A Field and Simulator Evaluation of All-Red Clearance Intervals for Use in Left-Turn Applications

SAFETY **R**ESEARCH USING **SIM**ULATION

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Abstract

As the implementation of the novel flashing yellow arrow (FYA) traffic control device advances throughout the country, agencies continually seek ways to improve intersection operations and safety, especially on left turns. For example, permissive left-turn intervals have been communicated to drivers using several traffic signal indications; however, most frequently these phases are represented using the circular green ball and, more recently, the FYA. Previous research in this area found that the FYA indication produced the most effective communication of permissive left-turns. As a result of the research findings, the FYA was included in the 2009 edition of the Manual on Uniform Traffic Control Devices.

In recent years, agencies across the country have embraced the implementation of the FYA for permissive left-turns. However, a lack of national guidance remains on how to define the 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. Research on driver comprehension and real-world operations of the transition between protected and permissive left turns will allow evaluation not only of current conditions, but also of experimental and future conditions.

This report presents findings from a static survey that studied the expectation of drivers after a signal indication is presented. This report also presents the results of a novel exploratory approach that allows the use of vehicle trajectory data to gain an insight into driver behavior during the transition between a protected left-turn movement and a permissive one. Research findings will provide a foundation for narrowing the scope and identifying elements that should be considered during a driving simulator evaluation.

1   Introduction

1.1   Problem Statement

Permissive left-turn intervals have historically been communicated to drivers using nearly every traffic signal indication available, including the circular green (CG), flashing circular red (FCR), flashing red arrow (FRA), flashing circular yellow (FCY), and flashing yellow arrow (FYA) indications. Research sponsored by the National Cooperative Highway Research Program (NCHRP), along with other research efforts, has demonstrated that by most measures, the FYA indication is the most effective for communicating permissive left turns [1, 2]. Therefore, the FYA indication was included in the 2009 edition of the Manual on Uniform Traffic Control Devices (MUTCD) [3]. Since that time, most agencies have embraced use of the FYA in permissive left-turn phasing. The permissive left-turn message communicated by the FYA indication requires drivers to yield to oncoming traffic. However, the traffic signal transition from a protected left-turn indication to the FYA is not well defined and varies across the country. Specifically, there is no clear national guidance on the need for and the extent of clearance and change intervals when transitioning from a protected left-turn phase to a permissive left-turn (FYA) phase. Furthermore, there is a specific need for guidance on the duration of any associated change/clearance intervals given their impact on safety.

1.2   Research Objectives and Hypotheses

The primary objective of this research is to develop recommendations for the use and duration of solid yellow change and solid red arrow clearance intervals after a leading left-turn solid green arrow transitioning to a permissive left-turn FYA. It is hypothesized that there will be significant safety improvements if guidelines are established for the efficient design of clearance intervals for protected-permissive left turns (PPLT) with the application of FYA. To achieve these objectives, researchers will have to "look through the lens of the driver" and evaluate their comprehension of signal indications and analyze their behavior on the field.

1.3   Scope

The evaluation will be primarily based on safety and operational efficiency considerations. Utilizing a computer-based static evaluation, current driver comprehension will be evaluated through a selection of PPLT phasing sequencing questions. In addition to this, a field study in Amherst, MA, and Appleton, WI, further explore the implications of the transition between a protected left turn and an FYA phasing. The field study is possible because of the implementation of an innovative data collection method. Vehicle trajectories obtained from a radar-based data collection system as vehicles approach intersections with PPLT phasing can be logged and analyzed by relying not only on the vehicle time-space diagram and but also on the signal status information.

1.4   Report Structure

Chapter 2 summarizes some of the key literature associated with FYA, red-light running, traffic detection systems, and the potential of vehicle trajectories obtained from radar-based vehicle detection systems. Chapter 3 outlines the methodology for the survey as well as the

characteristics of the trajectory data collection system and accuracy. Chapter 4 summarizes the results of the survey and provides a narrative of observations made by the research team when analyzing the trajectory data for each of the sites. At the end of Chapter 5, recommendations are made for the future use of the trajectory data. Finally, Chapter 6 outlines the conclusions.

2   Background

2.1   Implementation of FYA for Permissive Left Turns

As mentioned previously, the FYA permissive indication was evaluated in NCHRP Report 493 [1] and was thereafter included in the 2009 edition of the MUTCD [3]. Since this adoption in the national standards, state agencies across the country have introduced the FYA as a permissive indication for left turns. As of 2013, 31 states had implemented FYAs [4]; however, it is important to note that many other state agencies have adopted the FYA since. Additionally, the work completed herein will be included in part in the NCHRP 03-125 project, which is currently in progress.

While many states have implemented these novel permissive signal indications in recent years, there is a need to evaluate 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 in Massachusetts and Wisconsin [5, 6]. In addition, 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 a 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].

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 the 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., the 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   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. Red-clearance intervals are of crucial concern in intersection safety, as RLR remains one of the most common causes of intersection

crashes. The act of 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, RLR-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 RLR-related fatalities in the United States. The FHWA utilizes this database specifically to 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 [11]. 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 [12]. Although the annual number of fatalities due to RLR has reduced significantly in recent years, the need for reducing RLR still exists.

Other apparent safety implications with RLR 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 NCHRP Report 731 [13], researchers concluded that the utilization of the Institute of Transportation Engineers (ITE) guidelines in designing yellow and red change intervals can lead to a significant reduction in RLR-related conflicts. More specifically, the conclusion was made that the increase of red clearance intervals did not correlate to an increase in RLR [14]. 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 RLR-related crashes. Although significant research has not been conducted on crash effects with the implementation of red clearance intervals, Gates et al. investigated the promotion of a calibrated red clearance extension system [16]. This previous research promotes the improvement of signal operations, vehicle delay, and safety impacts for RLR scenarios, specifically anticipating the decrease in RLR-related crashes with this particular system. These studies both allude to the need for improving guidance for designing yellow and all-red clearance intervals, specifically in lowering RLR-related conflicts.

2.3 Traffic Detection System Technologies

As mentioned previously, many studies involving the application of FYAs revolve around the implementation of various intelligent transportation systems. 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 RLR [16]. 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. In addition to this technology, various novel traffic detection systems have advanced in recent years, 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, 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 [15, 17]. 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 [15]. In the second study, Medina et al. investigated the effects of adverse weather conditions on the performance of both devices [18]. Although each of the devices led to a greater than anticipated number of "false calls," the Intersector™ by MS Sedco™ and the Wavetronix™ were still deemed acceptable for microwave-based data collection [17]. Additional evaluation of the aforementioned devices was 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 [19]. 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, the results paint a picture in which radar-based detection, while not perfect, provides consistent detection performance.

2.3.1   Potential of Data from Radar-Based Vehicle Detection Systems

A radar-based vehicle detection system will be used to obtain vehicle trajectories to explore the speed profile of vehicles when navigating a left turn controlled by a FYA. Radar-based vehicle trajectory data from an intersection have been used in the past to push the boundaries of operational and safety evaluations at signalized intersections. The speed, position, and timestamp of vehicles logged from radar devices at a rate of 2 Hz vehicle trajectories have been used to obtain direct stopped delay measurements at signalized intersections. The direct delay measurements show how vehicle trajectories can be used to replace delay estimates from analytical procedures [20]. Vehicle trajectory data from radar-based devices have also been used to detect RLR at intersections by combining trajectories and signal status [21], thus showing the application of vehicle trajectory for safety evaluations. More recently, the same type of trajectory data has been used to estimate vehicle emissions at intersections, which demonstrates applications beyond the realm of operations and safety [22]. As shown, trajectory data obtained from radar-based vehicle detection provides researchers with a powerful and rich dataset that can be used for numerous applications, including the evaluation of driver behavior in FYA scenarios.

3   Methodology

The following section outlines the research components of this project, including a computer-based static evaluation and a vehicle trajectory field study. The computer-based survey provides insight into the comprehension of signal indications by drivers, while the field survey can be used to explore the nature of actual behavior observed in the field, a step beyond what is possible with driving simulation.

3.1   Computer-Based Static Evaluation

The computer-based static evaluation was initiated to investigate the current driver comprehension of PPLT phasing, specifically with the CG and FYA displays. As previously mentioned, existing strategies to transition between protected and permissive phasing lack proper guidance. Drivers' perspective on these indications was studied using a computer-based static evaluation. The survey platform used to develop the evaluation for this study was SurveyMonkey.

In the first step of the computer-based static evaluation, an experimental design for the survey was generated to investigate driver comprehension. The use of a static evaluation for analyzing driver comprehension of PPLT phasing stems from the work in NCHRP Report 493 [1]. This work by Brehmer et al. evaluated the driver comprehension with respect to the decision making of proceeding through a PPLT signalized intersection. However, the motivation for this study was developed based on the work of MacClellan [23]. In this previous research, a survey was conducted to evaluate the signal sequencing comprehension of drivers, particularly for CG and FYA indications for left turns. Like previous work, this study utilized the SurveyMonkey platform because of its efficient data reduction and user interface.

In an effort to evaluate all intricacies of PPLT phasing, the phase schemes for both CG and FYA display included: dual leading, lead-lag (lagging side), lead-lag (leading side), and dual lagging (Table 3.1). The following section further explains the development of the CG and FYA survey scenarios.

Table 3.1 – Breakdown of PPLT phasing with CG and FYA indications.

Permissive Indication	Phase Scheme	Sequence
Circular Green (CG)	Dual Leading	1
	Lead-Lag (Lagging Side)	2
	Lead-Lag (Leading Side)	3
	Dual Lagging	4
Flashing Yellow Arrow (FYA)	Dual Leading	5
	Lead-Lag (Leading Side)	6
	Lead-Lag (Lagging Side)	7
	Dual Lagging	8

3.1.1 Sequencing Survey Design

The static evaluation consisted of three main sections: introduction/demographic information, randomized signal sequences, and suggestions/comments. The first section introduced the design of the study, including an image of the four-head and cluster signal that each participant would encounter throughout the survey. Additionally, demographic information such as age, gender, driving experience, and current state of residence were collected in this section. These features were utilized in previous research to develop a better general understanding of the respondents [1, 23]. Following this, the survey consisted of randomized signal sequencing questions. Fifteen questions were developed to display various standard PPLT signal sequences, as indicated from the phase schemes in **Error! Reference source not found.**. Each question included an embedded signal sequence video, followed by a question asking respondents to predict the next phase (Figure 3.1). At the completion of the survey, participants were asked to provide optional feedback. The following section explains the development of the phasing schemes for CG and FYA scenarios.

Figure 3.1 – Example of signal sequencing question from static evaluation.

3.1.2   Signal Sequencing for CG and FYA

In accordance with the standard PPLT sequencing of CG and FYA signal phasing, the breakdown of each scheme is displayed in Table 5.2 and Table 5.3 in the appendix. Each of these sequence breakdowns were then developed in sequence questions for the survey. The information provided in Table 5.4, also found in the appendix, represents the complete list of questions that were presented to each of the respondents. The "Current Display" represents the signal that was last viewed in the sequence for each respective question. Each of the scenarios, as mentioned previously, was randomized based on the implementation of a randomization selection in SurveyMonkey. The randomization prevented a bias to arise within survey design, thus distributing each question appearance evenly throughout the survey.

The survey questions investigate existing driver comprehension in the current state of practice with CG and FYA indications for PPLT phasing. The results, analyses, and discussion of these data will be further explored in the remaining chapters.

3.2   Vehicle Trajectory Field Study

An innovative vehicle traffic data collection method was used in the field-evaluation part of the study. The method allows merging two parallel datasets that are key to exploring the behavior of drivers that face an FYA indication, left-turning vehicle trajectories, and the corresponding signal phasing information. The result of the merging process is a vehicle trajectories dataset that allows the research team to understand the acceleration/deceleration characteristic of vehicles as a function of the position within the approach and the signal indication displayed. To obtain the vehicle trajectories, the research team relied on a radar-based vehicle detection system known as Intersector™. A radar-based vehicle detection system was selected to log vehicle trajectories due to its proven reliability of tracking oncoming vehicles along the approach of an intersection [15, 17, 19]. The sections ahead describe the data collection system as well as the characteristics of the dataset.

3.2.1   Intersector™ Installation for Data Collection Purposes

The Intersector is a device commonly installed at signalized intersections as an alternative to loop detectors. However, through the use of a custom software tool, vehicle trajectory data can be extracted from the device without interfering with the primary stop bar vehicle detection function.   Two alternatives exist to collect vehicle trajectory data for research purposes. Alternative 1 involves a situation in which the intersection from which trajectory data is to be collected already uses Intersector devices. In this case, a laptop computer can be installed inside the signal cabinet of the intersection and connected to the same network as the Intersector. The software then logs vehicle trajectories by constantly monitoring the status of one or more Intersectors. Figure 3.2 shows an example of the instrumentation of a signal cabinet of an intersection that already uses Intersectors to supplement/replace inductive loop detectors for stop bar vehicle detection. Left-turn-trajectory data collection in Wisconsin relied on the instrumentation shown in Figure 3.2.
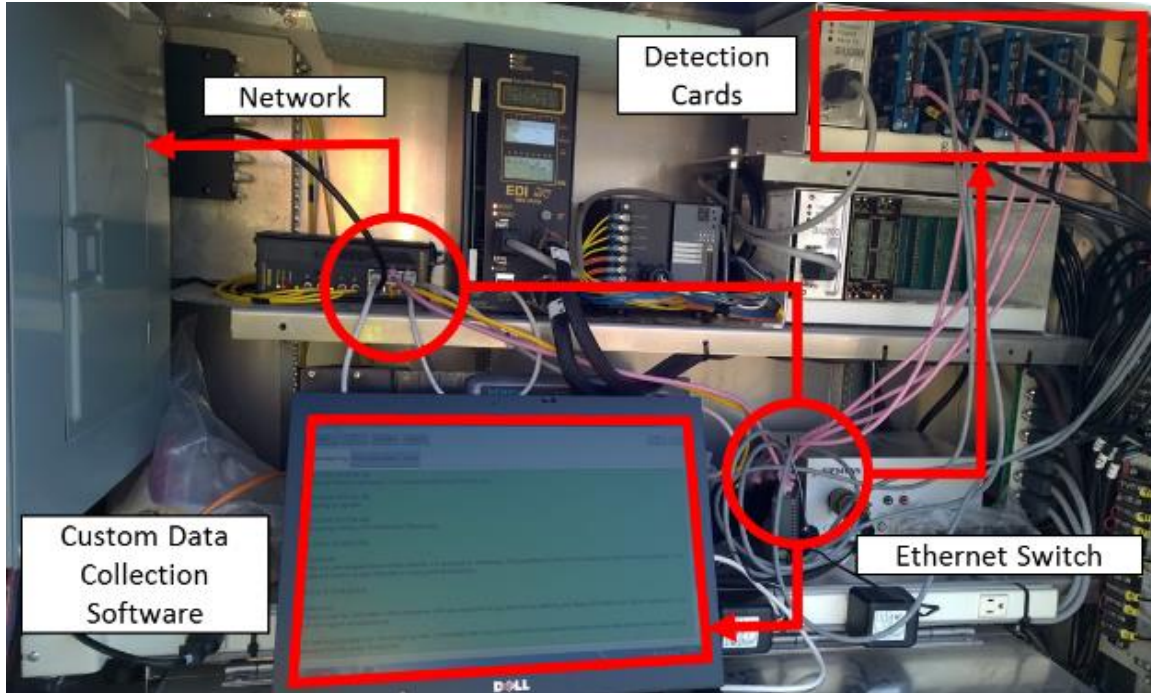
Figure 3.2 – Reference points used to compute spatial speeds.

Data collection alternative 2 involves deployment of a mobile version of the system to collect vehicle trajectories on a site without an Intersector. The mobile version of the system is composed of the radar head typically found at an intersection, a 12-volt battery, a crossover cable, a laptop computer, a power over Ethernet (POE) injector, and a carrying case. These components are then assembled into a mobile system like the one shown in Figure 3.8. Massachusetts trajectory data collection relied on a mobile instrumentation approach like the one shown in Figure 3.3.

Regardless of the data collection deployment used, the data collection software shown in Figure 3.4 was used. When the program is launched, the user is asked to enter the IP address of the Intersector from which trajectory data will be logged. Along with the IP address, a site name value and an approach name are also requested. In addition to logging the full trajectory of vehicles, the software can log debug data that includes detection zone information, which is useful to identify the location of lines during data collection efforts on a site already instrumented with an Intersector. All vehicle trajectory data recorded is stored as plain text files at the beginning of each hour. For example, if data collection starts at 7:35 AM, once the clock marks 8:00 AM, a file containing vehicle trajectory data from 7:35 – 7:59 AM is saved. Once the file is saved, a new file containing data from 8:00 – 8:59 AM is created to store the corresponding trajectory data. The process will continue until the data collection is stopped by the user.

Figure 3.3 – Mobile deployment of trajectory data collection system.
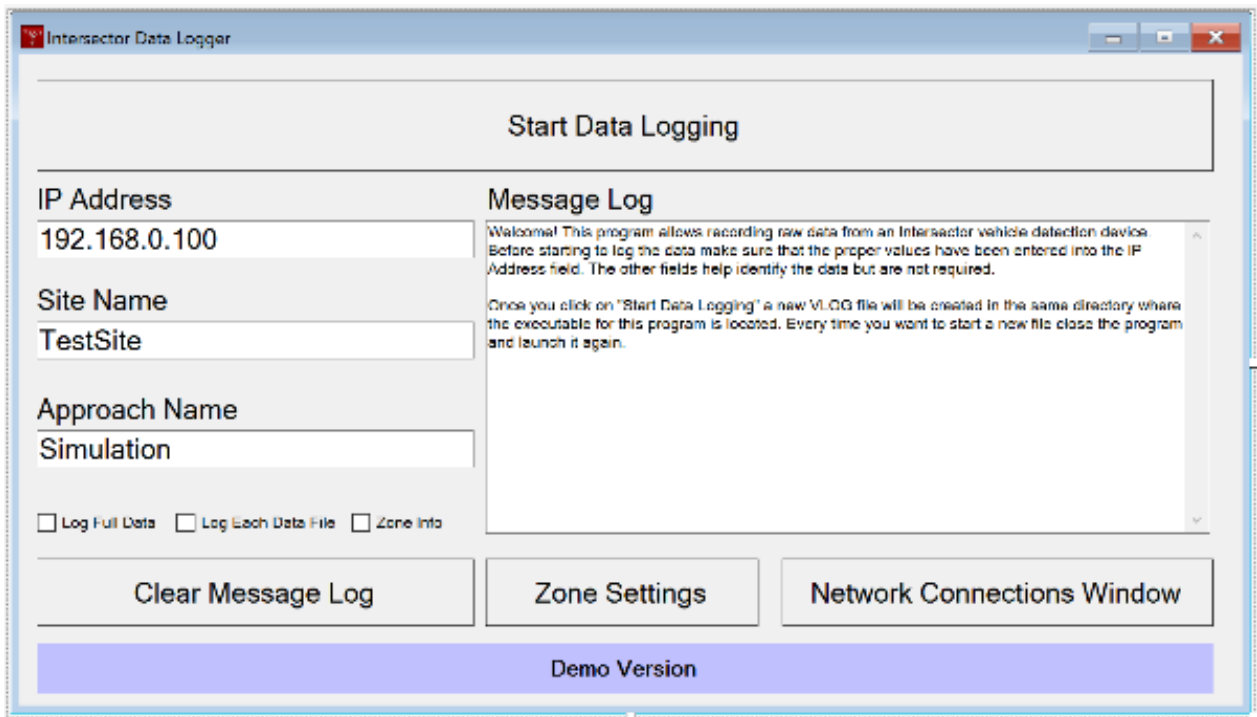
Figure 3.4 – Screenshot of data collection software.

3.2.2   Nature of Trajectory Data Available for Analysis

The trajectory data logged by the data collection software includes trajectory data points collected every 0.5 seconds. Each trajectory data point is associated with a Cartesian coordinate, speed, length, vehicle identifier, and timestamp values for each vehicle detected by the radar. Up to 32 vehicles can be simultaneously tracked by the radar. The structure in which the data is reported enables the type of visualization shown in Figure 3.5. In the figure, each point is associated with a trajectory data point. As the figure shows, the initial original dataset collected includes noise that is the result of nearby vehicle activities such as parking lots and driveways. Noise removal techniques, discussed by Santiago et al. [24, 25] allow eliminating the noise and creating a clean dataset for analysis such as the one shown in Figure 3.5c. The clean dataset makes the isolation of vehicle trajectories associated with a left turn possible. The isolation of left-turn trajectories can be done by querying vehicle identifiers found within the boundaries that define the point where the left turn lane intersects the stop bar of the approach.
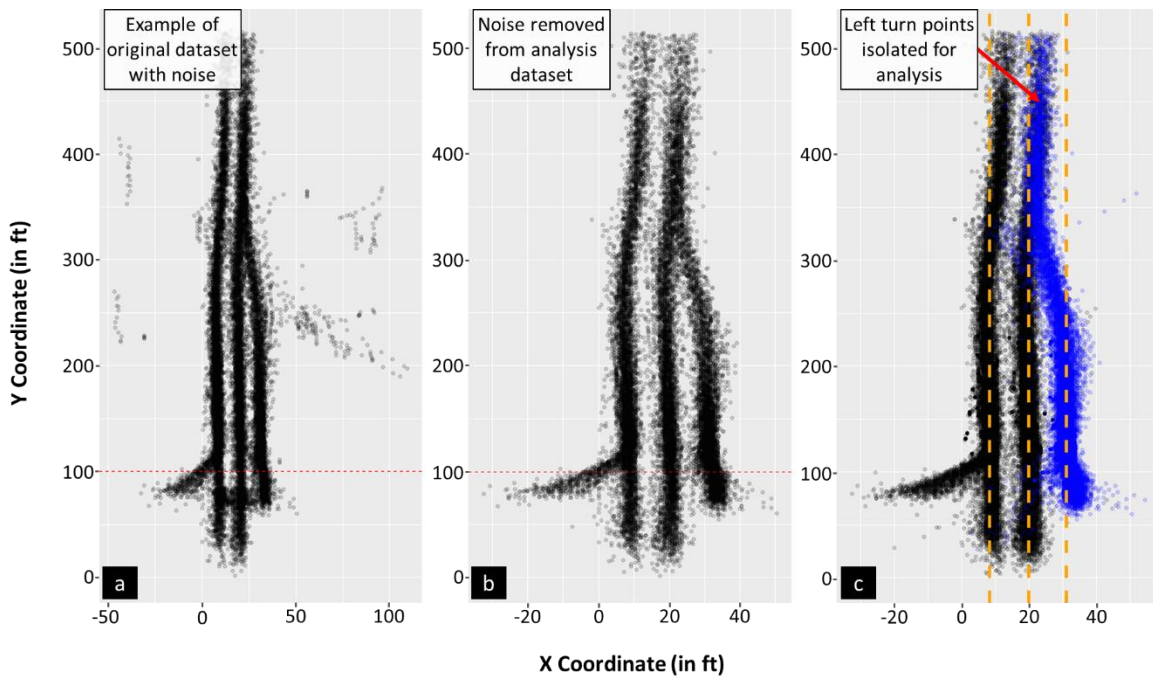
Figure 3.5 – Visualization of the dataset obtained using the custom software.

An example of an isolated left-turning vehicle trajectory is shown in Figure 3.6. The trajectory is expressed in terms of the distance from the stop bar as a function of time, thus allowing the computation of values such as deceleration rate. The figure also shows the signal status information overlaid on the same time frame used to plot the distance of the vehicle from the stop bar.
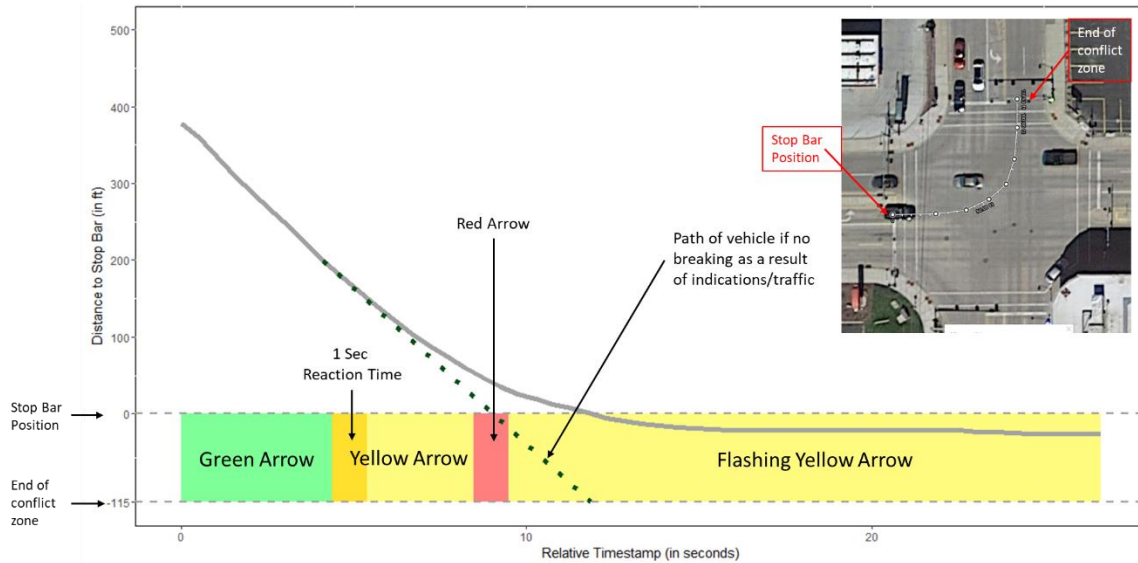
Figure 3.6 – Example of isolated left-turning vehicle trajectory

3.2.3 Merging Signal Status and Trajectory Datasets

Trajectory data collection is independent of the controller infrastructure. As a result, merging a dataset containing signal status information and one containing vehicle trajectories requires having a common reference frame. To log signal status information, a video camera was used to record video from the data collection site (from an angle showing the signal heads) while trajectory data collection was ongoing. Therefore, if signal status information is extracted from the video, then the information is expressed in terms of the video timeframe. In order to express the timestamps in the trajectory dataset in the same timeframe as the signal status dataset, at the beginning of the video recording, the camera was temporarily pointed at the clock of the computer running the trajectory data collection software. This allows creating a "time matching function" that returns an elapsed time on the video (signal status dataset) as a function of the elapsed time in the trajectory dataset. This allows identifying the signal status for every observation part of the trajectory dataset. An example of a left-turn trajectory with the corresponding signal status is shown in Figure 3.7. In this figure, the speed is expressed as a function of time, thus showing start-and-stopping actions near the stop bar of the approach. The time at which the stop bar is crossed is shown as a vertical dashed line.
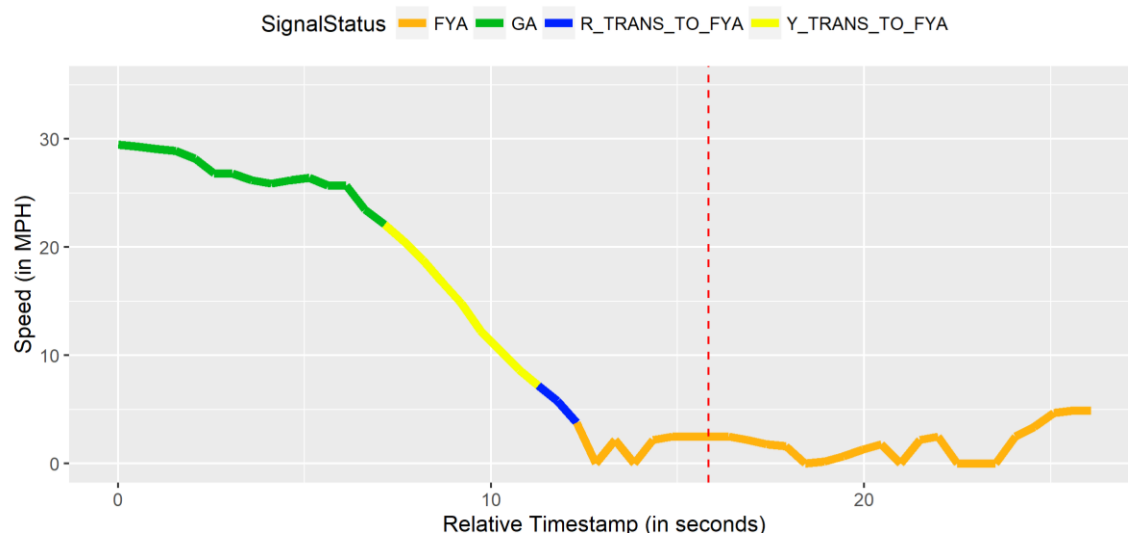
Figure 3.7 – Left-turn trajectory and corresponding signal status.

3.3 Accuracy of the Trajectory Data

Proceeding with a field evaluation that relies on trajectory data requires an assessment of the accuracy of the vehicle trajectory data. Specifically, the accuracy of the speed and position reported by the Intersector needs to be assessed. A frame-by-frame analysis of video from the W. Dayton St. and N. Charter St. in Madison, WI, was conducted. In the analysis, the timestamps for the moment when westbound-traveling vehicles crossed the two known points shown in Figure 3.8 were documented. The distance between Reference Point 1 (R_1) and Reference Point 2 (R_2) was measured using a measuring wheel and was determined to be 66 feet. Additionally, the distance between the temporarily installed Intersector and R_2 was found to be 135 feet. Frame-by-frame analysis of the video was conducted by using the MPV video player.

Figure 3.8 – Reference points used to compute spatial speeds.

The frame-by-frame analysis of the video resulted in R_1 and R_2 values for 30 leading westbound-traveling vehicles. A vehicle was determined to be a leading one if the headway between the leading vehicle and a vehicle ahead was greater than five seconds. While the majority of the vehicles of the dataset were passenger cars, three of the vehicles were bicycles. A screenshot of sample data from the aforementioned dataset is shown in

Table 3.2 – Screenshot of sample data from the ground truth dataset assembled.

VehicleId	Video Time (R1)	Video Time (R2)	Travel Time(s)	Spatial Speed (mph)
WB_27_08252016_093751867	0:19:02.741	0:19:04.810	2.07	21.75
WB_31_08252016_093816842	0:19:36.341	0:19:38.544	2.20	20.43
WB_37_08252016_093839743	0:19:49.021	0:19:52.491	3.47	12.97
WB_5_08252016_094000271	0:21:11.903	0:21:13.605	1.70	26.44
WB_18_08252016_094019256	0:21:19.811	0:21:21.680	1.87	24.08
WB_15_08252016_094013609	0:21:26.118	0:21:29.655	3.54	12.72
WB_24_08252016_094051470	0:22:05.557	0:22:07.292	1.74	25.94
WB_25_08252016_094100097	0:22:11.029	0:22:16.168	5.14	8.76
WB_43_08252016_094244632	0:23:54.733	0:23:56.468	1.74	25.94
WB_50_08252016_094314319	0:24:27.599	0:24:29.434	1.83	24.52
WB_1_08252016_094427889	0:25:43.275	0:25:45.277	2.00	22.48
WB_2_08252016_094443801	0:25:53.485	0:25:58.924	5.44	8.27
WB_45_08252016_092337484	0:04:51.924	0:04:54.327	2.40	18.73

. As shown, the known R_1 and R_2 values allow the calculation of the travel time, which in turn allows the calculation of the spatial speed of the vehicles. Finally, each vehicle in the shown dataset was matched with a corresponding vehicle identifier found in the trajectory dataset obtained from the temporary installation of the data collection system. The association with a

trajectory data vehicle identifier made the comparison of speeds and positions shown in the sections ahead possible.

Table 3.2 – Screenshot of sample data from the ground truth dataset assembled.

VehicleId	Video Time (R1)	Video Time (R2)	Travel Time(s)	Spatial Speed (mph)
WB_27_08252016_093751867	0:19:02.741	0:19:04.810	2.07	21.75
WB_31_08252016_093816842	0:19:36.341	0:19:38.544	2.20	20.43
WB_37_08252016_093839743	0:19:49.021	0:19:52.491	3.47	12.97
WB_5_08252016_094000271	0:21:11.903	0:21:13.605	1.70	26.44
WB_18_08252016_094019256	0:21:19.811	0:21:21.680	1.87	24.08
WB_15_08252016_094013609	0:21:26.118	0:21:29.655	3.54	12.72
WB_24_08252016_094051470	0:22:05.557	0:22:07.292	1.74	25.94
WB_25_08252016_094100097	0:22:11.029	0:22:16.168	5.14	8.76
WB_43_08252016_094244632	0:23:54.733	0:23:56.468	1.74	25.94
WB_50_08252016_094314319	0:24:27.599	0:24:29.434	1.83	24.52
WB_1_08252016_094427889	0:25:43.275	0:25:45.277	2.00	22.48
WB_2_08252016_094443801	0:25:53.485	0:25:58.924	5.44	8.27
WB_45_08252016_092337484	0:04:51.924	0:04:54.327	2.40	18.73

3.3.1   Accuracy of Speed Observations

The average speed reported by the Intersector between R_1 and R_2 for each of the 30 vehicles described in the previous sections was obtained from the vehicle trajectories dataset. As part of the analysis, an assumption was made that the spatial speed equals instant speed given the short distance between R_1 and R_2. As a result of the assumption, speeds reported by the Intersector were compared with spatial speeds obtained by analyzing the video. Figure 3.9 shows a histogram of the speed differences observed as part of the comparison. As shown, 83% of the vehicle speed measurements reported by the Intersector were within ±1.0 mph of the spatially weighted average speeds computed by analyzing the video. The speed difference found is consistent with the manufacturer specifications of ±0.68 mph for speed accuracy.
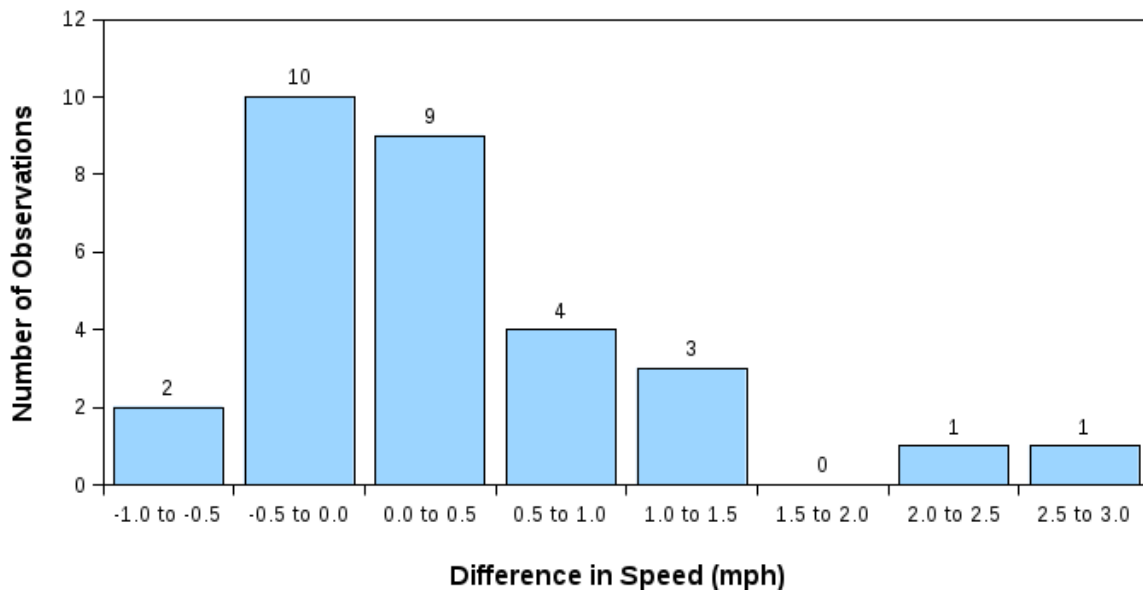
Figure 3.9 – Difference between average and instant speeds.

3.3.2   Accuracy of Time-Position Information

Each R_2 value in the ground truth dataset is associated with a known position. Using interpolation, the timestamp when a vehicle crosses R_2 can be identified. Figure 3.10 illustrates the process of interpolation. For each vehicle in the ground truth dataset, the timestamp (T_2) when the vehicle crosses R_2 is identified. The T_2 value for each vehicle can be compared with the equivalent time (T_1) associated with the crossing of the R_2 in the video.

The differences between T_1 and T_2 were computed for all 30 vehicles. A histogram of the differences is shown in Figure 3.11. As shown, all time differences are positive. Positive time differences imply that position information obtained via the data collection software has associated times later than what is suggested from the video analysis. If time and position pairs obtained are treated as ground truth, then the time difference data indicates that 77% of the time and position pairs obtained from the data collection software are within 0.5 seconds of "real values" and have an average difference equal to 0.386 seconds.
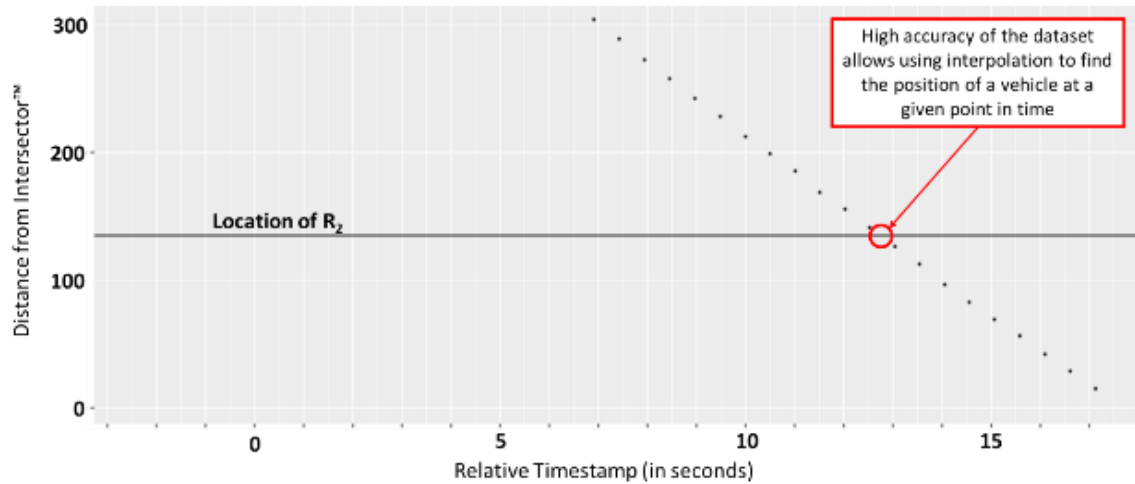
Figure 3.10 – Using interpolation to determine timestamp for known position on the road.
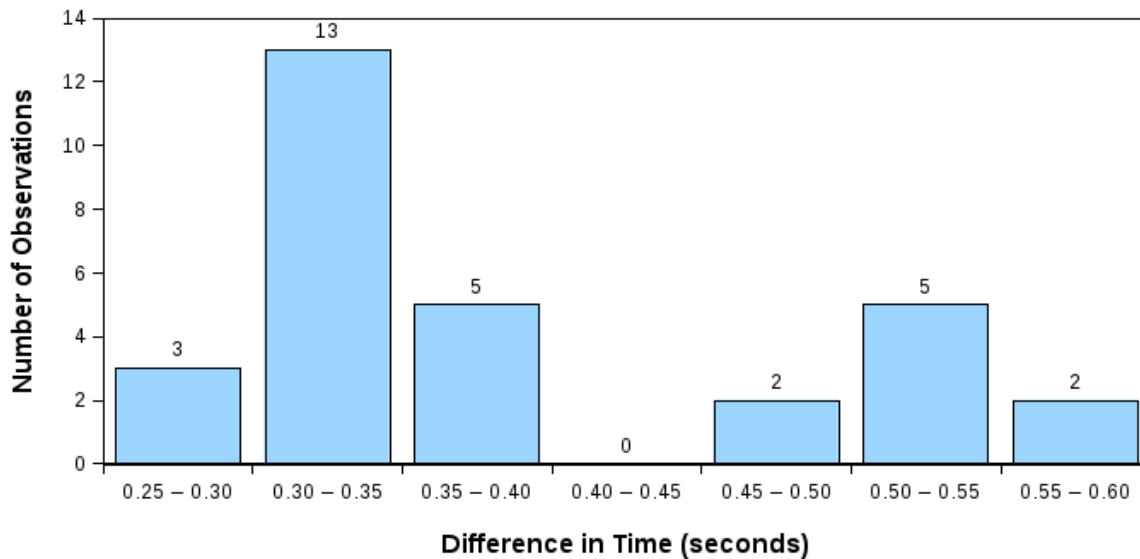

Difference in Time (seconds)
Figure 3.11 – Difference in time for a known position.

Several factors can explain the differences in the time and position pairs. When a request for trajectory data is made to the Intersector™ embedded web server, data returned could represent field conditions 100 ms prior to the request. Additionally, position information reported is based on the interpretations of "blobs" sensed by the radar, which could have inaccuracies due to the reflectivity of different vehicle surfaces. Finally, time and position pairs are only obtained every 500 ms, which means that no exact time observation exists in the dataset for the time a vehicle crosses the R_2. A review of the data, considerations of server responses, and the nature of procedures used to obtain ground truth data suggest that the average difference does not have a significant impact on data quality. Based on all these factors, the position information reported by the Intersector is deemed sufficiently accurate for the project.

4   Results

The following section represents the results from the computer-based static evaluation and findings from an exploratory approach to characterize driver behavior using trajectory data.

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 (Figure 4.1). Of the 212 participants, 49 percent were male and 51 percent were female. A total of 50 percent of the drivers were between the ages of 18-24, 28 percent were between 25 and 34 years of age, 9 percent were between 35 and 44 years of age, 5% were between 45 and 54 years of age, 5 percent were between 55 and 64 years of age, and 3 percent were over 65 years of age. In total, 12 percent of drivers participating had less than 5 years of driving experience, 52 percent had between 5 and 9 years of driving experience, and 36 percent 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 4.1.
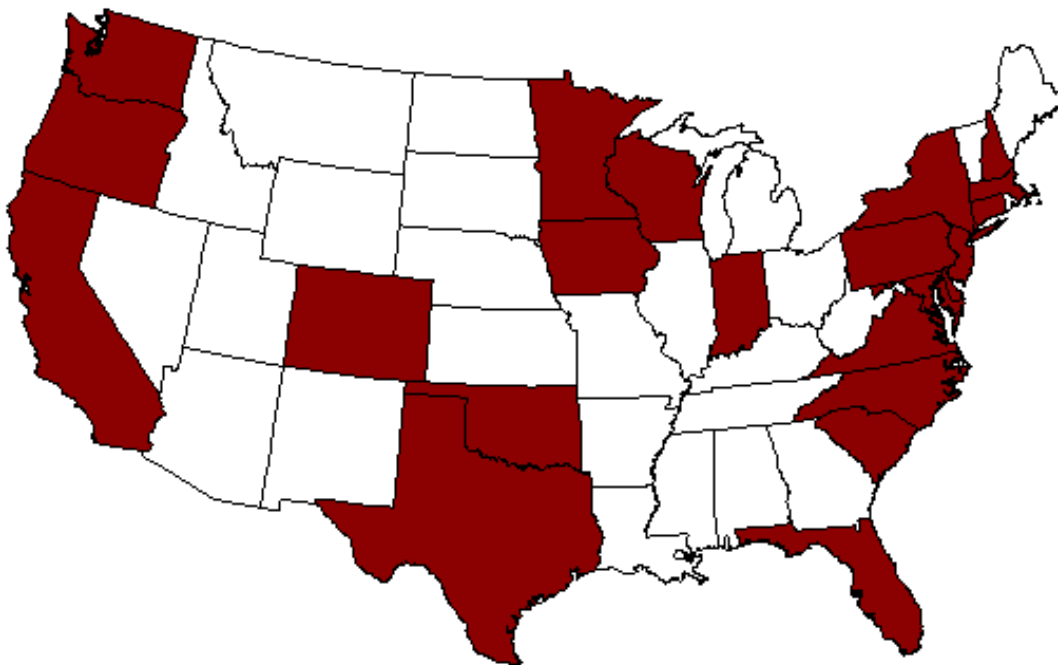

Figure 4.1 – Location of participants in computer-based static evaluation.

Table 4.1 – Demographic information from static evaluation.

Demographic	Level	No. of Participants	Percentage of 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 **Error! Reference source not found.**. 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 – Lead/Lag Protected Phasing

The following graphics represent the survey results from Sequences 2 and 3, the CG lead/lag protected phasing. Figure 4.2 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 4.3 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 4.4 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.
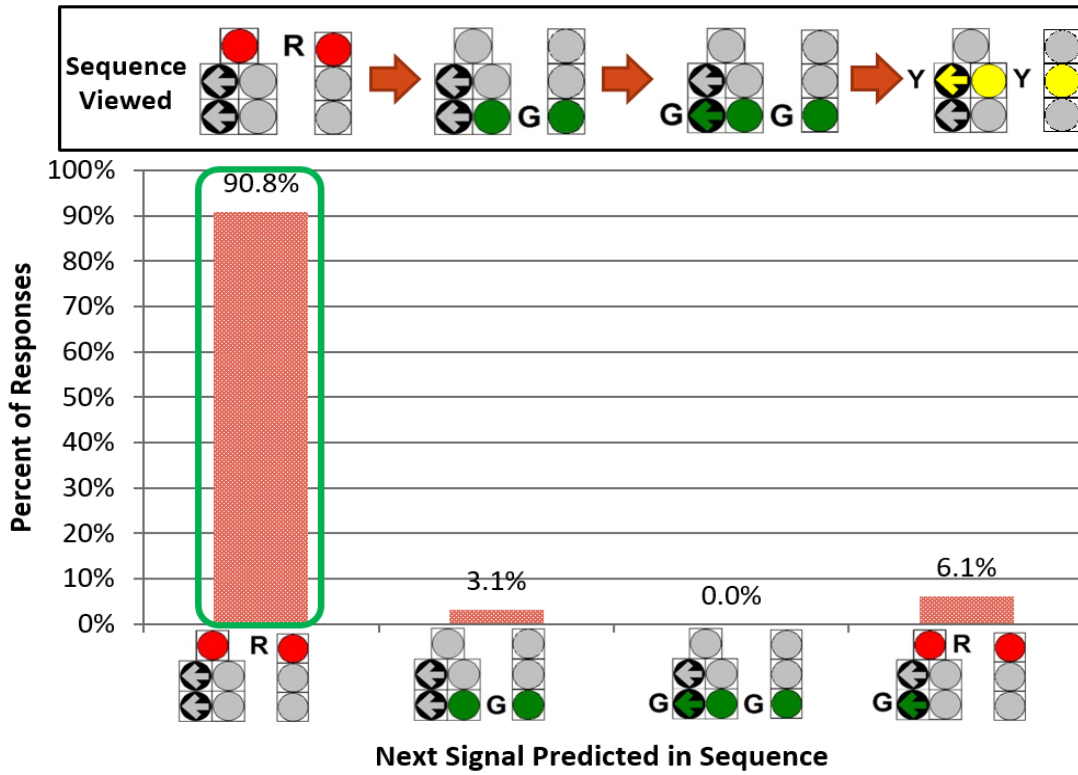
Figure 4.2 – Scenario 1 sequence and driver responses.

Figure 4.3 – Scenario 2 sequence and driver responses.

Figure 4.4 – Scenario 3 sequence and driver responses.

4.1.2   Circular Green – Dual Leading and Lagging Phasing

Based on the signal sequencing presented in Table 5.1, the CG PPLT dual leading and dual lagging phasing were combined for evaluation in the survey. Figure 4.5 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 4.6 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.

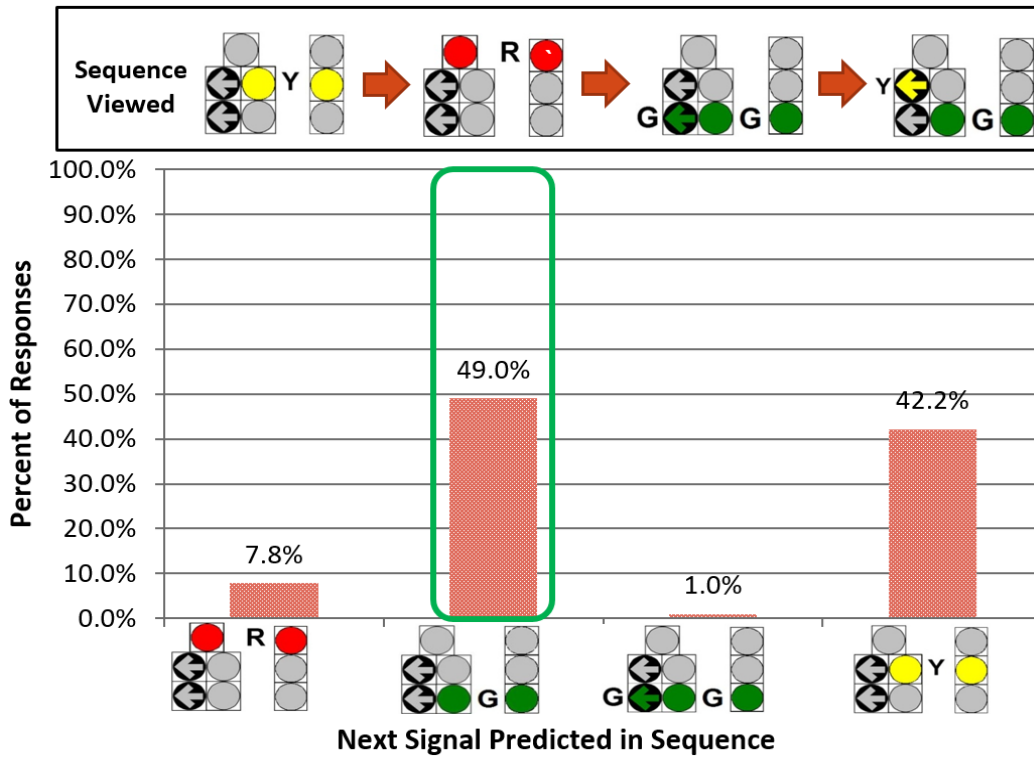**Figure 4.5 – Scenario 4 sequence and driver responses.**

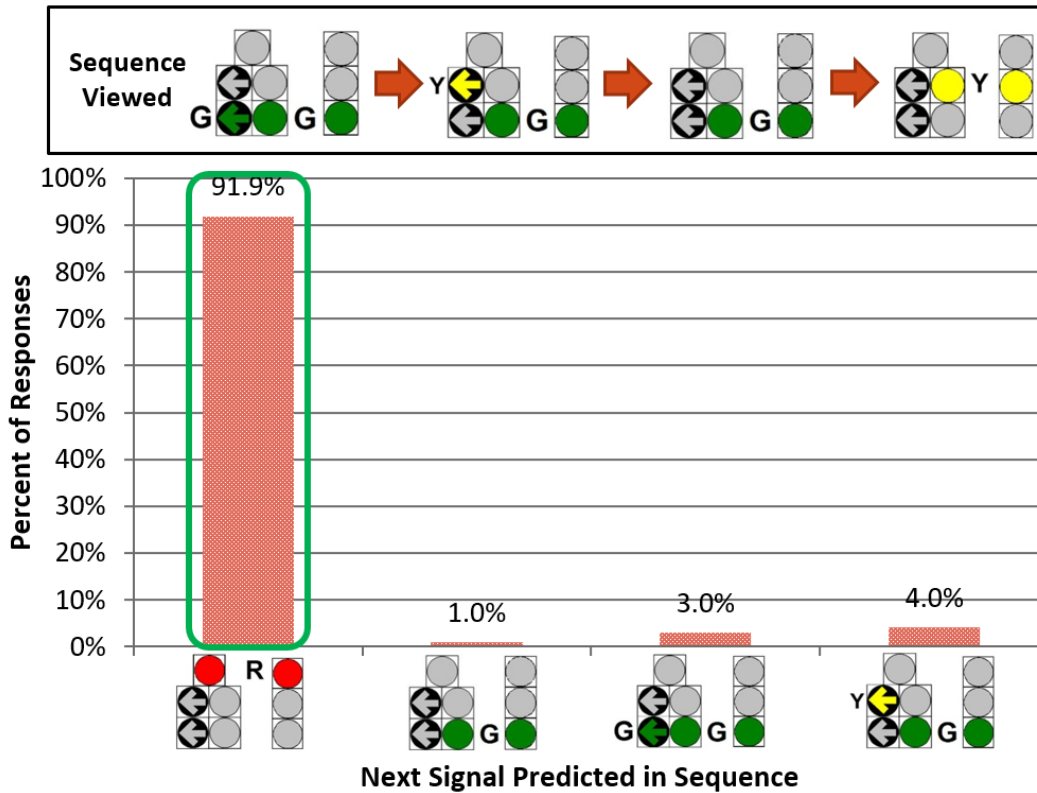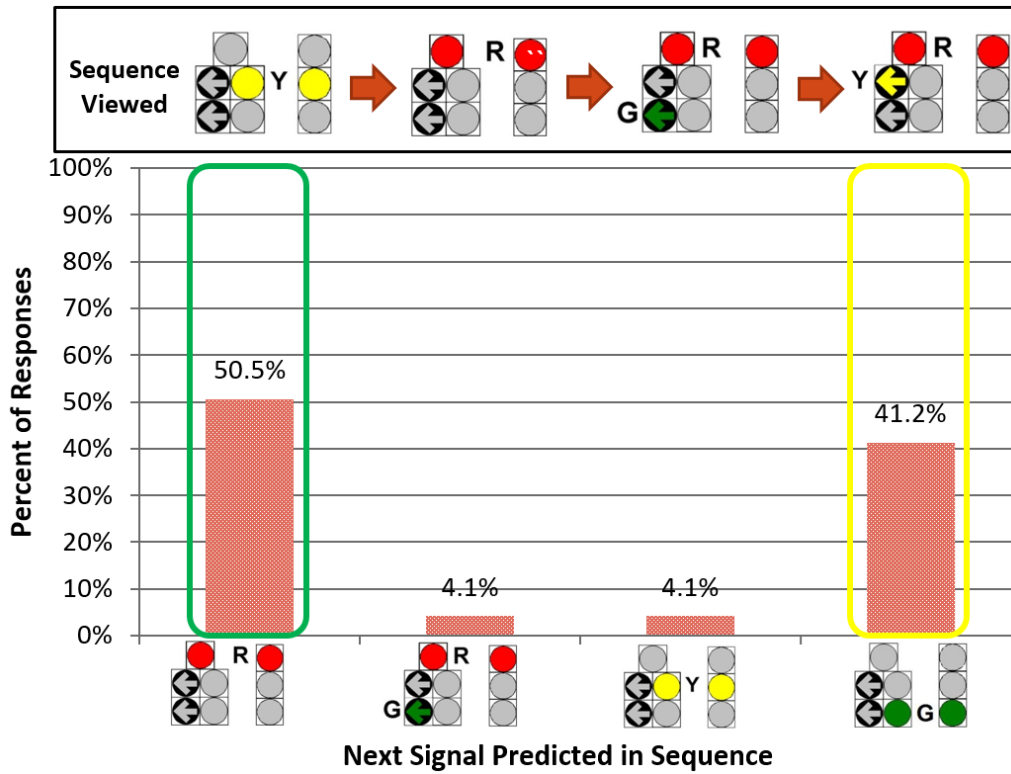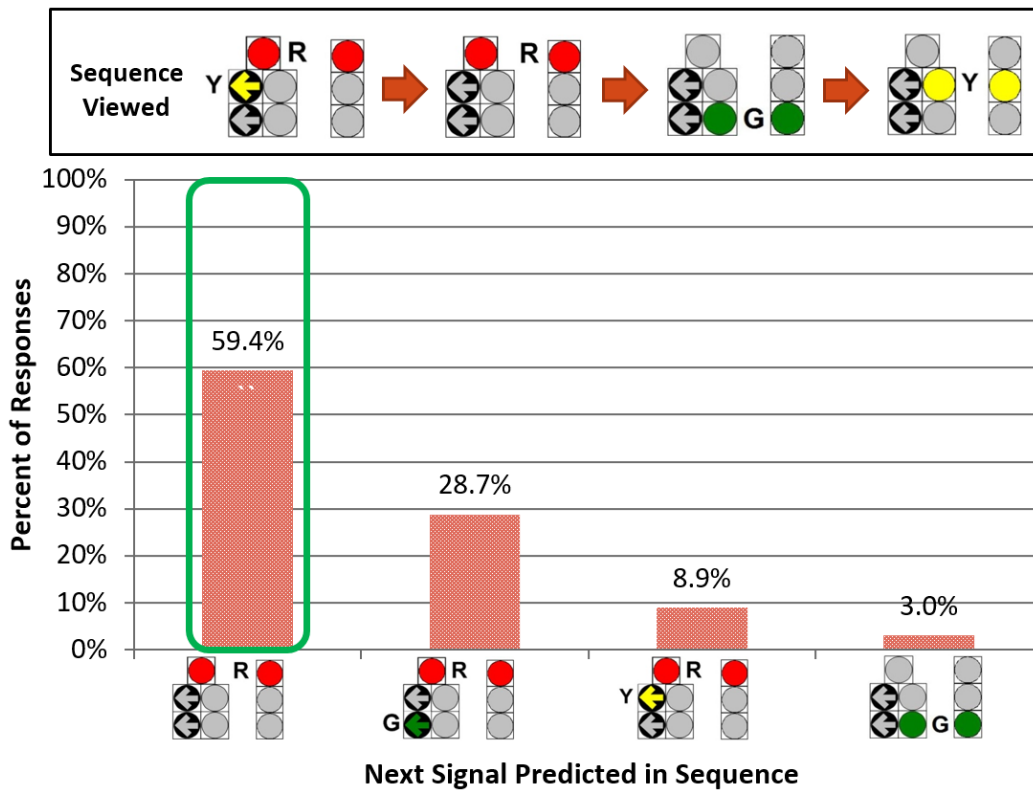**Figure 4.6 – Scenario 5 sequence and driver responses**

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 4.7 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 4.8 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 4.9 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 4.10 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 4.11 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.
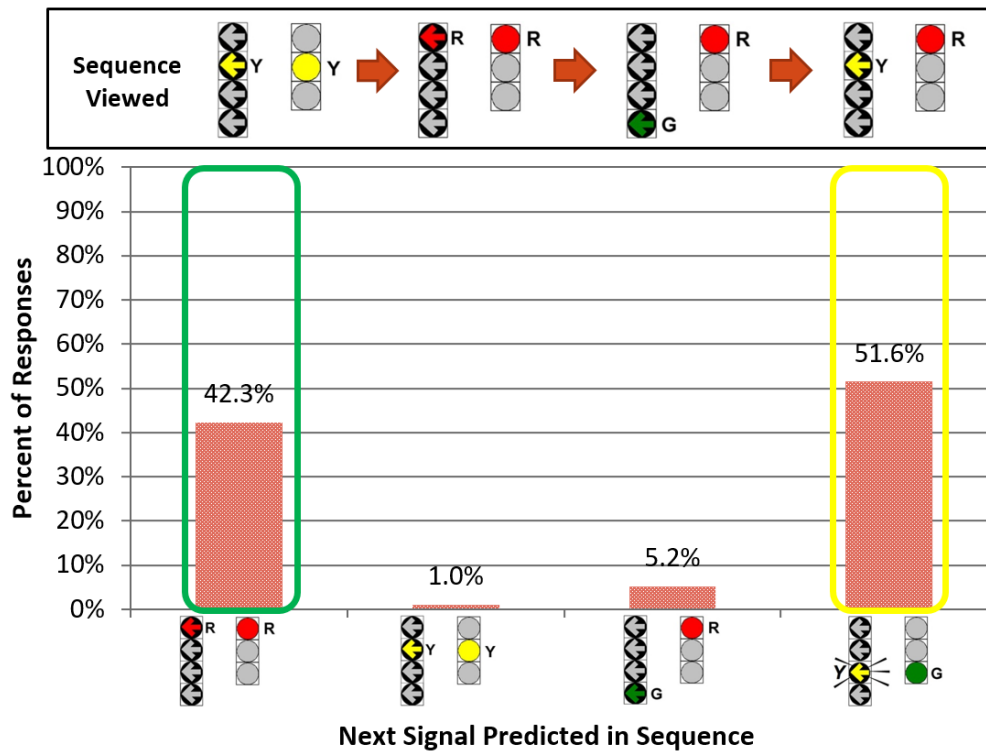

Figure 4.7 – Scenario 6 sequence and driver responses.

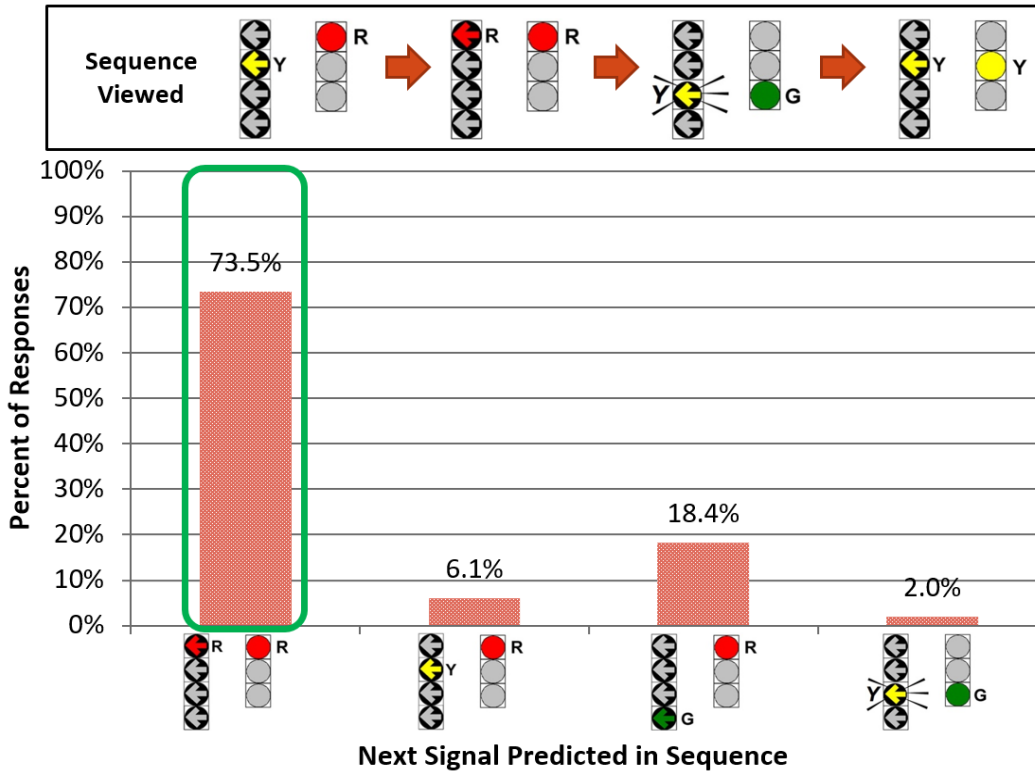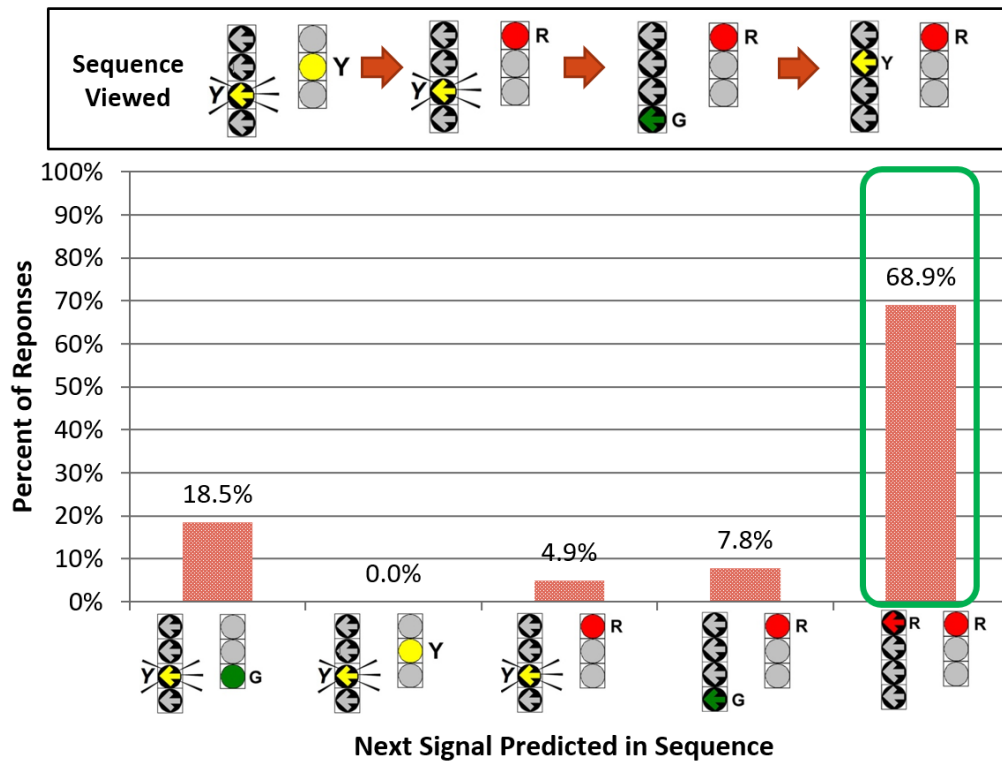**Figure 4.8 – Scenario 7 sequence and driver responses.**

Figure 4.9 – Scenario 13 sequence and driver responses.

Figure 4.10 – Scenario 14 sequence and driver responses.

Figure 4.11 – Scenario 15 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 4.12 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 4.13 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 4.14 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 4.15 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 4.16 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 4.12 – Scenario 8 sequence and driver responses.

Figure 4.13 – Scenario 9 sequence and driver responses.
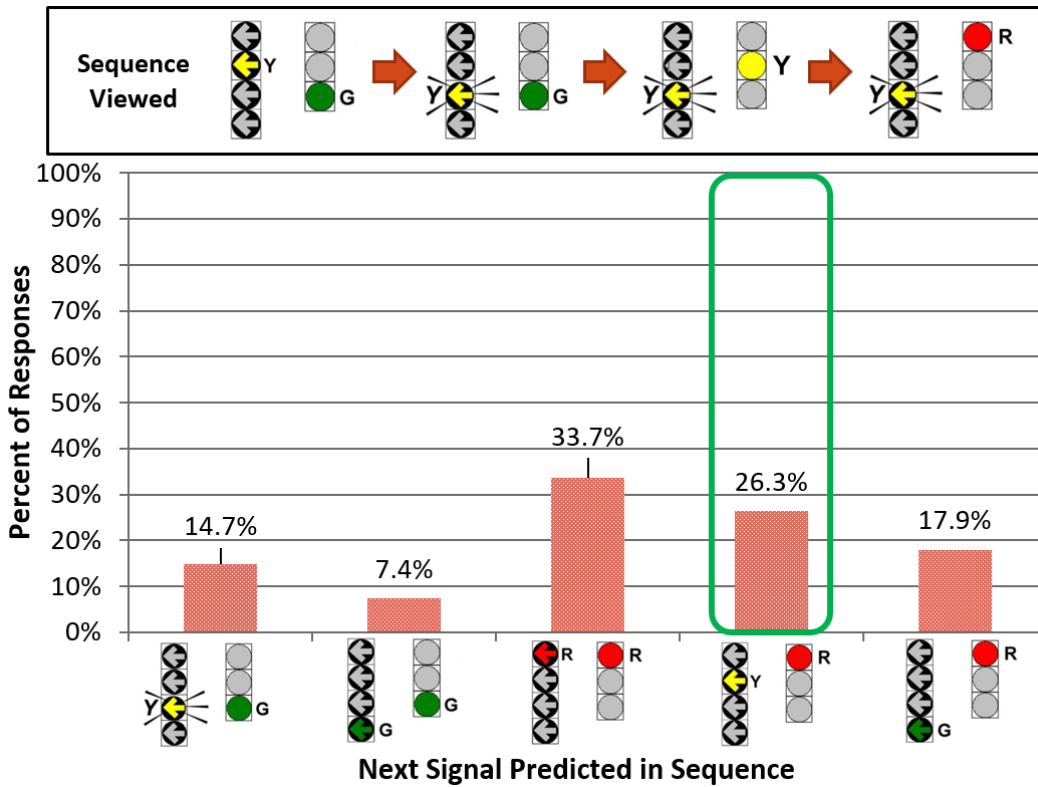
Figure 4.14 – Scenario 10 sequence and driver responses.
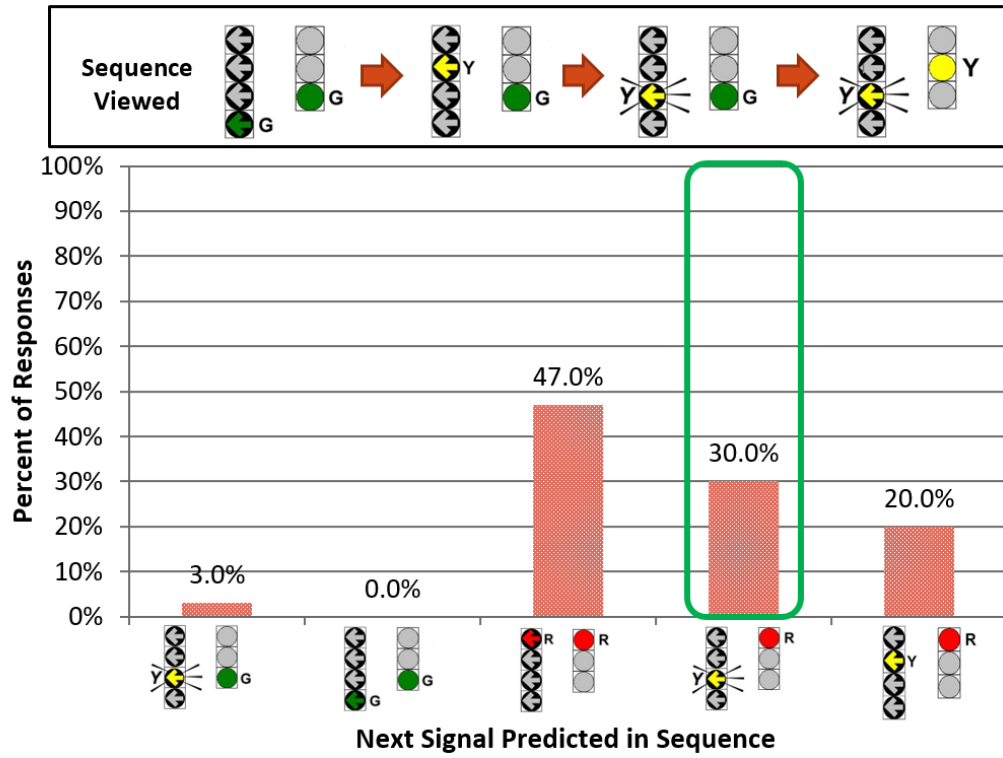
Figure 4.15 – Scenario 11 sequence and driver responses.
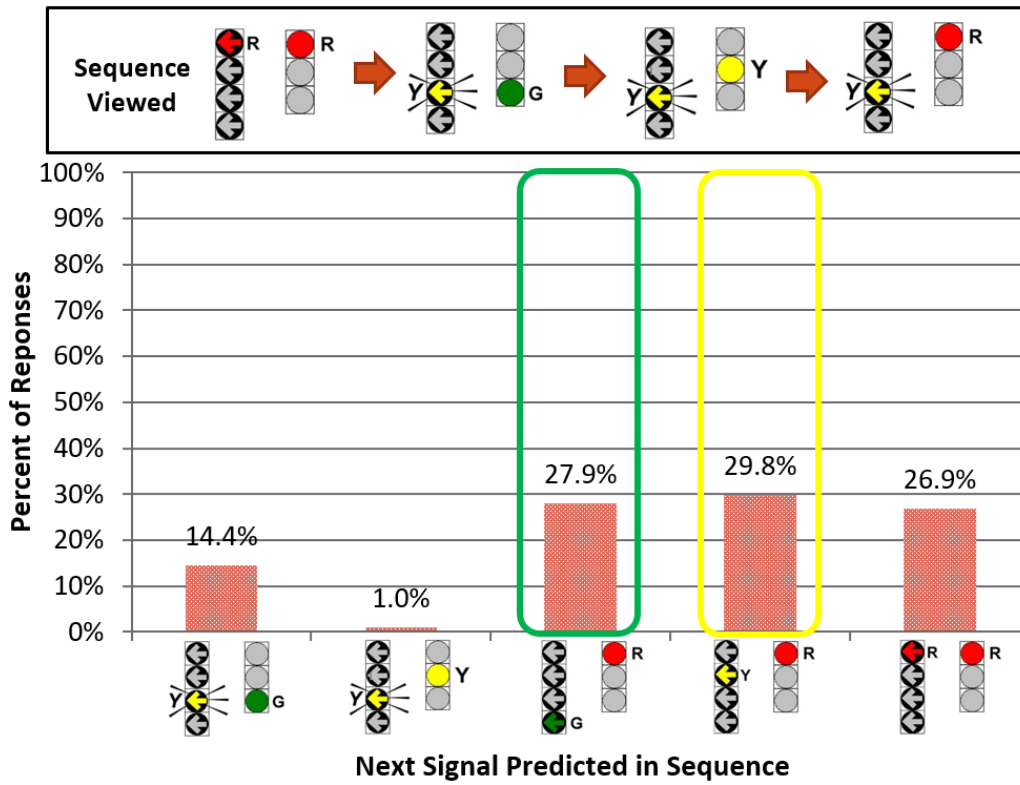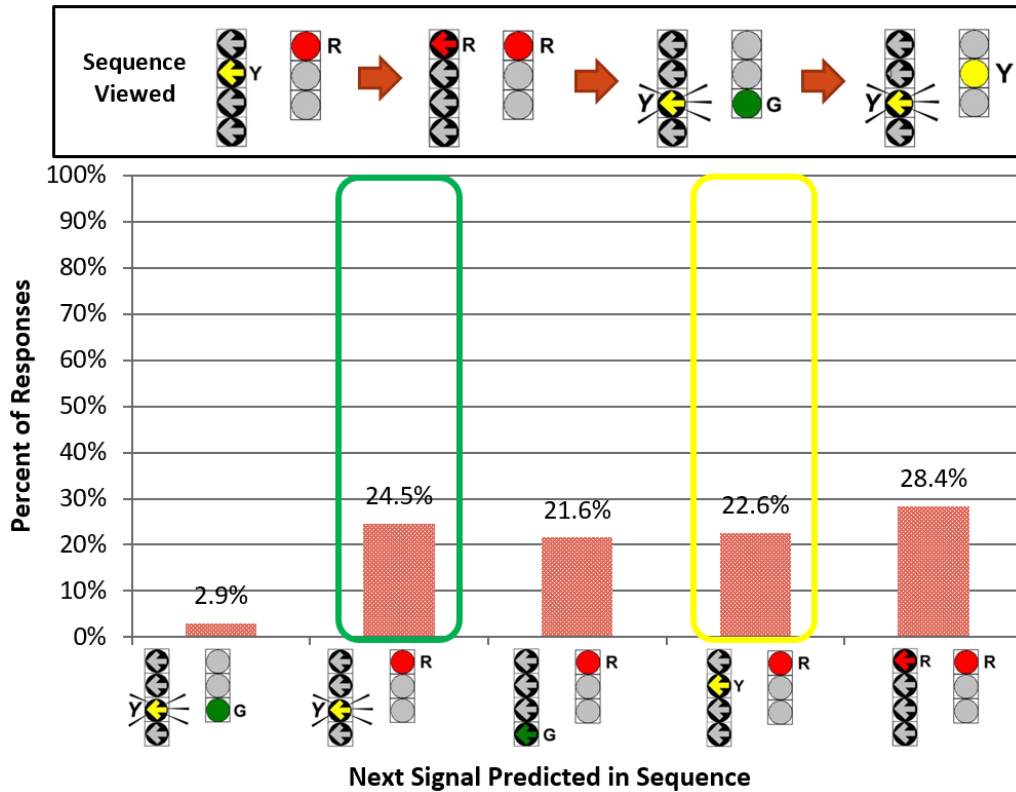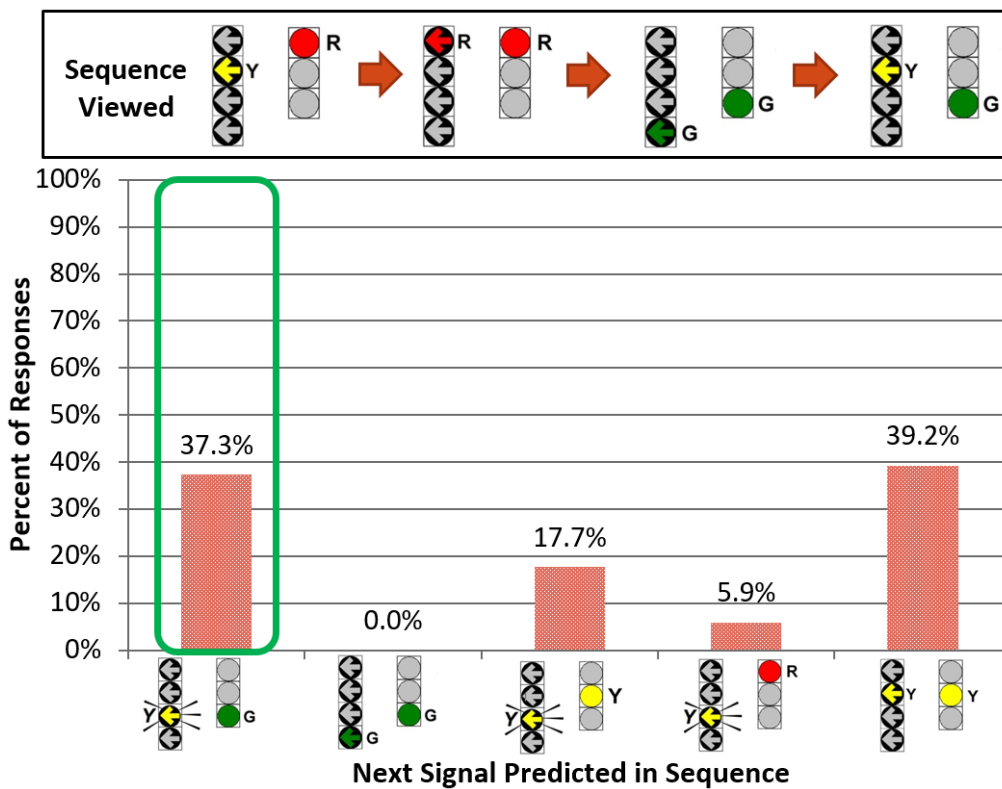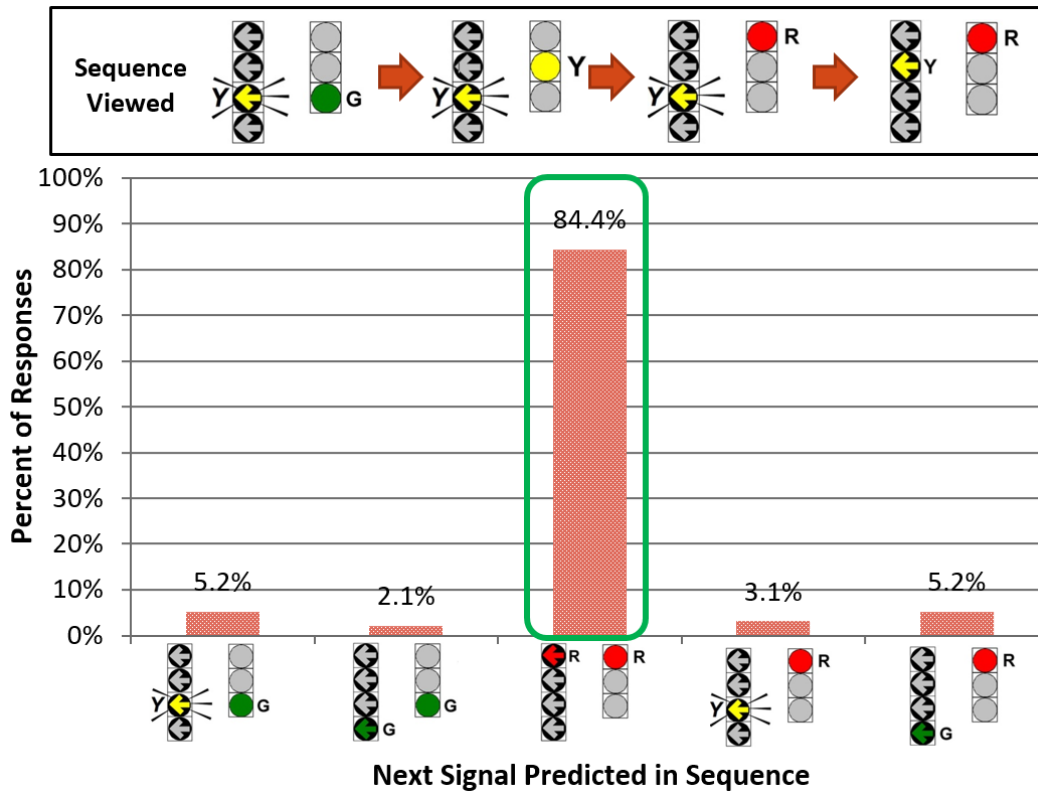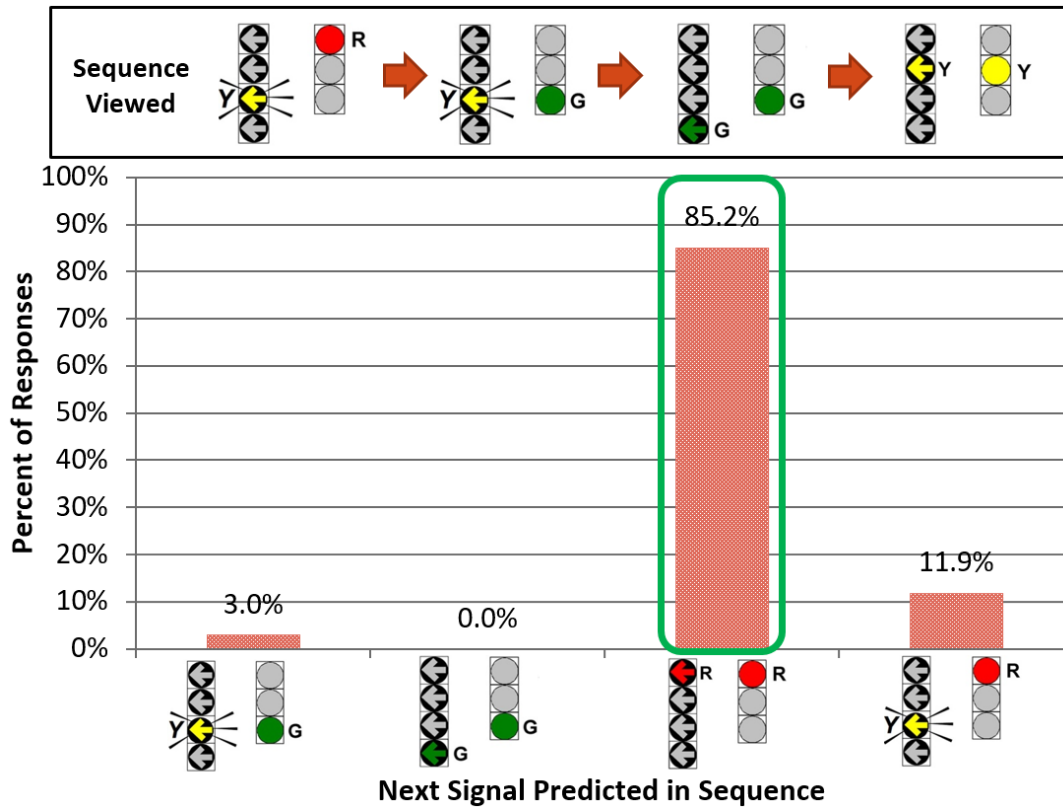

Figure 4.16 – Scenario 12 sequence and driver responses.

4.2   Preliminary Findings from Vehicle Trajectory Data

A mobile version of a trajectory data collection system like the one shown in **Figure 3.3** was used to obtain vehicle trajectories at intersections with CG and FYA indications for PPLT phasing in Amherst, MA. A trajectory dataset obtained from a site in Appleton, WI, was also available for analysis. The Appleton, WI, dataset was obtained from an intersection already instrumented with a radar-based vehicle detection system. The sections ahead present an exploration of sample data from a CG PPLT intersection with all-red phasing and from an FYA PPLT intersection with all-red phasing.

4.2.1   CG Indication with PPLT phasing (including all-red)

Peak vehicle trajectories from one hour were collected and analyzed in Amherst, MA. The data collection effort involved collecting vehicle trajectories using the mobile version of the system and a recording of the intersection using a video camera. Trajectory data for the left-turn movement shown in Figure 4.17 was obtained and isolated using the procedures described in the methodology section and by pointing the radar at the southbound approach of the intersection. Due to the concurrent phasing of both the northbound and southbound approaches, the video camera was placed adjacent to the radar on a pole located next to the sidewalk adjacent to the northbound approach.

Figure 4.17 – Vehicles using all-red as extension of protected phase in CG PPLT.

Figure 4.17 shows the trajectory of three unique vehicles during the aforementioned data collection period. The two video screenshots in the figure show vehicles traversing through the intersection during the all-red clearance interval. This clearly shows vehicles taking advantage of the all-red clearance interval as an extension of the protected phase. The vehicles presented in the graphic above were all traveling approximately 25 mph throughout their captured trajectory. Vehicle 1 had exceeded the y-position of the stop bar during the onset of the all-red; however, Vehicles 2 and 3 were further upstream at this timestamp. Vehicle 2 was located less than five feet upstream of the stop bar, and Vehicle 3 was located over 150 feet upstream of the stop bar during this onset. It is apparent that Vehicle 3 approached the intersection with intent to traverse during the all-red phase in transition between protected and permissive phasing.

4.2.2 FYA Indication with PPLT phasing (including all-red)

Peak vehicle trajectories from one hour were collected and analyzed in Holyoke, MA, using the mobile version of the data collection system. A video camera was placed upstream of the intersection to capture the signal timings that were parallel with the trajectory data of vehicles traversing the intersection. Trajectory data for the left-turn movement shown in Figure 4.18 was obtained and isolated using the procedures described in the methodology section and by pointing the radar at the southbound approach of the intersection.
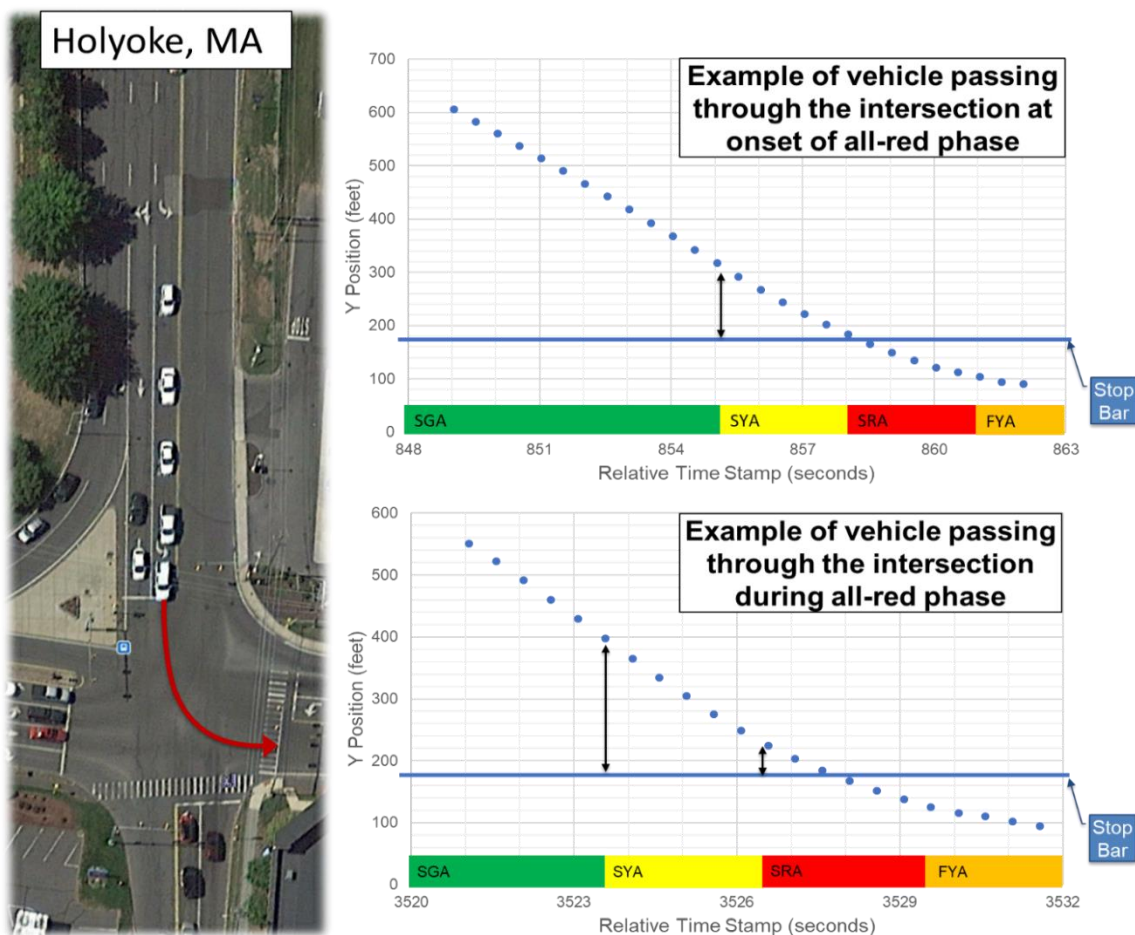

Figure 4.18 – Vehicles using all-red as extension of protected phase in FYA PPLT

Figure 4.18 shows the trajectory of two unique vehicles during the aforementioned data collection period. In this particular case, obtaining video screenshots that show the vehicle associated with each trajectory was not feasible because the camera was placed upstream of the intersection to capture the signal indications. As in the previous scenario, drivers took advantage of the all-red clearance interval as an extension of the protected phase.

The two vehicles above were traveling at approximately 27.5 mph, and both were approximately 120-200 feet upstream of the approach stop bar during the onset of the yellow change signal. Vehicle 1 (top curve) was less than five feet from the stop bar at the onset of the all-red phase; however, Vehicle 2 (bottom curve) was 40 feet from the stop bar at this timestamp. These vehicles continued traversing the intersection during the all-red clearance phase, transitioning from protected to permissive phasing.

Similar results were observed in a site in Appleton, WI. Figure 4.19 shows the trajectory of four vehicles that made a left turn during a signal cycle. In the figure, the signal status information is color coded, and each vehicle is labeled. As the figure shows, the same behavior observed in Holyoke, MA (use of all-red as an extension of protected phase), was observed in Appleton, WI.
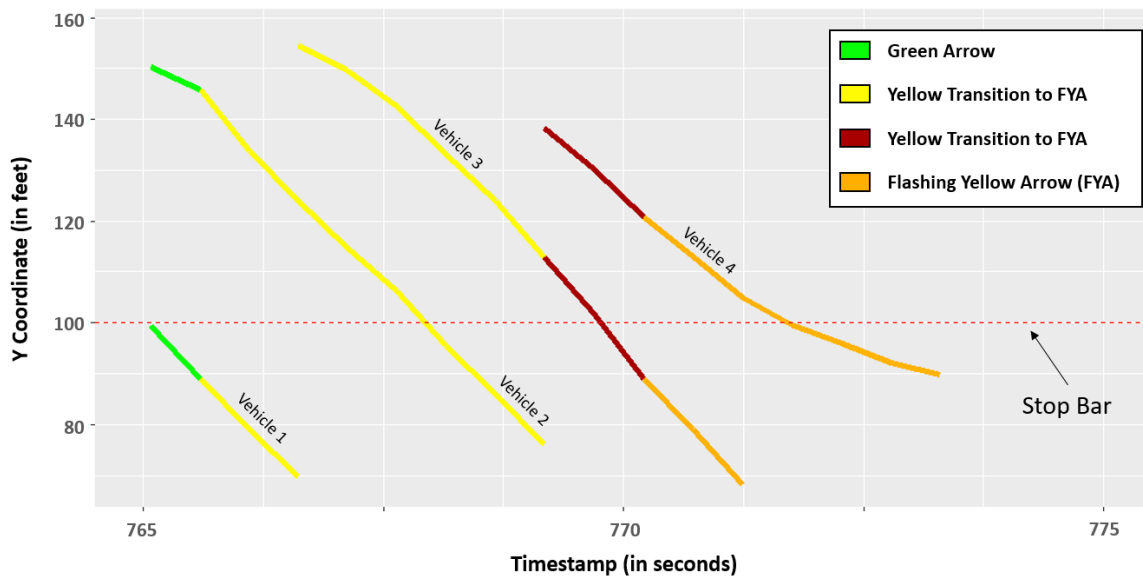
Figure 4.19 – Vehicles using all-red as extension of protected phase in FYA PPLT.

4.2.3   Implications of Observed Behavior for Future Research

It should be noted that, while the described behavior does take place at the intersections, it is not a behavior that can be guaranteed all the time. Therefore, a future evolution of the research presented should look at modeling the conditions associated with the use of the all-red clearance interval as an extension of the protected phase. Among the factors that could be part of a model are signal timing and the presence of leading vehicle, speed, distance from the stop bar, as well as the presence and status of opposing vehicles. Future research can be conducted by relying on field-based trajectory and signal status data across geographically distributed study locations.

5 Discussion & Conclusions

This research presented the application of a computer-based static evaluation and an innovative data collection method for obtaining left-turning vehicle trajectories. A static evaluation was conducted with 207 participants across 20 states in the U.S. The results in the previous section represented the driver comprehension for various PPLT phase sequences for both CG and FYA signal indications. Additionally, preliminary findings from the vehicle trajectory dataset were presented. The sections ahead present the results of drivers predicting the all-red clearance interval in both the CG and FYA PPLT signal phasing through the application of static evaluation and the vehicle trajectory field study.

5.1 Comparing the Comprehension of FYA and CG Permissive Indication

Further analysis was required to understand driver comprehension of the FYA and CG permissive indications for left turns. Table 5.1 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 was 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 on its own.

Table 5.1 – Breakdown of correct responses for each phase scheme.

Permissive Indication	Phase Scheme	Percentage of 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 in Static Evaluation

Two of the scenarios outlined in the static evaluation studied the potential prediction of the all-red clearance interval in PPLT CG and FYA phasing. The results provided in Figure 4.5 and Figure

4.7 represent these two scenarios. In Scenario 4 (Figure 4.5), only 51 percent of predictions were correct 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, 41 percent of drivers predicted the CG permissive phasing instead of the all-red. Thus, although the majority of drivers predicted the all-red, a significant number of responses 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 is 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 4.7), only 42 percent of predictions were correct for the next phase in the sequence. The correct prediction was again the all-red clearance phase that exists before the FYA is 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 an FYA), they will not expect an all-red clearance to be displayed.

5.3   Overall Summary

Through the application of static and field evaluation, this research aimed to develop an understanding of driver comprehension related to PPLT phasing, specifically focusing on the prediction of the all-red clearance interval. An analysis of the static evaluation results makes it apparent that drivers are more likely to understand the signal phasing with CG permissive phasing compared to the application of the FYA. With this, an assumption was made that drivers would be more willing to traverse through an intersection during the all-red clearance phase with the 5-section cluster signal (CG), than the 4-section signal (FYA). This assumption was evaluated through the results from the field study, which yielded similar findings. From the field study, vehicles approaching the PPLT transition for cluster signals were unlikely to alter their speeds, essentially utilizing the all-red phase as an extension of the protected left-turn phase. Comparably, this was not found in vehicle trajectory data for the 4-section signal (FYA), as vehicles were likely to yield to the signal and not traverse the intersection during the PPLT transition. The application of the all-red clearance interval appears necessary for the application of PPLT phasing with the FYA signal; however, a need exists for further research in determining guidelines for these intervals. The preliminary findings from the computer-based static evaluation and vehicle trajectory study will be used in future work to determine the guidelines for effective duration of the all-red clearance intervals when FYA PPLT phasing is used.

Acknowledgments

References

1. Brehmer, C. L., Kacir, K. C., Noyce, D. A., & Manser, M. P. (2003). *NCHRP 493: Evaluation of traffic signal displays for protected/permissive left-turn control*. Washington, DC: Transportation Research Board.

2. Noyce, D. A., & Knodler, M. (2007). Implementation of the flashing yellow arrow permissive left-turn indication in signalized intersections. *Proceedings of the 14th International Conference of Road Safety on Four Continents*, 14: 13p–13p.

3. Federal Highway Administration (FHWA). (2009). *Manual on Uniform Traffic Control Devices*, 2009 ed. Washington, D.C.: U.S. Department of Transportation.

4. Schattler, K. L., & Lund, J. A. (2013). *State-of-the-art literature review on permissive/protected left-turn control* (Report No. FHWA-ICT-13-004). Urbana, IL: Illinois Center for Transportation.

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*. Paper presented at the 86th Annual Meeting of the Transportation Research Board, Washington, D.C.

6. Knodler, M., & 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 (UMAR18-7). Amherst, MA: University of Massachusetts.

7. Knodler Jr, 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*, 131(4): 270–278.

8. Knodler Jr, M., Noyce, D., & Fisher, D. (2007). Evaluating effect of two allowable permissive left-turn indications. *Transportation Research Record: Journal of the Transportation Research Board*, 2018: 53–62, 2007.

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). Retrieved May 25, 2018, from http://www.trb.org/Publications/Blurbs/159759.aspx.

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*, 2463: 1–9.

11. National Highway Traffic Safety Administration (NHTSA). (n.d.). Fatality Analysis Reporting System (FARS). https://www.nhtsa.gov/research-data/fatality-analysis-reporting-system-fars

12. Federal Highway Administration (FHWA). (2009). *Engineering countermeasures to reduce red-light running*. Retrieved May 25, 2018, from https://safety.fhwa.dot.gov/intersection/other_topics/fhwasa09027/resources/Intersection%20Safety%20Issue%20Brief%206.pdf.

13. 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*. Washington, DC: Transportation Research Board.

14. McGee Sr, 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*, 2298: 1–8.

15. Medina, J. C., Benekohal, R. F., & Ramezani, H. (2012). *Field Evaluation of Smart Sensor Vehicle Detectors at Intersections–Volume 1: Normal Weather Conditions* (FHWA-ICT-12-016)*.* Urbana, IL: Illinois Center for Transportation.
16. 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: 341–350.
17. Medina, J. C., Benekohal, R. F., & Chitturi, M. (2009). *Evaluation of Video Detection Systems, Volume 2: Effects of Illumination Conditions* (Research Report ICT-09-046). Rantoul, IL: Illinois Center for Transportation.
18. Medina, J. C., Benekohal, R. F., & Chitturi, M. (2009). *Evaluation of video detection systems, volume 4: effects of adverse weather conditions in the performance of video detection systems* (Research Report ICT-09-039). Rantoul, IL: Illinois Center for Transportation.
19. Santiago-Chaparro, K., Chitturi, M., Bill, A., & Noyce, D. (2012). *A Signalized intersection for experimentation and evaluation of traffic signal and detection system technology* (Technical Report). Madison, WI: Traffic Operations and Safety Laboratory.
20. Santiago-Chaparro, K. R., Chitturi, M., Bill, A., & Noyce, D. A. (2012). *Realtime performance measures from radar-based vehicle detection systems*. Paper presented at the 19th ITS World Congress, Vienna, Austria.
21. Santiago-Chaparro, K. R., Chitturi, M., Bill, A., & Noyce, D. (2014). *Expanding the capabilities of existing vehicle detection infrastructure to monitor red light running*. Paper presented at the 93rd Annual Meeting of the Transportation Research Board, Washington, D.C.
22. Zhixia, L., Yu, L., Chitturi, M., Bill, A., & Noyce, D. (2015). Improved method for real-time vehicle emission estimation at intersections based on radar sensor data and MOVES model. Paper presented at the *94th Annual Meeting of the Transportation Research Board*, Washington, D.C.
23. MacClellan, P. (2013). *Identification of applicability for the implementation of the flashing yellow left-turn arrow in Massachusetts*. Honors Thesis, University of Massachusetts Amherst, Amherst, MA.
24. Santiago-Chaparro, K. R., Chitturi, M., Bill, A., & Noyce, D. A. (2016). Automated turning movement counts for shared lanes: leveraging vehicle detection data. *Transportation Research Record: Journal of the Transportation Research Board*, 2558: 30–40.
25. Santiago-Chaparro, K. R. (2017). *Data collection system and analysis methodology development using radar-based vehicle detection infrastructure*. Madison, WI: University of Wisconsin-Madison.

Appendix A Extra Information

Table 5.2 – 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**

Table 5.3 – 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

Table 5.4 – Signal sequence for each scenario, with final two displays presented accordingly

Sequence #	Scenario #	Preceding Display		Current Display	
		PPLT Signal	Through Signal	PPLT Signal	Through Signal
8	15				
	14				
	13				
7	12				
6	11				
	10				
	9				

Sequence #	Scenario #	Final Preceding Display		Follow-Up Display	
		PPLT Signal	Through Signal	PPLT Signal	Through Signal
	8	G◄		Y	
5	7	Y◄		Y	
	6	G◄		Y	
4 & 1	5	G		Y	
	4	R G◄	R	R Y◄	R
3	3	G		Y	
	2	G◄ G		Y◄ G	
2	1	G◄ G		Y◄ Y	