TECHNICAL REPORT STANDARD PAGE

1. Title and Subtitle

Evaluating Permitted/Protected Versus Protected Left-turn Signals in Louisiana

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P.O. Box 94245
Baton Rouge, LA 70804-9245

5. Report No.

FHWA/LA.22/669

6. Report Date

December 2022

7. Performing Organization Code

LTRC Project Number: 21-3SS
SIO Number: DOTLT1000378

8. Type of Report and Period Covered

Final Report
08/2020 – 07/2022

9. No. of Pages

95

10. Supplementary Notes

Conducted in Cooperation with the U.S. Department of Transportation, Federal Highway Administration

11. Distribution Statement

Unrestricted. This document is available through the National Technical Information Service, Springfield, VA 21161.

12. Key Words

Crash, Left-Turn Phase, Survey, Safety, Operation, CMF, Delay

13. Abstract

The main objective of this study is to evaluate the safety and operation of existing left-turn signal phases at intersections and investigate relevant data to develop proper guidance on when it is appropriate to install each signal type. The study considered protected-only (PO), protected permitted left-turn (PPLT), and flashing yellow arrow (FYA) left-turn phases for the evaluation. The study was conducted in four different folds — nationwide survey, decision tree modeling, safety analysis, and operation analysis. The nationwide survey revealed that the majority of the respondents indicated FYA as the preferred left-turn signal in terms of operation, followed by PPLT. At the same time, from a safety perspective, PO was desired, followed by FYA. The decision tree revealed several factors such as total left-turn crashes, median types, number of left-turning lanes, speed limit, and annual average daily traffic (AADT) controlling the selection of PO over PPLT. The safety analysis showed almost double left-turn crashes per year at PPLT compared to PO and FYA intersections. Crash modification factor (CMF) of PO over PPLT for total crashes showed that PO was only able to reduce fatal and severe crashes by 25.5% compared to PPLT; however, PO was able to reduce all severe levels of left-turn crashes. It indicates that PO performs better than PPLT from a safety perspective. Before-and-after evaluation at FYA intersections revealed a left-turn crash reduction of 17.73%. In addition, delay analysis showed an average delay of 50.69 seconds per vehicle (sec/veh) at PO, 46.04 at PPLT, and 31.49 at FYA. However, the delay only during the morning peak hour at PO was significantly higher than at PPLT. At other periods, it was not. Delay at FYA was all-time low compared to PO and PPLT, but the outcome from FYA is less robust due to the limited sample size. With left-turn crash reduction by more than 50% and delays not significantly more at all times of the day, the study indicates PO performs better than PPLT. The framework from the decision tree provides key information to help select the suitable left-turn phase between PO and PPLT.

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LTRC appreciates the dedication of the following Project Review Committee Members in guiding this research study to fruition.

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LTRC Project No. 21-3SS
SIO No. DOTLT1000378

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The main objective of this study is to evaluate the safety and operation of existing left-turn signal phases at intersections and investigate relevant data to develop proper guidance on when it is appropriate to install each signal type. The study considered protected-only (PO), protected permitted left-turn (PPLT), and flashing yellow arrow (FYA) left-turn phases for the evaluation. The study was conducted in four different folds — nationwide survey, decision tree modeling, safety analysis, and operation analysis.

The nationwide survey revealed that the majority of the respondents indicated FYA as the preferred left-turn signal in terms of operation, followed by PPLT. At the same time, from a safety perspective, PO was desired, followed by FYA. The decision tree revealed several factors such as total left-turn crashes, median types, number of left-turning lanes, speed limit, and annual average daily traffic (AADT) controlling the selection of PO over PPLT. The safety analysis showed almost double left-turn crashes per year at PPLT compared to PO and FYA intersections. Crash modification factor (CMF) of PO over PPLT for total crashes showed that PO was only able to reduce fatal and severe crashes by 25.5% compared to PPLT; however, PO was able to reduce all severe levels of left-turn crashes. It indicates that PO performs better than PPLT from a safety perspective. Before-and-after evaluation at FYA intersections revealed a left-turn crash reduction of 17.73%. In addition, delay analysis showed an average delay of 50.69 seconds per vehicle (sec/veh) at PO, 46.04 at PPLT, and 31.49 at FYA. However, the delay only during the morning peak hour at PO was significantly higher than at PPLT. At other periods, it was not. Delay at FYA was all-time low compared to PO and PPLT, but the outcome from FYA is less robust due to the limited sample size.

With left-turn crash reduction by more than 50% and delays not significantly more at all times of the day, the study indicates PO performs better than PPLT. The framework from the decision tree provides key information to help select the suitable left-turn phase between PO and PPLT.

Acknowledgments

This project was completed with the support of the Louisiana Department of Transportation and Development (DOTD) and the Louisiana Transportation Research Center (LTRC). The research team gratefully acknowledges the assistance of all the student workers who assisted during the data collection and reduction efforts. Lastly, the research team acknowledges the Project Review Committee (PRC) members for their valuable feedback and all other DOTD personnel involved in this project.

Implementation Statement

The findings from the nationwide survey revealed important information on left-turn phases other state agencies use to manage the left-turning traffic. The framework from the decision tree revealed several factors, such as total left-turn crashes, median types, number of left-turning lanes, speed limits, and AADT controlling the selection of PO over PPLT left-turn signals, which may help to select the suitable left-turn phase. The safety analysis revealed key information on CMF. The CMF analysis indicates how much better PO is than PPLT. The delay analysis suggests that though the overall delay at PO was significantly higher than at PPLT only during the morning peak hour, it was not significantly different at off-peak and afternoon peak hours. It indicates that PO phases do not always create more delay than PPLT. The decision tree, CMF, and delay analysis information can help DOTD determine the best left-turn phase at any intersection.

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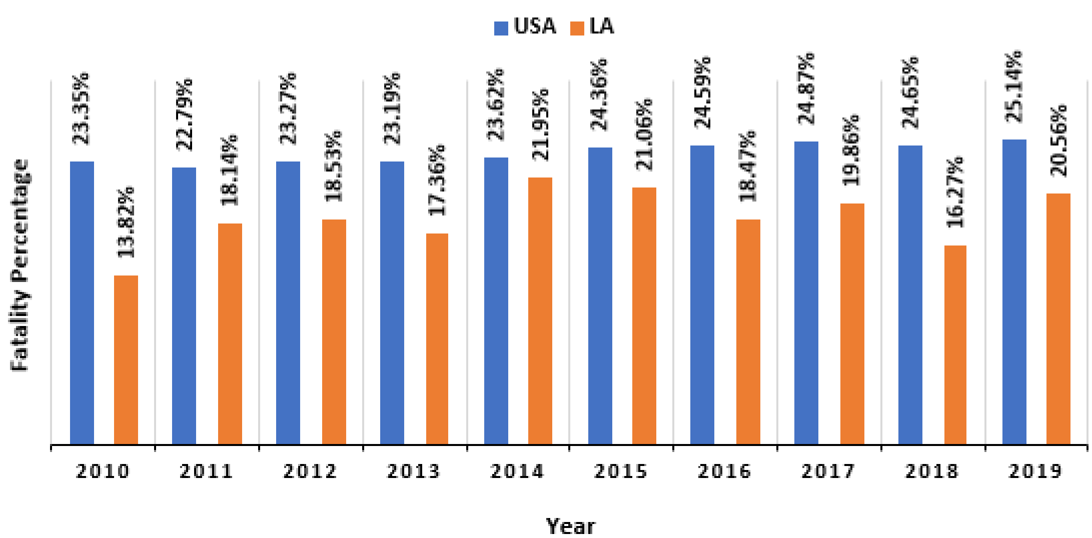
Introduction

Background

Each year a significant number of traffic fatalities occur at roadway intersections. Intersections create higher possibilities for collision between vehicles, vehicles and pedestrians, and vehicles with bicycles because intersections have more conflict areas than other roadway features. Figure 1 shows the percentages of motor vehicle fatalities at intersections in the USA and Louisiana from 2010 to 2019. All the fatal motor vehicle crash data shown in the figure were queried from Fatality Analysis Reporting System (FARS) [1]. It shows the period between 2015 and 2019 with slightly higher fatality rates above 24%. Comparing the rates within the 10 years, 2019 recorded the most fatalities (25.14%) nationwide. Specific to Louisiana, the fatality rate was recorded below the national rate. However, the trend showed that though the fatality rate slightly decreased from 19.86% in 2017 to 16.27% in 2018, it increased to 20.56% in 2019.

Figure 1. Intersection fatality percentages by year in USA and Louisiana [2]



Crashes at intersections are more likely to be serious since most crashes are right-angled [3]. Other factors affecting the severity of crashes at intersections are traffic volume [4, 5, 6], sight distance [5], traffic control devices [6], speed [7], and the percentage of through-moving and turning vehicles. According to a report from National Center for Statistics and Analysis, vehicles turning left (22.2 %), vehicles crossing over at intersections (12.6 %), and vehicles turning right at the intersections (1.2%) were three significant turning movements involved in intersection crashes [8]. The same report mentioned that most crashes (52.5%) occurred at signalized intersections, with the rest at stop signs or intersections without traffic control systems.

Problem Statement

Provision of left-turn signals at signalized intersections is necessary to prevent delays and crashes for left-turning traffic. Still, depending on its type, it may adversely affect the operation of intersections by increasing additional delay to through traffic, decreasing the intersection capacity, and reducing the overall efficiency of the signal coordination. As part of measures to manage left-turning vehicles at signalized intersections, three types of signal configurations are dominant in Louisiana: permitted (P), protected-only (PO), and protected/permitted left-turn phase (PPLT) [9]. The permitted left-turn phase (P) allows left-turning drivers the option to proceed when the light is green (on a 3-section signal head) but only after yielding to opposing traffic and pedestrians. The protected left-turn phase (PO), on the other hand, allow left-turning drivers to proceed unhindered but at green left arrows (on a 3- section signal head). Drivers cannot proceed through the intersection without a green arrow, even in the absence of opposing traffic or pedestrians. Lastly, permitted/protected (PPLT) affords left-turning drivers two options: the protected option lets the drivers proceed unhindered on a green arrow just like the protected left-turn signal, and the permitted option allows drivers to turn left only after yielding to oncoming traffic and pedestrians. Traditionally, yellow and green arrows have been added to a standard 3-section signal head to form a 5-section signal head to provide protected/permitted signal configuration movements. However, in recent times, a single unit has replaced the 2-section yellow and green arrows to transform the 5-section signal head into a 4-section signal head consisting of a solid red arrow, solid yellow arrow, flashing yellow, and a solid green arrow. These are referred to as the flashing yellow arrow signal (FYA) [9], which does not have different signal phases from the PPLT, but different displays. The FYA has a flashing yellow arrow for left-turning vehicles, while the PPLT signal head does not.

The DOTD's traffic signal manual sets guidelines for PO or PPLT left-turn movements. The guidance for protected-only phasing is based on inadequate left-turn sight distances, excessive street widths, speeds of opposing traffic, inadequate geometry, number of left-turn crashes, and the presence of two or more left-turn lanes. When none of the conditions for PO are met, PPLT phasing may be considered. Safety benefits of PO are higher than PPLT turns, but delays for the former are also greater. There is a need to balance the safety benefits of an intersection signal configuration with its operational benefits. This study aims to evaluate the effectiveness of PO versus PPLT signal phasing from both safety and operation perspectives using sample signalized intersections from Louisiana.

Louisiana Signalized Intersection

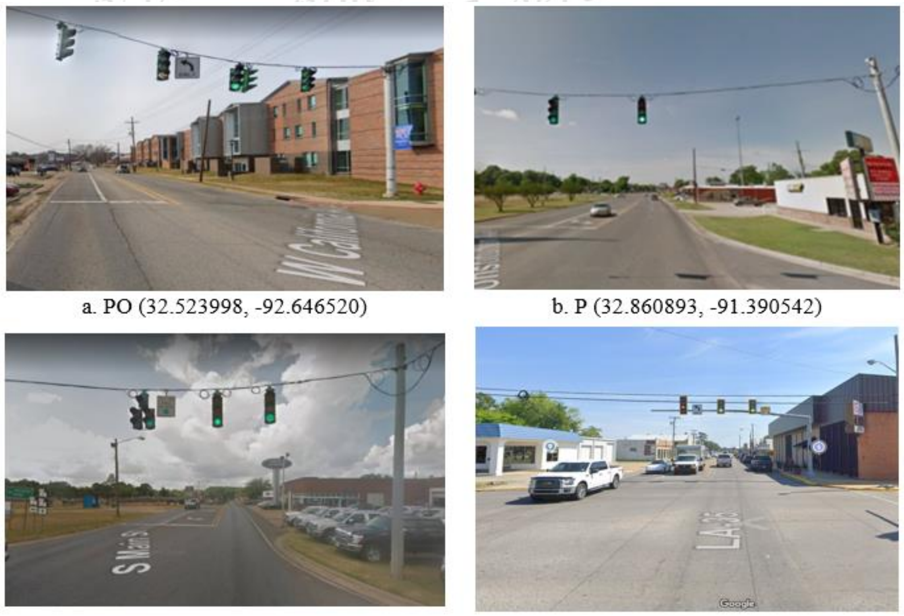
The study first compiled a list of 2,297 state-owned intersections for consideration. Table 1 shows a complete list of 2,297 signal intersections and the distribution across each DOTD district. As mentioned before, all of the intersections below were owned by the state. It may not be the list of all state-owned intersections but covers the major intersections with varieties of left-turn phases.

Table 1. Distribution of signalized intersections across Louisiana

District Name	Number of Intersections
District 02	551
District 03	284
District 04	351
District 05	241
District 07	159
District 08	175
District 58	35
District 61	215
District 62	286
Total	2,297

Intersections are either three-legged or four-legged, which means the number of approaches ranges from a minimum of three to a maximum of four. The study used street view in Google Maps to determine the intersection types, left-turn phases (P, PPLT, FYA, and PO), and the number of lanes (left, through, shared, and right) for each approach. Figure 2 shows different signal types within the state and signal head types for all four different left-turn signals. In the street view, the signal head configuration at each approach was used to identify the left-turn signal types. The study took significant time to detect the types of left-turn phases from all the above intersections. Cross-check was done to see if information reduced from Google Maps matched the field conditions and maintain the quality of information reduced. For example, the presence of a sign with a left-turning arrow indicates a PO signal type, while the presence of a sign with the text “LEFT-TURN YIELD ON GREEN” indicates the presence of a PPLT signal, as shown in Figure 2(a) and (c), respectively. Left-turn with no such signs shows the presence of permitted only (P) left-turn signal as shown in Figure 2(b). The flashing yellow arrow (FYA) includes both the sign with a left-turn arrow and a yellow indicator arrow in the signal head, as shown in Figure 2(d). As clarified previously, PPLT and FYA only differ in their display heads: FYA has a flashing yellow arrow for left-turning vehicles, while the PPLT signal head does not.

Figure 2. Various left-turn signal types at intersections (Source: Google Maps)



a. PO (32.523998, -92.646520)

b. P (32.860893, -91.390542)

c. PPLT (32.773300, -92.405383)

d. FYA (30.235091, -92.268795)

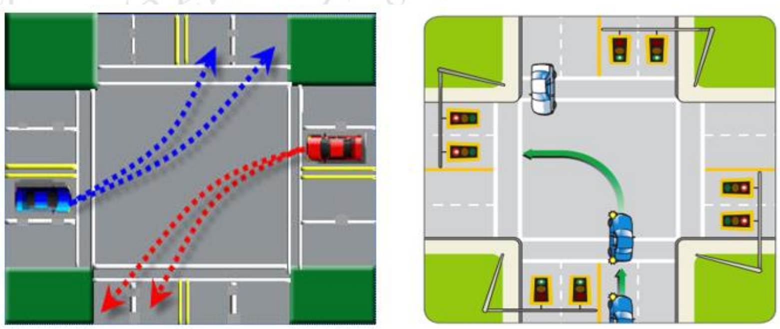
Literature Review

This section reviewed key information on different left-turn phases from safety and operation perspectives. It also discussed the detailed procedure to estimate delay at signalized intersections. At the end of the section, the study focused on the methodologies several past studies have used to analyze the crash data. The study used all the key information from this section to develop a methodology for this study.

Different Left-turning Signal Phases

Left turns at signalized intersections are widely recognized as challenging and high-risk maneuvers for drivers with conflicting movements to opposing through traffic, same-direction through traffic, cross street vehicular traffic, and pedestrian traffic. In order to have the most effective left-turn phase at signalized intersections, the phase should prevent unnecessary delays and reduce the total number of conflicts. Otherwise, the poorly designed left-turn phase would adversely affect the operation of the intersection by increasing delay to through traffic, decreasing the intersection capacity, and reducing the overall efficiency of the signal coordination. Figure 3 shows an example of typical left-turn maneuvers at an intersection. Properly designed left-turn phases can control all left-turn maneuvers.

Figure 3. Typical left-turn maneuvers at an intersection [10]



According to the Manual on Uniform Traffic Control Devices (MUTCD), a phase or signal phase is a right of way, yellow change, and red clearance interval in a cycle assigned to an independent traffic movement or combination of traffic movements [11]. It is the sequence of individual phases or combinations of signal phases within a cycle that defines the order in which various pedestrian and vehicular movements are assigned the right of way. There are three phasing configurations for intersections with left-turn lanes, mostly used all over the USA and are permitted only (P), protected-only (PO), and protected/permitted left-turn (PPLT) signal phasing. Below are details on the three different types of left-turn traffic signals used by the Louisiana Department of Transportation and Development (DOTD).

The permitted left-turn phase (P) indicates that left-turning drivers can proceed when the light is green only after yielding to opposing traffic and pedestrians. Figure 4 below shows an illustration of the permitted left-turn signal.

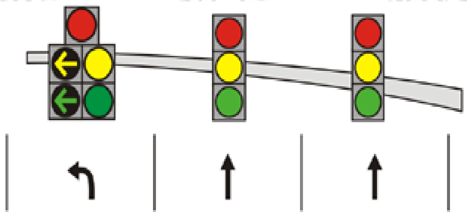
Figure 4. Permitted left-turn signal

However, the protected left-turn phase (PO) allows drivers to turn left without interruption but only at green left arrows. Even if there is no opposing traffic or pedestrians, drivers cannot pass through the intersection without a green arrow. Figure 5 below shows an illustration of a protected left-turn phase.

Figure 5. Protected (P) left-turn phase

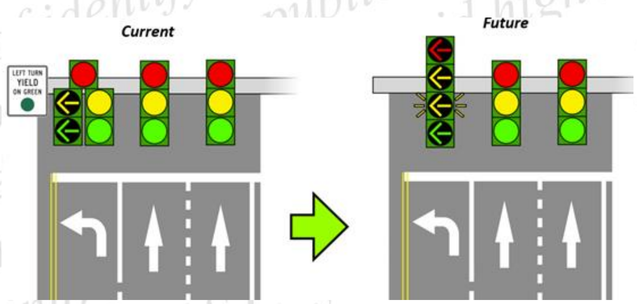
Finally, the protected/permitted left-turn phase (PPLT) provides left-turning drivers with two options: the protected and then the permitted option. The first one works similarly to the protected left-turn signal, allowing drivers to proceed unrestricted on a green arrow. The latter allows drivers to turn left only after giving way to oncoming traffic and pedestrians. Figure 6 shows an illustration of the permitted/protected left-turn phase.

Figure 6. Permitted/Protected (PPLT) left-turn signal



The permitted, protected and permitted/protected left-turn phases are all distinct in their mode of operation. Traditionally, yellow and green arrows have been added to a standard 3-section signal head to form a 5-section signal head to provide protected/permitted signal configuration movements. However, in recent times, the 2-section yellow and green arrows have been replaced by a single unit consisting of a solid red arrow, solid yellow arrow, flashing yellow arrow, and a solid green arrow. This is referred to as the flashing yellow arrow (FYA) left-turn phase. Figure 7 shows the newly implemented signal systems by the DOTD.

Figure 7. Flashing Yellow Arrow (FYA) left-turn signal [12]



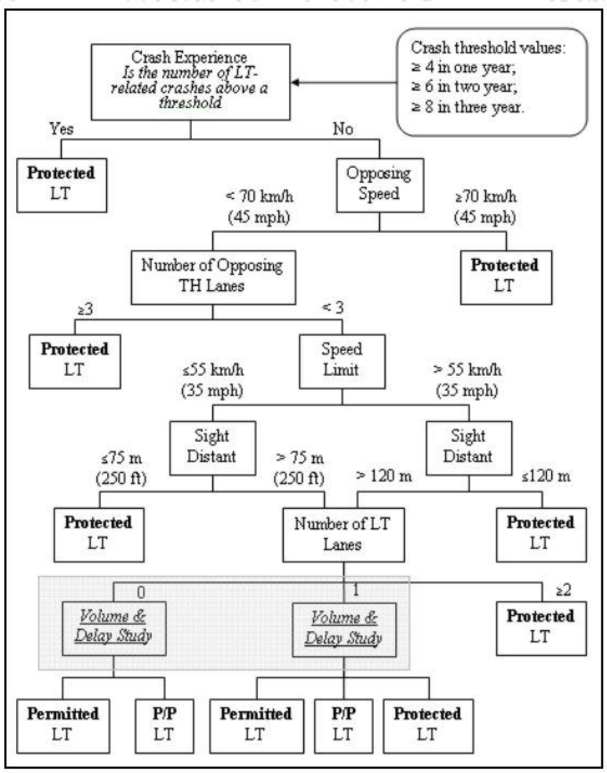
Different Guidelines for Left-Turn Operation

Several studies have created guidelines, standards, or justifications for determining the optimal mode for making a left-turn at a signalized intersection. The PPLT left-turn phase is widely accepted to have more operational benefits, while the PO left-turn phase provides higher safety performance. As a result, the decision between PO and PPLT left-turn phase must strike a reasonable balance between intersection operating performance and safety. Previous studies used left-turn delay, volume (including left-turn volume and opposing volume), accident or conflict experience, and geometric conditions to generate guidelines/warrants for PO and PPLT phases, including the number of left-turn lanes, number of opposing lanes, et cetera.

Al-Kaisy and Stewar (2001) proposed a method for developing warrants for a protected phase by minimizing the overall average delay at the intersection [13]. Using the basic characteristics of the intersection, the study estimated the overall delays of an intersection under permissive phasing and PPLT phasing. Then, the intersection delays under different types of signal phases were compared. The boundary-value of left-turn volume was derived for the intersection in the next step, where the protected left-turn phase has less delay than the permitted left-turn phase. Next, a multivariate linear regression model was developed using left-turning volumes of the boundary points using the number of left-turns, number of opposing through lanes, number of adjacent through lanes, and cross-volumes. The study concluded that changing from P to PPLT is mainly the function of traffic conditions.

Zhang and Prevedouros (2005) investigated both existing empirical warrants and optimization-based volume warrants from previous studies to develop a comprehensive flowchart for selecting left-turn control phases [14]. The complete flowchart is shown in Figure 8.

Figure 8. Procedure for determining left-turn phasing [14]



In the figure, the study suggested the selection of protected left-turn signal based on some criteria such as crash threshold values, opposing speed, number of opposing through lanes, speed limit, sight distance, number of left-turn lanes, volume, delay study, et cetera. It shows that a protected left-turn would be warranted when a factor exceeds the stated number and follows this flowchart sequentially.

Safety Impact of Different Left-Turn Phases

Hauer et al. (2005) studied the impact of changing the left-turn phases from PO to PPLT or vice versa from 1975 to 2003 [15]. The findings revealed a decrease in left-turn crashes when changing from PPLT to PO. However, the study showed no significant improvements in crashes when changing from PO to PPLT.

Srinivasan et al. (2012) analyzed the effect of changing the left-turn phase from permitted to PPLT phase by estimating the crash modification factor (CMF) [16]. The study used 59 intersections from Toronto and 12 intersections from North Carolina. The study found a significant reduction in crashes by changing the left-turn phase, though a small percentage of rear-end crashes were reported. In addition, the study also analyzed the effect of converting permitted signals to flashing yellow arrows by analyzing 51 signalized intersections in Oregon, Washington, and North Carolina. The result showed positive outcomes with the conversions.

Chen et al. (2015) evaluated the safety impacts of changing the left-turn phase from permitted to PO and PPLT [17]. A total of 68 intersections in New York City were selected. The result changing from permitted to PPLT and PO, respectively, reduced the number of total turn crashes by 33% and 55%; the number of multiple-vehicle crashes by 32% and 56%; the number of left-turn crashes by 17% and 77%; the number of rear-end collisions by 37% and 51%; and the number of over-taking collisions by 63% and 64%. However, the study did not find any significant change in the number of left-turn crashes when changing from permitted to PPLT.

Similarly, Pauw et al. (2015) studied the effect of changing the left-turn phase from permitted to PO by analyzing 103 signalized intersections in Flanders, Belgium [18]. The result showed a significant decrease (-46%) in left-turn crashes. However, the number of rear-end injury crashes did not change significantly.

Recently, Li et al. (2019) studied the impact of changing the left-turn phase from a PPLT signal to PO phase using a case study from Tucson, Arizona [19]. The study measured mobility in queue length and safety in multi-modal near-miss analysis. The result showed that after implementing PO phase, left-turn-related conflicts were reduced. However, there was still an increase in other types of conflicts, such as more pedestrians in the crosswalks during the stop walking indication and left-turning vehicles blocking the crosswalk when pedestrians were walking. The study also found an increase in delays by 4.9%. Some other studies, like Qi et al. (2017), found an increase in the probability of collision between pedestrians and left-turning vehicles under the permitted left-turn signal [20]. Other studies have also discussed the impact of different left-turn phases on pedestrian safety [18, 21, 22]. As mentioned in the above research papers, all left-turn signals can be served in any sequence, which defines the order and combination of the movement. For example, it can be left-turn first, followed by the through movement, and vice-versa. Previous studies have found that even the sequence of different left-turn phases has an impact on safety, and the following section will explore it in detail.

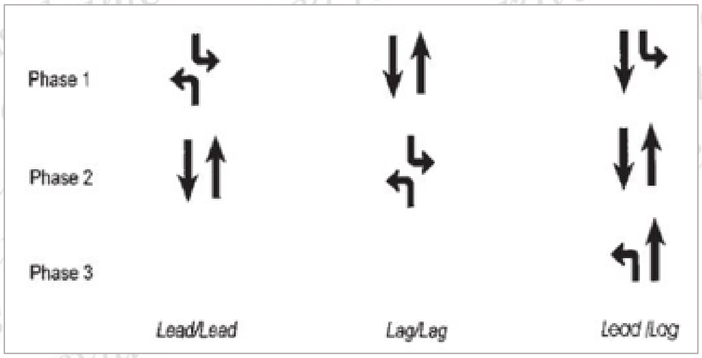
Impact of Different Left-turning Phase Sequences

Left-turn phase sequence shows when such phases are served relative to their complementary through movements. According to Federal Highway Administration (FHWA), the sequence options are advantageous under certain circumstances [11]. Generally, there are three types of left-turn phase sequences.

1. Lead-lead sequence: The traffic from the opposing left-turn moves before the through movements. It is the most common practice used in the left-turn phase.
2. Lead-lag sequence: The traffic from the opposing left-turn moves separately but simultaneously with their associated through movement in a phase. This left-turn phase sequence is used to accommodate movement progression in a coordinated signal system.
3. Lag-lag sequence: It is the opposite of the lead-lead left-turn sequence where the traffic from both the opposing left-turns moves after the through movements. This phase sequence is most used in coordinated signal systems with closely spaced signals, such as diamond interchanges.

The signal diagram of these three types of left-turn phasing sequences is provided below in Figure 9.

Figure 9. Left-turn phase sequence options [11]



A study by Upchurch (1991) used two methods, defined as cross-section and before-and -after, to investigate the safety impacts of different types of left-turn phasing sequences [23]. The study compared the accident experience of all five types of left-turn phasing — permitted, lead PPLT, lag PPLT, lead protected-only, and lag protected-only. The cross-section analysis found that the order of safety (from best to worst) was lead protected only, permitted, lead PPLT, and lag PPLT for the approaches with two opposing lanes. For approaches with three opposing lanes, the order of safety (from best to worst) was found to be lead protected-only, lead PPLT, permitted, and lag PPLT. In this comparison, lead protected-only phasing had a significantly lower accident rate than the other three types of phases. In before-and-after comparison, the result showed that lead protected-only phasing was always better than other types of left-turn phasing for approaches with two opposing lanes. The lag PPLT was better for the case of three opposing lanes than lead protected-only. However, the study could not determine the relationship between permitted and lead PPLT. This was because the accident rates for conversions from permitted to lead PPLT, and from lead PPLT to permitted contradicted each other.

Similarly, Hummer et al. (1991) explored three major issues relative to a left-turn phase sequence: driver's preference and understanding, intersection safety, and operational efficiency [24]. After analyzing accident data at 29 intersection approaches with lead or lag phase sequences, the study found that accidents occurred at a greater rate at intersections with lead sequences, though the difference was not significant. Overall, the study recommended the lag left-turn phase sequence for intersections serving heavy pedestrian volumes, diamond interchanges or one-way pairs, and intersections with fixed time signals.

Sheffer et al. (1999) investigated the safety impacts and operational efficiency of different left-turn phasing sequences for individual intersection approaches [25]. Six intersections with lead-lag left-turn phasing were studied. The six approaches with lead left-turn phasing were compared with similar approaches that lag left-turn phasing in terms of safety and operational effectiveness. Three traffic measures (flow rates, startup lost times, and fourth vehicle crossing times) were used to measure operational efficiency. The accident rate was compared between lead and lag left-turn phasing approaches for the safety analysis. The study found that lag-protected-only left-turn phasing operated better and safer than lead protected-only phasing.

In addition, Nandam et al. (2000) investigated the operation and safety effect of converting the left-turn phasing sequence from lead-lead to lead-lag by three different approaches: traffic safety review, response time analysis, and simulation analysis [26]. Nine intersections from Boca Raton City were selected for the safety analysis, and 4-year before-and-after crash data was reviewed to check the effect of sequence on overall intersection safety. The analysis showed no significant difference in total crashes even with the change in the left-turn sequence from lead-lead to lead-lag.

Box et al. (2003) evaluated the safety impact of the left-turn phasing sequence at individual intersection approaches [27]. The study compared the rates of left-turn head-on accidents at eight intersections with a lead-lead left-turn phase to 14 intersections with a lag-lag left-turn phase. The results showed no significant difference in accident rates between the intersection approaches with lead and lag left-turn phasing. Therefore, the study concluded that the use of lead or lag left-turn phasing does not significantly impact intersection safety.

Operation Impact of Different Left-Turn Phases

Asante et al. (1993) developed guidelines for left-turn phasing based on a three-level decision process [28]. The study estimated left-turn stopped delay of 194 approaches of 108 intersections for different phasing types (e.g., protected only, PPLT, lag Dallas phasing, lead Dallas phasing). The study found that in terms of average left-turn stopped delay, the lag PPLT was better than another left-turn phasing. Table 2 shows the result in detail.

Table 2. Average Stopped Delay by Phasing [28]

Phasing	Mean left-turn delay per vehicle (sec)
Protected	37.7
Protected/Permissive	20.3
Dallas Leading	29.3
Dallas Lagging	36.0

Phasing	Mean left-turn delay per vehicle (sec)
Permissive	N/A

Similarly, Shebeeb (1995) investigated the safety and efficiency of left-turn phasing at 179 approaches of 54 intersections in Texas and Louisiana [29]. The study used left-turn stopped delay in peak hours to measure the efficiency of left-turn phasing. The result showed that different left-turn phasing sequences (e.g., lead protected-only, lag protected-only, lead PPLT, lag PPLT, lead Dallas phasing, lag Dallas phasing, and permitted) recorded the left-turn stopped delay of 46.8, 44, 28.8, 32, 23, 24.6, and 13.7 seconds per vehicle, respectively. The study found protected-only phasing with the highest level of safety but least efficient. While permitted-only treatments offered the highest efficiency, it was less safe. No significant differences were observed between lead and lag left-turn sequences [29]. In addition, Stamatiadis et al. (1997) used simulation to estimate delay data collected from 217 intersections with protected, protected/permitted, and permitted left-turn phases [30]. The study found an average left-turn delay of 70 seconds in the protected phase with the highest recorded delay of 140 seconds. However, the delay was lower for the protected/permitted and permitted phasing than the protected phasing.

Nandam et al. (2000) investigated the operation and safety impact of a changing left-turn phasing sequence from lead-lead to lead-lag by conducting response time analysis and simulation analysis [26]. The study used average travel speed stops per vehicle, stop delay for the arterial through movements, and overall stop delay as a measure of effectiveness. Overall, the result showed that the use of lead-lag compared to lead-lead left-turn phasing had some benefits related to improving traffic flow at the intersections.

Hummer et al. (1991) used traffic simulation to analyze the impacts of left-turn signal sequence on traffic delay [24]. The intersections with four approaches were selected, and five separate experiments were conducted on those approaches. The results showed that the intersections having four approaches with the PPLT lead phase caused slightly more delay than the PPLT lag phase. The study recommended a lag left-turn phase sequence for intersections serving heavy pedestrian volumes and intersections with fixed-time signals. The study also found no significant differences between lead protected-only and lag protected-only signal phases.

Wright et al. (1992), investigated delay at one intersection to investigate the effect of left-turn phase change from protected-only to lead PPLT and then later to lag PPLT [31]. The study found that the conversion from protected-only to lead PPLT phasing reduced delay compared to the average delay under different left-turn phasing conditions. The result also showed that the conversion from lead PPLT to lag PPLT phasing increased delay. Finally, the study concluded that in terms of total average delay, the lead PPLT was better than lag PPLT, and lag PPLT was better than the protected only left-turn phase. The detail is shown in Table 3.

Table 3. Delay in seconds/vehicle [31]

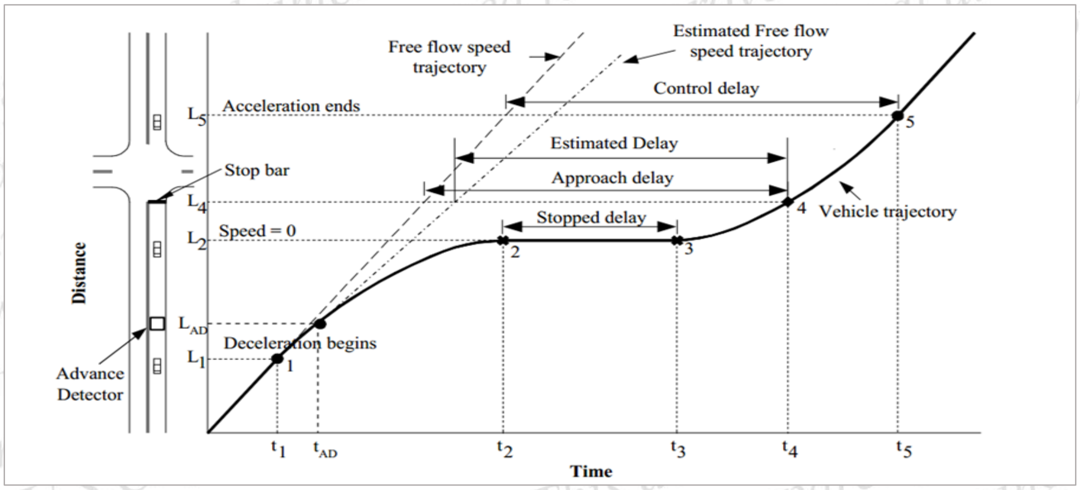
Direction	Movement Type	Protected	Protected/Permissive (leading)	Permissive/ Protected (lagging)
Northbound	Through	18.6	15.7	16.7
	Left-turn	59.7	28.4	42.3
Southbound	Through	18.8	24.3	17.4
	Left-turn	41.5	19.9	34.8

Sheffer et al. (1999) studied the performance of protected leading and lagging left-turn phasing at six intersections [25]. The result showed less start-up lost time and fourth vehicle-crossing times at left-turn lagging phases than at leading phases.

Control Delay at Signalized Intersections

For traffic engineers, evaluating the entire performance of a traffic system in terms of vehicle delay at a signalized intersection is considered one of the essential performance measures of traffic operations [32]. As discussed in the previous section, earlier studies show delay as a measure to assess the operational impact of different left-turning phases and sequences. How can such a delay at intersections be measured? First, there are several delay types at the signalized intersection, as shown in Figure 10. However, control delay, a part of the total delay, has been dominantly used to evaluate traffic signal efficiency. According to the 6th edition of the Transportation Research Board's Highway Capacity Manual (HCM), control delay is an additional travel time incurred by a vehicle affected by intersection control [33]. It can be divided into multiple parts, as indicated in Figure 10, such as deceleration delay, stopped delay, and acceleration delay. In the figure, these delays are plotted with the distance over time. Besides, it can also be attained by adding approach and intersection delay. The study discussed two different methods of measuring such control delay — one from the HCM 6 method using designated formulae and another using the HCM methodology but with field-collected data.

Figure 10. Delays at signalized intersections [34]



Control Delay using HCM 6 method

In HCM 6, chapter 19 introduces an analytical procedure for calculating the average control delay experienced by all vehicles that arrive during the analysis period at a lane group of a signalized intersection approach [33]. The average control delay per vehicle for a given lane group is computed with equation 2.1.

$$d = d_1 + d_2 + d_3 \qquad (2.1)$$

Where,

- d = control delay (s/veh),
- d_1 = uniform delay (s/veh),
- d_2 = incremental delay (s/veh), and
- d_3 = initial queue delay (s/veh)

A thorough description of the procedures for delay calculation is given in chapter 19 of HCM 6 [33]. The formula for each delay element is as follows (Equations 2.2, 2.3, 2.4):

Uniform delay (d_1):

$$d_1 = \frac{0.5C(1-g/C)^2}{1-[\min(1,x)g/C\,]} \qquad (2.2)$$

Where,

C = cycle length (s)
g = effective green time for lane group (s)
X = v/c ratio

Incremental delay (d_2)

$$d_2 = 900\,T\left[(X_A - 1) + \sqrt{(X_A - 1)^2 + \frac{8kIX_A}{C_A T}}\right] \quad (2.3)$$

Where,

T = duration of the analysis period (h)
k = incremental delay factor
I = upstream filtering/metering adjustment factor
C_A = lane group capacity (veh/h)
X_A = lane group v/c ratio

Initial queue delay (d_3)

$$d_3 = \frac{3600}{vT}\left[t_A \frac{Q_b + Q_e - Q_{eo}}{2} + \frac{{Q_e}^2 - {Q_{eo}}^2}{2C_A} - \frac{{Q_b}^2}{2C_A}\right] \quad (2.4)$$

Where,

Q_b = initial queue at the start of the analysis period (veh)
Q_e = queue at the end of the analysis period (veh)
Q_{eo} = queue at the end of the analysis period when $v \geq c_A$ and $Q_b = 0.0$ (veh)
t_A = adjusted duration of unmet demand in the analysis period (h)
v = demand flow rate (veh/h)

Control Delay Estimation from Field Measurement

Control delay can be calculated by simulations, analytical derivation, field measurement, or a combination of both. The field measurement technique is the most practical method for obtaining accurate field delays from signalized intersections. The procedure is discussed in detail in HCM. The following snapshot shows the detailed parameters required for the delay estimation in the field. Figure 11 shows the detailed procedure of calculating delay from the field measured data. Other details of it are described later in the methodology.

Figure 11. Worksheet for Measuring Control Delay in Field (snap extracted from HCM)

EXHIBIT A16-1. INTERSECTION CONTROL DELAY WORKSHEET

INTERSECTION CONTROL DELAY WORKSHEET

General Information		Site Information	
Analyst	____________	Intersection	____________
Agency or Company	____________	Area Type	☐ CBD ☐ Other
Date Performed	____________	Jurisdiction	____________
Analysis Time Period	____________	Analysis Year	____________

Input Initial Parameters

Number of lanes, N	________	Total vehicles arriving, V_{tot}	________
Free-flow speed, FFS (km/h)	________	Stopped-vehicle count, V_{stop}	________
Survey count interval, I_s (s)	________	Cycle length, C (s)	________

Input Field Data

Clock Time	Cycle Number	Number of Vehicles in Queue									
		Count Interval									
		1	2	3	4	5	6	7	8	9	10
Total											

Computations

Total vehicles in queue, $\sum V_{iq}$ =	________	Number of cycles surveyed, N_c =	________
Time-in-queue per vehicle, $d_{vq} = (I_s * \frac{\sum V_{iq}}{V_{tot}}) * 0.9$	________ s	Fraction of vehicles stopping, $FVS = \frac{V_{stop}}{V_{tot}}$	________
No. of vehicles stopping per lane each cycle = $\frac{V_{stop}}{(N_c \times N)}$	________	Accel/Decel correction delay, d_{ad} = FVS * CF	________ s
Accel/Decel correction factor, CF (Ex. A16-2)	________	Control delay/vehicle, $d = d_{vq} + d_{ad}$	________ s

Summary of Additional Studies at Intersection

This section summarizes past studies, especially on the methodologies and attributes used for the data analysis at intersections. The detail is shown in Table 4. As discussed previously, it is evident that intersection crashes are more likely to be fatal due to the right-angle nature of crashes [3]. Other several factors affecting the likelihood of crashes at intersections are traffic volume [4, 5, 6], sight distance [5], traffic control device speed, and percentage of through-moving and turning vehicles [4, 5]. Further detail on the methodologies and results is discussed in the following table. Overall, the table shows that the selection of methodology largely depends on the types of data and scope of the project.

Table 4. Summary of different studies focused on safety

Study	Objective	Methodology Used	Number of sites	Variables used to develop the model
[35]	To analyze the types of crashes at signalized intersections	Complete Crash Data and Tree-Based Regression	5	Divided roadway, speed limit, pedestrian/bicyclist lane
[36]	To examine crash frequencies at signalized three-legged intersections	Poisson underreporting model	104	Traffic volume, roads, permissive right-turning phase, number of signal phases per cycle, sight distance, existence of a surveillance camera, median railings, approach gradient.
[37]	To identify the significance of endogeneity problems in crash models	Limited-information maximum likelihood (LIML)	155	Traffic volume, Number of left-turn lanes
[38]	To identify the reasons, rear-end crashes at signalized intersections	Negative binomial link function	476	Traffic volume, number of phases per cycle, right and left-turn lanes, speed limit, area type, separate right turn lane, median type.
[39]	To identify factors to traffic crashes at signalized intersections	Poisson regression and negative binomial regression	262	Degree of curvature, number of pedestrians, the proportion of commercial vehicles, average lane width

Study	Objective	Methodology Used	Number of sites	Variables used to develop the model
[40]	To measure safety effectiveness at urban signalized intersections	Empirical Bayes method	60	AADT, Number of lanes at the major and minor road, Number of legs at the intersection.
[41]	To identify factors affecting motorcycle crashes at signalized intersections	Bayesian hierarchical models	371	Total number of lanes, median, presence of left-turn and a right-turn lane, the speed limit.
[42]	To analyze the approach-level real-time crash risk for signalized intersections.	Bayesian conditional logistic models	23	Through volume, left-turn volume, overall average flow ratio, higher average speed, the green ratio for the through/left-turn phase
[43]	To study the impact of type and condition of the road surface on signalized intersection	a field experiment on a signalized intersection	1	Saturation flow value, road surface type, and condition, cycle length, and timing,

In addition, the negative binomial regression model has been widely used in vehicle accident analysis for arterial roadways, rural highways, rural motorways, and urban motorways [44, 45, 46]. Several past studies have used negative binomial models to estimate safety performance function (SPF) and CMF as a part of the safety analysis [47, 48, 49].

Objective

The primary objective of this project is to study the safety and operation of different left-turn phases at intersections along with their geometric features, as described in the DOTD Traffic Signal Manual, with the view to developing guidance on when it is appropriate to install each signal type.

Specifically, the research aims to answer the following questions:

1. Does signal type (protected-only versus permitted/protected left-turns versus permitted only but with left-turn lanes) affect intersection control delay?
2. Does signal type affect crash type and frequency?
3. Which geometric features significantly impact the choice of signal type?
4. Do flow characteristics (traffic volumes) influence crash characteristics and, ultimately, the choice of signal type?
5. When is it most appropriate to install a specific signal type considering operation and safety concerns?

Scope

A preliminary assessment was conducted for several state-maintained signalized intersections to ensure they met the site selection criteria. The study was limited to only signalized intersections with uniform PO and PPLT left-turn phases at all the approaches. In order to avoid the effect of through moving traffic, approaches with at least one separate left-turn lane were chosen. The study removed the permitted only left-turn phase and only used PO and PPLT. Left-turn crash data were collected from 166 intersections, while only 28 of them were used for the delay analysis. Due to limited time and human resources, the study could not collect video data for delay from all 166 intersections.

Methodology

This chapter is divided into several sections. First, it discusses the detail of the national survey and its questionnaires. Next includes a description of intersection locations used for the crash data and delay data, followed by a discussion on the detailed procedure for collecting crash and delay data. Further, the chapter focused on the reduction of collected data. The final section includes the discussion of methodologies the study used for the crash and delay data analysis.

National Survey Design

A web-based survey was designed and conducted from November 6 to December 18, 2020. The purpose of the survey was to solicit information on the current practices of left-turn operation in other state departments of transportation (DOTs) and their suggestions on left-turn signal design and operation. The survey questionnaires were designed for traffic engineers, who either could complete them or could designate a more appropriate person to complete them. It also seeks information on the existing guidelines or criteria used for selecting the proper type of left-turn signal operations.

Finally, the survey was sent to traffic engineers at the DOTs of 49 different states through email. A total of 10 questions focused on different left-turn signal phases and signal display designs were developed for the questionnaire. The Project Review Committee (PRC) approved the questionnaire before they were sent out. The questionnaire was designed concisely in Qualtrics to be answered in less than 10 minutes. The survey sought information on various left-turn phases like protected-only (PO), protected permitted left-turn (PPLT), and permitted-only (P) left-turn phases, as well as their safety and operational benefits. In addition, the types of signal heads used for the left-turn phases were also included in the survey. The study sought information about the documentation of some of the survey responses that support the choice of that specific question. Finally, the survey asked the DOT personnel to share the statewide policy or guidance on implementing left-turn phases in their jurisdiction. The details of survey questions administered to the state DOT are attached in Appendix A. The following includes the list of 10 questions included in the survey. The multiple choices for each survey question are discussed in detail later.

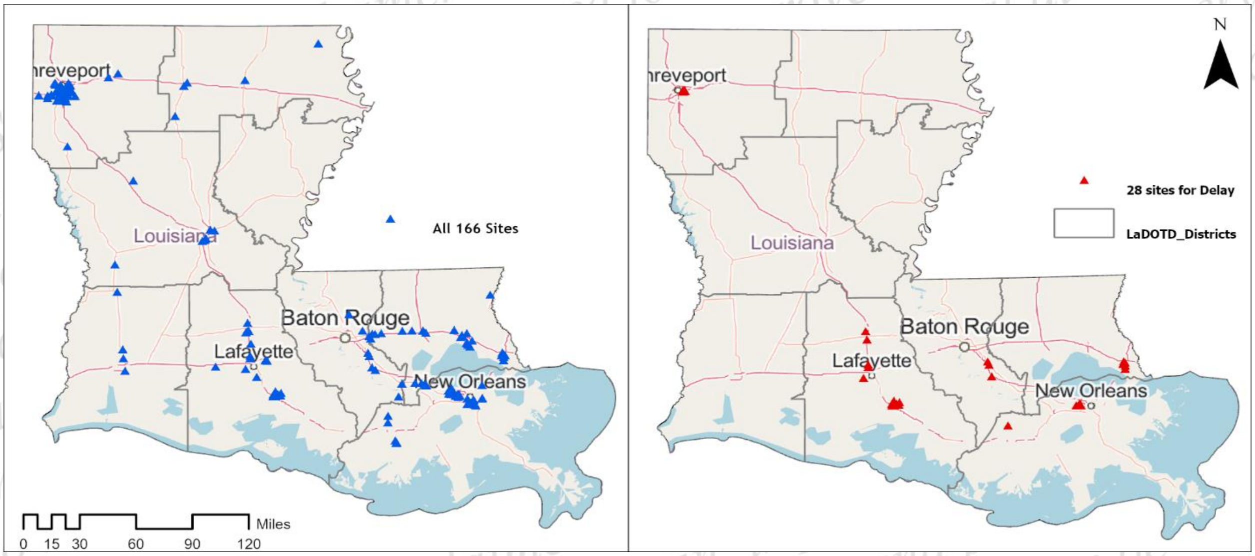
1. What types of left-turn signals do you currently operate/maintain in your jurisdiction?
2. What type of signal indication is used for the permitted left-turn phase?

3. For protected-only left-turn signal, which will work best with the following listed arrangement?
4. For PPLT left-turn signal, which will work best with the following listed arrangement?
5. For permitted-only left-turn signal, which will work best with the following listed arrangement?
6. For the listed different left-turn signals below, which one do you prefer in terms of operation?
7. In your opinion, which left-turn signal has the lowest crash rate?
8. Are there any intersections in your jurisdictions that have ever experienced changes in left-turn signal phase? [Example: PPLT to protected-only]
9. Do you have any suggestions/lessons learned about the selection of the MODE of left-turn signal controls that can be shared with us?
10. Do you have a statewide policy or guidance on implementing left-turn phases in your jurisdiction? Please share any guidelines or publications at the link below.

Site Description

The study used signal head configuration from the DOTD traffic signal manual [50] to select the potential sites. The Street View function in Google Maps was used to visually check the signal head configuration. Finally, the study selected 166 intersections scattered all around Louisiana. The intent was to select at least one intersection from each left-turn signal category from all the districts within the state. Only the intersections with similar PO, PPLT, or FYA signal phases on all the approaches were selected. Since intersection approaches with at least one separate left-turn lane were selected, signals with only a P left-turn phase were not considered because of the small sample size. Since district 3 started using FYA left-turn phase in 2017, the study selected intersections of such types only from that district. Figure 12 shows the location of 166 intersections.

Figure 12. Location of selected 166 intersections in Louisiana



Out of 166 intersections, 83 had PO, 68 had PPLT, and the remaining 15 FYA are left-turn phases. Around 82.53% (137 of 166) are 4-legged, and the remaining 17.47% (29 of 166) are 3-legged intersections. Approximately 94% (155 of 166) are in urbanized areas, and the remaining 6.62% (11 of 166) are in rural areas. The detailed summary of 166 intersections is shown in Table 5.

Table 5. Summary of intersections

Items	Type	Left-turn Signal Type			Total
		PO	PPLT	FYA	
Number of Intersections	Total	83	68	15	166
Intersection Leg	4-legged	58	68	11	137
	3-legged	25	0	4	29
Intersection based on location	Urban	77	63	15	155
	Rural	6	5	0	11

All 166 intersections were used for the safety analysis. However, for the operational analysis, the study only selected 28 sample intersections from the list of 166 (13 with PO, 6 with PPLT, and 9 with FYA left-turn phases) because it was not feasible to collect data from all 166 intersections due to limited time, available equipment, and human resource. CountCAM2 cameras from Spack Solutions [51] were installed at the selected approaches to collect field video data for the delay estimation. Video data were collected from 72 approaches of 28 intersections. The total number of approaches and intersections is shown in Table 6 below.

Table 6. Sample for the delay data collection

Signal Type	Intersections	Approaches
PO	13	28
PPLT	6	17
FYA	9	27
Total	28	72

Data Collection

Crash Data

For the safety analysis, the study extracted five years of crash data from January 1, 2015, to December 31, 2019, from the DOTD crash-1 database. Since this study focused on the provision of signal type at left-turn lanes at signalized intersections, only left-turn crashes at the sampled 166 intersections were selected. The study went through all the crash reports of the left-turn crashes to ensure they were correctly coded. In addition, all the pedestrian crashes, which were almost negligible in numbers, were excluded from the list. This ensures the quality of the left-turn crash data set used for this study. Initially, the study extracted 14,115 crashes at the 166 intersections from 2015 to 2019. It includes 13,278 crashes at PO and PPLT intersections and the remaining 837 crashes at FYA intersections. Then the study roughly filtered the left-turn crashes from the whole list and went through the crash reports to validate them as actual left-turn crashes. This avoided any possible error incurred while recording the crash data in the database. After going through the crash narratives, the study filtered 1,325 left-turn crashes from 14,115, accounting for 9.39% of the total during that five-year time frame. No pedestrian crashes were considered for the study.

Delay Data

For the operational analysis, video data was collected from 72 approaches of 28 intersections to estimate delay. Out of several field techniques available for measuring delays at signalized intersections, the study selected the queue-count technique, as discussed in HCM 6, for the delay estimation. A video capturing camera was used to record the actual traffic situation. A countCAM2 camera was installed at each approach to record the videos. The camera was set to capture the vehicular movement at left-turn lanes and traffic signal heads for the turning traffic. The cameras are rugged and easy-to-use traffic video recorders. These lightweight, portable devices record up to 50 continuous hours of video on a single charge. From each approach, two days of video data were collected. Figure 13 shows a snapshot of the countCAM2 camera and other details like the charging station in the lab, a field snapshot of it installed on the electric pole, and coverage of it from a sample video.

Figure 13. Installation of the camera

a. Charging cameras — b. Mounting camera to a pole

c. Camera in the field — d. Snapshot from the camera

The cameras were installed at all four approaches of 4-legged intersections, while it was only installed at one approach (left-turn from the main leg) of the 3-legged intersections. Locations were selected throughout the state to cover samples from most of the districts. The data collection tasks took more than three months, from the third week of February until the end of May 2021. The data collection tasks included charging the cameras, installing them at the required intersections, extracting the video data from the camera and providing enough space, and recharging the camera for the next data collection schedule. A team of two to three people continuously worked during the entire data collection period. Table 7 shows the detailed time frame for delayed data collection. This task was labor-intensive and challenging, especially when the traffic volume was very high and the weather was unfavorable.

Table 7. Delay data collection timeframe

District	Area	Number of intersections	Camera installation date	Camera uninstallation date
03	Lafayette	5	02-22-2021	02-25-2021
03	New Iberia	6	02-28-2021	03-02-2021
04	Shreveport	4	03-23-2021	03-26-2021
62	Hammond	5	04-07-2021	04-10-2021
61	Baton Rouge	3	04-21-2021	04-24-2021
02BC	New Orleans	4	05-05-2021	05-08-2021
02H	Houma	1	05-27-2021	05-30-2021
Total		28		

Data Reduction

Crash Data

After extracting 14,115 crashes, the study queried only left-turn crashes and went through the crash reports to check the quality of all queried data. This process eliminates any possible crash coding error resulting in a crash tagged as a different type. The study found few crashes of such types, which were tagged as left-turn crashes but were not after checking the crash narratives and collision diagram. After going through the process, the study filtered 1,325 left-turn crashes from 14,115 crashes.

Traffic and Roadway Data

The study also collected data like traffic characteristics and roadway geometric data. The study used the DOTD's MS2 data management system platform [52] to get traffic volume data. Features like the functional class of roadways and area type were extracted from DOTD's ArcGIS data sources. Vehicle classifications were manually extracted from the video data. The remaining features like the number of through lanes, number of left-turn lanes, offset turning lanes, median types, speed limit, and pedestrian push signals were extracted from Google Maps.

Delay Data

Out of several field techniques available for measuring delays at signalized intersections, the study selected the queue-count technique, as discussed in the HCM 6, for the delay estimation.

The method is based on direct observation of vehicle-in-queue counts for any lane group. Past studies have already used this field technique for calculating the control delay at intersections [28, 29, 30]. Figure 14 shows the snapshot of the Excel files as a delay calculation worksheet showing all the required information to get the control delay (highlighted with green color) for any approach. The worksheet was prepared based on the HCM 6 field measurement technique. The control delay was calculated for 15 minutes at a random hour. Each hour was chosen from the morning peak period (an hour between 7:00 a.m. to 9:00 a.m.), afternoon peak period (3:00 p.m. to 5:00 p.m.), and off-peak period (11:00 a.m. to 2:00 p.m.). It makes a total of three hours of delay from each intersection. In each hour, delay was estimated in each 15 minutes interval. For example, if the morning peak hour is 7:30 a.m. to 8:30 a.m., each hour was divided into 7:30 a.m.-7:45 a.m., 7:45 a.m.-8:00 a.m., 8:00 a.m.-8:15 a.m., and 8:15 a.m.-8:30 a.m. to estimate the delay in each 15 minutes time frame. The average of the control delays during peak, off-peak periods and the overall delay was used as surrogate measures to compare different left-turn signals from an operational perspective. As a note, the study did not have any detection information, but in order to verify if a detector at a location was working, videos from the sampled hours at the location were reviewed to check the incoming traffic flow and response of the traffic signal timing. From this, it was concluded that all the detectors were working properly at the time of data collection.

Figure 14 includes some basic terms like approach speed, data count period, count interval, vehicles in the queue, and stopped vehicles required to estimate the delay. All of the required information was reduced from the collected video. According to the HCM, approach speed is when vehicles would pass unimpeded through the intersection if the signal were green for an extended period and volume was light. The approach speed should be recorded at an upstream area least affected by the operation of the subject signalized intersection. Data count period must be clearly defined in advance so that the last arriving vehicle or vehicles that stop during the period can be identified and counted until they exit the intersection. A typical data count period used was 15 min. Regarding the count interval, a count interval in the range of 10 to 20 s was found to provide a good balance between delay estimate precision and observer capability. The study considered that a vehicle is supposed to join the queue when it approaches within one car length of a stopped vehicle and is about to stop. This definition was used because of the difficulty of keeping track of the moment when a vehicle comes to a complete stop. The stopped vehicles are those vehicles that arrive during the data count period and stop one or more times. Any vehicle stopping multiple times is counted only once as one stopped vehicle.

Figure 14. Delay calculation worksheet prepared by the team

General Information		*Site Information*	
Analysts:	Md Asaduzzaman	Intersection:	LA 30 @ Tanger Blvd
Agency or Company:	ULL	Area Type:	
Date Performed:	4/22/2021	Jurisdiction:	
Analysis Time period:	7:35:15-7:50:15	Analysis Year:	2021

Input Initial Parameters					
Number of lanes, N	2		Total vehicle, Vtot	22	veh
Approach speed, Sa	44.58	mi/h	Stopped vehicle, Vstop	20	veh
Survey Count Interval, Is	15	s	Cycle length, C	140	s

Input Field Data											
Clock Time	Cycle Nmuber	Number of Vehicles in Queue									
		Count Interval									
		1	2	3	4	5	6	7	8	9	10
7:35:15	1	2	2	2	2	2	3	3	0		
	2	0	2	3	4	4	4	4	0	0	
	3	1	1	1	1	1	1	0	0	0	
7:41:15	4	0	0	1	1	1	0	0	1		
	5	1	1	1	1	1	0	0	3	3	
	6	5	5	5	5	0	1	2	2	2	
7:48:15	7	2	2	2	0	1	3	3	3		
Total		11	13	15	14	10	12	12	9	5	0

Commputations					
Total vehicles in queue, Viq =	101	veh	No. of cycles surveyed, Nc =	6.89	
Time-in-queue/vehicle, dvq =	61.98	s/veh	Fraction of vehicles stopping	0.91	
No. of vehicle stopping/lane/cycle =	1.45	veh/ln	Acc.-dec correction delay, dad=FVS*CF	6.36	s/veh
Acc.-dec. correction factor, CF =	7	s/veh	Control delay, d=dvq + dad	68.34	s/veh

Analysis

First, the study conducted a general crash and roadway attribute analysis to explore the possible association of left-turn crashes with many crash attributes related to the vehicle, roadway, environment, and human-related factors. Next, the study combined all such attributes and developed a decision tree model. The study used all and only left-turn crashes at intersections to develop a negative binomial model (NBM) and ultimately develop a CMF for different left-turn phases. The following sections describe the detailed methodology behind decision tree models, NBM and CMF.

Decision Tree

The study used a decision tree approach to explore factors affecting crashes and their association with different left-turn phases. The decision tree is a flow diagram that represents the decision-making process by mapping out several courses of action and their possible outcomes. This data-driven analysis revolves around machine learning or regression modeling of crash patterns [53, 54, 55]. Some commonly used algorithms used in the decision tree are iterative dichotomiser 3 (ID3) [56], C4.5 (successor of ID3), and classification and regression tree (CART) [57]. CART is by far the most common of these methods that can be used to investigate the effect of several factors on crashes. This study used the decision tree method and the CART algorithm to generate a tree [55] [55, 56, 57]. The CART method's split criterion is based on Gini and Gini index [57]. The Gini coefficient is used to calculate the diversity of the first node (parent node), while the Gini index is used to calculate the heterogeneity of the next node (child node). The equations for Gini and Gini index are as follows:

$$Gini = 1 - \sum_i^n P_i^2, \text{ and } Gini\ Index = \sum_j^n P_{xij}\, gini(x_{ij}) \qquad (3.1)$$

Where, i equals target variable's category (Signal type PO or PPLT), n equals total number of targets. Since CART is a binary tree, the total number of targets is two, and P shares two signal types: PO or PPLT (in percentage). In addition, x equals the contributing factor (e.g., median type), whereas x_{ij} indicates signal type i of contributing factor j. Lastly, P_{xij} equals the percentage of x_{ij}.

To determine the next split node, the category with the largest diversity improvement can be chosen with the equation below:

$$Node = Max\{gini_{parent} - Gini\ Index\ (x = i)_{childi} \qquad (3.2)$$

Where, $gini_{parent}$ is the Gini value of the higher layer, whereas *Gini Index* is the index of the second layer. Until the improvement equals zero or reaches the maximum level, the procedure is repeated several times. The data used in this analysis was divided into two subsets — 75% of the data was used as a training set, and the remaining 25% was used as a testing set. The following equation calculates the accuracy of the model.

$$Accuracy = \frac{\sum_{i=1}^{n} TP_i}{\sum_{i=1}^{n} TP_i + FN_i} * 100 \qquad (3.3)$$

Where, TPi is true positive (observation is positive and is predicted to be positive), and FNi is a false negative (observation is negative but is predicted positive). The detailed calculation method and principles can be found in Montella et al. (2012) [55], Chang and Chien (2013) [58].

Crash Modification Factor (CMF)

The study developed CMF resulting for PO over PPLT left-turn phase at different severity levels using both all crashes and only left-turn crashes. Past studies have used both left-turning crashes [3] and total crashes [17, 59]separately to assess intersection safety. According to FHWA, a CMF is a multiplicative factor used to compute the expected number of crashes after implementing a given countermeasure at a specific site [60]. For the purpose of the study, it is the ratio of the expected number of crashes at intersections with a PO to the expected number with PPLT, as shown in Equation 3.4.

$$CMF = \frac{Expected\ crash\ frequency\ at\ intersections\ with\ PO}{Expected\ crash\ frequency\ at\ intersections\ with\ PPLT} = \frac{E_1}{E_2} \quad (3.4)$$

There are several ways of estimating CMF, such as the before-and-after study using the Empirical Bayes method, cross-sectional study, cohort studies, and case-control studies [60]. However, the selection of a suitable method primarily depends on the availability of the treatment dates and the nature of the study. For this study, since the implementation date of PPLT and PO left-turn phases were not available, the study opted to use a cross-sectional study design and developed a SPF using the NBM. Per FHWA, cross-sectional studies look at the crash experience at locations with and without some features and then attribute the difference in safety to those features. For this study, the CMFs can be projected as the ratio of the average crash frequency at intersections with PO and with PPLT.

For the cross-sectional study to have a reliable design, all intersection locations must be similar in all other factors affecting crash risks [60], like traffic volume, functional class, lane configuration, and speed limit. Several studies in the past have used a cross-sectional study design and developed NBM as an SPF to estimate CMF [61, 62, 63]. In addition, NBM has been widely employed in vehicle accident analysis for rural highways, arterial roadways, urban motorways, and rural motorways [44, 64, 65]. It has often been used to overcome the effect of over-dispersion in the Poisson model [66].

NBM is a generalization of Poisson regression which loosens the restrictive assumption that the variance must be equal to the mean, known as over-dispersion [65]. The traditional NBM is based on the Poisson-gamma mixture distribution. In NBM, the mean of y is determined by a set of k regressor variables (the x's) [66]. The parameter μ is interpreted as the risk of a new event occurrence during a specified exposure period. The expression relating to these quantities is expressed by Equation 3.5.

$$\mu_i = \exp(\beta_0 + \beta_1 x_{1i} + \beta_2 x_{2i} + \cdots + \beta_k x_{ki}) \quad (3.5)$$

Where, β_0 is the intercept, and the regression coefficients β_1, $\beta_2 \ldots \beta_k$ are unknown parameters that are estimated from a set of data. The way to represent the effect of different left-turn signals is through a SPF. An SPF is a mathematical equation that relates the expected number of crashes of different types to site characteristics/variables through a regression model [60, 67]. Using the exponential of the coefficients of the signal type from the model provides the CMF value.

For FYA intersections, before-and-after crash analysis was conducted. With limited crash data and intersections, it was not feasible to develop CMF.

Delay Analysis

After getting all the relevant information from the field, the delay was estimated using the HCM procedure [57]. Based on HCM 6, control delay is the sum of time vehicles are in queue (d_{vq}) and delay due to acceleration/deceleration (d_{ad}). First, the average queue time per vehicle needs to be estimated using Equation (3.6). Information like the time interval between vehicles in queue counts, sum of the vehicles in queue, and total number of vehicles that arrived during the queue count period were required for the estimation. An adjustment factor of 0.9 in the equation reflects the errors that can arise when using the queue-count technique to estimate delay. According to HCM 6, the value of the adjustment factor for a variety of conditions is relatively constant.

$$d_{vq} = \left(I_s \frac{\sum Viq}{V_T}\right) 0.9(3.6) \quad (3.6)$$

Where,

d_{vq} = time-in-queue per vehicle (s/veh),

I_s = interval between vehicle-in-queue counts (s),

$\sum V_{iq}$= sum of vehicle-in-queue counts (veh), and

V_T = total number of vehicles arriving during the data count period (veh).

The second part of the control delay includes the estimation of delay due to acceleration and deceleration (d_{ad}). Few additional information needs to be estimated to calculate such delay data. First, the average number of vehicles stopping per lane per cycle is calculated using Equation (3.7). This item and the approach speed are used to get the correction factor, as shown in Table 8.

$$V_{SLC} = \left(\frac{V_{STOP}}{Nc \; x \; N_L}\right) \tag{3.7}$$

Where,

V_{SLC}= number of vehicles stopping per lane per cycle (veh/ln/cycle),
V_{STOP} = total count of stopping vehicles during the data count period (veh),
N_c = number of cycles included in the survey, and
N_L = number of lanes.

Equation (3.8) is used to calculate the fraction of vehicles stopping (FVS) as follows:

$$FVS = \left(\frac{V_{STOP}}{V_T}\right) \tag{3.8}$$

Table 8 shows the acceleration-deceleration correction factor as a function of the average number of vehicles stopping (V_{SLC}) and approach speed (in miles per hour). The parameter is used to check for the correction factor (CF) appropriate to the approach speed and the average number of vehicles stopping per lane in each cycle [68]. This adjustment factor for deceleration and acceleration delay cannot be calculated directly with the manual techniques.

Table 8. Acceleration-Deceleration correction factor

Approach Speed (mph)	Acceleration-Deceleration Correction Factor CF (s/veh) as a The function of the Average Number of Vehicles Stopping, VSLC		
	≤ 7veh/ln/cycle	8-19 veh/ln/cycle	20-30 veh/ln/cycle
≤ 37	+5	+2	-1
> 37-45	+7	+4	+2
> 45	+9	+7	+5

According to HCM 6, the delay due to acceleration and deceleration is calculated using the following equation (3.9),

$$d_{ad} = FVS \; x \; CF \tag{3.9}$$

Finally, the total control delay due to traffic control devices, or the control delay, is the sum of the average time in the queue and the delay due to acceleration and deceleration, as shown in Equation (3.10).

$$d = d_{vq} + d_{ad} \tag{3.10}$$

Discussion of Results

This chapter presents the analysis and results obtained from the survey, crash analysis, roadway geometry analysis, and delay analysis from the field-collected traffic data.

National Survey Design

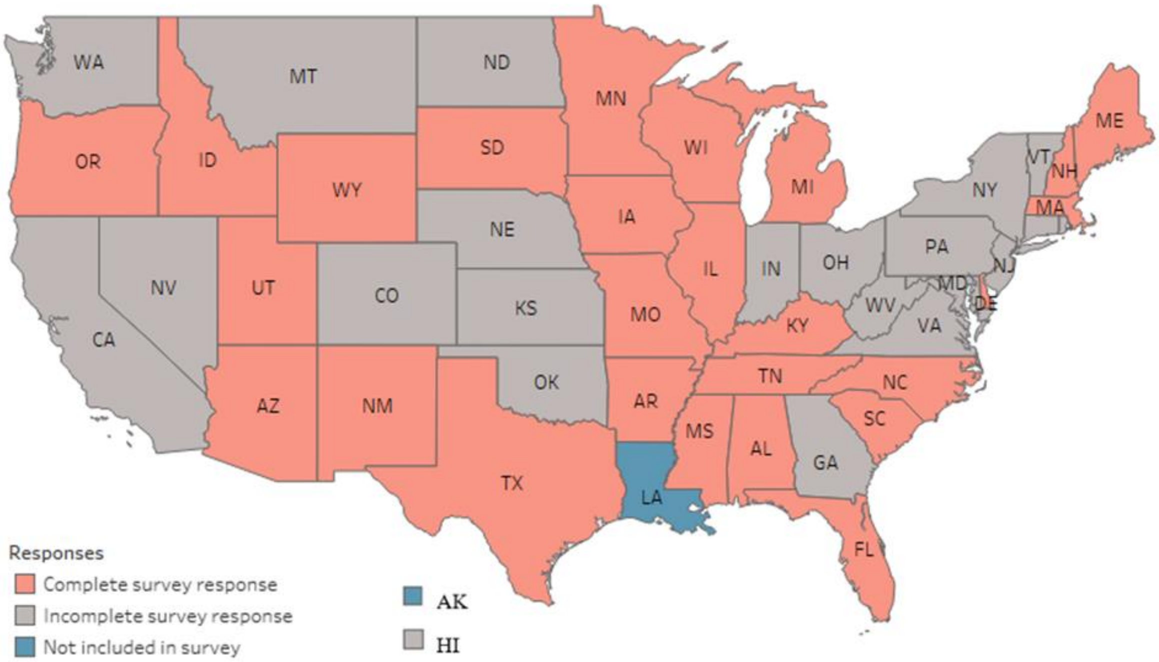
The purpose of the survey was to solicit information on the current practices of left-turn operation in their jurisdiction and suggestions on left-turn signal design and operation. It also sought information on the existing guidelines or criteria used for selecting the proper type of left-turn phases. The study frequently used left-turn signal, signal mode, or signal phase for PO, PPLT, and P in this section. The survey was focused on the following aspects.

- Modes of left-turn controls: permitted, protected, or protected/permitted (PPLT)
- Signal displays and signal head placement

Survey Response

Out of 49 states where the questionnaires were sent, 48 responded, of which 54% (26 of 48) were fully completed, while 46% (22 of 48) were incomplete. Figure 15 shows this representation by the responses from different states. The research team analyzed the survey results in the sections below based on the responses received. All the survey questions were italicized to make them distinct in the report.

Figure 15. Survey responses by state DOTs



Findings from Survey

The study summarizes responses to each question. With the multiple answers and large variations in the response, in some cases, the study grouped responses based on the overall responses for that specific question.

Q1. What types of left-turn signals do you currently operate/maintain in your jurisdiction? [Check all that apply]

a. Permitted-only

b. Protected-only

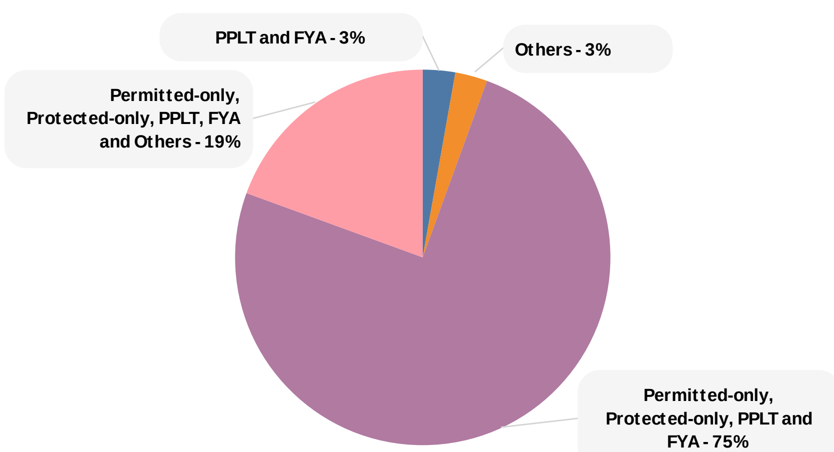
c. Protected/permitted (PPLT)

d. Flashing Yellow Arrow (FYA)

e. Others (please specify)

Question 1 was designed to seek information on different left-turn signals the jurisdiction currently operates/maintains. A total of 36 responses were received, including both the complete and partial responses. The question allowed for selecting multiple answers as the area might have various existing left-turn phases. Groupings in the result were made based on the respondents' submissions, and their details are shown in Figure 16. 75% of the respondents (27 out of 36) reported operating *"Permitted-only, Protected-only, PPLT, and FYA"* left-turn signal phases in their jurisdiction. *"Permitted-only, Protected-only, PPLT, FYA, and Others"* made up 19% (7 out of 36) of the responses received. *Other* was reported mostly lead/lag, split phase, phase by direction, time-of-day, movable left-turn signals for reversible lanes, and left-turn head switch from sequential phasing to concurrent with opposing side. Left-turn phases like *"PPLT and FYA"* contributed to 3% (1 out of 36) of the total responses received. Only one respondent stated they do not maintain or operate any of the signals in the state. It was labeled *"Others,"* which accounts for 3% of the total responses (1 out of 36). No response was received for the group *"Permitted-only, Protected-only, PPLT"* signal phases.

Figure 16. Types of left-turn signals currently operated/maintained in a jurisdiction

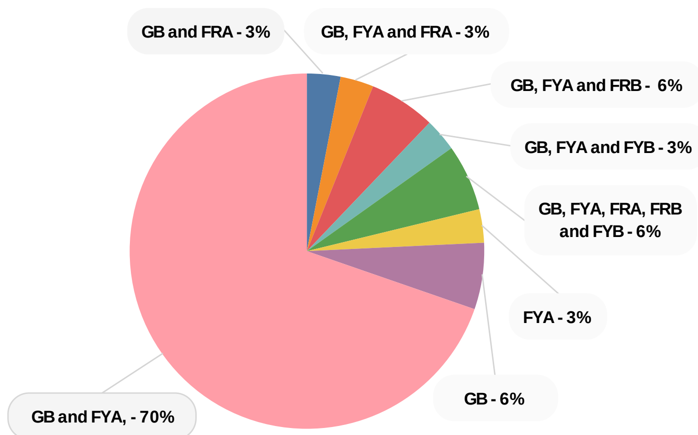


Q2. What type of signal indication is used for the permitted left-turn phase? (Check all that apply)

a. `Green Ball (GB)
b. Flashing Yellow Arrow (FYA)
c. Flashing Red Ball (FRB)
d. Flashing Yellow Ball (FYB)
e. Flashing Red Arrow (FRA)
f. Others (please specify

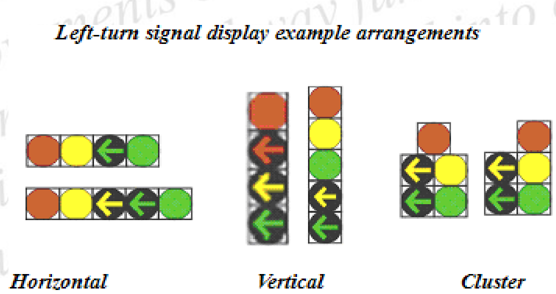
Question 2 was designed to know the type of signal indication used for the permitted left-turn phase. Figure 17 shows the survey responses in detail. 33 out of 48 DOTs responded to this question. Most respondents reported using *"GB and FYA"* as the primary signal indication type, and it made up 70% (23 out of 33) of the total responses. Also, 6% of responses (2 out of 33) mentioned *"GB," "GB, FYA, FRA, FRB, and FYB," and "GB, FYA, and FRB"* as primary signal types. The least type of signal indications used in most jurisdictions was *"FYA," "GB, FYA, and FRA," "GB and FRA,"* and *"GB, FYA, and FYB,"* which made up 3% each (1 out of 33) of the total responses received.

Figure 17. Type of signal indication for permitted left-turn phase



Q3. For Protected-only left-turn signal, which will work best with the following listed arrangement, and do you have any data to support your opinion?

a) 5-section horizontal?
b) 5-section vertical?
c) 5-section cluster?
d) 4-section horizontal?
e) 4-section vertical?
f) 4-section cluster?
g) 3-section horizontal?
h) 3-section vertical?
i) Other (please specify)

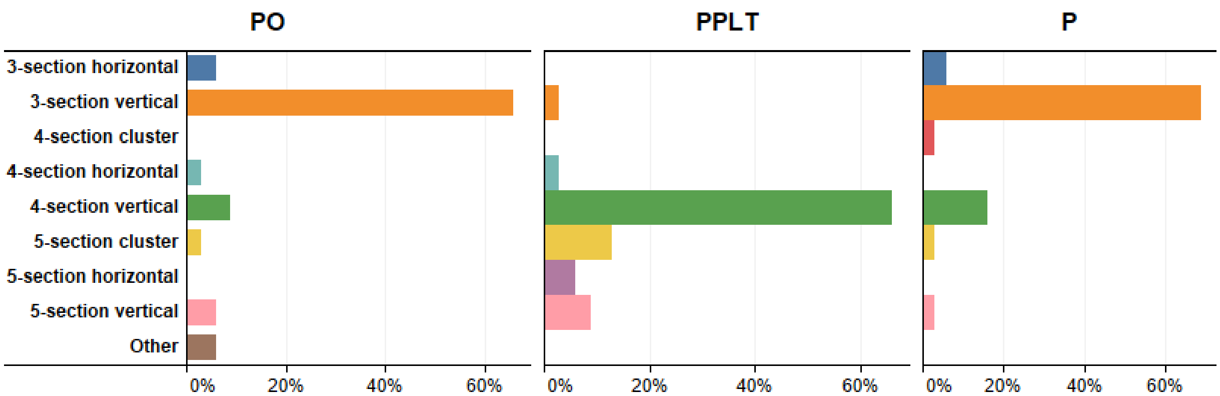


Question 3 was designed to solicit information on different signal head arrangements that best work with the "Protected-only" left-turn phase. A total number of 32 responses were obtained. Responses were plotted in Figure 18. Around 66% of the state DOTs (21 out of 32) responded "*3-section vertical"* as the signal arrangement best fits the protected-only phase. *"4-section vertical"* recorded 9% (3 out of 32) of the total response. *"3-section horizontal", "Other,"* and *"5-section vertical"* recorded 6% (2 out of 32) of each of the total responses. Under the response *"Other,"* one DOT stated that they use "*3-section all arrows and inverted T*" arrangement. The least recorded response was *"4-section horizontal"* and *"5-section cluster,"* each recording around 3% (1 out of 32) of the total responses representing the unique arrangement with the protected-only left-turn phase. There were no responses for *"4-section cluster"* and "*5-section horizontal"* arrangement types. Even though most respondents mentioned that they have data to support their claims in the comment box, several agencies use this application without any issues.

Like Q3, questions Q4 and Q5 were designed to solicit information on the best arrangements for PPLT and permitted-only left-turn phases, respectively. All the responses recorded from both the questions were combined in Figure 18. Both the questions were included in Appendix A. Q4 was designed to know which arrangement best works only with the "PPLT" signal. A total number of 32 responses were obtained. 66% of the respondents selected *"4-section vertical"* (21 out of 32), while only 3% selected *"3-section vertical"* and "*4-section horizontal"* for each (1 out of 32) category. The remaining categories, *"5-section cluster," "5-section horizontal,"* and *"5-section vertical,"* were selected by 13% (4 out of 32), 6% (2 out of 32), and 9% (3 out of 32) of the respondents, respectively. There were no records for *"Others," "4-section cluster"* and "*3-section horizontal"* arrangement types. Still, some suggestions were made for four sections vertical FYA, a steady yellow arrow (SYA), a red arrow (RA), and a green arrow (GA).

Q5 was designed to gather information on the arrangements that best work with the "Permitted-only" left-turn phase. Based on the responses from the 32 respondents, the majority of them responded *"3-section vertical"* as the best arrangement for the *"Permitted Only"* left-turn phase (69% or 22 out of 32). Approximately 6% (2 out of 32) and 16% (5 out of 32) of the state DOTs responded *"3-section horizontal"* and *"4-section vertical,"* respectively. *Only* 3% of the state DOTs (1 out of 32) selected each of the *"4-section cluster," "5-section cluster,"* and *"5-section vertical"* separately. There were no records for *"4-section horizontal,"* "*5-section horizontal,"* and *"Others"* arrangement types.

Figure 18. Arrangement types for PO, PPLT, and P left-turn phases

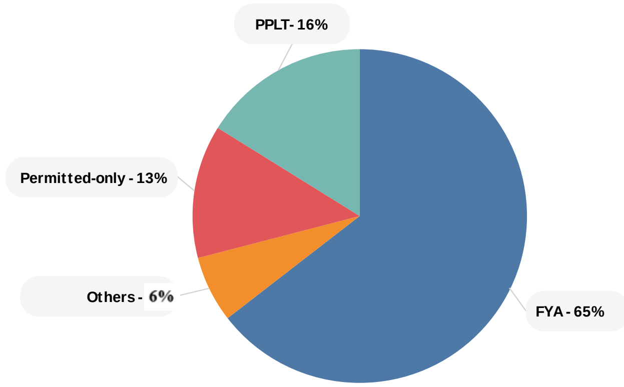


Q6. For the listed different left-turn signals below, which one do you prefer in terms of operation, and do you have any data to support your opinion?

- *a. Permitted-only*
- *b. Protected-only*
- *c. Protected/permitted (PPLT)*
- *d. Flashing Yellow Arrow (FYA)*
- *e. Others (please specify)*

Question 6 was designed to seek information on the left-turn signal type that serves best during the left-turning operation. The responses were plotted in Figure 19. Only a total of 31 responses were received. Around 65% (20 out of 31) of the total respondents indicated "*FYA*" as the preferred left-turn phase in terms of operation. 16% (5 out of 31) selected *"PPLT,"* and 13% (4 out of 31) selected *"Permitted-only"* for the best operation. *"Others"* made up only 6% (2 out of 31) of the total response. No responses were recorded for the *"Protected-only"* left-turn phase.

Figure 19. Operational preference among different left-turn phases



In addition, some states provided some remarks for their response, providing any information or data that supports their claim. The study summarized the responses below to fit into the report.

- The answer to this question entirely depends upon left-turn volumes and opposing through volumes. Ideally, permissive-only would be the best since it would limit the number of phases, but sometimes that is not feasible based upon volumes. Protected-only is a safety decision, not operational one. Practically, there is no operational difference between protected-permissive and FYA running protected-permissive.
- FYA is not a type of left-turn phase; it is just a method of displaying control of that left-turn. So, the best choice would be PPLT using FYA.
- FYA with the operation of variable phasing (can be protected-only, permissive-only, and PPLT).
- Flashing red arrow (24/7) or time of day.
- Lagging permitted-protected with 4-section FYA.
- While protected-permitted helps allow more traffic than protected-only, we use protection only when turning across two-lane. History has shown those to become high crash locations.
- Permitted only typically minimized intersection delay. A left-turn phasing spreadsheet is available for evaluating the need for permissive/protected and protected-only.
- Multiple studies show that lead and lag with flashing yellow arrow allows wider green bands.

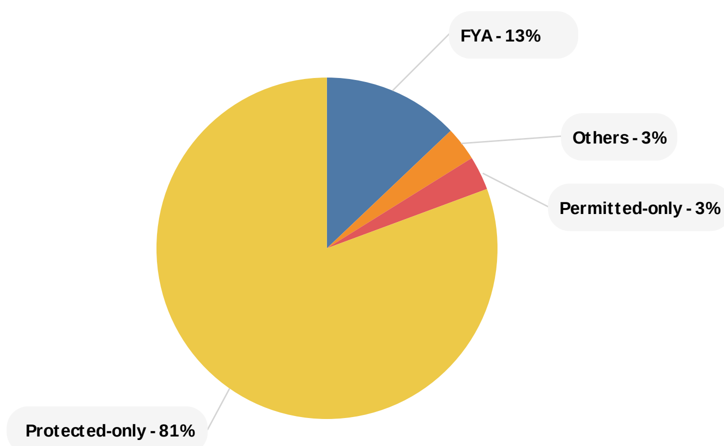
Q7. In your opinion, which left-turn signal has the lowest crash rate, and do you have any data to support your opinion?

a. Permitted-only

b. *Protected-only*
c. *Protected/permitted (PPLT)*
d. *Flashing yellow arrow (FYA)*
e. *Others (please specify)*

Question 7 was designed from a safety perspective to know which left-turn signal works best from the safety perspective. A total of 31 responses were received, as shown in Figure 20. It shows that 81% (25 out of 31) of the state DOTs mentioned: *"Protected-only"* with the lowest crash rate, followed by *"FYA"* with 13% (4 out of 31). *"Permitted-only"* and *"Others"* each accounted for 3% (1 out of 31).

Figure 20. Safety preference among the different left-turn signals



Again, as done previously, the study summarizes the additional information provided with the responses below. Responses were summarized to fit into the report.

- Safety cannot be the only metric for left-turn phasing at all locations.
- There cannot be an "opinion" on quantifiable data, but one would assume a protected-only left-turn phase would have the lowest crash rate. However, protected-only is usually used in heavy volumes and/or poor sight distance, so those factors could still lead to crashes. So it is site-specific, but in a vacuum, protected-only should be the lowest.
- Eliminating the opportunity to choose a gap reduces the chances of making the wrong choice.

- It depends on traffic conditions. Of all options, the respondent might select FYA because it allows for a protected-only phase by the time of day.

While the majority of the respondents do not have any data to support their opinions, some mentioned CMF Clearinghouse, Crash Data, and FYA safety evaluation to support their claim.

Q8. Are there any intersections in your jurisdictions that have ever experienced changes in left-turn signal phase? [Example: PPLT to Protected-only] Yes/No. If YES, approximately how many?

Around 87% (27 out of 31) of the total respondents agreed that some intersections experienced changes in left-turn signal phase; 13% (4 out of 31) responded that no such changes were experienced. On average, the number of intersections that experienced these changes ranged from 1 to 1000. Some have no idea or do not keep track of these changes.

Q9. Do you have any suggestions/lessons learned about the selection of the MODE of left-turn signal controls that can be shared with us?

This question sought ideas, suggestions, or any relevant information to this study. The study listed the ones from the response that are more relevant to the scope of this study. The study summarized the responses below to fit into the report.

- Flashing yellow arrow is superior/ better understood than expected.
- Others are now switching to FYA from PPLT due to a national study that found out FYA reduced crashes by 24%, and it will take drivers sometime before they get used to it.
- Need to establish criteria for each of the left-turn signal phases.
- Modes were selected based on the left-turn phasing warrant worksheet.
- Must use the technology better to respond to traffic. A one size fits all approach does not work.
- Anywhere there are left-turn-only lanes, the preference is to use a flashing yellow arrow for protected-permissive or permissive-only phases.
- Start with the least restrictive phase if possible, and then as conditions change, switch to meet the new conditions.
- One respondent mentioned that the agency is moving toward FYA as quickly as they can afford to do it, often reintroducing permissive left-turns where they had converted to protected-only due to crashes when using the green ball display.
- The capacity and storage capabilities of the left-turn lanes must be simulated and checked if considering changing from permissive or PPLT to protected-only since there will likely

be less available green time to make an allowable left-turn maneuver. The same holds when considering implementing split phasing from perm or PPLT.

- Be aware of the "perceived" left-turn trap associated with the FYA signal head. Some roadway agencies have sought to overcome this by placing a post-mounted supplemental signal head on the far-left corner of the intersection (relative to the subject left-turn lane) to draw the driver's eye away from the adjacent through lane signal.

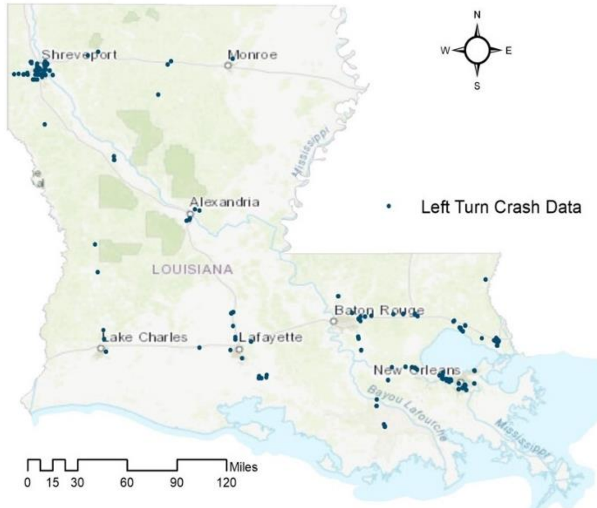
Q10. Do you have a statewide policy or guidance on implementing left-turn phasing in your jurisdiction? Yes/No. Please share any guidelines or publications at the link below.

Twenty-nine responses were recorded for this survey question. Of these, 72% (21 of 29) indicated the availability of statewide policy/guidance, while 28% (8 of 29) indicated the unavailability of such policies or guidance. Even some DOTs shared guidance documents with the survey response.

General Crash Analysis

The general crash analysis explores the possible association of left-turn crashes with many crash attributes related to the vehicle, roadway, environment, and human-related factors. Special focus was given to signal types involved in the crashes to evaluate whether signal types prevalently contributed to left-turn crashes at the approaches of selected 166 intersections. The study used only 1,325 left-turn crashes from 14,115 crashes for the general crash analysis. Figure 21 shows the plot of all 1,325 left-turn crashes. Out of total left-turn crashes, 0.22% were fatal, 0.51% were severe injury, 7.69% were moderate injury crashes, 30.33% were complaint only, and the remaining 61.25% were no injury crashes. In addition, 17.84% occurred in 2015, 22.95% in 2016, 17.40% in 2017, 21.05% in 2018, and the remaining 20.76% crashes occurred in the year 2019. Due to the unavailability of data when conducting the analysis, left-turn crash data from 2020 were not used. As a note, hereafter, the term crashes within the report implies left-turn crashes, in general. Figure 21 shows a map of left-turn crashes within selected intersections in Louisiana.

Figure 21. Left-turn crashes within selected intersections from 2015-2019



In recent years, DOTD implemented a flashing yellow arrow (FYA) signal on left turns, which works the same as PPLT by minimizing the 5-signal head (doghouse) to a 4-signal head (vertical) comprising three solid arrows with an additional flashing yellow arrow signal. The study selected 15 intersections from district-03, as the district has started replacing PPLT with FYA for the left-turn phases since 2017. With that, the crashes for FYA intersections were considered for three years from 2017 to 2019. However, it is still five years of crash data for PPLT and PO intersections. In the following analysis, the study used three years of crash data to compare. The sections below summarize 1,325 crash data at 166 intersection locations, including five years of crash data from PPLT and PO and three years from the FYA left-turn phase.

Crashes by Year

Table 9 shows the distribution of crashes each year from 2015 to 2019 by different left-turn phases. It shows 16.98%, 21.89%, 18.04%, 21.73%, and 21.36% of the total left-turn crashes occurred in 2015, 2016, 2017, 2018 and 2019, respectively at the 166 intersections. Intersections with PPLT recorded 2.29 crashes per year per intersection, almost double compared to PO intersections (1.20 crashes per year per intersection). Surprisingly, FYA recorded 1.11 crashes per year per intersection, which is lower than at PO intersections. That might be due to drivers new to the system, limited data, or limited vehicular movement at those intersections. The data shows a more significant number of crashes of above 20% occurred in 2018 for all three phases.

Table 9. Left-turn crash percentage in each year by different signal types

Signal	Total Intersections	In Percentage					Total	Crashes per year per intersection
		2015	2016	2017	2018	2019		
FYA	15	-	-	18	42	40	50	1.11
PPLT	68	18.53	22.39	19.18	20.21	19.69	777	2.29
PO	83	16.27	23.29	16.26	22.09	22.09	498	1.2
Total left-turn crashes	166	16.98	21.89	18.04	21.73	21.36	1325	

Crashes by Severity Types

Table 10 shows the percentage of crash severities at different signal types. Only 2% of the crashes at FYA intersections were fatal compared to 0.26% at PPLT intersections. PO left-turn intersections did not record any fatal crashes during that study period. No injury crashes were dominant at all the intersection types, with more than half of the crashes falling within this category.

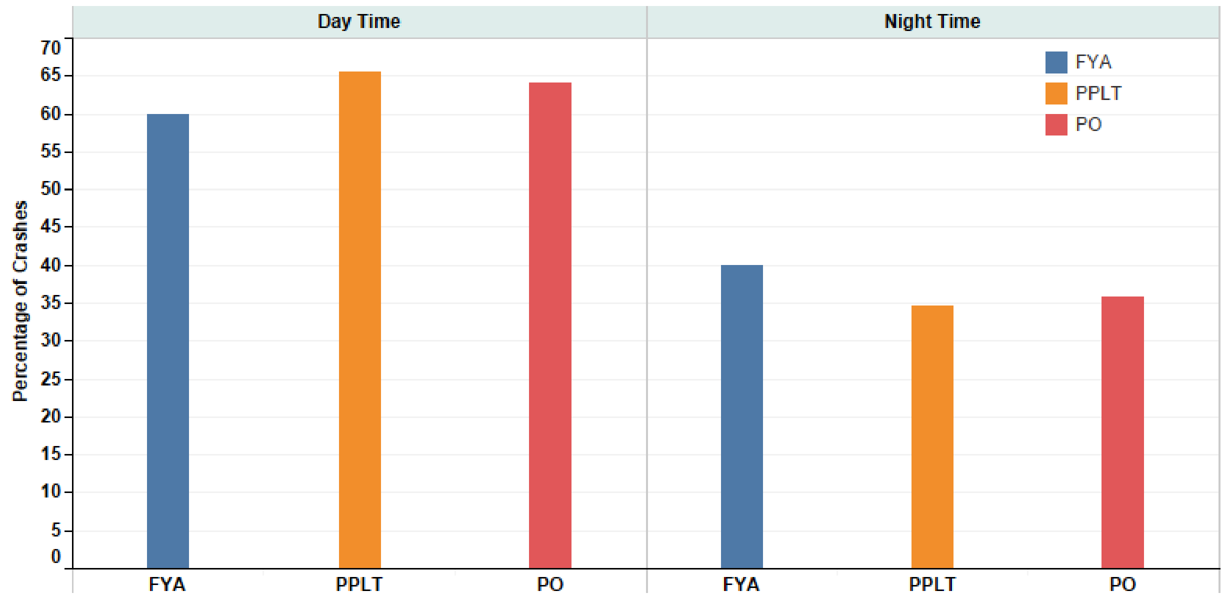
Table 10. Crash severity by different signal types, in percentage

Signal	Total Intersections	In percentages					Total
		Fatal (K)	Severe Injury (A)	Moderate Injury (B)	Complaint Injury (C)	No Injury (O)	
FYA	15	2	4	2	30	62	50
PPLT	68	0.26	0.64	9.91	33.33	55.86	777
PO	83	0	0	4.22	25.3	70.48	498

Crashes by Times of a Day

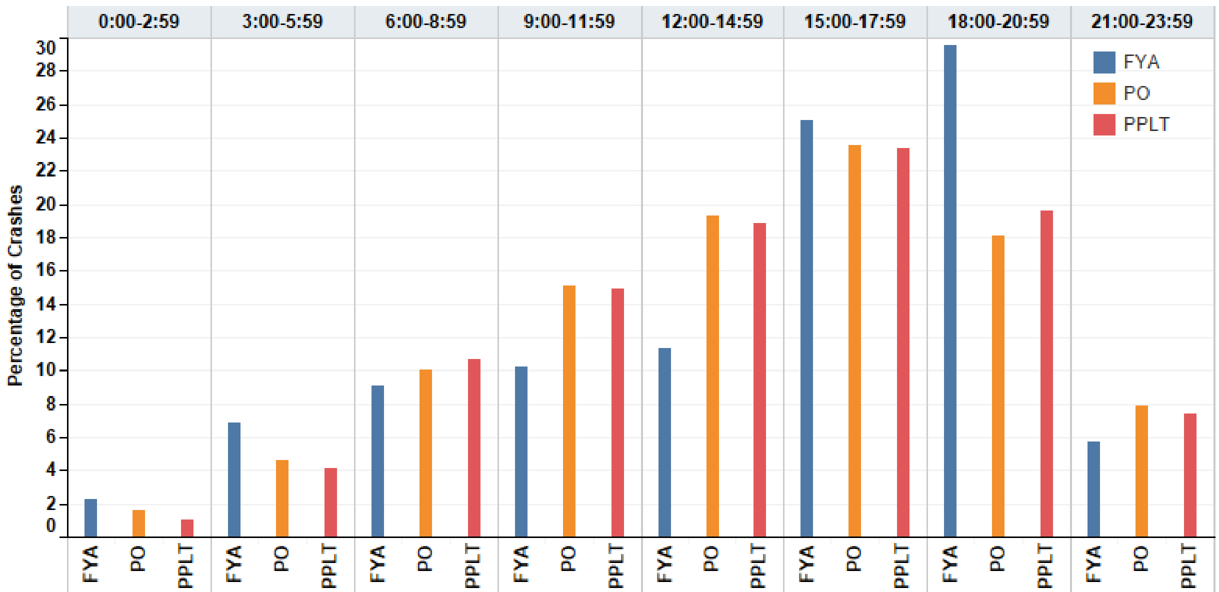
To visualize the distribution of crashes at different times of day, crashes were clustered into two groups: daytime crashes and nighttime crashes, as shown in Figure 22. The percentage of crashes at dawn and dusk was very low at less than 2% and tagged as nighttime crashes. The main objective of this figure is to explore the effect of lighting on crashes. The figure shows 60% of the left-turn crashes at each signal type occurred in the daytime. At FYA intersections, the nighttime crash was slightly higher than other signal types (40% at FYA, 34.5% at PPLT, and 35.9% at PO).

Figure 22. Left-turn crashes by times of a day



The study further explored the data at different times of the day to check any specific hours with frequent crash occurrences. Figure 23 shows the proportion of crashes in each signal type in three-hour time segments. It shows that 2.27% occurred between 12:00 a.m. and 2:59 a.m. out of total FYA crashes. Most of them (29.55%) were recorded between 6:00 p.m. and 8:59 p.m. In all signal types, crashes were very low in the morning peak hours — more than 50% were recorded between 3:00 p.m. and 8:59 p.m. Overall, the crash statistics show that around 60% of crashes occurred between 12:00 p.m. to 9:00 p.m., and the left-turn crashes were minimal during the midnight and morning hours.

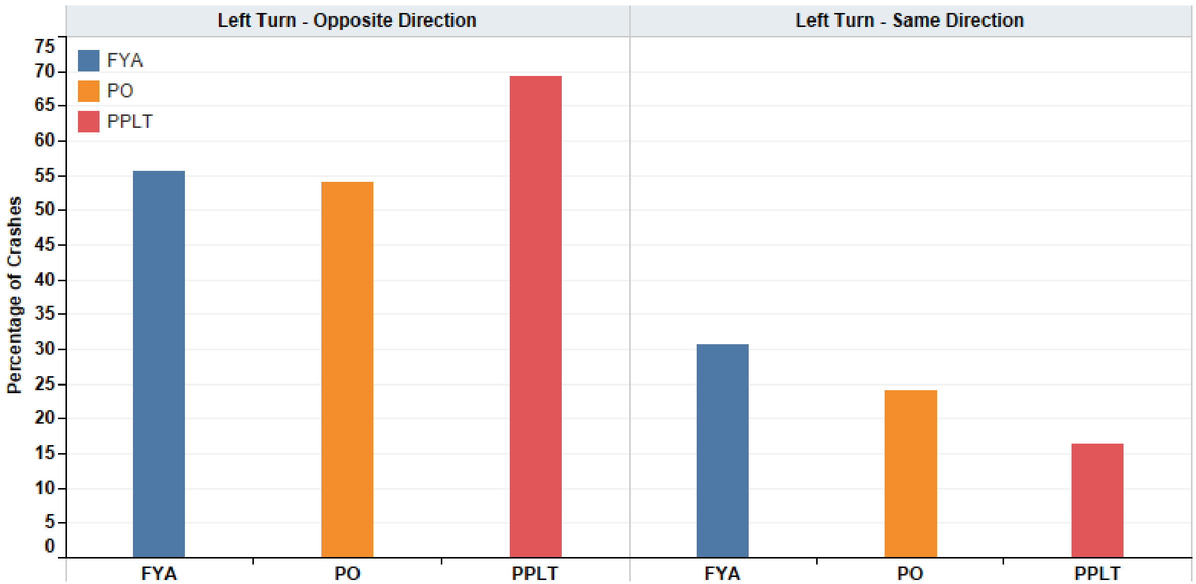
Figure 23. Crash percentages of different times in a day



Crashes by Manner of Collisions

Next, the study explored the distribution of crashes by different collisions. The study categorized collisions in two different levels: left-turn opposite-direction and left-turn same-direction. Other types of collisions, which were very few in number, were not included. Left-turn opposite-direction collision occurs when a vehicle turning left collides with another vehicle traveling in the opposite direction. This often happens when the right-turning or through-moving vehicles from the opposite directions fail to yield to the left-turning vehicles. The left-turn same-direction collision refers to a collision with another left-turning vehicle moving in the same direction either during overtaking or colliding with vehicles on nearby left-turn lanes. The detailed distribution of crashes is shown in Figure 24. The statistics show that above 50% of the crashes for each signal type were left-turn opposite-direction crashes, followed by left-turn same-direction crashes. Right angle types of crashes were rare, as they accounted for less than 6% and were most dominant in PO left-turn signal type.

Figure 24. Crash percentages by manner of collision



Crash Severity by Surface condition

From the previous studies, roadway surface condition plays a vital role in vehicle crashes. Of the 1325 crashes, 83.8% of crashes occurred on dry surfaces, and the rest (16.2%) occurred on wet surfaces. FYA, PO, and PPLT recorded 84, 83.35, and 85.11 percent of crashes on dry surfaces.

Crash Severity by Vehicle Types

The term "vehicle" refers to the vehicle responsible for the crash. Severities were symbolized as "K" for fatal, "A" for severe injury, "B" for moderate injury, "C" for complaint injury, and "O" for no injury. In addition, the study categorized vehicles into four different types: motorcycles, passenger cars, pickups and vans, and buses and trucks. The detail is shown in Table 11.

At all the intersections with three different phases, a passenger car was responsible for above 70% of the crashes, followed by pickups and vans. However, no significant trend was noted. Larger vehicles like trucks were not responsible for severe and fatal crashes during the left-turn at intersections.

Table 11. Crash severity by vehicle types

Signal Type	Severities	Vehicle Type				Total crashes
		Motorcycles	Passenger Cars	Pickup and Vans	Buses and Trucks	
FYA	K + A	0.00%	4.00%	2.00%	0.00%	3
	B + C	2.00%	22.00%	12.00%	0.00%	18
	O	0.00%	44.00%	12.00%	2.00%	29
	Total	2.00%	70.00%	26.00%	2.00%	50
PO	K + A	0.00%	0.00%	0.00%	0.00%	0
	B + C	0.20%	20.88%	8.23%	0.20%	147
	O	0.00%	50.20%	17.47%	2.81%	351
	Total	0.20%	71.08%	25.70%	3.01%	498
PPLT	K + A	0.00%	0.64%	0.26%	0.00%	7
	B + C	0.51%	31.53%	10.94%	0.26%	336
	O	0.00%	40.93%	13.00%	1.93%	434
	Total	0.51%	73.10%	24.20%	2.19%	777

Roadway Geometry Analysis

The analysis by roadway geometry explores the possible association of roadway features with the phase types. All the roadway geometry information from 166 sites was extracted using DOTD's ArcGIS database, Google Maps, and DOTD's MS2 platform [52]. Information like speed limit, roadway functional class, and rural/urban location was extracted from the ArcGIS database. The street view feature of Google Maps was used to collect information like total lanes, number of through lanes, number of left-turning lanes, offset of turning lanes, median types, separate right turn, and presence of pedestrian push button at the intersection for both major and minor approaches. AADT was extracted from the MS2 platform. As a note, both AADT and functional class were used to classify major street to minor street or major approach and minor approach. The term "approach" and "street" refer to the same and are clearly shown in Appendix B. The majority of the intersections used in this study share the common roadway geometry on both sides of the two approaches of major and minor streets.

Lane Numbers

Table 12 shows the summary of the lane by major and minor approaches. The first row in the table shows the number of approaches in each signal type. For instance, 15 major and minor approaches with FYA left-turn signals were identified from 15 intersections. Items were tagged in three different categories: number of separate left-turning lanes, number of separate right-turn lanes, and number of through lanes. The second column, "Number of Lanes," shows total lanes in both the approaches of that street, either major or minor. For instance, if there is one right-turning lane on both the approaches of a major street, then the study counted as two in this section. The study used total in both ways rather than just one approach because of the difference in the number of lanes in the two approaches. For example, at one major street approach, there was one lane, and on another side, there were two through lanes. Referring to Appendix B, the total number of right-turning lanes at major approaches is two.

The table shows that most PPLT and FYA have one separate left-turn lane in each direction, i.e., two in both directions (FYA and PPLT of 73.33% and 97.06% at major, and 73.33% and 73.53% at minor approaches). However, if the total left-turn lanes are more than 2, it is more likely to be a PO at both major and minor approaches (19.28% and 12.05%). The study also explored the effect of separate right-turn lanes by left-turn phases but found no significant trends. With the total number of through lanes, most (73.33%) of FYA approaches have a total through lanes of 2 or less. With an increase in the number of through lanes, more than 4, the left-turn signal type is more PO.

Table 12. Summary of number of lanes of roadways for 166 intersections

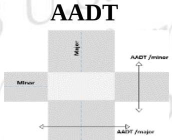
Variable	Number of Lanes (for both approaches)	Major Approach			Minor Approach		
		FYA	PPLT	PO	FYA	PPLT	PO
Observations		15	68	83	15	68	83
Number of separate left-turning lanes	1	26.67%	2.94%	34.94%	26.67%	26.47%	40.96%
	2	73.33%	97.06%	43.37%	73.33%	73.53%	40.96%
	3	-	-	19.28%	-	-	12.05%
	4	-	-	2.41%	-	-	6.02%
Number of through lanes	≤2	73.33%	17.65%	8.43%	93.33%	52.94%	65.06%
	3	-	1.47%	2.41%	6.67%	7.35%	9.64%
	4	26.67%	79.41%	69.88%	-	39.71%	21.69%
	5		1.47%	3.61%	-	-	1.20%
	≥ 6	-	-	15.66%	-	-	2.41%

AADT and Functional Class

Table 13 shows the summary of annual average daily traffic (AADT), and functional class at both major and minor approaches. AADT at the intersection was defined as the traffic volume for both-way traffic. The table shows major approaches with PO associated with higher AADT of more than 20,000 (both-way traffic) for the major approaches and above 12,000 for the minor approaches.

The roadway at major and minor approaches was functionally classified as principal arterial, minor arterial, major collector, minor collector, and local road. Overall, the study found no specific trend between the functional class and left-turn signal type at both major and minor approaches. Most of the major approaches at PO and PPLT left-turn phases were at principal arterial (75% for PPLT and 72.29% for PO). However, 86.67% of major approaches at FYA were at minor arterials. There are no specific roadway types for minor arterial for all left-turn signal types. But very few of them were on principal arterial, and most of them were on minor arterial and collector roads.

Table 13. Summary of AADT and Functional Class

Variables	Items	Major Approach			Minor Approach		
		FYA	PPLT	PO	FYA	PPLT	PO
Observations	**Number**	15	68	83	15	68	83
AADT 	**Min.**	7,031	3,150	4,453	518	1,567	1,253
	Max.	18,277	59,200	100,029	13,473	34,161	83,199
	STD.	4,019.20	9,297.40	16,740.30	44,60.87	6,447.70	13,719.70
	Mean	11,837.90	19,092.40	22,332.50	7,037.06	10,652.50	12,657.50
Functional Classification	**Principal Arterial (3)**	-	75.00%	72.29%	-	1.47%	9.64%
	Minor Arterial (4)	86.67%	22.06%	24.10%	20%	44.12%	38.55%
	Major Collector (5)	13.33%	2.94%	3.61%	33.33%	26.47%	31.33%
	Minor Collector (6)	-	-	-	26.67%	8.82%	2.41%
	Local (7)	-	-	-	20%	19.12%	18.07%

Speed Limit

Table 14 summarizes speed at all three left-turn signals. The data clearly shows no significant pattern in speed and then the signal types. The study recorded all kinds of phases – even at a higher approach speed of more than 50 mph. However, around 21% (8.43 and 13.25) of the major approaches of PO left-turn phases were at roadways with 50 mph or more speed compared to just 13.23% (2.94 and 10.29) of PPLT signal types.

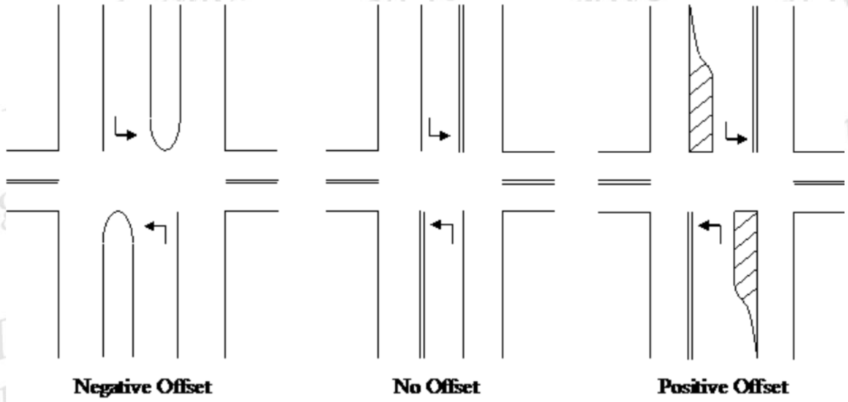
Table 14. Summary of speed limit

Variable	Value	Major Approach			Minor Approach		
		FYA	PPLT	PO	FYA	PPLT	PO
Observations		15	68	83	15	68	83
Speed limit (mph)	15	-	-	-	-	1.47%	1.20%
	20	-	-	-	-	2.94%	6.02%
	25	6.67%	1.47%	2.41%	6.67%	10.29%	15.66%
	30	-	1.47%	1.20%	-	5.88%	6.02%
	35	6.67%	17.65%	21.69%	13.33%	33.82%	31.33%
	40	26.67%	20.59%	18.07%	40.00%	14.71%	10.84%
	45	46.67%	45.59%	34.94%	26.67%	25.00%	21.69%
	50	-	2.94%	8.43%	-	1.47%	-
	55	13.33%	10.29%	13.25%	13.33%	4.41%	7.23%

Left-turn Lane Features

Signal types were further classified by left lane offset types and storage length of the left-turn lanes. Offset shows how two opposite left-turn lanes are aligned and can be termed as positive, negative, or no offset, as shown in Figure 25. When there is an overlap between two left-turning lanes, it is called a negative offset. It is the distance between the left edge of a left-turn lane and the right edge of the opposing left-turn lane. If the offset is in the right, it is called positive offset. This kind of offset enhances sight distance for opposing left-turn drivers. No offset defines opposing left-turn lanes are directly aligned. Figure 25 shows the types of offsets discussed above. The storage length of the left-turn lane, measured from Google Map, is the length of left-turn lanes from intersections to the end of the taper.

Figure 25. Different types of offsets at intersections [69]



The majority (60.24%) of PO major approaches have negative offsets, while on the minor approaches, only 36.14% of PO approaches have negative offsets, as shown in Table 15. The proportion of PO minor approaches with negative offsets is, however, greater than that of PPLT (26.47%) and FYA (6.67%). At PPLT, most of them do not have offsets between the left-turn lanes (67.65% at major approaches and 69.12% at minor approaches). Positive offsets were noticed at PPLT approaches only (5.88% at major and 4.41% at minor) though very few (1.2%) of PO minor approaches showed positive offsets too. Negative offset was dominant at PO major approaches (60.24%). The average length of storage left-turn lane is higher at PO than in PPLT and FYA left-turn lanes, both at major and minor approaches. An average storage length of 82.09m at PO, 66.9m at PPLT, and 49.27m at FYA were recorded.

Table 15. Summary of offset and storage length

Variable	Items	Major Approach			Minor Approach		
		FYA	PPLT	PO	FYA	PPLT	PO
Observations	Number	15	68	83	15	68	83
Offset	Positive	-	5.88%	-	-	4.41%	1.20%
	Negative	26.67%	26.47%	60.24%	6.67%	26.47%	36.14%
	No	73.33%	67.65%	31.33%	93.33%	69.12%	48.19%
	N/A	-	-	8.43%	-	-	14.46%
Storage Length, in meter	Min.	29	15.74	20.02	27.19	11.57	12.93
	Max.	76.13	204.67	216.1	97.22	105.82	255.48
	STD.	15.108	37.77	42.86	17.8	23.65	39.38
	Mean	49.273	66.91	82.09	51.81	54.56	63.01

Median Type, Pedestrian Walking Features

Other roadway attributes like median type and pedestrian walking features for major and minor roadways were summarized by left-turn phases, as shown in Table 16. All the information was extracted from Google Maps. Pedestrian walking distance is measured from one corner of the moving lane to another. The mean walking distance (in meters) from the table shows the order of PO>PPLT>FYA (23.85>20.9>13.79 at major and 20.63>17.48>13.01 at minor) for major and minor approaches.

The median type shows either raised (elevated, island, et cetera.) or painted. Table 16 shows the distribution of such median types by various left-turn phases. It shows that raised median types are dominant at PO phases (65.06%). FYA at both minor and major approaches are almost all painted (above 90%). Still, more than 65% of the median types are painted at PPLT. In addition, at PO, raised median type is dominant in major roadways compared to the minor (65.06% compared to 28.92%). The study also revealed that most intersections do not have push buttons at both major and minor approaches at the pedestrian crossing.

Table 16. Summary of additional roadway geometry

Variables	Items	Major Approach			Minor Approach		
		FYA	PPLT	PO	FYA	PPLT	PO
Observations	Number	15	68	83	15	68	83
Pedestrian walking distance, in meter	Mean	13.79	20.9	23.85	13.01	17.48	20.625
Median type	Painted	93.33%	67.65%	31.33%	100.00%	76.47%	61.45%
	Raised	6.67%	25.00%	65.06%	-	8.82%	28.92%
	Raised/Painted	-	7.35%	3.61%	-	14.71%	9.64%
Pedestrian push button	No	93.33%	82.35%	96.39%	93.33%	83.82%	91.57%

Decision Tree

The above analysis revealed a correlation between several crashes and roadway attributes with different left-turn phases. However, it is necessary to completely understand the effect of so many attributes in one single analysis that develops guidance on installing a specific signal type considering operation and safety concerns. The study researched several tools to meet this objective of understanding the effect of several factors at once and found the decision tree model as the best fit. A decision tree is a flow diagram representing the decision-making process by mapping several action courses and possible outcomes. It is a data-driven analysis that revolves around machine learning or regression modeling with significant variables.

Data Summary

A total of 151 intersections, 83 with PO and the remaining 68 with PPLT phase, were selected, including 1,275 left-turn crashes. Table 17 shows crash and roadway information for PO and PPLT left-turn signals. Data for the decision tree rely mostly on PO and PPLT phases separately rather than by approaches. A total of 498 crashes at 83 PO intersections and 777 crashes at 68 PPLT intersections were used. The crash distribution in the table shows almost negligible fatal and severe crashes at intersections with both signal types. Property damage only (PDO) crashes were dominant at all the intersection types, with more than half of the crashes falling within this category. AADT in the table means the annual average daily traffic at one approach for both-way traffic. Features of approaches were summarized in terms of the speed limit, roadway functional class, number of through lanes, number of left-turn lanes, offset turning lanes, median types, pedestrian push signals, length of the left-turn lane, and crosswalk length. For instance, of 307 approaches with PO, 286 were urban, and the remaining 21 were rural. Similarly, of 272 approaches with PPLT, 252 were in urban, and the remaining 20 were in rural areas. Roadway functional class was labeled as “3” for principal arterial, “4” for minor arterial, “5” for major collector, “6” for minor collector, and “7” for local roads.

Table 17. Data summary for decision tree analysis

Variable name	Description	Category	Left-Turn Signal Phasing	
			PO	PPLT
Number of Intersections	Both 4 and 3-legged	Total (151)	83	68
Intersection Leg	Types	4-legged - 3 legged	58 - 25	68 - 0
Approaches	Includes Major and Minor	Total (635)	307	272
Left-Turn Crashes	Crash Severities	K - A - B - C - O	0 - 0 - 21 - 126 - 351	2 - 5 - 77 - 259 - 434
Roadway Functional Class	See Table 13 in detail	Categories 3 - 4 - 5 - 6 - 7	133 - 95 - 53 - 3 - 23	104 - 90 - 40 -12 - 26
Major/Minor Approach	See Appendix B	Major - Minor	166 - 141	136 - 136
Urban/Rural	Area type	Urban - Rural	286 - 21	252 - 20
Turning lane offset	See Figure 25	Positive - Negative - No	2 - 159 - 146	14 - 72 - 186
Types of medians	Type	Raised - Painted	160 - 147	61 -211
Pedestrian Push button	Presence or not	Yes - No	19 - 288	45 - 227

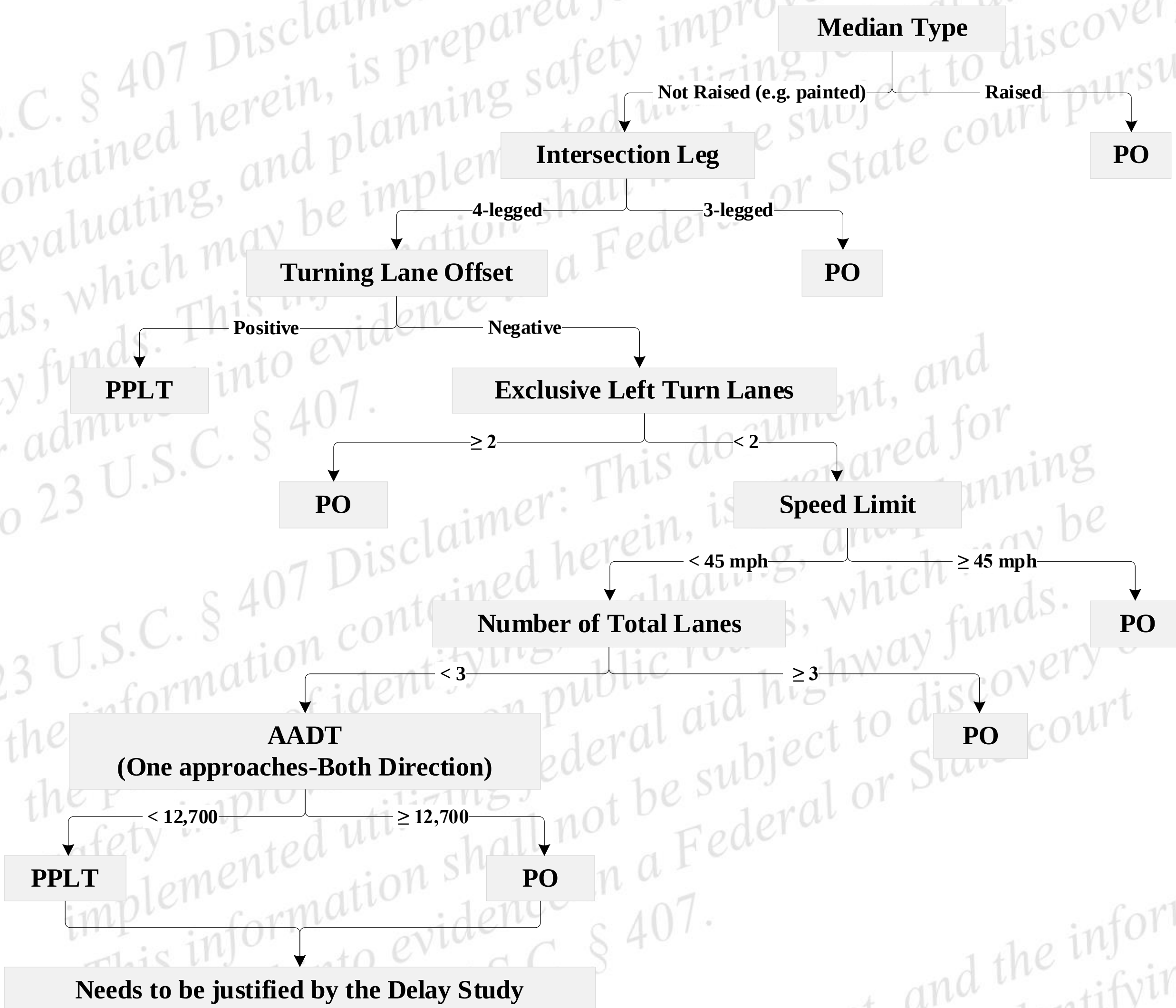
Presence of Rail Line	Presence of it within 500 feet of the intersection	Yes - No	4 - 303	3 - 269
AADT	At one approach for both way traffic	Min - Max. - STD - Mean	438 - 100029 - 16200.60 - 18919.74	1166 - 59200 - 9425.69 - 14872.47
Number of Total Lanes	From both sides of approach. For instance, 2 means one on each side of approach.	≤ 2 - More than 2 and ≤ 4 - > 4	98 - 186 - 23	79 - 193 - 0
Separate Right-Turn Lanes		0 / 1	187 - 120	194 - 78
Number of Through Lanes		≤ 1 - More than 1 and ≤ 2 - > 2	174 -111 - 22	220 - 52 - 0
Separate Left-Turn Lanes		≤ 1 / ≥2	262 - 45	272 - 0
Speed Limit	Maximum speed limit	≤ 35 mph - More than 35 to 45 mph - > 45 mph	126 - 137 - 44	102 - 144 - 26
Length of left-turn lane (m)	Storage length	Min - Max. - STD - Mean	12.7 - 255.48 - 37.33 - 93.78	9.64 - 205.35 - 33.28 - 62.71
Crosswalk Length (m)		Min - Max. - STD - Mean	6.63 - 59.1 - 8.44 - 22.37	6.07 - 40.48 - 6.2 - 19.2

Results

A statistical software was used to randomly select testing and training datasets from the whole dataset, as shown in Table 17. It considered 75% of data as a training dataset to develop the model and the remaining 25% of data as test datasets to check the accuracy of the model.

Figure 26 shows the customized flowchart for determining PO and PPLT phases from intersection geometry data. The study found the threshold values of a few significant variables that dictate the selection between PO and PPLT left-turn phases at intersections. It shows that if a "Median Type," classified as raised and not raised, is raised, the signal type will likely be PO. Otherwise, the model further created another tree under "Intersection Leg." The left-turn signal type will likely be PO if it is just a three-legged intersection. Otherwise, the decision will go further down to "Turning Lane Offset." With a positive offset between left-turning lanes, the phase will likely be PPLT. If the offset is NO or Negative, it goes to "Number of Separate Left-turn Lanes." Obviously, with the number of left-turning lanes of more than or equal to 2, the type of left-turn signal will likely be PO. If it is less than two, the decision goes to the speed limit. With less than 2 turning lanes, if the approach speed limit of through traffic is 45 mph or more, the signal will likely be PO. Otherwise, the tree goes further down to "Number of Total Lanes," including through and left-turns. With 3 or more total lanes, the left-turn signal will likely be PO; otherwise, the tree further splits to the AADT. AADT is defined as the annual average daily traffic at one approach. The final criteria in the whole tree determine the selection of PO or PPLT left-turn signal. If AADT is less than 12,700, it will favor the PPLT signal type; otherwise, it will be a PO left-turn signal. Further analysis needs to be done by conducting a delay study to justify the selection of a proper left-turn signal phase.

Figure 26. Customized flowchart for determining the signal type



Validation

Table 18 shows the validation of the decision tree model. The model accuracy was more than 79% in both the training and testing datasets. The R-squared value of 0.66 for training and 0.54 for testing dataset shows the model fitting the data well. In general, the higher the R-squared, the better the model fits your data. The area under the receiver operating characteristic curve, known as the area under the curve (AUC), is used as a measure of classifier performance (how much the model is capable of distinguishing between classes) in this study. The value of AUC lies between 0 and 1, with a value close to 1 being an indicator of a good measure of separability. For the model, the value of AUC lies within 0.87 ~ 0.85.

Table 18. Model validation results

Condition	Measure	Training		Testing	
PO vs PPLT	Correct	354	81.6%	115	79.3%
	Wrong	80	18.4%	30	20.7%
	Total	434	100%	145	100%
	AUC	0.87		0.85	
	R^2	0.66		0.54	

Crash Modification Factor (CMF)

This section first discusses the data used to develop the SPF. The SPF was developed using a NBM in the next section. Ultimately, using the SPF function or NBM model parameters, the study developed CMF for PO over PPLT.

Data Summary

The study used crash data from 83 PO and 68 PPLT intersections. Intersections with FYA left-turn phase were removed due to the application of such left-turn phase later in the state. A separate before-and-after study was conducted for intersections with the FYA phase. At PO and PPLT intersections, the study used a total crash data of 13,278, including 1,275 left-turn crash data. Table 19 summarizes different crash and roadway attributes used to develop the safety performance function. AADT at the intersection was defined as the total AADT of all three or four approaches in one way direction at a three-legged or four-legged intersection, respectively. Crashes at intersections were summarized separately by total and left-turn crashes for various severity levels. For instance, 73.54% of total crashes were property damage, while only 59.43% of left-turn crashes were of such crash type. Features of major and minor approaches were summarized in terms of the speed limit, roadway functional class, number of through lanes, number of left-turn lanes, offset turning lanes, median types, and pedestrian push signals. The offset of the turning lane was defined as positive, negative, or no offset. The median of a roadway was categorized as either painted or raised. Since intersections were selected with similar geometric layouts for both major and minor approaches, the features of one major or minor approach applied to the other for a given intersection.

Table 19. Data summary for crash data

Crash Data Summary				
General Variable	**Description**	**Type**	**Percentages (%), Total = 151**	
Intersection Type	Type based on left-turn signal, total = 151	PO (83) / PPLT (68)	54.97 / 45.03	
AADT	Estimated as the sum of AADT of all the approaches for one-way traffic	≤ 10000	25.17	
		10001 - 20000	50.33	
		20001 - 30000	14.56	
		>30000	9.93	
Intersection Leg	Number of legs of an intersection	4-Legged - 3 Legged	83.44 - 16.56	
Urban/Rural	Intersection type based on location	Urban - Rural	88.74 – 11.26	
Rail line	Presence of railroad in any approach within 500 feet of the intersection	Yes - No	6.62 - 93.38	
Crash Severity Type	**Description**	**Total Crashes (%), Total = 13,278**	**Left-Turn Crashes (%), Total = 1,275**	
Fatal (K)	Fatal crash type	0.1	0.27	
Severe (A)	Severe crash type	0.44	0.55	
Moderate (B)	Moderate crash type	4.3	8.39	
Compliant (C)	Compliant crash type	21.63	31.36	
PDO (O)	Property Damage Only crash type	73.54	59.43	
Injury + Fatal Crashes (KABC)	It is the sum of Fatal, Severe, Moderate, Complaint crashes	26.46	40.57	
Roadway Variable	**Description**	**Type**	**Major Approach 151 (%)**	**Minor Approach 151 (%)**
Number of Total Lanes	Number of total lanes at Number of total lanes at major/minor approach	≤ 2	8.61	43.71
		More than 2 and ≤ 4	83.44	54.3
		> 4	7.95	1.99
Separate Right-Turn Lanes	Separate right turn lane at major/minor approach	0	54.3	52.98
		1	45.7	47.02
Number of Through Lanes	Number of through lanes at major/minor approach	≤ 1	15.89	70.2
		More than 1 and ≤ 2	76.82	27.81
		> 2	7.28	1.99
Separate Left-Turn Lanes	Number of left-turning lanes at major/minor approach	≤ 1	88.08	92.72
		≥2	11.92	7.28
Functional Class	Functional Classification with the roadway class	3- Principal Arterial	73.51	5.96
		4- Minor Arterial	23.18	41.06
		5- Major Collector	3.31	29.14
		6- Minor collector	0	5.3
		7- Local	0	18.54
Speed Limit	Speed limit of the major/minor approach, in mph	≤ 35	22.52	58.28
		between 35 to 45	56.29	35.1
		> 45	21.19	6.62
Turning Lane Offset	Offset of turning lane defined as positive or negative or no offset	Positive	3.31	1.99
		Negative	43.71	33.11
		No	52.98	48.34
		N/A	0	16.56
Types of Medians	Median type as raised or not raised	Raised	52.32	32.45
		Not Raised (e.g., Painted)	47.68	67.55
Pedestrian Push Button	Presence of pedestrian push button at the intersection for major/minor approach	Yes	15.23	13.91
		No	84.77	86.09

Safety Performance Function (SPF)

The NBM was used to develop an SPF that relates crash frequency to intersection traffic and geometric parameters [67]. Six SPFs were developed using the NBM model: three for total crashes and three for left-turn crashes. The SPFs were developed for different crash severity levels, as shown in Table 20, using 5-year crash data from 2015 to 2019 for both total crashes and left-turn crashes. Model-I was for all severity level crashes, defined as fatal (K), incapacitating (A), non-incapacitating (B), possible injury (C), and property damage only (O) crashes, hereafter referred to as KABCO. Model-II was for fatal and injury crashes only referred to as KABC, and Model-III was for property damage only (O) crashes, hereafter also referred to as PDO crashes. A “glm.nb” function available in package “MASS” was used to fit the model in R 3.6.3. Table 20 shows the final best fit models.

Consequently, all variables, which were not significant at 95% confidence level, were removed. The process was done repeatedly to get the significant variables for each best fit model. The p-value shows the significance of variables at a 5% significance level. The result showed that all six SPFs largely depend on several variables like AADT, number of legs at an intersection, the functional class (both major and minor roadway), presence of separate right-turn lanes, number of through-moving lanes, number of major lanes, and median type. The maximum log-likelihood value shows the significance of the regression model and is a measure of goodness of fit. A higher log-likelihood value shows a better fit for the model [66]. Similar to the NBM model, Poisson models were developed and compared to the NBM to see the effect of the over-dispersion parameter. Results showed that NBM was the best fit model for the data set.

Table 20. Negative Binomial Models

	Total Crashes			Left-turn Crashes		
Model I / All Severity Levels (KABCO)	**Estimate**	**Std. Error**	**p-value**	**Estimate**	**Std. Error**	**p-value**
Intercept	-1.092	1.107	0.323	-4.427	1.869	0.017
Intersection Type (PO, PPLT)	-0.098	0.103	0.338	-1.095	0.198	0.000
Ln (AADT)	0.384	0.088	0.000	0.565	0.164	0.001
Intersection Leg	0.633	0.149	0.000	0.365	0.281	0.014
Functional Class (Major Approach)	-0.246	0.098	0.012		Not Used	
Number of Total Lanes (Major Approach)		Not Used		0.370	0.126	0.003
Number of Total Lanes (Minor Approach)	0.311	0.059	0.000		Not Used	
Types of Median (Minor Approach)		Not Used		-0.427	0.197	0.030
Functional Class (Minor Approach)	-0.137	0.041	0.001	-0.255	0.071	0.000
NBM: 2 x log-likelihood: -1519.527 and -844.508; Difference of maximum log-likelihood for NBM and Poisson Model: 1269.78 and 174.42; Over-dispersion parameter for Poisson model: 20.68, 4.87 for Total and Left-turn crashes						
Model II / Injury + Fatal Crashes (KABC)	**Estimate**	**Std. Error**	**p-value**	**Estimate**	**Std. Error**	**p-value**
Intercept	-0.278	1.028	0.786	-4.359	1.695	0.010
Intersection Type (PO, PPLT)	-0.295	0.106	0.005	-1.430	0.188	0.000
Ln (AADT)	0.419	0.094	0.000	0.654	0.176	0.000
Functional Class (Major Approach)	-0.262	0.105	0.012		Not Used	
Number of Total Lanes (Minor Approach)	0.227	0.070	0.001	0.326	0.105	0.002
Number of Through Lanes (Minor Approach)	0.295	0.091	0.001		Not Used	
Types of Medians (Minor Approach)	-0.191	0.115	0.051	-0.461	0.215	0.032
Functional Class (Minor Approach)	-0.123	0.043	0.005	-0.230	0.078	0.003
NBM: 2 x log-likelihood: -1135.07 and -592.64, Difference of maximum log-likelihood for NBM and Poisson Model: 245.44 and 49.17, Over-dispersion parameter for Poisson model: 6.09, 2.48 for Total and Left-turn crashes						
Model III / PDO crashes (O)	**Estimate**	**Std. Error**	**p-value**	**Estimate**	**Std. Error**	**p-value**
Intercept	-1.765	1.153	0.126	-5.808	1.876	0.001
Intersection Type (PO, PPLT)	-0.018	0.107	0.863	-0.795	0.184	0.000
Ln (AADT)	0.376	0.091	0.000	0.619	0.155	0.000
Intersection Leg	0.725	0.156	0.000	0.627	0.308	0.042
Separate Right-Turn Lanes (Major Approach)		Not Used		0.520	0.179	0.004
Functional Class (Major Approach)	-0.248	0.103	0.016		Not Used	
Number of Total Lanes (Minor Approach)	0.325	0.061	0.000		Not Used	
Functional Class (Minor Approach)	-0.136	0.043	0.002	-0.229	0.074	0.002
NBM: 2 x log-likelihood: -1431.29 and -715.56; 'Difference of maximum log-likelihood for NBM and Poisson Model: 985.02 and 98.95; Over-dispersion parameter for Poisson model: 16.58, 3.65 for Total and Left-turn crashes						

CMF Estimation

The study used coefficients from the above models to develop CMF for crash types and left-turn phases. The CMFs for PO over the PPLT phase were estimated from the SPF function as the exponential of the coefficient, as shown in Table 21. The standard error shows the significance of the value. The standard error of the CMF was calculated by Equation 4.1 as follows [67]:

$$SE = \frac{\exp\left(\beta_k + SE_{\beta_k}\right) - \exp(\beta_k - SE_{\beta_k})}{2} \qquad (4.1)$$

Where,

SE = Standard error of the CMF, and

β_k = standard error of the coefficient β_k.

A relatively small standard error in the magnitude of the CMF estimate indicates greater certainty in the estimate of the CMF. In comparison, a relatively large standard error indicates less confidence in the estimate of the CMF [60]. Table 21 shows the detail of CMF for both total and left-turn crashes. CMF of greater than 1 shows an increase in crashes after the treatment, while CMF of less than 1 shows the reverse effect. CMF of 1 indicates no effect of treatment at all. If the 95% confidence interval contains 1, CMF is statistically non-significant (NS); otherwise, it is significant (S) at the 95% significance level.

For both total and left-turn crashes, the results show a decrease in all severity levels of crashes. For total crashes, the results show a 9.40%, 25.5%, and 1.90% reduction in crashes for All Severity Levels, Injury + Fatal Crashes, and PDO Crashes, respectively, with the second severity levels showing the maximum reduction. As a note, the confidence level, including 1 in it, shows the CMF is not significant. The pattern was similar for left-turn crashes, with a significant reduction in left-turn crashes by 66.6%, 76.1%, and 54.8% for all three different severity levels. Thus, it indicates that the CMF resulting from PO over the PPLT phase shows a reduction in the number of crashes for all severity levels.

Table 21. Crash Modification Factors

Model	**Total crashes**	**CMF**	**Standard Error**	**Change in Crashes**	**95% Confidence Interval**	
Model I	All Severity Levels	0.906	0.103	9.40% reduction	0.704	1.108
Model II	Injury+Fatal Crashes	0.745	0.106	25.5% reduction	0.537	0.953
Model III	PDO Crashes	0.981	0.107	1.90% reduction	0.771	1.191
Model	**Left-turn crashes**	**CMF**	**Standard Error**	**Change in Crashes**	**95% Confidence Interval**	
Model I	All Severity Levels	0.334	0.198	66.6% reduction	-0.054	0.722
Model II	Injury+Fatal Crashes	0.239	0.188	76.1% reduction	-0.129	0.607
Model III	PDO Crashes	0.452	0.184	54.8% reduction	0.091	0.813

Before-and-After Analysis at FYA Intersections

A simple before-and-after study was conducted at 15 intersections locations with FYA left-turn phases (with 11, 4-legged, and 4, 3-legged), including a total of 56 approaches. All of the PPLT left-turn phases were converted to FYA in 2017. A total crash in each year at all of the 15 intersections was analyzed, as shown in Table 22 below. It shows a 15.76% reduction in all types of crashes and a 17.73% reduction in the left-turn crashes at those intersections, resulting from changing the left-turn phase from PPLT to FYA.

Table 22. Simple before-and-after study at FYA intersections

15 FYA intersections crash in numbers	Before period			Total	Installation Year	After period			Total	Reduction
	2014	2015	2016		2017	2018	2019	2020		
Total crashes	183	159	153	495	147	145	134	138	417	15.76%
Left-turn crashes	55	45	41	141	45	44	33	39	116	17.73%

General Delay Analysis

For the operational analysis, the study selected 28 sample intersections from the list of 166, as it was not feasible to collect field data from all 166 intersections. The total includes 13 intersections with PO, 6 with PPLT, and 9 with FYA left-turn signals. The study installed countCAM2 cameras at the selected approaches to collect field video data for the delay calculation. The timeline for the data collection is discussed previously in the data source section. Video data were collected from 72 approaches of 28 intersections. The total number of approaches and intersections is shown in Table 23 below.

Table 23. Sample approaches for delay data collection

Signal Type	Intersections	Approaches
PO	13	28
PPLT	6	17
FYA	9	27
Total	28	72

The average delay at 28 intersections was estimated with the field-collected data, as shown in Table 24. An hour within three different time frames was used to estimate delay. The delay was estimated in seconds per vehicle (sec/veh), and an average was estimated at the end. The data revealed PO was associated with more delay (50.69 sec/veh) than 46.04 sec/veh at PPLT and 31.49 sec/veh at FYA left-turn phase. Delay at several time frames was compared using a simple t-test. Overall, delay at PO (50.69) was significantly high compared to delay at PPLT (46.04) ($p = 0.001$). Similar was the result to the delay data from PPLT (46.04) and FYA (31.49) ($p = 0.000$). It shows FYA with the lowest average delay than delay at PPLT and PO left-turn phase. Comparing delay data by different times of the day, during the morning peak hour, delays at PO (52.40), PPLT (43.80), and FYA (29.83) were significantly different from each other. However, delay between PO (47.93) and PPLT (47.30), and PO (51.74) and PPLT (47.03) were not significantly different during off-peak hour ($p = 0.799$) and peak afternoon hour ($p = 0.064$), respectively. The delay between PPLT and FYA during those time frames was statistically different, with PPLT showing a higher delay than FYA.

Table 24. Control delay for PO, PPLT, and FYA signal phasing

Time Frames	Control Delays in seconds/vehicle						t-test	
	PO - 28 approaches		PPLT - 17 approaches		FYA - 27 approaches		PO vs PPLT	PPLT vs FYA
	Mean1	Max – Min - STD	Mean2	Max – Min - STD	Mean3	Max – Min - STD		
Peak hour (7 a.m.-9 a.m.)	52.40	103.50 – 18.17 – 17.85	43.80	89.18 – 8.29 – 17.42	29.83	99.50 – 0.00 -13.48	0.001	0.000
Off-peak hour (11 a.m.-2 p.m.)	47.93	90.00 – 21.04 – 14.82	47.30	94.55 – 12.50 – 17.14	29.91	65.75 – 0.00 – 13.92	0.799	0.000
Peak hour (3 p.m.-5 p.m.)	51.74	93.74 – 17.23 – 16.85	47.03	80.62 – 17.04 – 16.24	34.80	70.22 – 3.00 – 14.00	0.064	0.000
Overall	50.69	103.50 -17.23 – 16.62	46.04	94.55 – 8.29 – 16.93	31.49	99.50 -0.00 – 13.95	0.001	0.000

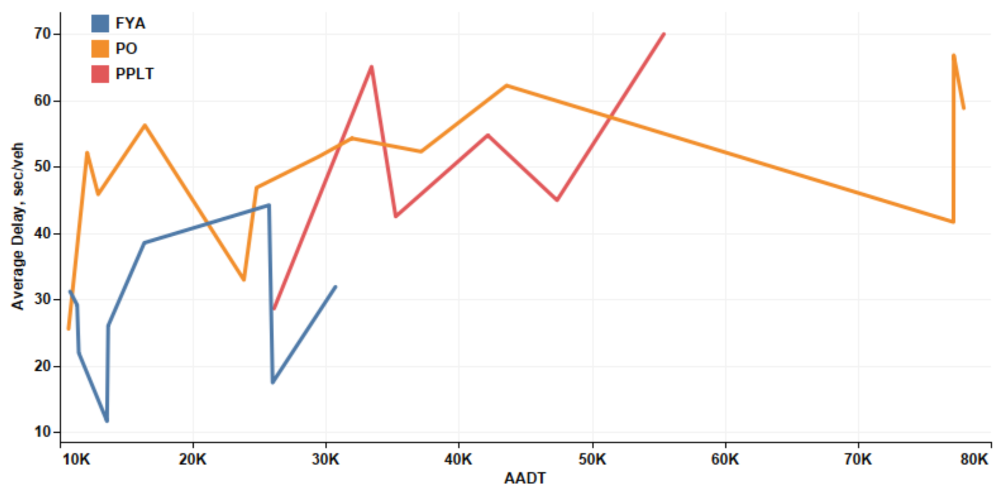
Note: The delay was calculated by randomly selecting one hour (4, 15-min) from each timeframe, not the two hours as shown in the table. Min. = Minimum, Max. = Maximum, STD. = Standard Deviation

Combined Analysis

Delay vs. AADT

In order to check any possible correlation between the average delay and traffic volume, the study plotted average delays from 28 intersections to the AADT of the whole intersections, as shown in Figure 27. With traffic volume data not available by approach, the study opted to use traffic volume of intersection instead. AADT of the intersection was considered the summation of AADT at major and minor roadways. It shows higher AADT at PO intersections followed by PPLT and FYA intersections. AADT at FYA intersections was significantly low compared to those at PPLT intersections. The trend of delay and AADT shows no clear pattern or trend between delay and AADT at intersections.

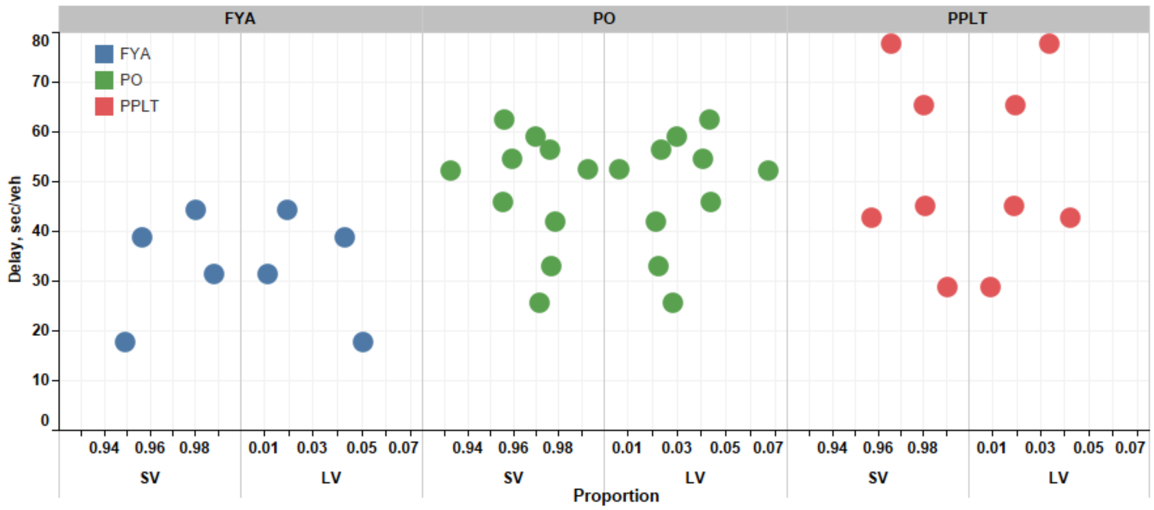
Figure 27. AADT vs. delay



Delay vs. Vehicle Type

The study further explored if vehicle classifications have any effect on the average left-turn delay at intersections. The study assumed that large vehicles like trucks and buses at left-turn signals directly affect the left-turn delay. With that, the study reduced vehicle classification data from the period delay data was reduced to check if any such positive correlation exists. Delay was considered as an average of delay at all the approaches. Vehicles were classified as either smaller vehicles or large vehicles. Smaller vehicles (SV) consist of motorcycles, passenger cars, pickups, and vans. The remaining vehicles, like trucks and buses, were classified as large vehicles (LV). Figure 28 shows the proportion of the corresponding category of vehicles and delays associated with that period. It shows no clear correlation between the delay and vehicle types within that period. The initial assumption of higher delay associated with larger vehicles, especially at PPLT intersections, cannot be verified from Figure 28.

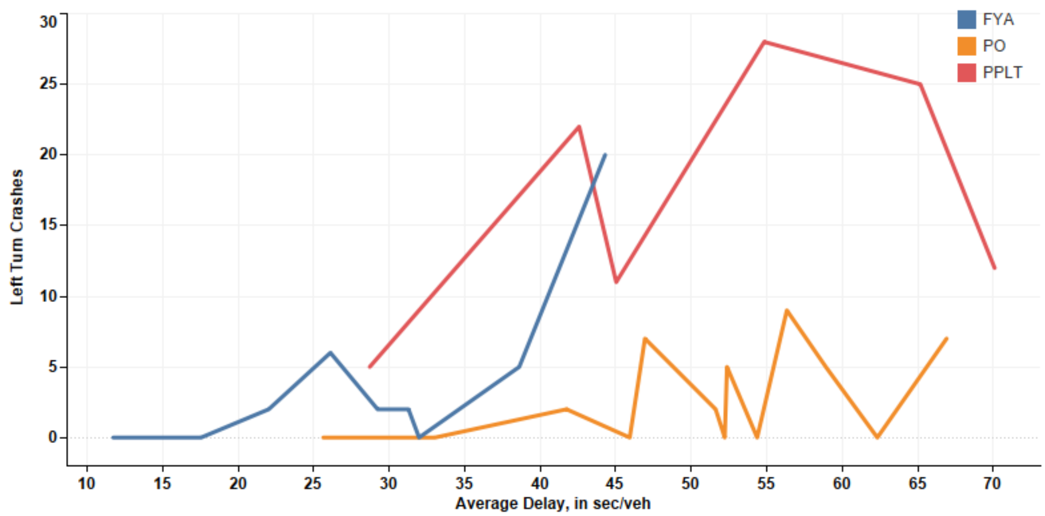
Figure 28. Variation of delay by vehicle types



Delay vs. Left-turn Crashes

The number of left-turn crashes at each of 28 intersections, where delay data was estimated, was plotted with the delay data to check if any positive correlation exists between crash and delay. Delay was first calculated as an average delay at all the approaches, and total left-turn crashes within that intersection were plotted in Figure 29. The six data points for the PPLT show the delay and crash data from six intersections with PPLT signal phases. Similarly, delay and crash data from 13 PO intersections and 9 FYA intersections were used for the plotting. Overall, it shows that PPLT intersections are associated with higher delay and more left-turn crashes at all the intersections. Overall, the trend at all the left-turn signal types shows an increasing trend in left-turn crashes with an increase in the delay, which is more dominant in PPLT and FYA intersections.

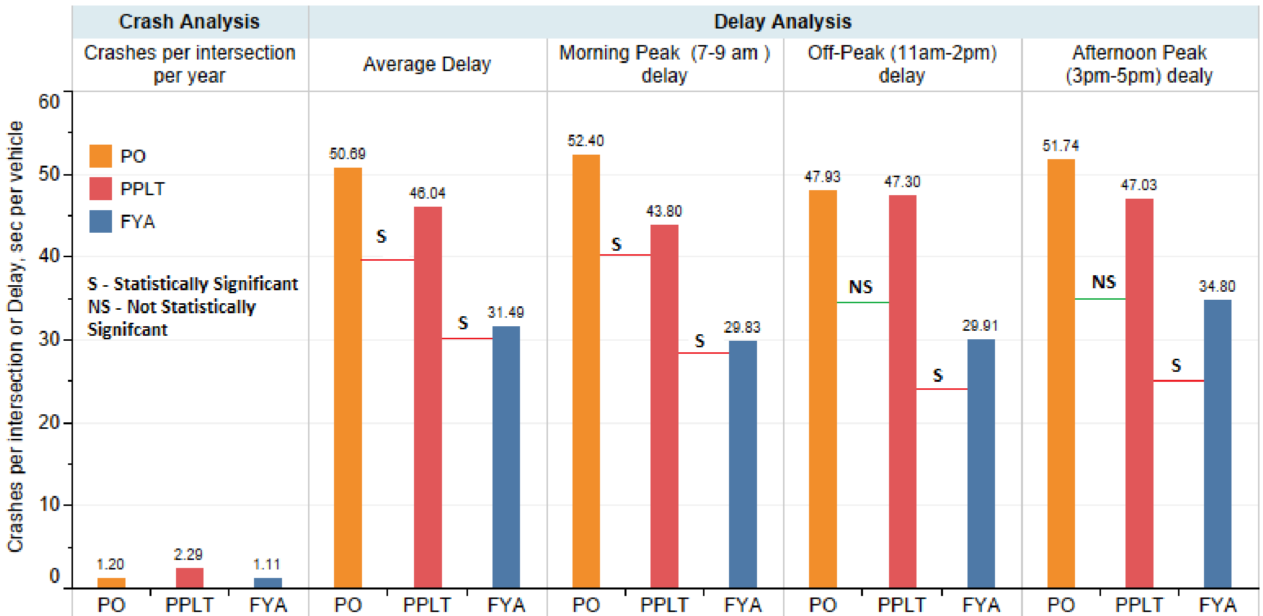
Figure 29. Left-turn crashes and delay



Delay and Crashes

This section summarizes all the delay and crash data from the previous analysis in one plot. Crash analysis was done at 166 intersections, while the delay was conducted using just 28 sampled intersections. Figure 30 shows the data in detail. It shows that left-turn crashes at PPLT (2.29 crashes per intersection per year) are almost double that of PO (1.2) and FYA (1.11). The delay analysis shows that the delays at PO (50.69 sec/veh), PPLT (46.04 sec/veh), and FYA (31.49 sec/veh) are significantly different from each other. However, the delay between PO and PPLT is not significantly different during the peak afternoon and off-peak hours. Delays at FYA intersections are lower than that of PPLT and PO.

Figure 30. Comparison of delay and left-turn crashes



Conclusions

The main objective of this study is to evaluate the safety and operation of existing left-turn phases at intersections and investigate relevant data to develop proper guidance on when it is appropriate to install each left-turn phase. The study considered PO, PPLT, and FYA left-turn phases for the evaluation. The study was conducted in four different folds — nationwide survey, decision tree modeling, safety analysis, and operation analysis.

The nationwide survey revealed that most agencies (75%) currently operate P, PO, PPLT, and FYA left-turn phases in their jurisdiction. More than 60% of the respondents mentioned that they used 3-section vertical left-turn signal arrangements for P and PO left-turn phase, respectively, while for the PPLT, the majority mentioned using a 4-section vertical arrangement. 65% of the total responses indicated FYA as the preferred left-turn phase in operation, followed by PPLT with 16%. Moreover, 81% of the total responses suggested PO has the lowest crash rate, followed by 13% for FYA. As clarified previously, PPLT and FYA only differ in their display heads: FYA has a flashing yellow arrow for left-turning vehicles, while the PPLT signal head does not.

The study framed all the variables affecting the choice of three different left-turn phases in a decision tree model. This answers the research questions regarding the effect of roadway geometry, crashes, and traffic flow on selecting a suitable left-turn phase. Overall, the result shows a PO is preferred over PPLT at any intersection with 8 or more left-turn crashes within five years. The tree revealed other factors such as negative turning lane offset, raised median type, number of left-turning lanes of more than two, the speed limit of 45 mph or more, and higher AADT controlling the selection of PO over PPLT left-turn phase.

From the safety analysis, the result shows the effect of left-turn phases on crash frequency and severities. The safety analysis revealed almost double crashes per intersection per year at PPLT than PO and FYA (2.29 vs. 1.20 and 1.11). It supports the survey respondents for not choosing PPLT over PO and even FYA. Data shows no left-turn fatal crashes were recorded at PO intersections, while few (0.26 to 4%) fatal and severe crashes were recorded at PPLT and FYA intersections. In addition, CMF of PO over PPLT for total crashes of 13,278 revealed that PO was able to reduce fatal and severity crashes by 25.5% compared to PPLT intersections. However, its effect on PDO crashes and all crashes was not significant. Analyzing just left-turn crashes revealed that PO was able to reduce all severity levels of crashes by more than 50%. It supports the finding from the past studies that PO is preferred over PPLT from a safety perspective. In addition, before-and-after crash analysis at FYA intersections showed around a 17% reduction in left-turn crashes in three years.

Regarding the effect of left-turn phases on delay, the results from delay analysis show maximum delay at PO (50.69), followed by PPLT (46.04) and FYA (31.49) intersections. Comparing delay data by different times of the day, the delay only during the morning peak hour at PO was significantly higher than at PPLT. Otherwise, delays at off-peak and afternoon peak hours were not significantly different. Delay at FYA is an all-time lower compared to PO and PPLT. The lowest delay at FYA intersections supports the majority of survey respondents, indicating FYA as the preferred left-turn phase in operation.

Comparing the safety and delay data, intersections with PO were able to reduce left-turn crashes by more than 50%. While only a delay of around additional 4 seconds was estimated at PO, it was not significantly different at other times of the day. It indicates that intersections with PO perform better than PPLT left-turn phase, both from safety and operation perspectives. However, both crashes and delays at FYA recorded the lowest. Because of the limited sample and sites mostly with fewer AADT than PO and PPLT, the outcome from FYA data is less robust. The study recommended using a larger sample size and exploring FYA in detail. Overall, the framework from the decision tree, safety analysis, and delay analysis provides key information for selecting the suitable left-turn phase.

Recommendations

Overall, PO was found to be performing better than PPLT left-turn phase from both a safety and operational perspective. FYA looks even better than the previous two, but the study recommended using a larger sample size and exploring FYA in detail. As the DOTD is changing PPLT to FYA in most districts within the state soon, some sort of driving behavior analysis approach might be a good option to evaluate the effect of such two left-turn phases since crash analysis is not feasible within a short period of time. In addition to safety and operation, the framework from the decision tree can be used to check the effect of several other roadway attributes in the proper selection of left-turn signals.

Acronyms, Abbreviations, and Symbols

CMF	Crash Modification Factor
AADT	Annual Average Daily Traffic
AUC	Area Under the Curve
CART	Classification and Regression Tree
CF	Correction Factor
DOT	U.S. Department of Transportation
DOTD	Louisiana Department of Transportation and Development
DOTs	State Department of Transportation
FARS	Fatality Analysis Reporting System
FHWA	Federal Highway Administration
FVS	Fraction of Vehicles Stopping
FYA	Flashing Yellow Arrow
GA	Green Arrow
HCM	Highway Capacity Manual
ID3	Iterative Dichotomiser 3
KABCO	Fatal (K), Incapacitating (A), Non-Incapacitating (B), Possible Injury (C), and Property Damage Only (O) Crashes
LIML	Limited-Information Maximum Likelihood
LTRC	Louisiana Transportation Research Center
LV	Large Vehicle
mph	Miles per Hour
MUTCD	Manual on Uniform Traffic Control Devices
NBM	Negative Binomial Model
NS	Non-Significant
P	Permitted Only
PDO	Property Damage Only
PO	Protected Only
PPLT	Protected/Permitted Left-turn
PRC	Project Review Committee
RA	Red Arrow
S	Significant
SE	Standard Error

sec/veh	Seconds per Vehicle
SPF	Safety Performance Function
SV	Small Vehicle
SYA	Steady Yellow Arrow

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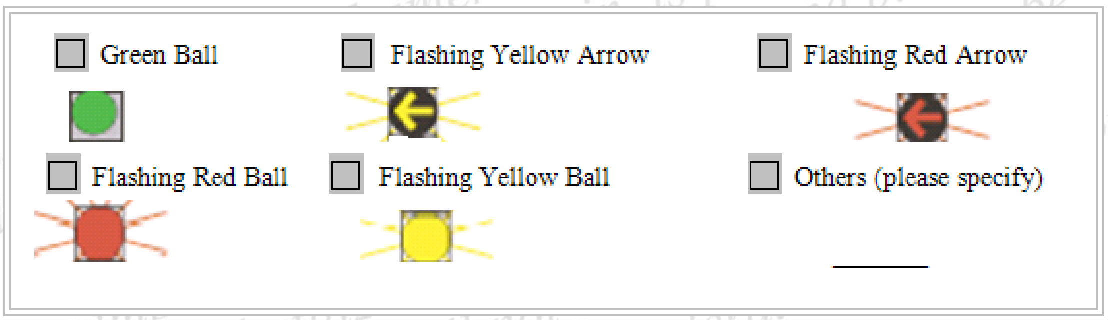
Appendix A

Survey Questionnaire

Q1. What types of left-turn signals do you currently operate/maintain in your jurisdiction? [Tick all that apply]

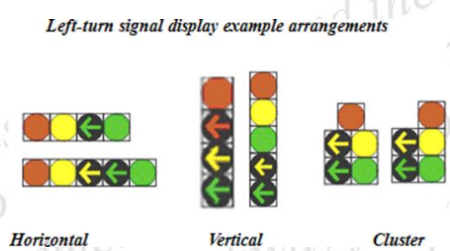
a. Permitted-only
b. Protected-only
c. Protected/permitted (PPLT)
d. Flashing Yellow Arrow (FYA)
e. Others (please specify)

Q2. What type of signal indication is used for the permitted left-turn phase? (Check all that apply)



Q3. For Protected-only left-turn signal, which will work best with the following listed arrangement? [Drop down]

a. 5-section horizontal？
b. 5-section vertical?
c. 5-section cluster?
d. 4-section horizontal?
e. 4-section vertical?
f. 4-section cluster?
g. 3-section horizontal?
h. 3-section vertical?
i. Other (please specify)



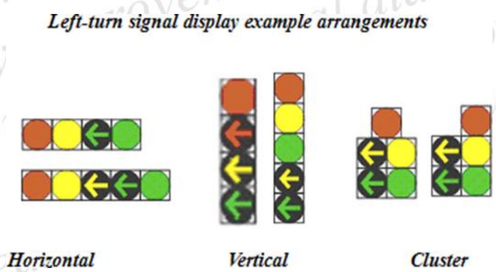
Do you have any data to support for your opinion?

____

____

Q4. For PPLT left-turn signal, which will work best with the following listed arrangement? [Drop down]

a. 5-section horizontal？
b. 5-section vertical?
c. 5-section cluster?
d. 4-section horizontal?
e. 4-section vertical?
f. 4-section cluster?
g. 3-section horizontal?
h. 3-section vertical?
i. Other (please specify)



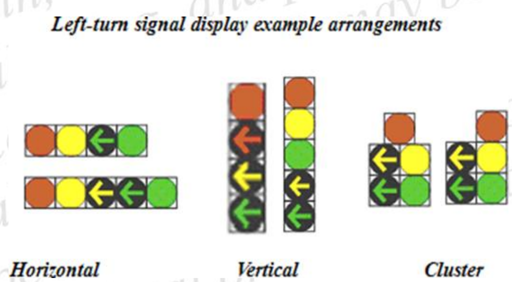
Do you have any data to support for your opinion?

____

____

Q5. For Permitted-only left-turn signal, which will work best with the following listed arrangement? [Drop down]

a. 5-section horizontal？
b. 5-section vertical?
c. 5-section cluster?
d. 4-section horizontal?
e. 4-section vertical?
f. 4-section cluster?
g. 3-section horizontal?
h. 3-section vertical?
i. Other (please specify)



Do you have any data to support for your opinion?

____

____

Q6. For the listed different left-turn signals below, which one do you prefer in terms of **<u>operation</u>**? [Drop down].

a) Permitted-only
b) Protected-only
c) Protected/permitted (PPLT)
d) Flashing Yellow Arrow (FYA)
e) Others (please specify)

Do you have any data to support your preference?

____

____

Q7. In your opinion, which left-turn signal has the **<u>lowest crash rate</u>**? Choose one [drop down].

f) Permitted-only
g) Protected-only
h) Protected/permitted (PPLT)
i) Flashing Yellow Arrow (FYA)
j) Others (please specify)

Do you have any data to support your opinion?

____

Q8. Are there any intersections in your jurisdictions that have ever experienced changes in left-turn signal phase? [Example: PPLT to Protected-only]

Y/N

If YES, approximately how many?

Q9. Do you have any suggestions/lessons learned about the selection of the MODE of left-turn signal controls that can be shared with us?

____

Q10. Do you have a statewide policy or guidance on implementing left-turn phasing in your jurisdiction?

Yes/no

Please share any guidelines or publications at link below.

____

Appendix B

Sample Intersection showing the Detail of Intersection Attributes