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# ALL-RED CLEARANCE INTERVALS FOR USE IN THE LEFT-TURN APPLICATION OF FLASHING YELLOW ARROWS

A Thesis Presented

by

FRANCIS TAINTER

Submitted to the Graduate School of the
University of Massachusetts Amherst in partial fulfillment
Of the requirements for the degree of

MASTER OF SCIENCE IN CIVIL ENGINEERING

May 2018

Department of Civil and Environmental Engineering

# ALL-RED CLEARANCE INTERVALS FOR USE IN THE LEFT-TURN APPLICATION OF FLASHING YELLOW ARROWS

A Thesis Presented

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Approved as to style and content by:

________________________________________
Michael A. Knodler, Jr., Chair

________________________________________
Eleni Christofa, Member

________________________________________
Richard Palmer, Department Head
Department of Civil and Environmental Engineering

# ACKNOWLEDGEMENTS

There have been a great deal of people that have helped me along the way, and without them this journey would not be possible.

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My friends and family, the support you have provided me in my chosen career path have been nothing short of remarkable. And specifically, mom and dad, thank you for continuing to support my passion.

Two down, one to go.

# ABSTRACT

## ALL-RED CLEARANCE INTERVALS FOR US IN THE LEFT TURN APPLICATION OF FLASHING YELLOW ARROWS

MAY 2018

B.S.C.E, UNIVERSITY OF MASSACHUSETTS AMHERST

M.S.C.E., UNIVERSITY OF MASSACHUSETTS AMHERST

Directed by: Prof. Michael A. Knodler Jr.

With the advancement of implementation for a novel traffic control device, the Flashing Yellow Arrow (FYA), agencies across the country have continually sought strategies to improve intersection operations and safety, specifically with respect to the left-turn application. More so, permissive left-turn intervals have been communicated to drivers using several traffic signal indications; however, most frequently these phases are represented through the circular green (CG) ball and more recently, the FYA. Previous research in this area determined that the FYA indication produced the most effective communication of permissive left-turns. Further, this previous research led to the inclusion of the FYA in the 2009 edition of the Manual on Uniform Traffic Control Devices (MUTCD). In recent years, agencies across the country have embraced the implementation of the FYA for permissive left-turns. However, there remains a lack of national guidance on the definition of change and clearance intervals for transitioning between protected and permissive left-turns. Complicating the matter is the connection between traditional signal phasing/design and human factors. Investigation through driver comprehension and real-world operations will allow us to not only evaluate current conditions, but also experimental and future conditions. Recommendations provided from this research will ultimately offer agencies with the strategies for the most effective transition from a protected left-turn to a permissive left-turn phase.

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# CHAPTER 1

# INTRODUCTION

While the application of Flashing Yellow Arrows (FYA) have become prevalent across the United States in recent years, many practitioners still lack operational guidance, specifically in the FYA left-turn designation. In the 2009 edition of the Manual on Uniform Traffic Control Devices (MUTCD), FYAs were introduced as an acceptable signal specifically in displaying permissive left-turn movements, based on the research from NCHRP Report 493 (1). In the left-turn application, the use of FYA communicates a yield before proceeding to drivers approaching the intersection. Furthermore, the transition between protected and permissive phasing of left-turn movements lack guidance. The research provided herein investigate the effects of clearance intervals transitioning between these phases, driver comprehension of PPLT with FYA and circular green (CG) ball indications, and driver operations approaching a left-turn movement.

## 1.1 Problem Statement

Although many state and city intersections with PPLT phasing have included the FYA as a permissive signal since its inclusion in the 2009 edition of the MUTCD, transportation engineers across the country continue to seek stronger guidelines with the safe and efficient implementation of these novel traffic control devices. In part, previous research has investigated the operational and safety impacts of signal clearance intervals in the left-turn protected and permissive phasing. As of now, a need exists to investigate the transition clearance intervals of PPLT phasing with FYA, particularly for developing strategies for agencies around the country in designing the transition between a protected left-turn and a permissive left-turn phase.

## 1.2 Research Objectives and Hypotheses

In completing this study, the overarching goal is to develop strategies for the traffic engineering industry for the safe and efficient designs of intersections involving signal phasing for PPLT approaches. In regard to this goal, the main hypothesis generated from this research states: the design of clearance interval durations for PPLT with FYAs will be significantly improved through the analysis of PPLT phasing driver comprehension and behavior (i.e. vehicle trajectory data through PPLT intersections). In achieving the aforementioned goal of this research, the following section introduces a set of the anticipated objectives.

### *1.2.1 Objectives*

There were three main objectives developed in order to achieve the goal of developing guideline strategies for FYA clearance intervals, as mentioned previously.

Objective 1: Review previous literature on FYA in PPLT phasing, specifically since the inclusion in the 2009 Edition of the MUTCD. Understand the current standards that exist nationwide in designing FYA clearance intervals, and whether these current designs have safety and operational impacts.

Objective 2: Develop a computer-based static evaluation to investigate the current state of driver comprehension with PPLT phasing. This static evaluation will provide an overall sense of current driver comprehension of PPLT phasing with both the FYA and CG signal displays.

Objective 3: Conduct a field study utilizing an innovative traffic data collection method; developing a parallel between left-turn vehicle trajectories and the corresponding signal phasing information. This field study will reveal the current state of driver behavior at intersections with PPLT utilizing both the FYA and the CG for permissive left-turn indication.

It is important to note that the computer-based static evaluation will be conducted to drivers across the country; however, the field study will be limited to four intersections located in Western Massachusetts, specifically.

## 1.3 Scope

In order to evaluate the current state of practice of FYA in the left-turn application, this research will evaluate: (i) the driver comprehension of protected-permissive left-turn phasing and, (ii) the existing operational impacts of clearance intervals transitioning with both the FYA indication and the CG indication. Utilizing a computer-based static evaluation, current driver comprehension will be evaluated through a selection of PPLT phasing sequencing questions. This overall understanding of driver comprehension will be evaluated in a corresponding field study. With the implementation of an innovative data collection method, vehicle trajectories approaching an intersection will be evaluated in parallel with the current signal status information. As a result, intersection geometry, vehicle data, and signal data will be collected in the process.

Through the combination of static evaluation and field study, a stronger correlation between driver comprehension and operations will develop. The scope of this research will create a foundation for future work in regard to developing stronger guidance for FYA in the left-turn application.

# CHAPTER 2

# BACKGROUND

Given the increased implementation of FYAs at signalized intersections across the country, it is crucial to review the background of literature on these signals. The following review of recent literature focused on several FYA research areas within the scope of this thesis, including:

- Implementation of FYA for Permissive Left-Turn Phasing
- FYA Driver Comprehension
- Safety Impacts of Red-Light Running
- Traffic Detection System Technologies

The literature reviewed in the following sections provides a unique perspective of the thesis scope of investigating FYA clearance intervals in the left-turn application.

## 2.1 Implementation of FYA for Permissive Left-Turns

As mentioned previously, the FYA permissive indication was evaluated with the NCHRP Report 493 (1), and thereafter included in the 2009 edition of the MUTCD (3). The graphic provided in Figure 1, represents the recommendation for inclusion into the 2009 Edition of the MUTCD. Since this adoption in the national standards, state agencies across the country have introduced the FYA as permissive indications for left-turns. As of 2013, there were 31 states that had implemented FYAs (4); however, it is important to note that many other state agencies have adopted the FYA since, as seen in Figure 2.

Additionally, the work completed herein will be included in part, in the NCHRP 03-125 project, which is currently in progress.

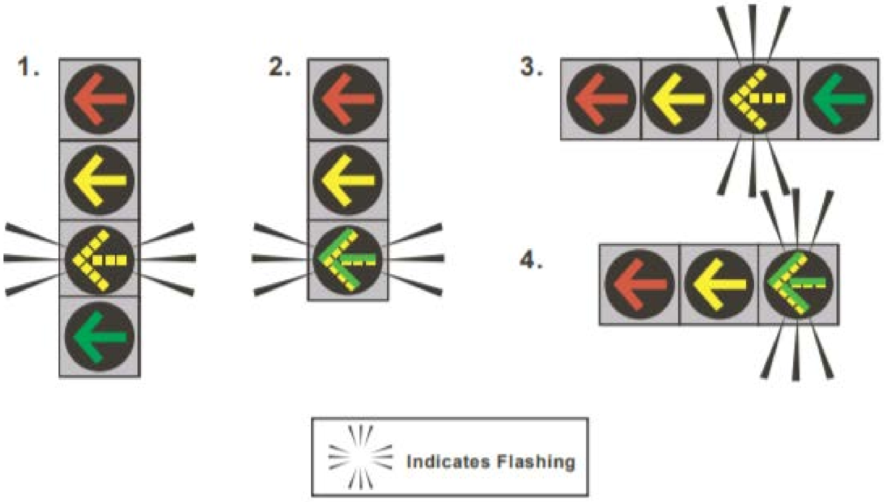


Figure 1 Proposed Signal Display Face for Flashing Yellow Arrows (3)

While many states have implemented these novel permissive signal indications in recent, there is a need to evaluate the driver comprehension of FYA signals in terms of their effects on current operations. Previous research from Knodler et al. (5), (6) developed an understanding that FYA exposure did not have a negative impact on the comprehension of the SYA indication. These were evaluated through an extensive sequential evaluation of drivers from Massachusetts and Wisconsin (5), (6). In addition to this, a study completed by Knodler et al. (7) discovered a high level of comprehension and low fail critical rate in FYA compared to the existing CG indication. This particular study (7) was completed through both a static evaluation and driving simulation evaluation. However, additional research was completed to evaluate the impacts on the comprehension of CG indications after exposure to the FYA permissive indication. Through a dynamic driving simulator study paired with static evaluation, it was determined that there was little to no impact on driver comprehension of the CG indication (8).

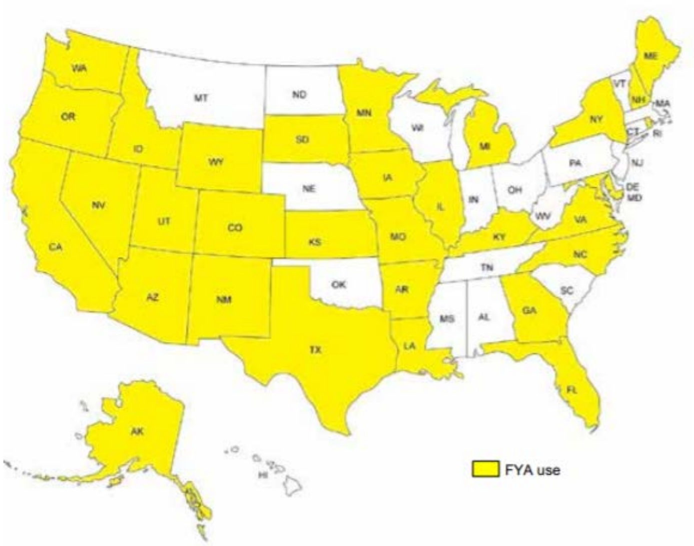


Figure 2 Implementation of FYAs by State Agencies, as of 2013 (4)

In addition to evaluating the comprehension of MUTCD regulated implementation of the FYA permissive indication in left-turns, previous research studied alternative methods of implementation. Through the results of a static evaluation, Noyce et al. found that FYA does not impact driver comprehension when bimodally implemented in the bottom or middle section of a three-section vertical signal (9). Additional findings in this study showed a significant decline in driver comprehension when the FYA was bimodally added to the five-section cluster signal, concurrent with the through movement indication (i.e. CG). A study completed by Hurwitz et al. evaluated the effects of FYA vertical positioning, with the inclusion of three- and four-section vertical signal displays. Through a dynamic driving simulator experiment, it was concluded that the inclusion of the FYA did not significantly impact driver fixation durations based on three- versus four-section signals (10).

## 2.2 Effects of FYA Driver Comprehension and Supplementary Signage

Following the implementation of the FYA in the 2009 Edition of the MUTCD, many transportation agencies and researchers across the country reviewed post-study analyses for signal effectiveness as well as any supplementary signage that paired with the newly implemented indication. In addition to the comprehension studies discussed in the previous section, researchers continued to investigate the comparison between previous CG indications and the newly introduced FYA indications. Rietgraf et al. found that there was no significant difference in having areas with one permissive indication for left-turns compared to areas with multiple permissive left-turn indications; however, that evidence suggests consistency in permissive indications may yield a stronger comprehension rate (11). In addition to this, researchers continue to focus on the comprehension of supplementary signage with the FYA left-turn indication (12), (13). The signs displayed in  Figure 3 were evaluated in a study by Schattler et al., which evaluated the impacts of these supplementary signs on the comprehension of the FYA indication. The results from this study yielded evidence to suggest an improvement in safety based on a naïve before and after analysis of crash frequencies (12). More recently, supplementary signage was evaluated in parallel to FYA installation in a four- and five-section signal. In this study by Schattler et al., the results found that supplemental signage has a need in assisting driver comprehension with the FYA indication (13). Research continues to prosper in this area as safety impacts of the implementation of the FYA continue to emerge.

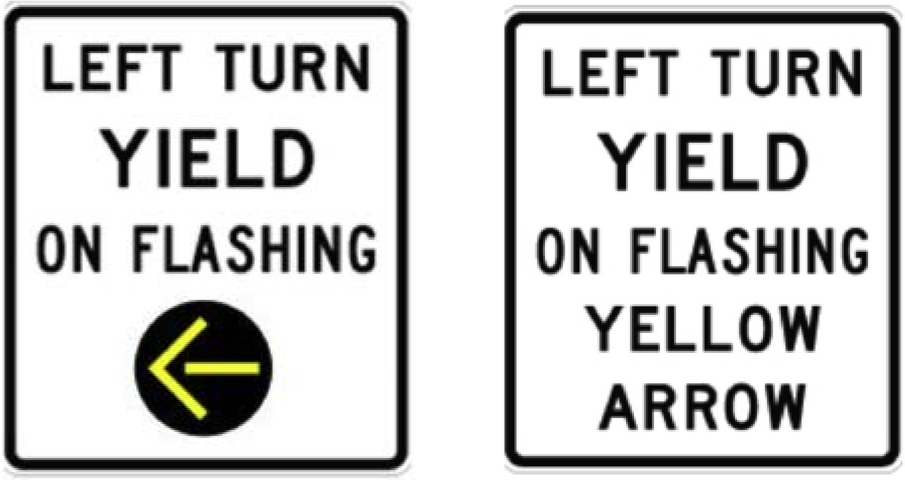


Figure 3 Example of supplementary signage evaluated in (12)

## 2.3 Safety Impacts of Red-Light Running

With the focus of this research on guidance implementation for all-red clearance intervals in FYA sequencing, a significant review of safety impacts exists. This being said, red-clearance intervals are of crucial concern in intersection safety, as red-light running remains one of the most common causes for intersection crashes. The act of red-light running (RLR) may simply be explained as the process of entering and proceeding through an intersection where the traffic signal has already turned to a red indication. In the United States, red-light running related fatalities at intersections have been seemingly consistent over the years. The National Highway Traffic Safety Administration (NHTSA) Fatality Analysis and Reporting System (FARS) was utilized in summarizing the annual number of red-light running relating fatalities in the United States. More so, the FHWA utilizes this database to specifically scope out fatal crashes that occurred at an active signalized intersection, with the driver being charged with disobeying the red signal. According to data extracted from the NHTSA FARS database, these RLR-related fatalities have hovered around 700 annual fatalities between 2010 and 2014 (14). Comparatively to data from the early 2000s, these numbers appear to have diminished slightly. Additional FARS data from another FHWA study showed that between 2000 and 2007, RLR-related fatalities averaged around 900 annually (15). Although the annual number of fatalities due to RLR have reduced significantly in recent years, the need for reducing red-light running still exists.

Other apparent safety implications with red-light running exist with the lack of universal guidance in determining change and clearance intervals. Previous research has studied the effects of adjusting the yellow and red intervals in signal sequencing and analyzing their respective impacts on intersection safety. In the NCHRP Report 731 (16), researchers concluded that the utilization of the ITE guidelines in designing yellow and red change intervals can lead to a significant reduction in red-light running related conflicts. More specifically, the conclusion was made that the increase of red clearance intervals did not correlate to an increase in red-light running (17). While these outcomes promote the increase of clearance intervals, the report also states that the effects of an excessively long yellow interval can create hazardous driving conditions, and potentially result in more crashes. This being said, the report does not delve into the crash effects associated with red clearance intervals, with respect to the duration impacts on red-light running related crashes. Although significant research has not been conducted in crash effects with the implementation of red clearance intervals, Gates et al. investigated the promotion of a calibrated red clearance extension system (18). This previous research promotes the improvement of signal operations, vehicle delay, and safety impacts for red-light running scenarios; specifically anticipating the decrease in RLR-related crashes with this particular system. These studies both allude to the need of improving guidance for designing yellow and all-red clearance intervals, specifically in lowering red-light running related conflicts.

In addition to these safety impacts mentioned previously, the confusion that is created with drivers in the dilemma zone suggests further investigation. The dilemma zone may be separated into two segments, Type I and Type II. The Type I dilemma zone represents the segment of a roadway where, if a vehicle is present at the onset of the yellow indication, it will not be able to safely traverse the intersection nor comfortably stop prior to the intersection stop bar (19). The Type II dilemma zone has been coined as the more prominent dilemma zone, which represents the segment of roadway where between 10-90% of drivers will stop following the onset of the yellow indication (20). While investigating the Type II dilemma zone further, Gates et al. found that the comfortable deceleration rate of 10 $ft/s^2$ that is typically used for timing yellow change intervals, may be overly conservative based on the intersection approach speed (21). Similarly, research conducted by Elmitiny et al. found that there is evidence to suggest that one of the key predictors for stop/go decisions and red-light running may exist in the operating speed of the vehicle, amongst others (22). More so, recent dilemma zone research has investigated the opportunities with advancement in vehicle detection technologies as discussed in the next section. Other research over recent years aims to increase understanding of the Type II dilemma zone specifically in relation to signal timings, with the hopes of improving overall signalized intersection safety (23).

## 2.4 Traffic Detection System Technologies

As mentioned previously, many studies involving the application of FYAs revolve around the implementation of various intelligent transportation systems. The use of technologies such as vehicle detection and advanced traffic control have been utilized at signalized intersections for decades. Vehicle sensor technologies applied to these intersections allow for on-demand extensions of phasing during various signal cycles, given specific demand and operational needs. The most common application of this exists in the extension of green phasing with actuated signals. Recent literature has advanced this concept, adapting it to the application of vehicle detection systems in an effort to reduce safety impacts from red light running (18). This study, conducted at the University of Wisconsin at Madison, investigated the dynamic extension of the red clearance interval at signalized intersections. Advancement in technologies such as this allows for practitioners to optimize safety when designing traffic signal intersection timing. Savolainen et al. explored the opportunities with the advancement of vehicle detection technologies particularly in terms of dilemma zones, and ultimately found that there exists direction for connecting vehicle detection technology with probable red-light running events (24). In addition to this technology, various novel traffic detection systems have advanced in recent year, including the use of mobile vehicle detection systems (i.e. RADAR, LiDAR, etc.). The application of microwave-based RADAR was used specifically in the field study component of this research.

With the rapid advancement in technology, companies in this field compete to produce state-of-the-art equipment. A focus of competition, in particular to this study, relies on data collection accuracy for stop-bar vehicle detection. Medina et al. teamed up with the Illinois Department of Transportation to analyze two microwave-based systems for the application of vehicle detection. The research team participated in a two-volume study analyzing both normal and adverse weather conditions (25), (26). Specifically, an evaluation of performance was conducted for both Wavetronix™ and MS Sedco™ devices. The evaluation focused primarily on the creation of false calls, missed calls, stuck-on calls, and dropped calls; meaning that the devices were malfunctioning. In the first study, both devices were evaluated based on normal weather conditions. As a result, each device performed with less than 5% error in detecting vehicles at intersection stop-bars (25). In the second study, Medina et al. investigated the effects of adverse weather conditions on the performance of both devices (26). Although each of the devices led to greater than anticipated amount of “false calls”, the Intersector™ by MS Sedco™ and the Wavetronix™ were still deemed acceptable for microwave-based data collection (26). Figure 4 displays a graphic representing the Intersector™ setup from these two studies by Medina et al. Additional evaluation of the aforementioned devices as conducted in other regions of the country as well. The TOPS Laboratory at the University of Wisconsin at Madison conducted a study of six different vehicle detection systems in adverse weather conditions (27). In this study, the performance of various detection technologies was measured based on missed calls, false calls, dropped calls, and stuck-on calls. And while the study did not explicitly rank the technologies, results paint a picture in which radar-based detection, while not perfect, provides consistent detection performance. Other research conducted by Santiago et al. discuss the opportunities of combining signal timings with captured vehicle trajectories, specifically in discovering potential red-light runners (28).

Figure 4 Example of the Intersector™ setup from (25), (26)

# CHAPTER 3

# METHODOLOGY

Through the completion of this research, a series of tasks were developed to investigate the all-red clearance intervals applied with FYAs in left-turns. This research employed three main components: a review of recent literature, a computer-based static evaluation, and a field study evaluating vehicle trajectories approaching left-turn movements. The following section outlines the three research components involved in the scope, further addressing the main objectives of this research and ultimately evaluating the experimental hypothesis established previously.

## 3.1 Literature Review

In order to gain an understanding of previous research in the area of FYAs, a review of recent literature was conducted. Throughout the past two decades, the advancement and implementation of FYAs have brought with it many operational and safety concerns. Research regarding the effects of FYA implementation and current operations were studied. In addition to this, an added emphasis was included to study the effectiveness of various vehicle detection technology. Overall, this literature review focused primarily on:

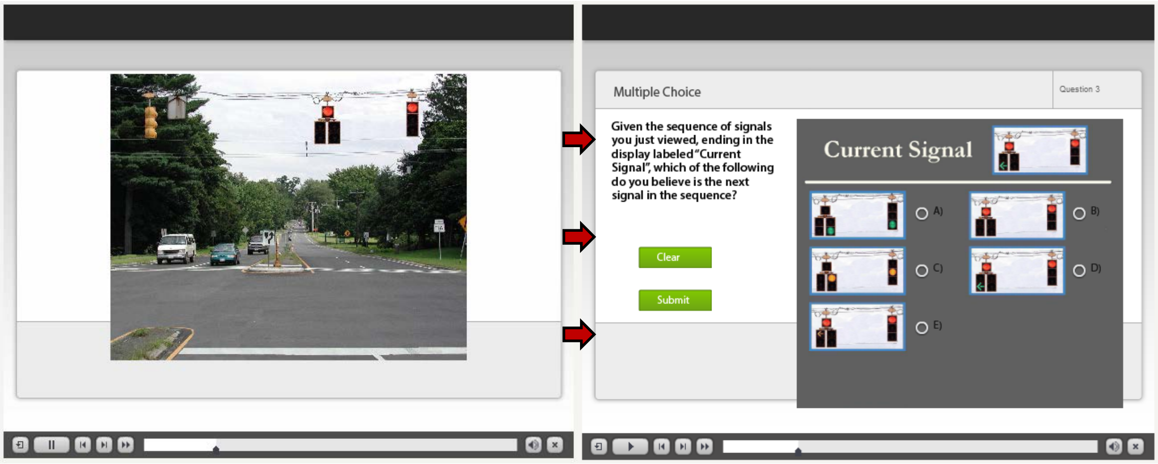
- the implementation of FYA for permissive left-turns,
- effects of FYA driver comprehension,
- safety impacts of red-light running, and
- traffic detection system technologies.

The results from this review of literature were presented previously in Chapter 2 and more so integrated in the remaining sections as needed.

## 3.2 Computer-Based Static Evaluation

In accordance with Objective 2, explained previously in Chapter 1, the computer-based static evaluation was initiated to investigate the current driver comprehension of PPLT phasing, specifically with the CG and FYA displays. While existing strategies of PPLT phase transitioning currently lack proper guidance, an overview of the driver's understanding of these indications will be targeted through the application of a static evaluation.

The survey platform utilized to develop the evaluation in this study was SurveyMonkey. The first step in developing this survey was to generate an experimental design for the evaluation. The use of static evaluation for analyzing driver comprehension of PPLT phasing stems from the NCHRP 493 Report (1). The work of Brehmer et al. evaluated the driver comprehension with respect to the decision making of proceeding through a PPLT. However, the motivation for the comprehensive study discussed in this paper, was developed based on the work of (29). In this previous research, a survey was conducted to evaluate the signal sequencing comprehension of drivers; particularly with CG and FYA indications for left-turns. Comparatively to the current study, this previous research utilized the software Adobe Captivate for survey creation. SurveyMonkey was the desired platform for this study, as it combines all of the information presented in Figure 5 into a single-view window.



Given the sequence of signals you just viewed, ending in the display labeled "Current Signal", which of the following do you believe is the next signal in the sequence?

Figure 5 Example of PPLT survey sequence using the Adobe Captivate software (29)

The explanation of phase schemes for both the CG and FYA display for PPLT are split into four sequences: Dual Leading, Lead-Lag (Lagging Side), Lead-Lag (Leading Side), and Dual Lagging Table 1. The follow section further explains the development of the survey scenarios concentrating on the CG and FYA display.

Table 1 Breakdown of PPLT phasing with CG and FYA indications

| Permissive Indication | Phase Scheme | Sequence # |
|---|---|---|
| CG | Dual Leading | 1 |
|  | Lead-Lag (Lagging Side) | 2 |
|  | Lead-Lag (Leading Side) | 3 |
|  | Dual Lagging | 4 |
| FYA | Dual Leading | 5 |
|  | Lead-Lag (Leading Side) | 6 |
|  | Lead-Lag (Lagging Side) | 7 |
|  | Dual Lagging | 8 |

### 3.2.1 Sequencing Survey Design

While maintaining the focus of emulating prior static evaluations for investigating driver comprehension with FYAs, the following layout was utilized:

- Introduction and agreement
- Demographic Information
- Randomized Signal Sequences (FYA and CG)
- Suggestions and comments

The introduction and agreement slide consisted of a brief synopsis of the overall objective of the survey as follows:

*“Thank you for agreeing to take this survey. The objective of this study is to evaluate the understanding in sequencing of traffic signals during left turns at signalized intersections. While this survey is anonymous, you will be asked to provide some non-identifiable demographic information. The responses collected from this survey will be reviewed and analyzed only by members of our research team.”*

This was followed by a representation of the two signal head arrangements that would be seen throughout the remainder of the survey. A 4-head signal and cluster signal arrangement were included to ease the effects of respondent confusion and relinquish the concern with familiarity of certain signal arrangements. These graphics are represented below in Figure 6.

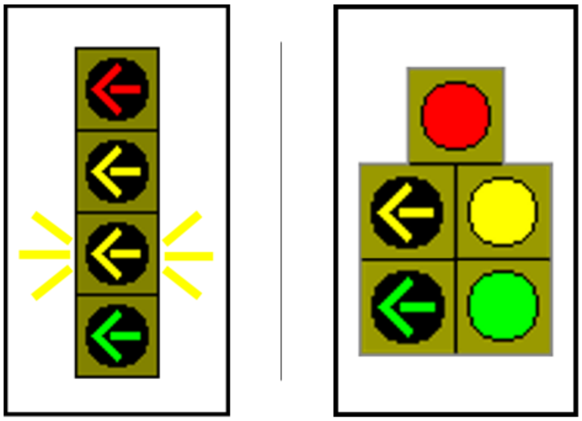


Figure 6 Standard Arrangement of 4-Signal Head (left) and cluster signal (right)

The next section of the survey included a selection of questions to gather respondent demographic statistics. The questions reflected characteristics such as: age, gender, driving experience, and current state of residence. These features have been utilized in previous research to develop a general understanding of the respondent demographics (1), (29). Here are the demographic questions, as formatted in the survey:

*Age:*
- *18-24*
- *25-34*
- *35-44*
- *45-54*
- *55-64*
- *65+*

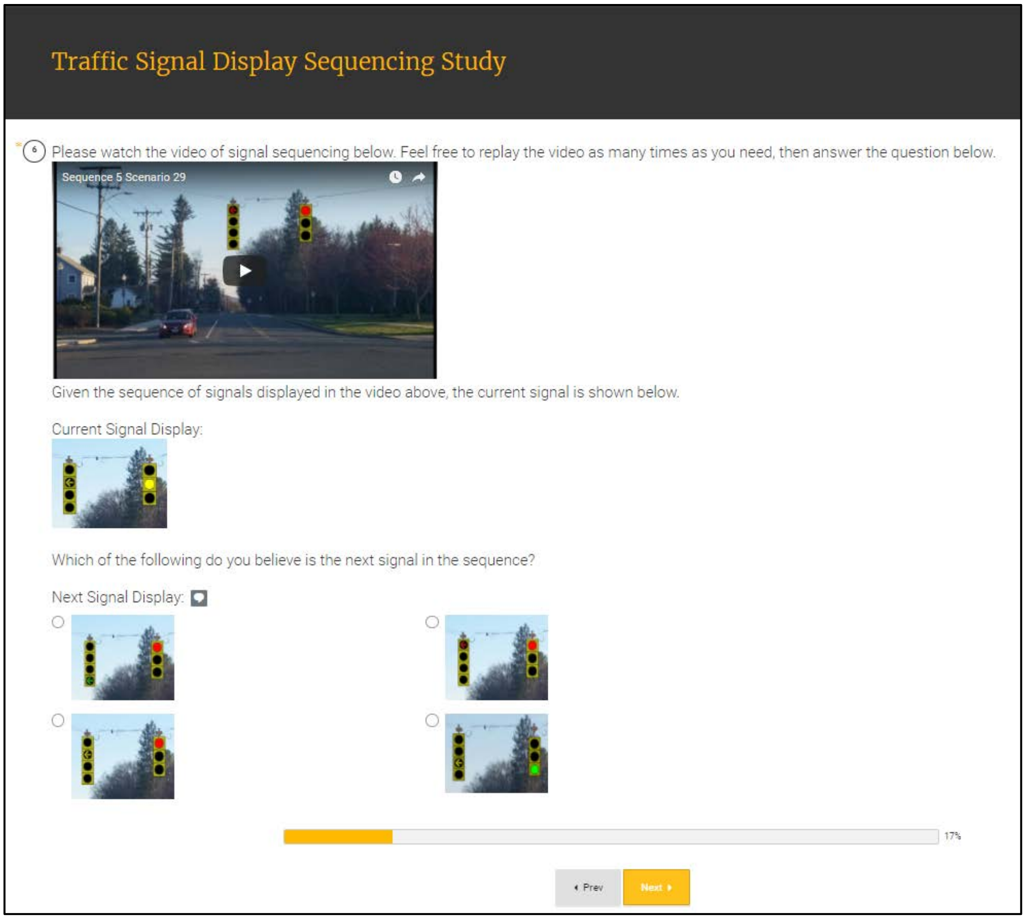
*Gender:*
- *Male*
- *Female*

*Driving Experience:*
- *Less than 5 years*
- *5 to 9 years*
- *More than 10 years*

*Current State of Residence:*
*[text box provided]*

Respondents were instructed to select one option for each question, except for the empty text box for the '*Current State of Residence*' question. The '*Current State of Residence*' option was included based on the wide array of regional locations that the survey was distributed in.

The majority of the survey consisted of a randomization of signal sequencing questions. In total, there were 15 questions developed to display various standard PPLT signal sequences, as indicated from the phase schemes in Table 1. Each question consisted of the following: an embedded video that could be replayed by each respondent as necessary, an image of the final signal display shown in the video, and a selection of 'Next Signal Display' options for the respondents to choose from. An example of a signal sequencing question is represented in Figure 7 below. The development of the phasing schemes for the CG and FYA scenarios are explained further in sections 3.2.2 and 3.2.3, respectively.



Traffic Signal Display Sequencing Study

* ⑥ Please watch the video of signal sequencing below. Feel free to replay the video as many times as you need, then answer the question below.

Sequence 5 Scenario 29

Given the sequence of signals displayed in the video above, the current signal is shown below.

Current Signal Display:

Which of the following do you believe is the next signal in the sequence?

Next Signal Display:

○ ○

○ ○

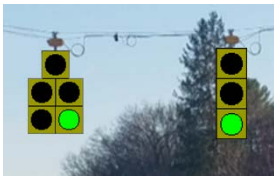
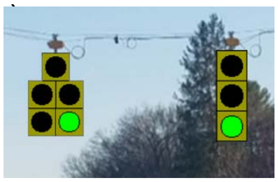
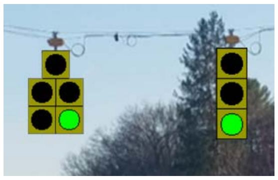
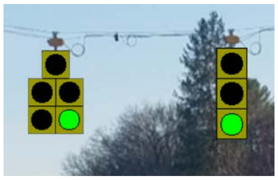
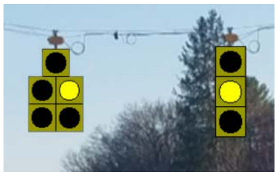
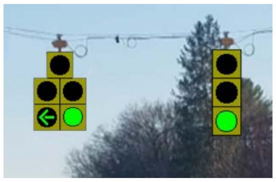
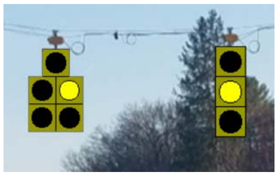
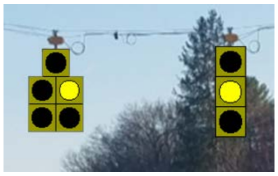
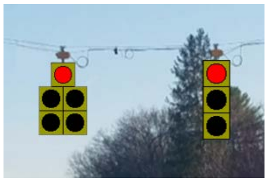
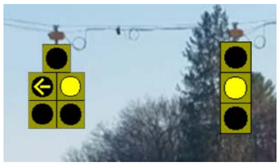
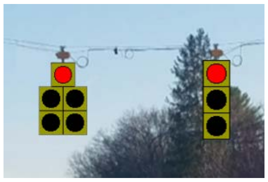
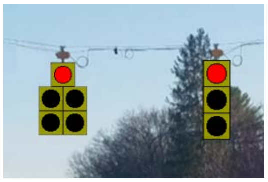
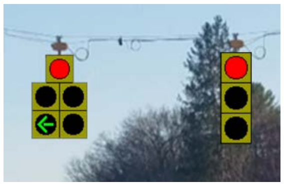
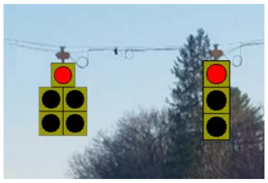
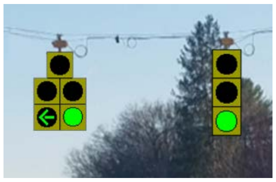
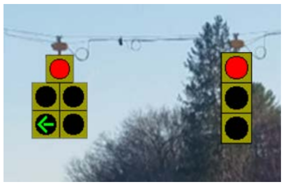
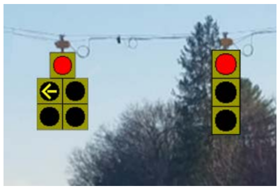
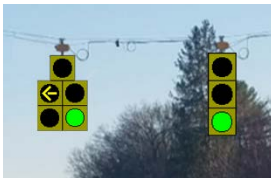
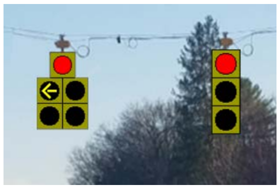
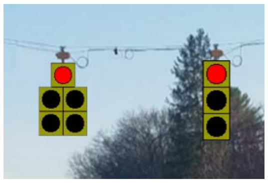
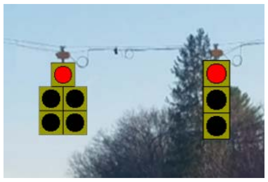
Figure 7 Example of signal sequencing question from survey

Following the completion of the survey, respondents were asked to leave constructive feedback. This question was optional, so it was not anticipated for every respondent to provide feedback in this section.

### 3.2.2 Circular Green (CG) Scenarios

In developing the sequencing questions for the circular green (CG) PPLT phasing, the phase schemes outlined in Table 1 were extrapolated. In accordance with the standard sequencing of cluster signals in PPLT phasing, the breakdown of phases for dual leading, lead-lad (lagging), lead-lag (leading), and dual lagging were expressed in Table 2.

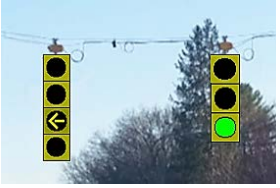
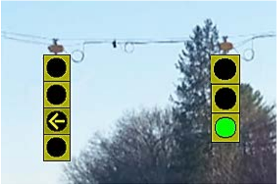
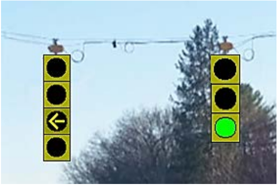
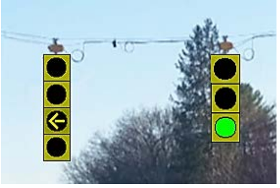
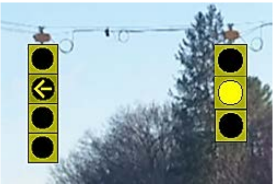
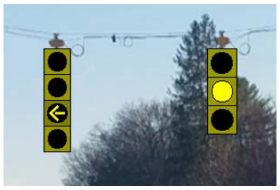
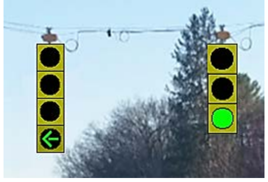
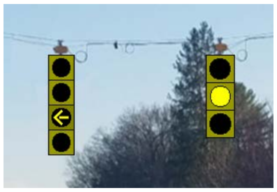
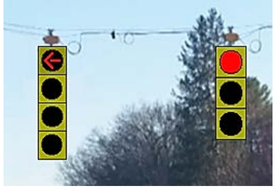
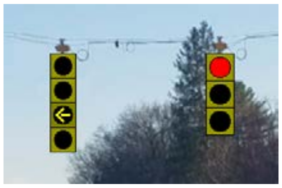
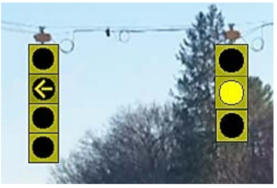
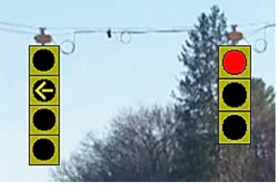
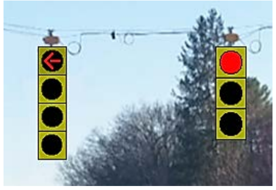
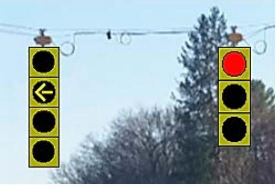
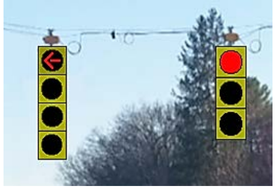
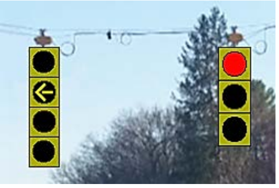
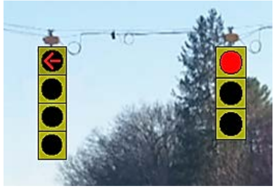
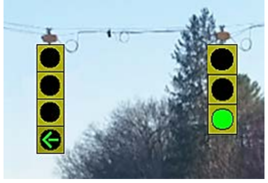
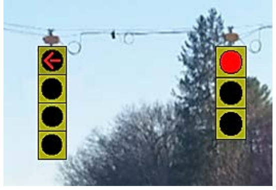
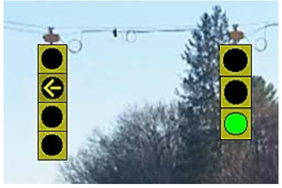
Table 2 Breakdown of CG PPLT phase schemes (from left to right): Dual Leading, Lead-Lag (lagging), Lead-Lag (leading), Dual Lagging

| Sequence 1 | Sequence 2 | Sequence 3 | Sequence 4 |
|---|---|---|---|
| **Dual Leading** | **Lead-Lag (Lagging)** | **Lead-Lag (Leading)** | **Dual Lagging** |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |

### 3.2.3 Flashing Yellow Arrow (FYA) Scenarios

In developing the sequencing questions for the flashing yellow arrow (FYA) PPLT phasing, the schemes from Table 1 were again extrapolated. In accordance with the standard format for sequencing FYA signals at PPLT intersections, the breakdown of phases for dual leading, lead-lag (lagging), lead-lag (leading), and dual lagging were expressed in Table 3.

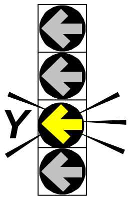
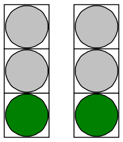
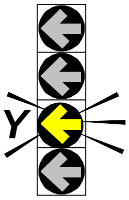
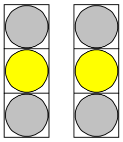
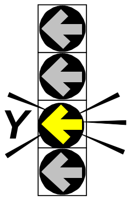
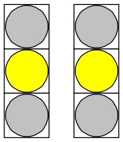
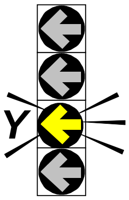
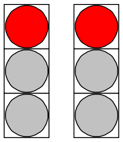
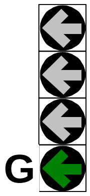
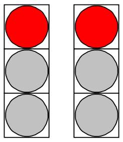
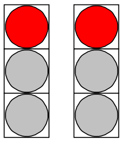
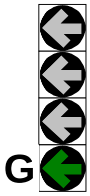
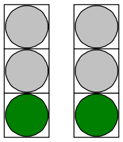
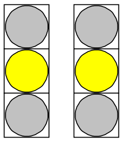
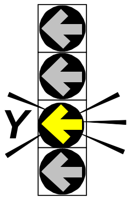
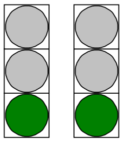
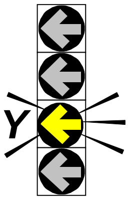
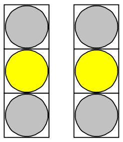
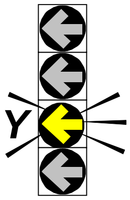
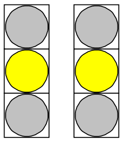
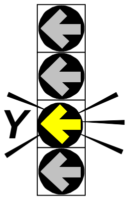
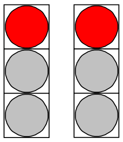
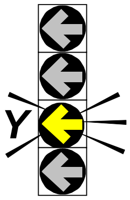
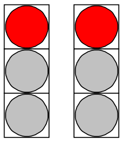
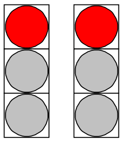
Table 3 Breakdown of FYA PPLT phase schemes (from left to right): Dual Leading, Lead-Lag (lagging), Lead-Lag (leading), Dual Lagging

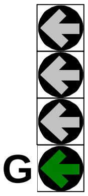
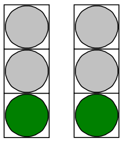
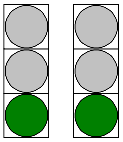
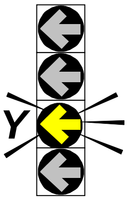
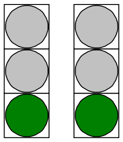
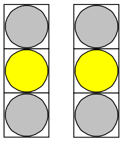
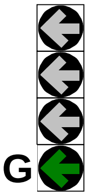
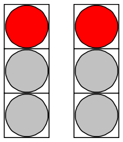
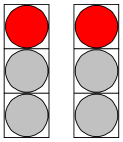
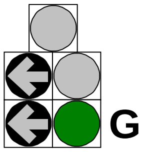
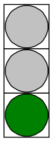
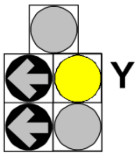
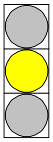
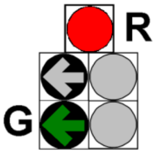
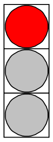
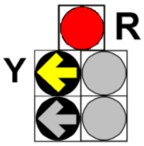
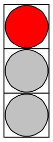
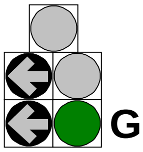
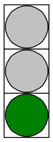
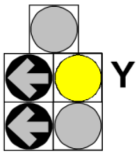
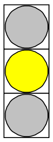
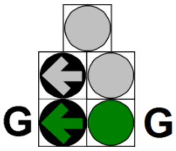
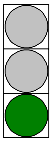
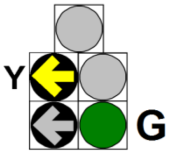
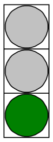
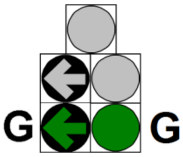
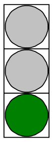
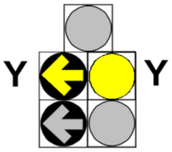
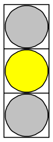
| **Sequence 5** | **Sequence 6** | **Sequence 7** | **Sequence 8** |
|---|---|---|---|
| **Dual Leading** | **Lead-Lag (Lagging)** | **Lead-Lag (Leading)** | **Dual Lagging** |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |
|  |  |  |  |

### 3.2.4 Signal Sequencing for CG and FYA

From the detailed descriptions of phase schemes for both CG and FYA PPLTs presented in the previous section, the questions were sculpted for the survey. The information provided in Table 4 represents the allotment of various phasing that were presented to each of the respondents throughout the survey. The Current Display represents the signal that is last viewed by the respondent, and the Preceding Display represents the phase prior to the Current Display. As seen in 3.2.2 Circular Green (CG) Scenarios, the dual leading and dual lagging phases for the CG cluster signal are interchangeable. Therefore, these phases were categorized into a single sequence (scenarios 11 & 12). Sequences 5-8 represent the various schemes for FYA signals, with the scenarios consisting of each possible sequence arrangement to test driver comprehension of that specific scheme. For instance, Sequence 7 only requires the inclusion of one scenario due to its simple five-phase cycle. Sequences 1-4 represent the various schemes for CG PPLT signals, with the scenarios representing all possible sequence arrangements to best evaluate driver comprehension of that cycle. Each of the scenarios, as mentioned previously, were randomized based on the implementation of a randomization selection in SurveyMonkey. By randomizing the scenarios, it was anticipated that respondents would receive each signal scheme at various points throughout the survey. This reduces the question appearance bias and allows for even question distribution for each sequence scenario.

Table 4 Signal sequences split into scenarios, with the final two displays presented accordingly

| **Sequence #** | **Scenario #** | **Preceding Display** | | **Current Display** | |
|---|---|---|---|---|---|
| | | **PPLT Signal** | **Through Signal** | **PPLT Signal** | **Through Signal** |
| 8 | 1 |  |  |  |  |
| | 2 |  |  |  |  |
| | 3 |  |  |  |  |
| 7 | 4 |  |  |  |  |
| 6 | 5 |  |  |  |  |
| | 6 |  |  |  |  |
| | 7 |  |  |  |  |

| Sequence # | Scenario # | Final Preceding Display | | Follow-Up Display | |
|---|---|---|---|---|---|
| | | PPLT Signal | Through Signal | PPLT Signal | Through Signal |
| | 8 |  |  |  |  |
| 5 | 9 |  |  |  |  |
| | 10 |  |  |  |  |
| 4 & 1 | 11 |  |  |  |  |
| | 12 |  |  |  |  |
| 3 | 13 |  |  |  |  |
| | 14 |  |  |  |  |
| 2 | 15 |  |  |  |  |

The survey questions explained previously will investigate driver comprehension in the current state of practice in terms of circular green (CG) and flashing yellow arrows (FYA) indications for PPLT phasing. The results, analyses, and discussion of these survey data will be further explored in the remaining chapters of this paper.

### 3.2.5 Follow-Up Static Evaluation

Upon analyzing the data from the original computer-based static evaluation, a follow-up survey was developed to further investigate driver comprehension of all-red clearance intervals. This survey was cloned from the original and included the demographic questions, as discussed previously. Specifically, four scenarios were developed to evaluate the transition between protected and permissive left-turn phasing using both the CG and FYA indications (Figure 8). Two scenarios were designed with the cluster signal, which evaluated the participants' prediction of the all-red clearance interval and the permissive green indication. In addition, two scenarios were designed with the four-section head (FYA) to evaluate the participants' prediction of the all-red clearance interval and the permissive FYA indication.

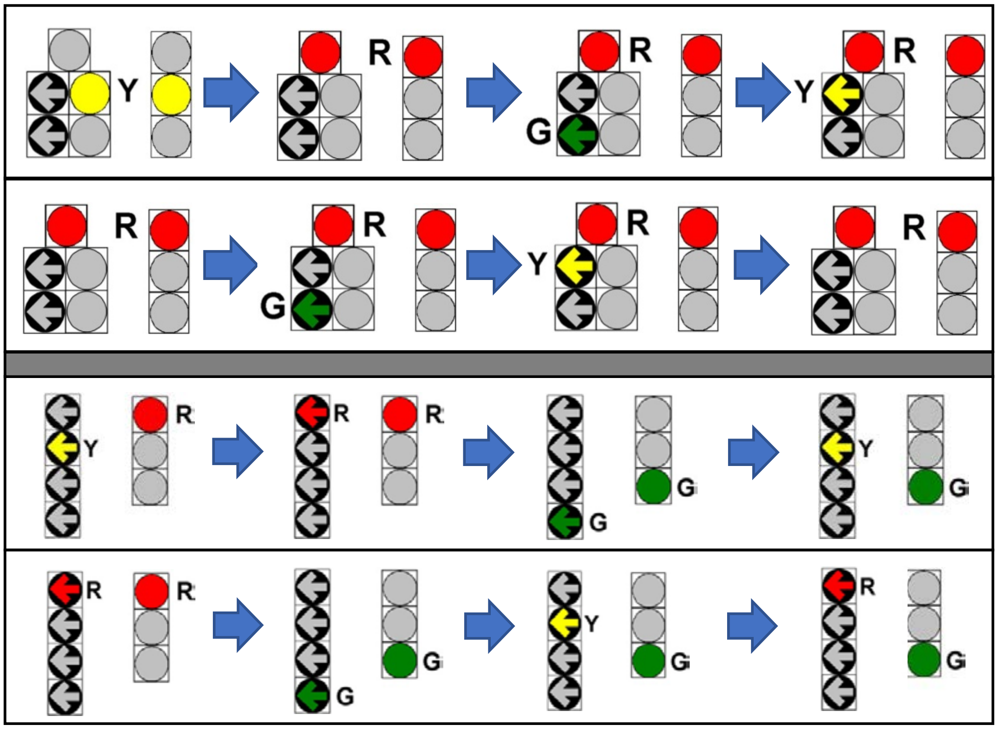


Figure 8 PPLT Sequences Displayed in Follow-Up Static Evaluation

This survey was evaluated on the premise that drivers would not have taken the previous survey. Thus, the participants in this follow-up static evaluation would have only seen the four scenarios, as listed previously, for PPLT phasing. These scenarios were again randomized to prevent order of appearance bias. The results from this follow-up study will be presented in the next chapter.

### 3.3 Field Study: Vehicle Trajectory Data

The final objective of this paper encompasses the implementation of a field study utilizing an innovative traffic data collection method. The application of this data collection method included developing a parallel between left-turn vehicle trajectories and corresponding signal phasing information. In essence, creating a visualization of driver acceleration/deceleration behavior, and the corresponding adjustments, as they approached various phases of a signalized intersection.

As mentioned previously in Chapter 2, the field study employed the use of a microwave-based sensor technology for vehicle detection. Specifically, the Intersector™ by MS Sedco was chosen for application in this study, based on its reliable capability of tracking oncoming vehicle trajectories through a specific corridor (or intersection in this case). The next sections explain the details with respect to device installation and data collection.

### 3.3.1 Intersector™ Installation

The Intersector™ has a two-fold application for installation in the field. The device may be applied in a more permanent fashion, existing on the mast arms of intersections for alternative loop detectors. In this case, the device would be connected to the signal cabinet of the intersection, continuously logging vehicle trajectories primarily for stop bar vehicle detection. The second application method, involves a mobile installation process, allowing for a more simplistic installation for short-term data collection. The latter was the installation process utilized in this particular study. The graphic in Figure 9 represents the comprehensive setup of the device including: the microwave motion and presence sensor, 12-volt power source, power converter, and laptop computer. In this system, the laptop was connected into the sensor through a passive power over ethernet (PoE) injector. The passive POE injector provided the conversion between 12-volt power source and ethernet connection to the device.  The equipment was contained in a mobile, weatherproof case that allowed for ease of transport. The mobile version of this device allowed for an efficient setup and take-down process, for each of the observed intersections.

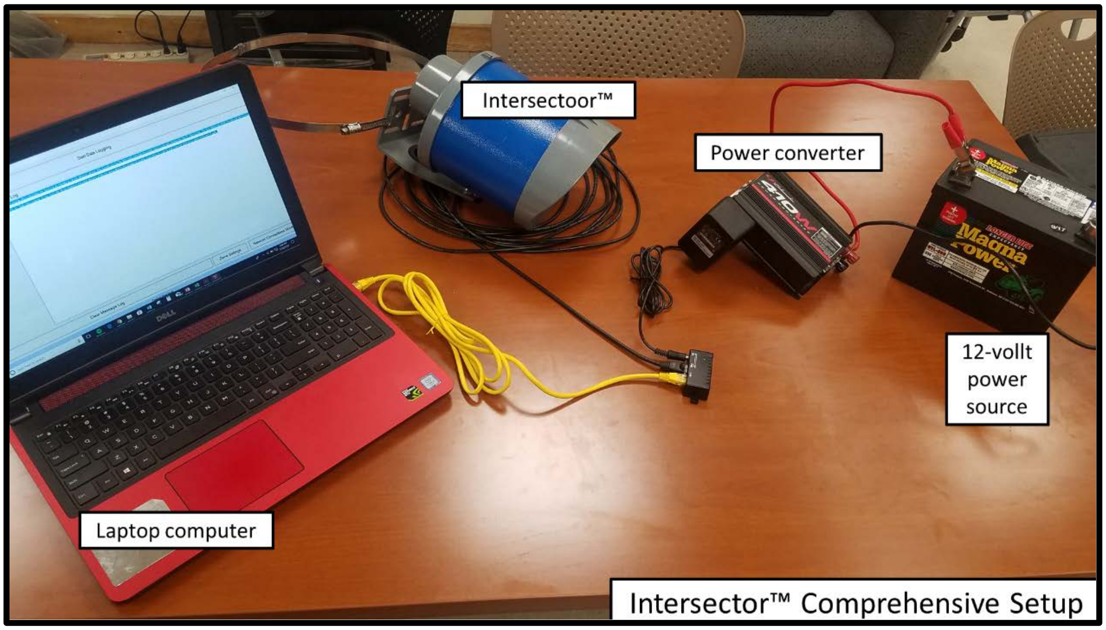


Figure 9 Comprehensive Setup of the Intersector™

Once all ethernet and power connections were assembled, the internet connection and calibration processes were initiated. An ethernet connection between the computer and device needed to be manually established through the computers network settings. After creating a matching IP address to the device, the computer was capable of connecting with the device. The IP address was then opened in a web browser and immediately connected to the calibration window. The display in Figure 10 represents this calibration window, particularly from a sample zone configuration of an intersection studied previously by researchers at UMass. In this window, the zone configuration for the intersections were calibrated in a unique fashion dependent on the proximity of the device to the observed stop bar. First, the “Set Sensor Orientation” option was calibrated based on the positioning of the sensor in relation to the stop-bar of the specified intersection approach. The X and Y values refer to the coordinate vector distance from where the sensor was mounted to the stop-bar location. The Offset Angle value was dependent on the height of the sensor mount. Once these values were properly calibrated, the oncoming vehicles were essentially parallel to the vertical lines in the trajectory output. The ‘bread crumbs’ option allowed for the software to provide a continuous trajectory visualization for each Vehicle ID captured by the sensor.

Target Setup Table

| Zone | Y (feet ) | X (feet ) | Y Front (feet ) | Y Behind (feet ) | Width of Zone (feet ) | Delay Time | Extension Time | Opto Output | Vehicle Count | Bike | Pulse | Zone Description |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 100.0 | 15.0 | 20.0 | 50.0 | 100.0 | 0.0 | 1.0 | 1 | 83 | ☐ | ☐ | |
| 2 | 100.0 | 0.0 | 20.0 | 20.0 | 12.0 | 0.0 | 1.0 | 0 | 1 | ☐ | ☐ | |
| 3 | 100.0 | 0.0 | 20.0 | 20.0 | 12.0 | 0.0 | 1.0 | 0 | 0 | ☐ | ☐ | |
| 4 | 100.0 | 0.0 | 20.0 | 20.0 | 12.0 | 0.0 | 1.0 | 0 | 0 | ☐ | ☐ | |
| 5 | 100.0 | 0.0 | 20.0 | 20.0 | 12.0 | 0.0 | 1.0 | 0 | 0 | ☐ | ☐ | |
| 6 | 100.0 | 0.0 | 20.0 | 20.0 | 12.0 | 0.0 | 1.0 | 0 | 0 | ☐ | ☐ | |
| 7 | 100.0 | 0.0 | 20.0 | 20.0 | 12.0 | 0.0 | 1.0 | 0 | 0 | ☐ | ☐ | |
| 8 | 100.0 | 0.0 | 20.0 | 20.0 | 12.0 | 0.0 | 1.0 | 0 | 0 | ☐ | ☐ | |

Set Sensor Orientation X 0 Y 0 or Offset Angle 0

ZoneSelect 1 ID 1 Copy Data Clear Vehicle Count

Unit Select feet Configure

Set Display Area Move left or right 120

☐ Auto Detect 20

Stop

☑ Tech Mode ☑ Bread Crumbs

Opto Output

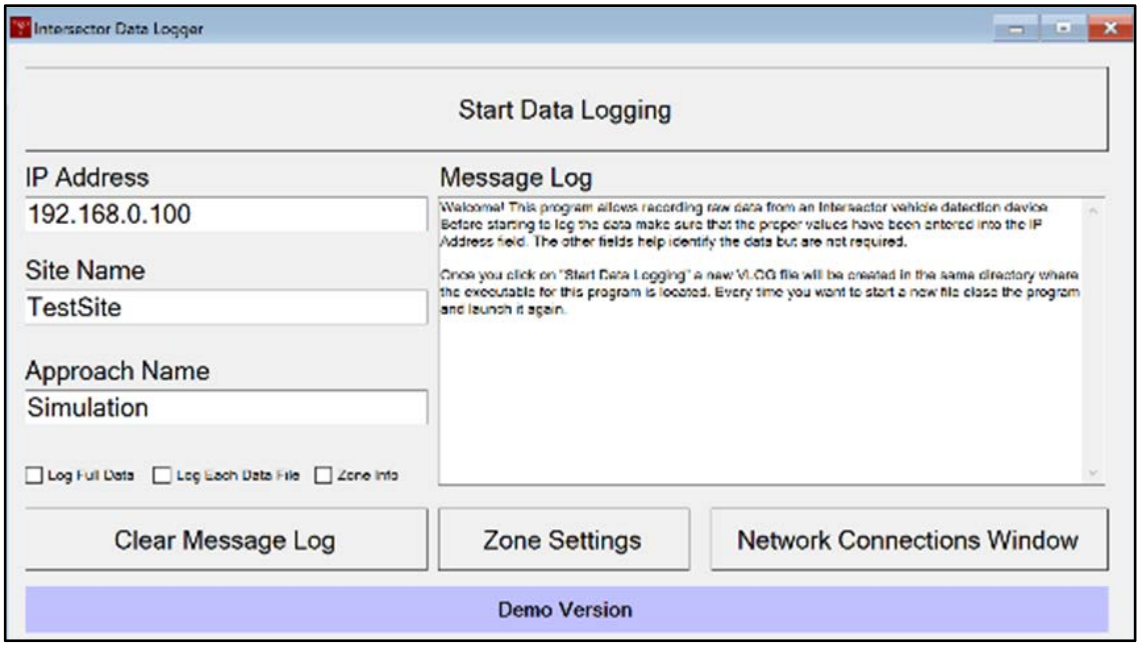
| 🟥 1 | 🟩 2 | 🟩 3 | 🟩 4 | 🟩 5 | 🟩 6 | 🟩 7 | 🟩 8 |
|---|---|---|---|---|---|---|---|

Vehicle Table

| ID | Vehicle Number | y position (feet ) | x position (feet ) | speed (mph ) | Classification |
|---|---|---|---|---|---|
| 1 | 10 | 147.9 | 5.6 | 0 | 14.4 |
| 2 | 16 | 234.5 | 1.6 | 20.2 | 14.4 |
| 3 | 18 | 51.5 | -9.8 | 10.9 | 28.2 |
| 4 | 19 | 699.6 | -22.6 | 29.1 | 14.4 |
| 5 | 0 | 0.0 | 0.0 | 0 | 0.0 |
| 6 | 0 | 0.0 | 0.0 | 0 | 0.0 |
| 7 | 0 | 0.0 | 0.0 | 0 | 0.0 |
| 8 | 0 | 0.0 | 0.0 | 0 | 0.0 |

Figure 10  Sample Zone Configuration Data from intersection in Amherst, MA

Following the final calibration, the software menu, as seen in Figure 11, was initialized. The device calibration window was closed and the “start logging” option was selected. By selecting this option, the software begins to log the data in .txt format. With a frequency of 2.0 Hz, the sensor records the following variables: Vehicle ID, Time Stamp (mm-dd-yyyy, hh:mm:ss), X-Position, Y-Position, Speed (mph), and Length (ft). The  APPENDIX includes a sample output of raw data from the Intersector™ Figure 37.



IP Address: 192.168.0.100

Site Name: TestSite

Approach Name: Simulation

Message Log

```
Welcome! This program allows recording raw data from an Intersector vehicle detection device
Before starting to log the data make sure that the proper values have been entered into the IP
Address field. The other fields help identify the data but are not required.

Once you click on "Start Data Logging" a new VLOG file will be created in the same directory where
the executable for this program is located. Every time you want to start a new file close the program
and launch it again.
```

Figure 11 Screenshot of Data Collection Software

### 3.3.2 Experimental Design for Data Collection

As mentioned previously, the setup for each data collection location included the Intersector™ sensor paired with a video camera to capture both vehicle trajectories and real-time traffic signal information. As seen in Figure 12, the sensor was located upstream of the intersection and directed at the approach being investigated. In addition to this, the video camera was set up to capture the traffic signal information from the matching intersection approach.

Figure 12 Intersector™ Setup with Video Capture taken in Western MA

In order to evaluate the impact of all-red clearance intervals at PPLT locations, an experimental design was developed to outline the locations of data collection. The phasing included in Table 5 represents the scope of PPLT phasing that was considered necessary for this evaluation. For each permissive left-turn signal display, CG and FYA, the leading protected phases were evaluated. The intersection with the CG permissive left-turn indication was considered the control, with the all-red clearance interval transitioning between protected and permissive. The FYA intersections included both signal sequences with and without the all-red clearance interval when transitioning.

Table 5 Signal indication collected in the field study

| **Left-Turn Signal Display** | **Leading Protected Phase** |
|---|---|
| Circular Green (CG) | With All-Red |
| Flashing Yellow Arrow (FYA) | With All-Red |
| | Without All-Red |

With these intersection specifications in mind, the following locations were selected for the field study:

- SB Approach of Rte. 9 at South East St. – Amherst, MA
- EB Approach of Whiting Farms Rd at Lower Westfield Rd. – Holyoke, MA
- WB Approach of Springfield Rd at Little River Rd – Westfield, MA

The selected intersections were chosen based on proximity to the University of Massachusetts Amherst campus. All of the intersections mentioned above were located in Western Massachusetts. While the specifications of intersection control and signal head displays were considered, these intersections were also selected without any apparent impact from insufficient signal sight distance or significant grade changes. The intersections outline previously were different in size (i.e. number of lanes, width of lanes, width of intersection, etc.); however, the discussion section will outline how these challenges were overcome.

### 3.3.3 Data Processing and Filtering

Following the collection of data at each intersection, the output was collected for each individual location and converted into a .txt file. The data processing and filtering was completed using RStudio, incorporating both the trajectory data and the signal timing data. A script was written to filter through the raw data output, focusing primarily on the oncoming left-turning vehicles that were captured during the collection period. In addition to this, the signal timings for each intersection were embedded in the script for each intersection. It is important to note that the signal timings were manually scored using the video data for each intersection except for the Amherst location. For the Amherst intersection, a script was developed in MATLAB, providing video signal detection and outputting the change in signal sequence throughout the collection period. Overall, the signal timings were included in the filtering script, specifically including a column depicting the signal indication for each vehicle at the intersection stop bar.

# CHAPTER 4

# RESULTS

The following chapter outlines the results obtained from the initial computer-based static evaluation, the follow-up study, and the vehicle trajectory study.

## 4.1 Evaluating Signal Sequence Comprehension

The computer-based static evaluation was conducted to better understand the existing driver comprehension of PPLT phasing with the use of CG and FYA signal indications for permissive left-turns. The data were compiled into a spreadsheet database and analyzed to determine the drivers' understanding of the various PPLT signal sequences, including both CG and FYA indications.

A total of 212 drivers from over 20 states participated in the online survey. Of the 212 participants, 49% were male and 51% were female. A total of 50% of the drivers were between 18 and 24 years of age, 28% between 25 and 34 years of age, 9% between 35 and 44 years of age, 5% between 45 and 54 years of age, 5% between 55 and 64 years of age, and 3% over 65 years of age. In total, 12% of drivers participating had less than 5 years of driving experience, 52% had between 5 and 9 years of driving experience, and 36% had more than 10 years of driving experience. An overall analysis of the demographic characteristics in relation to the percentage of correct responses is presented below in Table 6.

Table 6 Demographic information from computer-based static evaluation

| Demographic | Level | No. of Participants | Percentage Correct Responses |
|---|---|---|---|
| Gender | Male | 102 | 59.2 |
| | Female | 105 | 52.2 |
| Age | 18-24 | 102 | 55.9 |
| | 25-34 | 58 | 59.1 |
| | 35-44 | 19 | 58.5 |
| | 45-54 | 10 | 48.1 |
| | 55-64 | 11 | 58.6 |
| | 65+ | 6 | 30.6 |
| Driving Experience | Less than 5 years | 24 | 59.2 |
| | 5 to 9 years | 107 | 55.1 |
| | More than 10 years | 75 | 56.8 |

The following sections display the results from the static evaluation, specifically representing each of the phase scheme scenarios represented in Table 1. The graphics in this section provide the sequence viewed by each participant along with the percentage of responses for each. The green rectangles represent the correct signal prediction in the sequence, while the yellow rectangles represent a secondary potential correct signal prediction.

### 4.1.1 Circular Green – Dual Leading and Lagging Phasing

Based on the signal sequencing presented in Table 2, the CG PPLT dual leading and dual lagging phasing were combined for evaluation in the survey. Figure 13 represents the driver responses from scenario 5, a dual leading/lagging sequence. 59.4 percent of drivers correctly predicted the next signal phase in the sequence. Figure 14 represents the driver responses from scenario 4, another dual leading/lagging sequence. 50.5 percent of drivers correctly predicted the next signal phase in the sequence.

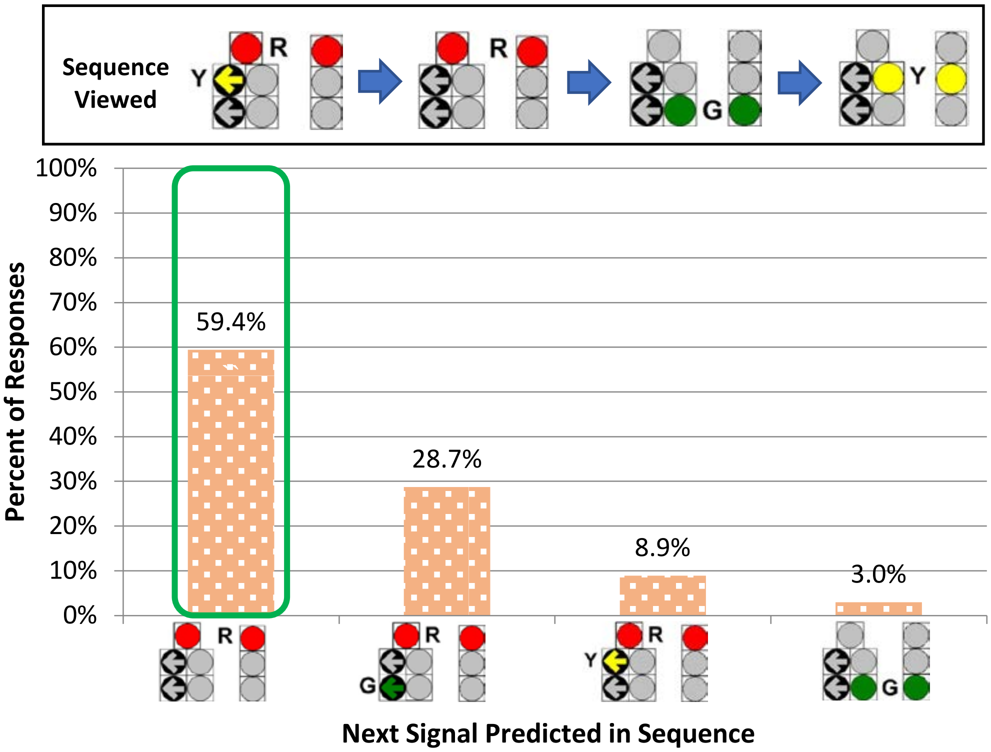


Figure 13 – Scenario 5 Sequence and Driver Responses

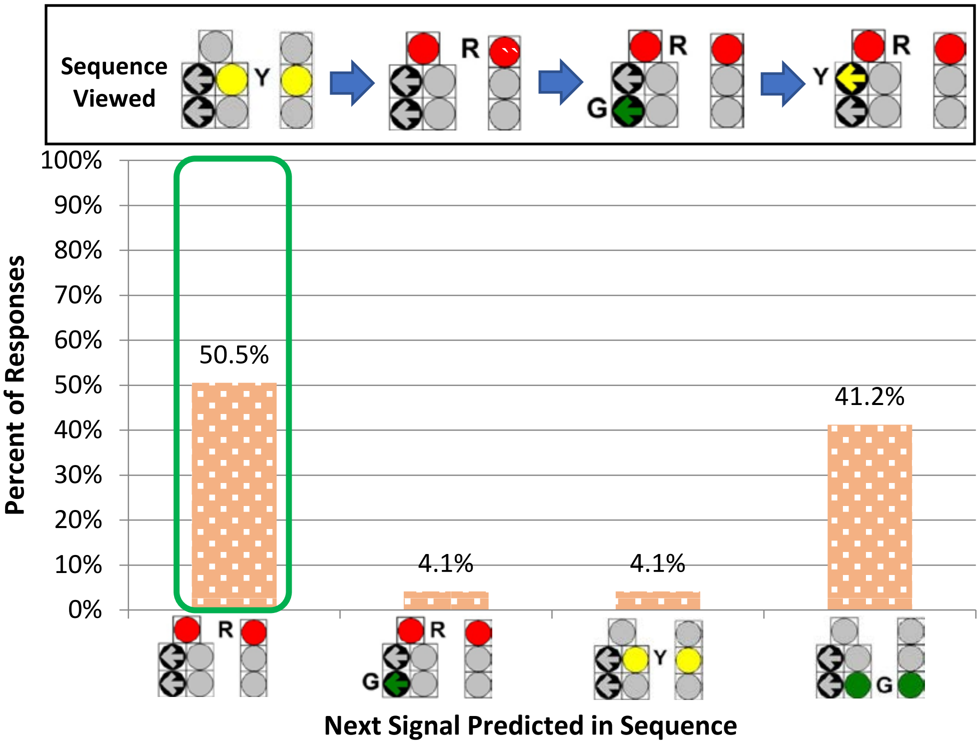


Figure 14 – Scenario 4 Sequence and Driver Responses

### 4.1.2 Circular Green – Lead/Lag Protected Phasing

The following graphics represent the survey results from sequence 2 and 3, the CG lead/lag protected phasing. Figure 15 represents the driver responses from scenario 3, a lead/lag leading protected sequence. 91.9 percent of drivers correctly predicted the next signal phase in the sequence. Figure 16 represents the driver responses from scenario 2, another lead/lag leading protected sequence. 49 percent of drivers correctly predicted the signal phase in the sequence. Figure 17 represents the driver responses from scenario 1, a lead/lag lagging protected sequence. 90.8 percent of drivers correctly predicted the next signal phase in the sequence.

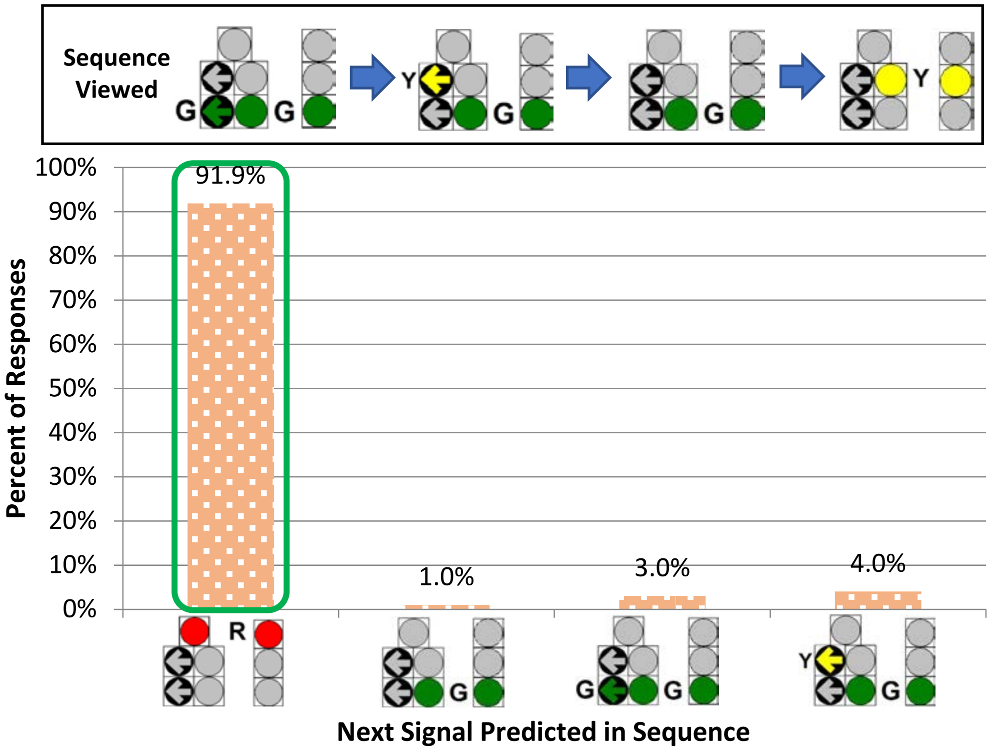


Figure 15 - Scenario 3 Sequence and Driver Responses

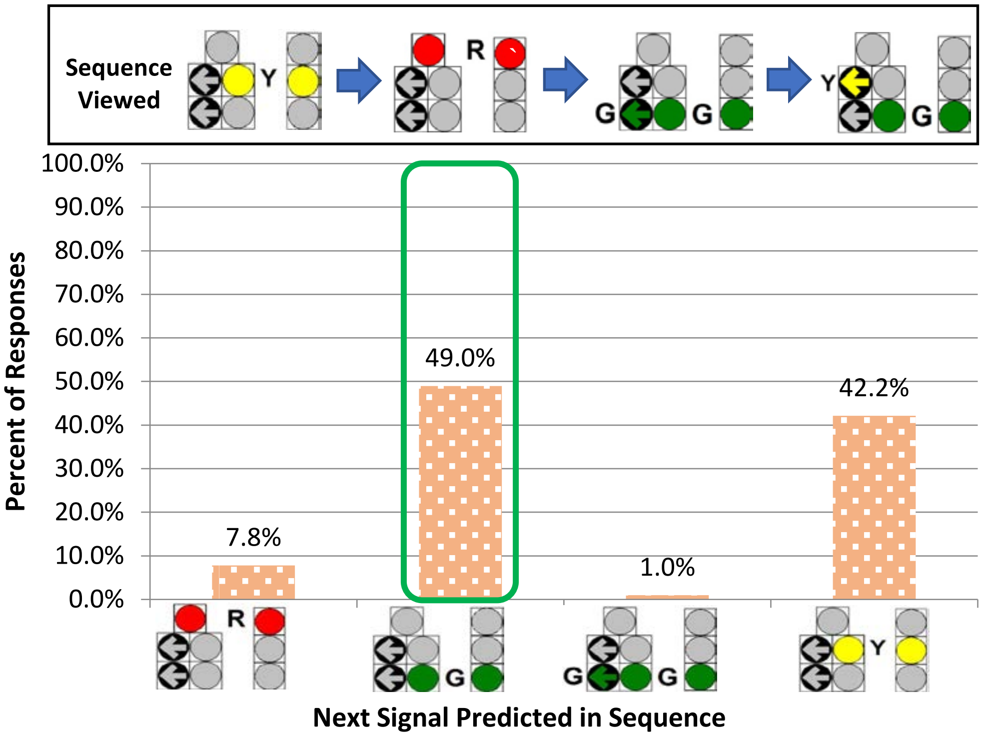


Figure 16 - Scenario 2 Sequence and Driver Responses

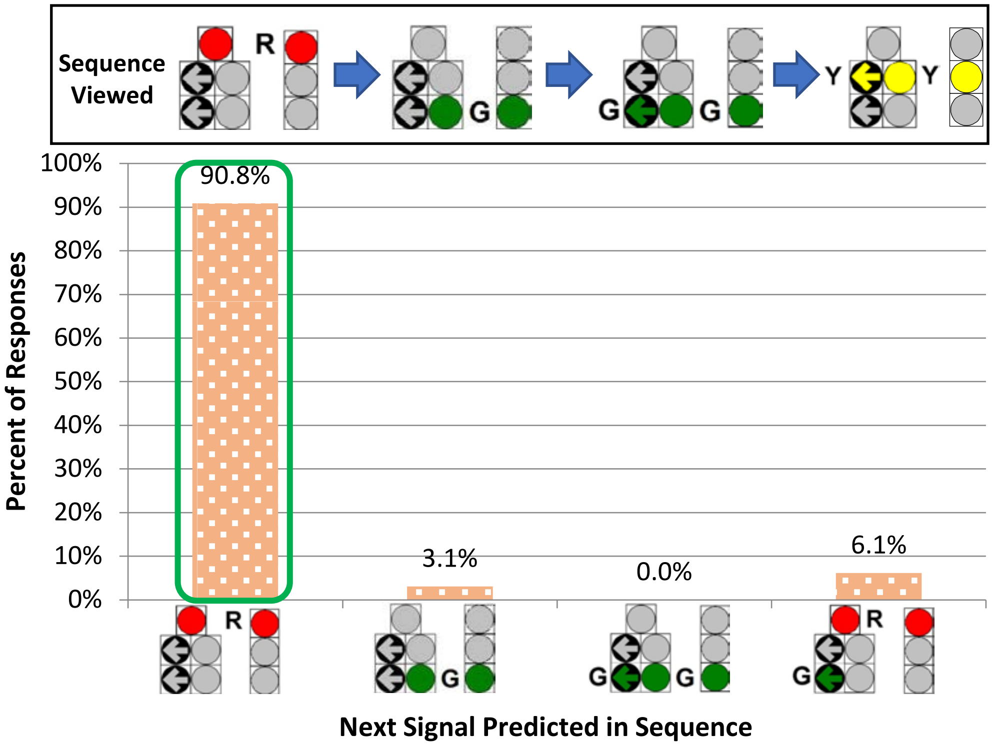


Figure 17 - Scenario 1 Sequence and Driver Responses

### 4.1.3 Flashing Yellow Arrow – Dual Leading and Lagging Phasing

The following graphics represent the survey results from both sequences 5 and 8, FYA dual leading/lagging protected phasing. Figure 18 represents the driver responses from scenario 15, a dual lagging protected sequence. 24.5 percent of drivers correctly predicted the next signal phase in the sequence. Figure 19 represents the driver response from scenario 14, another dual lagging protected sequence. 27.9 percent of drivers correctly predicted the next signal phase in the sequence. Figure 20 represents the driver responses from scenario 13, another dual lagging protected sequence. 68.9 percent of drivers correctly predicted the next signal phase in the sequence. Figure 21 represents the driver responses from scenario 7, a dual leading protected sequence. 73.5 percent of drivers correctly predicted the next signal phase in the sequence. Figure 22 represents the driver responses from scenario 6, another dual leading protected sequence. 42.3 percent of drivers correctly predicted the next signal phase in the sequence.

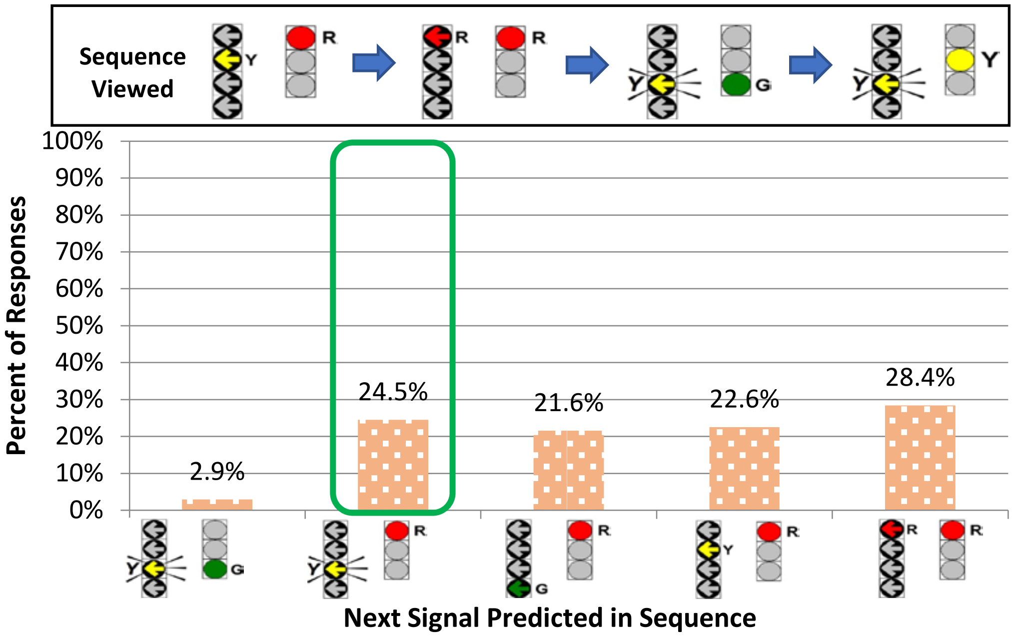


Figure 18 - Scenario 15 Sequence and Driver Responses

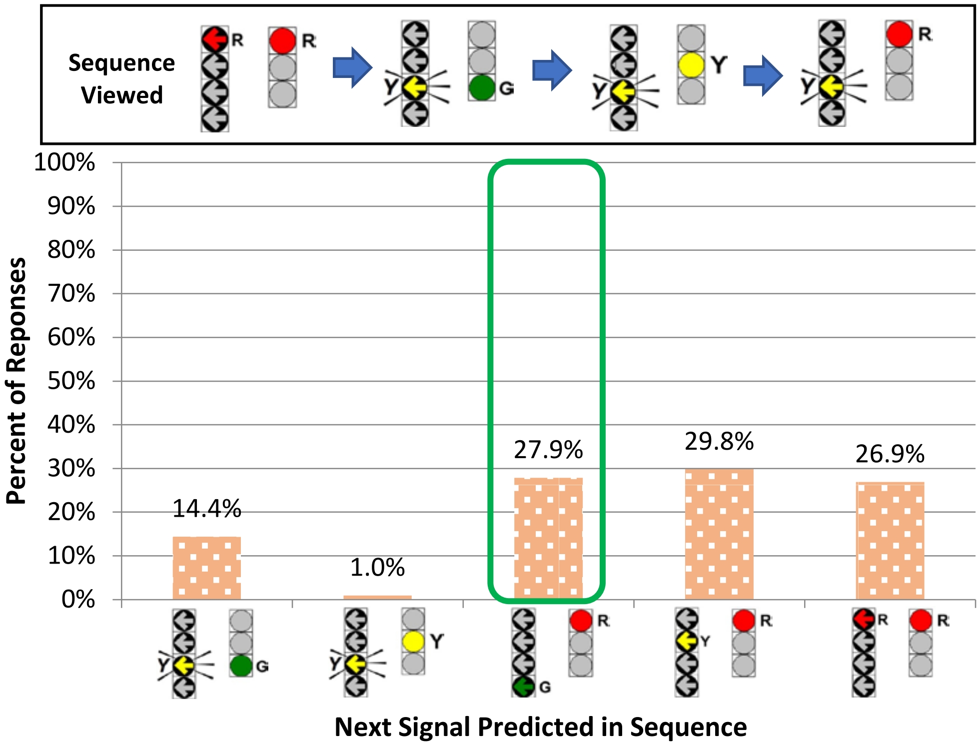


Figure 19 - Scenario 14 Sequence and Driver Responses

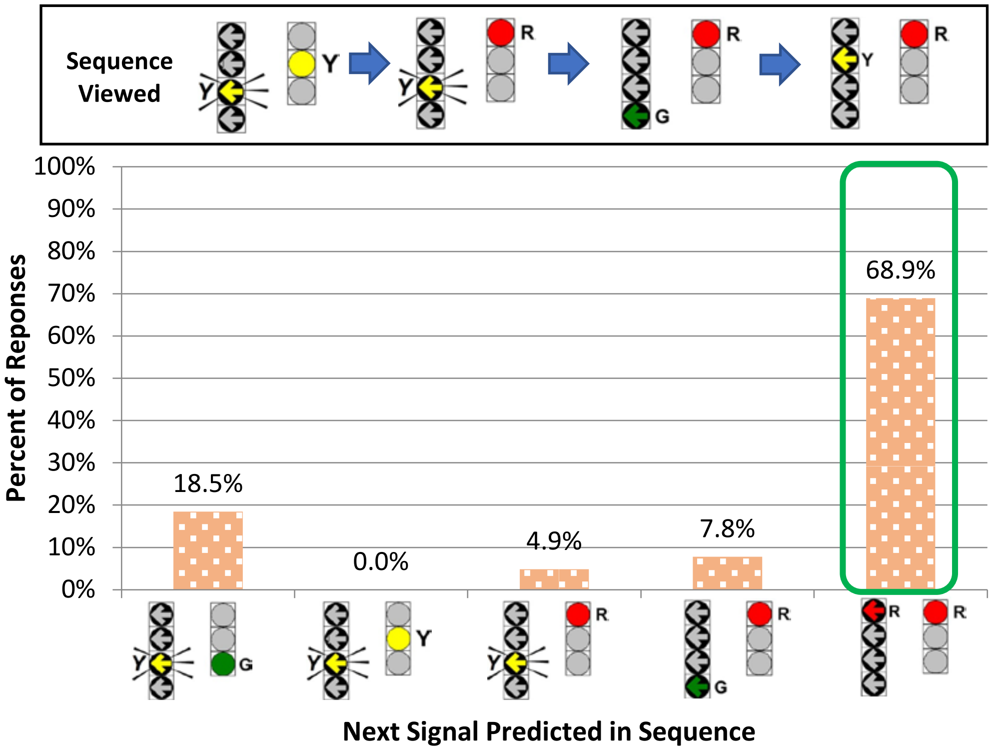


Figure 20 - Scenario 13 Sequence and Driver Responses

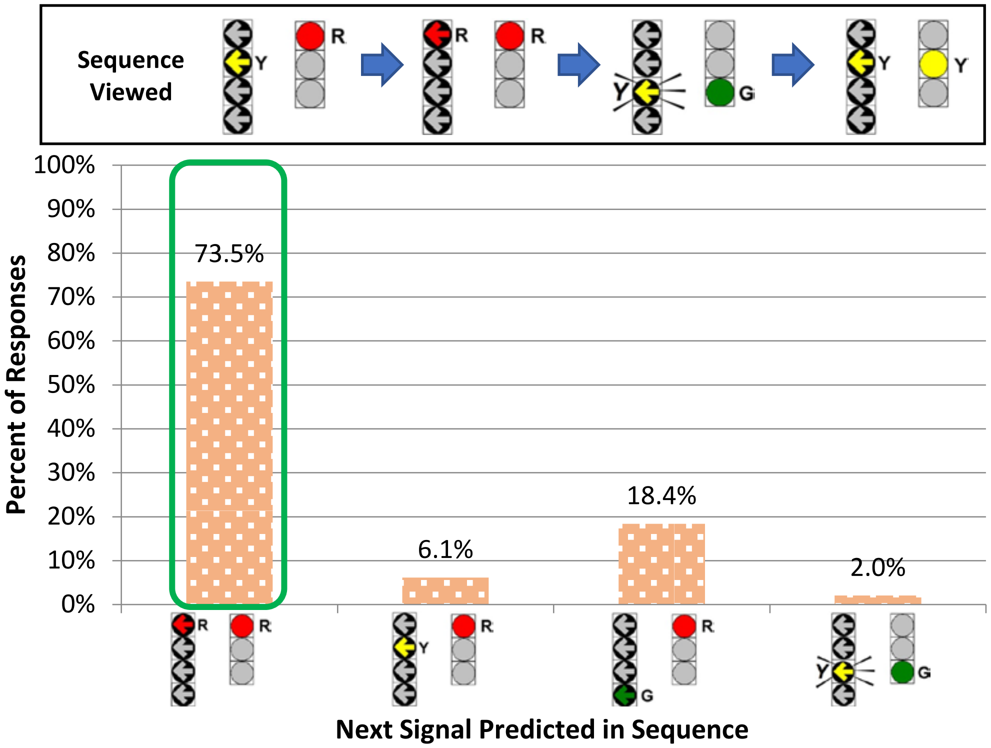


Figure 21 Scenario 7 Sequence and Driver Responses

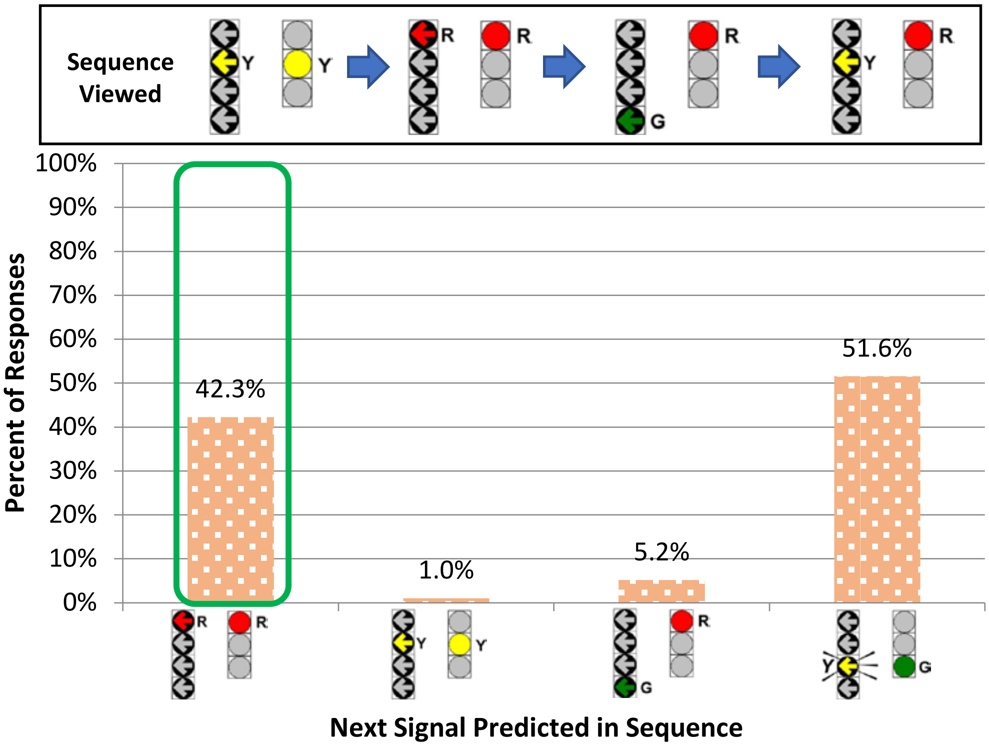


Figure 22 - Scenario 6 Sequence and Driver Responses

### 4.1.4 Flashing Yellow Arrow – Lead/Lag Protected Phasing

The following graphics represent the survey results from both sequences 6 and 7, FYA lead/lag protected phasing. Figure 23 represents the driver responses from scenario 12, a lead/lag lagging protected sequence. 85.2 percent of drivers correctly predicted the next signal phase in this sequence. Figure 24 represents the driver responses from scenario 11, a lead/lag leading protected sequence. 30 percent of drivers correctly predicted the next signal phase in this sequence. Figure 25 represents the driver responses from scenario 10, another lead/lag leading protected sequence. 26.3 percent of drivers correctly predicted the next signal phase in this sequence. Figure 26 represents the driver responses from scenario 9, another lead/lag leading protected sequence. 84.4 percent of drivers correctly predicted the next signal phase in this sequence. Figure 27 represents the driver responses from scenario 8, another lead/lag leading protected sequence. 37.3 percent of drivers correctly predicted the next signal phase in this sequence.

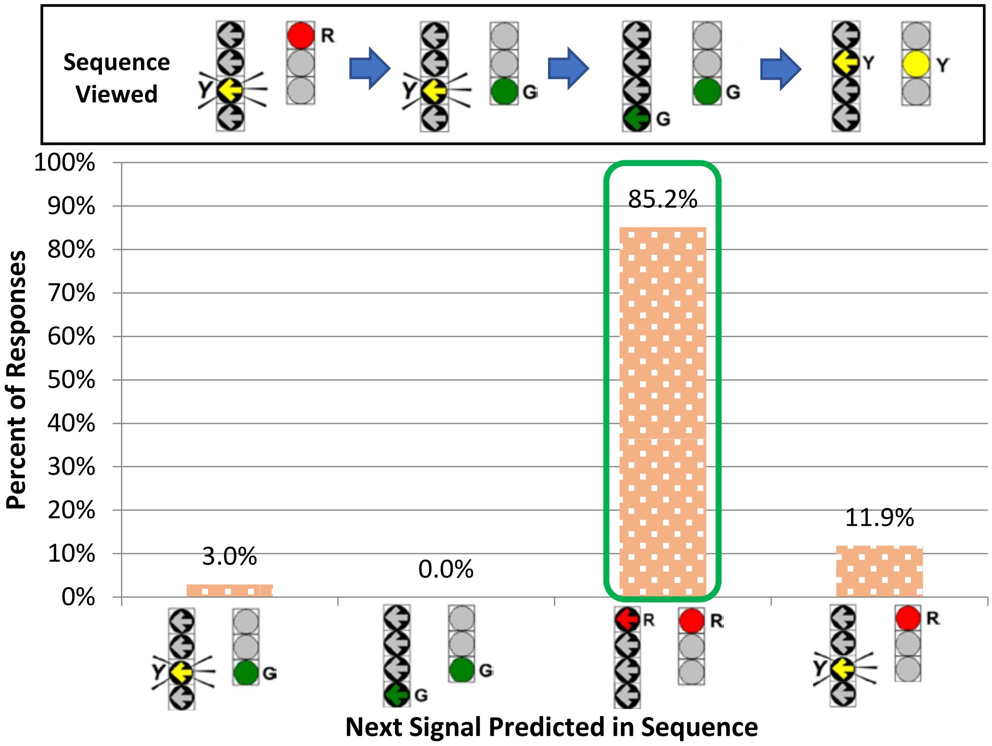


Figure 23 - Scenario 12 Sequence and Driver Responses

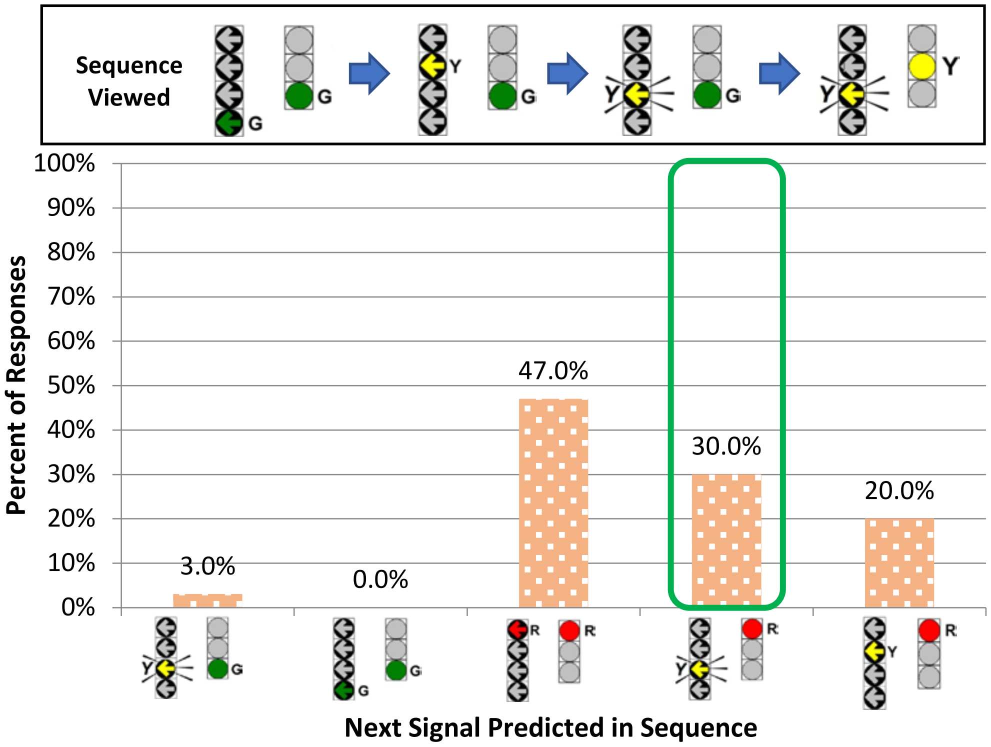


Figure 24 - Scenario 11 Sequence and Driver Responses

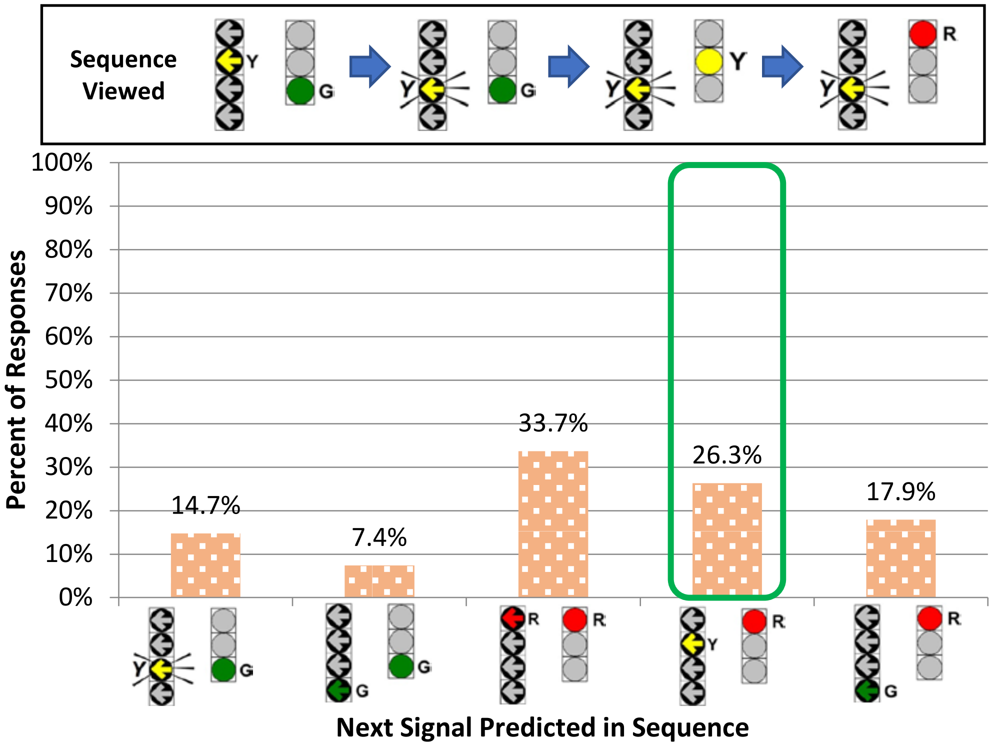


Figure 25 - Scenario 10 Sequence and Driver Responses

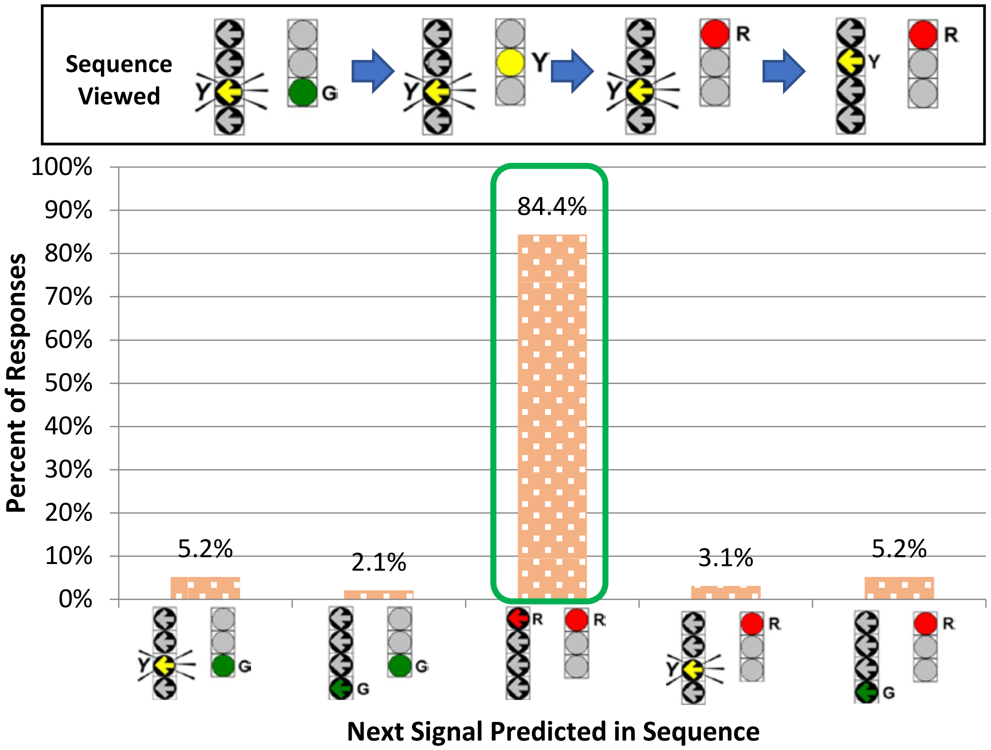


Figure 26 - Scenario 9 Sequence and Driver Responses

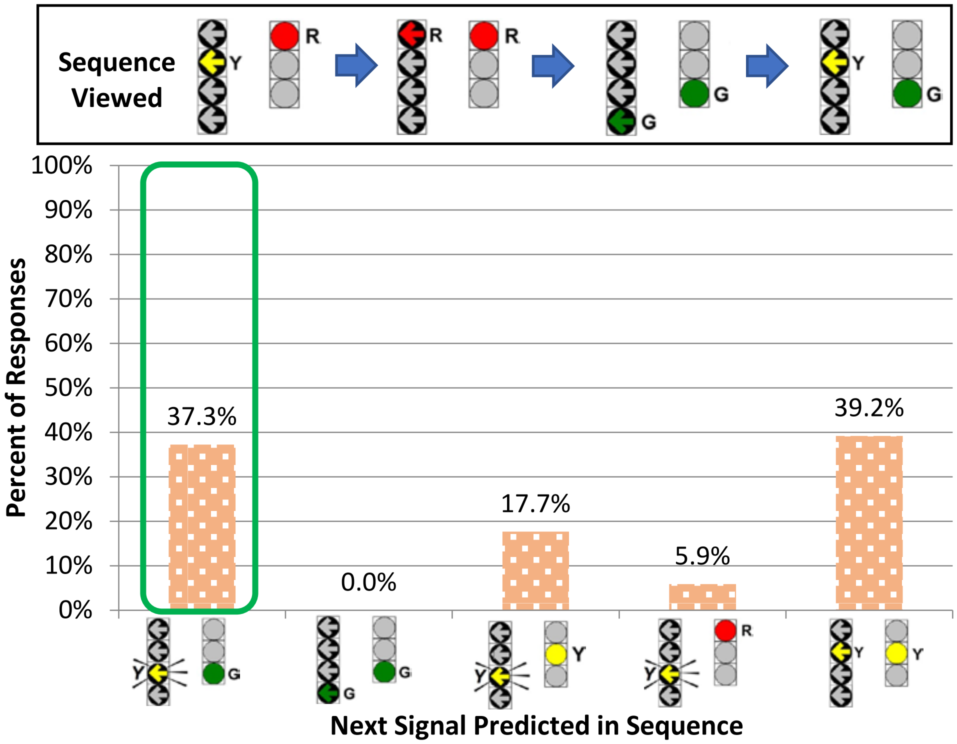


Figure 27 - Scenario 8 Sequence and Driver Responses

### 4.2 Follow-Up Static Evaluation

Upon analyzing the initial data collected from the static evaluation, a follow-up study was developed to further investigate the driver comprehension of transitioning between protected and permissive left-turns. The survey was cloned with similar format to the initial study, including the demographic questions that were queried at the start. A total of 107 drivers participated in the follow-up study. Of the 107 participants, 56% were male and 44% were female. In total, 58% of participants were between 18 and 24 years of age, 22% were between 25 and 34 years of age, 7% were between 35 and 44 years of age, 6% were between 45 and 54 years of age, 6% were between 55 and 64 years of age, and 1% were over the age of 65. A total of 19% of drivers had less than 5 years of driving experience, 45% had 5 to 9 years of driving experience, and 36% had more than 10 years of driving experience. An overall analysis of the demographic characteristics in relation to the percentage of correct responses is presented below in Table 7.

Table 7 Demographic information from follow-up study

| Demographic | Level | No. of Participants | Percentage Correct Responses |
|---|---|---|---|
| Gender | Male | 60 | 55.3 |
| | Female | 57 | 46.5 |
| Age | 18-24 | 62 | 51.9 |
| | 25-34 | 24 | 60.3 |
| | 35-44 | 8 | 55.0 |
| | 45-54 | 6 | 58.3 |
| | 55-64 | 6 | 26.7 |
| | 65+ | 1 | 75.0 |
| Driving Experience | Less than 5 years | 20 | 48.5 |
| | 5 to 9 years | 48 | 54.7 |
| | More than 10 years | 39 | 51.6 |

### 4.2.1 CG PPLT Phasing Sequences

The results from the two CG PPLT sequences in the follow-up study are represented in the graphics below. Figure 28 represents the results from drivers predicting the transition from SYA indication to the all-red clearance interval. The majority of drivers, 72%, correctly predicted the next signal in the sequence. 24 percent of drivers predicted the transition directly to circular green indication. Figure 29 represents the results from drivers predicting the transition from all-red clearance interval to permissive CG indications. 40 percent of drivers correctly predicted the next signal in the sequence. However, 40% of drivers also incorrectly predicted the next signal in the sequence, leading from all-red clearance interval to a protected left-turn SGA indication. It is important to note here that this may be due to a lack of clarity in the small images presented in the survey window. Drivers may have accidentally selected the SGA option, as this option does not make any sequential sense based on the signals presented prior.

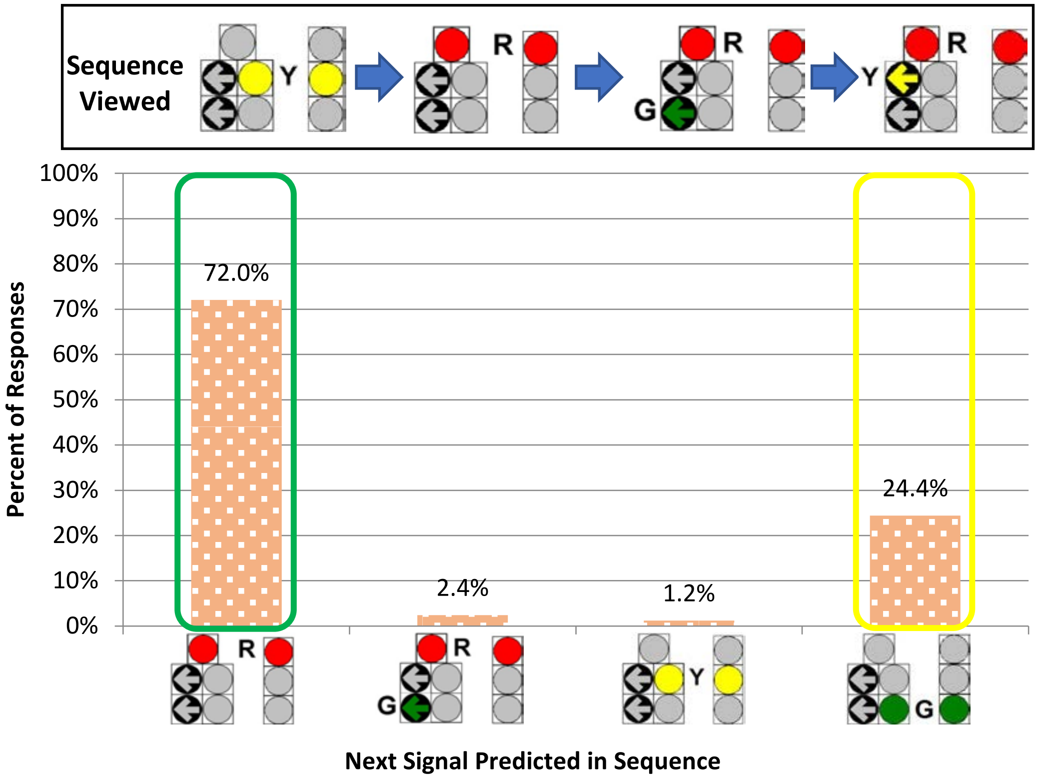


Figure 28 CG PPLT Scenario Predicting All-Red Clearance

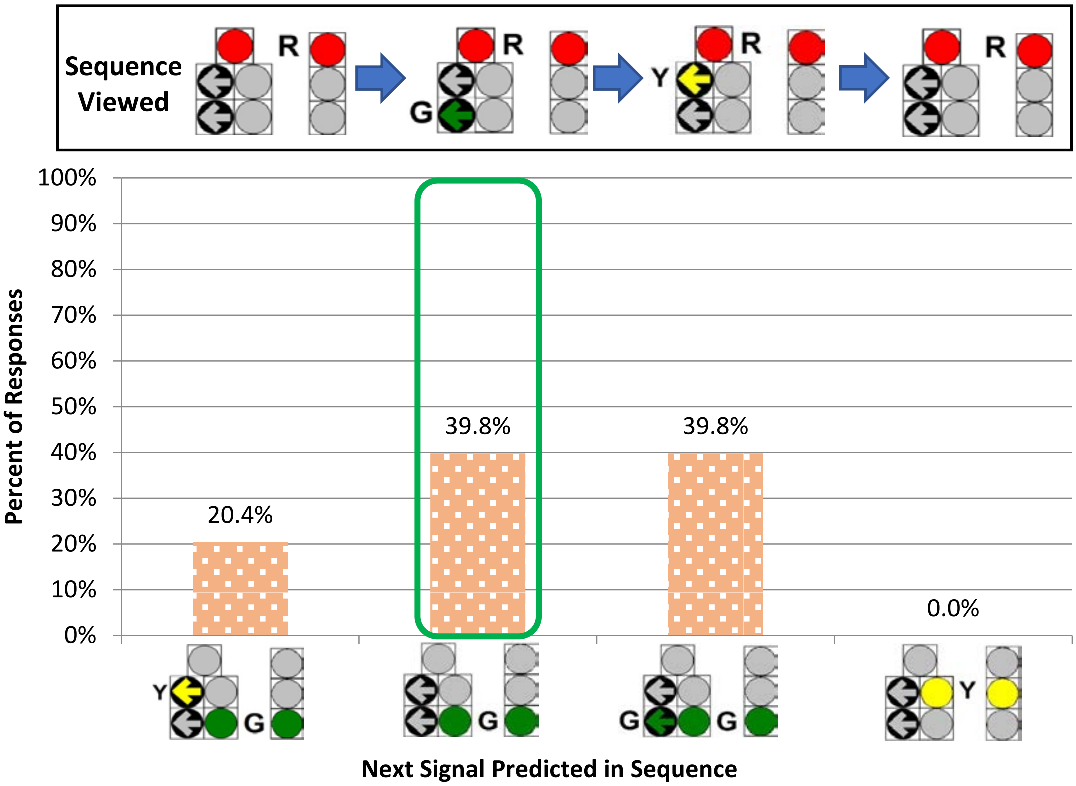


Figure 29 CG PPLT Scenario Predicting CG Permissive Indication

### 4.2.2 FYA PPLT Phasing Sequences

The results from the two FYA PPLT sequences in the follow-up study are presented in the graphics below. Figure 30 represents the results from drivers predicting the transition from the SYA indication to the all-red clearance interval. 59% of drivers correctly predicted the all-red clearance interval as the next signal in the sequence. In addition, 16% of drivers predicted the transition directly to the permissive FYA left-turn indication, which was also a plausible scenario. Figure 31 represents the results from drivers predicting the transition from all-red clearance interval to the permissive FYA left-turn indication. 38% of drivers correctly predicted the FYA left-turn indication as the next signal in the sequence.

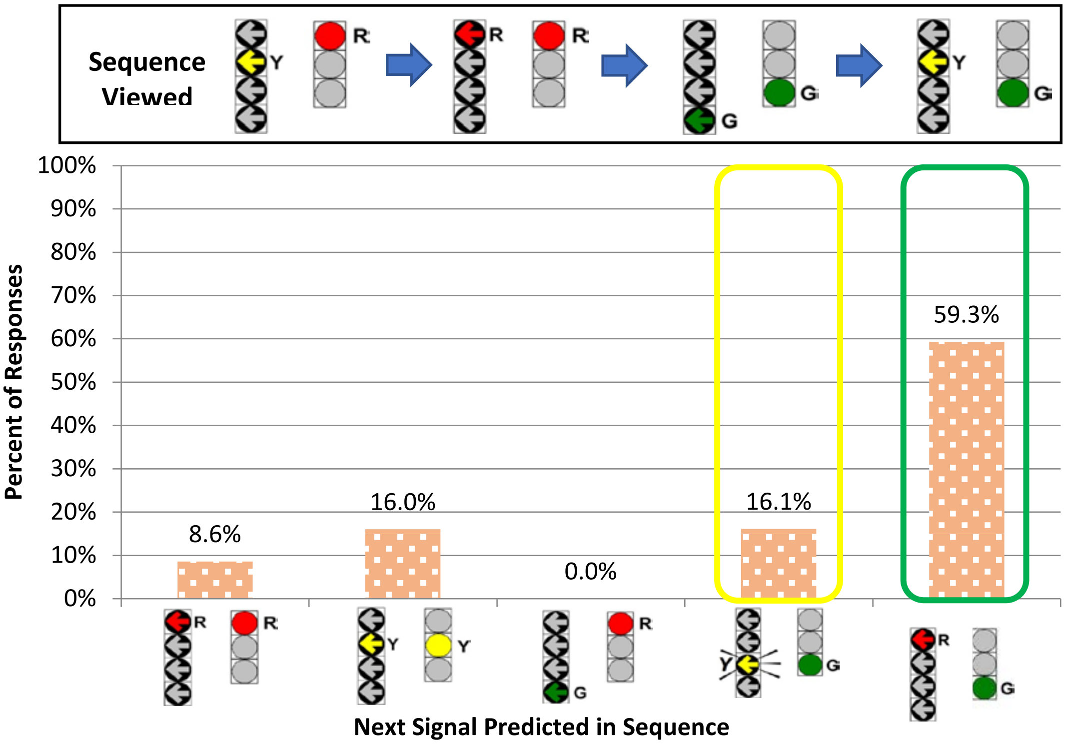


Figure 30 FYA PPLT Scenario Predicting All-Red Clearance

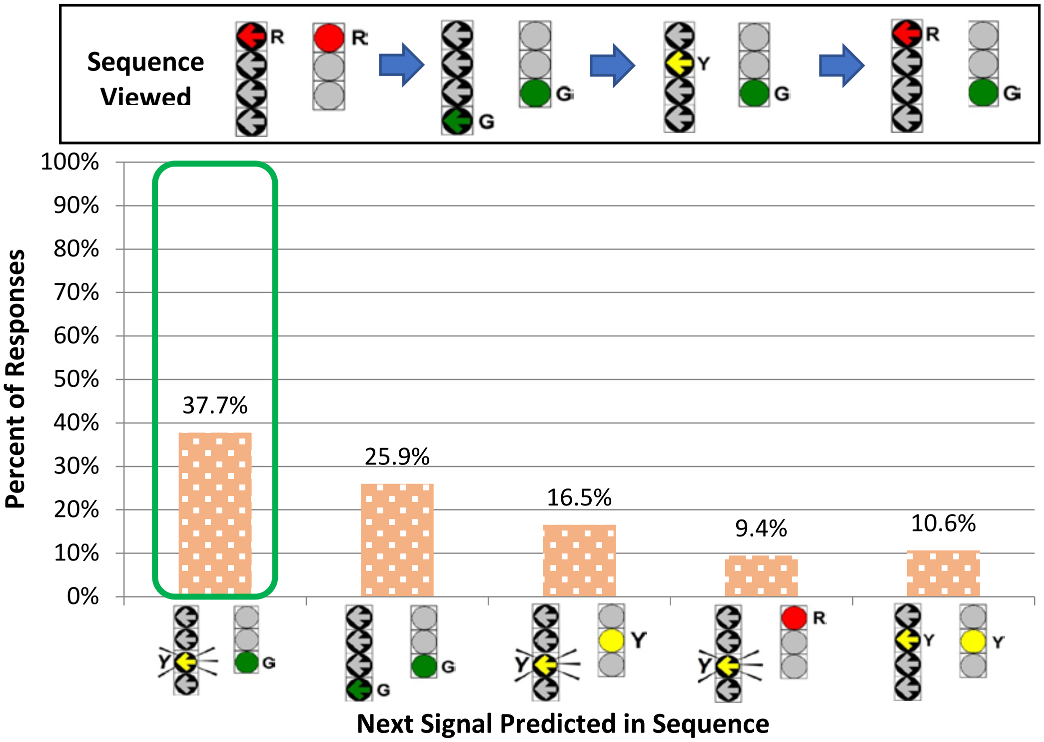


Figure 31 FYA PPLT Scenario Predicting FYA Permissive Indication

## 4.3 Evaluating the Field Study Vehicle Trajectories

The vehicle trajectory field study was initiated to develop a parallel between collecting the trajectories of left-turning vehicles at PPLT phased signalized intersection with the Intersector™ device and the coordination of signal timings throughout the data collection process. The vehicle trajectory field study was conducted at three intersections across western Massachusetts. The information provided in Table 8 represents the descriptions of each site including: number of approach lanes, left-turn volume (in vehicles per hour), posted speed limit, width of intersection, and device distance from the stop bar. The graphic presented in Figure 32 represents aerial images for each of the three intersections.

Table 8 Field Study - Site Locations and Descriptions

| Left-Turn Approach Analyzed | Intersection Name | Number of Approach Lanes (LT) | Left-Turn Volume (veh/hr) | Posted Speed Limit | Width of Intersection | Device Distance from Stop Bar |
|---|---|---|---|---|---|---|
| Site 1: CG<br>SB S East St. | S East St. at Route 9 (Belchertown Rd.) | 2 (1) | 366 | 25 mph | 70 ft | 145 ft |
| Site 2: FYA (with AR)<br>EB Lower Westfield Rd. | Lower Westfield Rd. at Whiting Farms Rd. | 4 (1) | 234 | 30 mph | 85 ft | 180 ft |
| Site 3: FYA (without AR)<br>WB Springfield Rd. | Route 20 (Springfield Rd.) at Little River Rd. | 3 (1) | 456 | 40 mph | 75 ft | 310 ft |

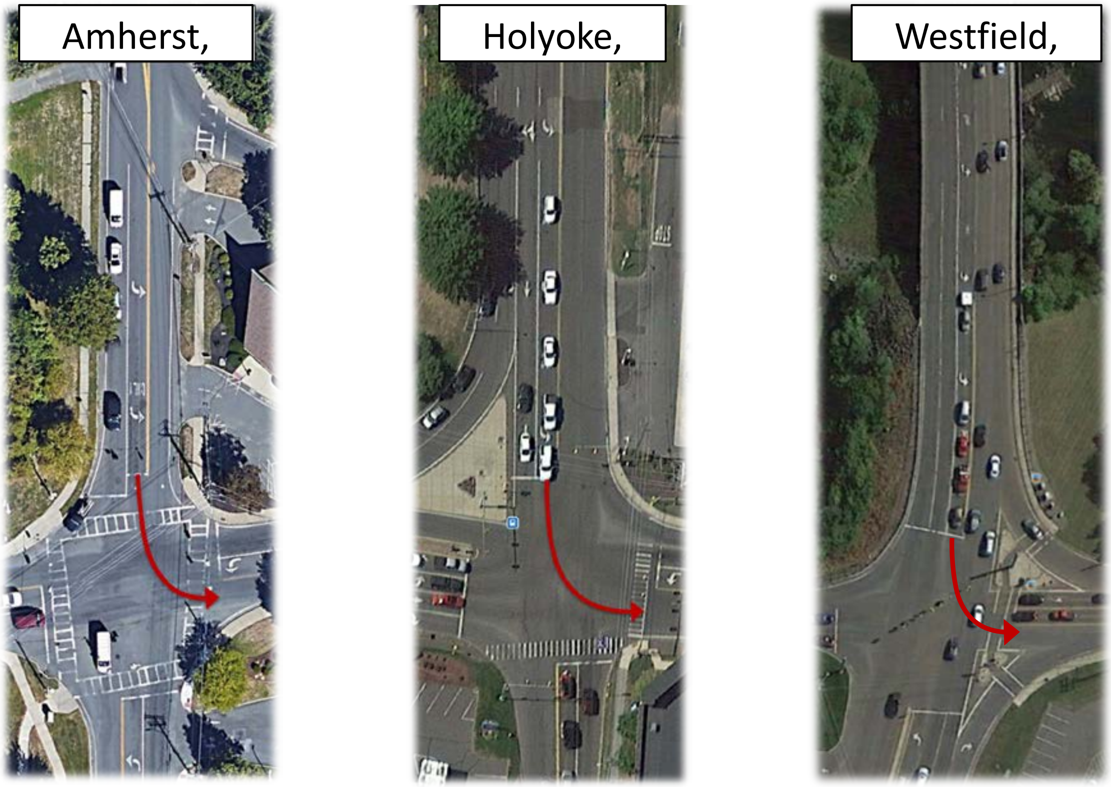
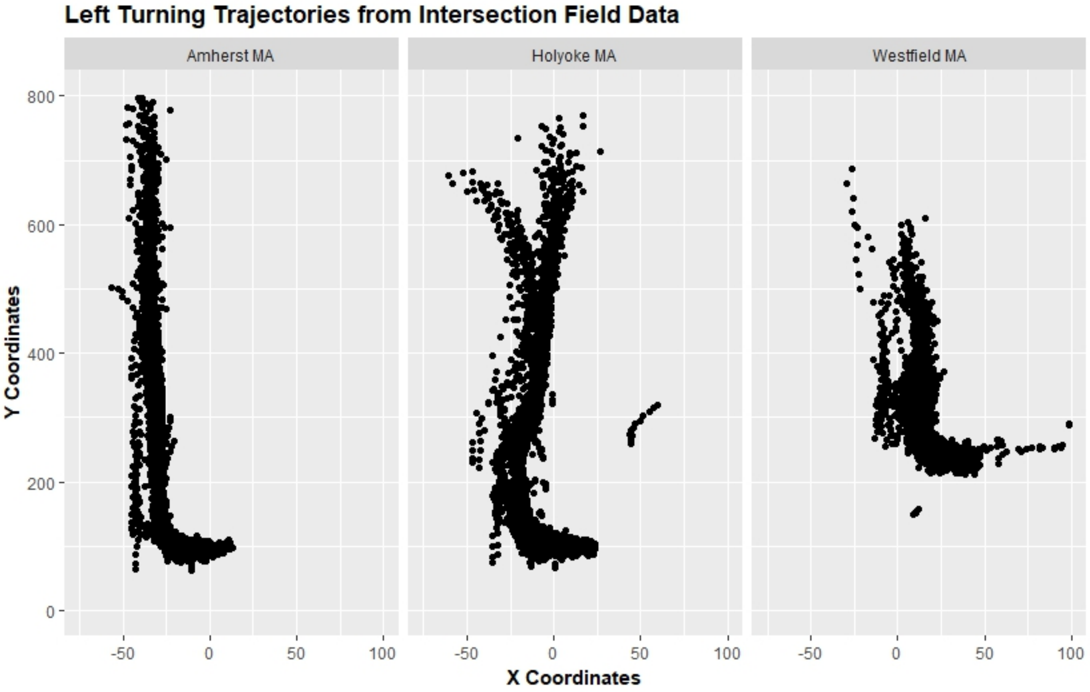


Figure 32 Field Study Locations and Left-Turn Movements

The left turning trajectories for each intersection were filtered using the process mentioned previously. Once the data was filtered, it was graphically represented as x-coordinate vs y-coordinate, in proximity to the Intersector™. The trajectories for each location were presented in Figure 33 below. It is important to note that the Westfield location had a vertical curve located approximately 600 feet away from the device, which prevented the device from capturing beyond this point. However, the data captured at this location still yielded a significant distance of vehicle trajectory data; to be utilized in our analysis.



safe

Figure 33 Filtered Left-Turn Vehicle Trajectories from each Location

The following sections present unique findings from each of the three locations. The examples provided below display the vehicle trajectories and signal sequencing for drivers traversing the intersection after the onset of the yellow change interval.

### 4.3.1 Amherst, MA – Five-Section Cluster Signal with CG Indication

The first intersection evaluated was the intersection in Amherst, MA which included a CG permissive left-turn indication with an all-red clearance interval. There were several unique scenarios that were observed during the data collection period, specifically with vehicles traversing the intersection after the onset of the change and clearance intervals. The information presented in Figure 34 represent 3 an occurrence where three vehicles continued through the intersection following the onset of the change interval. Their trajectories are displayed as Relative

Time Stamp vs Y Coordinate. The specific signal sequences are displayed in color at the bottom of each graph. It is important to note the distance from the stop bar, the horizontal blue bar, which was located approximately 160 feet from the Intersector™ device. The third vehicle, as labeled in the images of Figure 34, was 160 feet away from the stop bar during the onset of the all-red clearance interval. This graphic represents an example of the vehicle trajectories captured; however, the normalized rate of RLRs and "sneakers" will be discussed in the next chapter.

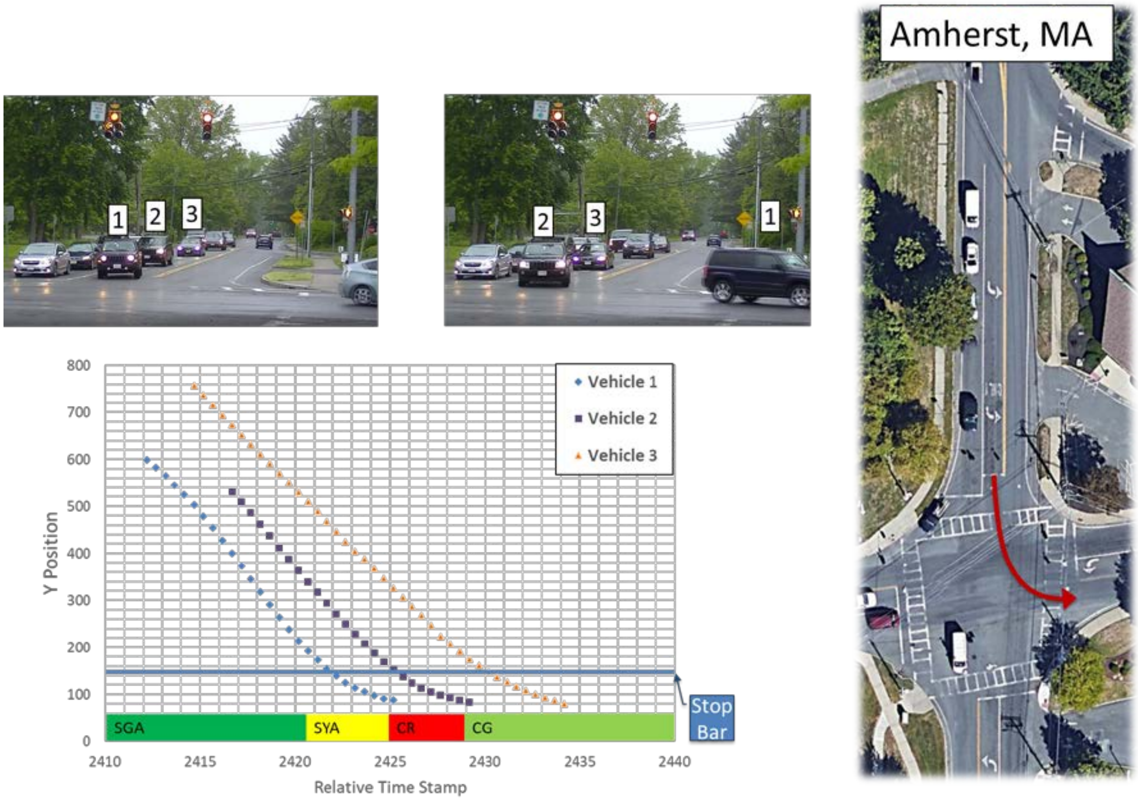


Figure 34 Examples of Vehicle Trajectories in Amherst, MA

### 4.3.2 Holyoke, MA – Four-Section Vertical Signal with FYA Indication

The second intersection observed was in Holyoke, MA which included a FYA permissive left-turn indication with an all-red clearance interval. There was a significantly lower amount of

RLR and "sneakers" at this intersection. The examples provided in Figure 35 represent two cases where vehicles traversed the intersection after the onset of the change interval. The trajectories in these examples are displayed as Relative Time Stamp vs Y Coordinate. The signal sequences were again represented on the bottom of each graph in Figure 35. It is important to note that the vehicles in these examples were not nearly as far from the intersection stop bar (the horizontal blue bar) at the onset of both the yellow change interval and all-red clearance interval. This graphic represents an example of the vehicle trajectories captured; however, the normalized rate of RLRs and "sneakers" will be discussed in the next chapter.

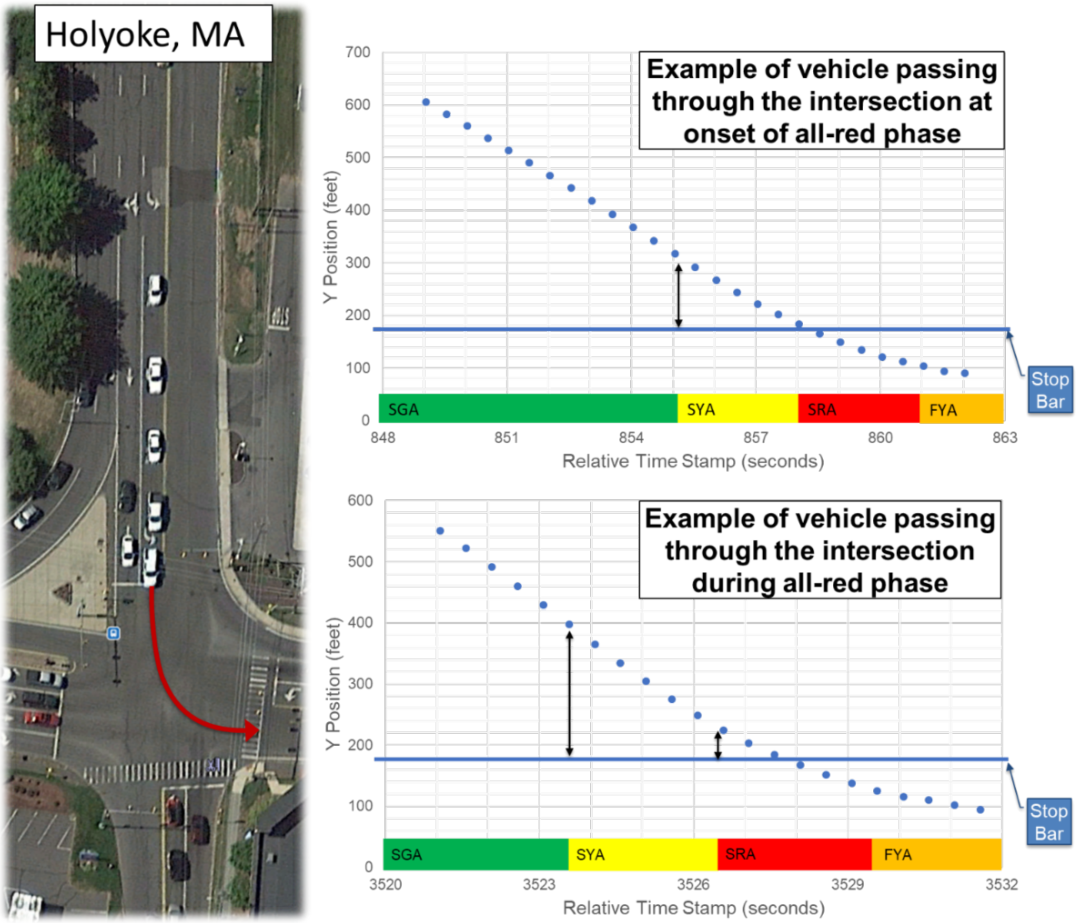
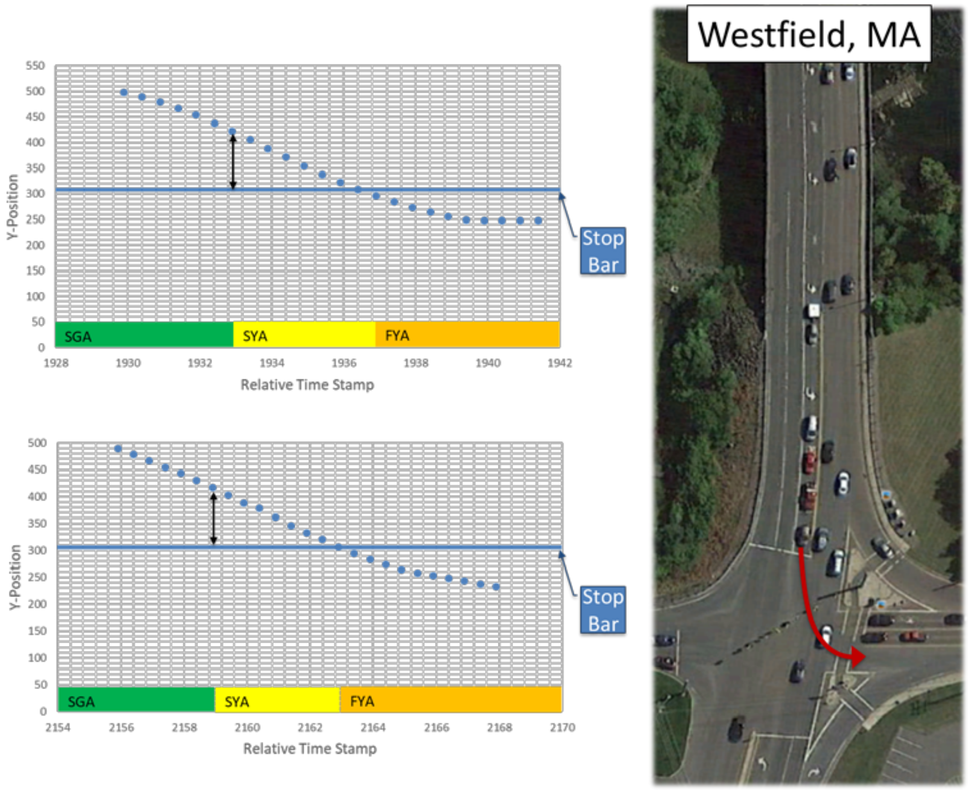


Figure 35 Examples of Vehicle Trajectories in Holyoke, MA

### 4.3.3 Westfield, MA – Four-Section Vertical Signal with FYA Indication

The third intersection observed was in Westfield, MA which included a FYA permissive left-turn indication without an all-red clearance interval. At this intersection, the transition between the protected and permissive left-turn phasing consisted of only the yellow change interval. The examples provided below in Figure 36 represent cases where the vehicles continue to traverse the intersection after the onset of the yellow change interval. There were a number of other examples that could not be represented through the vehicle trajectory data at this intersection, however video evidence was utilized to capture the trajectories for RLRs and "sneakers". The signal sequences were layered on top of each graph below, and the distanced from the stop bar at the onset of the yellow phase were marked. The normalized rate of RLRs and "sneakers" will be further discussed in the next chapter.



‘

Figure 36 Examples of Vehicle Trajectories in Westfield, MA

# CHAPTER 5

# DISCUSSION

This research included the application of a computer-based static evaluation and an innovative data collection method for obtaining left-turning vehicle trajectories. An initial static evaluation was conducted with 212 participants from across 20 states in the U.S. In addition, a follow-up static evaluation was conducted to a localized region of participants, focusing primarily on the transition between leading protected and permissive phasing for CG and FYA indications. The follow-up study was administered to 107 participants, mainly residing in Massachusetts. The results from the previous chapter represent the evaluated driver comprehension for various PPLT phase sequences for both CG and FYA signal indications. Additionally, the field study component of this research yielded findings comparable to the comprehension of PPLT phasing. The following sections present the results of driver prediction aptitude for all-red clearance intervals in both CG and FYA PPLT signal phasing through the application of static evaluation and vehicle trajectory analyses.

## 5.1 Comparing the Driver Comprehension of CG and FYA Indications

Further analysis was required to understand the driver comprehension of the FYA and CG permissive indications for left-turns. Table 9 shows a breakdown of correct responses for each phase scheme in the survey. In total, 67.8 percent of drivers correctly predicted the next signal in the sequence for CG indications. This was greater than the percentage of correct predictions for the FYA indications, which resulted in only 57 percent. These differences were not statistically significant and therefore a comprehensive variance analysis between FYA and CG permissive indications was not included in the report. And while there was no statistical significance between the comprehension of CG permissive sequencing and FYA permissive sequencing, this was in and of itself significant. Drivers were able to correctly predict the next signal in the sequence over 50 percent of the time for both cases, which represents a significant finding alone.

Table 9 Breakdown of correct responses for phase schemes

| **Permissive Indication** | **Phase Scheme** | **Percentage Correct Responses** | **Average Percentage** |
|---|---|---|---|
| Circular Green (CG) | Dual Leading | 55.0% | 67.8% |
| | Lead-Lag (Lagging Side) | 90.8% | |
| | Lead-Lag (Leading Side) | 70.5% | |
| | Dual Lagging | 55.0% | |
| Flashing Yellow Arrow (FYA) | Dual Leading | 57.9% | 57.0% |
| | Lead-Lag (Leading Side) | 44.5% | |
| | Lead-Lag (Lagging Side) | 85.2% | |
| | Dual Lagging | 40.4% | |

### 5.2 Predicting the All-Red Clearance Interval with Static Evaluation Data

In the initial computer-based static evaluation, there were two scenarios that specifically inquired the potential prediction of the all-red clearance interval in PPLT CG and FYA phasing. The results provided in Figure 14 and Figure 22 represent these two scenarios. In Scenario 4 (Figure 14), there were only 51 percent of correct predictions for the next phase in the sequence. The correct prediction was the all-red clearance phase that exists before both CG permissive indications would be displayed in the left-turn cluster signal and the adjacent three-section signal. This being said, there were 41 percent of drivers that predicted the CG permissive phasing instead of the all-red. Thus, although the majority of drivers predicted the all-red, there was still a significant number of responses that skipped this phase and jumped to the permissive phasing. It is important to note that this sequence of skipping the all-red in this scenario is not prevalent in the field and atypical for most practitioners. However, it should be noted that the results show that drivers anticipate the appearance of an all-red phase during the transition of PPLT phasing in five-section signals. In Scenario 6 (Figure 22), there were only 42 percent of correct predictions for the next phase in the sequence. The correct prediction was again the all-red clearance phase that exists before the FYA would be displayed concurrently with the adjacent CG through movement indication. In this particular case, there was a secondary answer that could be accepted for the next signal phase. In fact, the majority of drivers, 52 percent, predicted that the next phase would be the FYA signal with the adjacent CG through movement indication. These drivers did not anticipate the all-red clearance phase, but instead expected the permissive phase to begin immediately following the current display. This result shows that when drivers are presented a PPLT transition at a four-section signal (including a FYA), they will not expect an all-red clearance to be displayed.

Based in part on these initial survey results, the scenarios predicting the all-red clearance interval in PPLT CG and FYA phasing were queried in the follow-up static evaluation. In the follow-up study, four scenarios were presented to analyze these scenarios (refer to Figure 8). From the results provided in 4.2 Follow-Up Static Evaluation, it was apparent that drivers had a strong understanding in predicting the all-red clearance interval for the CG signal sequence and the FYA signal sequence (Figure

28 and Figure 30). Additionally, in predicting the next phase as the permissive left-turn movement, the responses in the follow-up study yielded stronger comprehension with the CG signal comparatively to the FYA signal. Although, as mentioned previously, the results in Figure 29 appear deceiving based on the layout of the survey, the two highest selected answers represent approximately 80% of the total predictions. Based on these results, the assumption was made that the CG indication was better understood, as compared to the FYA indication, in terms of predicting the all-red clearance interval and the following permissive CG indication.

## 5.3 Connecting Static Evaluation Data with Field Study

Upon analyzing the data collected during the vehicle trajectory field study, an assessment between the static evaluation results and field study was completed. It was apparent that a stronger comprehension rate in the static evaluation was skewed towards the CG indications versus the FYA indications. With this, the field study was evaluated in a two-fold method. A comparison was made between the CG permissive indication located in Amherst, MA and the FYA permissive indication (with an all-red clearance) located in Holyoke, MA. Additionally, a comparison was made between the FYA permissive indication (with an all-red clearance) located in Holyoke, MA and the FYA permissive indication (without and all-red clearance) located in Westfield, MA. The following measures were taken into consideration at each intersection: vehicles per cycle, vehicles per second of yellow (change) time, vehicles per second of all-red (clearance) time, and elapsed time after onset of yellow.

### 5.3.1 Comparing Circular Green and Flashing Yellow Arrow with All-Red

In order to compare the intersections in Amherst and Holyoke, the rates of red-light-running needed to be normalized based on the varying vehicle demand at each intersection. The demand per intersection was evaluated based on vehicles per cycle. The intersections in Amherst and Holyoke had a vehicle demand of 11.7 vehicles per cycle and 11.0 vehicles per cycle, respectively. The vehicles per second of yellow time for the Amherst and Holyoke intersections was 0.308 and 0.127, respectively. The vehicles per second of all-red (clearance) time for the Amherst and Holyoke intersections was 0.367 and 0.063, respectively. The elapsed time after onset of yellow for the Amherst and Holyoke intersections was 1.92 seconds and 0.99 seconds, respectively. A z-score statistical test was utilized to evaluate significance for each the ratios above. The vehicles per second of yellow and all-red times was statistically significant between these two intersections. The elapsed time after onset yellow was evaluated using paired t-tests, and these intersections yielded statistical significance.

### 5.3.2 Comparing Flashing Yellow Arrow With and Without All-Red

In comparing the intersections in Holyoke and Westfield, the rates of “sneakers” needed to be normalized based on the varying vehicle demand at each intersection. The demand per intersection was evaluated based on vehicles per cycle. The intersections in Holyoke and Westfield had a demand of 11.0 vehicles per cycle and 14.4 vehicles per cycle, respectively. The vehicles per second of yellow (change) time for the Holyoke and Westfield intersections was 0.127 and 0.674, respectively. The vehicles per second of all-red (clearance) time for the Holyoke and Westfield was not analyzed due to the Westfield location not having an all-clearance interval. Again, a z-score statistical test was utilized to evaluate significance for the ratios above. The vehicles per second of yellow time was statistically significant between these two intersections.

The elapsed time after onset yellow was evaluated using paired t-tests, and these intersections yielded statistical significance.

# CHAPTER 6

# CONCLUSIONS

This research investigated the driver comprehension and behavior for all-red clearance intervals using a computer-based static evaluation, a follow-up static evaluation, and a vehicle trajectory field study, which focused on the operational characteristics associated with drivers traversing an intersection with PPLT phasing. The results and discussion presented in previous chapters resulted in a myriad of conclusions which are outlined in the following section.

## 6.1 Computer-based Static Evaluation & Follow-Up Study

The initial computer-based static evaluation included 207 participants from over 20 different states across the country. Following a brief list of demographic questions, respondents were required to answer fourteen questions based on the short videos presented on each question page. Drivers were asked to provide their prediction for the next signal in the sequence provided in the video. The results are as follows:

- Overall, respondents had a higher rate of comprehension in predicting the next signal in sequences involving the five-section signal, with a CG permissive indication.
- Anecdotal evidence suggests that there still exists significant confusion in comprehending the four-section signal with the FYA permissive indication. Potential reasoning for this exists with the regional misconception, and latent integration of the FYA in various state agencies across the country.

- Responses for questions relating to the prediction of all-red clearance intervals led to a consensus that driver are more likely to predict the all-red interval in five-section signals with CG permissive indications, compared to the four-section signal with FYA permissive indications. Responses to these questions, specifically, led to the development of the follow-up static evaluation.

The follow-up computer-based static evaluation included 107 participants. Following the emulated demographic questions queried in the initial static evaluation, participants were provided four questions specifically predicting the all-red clearance interval and successive permissive indication in the CG and FYA signal displays. The results are as follows:

- The prediction of the all-red clearance interval was well comprehended in the five-section signals with CG indications; however, the FYA signal did not provided strong comprehensive knowledge of predicting the all-red interval.
- The prediction of the permissive indication following the all-red clearance interval were better comprehended in the CG indication sequences compared to the FYA sequences.
- The summary of responses suggests that drivers will be more likely to predict the sequencing of five-section signals with CG permissive indications, as compared to the sequencing of four-section signals with FYA permissive indications. The assumption was made that drivers were generally more understanding of the CG phasing than the FYA phasing.

## 6.2 Vehicle Trajectory Field Study

The vehicle trajectory field study was conducted using the Intersector™ device paired with video data, in order to parallel the vehicle trajectories with intersection signal timings. The field study was completed with three intersections in Western Massachusetts. The following intersections were investigated: a CG permissive left-turn indication with all-red clearance in Amherst MA, a FYA permissive left-turn indication with all-red clearance in Holyoke MA, and a FYA permissive left-turn indication without an all-red clearance in Westfield MA. The results are as follows:

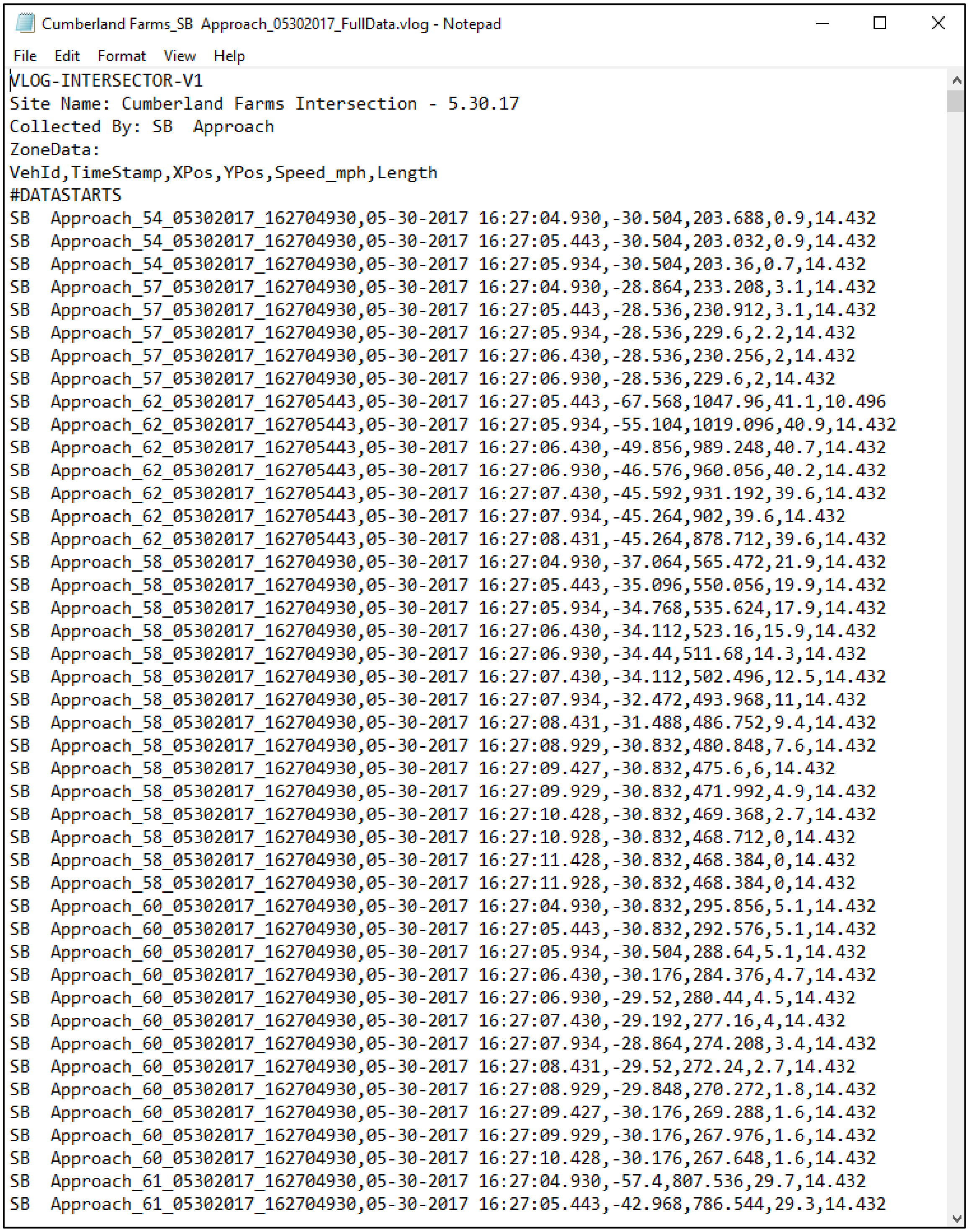
- Results from the number of RLR's collected in the field data confirms the initial hypothesis with driver comprehension of signal sequencing, due to a much larger number of RLR's at the intersection in Amherst, MA with the CG (cluster signal) indication.
- When looking into the number of drivers traversing the intersection after the onset of a SYA indication, there were a significantly larger number of "sneakers" at the intersection in Westfield, MA (FYA without AR) than at the intersection in Holyoke, MA (FYA with AR).
- It appears that there is an aspect of familiarity that exists behind the reason for sneakers and RLR's. With the results from the static evaluation, it may also be supposed that drivers understand the sequence of transition between protected and permissive left-turn indications, particularly at intersections such as Amherst, MA.

## 6.3 Future Work

Based on the findings in this comprehensive research, additional research questions still exist for further investigation. As mentioned previously, the work conducted herein was developed as a foundation for future work conducted in support with the NCHRP 03-125 project. More so, the next steps include: a full scale driving simulator study and, additional field evaluations to conduct conflict analyses with advanced vehicle detections systems.

- The full scale driving simulator study will evaluate the behavioral characteristics of drivers approaching intersections with varying all-red clearance intervals at PPLT intersections. This study will focus primarily on understanding the operational impacts from the CG and FYA signals, with and without the all-red clearance interval, while immersing the participants in a controlled simulator environment.
- Future field studies will focus on the improvement of utilizing vehicle detection technologies to advance conflict assessments, particularly with the transition between protect and permissive left-turns at CG and FYA signalized intersections. The advancement of vehicle detection systems appears to have significant potential in improving the safety assessment conducted in intersection conflict analyses.

# APPENDIX
# RAW FIELD DATA OUTPUT



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ZoneData:
VehId,TimeStamp,XPos,YPos,Speed_mph,Length
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SB  Approach_57_05302017_162704930,05-30-2017 16:27:05.934,-28.536,229.6,2.2,14.432
SB  Approach_57_05302017_162704930,05-30-2017 16:27:06.430,-28.536,230.256,2,14.432
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SB  Approach_62_05302017_162705443,05-30-2017 16:27:06.930,-46.576,960.056,40.2,14.432
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SB  Approach_62_05302017_162705443,05-30-2017 16:27:07.934,-45.264,902,39.6,14.432
SB  Approach_62_05302017_162705443,05-30-2017 16:27:08.431,-45.264,878.712,39.6,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:04.930,-37.064,565.472,21.9,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:05.443,-35.096,550.056,19.9,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:05.934,-34.768,535.624,17.9,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:06.430,-34.112,523.16,15.9,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:06.930,-34.44,511.68,14.3,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:07.430,-34.112,502.496,12.5,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:07.934,-32.472,493.968,11,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:08.431,-31.488,486.752,9.4,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:08.929,-30.832,480.848,7.6,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:09.427,-30.832,475.6,6,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:09.929,-30.832,471.992,4.9,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:10.428,-30.832,469.368,2.7,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:10.928,-30.832,468.712,0,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:11.428,-30.832,468.384,0,14.432
SB  Approach_58_05302017_162704930,05-30-2017 16:27:11.928,-30.832,468.384,0,14.432
SB  Approach_60_05302017_162704930,05-30-2017 16:27:04.930,-30.832,295.856,5.1,14.432
SB  Approach_60_05302017_162704930,05-30-2017 16:27:05.443,-30.832,292.576,5.1,14.432
SB  Approach_60_05302017_162704930,05-30-2017 16:27:05.934,-30.504,288.64,5.1,14.432
SB  Approach_60_05302017_162704930,05-30-2017 16:27:06.430,-30.176,284.376,4.7,14.432
SB  Approach_60_05302017_162704930,05-30-2017 16:27:06.930,-29.52,280.44,4.5,14.432
SB  Approach_60_05302017_162704930,05-30-2017 16:27:07.430,-29.192,277.16,4,14.432
SB  Approach_60_05302017_162704930,05-30-2017 16:27:07.934,-28.864,274.208,3.4,14.432
SB  Approach_60_05302017_162704930,05-30-2017 16:27:08.431,-29.52,272.24,2.7,14.432
SB  Approach_60_05302017_162704930,05-30-2017 16:27:08.929,-29.848,270.272,1.8,14.432
SB  Approach_60_05302017_162704930,05-30-2017 16:27:09.427,-30.176,269.288,1.6,14.432
SB  Approach_60_05302017_162704930,05-30-2017 16:27:09.929,-30.176,267.976,1.6,14.432
SB  Approach_60_05302017_162704930,05-30-2017 16:27:10.428,-30.176,267.648,1.6,14.432
SB  Approach_61_05302017_162704930,05-30-2017 16:27:04.930,-57.4,807.536,29.7,14.432
SB  Approach_61_05302017_162704930,05-30-2017 16:27:05.443,-42.968,786.544,29.3,14.432
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Figure 37 Excerpt of raw data output from Intersector™ in Amherst, MA

# REFERENCES

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

(2) Manual on Uniform Traffic Control Devices, 2003 Edition. Federal Highway Administration, United States Department of Transportation, Washington, D.C.

(3) Manual on Uniform Traffic Control Devices, 2009 Edition. Federal Highway Administration, United States Department of Transportation, Washington, D.C.

(4) Schattler, K. L, & Lund, J. A. (2013). State-of-the-art literature review on permissive/protected left-turn control. *Illinois Center for Transportation, Urbana, IL.* FHWA-ICT-13-004

(5) Knodler, M. A., Noyce, D. A., Kacir, K. C., & Brehmer, C. L. (2007). An evaluation of driver comprehension of solid yellow indications resulting from implementation of flashing yellow arrow. *Presented at the 86th annual meeting of the Transportation Research Board, Washington, D.C.*

(6) Knodler, M. A., & Fisher, D. (2009). An evaluation of driver comprehension related to solid yellow change indications and the potential impact of the flashing yellow arrow permissive indication. *Amherst, MA. UMAR18-7.*

(7) Knodler, M. A., Noyce, D. A., Kacir, K. C., & Brehmer, C. L. (2005). Evaluation of traffic signal displays for protected-permissive left-turn control using driving simulator technology. *Journal of Transportation Engineering,* Vol. 131, No. 4, pp. 270-278.

(8) Knodler, M. A., Noyce, D. A., & Fisher, D. (2007). Evaluating effect of two allowable permissive left-turn indications. *Transportation Research Record: Journal of the Transportation Research Board.* No. 2018, pp. 53-62.

(9) Noyce, D. A., Bergh, C. R., & Chapman, J. R. (2007). Evaluation of the flashing yellow arrow permissive-only left-turn indication field implementation. *NCHRP Web Document,* No. 123.

(10) Hurwitz, D., Monsere, C., Marnell, P., & Paulsen, K., (2014). Three-or four- section displays for permissive left-turns? Some evidence from a simulator-based analysis of driver performance. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2463, pp. 1-9.

(11) Rietgraf, A., & Schattler, K. (2013). Behavior of left-turning drivers during permissive interval of protected-permissive operation: effect of signal display. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2384, pp. 35-44.

(12) Schattler, K. L., Gulla, C. J., Wallenfand, T. J., Burdett, B. A., & Lund, J. A. (2015). Safety effects of traffic signing for left turn flashing yellow arrow signals. *Accident Analysis & Prevention,* No. 75, pp. 252-263.

(13) Schattler, K. L., Anderson, E. P., & Hanson, T. (2017). Safety performance of flashing yellow arrow for protected-permissive left-turn signal control in central Illinois. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2636, pp. 32-42.

(14) National Highway Traffic Safety Administration (NHTSA). Fatality Analysis Reporting System (FARS). *U.S. Department of Transportation.*

(15) Engineering Countermeasures to Reduce Red-Light Running, FHWA-SA-10-005. (2009). *Federal Highway Administration – Office of Safety, United States Department of Transportation,* Washington, D.C.

(16) McGee, H., Moriarty, K., Eccles, K., Liu, M., Gates, T., & Retting, R. (2012). NCHRP 731: Guidelines for timing yellow and all-red intervals at signalized intersections. *Transportation Research Board.*

(17) McGee, H., Moriarty, K., & Gates, T. (2012). Guidelines for timing yellow and red intervals at signalized intersections. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2298, pp. 1-8.

(18) Gates, T. J., & Noyce, D. A. (2016). A conceptual framework for dynamic extension of the red clearance interval as a countermeasure for red-light-running. *Accident Analysis & Prevention*, *96*, pp. 341-350.

(19) Gazis, D. C., Herman, R., & Maradudin, A. (1960). The problem with the amber signal light in traffic flow. *Operations Research,* 8(1), pp. 112-132.

(20) Zegeer, C. V., Deen, R. C., (1978). Green-extension systems at high-speed intersections. *ITE Journal.* 48. Pp. 19-24.

(21) Gates, T. J., Noyce, D. A., & Larauente, L. (2007). Analysis of dilemma zone behavior at signalized intersections. *Presented at the 86th annual meeting of the Transportation Research Board,* Washington, D.C.

(22) Elmitiny, N., Yan, X., Radwan, E., Russo, C., & Nashar, D. (2010). Classification analysis of driver's stop/go decision and red-light running violation. *Accident Analysis & Prevention,* 42(1), pp. 101-111.

(23) Hurwitz, D. S., Wang, H., Knodler, M. A., Ni, D., & Moore, D. (2012). Fuzzy sets to describe driver behavior in the dilemma zone of high-speed signalized intersections. *Transportation Research Part F: Traffic Psychology and Behavior*, 15(2). pp. 132-143.

(24) Savolainen, P. T., Sharma, A., & Gates, T. J. (2016). Driver decision-making in the dilemma zone-Examining the influences of clearance intervals, enforcement cameras and the provision of advance warning through a panel data random parameters probit model. *Accident Analysis & Prevention.* 96. pp. 351-360

(25) Medina, J. C., Benekohal, R. F., & Ramezani, H. (2012). *Field Evaluation of Smart Sensor Vehicle Detectors at Intersections–Volume 1: Normal Weather Conditions*.

(26) Medina, J. C., Benekohal, R. F., & Ramezani, H. (2013). *Field evaluation of smart sensor vehicle detectors at intersections—Volume 2: Performance under adverse weather conditions*.

(27) Santiago-Chaparro, K. R., Chitturi, M. V., Bill, A. R., & Noyce, D. A. (2012). *A Signalized Intersection for Experimentation and Evaluation of Traffic Signal and Detection System Technology*. University of Wisconsin-Madison, Traffic Operations and Safety (TOPS) Laboratory.

(28) Santiago-Chaparro, K. R., Chitturi, M., Bill, A., Noyce, D. A. (2014). Expanding the capabilities of existing vehicle detection infrastructure to monitor red light running. *Presented at the 93rd annual meeting of the Transportation Research Board,* Washington, D.C.

(29) MacClellan, P. (2013). Identification of applicability for the implementation of the flashing yellow left-turn arrow in Massachusetts. *Thesis. University of Massachusetts Amherst,* Amherst MA.