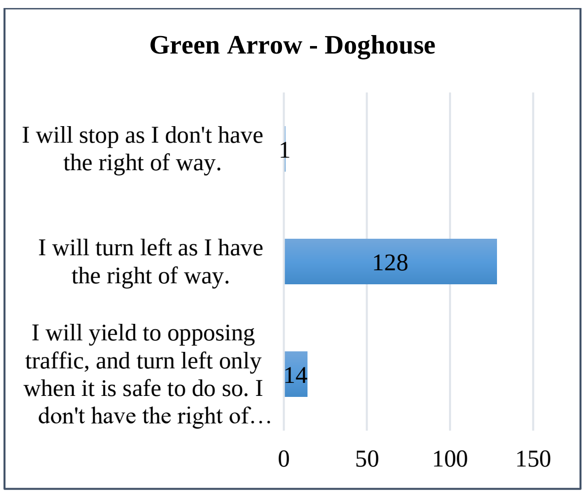


Figure 3-10. Right-of-way signal – doghouse display

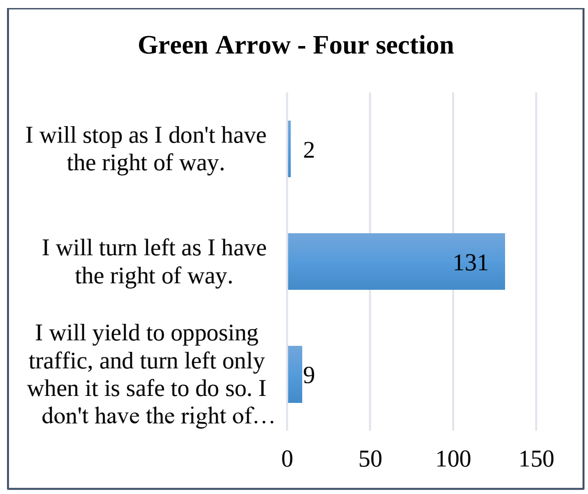


Figure 3-11. Right-of-way signal – four-section display

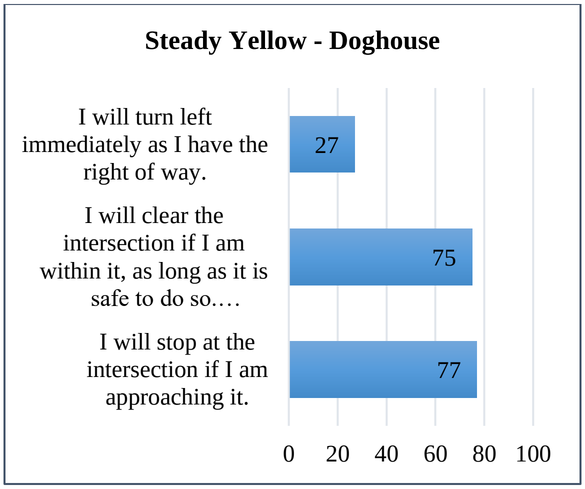


Figure 3-12. Change of interval signal – doghouse display

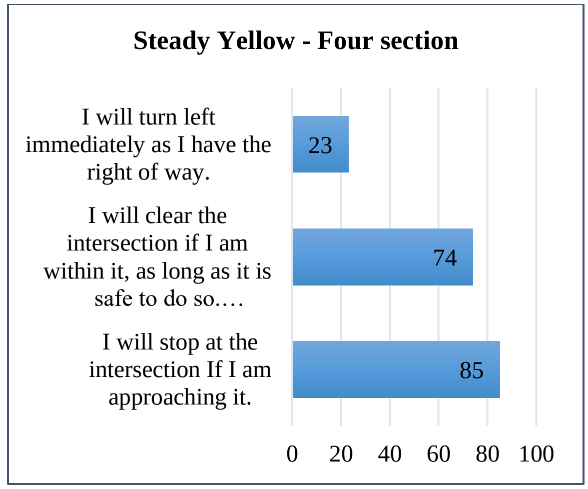


Figure 3-13. Change of interval signal – four-section display

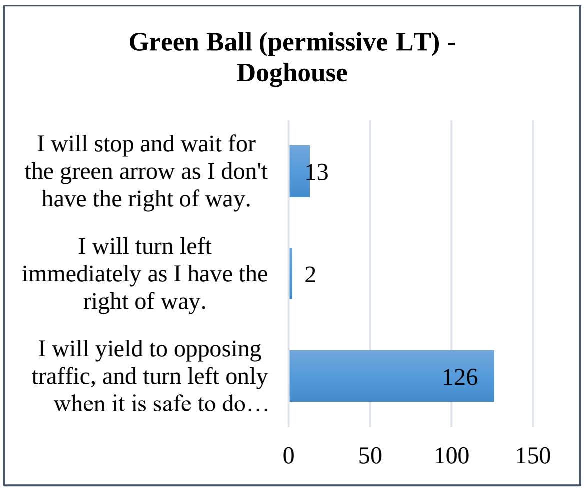


Figure 3-14. Permissive left-turn – doghouse display

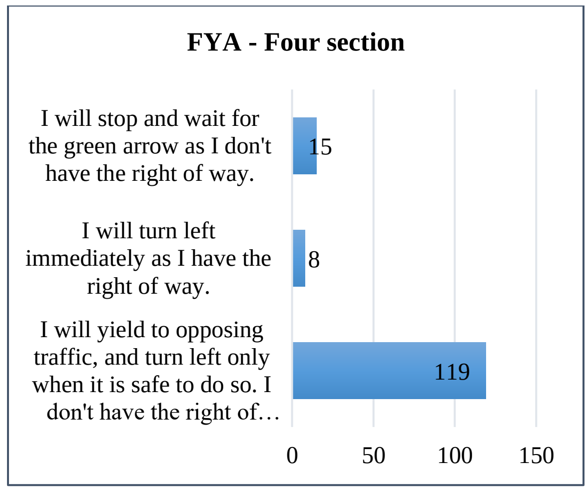


Figure 3-15. Permissive left-turn – four-section display

3.3. Statistical Analysis of Survey Results

Only fully completed answers were chosen to perform statistical analyses, which resulted in 138 responses. Two comparative tests were performed for the three signals across doghouse and four-section displays: steady yellow, permissive LT, and green arrow. Since the steady yellow question included two correct answers for the cases in which a driver is at the intersection and in the intersection, those correct answers were compared separately. Therefore, there were two cases for the steady yellow signal to be compared: a driver's response to a steady yellow at the intersection, denoted as steady yellow 1, and a driver's response to a steady yellow in the intersection, denoted as steady yellow 2.

3.3.1. Comparing Proportions of Correct Answers to LT Signal Questions between Doghouse and Four-Section Vertical Displays

Hypothesis structure:

- H0: Proportions of correct answers across displays are equal
- Ha: Proportions of correct answers across displays are NOT equal
- Calculate Z-statistic, and the P value
- H0 is rejected or failed to be rejected based on the significance level of 0.05
- Conclusion

Z-statistic is calculated as follows:

$$Z = \frac{(p_1 - p_2)}{\sqrt{\frac{pq}{n_1} + \frac{pq}{n_2}}} \tag{3-1}$$

where: p_1 is the proportion of correct answers to LT signals for the doghouse display

p_2 is the proportion of correct answers to LT signals for the four-section display

$p = (p_1 + p_2)/2$

$q = (1 - p)$

$n_1 = n_2$ – equal samples

Table 3-1. Comparative proportion test results across displays

Signal	Proportion of Correct answers	Z-statistic	P value	Statistically Significant?
Steady Yellow 1 Doghouse vs. Four - section	0.304 vs. 0.551	-4.137	0.00	Yes
Steady Yellow 2 Doghouse vs. Four - section	0.609 vs. 0.486	2.056	0.04	Yes, but close to insignificance
Permissive Doghouse vs. Four - section	0.899 vs. 0.833	1.590	0.06	No
Green Arrow Doghouse vs. Four - section	0.906 vs. 0.928	-0.653	0.51	No

The correct response to the steady yellow 1 question was, "I will stop at the intersection if I am approaching it" (see Appendix 3). More respondents chose this correct answer for the four-section display with an FYA than for the doghouse display, and the result was statistically significant. However, for the steady yellow 2 question—the correct answer to which was, "I will clear the intersection if I am within it, as long as it is safe to do so. Otherwise, I will back up into the left lane."—the doghouse display caused more respondents to select the correct answer. Nevertheless, the P value for this test was close to a significance level of 0.05. Proportions of correct answers for permissive and green arrow signals across both displays failed to reject H0, meaning that there was not sufficient evidence to conclude that the respective proportion pairs differed significantly.

3.3.2. Comparing Proportions of Correct Answers to Signal Questions Grouped by Varying Responses across Doghouse and Four-Section Displays - McNemar Test

Only varying responses across displays for the same respondent were extracted for this test. In other words, if a respondent knew the correct meaning of a signal and selected correct answers for both displays, or if a responded didn't know the meaning of a signal and selected wrong answers for both displays, then those answers were omitted. The purpose was to evaluate which of the displays caused respondents to select more correct responses if theywere confused with the meaning of a signal.

The McNemar test hypothesis structure was as follows:

- H0: Proportions of correct answers for variable responses across displays are equal.
- Ha: Proportions of correct answers for variable responses across displays are NOT equal.
- Calculate χ^2–statistic with 1 degree of freedom, and the P value.
- H0 is rejected or failed to be rejected based on the significance level of 0.05.
- Conclusion.

The χ^2 -statistic was calculated as follows:

$$\chi^2 = \frac{(b-c)^2}{b+c} \tag{3-2}$$

where: b is the count of responses with the sequence of doghouse= Incorrect and four-section=Correct for the same respondent

c is the count of responses with the sequence of doghouse=correct and four-section=Incorrect for the same respondent

Table 3-2. McNemar test – steady yellow 1 signal results

Steady Yellow 1		Four-section		Total
		Incorrect	Correct	
Doghouse	Incorrect	51	b = 45	96
	Correct	c=11	31	42
Total		62	76	138

Test result: χ^2–statistic = 20.643, P value ≈ 0. Reject H0
Conclusion: There is evidence to conclude that proportions of correct answers differ significantly

The conclusions from the McNemar test results for confused respondents were the same as those of the pairwise proportion test, as shown in table 3-2. Among confused respondents, the number of correct answers for the steady yellow 1 questions was significantly greater for four-section vertical displays than for doghouse displays.

Table 3-3. McNemar test – steady yellow 2 signal results

Steady Yellow 2		Four-section		Total
		Incorrect	Correct	
Doghouse	Incorrect	25	b=29	54
	Correct	c=46	38	84
Total		71	67	138

Test result: χ^2–statistic = 3.853, P value ≈ 0.05. Reject H0
Conclusion: There is evidence to conclude that proportions of correct answers differ significantly. However, the result is very close to the significance threshold.

However, for the steady yellow 2 question, doghouse displays received the greater number of correct answers, though their statistical significance was very close to the significance threshold of 0.05 (see table 3-3).

Table 3-4. McNemar test – permissive signal results

Permissive LT		Four-section		Total
		Incorrect	Correct	
Doghouse	Incorrect	2	b=12	14
	Correct	c=21	103	124
Total		23	115	138

Test result: χ^2–statistic = 2.455, P value= 0.12. Failed to Reject H0
Conclusion: There is not enough evidence to conclude that proportions of correct answers differ significantly

As shown in table 3-4, the result for the permissive signal failed to reject H0, meaning that there was not enough evidence to conclude that respective proportion pairs differed significantly.

Table 3-5. McNemar test – green arrow signal results

Green Arrow		Four-section		Total
		Incorrect	Correct	
Doghouse	Incorrect	7	b=6	13
	Correct	c=3	112	115
Total		10	118	138

Test result: Since b+c< 30, not enough varying responses
Conclusion: Green Arrow signal is understood well across displays

As shown in table 3-5, the results for the green arrow signal did not have enough responses for the McNemar test to be performed, which means the understanding of the green arrow signal was mostly uniform across displays, as there were only a few confused drivers with varying responses.

3.4. Selected Survey Comments

1) Using this type of survey for education:

- “The test to get a license to operate vehicles should include many of these types of questions”

2) Arrow indication preference:

- “It is better to use the left turn arrow because it is safer and less confusing than the doghouse signal”
- “I'd prefer to see the arrow as an indicator of my lane at all times”
- “Whenever you have the arrow you should be able to make that turn without fear of getting hit”

3) Comments related to the flashing yellow arrow

- “blinking or normal yellows mean you should observe opposing traffic and then make decision to turn or not”
- “I am always confused on how to proceed if the sign is yellow and/or blinking.”

4) Comments related to displays

- “It seems a 4 vertical light is more applicable to a left-turn-only lane. While the dog house is better for a general lane”
- “A doghouse display is better so drivers focus and see the same light therefore knowing which driving reaction to make.

5) Remark on a confusing question

- “I was confused about the questioning about after the protected left turn. I believe it is illegal to back up out of the intersection once you enter. If you meant to say exit the intersection, then I would have answered differently.”

3.5. Survey Conclusions

1) About 35 percent of respondents believed that they had the right of way when they saw a steady yellow signal for making a left turn. This result suggests that more rigorous driver's education should be provided on the steady yellow signal among Washington state drivers.
2) More respondents answered the steady yellow 1 question correctly for four-section vertical displays than for doghouse displays.
3) More respondents answered the steady yellow 2 question correctly for doghouse displays than for four-section vertical displays.
4) The majority of respondents correctly understood the meaning of the permissive LT signal in both signal displays. However, there were a few respondents who preferred to stop and wait for the green arrow to make a left-turn
5) The majority of respondents understood the meaning of the green arrow correctly in both signal displays.
6) About 40 percent of respondents reported having been confused by LT signals in both displays.
7) Most respondents preferred to see four-section displays with an FYA for making left turns.
8) Almost 70 percent of respondents believed they had encountered adaptive intersections where left-turn phases varied on the basis of time of day. Almost half of those believed they had been confused by that phasing strategy. This result suggests that further research is warranted to verify their experience.
9) A very few respondents reported difficulty in recognizing colors.

10) Some of the comments reflected the need to provide more driver's education on left-turning signals.

Chapter 4: Operational Effects of Time-of-Day Left-Turn Control Mode

Most available signal timing methods determine green splits on the basis of a predefined left-turning control mode (e.g., Abu-Lebdeh and Benekohal, 2000; Medina, Hajbabaie and Benekohal, 2011; Hajbabaie and Benekohal, 2011, 2013, 2015, Hajbabaie *et al.*, 2011, 2017; Hajbabaie, 2012; He, Head and Ding, 2012; N. Goodall B. Park, 2013; Kim *et al.*, 2016, 2014; Mehrabipour and Hajbabaie, 2017; Islam and Hajbabaie, 2017). However, the operations of an intersection can be improved further if the best LT control mode can be selected on the basis of traffic conditions (Hajbabaie, Medina and Benekohal, 2010). There is a need to evaluate the effects of different left turn control modes and changes during TOD on intersection operations. This project designed a simulation-based approach to identify the effects of the left turn control mode on intersection operations and to determine which control mode can provide the most efficient operations.

4.1. Methodology

The research developed a simulation-based approach that relied on creating representative scenarios (various intersection geometries, traffic demand patterns, left-turn percentages, and left-turn control modes), finding the optimal signal timing parameters for each scenario, simulating them in Vissim, and measuring their performance. The analysis continued with fitting statistical models to predict the probability of selecting a control mode under the mentioned geometric and operational conditions. The optimization component determined the best signal timings for each LT control mode, intersection geometry, and traffic conditions. The simulation component evaluated the intersection performance in terms of vehicle delays, given the signal timings from the optimization component. The statistical modeling component collected all the available data from the simulations and estimated a binary probit model to determine the suggested LT control mode. Figure 4-1 shows the different steps of the proposed framework.

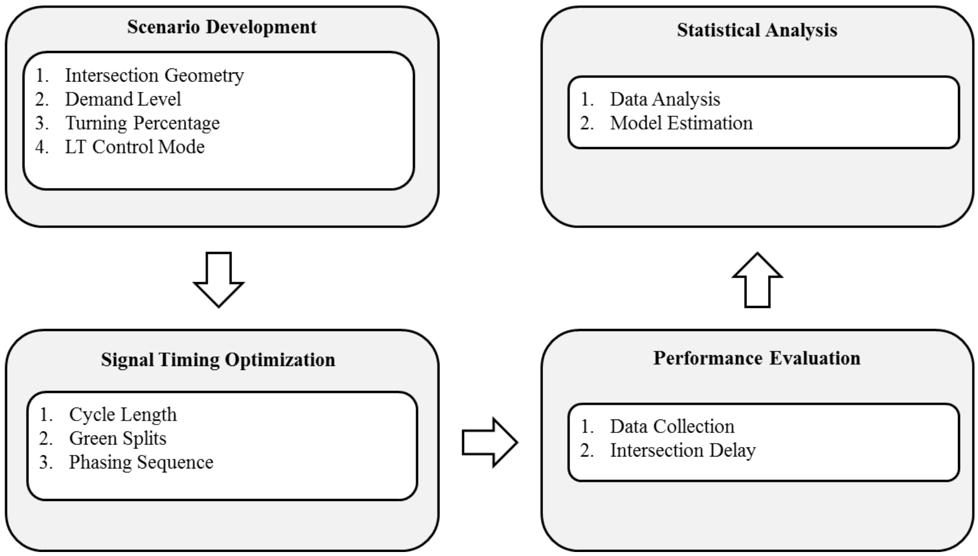


Figure 4-1. The framework to evaluate operational effects of TOD LT control mode

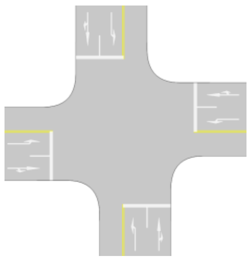
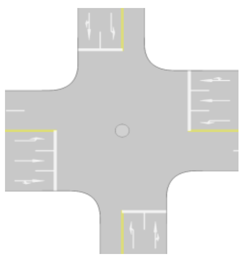
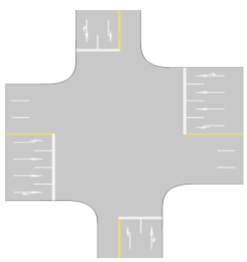
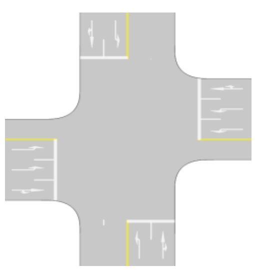
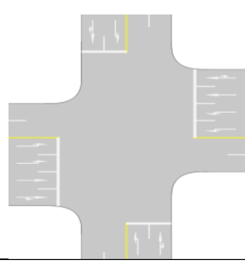
4.1.1. Scenario Development

The first step of the framework included defining various scenarios, each with different intersection geometries, traffic volumes, and LT control modes. The research team considered five types of intersection geometries, six traffic volume levels, three turning percentage ratios, and three LT control modes, yielding 270 scenarios. The following subsections discuss the defined intersection geometries, volume levels, and LT turning percentages.

4.1.1.1. Intersection Geometry

Each scenario consisted of a single intersection, as shown in table 4-1. Note, minor approaches had only one lane with through-movement; this set-up allowed exclusion of the effects of vehicles' interactions in the minor direction and evaluate of only the influencing factors on the LT control mode in the major direction. Moreover, all left-turn lanes were exclusive and 250 feet long, through -lanes of major approaches were 5,280 feet, and through-lanes of minor approaches were 250 feet. The lane width was 12 feet.

Table 4-1. Intersection geometries

Geometry Number	**Configuration**	**Major approaches: EB-WB # of lanes and movements**	**Minor approaches: NB-SB # of lanes and movements**
1		1 – LT, 1 – THR+RT	1 - THR
2		1 – LT, 2 – THR+RT	1 – THR
3		1 – LT, 3 – THR+RT	1 – THR
4		2 – LT, 1 – THR+RT	1 – THR
5		2 – LT, 2 – THR+RT	1 – THR

4.1.1.2. Intersection Traffic Volumes and Turning Percentages

The total incoming volumes per lane on major approaches were 200, 400, 600, 800, 1000, and 1200 vphpl. The volume for minor through-movements was 100 vphpl. Left-turn percentages were , 15, and 25 percent of the total per lane volume. The LT flow rate of each intersection with respect to the through-movement volume and LT percentages is summarized in table 4-2.

Table 4-2. Left turning flow rate (vphpl)

	Through Movement Volume on the Major Direction (vphpl)					
	200	400	600	800	1000	1200
LT percentage	**Left Turn Movement Volume on the Major Direction (vphpl)**					
5%	10	20	30	40	50	60
15%	30	60	90	120	150	180
25%	50	100	150	200	250	300

4.1.2. Signal Timing Optimization

The second step of the framework was signal timing optimization. Vistro (America, 2014)—one of the state-of-the-practice signal timing optimizers—was used to optimize green splits for each scenario. In other words, all of the above-mentioned scenarios were created in Vistro, and their signal timing plans were optimized to ensure that for each intersection geometry, traffic volume, turning percentage, and LT control mode, the best cycle length and green splits were selected. The minimum and maximum cycle lengths were set to 60 and 240 seconds, respectively. Thus, Vistro optimized the fixed-time signal splits as well as the cycle length for each scenario.

4.1.3. Performance Evaluation

In the next step of the framework, the performance of each scenario was evaluated in Vissim (PTV Group, 2013). Each scenario was simulated for a duration of 30 minutes with 15 replications to account for stochastic driver behavior and vehicle arrival to the intersection. The intersection loading commenced during the initial 10-minute interval, after which the vehicles would stop arriving, and existing vehicles would be allowed to clear the intersection in the next 20 minutes. Therefore, the results of the developed framework represented a broad range of arrival patterns and driver behavior at the constructed scenarios. Vehicle delays were recorded during traffic simulations and used as the criterion for performance evaluation of the scenarios.

4.1.4. Statistical Analysis

Finally, vehicle delays, traffic volumes, intersection geometries, and left-turn control modes were used to create a data set. This data set was used to perform several statistical tests to evaluate the effects of LT control modes and other variables on the measured delay of vehicles. Then, the data set was utilized to develop a binary probit model to predict the probability of selecting a PPLT or a PRLT control mode. The POLT control mode was not included because it yielded delays that were longer than either or both other control modes in the majority of the scenarios. The detailed results of the analysis are presented and discussed as follows.

4.2. <u>Results</u>

We collected the data that were generated by 4,050 observations, each associated with a different intersection geometry, traffic volume, left-turning percentage, LT control mode, or random seed. Table 4-3 shows the defined notations for each variable and the mean, standard deviation, and minimum and maximum values for each variable.

Table 4-3. Data description

Variable	Description	Mean	Standard deviation	Minimum	Maximum
Scenario characteristics					
GEO*	Intersection geometry 1 to 5	-	-	1	5
GEOM*	0: Intersection geometries 1, 2, and 3; 1: Intersection geometries 4 and 5	-	-	0	1
VOL	Major direction volume (veh/hr/lane)	700	341.6	200	1,200
LTP	Left-turning percentages ranging from 5% to 25%	15	8.17	5	25
CROS	Cross product of the LT and TH vehicles (veh^2/hr^2)	23,958	7,210.6	132	150,400
LTM*	Left-turn control mode that is 1: POLT, 2: PPLT, 3: PRLT	-	-	1	3
LTMM*	LT control mode; 0: PRLT/1: PPLT	-	-	0	1
Performance measure					
DEL	Average delay of vehicles in the major direction (sec)	18.8	22.8	3.4	165.1

* Shows the categorical variables
The data set included 4,050 observations

According to table 4-3, seven variables describing the characteristics of the scenarios and one variable showing their associated delay in the analysis period were considered in the data set. GEO was the intersection geometry category that was numbered from 1 to 5 according to defined geometries in table 4-1. GEOM was a dummy variable that was constructed on the basis of GEO, whose value was 0.0 for intersection geometries 1, 2, and 3, and 1.0 otherwise. VOL was the traffic volume of the major direction of the intersection ranging from 200 veh/hr/lan to 1200 veh/hr/lane, with a mean of 700 veh/hr/lane. These volumes enabled the research team to evaluate the LT control modes for different traffic regimes, ranging from undersaturated to oversaturated flow conditions. LTP was the percentage of the left-turning volumes. Note that because the LTP was considered to be a portion of the major direction volume (per lane), the number of left-turning vehicles had a broader range in the scenarios. LTM was a categorical variable indicating the LT control mode, which was numbered from 1 to 3 for the POLT, PPLT, and PRLT control modes, respectively. LTMM was a dummy variable that took on the value of 0.0 for the PRLT control mode and 1.0 for the PPLT mode.

The weighted average delay of vehicles is shown by DEL in table 4-3. In the simulation analysis, the research team calculated the average delay of each movement individually and then used the weighted average delay of all movements in the major direction of the intersection as the performance measure of each LT control mode. The weighted average was found on the basis of the number of processed vehicles in each direction. Table 4-3 shows that the mean of DEL values was 18.81 seconds, with a minimum of 3.44 and a maximum of 165.05 seconds.

4.2.2. Effect of the LT Control Mode (LTM) on the Average Delay of Vehicles (DEL)

Table 4-4 shows the average delay of vehicles (DEL) for each LT control mode (LTM) across all scenarios. The table shows that each control mode had 1,350 observations in the data set, and the average DEL values for POLT, PPLT, and PRLT were respectively 26.90, 14.68, and 14.84 seconds. DEL values showed that delay of vehicles associated with the POLT mode was 83.2 percent more than the PPTL control mode and 81 percent more than PRLT, while the difference between the average delay of PPLT and PRLT was less than 1.5 percent.

Table 4-4. Average delays (DEL) across the LT control modes (LTM)

LT control mode (LTM)	Average delay (DEL, sec)	Standard deviation	Number of observations
1 (POLT)	26.90	27.63	1350
2 (PPLT)	14.68	15.61	1350
3 (PRLT)	14.84	21.43	1350

The research team performed a global Analysis Of Variance (ANOVA) hypothesis test to identify whether the observed average delays for each LT control mode were statistically different. The null and alternative hypothesis for this test were as follows:

- H0: All average delays across LT control modes are equal.
- H1: Not all average delays are equal.

Then a pairwise Tukey's test was performed to identify statistically significant pairs of average delays. On the basis of the above hypothesis, the Tukey's pairwise comparison of average delays is shown in table 4-5. This table shows the P values for each pair of LT control modes. The results in table 4-5 indicate that there was enough evidence to conclude that the average delays of vehicles between POLT and PPLT (1-2) and between POLT and PRLT (1-3) were significantly different, while the average delay of vehicles in PPLT and PRLT (2-3) did not reject the null hypothesis.

Table 4-5. Average delay pairwise comparison grouped by LT control modes

LT control mode pair	P value
1-2	0*
1-3	0*
2-3	0.98

* indicates statistical significance

In other words, the statistical test showed that the average delay of vehicles in the POLT control mode was significantly higher than that of the PPLT and PRLT modes. Therefore, the POLT control mode was not included in the regression analysis.

4.2.3. Effect of Intersection Geometry (GEO) on the Average Delay of Vehicles (DEL)

Similar to the previous analyses, the average delay of vehicles with respect to the intersection geometry is shown in table 4-6. The table shows that the lowest average delay was observed for intersection geometry 2, and the highest average delay was associated with intersection geometry 4 among the evaluated scenarios.

Table 4-6. Average delays (DEL) across the intersection geometries (LTM)

Geometry (GEO)	Average delay (DEL)	Standard deviation	Number of observations
1	18.51	20.38	810
2	16.13	20.05	810
3	17.60	23.66	810
4	21.92	24.08	810
5	19.88	25.15	810

The results of the ANOVA hypothesis test, shown in table 4-7, supported that the average delay of vehicles for geometry 4 was statistically different than those for geometries 1, 2, and 3, and geometry 5 was statistically higher than geometry 2.

Table 4-7. Pairwise comparison of average delays grouped by intersection geometry

Intersection geometry (GEO)	1	2	3	4	5
1	-	0.2206	0.9299	0.0213*	0.7435
2	-	-	0.6934	0.0000*	0.0083*
3	-	-	-	0.0013*	0.2584
4	-	-	-	-	0.3686
5	-	-	-	-	-

* indicates statistical significance

4.2.4. Effect of Left-Turning volume (LTP) on the Average Delay (DEL)

An important factor influencing the LT control mode is the number of LT vehicles. The research team considered the LT turning percentages, but because of different levels of through-movement volumes and the number of through-movement lanes, a variety of left-turning flow rates was observed. The flow rate of LT vehicles was categorized into four equal size groups, shown in table 4-8, on the basis of the minimum and maximum observed LT vehicles. Table 4-8 shows that the average delay increased with the LT flow rate, as expected. Note that the changes in the difference between delays in group 4 (450-600 veh/hr) were almost six times higher than that for group 1 (0-150 veh/hr), indicating the significance of LT vehicles on the average delay of the entire major direction, while the number of LT vehicles was at most 25 percent of a through-lane.

Table 4-8. Average delays across LT flow rates with the bins of sizes of 150 veh/hr

Left-turning flow rate (veh/hr)	Average delay (sec)	Standard deviation	Number of observations
1: [0-150)	9.88	3.951	2430
2: [150-300)	20.43	17.29	951
3: [300-450)	40.28	34.61	489
4: [450-600]	72.40	38.51	180

Moreover, the results of the Tukey pairwise test shown in table 4-9 supported the statistical difference between the groups of the LT flow rates. In other words, the P values were 0.0, which indicates that the average delays were statistically different.

Table 4-9. P values of the pairwise comparison of average delays grouped by LT flow rate

LT flow rate category	1	2	3	4
1	-	0*	0*	0*
2	-	-	0*	0*
3	-	-	-	0*
4	-	-	-	-

* indicates statistical significance

4.2.5. Effect of Through-Movement Flow Rate (VOL) on the Average Delay (DEL)

Finally, the effects of the through-movement flow rate on the average delay of vehicles were evaluated, as shown in table 4-10. The table shows that the average delay of vehicles with 200 and 400 veh/hr/lane differed by less than 5 percent, whereas the average delay from 1000 to 1200 increased by more than 100 percent. This analysis showed that delay of vehicles was not sensitive to VOL values for low flow rates (less than 600 veh/hr/lane) but was for flow rates of more than 600 veh/hr/lane.

Table 4-10. Average delays across the through-movement volume level

Major direction volume (veh/hr/lane)	Average delay (sec)	Standard deviation	Number of observations
200	10.08	3.081	675
400	9.600	4.116	675
600	10.37	5.369	675
800	13.08	8.122	675
1000	22.71	19.81	675
1200	47.01	39.24	675

The pairwise test between the groups of flow rates in table 4-11 also showed that the difference between the average delays of flow rates of 200, 400, and 600 was not statistically significant. However, in higher flow rates of 800, 1000, and 1200 veh/hr/lane, the average delays were statistically different.

Table 4-11. P values of pairwise comparison of average delays grouped by demand volume

Through movement flow rate (veh/hr/lane)	200	400	600	800	1000	1200
200	-	0.997	1.000	0.034*	0.000*	0.000*
400	-	-	0.973	0.007*	0.000*	0.000*
600	-	-	-	0.077	0.000*	0.000*
800	-	-	-	-	0.000*	0.000*
1000	-	-	-	-	-	0.000*
1200	-	-	-	-	-	-

* indicates statistical significance

4.2.6. LT Control Mode Selection

The effect of each variable on the average delay of vehicles was evaluated. The results showed that the intersection geometry, control mode, and the number of LT vehicles were among the influential variables on intersection delay. Thus, for each scenario, we selected the control mode with the least average delay as the suggested LT control mode for the intersection. The suggested LT control modes for each scenario showed that the POLT control mode was selected in less than 0.5 percent of the observations. In other words, in most of the scenarios, POLT was associated with higher delays than the PRLT and PPLT control modes. This observation was expected because the PPLT control mode can provide both permissive and protected phases, and thus, it can use the green times more efficiently from an operations perspective. Therefore, the research team developed a binary probit model to select between the PRLT and PPLT control modes on the basis of intersection characteristics and traffic flow rates throughout a day.

The research team used a backward elimination method to select from the available variables in table 4-3 and their combinations in the model fitting process. Moreover, the team selected the best model on the basis of different criteria such as Akaike, Log-Likelihood, and McFadden values. The final model is presented in table 4-12. In this table, GEOM is the intersection geometry and CROS is the cross-product of the left-turning and through-vehicles (see table 4-3 for the variable definitions).

Table 4-12. Final binary probit model for the PPLT and PRLT control mode selection

Variables	Coefficient	Standard error	***P*-value**
Intercept	-4.052	0.2548	0.000
GEOM	1.509	0.3176	0.000
(GEOM=0) × CROS	0.00009054	0.000	0.000
(GEOM=1) × CROS	0.00002032	0.000	0.000
Log-likelihood	-399.584		
AIC	807.17		
McFadden R squared	0.34		

The estimated model in table 4-12 showed that the LT control mode was directly related to intersection geometry, whether intersection geometry 1, 2, and 3 (GEOM=0) or intersection geometry 4 and 5 (GEOM=1), and a cross-product of LT and opposing through-vehicles. The model in table 4-12 estimates the probability of selecting the PPLT control mode on the basis of the following equations:

$$U = -4.052 + 1.509GEOM + 0.00009054(GEOM = 0)CORS + 0.00002032(GEOM = 1)CORS \quad (4\text{-}1)$$

$$\Pr(\text{Control Mode} = \text{PPLT}) = \frac{e^U}{1 + e^U} \quad (4\text{-}2)$$

$$\Pr(\text{Control Mode} = \text{PRLT}) = 1 - \frac{e^U}{1 + e^U} \quad (4\text{-}3)$$

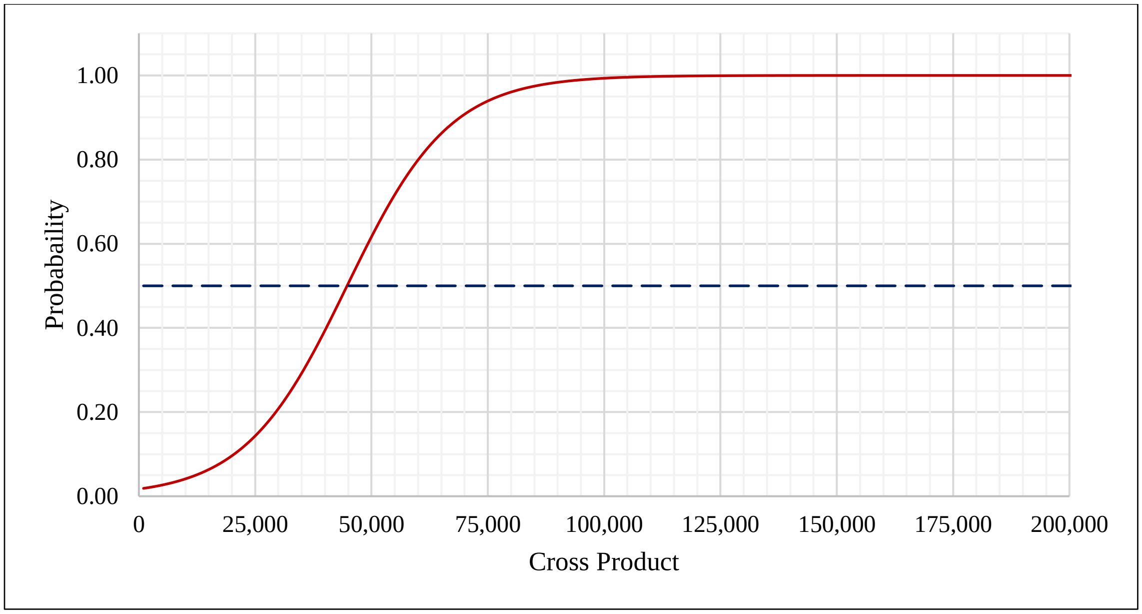
The coefficient sign of the GEOM showed that the probability of selecting PPLT as the control mode for geometries 4 and 5 was higher than for PRLT. Furthermore, the coefficient of the CROS in the model was positive, indicating that the probability of selecting PPLT increased with an increase in CROS values. Moreover, the cross-product, CROS, coefficient for GEOM=0 (intersection geometries 1,2 and 3) was higher than the coefficient of GEOM=1, showing that the probability of selecting PPLT as the LT control mode was higher for geometries 1, 2 and 3 (GEOM=0) when CROS increased.

The estimated model in table 4-12 can be used to determine the suggested LT control mode as traffic volume changes throughout a day. For example, the PPLT control mode can be selected when the given probability from equation (4-2) is more than a threshold (e.g., 0.5). Figure 4-2 shows how the probability of selecting the PPLT control mode varies with a change in the cross-product value. It is evident that for low cross-product values, the probability of selecting the PPLT control mode is low, as a permissive control mode can process the left turns efficiently. However, as the cross-product increases, the probability of selecting the PPLT control mode grows, since a protected phase is needed.

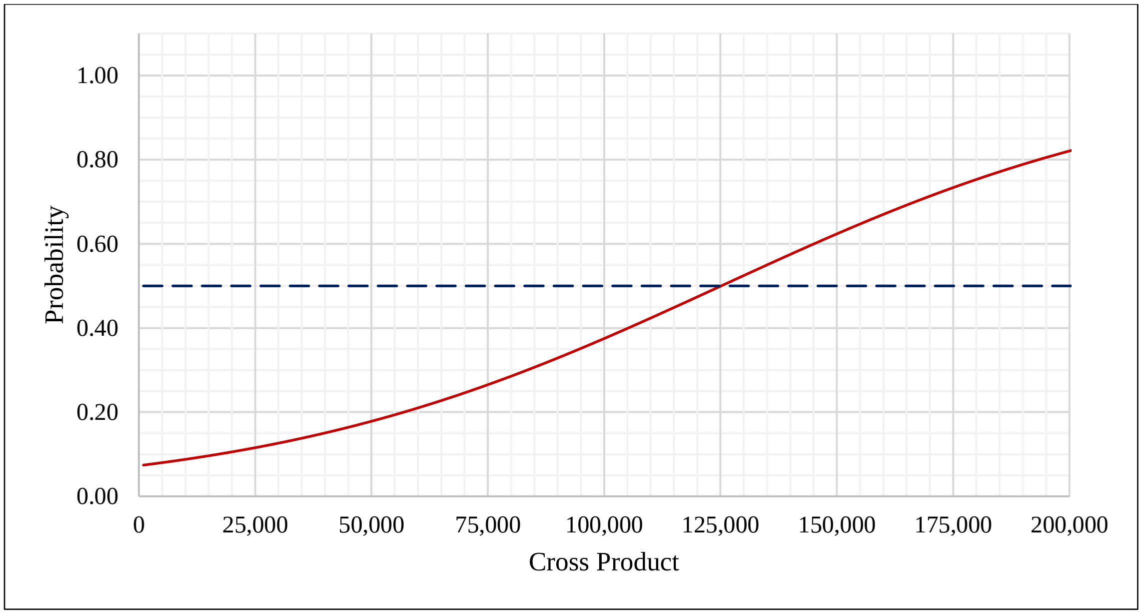
If the probability of 0.5 is selected as a decision criterion, the following conclusions can be made:

- For intersection geometries 1, 2, and 3, the PRLT control mode can be selected for cross-products of less that 45,000 (veh^2/hr^2) and the PPLT control mode for cross-products of more than 45,000 (veh^2/hr^2) (see figure 4-2 (a)).
- For intersection geometries 4 and 5, the PRLT control mode can be selected for cross-products of less that 125,000 (veh^2/hr^2) and the PPLT control mode for cross-products of more than 125,000 (veh^2/hr^2) (see figure 4-2 (b)).

Note that this study does not recommend thresholds for selecting the LT control mode, as the findings are based on simulation runs. On the other hand, the study, showed trends that influence the LT control mode selection.



(a) Intersection geometries 1, 2 and 3



(b) Intersection geometries 4, and 5

Figure 4-2. Probability of selecting the PPLT control mode on the basis of intersection geometry and cross-products

Chapter 5: Conclusions and Recommendations

5.1. Safety and Operational Impacts of POLT and PPLT Phasing with an FYA

According to the literature review, overall crash rates increase by changing the control mode from POLT to PPLT (Agent, 1985; Noyce, Bergh and Chapman, 2007; Qi *et al.*, 2012; Simpson and Troy, 2015). Before the POLT control mode is converted to PPLT with an FYA, agencies should evaluate the suitability of allowing permissive LT movements on the basis of LT demand, opposing traffic volumes, speed limit, sight distance, number of LT lanes and opposing through-lanes, U-turn demand, and LT crash history (Qi *et al.*, 2012). In terms of operational impacts, PPLT phasing may reduce intersection delay in comparison to POLT phasing (Lei *et al.*, 2008).

5.2. Safety and Operations Impacts of Doghouse and Four-Section Vertical Display with an FYA

5.2.1. Doghouse Displays -- Safety Considerations

Under the lead-lag phasing sequence, doghouse displays are prone to yellow traps (Brehmer *et al.*, 2003; Qi *et al.*, 2012). Doghouse displays operate the permissive LT phase by indicating a green ball signal with a yield sign. This set-up may confuse some drivers, as green signals indicate the right of way. Furthermore, simultaneous indication of a green arrow with a green ball may be confusing, too (Drakopoulos and Lyles, 2000; Brehmer *et al.*, 2003). The average response times to LT driver comprehension questions related to doghouse displays and other five-section displays were longer than those for four- or three-section PPLT displays (Brehmer *et al.*, 2003).

5.2.2. Four-Section Vertical Displays with an FYA – Safety Considerations

The FYA is an effective remedy for yellow traps (Brehmer *et al.*, 2003). Crash modification factors decreased when doghouse displays were changed to four-section vertical displays with an FYA (Srinivasan, 2011; Simpson and Troy, 2015). The FYA has no significant impact on the number of traffic conflicts in PPLT phasing. In some cases, it was associated with a reduction in LT traffic conflicts (Brehmer *et al.*, 2003; Qi *et al.*, 2012; Schattler *et al.*, 2013). The FYA reduces confusion among left-turning drivers, as it conveys solely permissive left-turn phases (Brehmer *et al.*, 2003). The flashing indications draw more attention and are better understood than solid indications. The MUTCD does not require complementary signs to convey the meaning of the FYA (Brehmer *et al.*, 2003). However, the FYA may dilute the meaning of a steady yellow arrow for the change of interval. When a steady yellow arrow follows a green arrow, LT drivers clearing the intersection have the right of way. On the other hand, if it follows an FYA, LT drivers clearing the intersection must yield to the oncoming traffic (Qi *et al.*, 2012). Under heavy LT volume conditions, LT drivers may confuse a steady yellow arrow for an FYA and proceed to the center of intersection to make a permissive LT. Nevertheless, the PPLT control mode is not appropriate for intersections with heavy LT volumes (Qi *et al.*, 2012). A dedicated compartment for an FYA in four-section vertical displays provides a redundant safety measure for drivers who have difficulty recognizing colors. The FYA is a relatively fail-safe indication. Misunderstanding of an FYA may result in a safe action such as stopping completely before turning left (Brehmer *et al.*, 2003). Four-section displays with an FYA have the capability to delay the start of a permissive indication. This strategy is employed to ensure that LT permissive drivers are aware that the opposing through-traffic has the right of way (Brehmer *et al.*, 2003). In four-section displays with an FYA, a red indication can be displayed after a leading LT. This is not convenient with doghouse displays, as their red indication is shared between LT and adjacent through-movements (Brehmer *et al.*, 2003). A study indicated that a change in signal phasing has more significant impact on safety than a change in permissive LT indication. Overall, a PPLT with an FYA is safer than a PPLT (Noyce, Bergh and Chapman, 2007).

5.2.3. Doghouse and Four-Section Vertical with an FYA Display – Operational Considerations

One study suggested that four-section displays with an FYA reduced the delay of LT vehicles and increased LT throughput in comparison to doghouse displays (Almoshaogeh, 2014). Under the engineering assessment task of NCHRP project 3-54, the FYA indication scored higher in categories of operations and versatility than the circular green ball indication in five-section displays (see section 2.2.2.5).

5.3. <u>Safety of the TOD Left-Turn Control Mode with an FYA</u>

This study performed a driver comprehension survey. The survey results showed that almost 70 percent of respondents believed they had encountered intersections where the LT control mode changed by TOD. Almost half of those believed they had been confused by that phasing strategy. More research is necessary to evaluate driver confusion due to TOD-varying LT phasing. It is necessary to select the drivers from those areas of Washington state where such TOD-varying signalized intersection operate.

5.4. <u>Operational Effects of the TOD Left-Turn Control Mode</u>

A total of 270 scenarios with different intersection geometries, volumes, LT percentages, and LT control modes were considered for the analysis. Each scenario was modeled in Vistro to find the optimal signal timing. Then, the scenarios were created in Vissim, and the intersection delay was measured for 15 different random seeds. Accordingly, the results were combined in a data set with 4,050 observation. The statistical analysis of the observations showed that the number of LT vehicles and the LT control mode were among the most influential variables on intersection delay. Moreover, a binary probit model was estimated to select the best LT control mode on the basis of intersection geometry and the cross-product of the LT and their opposing through-movements.

References

Abu-Lebdeh, G. and Benekohal, R. (2000) 'Genetic algorithms for traffic signal control and queue management of oversaturated two-way arterials', *Transportation Research Record: Journal of the Transportation Research Board*. Transportation Research Board of the National Academies, (1727), pp. 61–67.

Agent, K. R. (1985) 'Guidelines for the use of protected/permissive left-turn phasing'.

Almoshaogeh, M. I. (2014) *Evaluating the Effectiveness of Conversion of Traditional Five Section Head Signal to Flashing Yellow Arrow (FYA) Signal*. University of Central Florida Orlando, Florida.

America, P. T. V (2014) 'PTV VISTRO User Manual', *Ptv Ag*, 2, p. 7.

Appiah, J. and Cottrell, B. (2014) 'Safety and operational impacts of optional flashing yellow arrow delay', *Transportation Research Record: Journal of the Transportation Research Board*. Transportation Research Board of the National Academies, (2463), pp. 26–34.

Brehmer, C. L., Kacir, K. C., Noyce, D. A. and Manser, M. P. (2003) 'NCHRP Report 493: Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control', *Transportation Research Board of the National Academies, Washington, DC*.

Chalise, S. K., Radwan, E. and Abou-Senna, H. (2015) 'Analysis of Variable Left-Turn Mode by Time of Day for Flashing Yellow Arrow Signals', in *Transportation Research Board 94th Annual Meeting*.

Davis, G. A., Hourdos, J. and Moshtagh, V. (2015) 'Development of Guidelines for Permitted Left-Turn Phasing Using Flashing Yellow Arrows.' Center for Transportation Studies, University of Minnesota.

Drakopoulos, A. and Lyles, R. W. (2000) 'Preferences for permitted and protected left-turn signal displays', *Journal of transportation engineering*. American Society of Civil Engineers, 126(3), pp. 202–211.

Fisher, E. and Obery, G. (2009) *Flashing yellow arrows*.

Hajbabaie, A. (2012) *Intelligent dynamic signal timing optimization program*. University of Illinois at Urbana-Champaign.

Hajbabaie, A. and Benekohal, R. F. (2011) 'Which policy works better for signal coordination? Common, or variable cycle length', in *Proceedings of the 1st ASCE T&DI Congress*, pp. 13–16.

Hajbabaie, A. and Benekohal, R. F. (2013) 'Traffic Signal Timing Optimization: Choosing the Objective Function', *Transportation Research Record: Journal of the Transportation Research Board*. Transportation Research Board of the National Academies, 2355, pp.

10–19. doi: 10.3141/2128-02.

Hajbabaie, A. and Benekohal, R. F. (2015) ‘A Program for Simultaneous Network Signal Timing Optimization and Traffic Assignment’, *IEEE Transactions on Intelligent Transportation Systems*. doi: 10.1109/TITS.2015.2413360.

Hajbabaie, A., Kim, S., Schroeder, B. J., Aghdashi, S., Rouphail, N. M. and Tabrizi, K. (2017) *Estimation of saturation headway in work zones on urban streets, Transportation Research Record*. doi: 10.3141/2615-04.

Hajbabaie, A., Medina, J. C. and Benekohal, R. F. (2010) ‘Effects of ITS-Based Left Turn Policies on Network Performance’, in *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, pp. 80–84.

Hajbabaie, A., Medina, J. C., Benekohal, R. F. and NEXTRANS, C. (2011) ‘Traffic signal coordination and queue management in oversaturated intersections’, *Purdue University Discovery Park.*

He, Q., Head, K. L. and Ding, J. (2012) ‘PAMSCOD: Platoon-based arterial multi-modal signal control with online data’, *Transportation Research Part C: Emerging Technologies*. Elsevier Ltd, 20(1), pp. 164–184. doi: 10.1016/j.trc.2011.05.007.

Henery, S. (2008) *Assessment of Driver Recognition of Flashing Yellow Left-Turn Arrows in Missouri*.

Hurwitz, D. and Monsere, C. M. (2013) ‘Improved Pedestrian Safety at Signalized Intersections Operating the Flashing Yellow Arrow’.

Hurwitz, D., Monsere, C., Marnell, P. and Paulsen, K. (2014) ‘Three-or four-section displays for permissive left turns? Some evidence from a simulator-based analysis of driver performance’, *Transportation Research Record: Journal of the Transportation Research Board*. Transportation Research Board of the National Academies, (2463), pp. 1–9.

Islam, S. and Hajbabaie, A. (2017) ‘Distributed coordinated signal timing optimization in connected transportation networks’, *Transportation Research Part C: Emerging Technologies*. Elsevier, 80, pp. 272–285. doi: 10.1016/j.trc.2017.04.017.

Kim, S., Hajbabaie, A., Williams, B. M. and Rouphail, N. M. (2016) ‘Dynamic Bandwidth Analysis for Coordinated Arterial Streets’, *Journal of Intelligent Transportation Systems: Technology, Planning, and Operations*, 20(3). doi: 10.1080/15472450.2015.1074575.

Kim, S., Hajbabaie, A., Williams, B. M., Rouphail, N. and others (2014) *Development of near real time performance measurements for closed-loop signal systems (CLS) using historical traffic data from existing loop detectors and signal timing data*.

Knodler Jr, M., Noyce, D., Kacir, K. and Brehmer, C. (2006) ‘Analysis of driver and pedestrian comprehension of requirements for permissive left-turn applications’, *Transportation*

Research Record: Journal of the Transportation Research Board. Transportation Research Board of the National Academies, (1982), pp. 65–75.

Lee, J.-T., Dittberner, R. and Kweon, Y.-J. (2012) *Safety Effect of Different Left-Turn Signal Phasing in Opposing Directions*.

Yu, Lei et al. *"Development of Left-Turn Operations Guidelines at Signalized Intersections."* (2009).

Maze, T. H., Henderson, J. L. and Sankar, R. (1994) *Impacts on Safety of Left-Turn Treatment at High Speed Signalized Intersections*.

Medina, J. C., Hajbabaie, A. and Benekohal, R. F. (2011) 'A comparison of approximate dynamic programming and simple genetic algorithm for traffic control in oversaturated conditions - Case study of a simple symmetric network', in *IEEE Conference on Intelligent Transportation Systems, Proceedings, ITSC*, pp. 1815–1820.

Mehrabipour, M. and Hajbabaie, A. (2017) 'A Cell Based Distributed-Coordinated Approach for Network Level Signal Timing Optimization', *Computer Aided Civil and Infrastructure Engineering: an International Journal*, 32(7), pp. 599–616.

N. Goodall B. Park, B. S. (2013) 'Traffic signal control with connected vehicles', *Transport. Res. Rec. J. Transport. Res. Board, 2381*, pp. 65–72.

Noyce, D. A., Bergh, C. R. and Chapman, J. R. (2007) *Evaluation of the Flashing Yellow Arrow Permissive-Only Left-Turn Indication Field Implementation*. Transportation Research Board.

Noyce, D. A., Bill, P. E. A. R. and Knodler Jr, M. A. (2014) 'NCHRP 20-07: Evaluation of the Flashing Yellow Arrow (FYA) Permissive Left-Turn and Yellow Arrow Change Indications in Protected/Permissive Left-Turn Control: The Impact of Separate and Shared Yellow Signal Sections and Head Arrangements'.

Noyce, D. and Smith, C. (2003) 'Driving simulators for evaluation of novel traffic-control devices: Protected-permissive left-turn signal display analysis', *Transportation Research Record: Journal of the Transportation Research Board*. Transportation Research Board of the National Academies, (1844), pp. 25–34.

Pline, J. L. (1996) *NCHRP Synthesis 225: Left-turn treatments at intersections*. National Academy Press.

PTV Group (2013) 'PTV Vissim 7 User Manual', *PTV AG*.

Pulugurtha, S. S. and Chittoor Khader, K. S. (2014) 'Assessing the effect of introducing a permitted phase through the use of flashing yellow arrow signal for left-turning vehicles', *International journal of injury control and safety promotion*. Taylor & Francis, 21(4), pp. 338–347.

Qi, Y., Chen, X., Yu, L., Wang, Y., Zhang, M., Yuan, P. and Persad, K. R. (2012) *Use of Flashing Yellow Operations to Improve Safety at Signals with Protected-Permissive Left Turn (PPLT) Operations*.

Qi, Y., Ph, D. and Chen, X. (2008) 'Development of Left-Turn Operations Guidelines at Signalized Intersections', (August).

Radwan, E., Abou-Senna, H., Navarro, A. and Chalise, S. (2013) 'Dynamic Flashing Yellow Arrow (FYA): A Study on Variable Left Turn Mode Operational and Safety Impacts'.

Rescot, R. A., Qu, S., Noteboom, R. and Nafakh, A. (2015) *Evaluation of Flashing Yellow Arrow Traffic Signals in Indiana*. Joint Transportation Research Program.

Rietgraf, A. and Schattler, K. (2013) 'Behavior of Left-Turning Drivers During Permissive Interval of Protected-Permissive Operation: Effect of Signal Display', *Transportation Research Record: Journal of the Transportation Research Board*. Transportation Research Board of the National Academies, (2384), pp. 35–44.

Schattler, K. L., Rietgraf, A., Burdett, B. and Lorton, W. (2013) *Driver Comprehension and Operations Evaluation of Flashing Yellow Arrows*.

Shea, M. S., Medina, J. C., and Porter, R. J. (2016). "Safety Effects of Protected and Protected/Permitted Left-Turn Phases: Literature Review and Current State of Practice," University of Utah Traffic Lab, Salt Lake City, UT.

Simpson, C. L. and Troy, S. A. (2015) 'Safety effectiveness of flashing yellow arrow: evaluation of 222 signalized intersections in North Carolina', *Transportation Research Record: Journal of the Transportation Research Board*. Transportation Research Board of the National Academies, (2492), pp. 46–56.

Srinivasan, R. (2011) *Evaluation of safety strategies at signalized intersections*. Transportation Research Board.

Appendix 1. Survey of Traffic Engineers (Qi et al., 2012)

PART I: Current Practices Regarding Installation of FYA

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

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

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

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

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

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

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

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

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

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

PART II: General Questions for Permissive Left-Turn Operation

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

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

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

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

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

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?

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

Appendix 2: Agency Survey (Brehmer et al., 2003)

I General information

Q1: How many signalized intersections are currently operated and maintained by your jurisdiction?

Q2: How many signalized intersections with PPLT phasing are currently operated and maintained by your jurisdiction?

II PPLT signal displays

Q3: Of the total number of PPLT signalized intersections reported in question 2, how many of the PPLT signalized intersections contain the following left-turn signal display arrangements:

Q4. If you identified multiple signal display arrangements in Question 3, are there geometric conditions, phasing types, or other factors that your agency uses as criteria for selecting one PPLT signal display arrangement over another?

Q5. Do you use Green and Yellow (bi-modal) arrow indications in the same section of a PPLT signal display in one or more PPLT intersections in your jurisdiction?

Q6. What type of PPLT signal display arrangements do you use with the following mounting types: (check all that apply)

Q7. When using Mast Arm or Span Wire mounts, the primary PPLT signal display(s) is mounted:

Q8. If a secondary PPLT signal display(s) is used, where is it mounted?

Q9. Do you use the PPLT signal display as one of the two required signal displays for through traffic?

Q10. What type of signal indication is used for the permitted phase of PPLT?

Q11. Do you use supplemental signs with your PPLT signal displays?

III Geometry and Phasing

Q12. Does your jurisdiction do anything different or unique with PPLT signal phasing, mounting location, mounting type, or signal display arrangement in the following conditions:

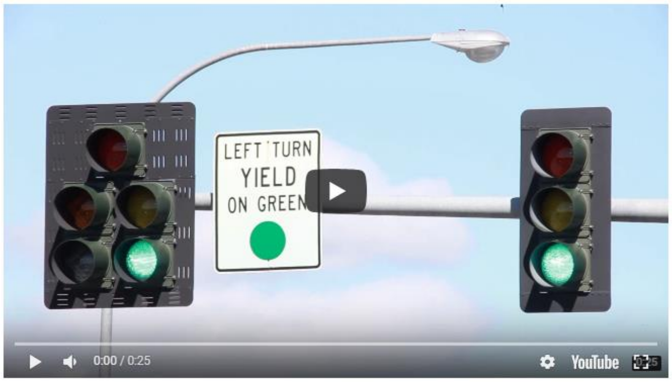
Q13. What percentage of PPLT usage in your jurisdiction are used with the following left-turn lane and phasing types:

Q14. Do you use special phasing or techniques to avoid the yellow trap problem?

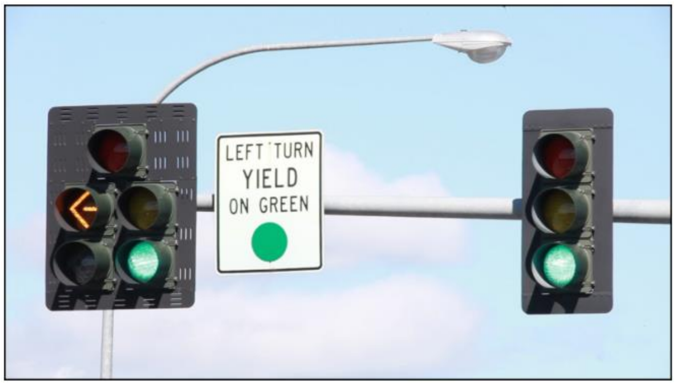
Q15. Are there laws/ordinances within your jurisdiction that effect the usage of PPLT phasing or mandate the signal indications shown with the protected or permitted phase?

Appendix 3: Survey Questions

Q 1.1 This video shows a complete signal sequence of a doghouse display. Next questions are based on the signals you observe in this video. Please watch carefully.

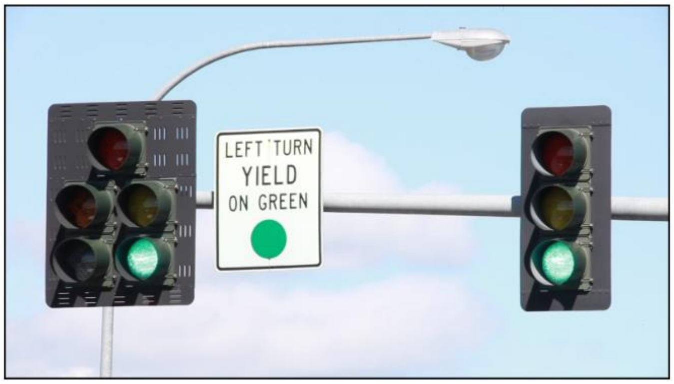


Q 1.2 Please take a look at the following picture. If you are a left-turning driver and observe the following signal, how will you proceed? Choose all that apply.



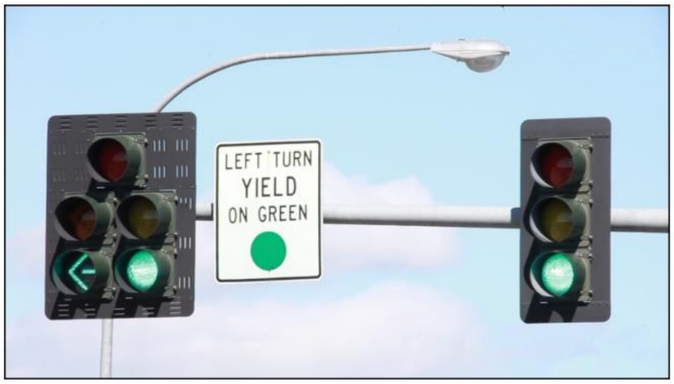
- ☐ I will stop at the intersection if I am approaching it.
- ☐ I will clear the intersection if I am within it, as long as it is safe to do so. Otherwise, I will back up into the left lane.
- ☐ I will turn left immediately as I have the right of way.

Q 1.3 Please take a look at the following picture. If you are a left-turning driver and observe the following signal, how will you proceed?



- ☐ I will yield to opposing traffic, and turn left only when it is safe to do so. I don’t have the right of way
- ☐ I will turn left immediately as I have the right of way.
- ☐ I will stop and wait for the green arrow as I don't have the right of way.

Q 1.4 Please take a look at the following picture. If you are a left-turning driver and observe the following signal, how will you proceed?



- ☐ I will yield to opposing traffic, and turn left only when it is safe to do so. I don’t have the right of way
- ☐ I will turn left as I have the right of way.

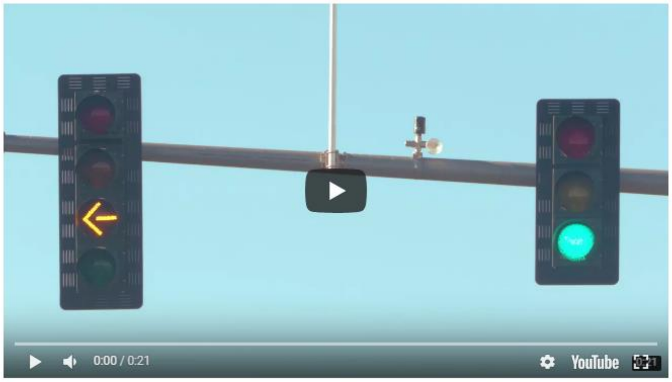
☐ I will stop as I don't have the right of way.

Q 1.5 Have you ever been confused by doghouse display signals as a left-turning driver?

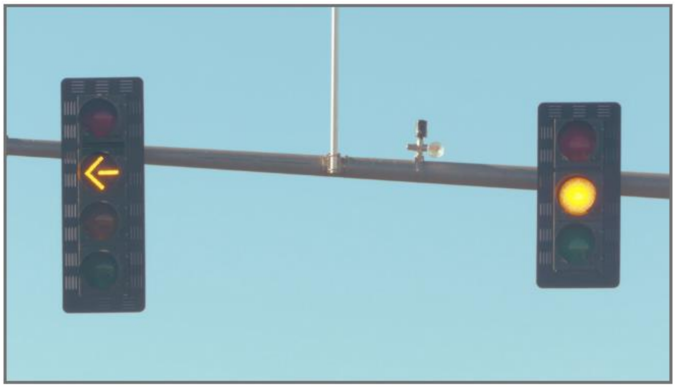
☐ Yes

☐ No

Q 2.1 This video shows a complete signal sequence of a vertical four-section display with flashing yellow arrow. Next questions are based on the signals you observe in this video. Please watch carefully.



Q 2.2 Please take a look at the following picture. If you are a left-turning driver and observe the following signal, how will you proceed? Choose all that appy.

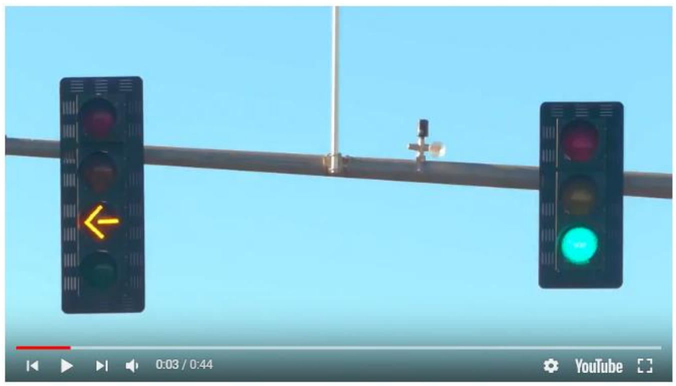


☐ I will stop at the intersection if I am approaching it.

☐ I will clear the intersection if I am within it, as long as it is safe to do so. Otherwise, I will back up into the left lane.

☐ I will turn left immediately as I have the right of way.

Q 2.3 If you observe the flashing yellow arrow signal (shown below) as a left-turning driver, how should you proceed?

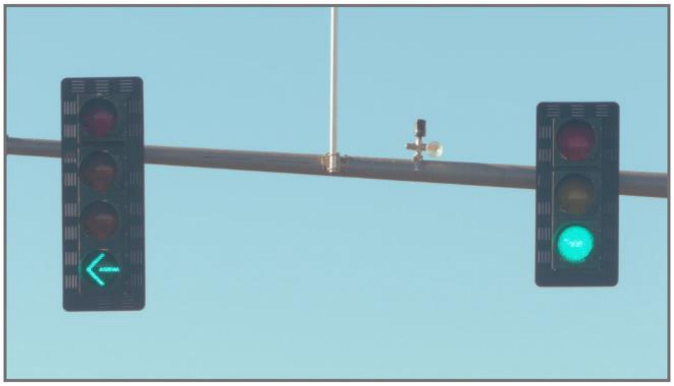


☐ I will yield to opposing traffic, and turn left only when it is safe to do so. I don't have the right of way

☐ I will turn left immediately as I have the right of way.

☐ I will stop and wait for the green arrow as I don't have the right of way.

Q 2.4 Please take a look at the following picture. If you are a left-turning driver and observe the following signal, how will you proceed?



- ☐ I will yield to opposing traffic, and turn left only when it is safe to do so. I don't have the right of way
- ☐ I will turn left as I have the right of way.
- ☐ I will stop as I don't have the right of way.

Q 2.5 Have you ever been confused by signals of the vertical four-section display with flashing yellow arrow as a left-turning driver?

- ☐ Yes
- ☐ No

Q 3.1 As a left-turning driver, have you ever encountered an intersection, where the flashing yellow arrow is displayed selectively at some hours of the day?

- ☐ Yes
- ☐ Maybe
- ☐ No

Q 3.2 (if yes or maybe was selected) Have you ever been confused by the variable or inconsistent usage of the flashing yellow arrow in such intersections?

- ☐ Yes

☐ No

Q 4.1 Which of the shown displays do you prefer to see as a left-turning driver?

☐ Vertical four-section display with flashing yellow arrow

☐ Doghouse display

Q 5.1 Do you have difficulty recognizing colors?

☐ Yes

☐ No

Q 5.2 (if yes was selected) Which colors?

☐ Red

☐ Yellow

☐ Green

☐ Other

Q 6.1 How many years of driving experience do you have?

☐ 0

☐ >0-5

☐ >5-15

☐ >15-25

☐ >25-35

☐ >35

Q 6.2 Select your age category

☐ <25

☐ >25-35

☐ >35-45

☐ >45-55

☐ >56-65

☐ >65

Q 7.1 Please provide any comments/recommendations based on your experience as a left-turning driver (optional)

Appendix 4: Signal Timing Plans

For all scenarios: 1) Signal sequence is Lead-Lead, 2) Change of interval = 3 seconds, 3) All red = 1 second.

Sc. N	THR Demand (vphpl)	Control Mode	LT %	Geometry	Major LT Green EB&WB (s)	Major THR Green EB&WB (s)	Minor THR Green NB&SB (s)	Cycle Length (s)
1	1200	POLT	25	1	46	174	20	240
2				2	46	174	20	240
3				3	46	174	20	240
4				4	41	135	19	195
5				5	46	174	20	240
6			15	1	31	184	20	235
7				2	31	184	20	235
8				3	31	184	20	235
9				4	30	168	20	218
10				5	30	184	20	234
11			5	1	16	204	20	240
12				2	16	204	20	240
13				3	16	204	20	240
14				4	15	193	20	228
15				5	15	202	20	237
16		PPLT	25	1	24	133	19	176
17				2	19	126	19	164
18				3	16	135	19	170
19				4	30	128	19	177
20				5	26	121	19	166
21			15	1	9	211	20	240
22				2	17	200	20	237
23				3	22	196	20	238
24				4	9	205	20	234
25				5	18	188	20	226
26			5	1	9	211	20	240
27				2	9	211	20	240
28				3	9	206	20	235
29				4	9	205	20	234
30				5	9	202	20	231
31		PRLT	25	1	0	221	19	240
32				2	0	221	19	240
33				3	0	64	19	83
34				4	0	221	19	240
35				5	0	221	19	240
36			15	1	0	169	19	188
37				2	0	221	19	240
38				3	0	99	19	118

Sc. N	THR Demand (vphpl)	Control Mode	LT %	Geometry	Major LT Green EB&WB (s)	Major THR Green EB&WB (s)	Minor THR Green NB&SB (s)	Cycle Length (s)
39				4	0	220	20	240
40				5	0	221	19	240
41			5	1	0	186	20	206
42				2	0	201	20	221
43				3	0	180	19	199
44				4	0	191	20	211
45				5	0	216	20	236
46	1000	POLT	25	1	37	136	20	193
47				2	38	149	20	207
48				3	39	164	20	223
49				4	34	121	20	175
50				5	35	128	20	183
51			15	1	26	135	20	181
52				2	27	163	20	210
53				3	27	169	20	216
54				4	24	125	20	169
55				5	24	130	20	174
56			5	1	15	149	20	184
57				2	15	169	20	204
58				3	15	182	20	217
59				4	14	137	20	171
60				5	14	156	20	190
61		PPLT	25	1	9	175	20	204
62				2	18	146	20	184
63				3	12	86	19	117
64				4	9	192	20	221
65				5	20	125	20	165
66			15	1	9	160	20	189
67				2	9	170	20	199
68				3	12	152	20	184
69				4	9	167	20	196
70				5	9	167	20	196
71			5	1	9	154	20	183
72				2	9	167	20	196
73				3	9	171	20	200
74				4	9	155	20	184
75				5	9	167	20	196
76		PRLT	25	1	0	177	20	197
77				2	0	196	19	215
78				3	0	58	19	77
79				4	0	203	20	223
80				5	0	169	19	215
81			15	1	0	146	20	166
82				2	0	161	19	180
83				3	0	82	19	101

Sc. N	THR Demand (vphpl)	Control Mode	LT %	Geometry	Major LT Green EB&WB (s)	Major THR Green EB&WB (s)	Minor THR Green NB&SB (s)	Cycle Length (s)
84				4	0	159	20	179
85				5	0	161	19	180
86			5	1	0	132	20	152
87				2	0	153	20	173
88				3	0	165	20	185
89				4	0	136	20	156
90				5	0	153	20	173
91	800	POLT	25	1	29	97	20	146
92				2	30	112	20	162
93				3	30	112	20	162
94				4	26	82	20	128
95				5	26	84	20	130
96			15	1	23	104	20	147
97				2	23	123	20	166
98				3	23	139	20	182
99				4	21	89	20	130
100				5	21	103	20	144
101			5	1	14	131	20	165
102				2	14	134	20	168
103				3	14	152	20	186
104				4	13	116	20	149
105				5	13	122	20	155
106		PPLT	25	1	9	122	20	151
107				2	9	147	20	176
108				3	11	107	20	138
109				4	9	131	20	160
110				5	9	157	20	186
111			15	1	9	119	20	148
112				2	9	140	20	169
113				3	9	147	20	176
114				4	9	121	20	150
115				5	9	145	20	174
116			5	1	9	114	20	143
117				2	9	133	20	162
118				3	9	140	20	169
119				4	9	115	20	144
120				5	9	140	20	169
121		PRLT	25	1	0	116	20	136
122				2	0	118	19	137
123				3	0	71	19	90
124				4	0	132	20	152
125				5	0	202	20	222
126			15	1	0	103	20	123
127				2	0	127	20	147
128				3	0	113	19	132

Sc. N	THR Demand (vphpl)	Control Mode	LT %	Geometry	Major LT Green EB&WB (s)	Major THR Green EB&WB (s)	Minor THR Green NB&SB (s)	Cycle Length (s)
129				4	0	113	20	133
130				5	0	140	20	160
131			5	1	0	89	20	109
132				2	0	118	20	138
133				3	0	134	20	154
134				4	0	98	20	118
135				5	0	120	20	140
136	600	POLT	25	1	24	68	20	112
137				2	24	77	20	121
138				3	25	101	20	146
139				4	22	57	20	99
140				5	22	68	20	110
141			15	1	20	74	20	114
142				2	20	96	20	136
143				3	20	113	20	153
144				4	19	63	20	102
145				5	18	94	20	132
146			5	1	14	99	20	133
147				2	14	106	20	140
148				3	14	113	20	147
149				4	14	82	20	116
150				5	13	97	20	130
151		PPLT	25	1	9	87	20	116
152				2	9	111	20	140
153				3	9	119	20	148
154				4	9	91	20	120
155				5	9	114	20	143
156			15	1	9	84	20	113
157				2	9	108	20	137
158				3	9	111	20	140
159				4	9	88	20	117
160				5	9	110	20	139
161			5	1	9	83	20	112
162				2	9	108	20	137
163				3	9	110	20	139
164				4	9	83	20	112
165				5	9	108	20	137
166		PRLT	25	1	0	79	20	99
167				2	0	100	20	120
168				3	0	121	20	141
169				4	0	90	20	110
170				5	0	112	20	132
171			15	1	0	73	20	93
172				2	0	93	20	113
173				3	0	108	20	128

Sc. N	THR Demand (vphpl)	Control Mode	LT %	Geometry	Major LT Green EB&WB (s)	Major THR Green EB&WB (s)	Minor THR Green NB&SB (s)	Cycle Length (s)
174				4	0	79	20	99
175				5	0	99	20	119
176			5	1	0	68	20	88
177				2	0	89	20	109
178				3	0	103	20	123
179				4	0	70	20	90
180				5	0	90	20	110
181	400	POLT	25	1	14	25	19	58
182				2	21	64	20	105
183				3	21	74	20	115
184				4	13	25	19	57
185				5	20	52	20	92
186			15	1	18	62	20	100
187				2	18	71	20	109
188				3	18	74	20	112
189				4	10	23	19	52
190				5	17	62	20	99
191			5	1	15	67	20	102
192				2	15	74	20	109
193				3	15	77	20	112
194				4	15	61	20	96
195				5	14	73	20	107
196		PPLT	25	1	9	58	20	87
197				2	9	79	20	108
198				3	9	80	20	109
199				4	9	60	20	89
200				5	9	80	20	109
201			15	1	9	57	20	86
202				2	9	73	20	102
203				3	9	74	20	103
204				4	9	59	20	88
205				5	14	69	20	103
206			5	1	9	56	20	85
207				2	9	73	20	102
208				3	9	73	20	102
209				4	9	56	20	85
210				5	9	73	20	102
211		PRLT	25	1	0	51	20	71
212				2	0	68	20	88
213				3	0	74	20	94
214				4	0	59	20	79
215				5	0	73	20	93
216			15	1	0	48	20	68
217				2	0	65	20	85
218				3	0	74	20	94

Sc. N	THR Demand (vphpl)	Control Mode	LT %	Geometry	Major LT Green EB&WB (s)	Major THR Green EB&WB (s)	Minor THR Green NB&SB (s)	Cycle Length (s)
219				4	0	52	20	72
220				5	0	68	20	88
221			5	1	0	45	20	65
222				2	0	62	20	82
223				3	0	74	20	94
224				4	0	47	20	67
225				5	0	63	20	83
226	200	POLT	25	1	11	19	19	49
227				2	9	19	19	47
228				3	9	19	19	47
229				4	9	19	19	47
230				5	9	19	19	47
231			15	1	9	19	19	47
232				2	9	19	19	47
233				3	9	19	19	47
234				4	9	19	19	47
235				5	9	19	19	47
236			5	1	9	19	19	47
237				2	9	19	19	47
238				3	9	19	19	47
239				4	9	19	19	47
240				5	9	19	19	47
241		PPLT	25	1	9	31	20	60
242				2	9	39	20	68
243				3	9	39	20	68
244				4	9	32	20	61
245				5	9	40	20	69
246			15	1	9	30	20	59
247				2	9	40	20	69
248				3	9	42	20	71
249				4	9	31	20	60
250				5	9	40	20	69
251			5	1	9	30	20	59
252				2	9	39	20	68
253				3	9	39	20	68
254				4	9	30	20	59
255				5	9	40	20	69
256		PRLT	25	1	0	25	19	44
257				2	0	38	20	58
258				3	0	39	20	59
259				4	0	24	19	43
260				5	0	39	20	59
261			15	1	0	24	19	43
262				2	0	37	20	57
263				3	0	39	20	59

Sc. N	THR Demand (vphpl)	Control Mode	LT %	Geometry	Major LT Green EB&WB (s)	Major THR Green EB&WB (s)	Minor THR Green NB&SB (s)	Cycle Length (s)
264				4	0	24	19	43
265				5	0	39	20	59
266			5	1	0	24	19	43
267				2	0	36	20	56
268				3	0	39	20	59
269				4	0	24	19	43
270				5	0	36	20	56