OTREC

OREGON TRANSPORTATION RESEARCH AND EDUCATION CONSORTIUM

FINAL REPORT

Improved Pedestrian Safety at Signalized Intersections Operating the Flashing Yellow Arrow

OTREC-RR-13-02

April 2013

A National University Transportation Center sponsored by the U.S. Department of Transportation's Research and Innovative Technology Administration

IMPROVED PEDESTRIAN SAFETY AT SIGNALIZED INTERSECTIONS OPERATING THE FLASHING YELLOW ARROW

FINAL REPORT

OTREC-RR-13-02

by

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April 2013

Technical Report Documentation Page

1. Report No. OTREC-RR-13-02	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle Improved Pedestrian Safety at Signalized Intersections Operating the Flashing Yellow Arrow		5. Report Date April 2013
		6. Performing Organization Code
7. Author(s) David S. Hurwitz, Chris Monsere, Halston Tuss, Kirk Paulsen, and Patrick Marnell		8. Performing Organization Report No.
9. Performing Organization Name and Address Oregon State University School of Civil & Construction Engineering 305 Owen Hall Corvallis, OR 97331	Portland State University Dept. of Civil & Environmental Engineering PO Box 751 Portland, OR 97207	10. Work Unit No. (TRAIS)
		11. Contract or Grant No. 2012-484
12. Sponsoring Agency Name and Address Oregon Transportation Research and Education Consortium (OTREC) P.O. Box 751 Portland, Oregon 97207		13. Type of Report and Period Covered
		14. Sponsoring Agency Code
15. Supplementary Notes		

16. Abstract

In some jurisdictions, protected left-turn phasing has been replaced with the flashing yellow arrow (FYA) for protected/permissive left turns (PPLTs) to reduce delay. However, it is important to have a thorough understanding of the conflict between pedestrians and the permissive left-turning vehicle. This presentation summarizes the results of research conducted with a high-fidelity, motion-based driving simulator and mobile eye-tracking equipment to study the effects of the opposing traffic, the presence and walking direction of pedestrians, and the number of section heads to display the FYA on driver performance. To accomplish this research, a six-intersection simulated environment was created. In total, 27 subjects completed the course, allowing the analysis of 620 permissive left-turn maneuvers. Eye-glance durations for the intersection approach and turning maneuver were captured for left-turn pavement bay markings, the signal indication, the pedestrian and vehicle waiting area, and the pedestrian signal heads. The total glance durations for each of these areas were analyzed. The following results were obtained: 1) the increased presence of pedestrians led drivers to focus more attention on these crossing pedestrians; 2) as the number of opposing vehicles increased, drivers spent less time fixating on pedestrians; 3) Four to seven percent of drivers did not focus on pedestrians in the crosswalk; and 4) there did not appear to be a difference between any variable and the presence of a three- or four-section head. In terms of practice, the results suggest that it may be desirable to limit the permissive operation when pedestrians are present. Moreover, the findings may indicate that the additional cost of four-section heads is not justified.

17. Key Words Flashing Yellow Arrow, FYA, Pedestrian, Safety, Signalized Intersection, Driving Simulation		18. Distribution Statement No restrictions. Copies available from OTREC: www.otrec.us	
19. Security Classification (of this report) Unclassified	20. Security Classification (of this page) Unclassified	21. No. of Pages 76	22. Price

ACKNOWLEDGEMENTS

This project was funded by the Oregon Transportation Research and Education Consortium (OTREC). The authors would like to recognize the contributions of time and technical expertise to the project made by several individuals. Stacy Shetler and Ed Anderson, transportation engineers with Washington County, OR, were instrumental in providing crash data and analysis to help identify possible intersections for testing and data on cost estimates of three- and four-section vertical signal heads. Shaun Quayle, a senior engineer with Kittelson & Associates, Inc., provided technical guidance regarding state-of-the-art traffic timing solutions to the permissive left-turning vehicle/pedestrian conflict.

Additionally, the authors would like to recognize the matching support provided by Washington County, OR, Oregon State University and Portland State University. Without this matching support, the research would not have been possible.

DISCLAIMER

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EXECUTIVE SUMMARY

When a separate lane is provided for left-turning vehicles, the interval during which drivers turn can be described as either protected or permissive. In a protected interval, the left-turning driver has the exclusive right-of-way and will face no other (legal) conflicts. In permissive operation, the driver can only turn after yielding to conflicting movements, such as pedestrians, vehicles or bicycles. The permissive interval may be communicated to drivers with various traffic-signal indications, such as a circular green, flashing circular red, flashing circular yellow or, more recently, with a flashing yellow arrow (FYA). Following the publication of research that demonstrated its effectiveness (Brehmer et al., 2003; Noyce, 2007), use of the FYA indication for permissive left turns was included in the *Manual on Uniform Traffic Control Devices* (2009). Unlike protected left-turn movements, drivers making a permissive left turn must also search, identify and yield to opposing vehicles, pedestrians and bicycles. The magnitude of the effect of parameters that are likely to affect driver behaviors has not been extensively studied. Based on a review of the literature and discussions with practicing engineers, a set of influential operational situations were identified. These situations included the number of pedestrians and their direction of travel relative to the left-turning driver, the volume of opposing vehicles, and the type of signal head (a three- or four-section head).

An observational field study of these parameters is not possible without significant cost. However, high-fidelity driver simulators offer a robust mechanism to conduct these experiments in a controlled setting. Thus, this research used a simulator to study differences in driver behavior in permissive left turns. Some aspects of the simulator observations were validated with video-based empirical data collected from the field. The research team used Oregon State University's Driving Simulator, a high-fidelity, one-dimensional, motion-based simulator that provides approximately 220 degrees of projection on three forward-projection screens, one rear screen, and two LCD screens on the side-view mirrors. Within the simulated environment, subjects were presented with combinations of approaches with zero, three or nine oncoming vehicles; pedestrians walking towards, away or from both sides; and a four-section vertical configuration or a three-section vertical configuration with a dual-arrow lens (summarized in Table E1). These options resulted in 24 combinations of cases to be analyzed.

Table E 1: Experimental Design

Crossing Pedestrians	Opposing Vehicles	FYA Signal Configuration
No pedestrians	No vehicles	Three-section dual-arrow vertical
One pedestrian *toward* the subject	Three vehicles	Four-section vertical
One pedestrian *away* from subject	Nine vehicles	
Four pedestrians (two each side)		

Drivers were exposed to 24 independent left-turn maneuvers during one 45-minute experimental trial. During each left-turn maneuver, the driver's eye-fixation information (location and duration) and the vehicle's trajectory and lateral position were recorded.

The research tested six hypotheses:

1) ***H_0****: There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with pedestrians walking towards, away or from both sides.*

2) ***H_0****: There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with zero, three or nine opposing vehicles.*

3) ***H_0****: There is no difference in the location of the pedestrian in the crosswalk when the driver initiates a permitted left-turn maneuver at signalized intersections operating the FYA with zero, three or nine opposing vehicles.*

4) ***H_0****: There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with a four-section vertical or a three-section, dual-arrow vertical configuration.*

5) ***H_0****: There is no difference in the location of the pedestrian in the crosswalk when the driver initiates a permitted left-turn maneuver at signalized intersections operating the FYA with a four-section vertical or a three-section, dual-arrow vertical configuration.*

6) ***H_0****: There is no difference in the proportion of drivers who fixate on areas where pedestrians are or may be present during permitted left-turn maneuvers at signalized intersections operating the FYA when pedestrians are present or not in the crosswalk.*

The following results were obtained:

- Compared to the case with minimal pedestrian activity, as the number of pedestrians increased, drivers focused more of their attention on these crossing pedestrians.
- As the number of opposing vehicles increased, drivers spent less time fixating on pedestrians.
- Four to seven percent of drivers did not focus on pedestrians in the crosswalk.
- There did not appear to be a difference between any variable and the presence of a three- or four-section head.

In terms of practice, the results suggest that it may be desirable to limit the permissive operation when pedestrians are present, and that the additional cost of four-section heads may not be justified.

1 INTRODUCTION

When a separate lane is provided for left-turning vehicles, the interval during which drivers turn can be described as either protected or permissive. In a protected interval, the left-turning driver has the exclusive right-of-way and will face no other (legal) conflicts. In permissive operation, the driver may only turn after yielding to conflicting movements, such as pedestrians, vehicles or bicycles. The permissive intervals may be communicated to drivers with various traffic-signal indications, such as a circular green, flashing circular red, flashing circular yellow and, more recently, with a flashing yellow arrow (FYA). After research was published that demonstrated its effectiveness (Brehmer et al., 2003; Noyce, 2007), use of the FYA indication for permissive left turns was included by the Federal Highway Administration (FHWA) in the 2009 edition of the *Manual on Uniform Traffic Control Devices* (MUTCD). The Oregon Department of Transportation (ODOT) was an early adopter and a national leader in the application of the FYA indication for protected/permissive left-turn (PPLT) signal operation, requiring installation of the FYA on all state highways operating using PPLT phasing (ODOT, 2006). Other jurisdictions in Oregon have followed suit and adopted a similar policy.

One advantage of a permissive left-turn operation is that it allows additional time for turning traffic and can potentially reduce overall delay. At intersections and time intervals where demand for the left-turn movement is high and the conflicting movements are low, the savings over protected-only operation can be significant. Policies to determine which intersections should run protected-only or PPLTs usually include safety-related thresholds, such as the approach speed, expected number of turning conflicts, and number of turning lanes. Delay is also a typical consideration. A clear disadvantage of permissive operation is the potential for increased conflicts and decreased safety.

1.1 RESEARCH OBJECTIVES

Unlike protected left-turn movements, drivers making a permissive left turn must also search, identify and yield to pedestrians. Although other aspects of the safety and operation of FYA displays have been studied, driver behaviors with respect to these actions have not been extensively researched. This research was conducted with a high-fidelity, motion-based driving simulator and mobile eye-tracking equipment to study the effect of opposing traffic, the presence of pedestrians and their walking direction, and the number of section heads to display the FYA display (three or four) on driver performance. In total, 27 subjects completed the six-intersection course, which resulted in the analysis of 620 permissive left-turn maneuvers. Eye-glance durations for the intersection approach and turning maneuver were captured for the left-turn pavement bay markings, the signal indication, the pedestrian and vehicle waiting area, and the pedestrian signal heads.

Three experimental factors were tested in the experiment: vehicular volume, pedestrian volume and signal configuration type. Within the simulated environment, subjects were presented with combinations of approaches, with zero, three or nine oncoming vehicles; pedestrians walking towards, away or from both sides; and a four-section vertical configuration or a three-section vertical configuration with a dual-arrow lens. The research tested six hypotheses:

1) $\boldsymbol{H_0}$: *There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with pedestrians walking towards, away or from both sides.*

2) $\boldsymbol{H_0}$: *There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with zero, three or nine opposing vehicles.*

3) $\boldsymbol{H_0}$: *There is no difference in the location of the pedestrian in the crosswalk when the driver initiates a permitted left-turn maneuver at signalized intersections operating the FYA with zero, three or nine opposing vehicles.*

4) $\boldsymbol{H_0}$: *There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with a four-section vertical or a three-section, dual-arrow vertical configuration.*

5) $\boldsymbol{H_0}$: *There is no difference in the location of the pedestrian in the crosswalk when the driver initiates a permitted left-turn maneuver at signalized intersections operating the FYA with a four-section vertical or a three-section, dual-arrow vertical configuration.*

6) $\boldsymbol{H_0}$: *There is no difference in the proportion of drivers who fixate on areas where pedestrians are or may be present during permitted left-turn maneuvers at signalized intersections operating the FYA when pedestrians are present or not in the crosswalk.*

1.2 ORGANIZATION OF THE REPORT

The remainder of this report is organized as follows. In Chapter 2, the relevant literature is reviewed and summarized. Chapter 3 describes the research methods and design. The results and data analysis are presented in Chapter 4, and conclusions are presented in Chapter 5.

2 BACKGROUND AND LITERATURE REVIEW

2.1 PPLT SIGNAL PHASING AND THE MUTCD

The MUTCD provides guidance for multiple arrangements of shared signal faces for PPLT movements (FHWA, 2009). Included configurations consist of the five-section cluster (commonly referred to as the "dog house"), as well as three- and four-section vertical and horizontal arrangements, all of which include a solid green arrow for the protected phase and a circular green permissive indication. The MUTCD does allow dual-arrow signal displays in which, for example, green arrow indications and yellow arrow indications are given from the same signal head. However, such displays are only permitted at locations that have height limitations for the signal head. Today, many locations operate dual-arrow configurations against MUTCD standards. However, the FHWA does not have a mandated compliance period for separated signal faces, according to section 4D.20 of the 2009 MUTCD. Figure 2.1 displays approved MUTCD PPLT configurations.

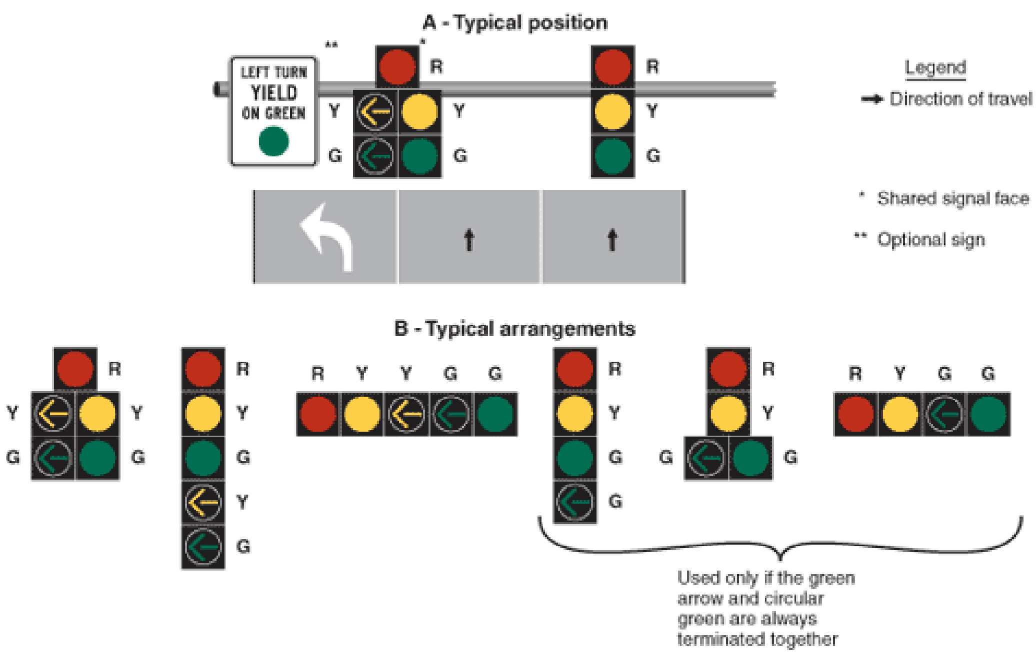


Figure 2.1: Typical Positions (A) and Arrangements (B) of Shared Signal Faces for PPLTs (MUTCD, 2009)

Although a protected left turn can improve intersection safety in certain situations, it can also reduce the efficiency of the intersection by preventing vehicles from accepting adequate gaps when presented. Prior to inclusion of the FYA indication in the MUTCD, PPLT signal phasing indicated this permitted movement with the circular green indication and used a solid green arrow for the protected phase (FHWA, 2009). Knodler et al. (2005) have suggested that the circular green indication, which is also used to give the right-of-way in the through and right-turning lanes, may lead to poor driver comprehension because the same indication provides different messages depending on the particular movement being performed by the driver (i.e., through movement or permissive left-turn). Figure.2.2 shows an example of the traditional PPLT with a circular green signal configuration compared to the current PPLT with a FYA configuration.

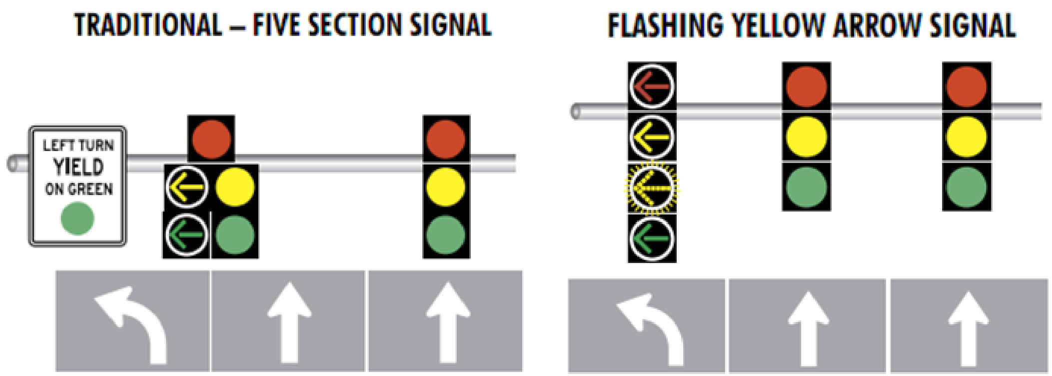


Figure.2.2: Example of Traditional PPLT vs. FYA PPLT Signal Configuration (ODOT, 2012)

With PPLT control, if the left turns are operated as lead-lag, then a "yellow trap" conflict may result. The yellow trap occurs when the driver of a left-turning vehicle is presented a circular yellow after a circular green permissive indication is provided and erroneously assumes that the opposing through traffic is simultaneously presented a circular yellow. When the driver attempts to complete the turn, there is an enhanced possibility of a right-angle crash. With the FYA operating at the same time as the opposing through circular green, the yellow trap is completely eliminated without any additional traffic control devices, reducing the incidence of right-angle crashes (Brehmer et al., 2003).

2.2 PPLT DRIVER CHALLENGES

Work documented in the National Cooperative Highway Research Program (NCHRP) Report 493 identified two independent tasks that a driver must perform in order to accept or reject an adequate gap. The first task is to acknowledge and process the message provided by the left-turn indication, whether by a circular green or a FYA. The second task is to analyze the opposing vehicles and to make the correct decision to turn when an adequate gap in traffic has occurred (Brehmer et al., 2003). Depending on the intersection, different geometric attributes and traffic characteristics can cause this yielding maneuver to vary in complexity for the driver, reducing efficiency or safety at the intersection.

Choosing the appropriate time to enter the intersection requires the driver to assess gaps in the conflicting traffic streams. Drivers often have difficulties when attempting to judge the size of the gaps, in terms of both time and distance. Occasionally, drivers choose to proceed into the intersection when oncoming vehicles are too close or traveling too fast, increasing the likelihood of a severe crash (Neuman et al., 2003). Therefore, gap-acceptance behavior is critical to both the safety and operational performance of signalized intersections operating the FYA.

2.3 INITIAL SIMULATOR AND CONFLICT STUDIES

Before the FYA indication became the standard replacement of circular green indications in separate left-turn signal faces at approaches operating PPLT phasing, several different indications across the country were used for permissive left-turn movements, such as the flashing red arrow, flashing circular yellow and flashing circular red in addition to the FYA (Figure 2.3). Although not uniform, these indications were developed to improve driver comprehension and safety during PPLT operations. The use of various different indications to communicate the same message to drivers was identified as a significant issue. Therefore, research was undertaken to determine a single permissive left-turn indication that could be adopted uniformly.

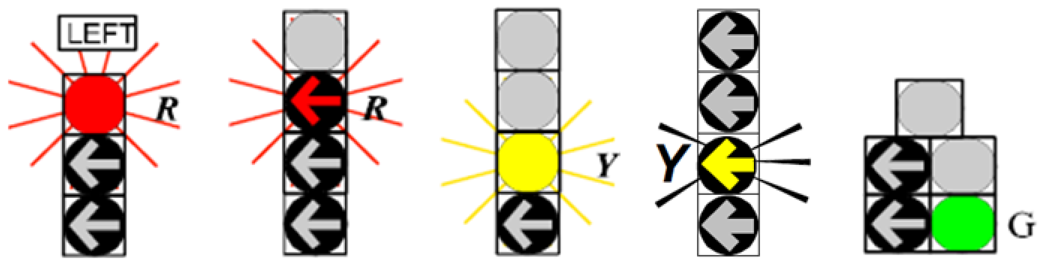


Figure 2.3: Examples of PPLT Indications Used Before MUTCD Recommendations

In 2000, Smith and Noyce tested 34 drivers at the Arbella Human Performance Laboratory Driving Simulator Lab at the University of Massachusetts Amherst (UMass Amherst). They collected 991 responses from indication scenarios to understand the difference in driver comprehension of five different permissive left-turning signal head configurations. The circular green, FYA and flashing circular yellow indications provided relatively equal responses (difference of 1%), but outperformed the flashing red arrow and flashing circular red indications by an average of 28.2%. Moreover, the type of five-section PPLT signal-display configuration (i.e., vertical, horizontal or cluster) had a negligible effect on the percentage of correct responses (Smith and Noyce, 2000).

In 2000, in the *Transportation Research Record: Journal of the Transportation Research Board*, Noyce et al. describe collecting saturation flow rate, start-up lost time, response time, and follow-up headway data from eight U.S. cities and 24 intersections with different PPLT displays. They found no statistically significant difference ($\alpha = 0.05$) in saturation flow rate or start-up lost time between different types of PPLT signal displays across the country. They concluded that any minor differences observed could be attributed to the different traffic operations and driver behaviors at each geographical area studied. Noyce et al. (2000, presented at the 79th annual TRB meeting) also explored traffic conflicts associated with PPLT signal displays and found no statistical difference in conflict rates ($\alpha = 0.05$). The rates were very low for the different PPLT signal displays. Due to the low conflict rates during this research, no conclusions were made concerning the safety effects of operating the different PPLT signal displays.

These preliminary works by Noyce and Knodler provided evidence that the FYA indication could be used to replace flashing circular reds and flashing red arrows for permitted left-turn movements. In 2003, Brehmer et al. published NCHRP Report 493, which comprehensively evaluated PPLT alternatives and recommended inclusion of the FYA in future editions of the MUTCD as an allowable alternative display to the circular green during PPLT operation, but only as an exclusive signal display for the left-turn lane. Additionally, they recommended that the use of a flashing red indication should be restricted to locations where all drivers must come to a full stop during permissive operation (Brehmer, 2003).

Knodler et al. continued research on PPLT signal displays in 2005 using a driving simulator, with an additional focus on the effects of having the FYA indication operating. They observed that when presented with a five-section cluster signal configuration, in which both the left-turn FYA and the through-movement circular yellow are located in the same signal house, some drivers would completely stop in the left-turn lane and have to be directed to proceed by the researchers. However, when drivers were presented with a four-section vertical exclusive left-turn signal configuration and a separate signal for the through lane, a greater percentage of drivers yielded during the permissive left-turn phase (Knodler et al., 2005).

2.4 SAFETY EFFECTS

In 2004, Hauer wrote a draft literature review of research that had been conducted about the safety at intersections that operated with left-turn protection or permissive operations to that date. David and Norman *(*1975*)* determined that, by operating an intersection with a protected left turn, the total number of collisions at an intersection would be reduced by about one-third. Their work also implied that nearly 70% of collisions involving left-turning vehicles would be eliminated by implementing protected phasing. Similarly, Agent and Deen (1979) found that the addition of a protected left-turn phase reduced the incidence of collisions with left-turning vehicles by 85%, increased rear-end collisions by 33%, and decreased total collisions at the intersection by 15%. Benioff et al (1980) looked at the conversion of intersections from protected to protected/permissive. They found that the incidence of total intersection collisions increased by a rate of 1.4, with a 15-fold increase in collisions involving left-turning vehicles, whereas the incidence of rear-end collisions decreased by a rate of 0.4. Warren *(*1985*)* determined that converting from protected to protected/permissive left turns resulted in a 65% increase in collisions involving left-turning vehicles, with no change in "other" collisions. Agent (1987) analyzed the conversion from protected to protected/permissive phasing and concluded that the incidence of collisions involving left-turning vehicles increased by a rate of 4.6, with the same number of total collisions. Analyzing intersections involving two opposing lanes, Upchurch (1991) found that protected phasing accounted for 1.09 left-turning collisions per million left-turning vehicles (collisions/mltv); permissive phasing accounted for 2.62 collisions/mltv; protected/permissive phasing accounted for 2.72 left-turning collisions/mltv; and permissive/protected phasing accounted for 3.02 left-turning collisions/mltv.

In his review, Hauer concluded that it was difficult to arrive at a concrete conclusion because the studies differed in approaches (cross-section vs. before-after), exposure (number of entering vehicles, cross-product, sum of volumes), and the number of approaches or intersections in the data. However, he did determine general accident modification factors (AMFs) for different conversions based on the literature reviewed. In general, an intersection converted from permissive to protected should expect to have an AMF of 0.3 for left-turning collisions and 1.0 for other collisions. An intersection converted from protected/permissive or permissive/protected to protected should expect to have an AMF of 0.3 for left-turning collisions and 1.0 for other collisions.

Since Hauer's review, additional studies have been performed, which are summarized in the Crash Modification Factors (CMF) Clearinghouse (accessed December 2012). A search of the clearinghouse revealed 17 four- or five-star CMFs that relate to left-turn phasing (as shown in Table 2.1). None of these CMFs is included in the first edition of the *Highway Safety Manual*. A five-star rating is the clearinghouse's highest rating. A CMF greater than one indicates an expected increase in crashes when the change is made; a CMF less than one indicates a reduction in crashes. When changing from protected phasing to a FYA, the CMF is 1.338 (standard error [SE] = 0.097) for all crash types and severities. If the change is from protected/permissive to FYA, the CMF is 0.922 (SE = 0.104). For angle-type crashes, the introduction of protected phasing virtually eliminates these crashes (CMFs of 0.04–0.10). For left turn-related crashes, a change of left-turn phasing from protected to FYA has a CMF of 2.242 (SE of 0.276), indicating that the expected crashes more than double. Similar to the trend with all crashes, changing left-turn phasing from protected/permissive to FYA improves safety (CMF = 0.806, SE = 0.146).

Additional studies have been conducted of FYA conversions to PPLT phasing. FYA indications from a protected-only, left-turn phase experienced greater efficiency but reduced safety. The FHWA CMF predict an approximately 65% increase in angle crash frequency due to conversions at locations that exclusively operated protected left-turning movements with a green arrow. This specific CMF cites Hauer (2004) as the source of this information, but the data is ultimately based on Warren's 1985 work. This conclusion is supported by Srinivasan et al., who conducted research to develop CMFs for treatments at signalized intersections in 2011. Treatments analyzed included the installation of the FYA at intersections that previously had protected-only, permissive-only, and protected/permissive left-turn operations. Crash data were collected for 39 total locations, including five in Kennewick, WA, and 34 in Oregon, primarily in the Portland metropolitan area. The analysis by Srinivasan et al. found that for locations with a previously protected condition, the CMF for a FYA was 2.043 for left-turn crashes, which translated into a 49% increase in crashes. However, a CMF of 0.734 was found for FYA treatments at locations that previously had PPLT or permissive-only operation (Srinivasan et al., 2011).

Table 2.1: Protected and Permissive Related CMFs from CMF Clearinghouse

CMF ID	*Countermeasure*	*CMF*	*Crash Type*	*Crash Severity*	*Area Type*	*Pub. Year*	*Star Quality Rating*
4164	Changing left-turn phasing on 1 approach from permissive to protected-permissive	1.081	All	All	Urban	2011	4
4168	Changing left-turn phasing on >1 approach from permissive to protected-permissive	0.958	All	All	Urban	2011	4
4172	Changing left-turn phasing from protected to FYA	1.338	All	All	Urban	2011	5
4176	Changing left-turn phasing from protected-permissive to FYA	0.922	All	All	Urban	2011	4
4165	Changing left-turn phasing on 1 approach from permissive to protected-permissive	0.995	All	Fatal, Serious injury, Minor injury	Urban	2011	4
4169	Changing left-turn phasing on >1 approach from permissive to protected-permissive	0.914	All	Fatal, Serious injury, Minor injury	Urban	2011	4
333	Change from permitted or permitted-protected to protected	0.010	Angle	All	Urban	2008	5
335	Change from permitted to protected on minor approach	0.010	Angle	All	Urban	2007	5
337	Change from permitted-protected to protected on minor approach	0.040	Angle	All	Urban	2007	4
339	Change from permitted-protected to protected on major approach	0.010	Angle	All	Urban	2007	5
2252	Replace permissive with protected	0.021	Angle	All	Urban	2008	4
4166	Changing left-turn phasing on 1 approach from permissive to protected-permissive	0.925	Left turn	All	Urban	2011	4
4170	Changing left-turn phasing on >1 approach from permissive to protected-permissive	0.787	Left turn	All	Urban	2011	4
4173	Changing left-turn phasing from protected to FYA	2.242	Left turn	All	Urban	2011	5
4177	Changing left-turn phasing from protected-permissive to FYA	0.806	Left turn	All	Urban	2011	4
4167	Changing left-turn phasing on 1 approach from permissive to protected-permissive	1.094	Rear end	All	Urban	2011	4
4171	Changing left-turn phasing on >1 approach from permissive to protected-permissive	1.050	Rear end	All	Urban	2011	4

2.5 DRIVER BEHAVIOR

Driving is a complicated, multitasking activity. When dealing with multiple tasks that require continuous and careful attention, the human brain does not perform as well as it does when involved in individual tasks performed separately. The brain can only contribute to a limited number of tasks simultaneously. Once drivers attempt to multitask, their ability to do either task is degraded (Regan, Lee and Young, 2008).

2.5.1 Driver Comprehension

It is important to establish a working definition for the term “driver comprehension,” as it will be referred to within this document. The manual for Human Factors and Traffic Safety defines driver comprehension as “the ease with which the driver can understand the intended message.” It is important for the driver to understand the message of any traffic control device immediately because any delay or misinterpretation may result in driver error (Dewar and Olsen, 2007).

2.5.2 Survey Research on FYA Comprehension

In 2001, Noyce and Kacir conducted a driver comprehension survey and found that FYA indications had a significantly higher correct response rate (61.7%) and lower fail-critical rates. In their study, a fail-critical response was defined as incorrectly assuming left-turn priority. Their findings suggest that the circular green indication, which received a 50.4% correct response rate, may lead to confusion due to its dual purpose during PPLT phasing (Noyce and Kacir, 2001). This conclusion was also supported by work done by Smith and Noyce in 2000 using a driving simulator to evaluate five-section PPLT signal displays. They determined that for a PPLT signal display to be effective, it needed to be understood by nearly all drivers, experienced and inexperienced. The FYA fulfilled this requirement, although the results showed a slightly higher correct response rate with circular green indications, with a difference of approximately 1%. Although they found little difference in driver comprehension between the circular green and FYA indications, both indications had much higher correct response rates than the flashing red arrow and flashing circular red indications, with differences of about 33% and 23%, respectively (Smith and Noyce, 2000).

2.5.3 Driving Simulation Research on FYA Comprehension

In 2005, Knodler and Noyce conducted research using eye-tracking equipment in a driving simulator to understand driver glance patterns and when information sources were being fixated upon. Eleven subjects and 66 simulated intersection interactions were evaluated. The researchers found that 90% of drivers initially focused on the PPLT before focusing on the opposing through traffic to find an adequate gap. Interestingly, drivers were more likely to scan the environment and glance at other sources of information when there was an absence of opposing vehicles, and tended to focus primarily on opposing through traffic when vehicular volumes were high. Additionally, when drivers scanned the environment for alternative cues, they most often glanced from the right to the left (Knodler and Noyce, 2005).

In 2003, to evaluate 12 experimental PPLT signal displays, Knodler et al. conducted a driver simulator experiment and administered a questionnaire to the subjects. The experiment included 432 drivers split between simulators located at UMass Amherst (223 drivers) and the Texas Transportation Institute (209 drivers). In the experiment, left-turn permissive indications, including the circular green, FYA and a combination of both were presented on a five-section cluster, five-section vertical, or four-section vertical signal configuration. Overall, with the 432 subjects in the simulator, scenarios with the FYA and the circular green/FYA combination had more correct responses than scenarios operating with only the circular green ($P < 0.001$). This result was supported by the results of the survey given to the 436 subjects ($P < 0.001$) (Knodler et al., 2003).

In 2006, Knodler et al. used a driving simulator to evaluate driver comprehension of pedestrian requirements at intersections operating the FYA. Drivers maneuvering through a FYA in the simulated environment either did so with a “correct” response, wherein the driver recognized the need to yield to the pedestrian; a “fail-safe” response, wherein the driver began to make the maneuver but eventually noticed the pedestrian and allowed the pedestrian to cross; or a “fail-critical” response, wherein the driver did not yield to the pedestrian in any way. This definition for the fail-critical response differed from that used in the 2001 study by Noyce and Knodler. Knodler et al. found that with 180 simulator responses, there were a statistically lower percentage of “correct” responses than there were of “fail-safe” responses, suggesting that drivers do not understand that they must yield to pedestrians (Knodler et al., 2006).

2.5.4 Driver Inattention

As mentioned in subsection 1.3, the driver may be so attentive to the FYA indication and the demands of vehicle control during the required maneuver that he or she may not notice pedestrians or may even “look but not see” any pedestrians—even though pedestrians may be present. The National Safety Council describes inattention as "cognitive distraction [that] contributes to a withdrawal of attention from the visual scene, where all the information the driver sees is not processed" (National Safety Council, 2010). More simply, inattention occurs when a driver is looking directly at something and does not detect the details of the object due to a mental processing conflict.

2.6 PEDESTRIAN BEHAVIOR

The 2009 MUTCD states that vehicles presented with the FYA must yield to opposing traffic and pedestrians in the crosswalk (FHWA, 2009). However, in many situations, the driver workload is elevated, and drivers fail to scan for pedestrians while performing permissive left-turns (Lord, Smiley and Haroun, 1998). This issue is particularly true in suburban settings, where the expectation for encountering pedestrians is lower. From the pedestrian’s perspective, when a walk signal is presented, they likely expect that vehicles will yield to them as they cross the intersection. When the driver or pedestrian fails to obey traffic laws and either party fails to react to the other’s actions, a potentially serious conflict or crash may occur.

2.6.1 Leading Pedestrian Interval

One potential option to mitigate the right-of-way confusion that contributes to the pedestrian/left-turning vehicle conflict is to use advanced signal software logic to provide an exclusive leading pedestrian interval. Although this modification may help to mitigate the conflict (Fayish and Gross, 2010), this increased safety comes at the cost of decreased vehicular throughput. It is critical to understand when this alternative should be applied because the overall safety at certain intersections may be adversely affected due to its respective layout (Lord, 1996). When the exclusive leading pedestrian interval phase was implemented at three intersections in Florida to provide greater separation in time between movements, 60% fewer pedestrians yielded the right-of-way to vehicles while crossing the intersection (Van Houten et al., 2000). In a related example, 85% of pedestrian conflicts with left-turning vehicles at four-leg signalized intersections occurred during the last half of the green phase. This result suggests that there is a greater risk of conflict when the pedestrian waits longer to initiate walking during the pedestrian phase (Lord, 1996).

2.6.2 Pedestrian Activity

In addition to driver behavior and comprehension, it is important to characterize pedestrian behavior. The behavior of pedestrians at signalized intersections can be unpredictable, and their actions are quite varied (Cinnamon, Schuurman and Hameed, 2011). In a 1971 study of 2,157 pedestrian collisions in 13 U.S. cities, police records indicated that 34% of the collisions were the result of pedestrians abruptly entering the roadway (darting out) at midblock locations, whereas only 7% of the collisions were the result of a vehicle attending to oncoming traffic and not noticing the pedestrian (Shinar, 2007).

When a pedestrian does comply with the walk indication, they tend to walk slower than those who initiate their crossing during either the “flashing don’t walk” or “don’t walk” indication (Knoblauch, Pietrucha, and Nitzburg, 1996) because they are likely not feeling rushed to complete the movement. Ironically, this slower walking speed increases the amount of time that the pedestrian is exposed within the crosswalk. This exposure increases the chance that the pedestrian will become involved in a conflict in which he or she does not have an exclusive phase and vehicles are allowed to turn across his or her path (after yielding to pedestrians). Cinnamon and colleagues observed 9,808 pedestrian crossings at seven urban, four-leg signalized intersections in Vancouver, B.C., where 13% of pedestrians entered the crosswalk illegally (during the “flashing don’t walk” or “don’t walk” phase) (Cinnamon, Shuurmann, and Hameed, 2011). The 13% noncompliance rate consisted of 9.8% of pedestrians (7.2-15.8% at the intersection of Broadway and Commercial) who entered the intersection during the “flashing don’t walk” phase and 3.2% of pedestrians (0.5-9.7% at the intersection of Hastings and Gore) who entered during the “don’t walk” phase.

Pedestrian behavior is highly variable, even within the same city, and likely depends on numerous factors at each individual intersection. A significant reason for noncompliance is the use of a signal-timing plan that includes an unnecessarily excessive amount of pedestrian delay. The longer pedestrians wait, the more likely it is that they will violate the pedestrian signal (Wang et al., 2011).

2.6.3 Young and Elderly Pedestrians

It is intuitive that young and elderly pedestrians act much differently than average adult pedestrians. For example, 67% of elderly pedestrians aged 55 years and older (10 out of 15 people) were observed through video to wait at a signalized crossing in Dublin until they received a walk sign, compared to 44% of those aged 15–24 years (54 out of 123 people) at the same signal (Keegan and O’Mahony, 2003). Rather than choosing not to comply, one reason many elderly pedestrians wait to cross may be their slower walking speeds, which can lead to greater exposure and, therefore, risk. According to Knoblauch and colleagues (1996), for the 15th percentile of pedestrians, young adults walk 4.1 feet per second or less, whereas elderly people walk 3.2 feet per second or less. As an entire population, the 15th percentile of pedestrians walk 3.5 feet per second or less, which is the current speed used when timing walk phases (FHWA, 2009).

As many children lack a complete understanding of traffic laws, they are a group of particular concern. At an urban community in Ontario (Kitchener-Waterloo), MacGregor, Smiley and Dunk (1999) showed that child pedestrians were less likely to search for traffic at signalized intersections (48% of the time) as compared to unsignalized intersections, likely due to the false sense of security provided by the cross walk. In the same community, when children were accompanied by an adult, the children made fewer visual searches than when unaccompanied, likely because they relinquished decision making to the adult.

2.6.4 Pedestrian Gender Differences

Significant differences in pedestrian behaviors are also apparent between genders. In general, males appear to violate traffic rules more often than females. For example, 61% of females (98 out of 160 people) compared to 38% of males (61 out of 161 people) were observed through video to have waited for the walk signal at the aforementioned signalized intersection in Dublin (Keegan and O'Mahony, 2003). Hatfield and Murphy (2007) found that the behavior of females tends to be more influenced than that of males when using a cell phone while crossing an intersection. Males crossed at slower speeds while using a cell phone compared to their crossing speeds when not using a cell phone. When females were using a cell phone, they tended to cross at slower speeds, were less likely to look at traffic before and while crossing, and were less likely to wait for traffic to stop before crossing, as compared to their actions when not using a cell phone.

2.6.5 Group Behavior

Group behavior also affects pedestrian crossing behavior, with pedestrians in groups being more likely to violate the signal. Once one person commits to violating the signal, others tend to follow suit (Wang et al., 2011), even if they may not have violated the signal had they been crossing the intersection as individuals. When groups do choose to comply with the signal and walk during the walk phase, they tend to walk slower than individual pedestrians complying with the same walk phase. For example, "younger" pedestrians (<65 years old by appearance) who crossed as individuals had a mean speed of 5.04 feet per second and a 15th percentile speed of 4.19 ft/s, as compared to groups of younger pedestrians that had a mean speed of 4.66 ft/s and a 15th percentile speed of 3.86 ft/s. Older pedestrians (≥65 years old by appearance) who crossed as individuals had a mean speed of 4.15 ft/s and a 15th percentile speed of 3.23 ft/s, as compared to groups of older pedestrians that had a mean speed of 4.00 ft/s and a 15th percentile speed of 3.12 ft/s (Knoblauch, Pietrucha, and Nitzburg, 1996).

When walking, groups of pedestrians and individual pedestrians proceed at different speeds. However, both groups and individuals experience similar start-up times before fully walking. Younger pedestrians experience a 1.93-second mean start-up time as individuals and as part of a group, whereas older pedestrians experience a mean start-up time of 2.43 seconds when walking as individuals and 2.5 seconds when with a group (Knoblauch, Pietrucha and Nitzburg, 1996).

2.6.6 Driving Simulator Validation

A driving simulator may be validated on an absolute or relative manner, based on observed differences in any number of performance measures, such as speed or acceleration. A driving simulator is "relatively validated" when the differences in observed performance measures in the simulated environment are of similar magnitude and in the same direction as those observed in the real world. A simulator is "absolutely validated" when the magnitude of these differences is not significantly different.

It has been repeatedly found (Godley, Triggs and Fildes, 2002; Bella, 2008) that drivers tend to travel at slightly higher speeds in simulated environments, which some have contributed to a difference in perceived risk. Hurwitz et al. (2007) determined the accuracy with which drivers could perceive their speed in both a real-world environment and a driving simulator. Drivers consistently travelled about 5 mph faster in the simulated environment compared to the real world, consistent with the findings of Godley, Triggs, and Fildes (2002) and Bella (2008). The authors concluded that driving simulation could be an effective tool for speed-related research if the appropriate question was asked.

Bella (2005) tested the validity of the CRISS simulator located at the European Interuniversity Research Center for Road Safety by carefully recreating an existing work zone on Highway A1 in Italy. Over 600 speed observations were taken throughout the work zone and compared to the speed measurements from the simulated environment. The study found that there were no statistically significant differences between field-observed speeds and those from the simulated environment at any location throughout the work zone. Additionally, Bella hypothesized that the lack of inertial forces on the driver, because it was a fixed-base simulator, contributed to a decrease in speed reliability under simulated conditions as the maneuvers became more complex. There is a persistent concern among researchers about the validity of using driving simulation to evaluate driver behavior, due primarily to differences in perceived risk between the simulated environment and the real world. For a simulator experiment to be useful, it is not required that absolute validity be obtained; however, it is necessary that relative validity be established (Törnros, 1998).

2.6.7 Driving Simulator Validation for Left-Turn Research

Knodler et al. (2001) conducted a simulator experiment with 211 subjects that resulted in 2,313 data points. They determined that a driving simulator is an effective way to evaluate PPLT signals and is more accurate than static evaluations. However, this conclusion was determined from the percentage of correct results of the driving simulator versus the static survey and was not validated against field data. To identify the sources of information used by drivers, Knodler and Noyce used eye-tracking equipment on subjects within the UMass Amherst driving simulator laboratory in 2005. Eye movements were classified as "focused" when the driver fixated on an object or area for a second or more and as "glances" when the driver fixated for less than one second.

3 METHODOLOGY

Multiple operational and safety issues regarding implementation of the FYA indication have been studied. However, many details of the permissive left-turn vehicle conflict with pedestrians remain unknown. This research investigated the influence of three factors on this relationship: the opposing traffic volumes, pedestrian volumes and signal display configurations (three- and four-section vertical heads for the FYA). Driver glance durations and behavior patterns were used to identify the fundamental causes of permissive left-turning vehicle conflict with pedestrians.

The research design included experimental tasks in the driving simulator and an empirical study in the field. First, candidate FYA locations were identified from historical crash data from the many installations in Oregon. From this candidate list, a selected set of intersections was identified. Elements of those intersections (approach widths, lane configurations, signal head configurations, and adjacent land use) were modeled in the Oregon State University (OSU) Driving Simulator, a high-fidelity, one-dimensional, motion-based driving simulator providing approximately 220 degrees of projection on three forward-projection screens, one rear screen, and two LCD screens on the side-view mirrors (OSU, 2011). Drivers were exposed to 24 independent left-turn maneuvers during one 45-minute experimental trial. During each left-turn maneuver, fixation information (location and duration), vehicle trajectory and lateral position were recorded.

3.1 RESEARCH DESIGN

Three experimental factors were tested in the experiment: vehicular volume, pedestrian volume and signal configuration type. Within the simulated environment, subjects were presented with combinations of approaches, with zero, three or nine oncoming vehicles; pedestrians walking towards, away or from both sides; and a four-section vertical configuration or a three-section vertical configuration with a dual-arrow lens (Table 3.1). These options resulted in 24 combinations of cases to be analyzed.

Table 3.1: Independent Variables and Levels

Crossing Pedestrians	Opposing Vehicles	FYA Signal Configuration
No pedestrians	No vehicles	Three-section dual-arrow vertical
One pedestrian *toward* the subject	Three vehicles	Four-section vertical
One pedestrian *away* from subject	Nine vehicles	
Four pedestrians (two each side)		

Based on the scenarios presented, three pedestrian-related hypotheses were created:

1) ***H_0**: There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with pedestrians walking towards, away or from both sides.*

2) ***H_0**: There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with zero, three or nine opposing vehicles.*

3) ***H_0**: There is no difference in the location of the pedestrian in the crosswalk when the driver initiates a permitted left-turn maneuver at signalized intersections operating the FYA with zero, three or nine opposing vehicles.*

According to the 2009 MUTCD, a three-section signal face using a dual-arrow signal section can only be used at intersections with height limitations for the signal head. If a three-section signal face is used, only a solid green arrow and FYA can be used in the dual-arrow signal section (FHWA, 2009). An extensive literature review revealed that little to no research has been conducted to determine the specific operational and safety effects of using a three-section dual arrow versus four-section signal configurations (Figure 3.1). Although several dual-arrow configurations exist (for example, in Jackson County, OR), the dual-arrow signal operates a solid yellow arrow and FYA. This research will only focus on the three-section dual arrow that is provided by the 2009 MUTCD.

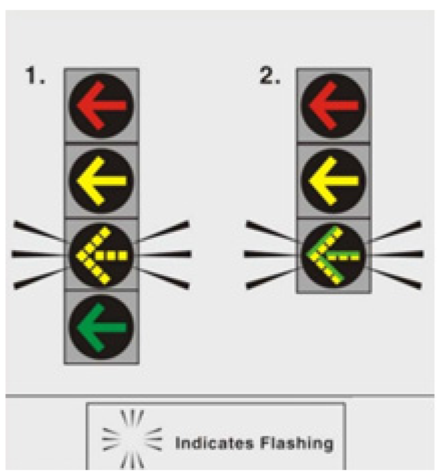


Figure 3.1: The Four-Section Configuration (1) and the Three-Section, Dual-Arrow Configuration (2), in which the Green Arrow is Solid and Only the Bottom Yellow Arrow Flashes.

There is a marked cost difference between the three-section dual-arrow configuration (estimated by Washington County engineers to be $790, including materials and labor) and the four-section configuration ($1,540). Therefore, the effects of the two configurations on driver glance behavior were tested, which led to the following null hypotheses related to the number of sections:

4) ***H_0**: There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with a four-section vertical or a three-section, dual-arrow vertical configuration.*

5) ***H_0**: There is no difference in the location of the pedestrian in the crosswalk when the driver initiates a permitted left-turn maneuver at signalized intersections operating the FYA with a four-section vertical or a three-section, dual-arrow vertical configuration.*

If the subjects tested in the simulator fail to fixate on a crossing pedestrian at any time during the approach and turning movement, then this failure could lead to concerning results. Therefore, the following null hypothesis related to fixation on the pedestrian was tested:

6) ***H_0**: There is no difference in the proportion of drivers who fixate on areas where pedestrians are or may be present during permitted left-turn maneuvers at signalized intersections operating the FYA when pedestrians are present or not in the crosswalk.*

3.2 DRIVING SIMULATOR

3.2.1 OSU Simulator Description

The OSU Driving Simulator is a high-fidelity, motion-based simulator, consisting of a full 2009 Ford Fusion cab mounted above an electric pitch motion system capable of rotating ±4 degrees. The vehicle cab is mounted on the pitch motion system with the driver's eye-point located at the center of the viewing volume. The pitch motion system allows for the accurate representation of acceleration or deceleration (OSU, 2011). Researchers build the environment and track subject drivers from within the operator workstation shown in Figure **3.2:** , which is out of view from subjects within the vehicle.

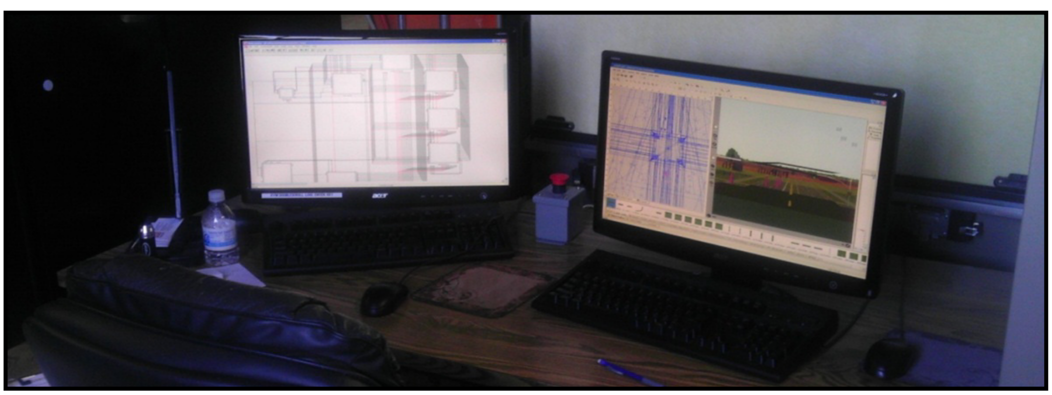


Figure 3.2: Operator Workstation for the Driving Simulator

Three liquid crystals on silicon projectors with a resolution of 1,400 by 1,050 are used to project a front view of 180 degrees by 40 degrees. These front screens measure 11 feet by 7.5 feet. A digital light-processing projector is used to display a rear image for the driver's center mirror. The two side mirrors have embedded LCD displays. The update rate for the projected graphics is

60 hertz. Ambient sounds around the vehicle and internal sounds to the vehicle are modeled with a surround sound system. Figure 3.3 shows views from inside (left) and outside (right) the vehicle.

Figure 3.3: OSU Driving Simulator

3.3 EYE GLANCE DATA

Eye-tracking data were collected by the Mobile Eye-XG platform from Applied Science Laboratories (Figure 3.4). This platform allows the user to have both unconstrained eye and head movement. A sampling rate of 30 Hz was used, with an accuracy of 0.5-1.0 degrees. The subject's gaze was calculated based on the correlation between the subject's pupil position and the reflection of three infrared lights on the eyeball. Eye movement consists of fixations and saccades. Fixations are points that are focused on for a short period of time. Saccades occur when the eye moves to another point. The Mobile Eye-XG system records a fixation when the subject's eyes pause in a certain position for more than 100 milliseconds. Quick movements to another position (saccades) are not recorded directly but are calculated based on the dwell time between fixations. For this research, the saccades were not analyzed due to the research questions being considered.

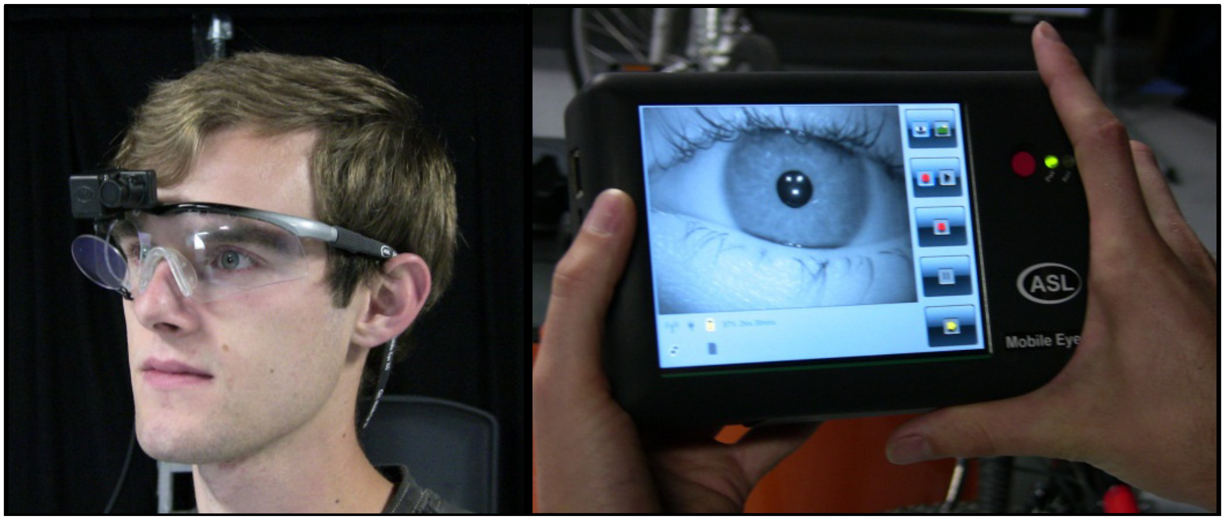


Figure 3.4: OSU Researcher Demonstrating the Mobile Eye XG Glasses (Left) and Mobile Recording Unit (Right)

3.4 SUBJECT RECRUITMENT AND SAMPLE SIZE

Participants in this study were selected from among OSU students and the surrounding community. Participants were required to possess a valid driver's license, not have vision problems, and be physically and mentally capable of legally operating a vehicle. Participants also needed to be deemed competent to provide written, informed consent. Subjects were offered $25 as compensation for study participation. Recruitment of participants was accomplished through the use of flyers posted around campus and emailed to different campus organizations, as well as announcements during transportation engineering classes. Interested participants were screened to ensure that they possessed a valid driver's license and were not prone to motion sickness. This study targeted an enrollment of 30 participants with a balance of gender. Researchers did not screen interested participants based on gender until the quota for either males or females had been reached, at which point only the gender with the unmet quota was allowed to participate. Although it was expected that most participants would be OSU students, an effort was also made to incorporate participants of all ages within the specified range of 18 to75 years. Throughout the entire study, information related to the participants was stored securely in a locked file cabinet in a locked room security in compliance with accepted Internal Review Board procedures. Each participant was randomly assigned a number to remove any uniquely identifiable information from the recorded data.

There was an over-representation of college-aged students, resulting in a relatively low average age of 25.8 years (range, 18–67 years). In total, 38 drivers participated in the test. Eight were unable to complete the test due to simulator sickness or eye-tracker calibration failures. A total of 27 subjects (14 male, 52%) completed the experiment. Other demographic information of the subject population is shown in Table 3.2.

Table 3.2: Subject Summary Demographics

How many years have you been a licensed driver?		
Possible Responses	***Number of Participants***	***Percentage of Participants***
0–5 years	11	41%
6–10 years	7	26%
11–15 years	6	22%
16–20 years	2	7%
20+ years	1	4%
How many miles did you drive last year?		
0–5,000 miles	10	37%
6,000–10,000 miles	8	30%
11,000–15,000 miles	7	26%
15,000–20,000 miles	1	4%
20,000+ miles	1	4%
What type of vehicle do you typically drive?		
Passenger Car	17	63%
SUV	4	15%
Pickup Truck	5	19%
Van	1	4%
Heavy Vehicle	0	0%

3.5 PROCEDURE

Selected participants were invited to meet a researcher at the OSU Driving Simulator Office (Rm. 206A, Graf Hall) on the OSU Campus. At that time, the participants were given the informed-consent document and were provided the opportunity to read the entire document and ask any necessary clarifying questions. The researcher summarized each section of the consent document aloud to reduce confusion. Participants were informed of the potential risk of simulator sickness during this process and were told that they could stop participating in the experiment at any time without monetary penalty. Participants were not told of the research objective or hypothesis.

Subjects were then led to the driving simulator lab, where they were equipped with the ASL Mobile Eye-XG device and were positioned in the driver's seat of the vehicle. Once seated, subjects were allowed to adjust the seat, mirror and steering wheel to maximize comfort and performance while participating in the experiment. The drivers were instructed to behave and follow all traffic laws that they normally would.

Before the eye-tracking equipment was calibrated, each participant was allowed a three-minute test drive within a generic city environment, so that they could become accustomed to both the vehicle's mechanics and the virtual reality itself. The city environment was chosen due to the short turning movements at intersections, which reportedly may contribute to simulator sickness. This test drive provided the opportunity to assess the likelihood that a subject would experience simulator sickness during further experimentation. If the possibility of simulator sickness was believed to be low and the subject was able to drive within the virtual environment successfully, then the researchers calibrated the subject's eyes to points on the screen from their position in the driver's seat. Figure 3.5 illustrates the calibration image shown during the test. If the eye-tracking equipment was unable to perform the calibration, which depended on eye position and other physical attributes, then the experiment was not continued.

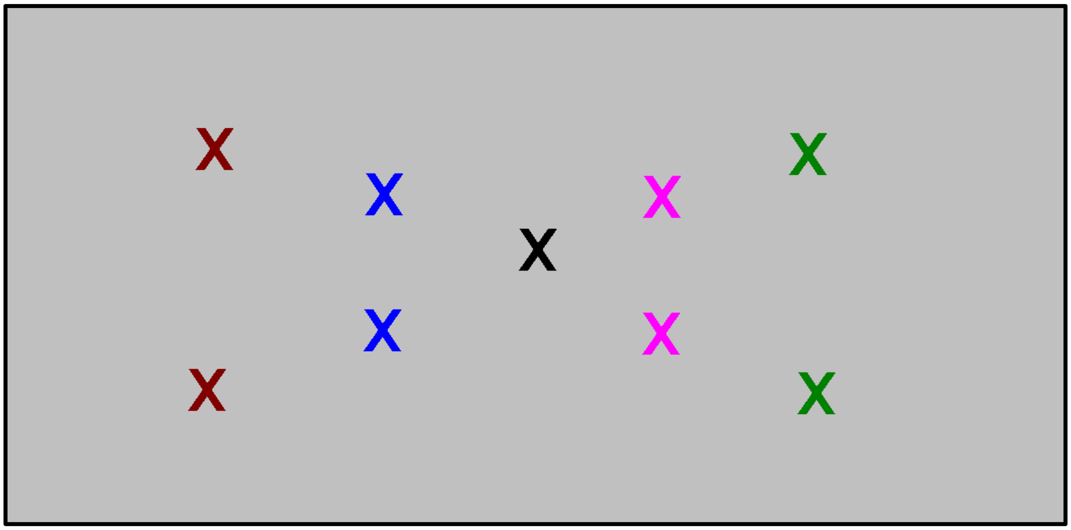


Figure 3.5: Eye-Tracking Calibration Image Shown on the Driving Simulator Screen

After the driver's eyes were calibrated to the driving simulator screens, the driver was given instructions on how to drive through each of the four series of intersections included in the experiment, which are described below.

3.6 SCENARIO LAYOUT AND INTERSECTION CONTROL

Simulator software packages, including Internet Scene Assembler, Simcreator and Google Sketchup, were used to create a virtual environment that could be projected around the driver. This environment was designed to put the driver in situations where observations could be made to address specific experimental questions. The virtual driving course itself was designed to take the subject 20 to 30 minutes to complete. The entire experiment, including the consent process and post-drive questionnaire, lasted about 45 minutes. To reduce the chances of simulator sickness, the driving scenario was split into four grids of six intersections each (Figure **3.6:**). Subjects were given the opportunity to take small breaks between scenarios, rather than being forced to maneuver through all of the intersections without a break. This arrangement also allowed the researchers to introduce one distractor question between each grid. The distractor questions included the following:

- Did you find that the posted mph was appropriate for the road driven?
- How did the presence of bike lanes affect your driving behavior?
- What are your thoughts on the digital dashboard configuration?

Figure 3.6 shows the start point, finish point, and the through and left-turning movements that the subjects were asked to make. The subjects were directed to take the following path: left, left, through, left, left, left, and left within each grid.

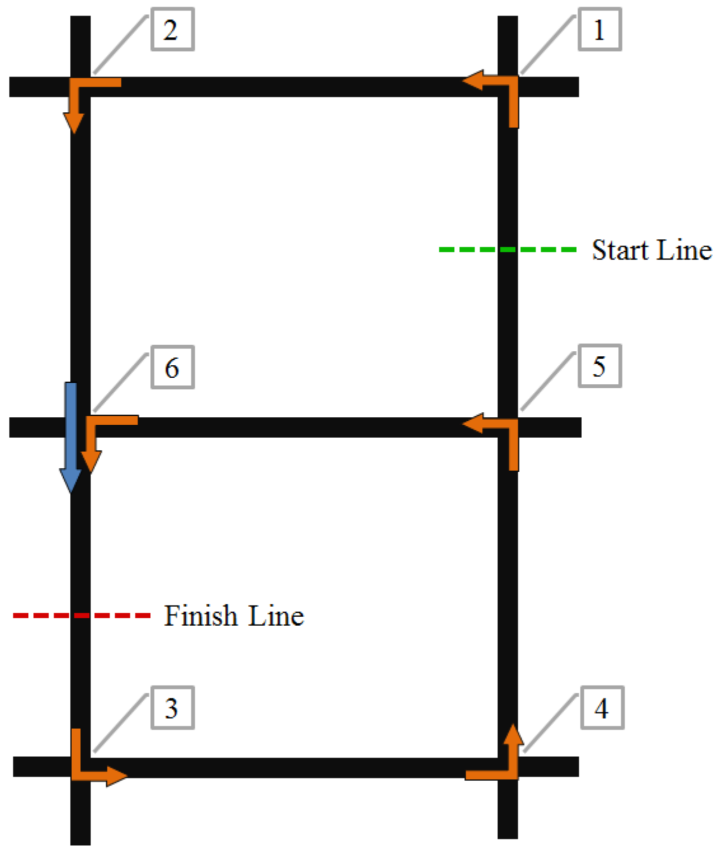


Figure 3.6: Intersection Grid Layout

Subjects were asked to conduct a total of six left-turn movements in each grid while being presented with FYA turn signals in either the four-section vertical or the three-section, dual-arrow vertical configuration. Other experimental variables included combinations of crossing pedestrians and opposing vehicular volume. The tangent sections between intersections measured approximately 1,650 feet. The geometry was two 12-foot lanes with four-foot bike lanes. Figure 3.7 shows an example of an intersection with no opposing vehicles, a pedestrian walking toward the subject, and a three-section, dual-arrow vertical signal.

Figure 3.7: A Three-Section, Dual-Arrow Signal Configuration with Pedestrian Walking Toward Subject

In total, 24 different combinations of the variables were presented to the driver when approaching the intersections (Table 3.3). All intersections consisted of five lanes: two through lanes in each direction and an exclusive left-turn bay. Bike lanes were also included in the virtual environment. The intersection approaches had a posted speed limit of 45 mph.

Table 3.3: Grid and Intersection Layout

Intersection #	Crossing Pedestrians	Opposing Vehicles	FYA Signal Configuration
Grid 1			
1	1 pedestrian *toward* the subject	3 vehicles	3-section dual-arrow vertical
2	No pedestrians	No vehicles	3-section dual-arrow vertical
3	4 pedestrians (2 each side)	No vehicles	4-section vertical
4	1 pedestrian *toward* the subject	9 vehicles	3-section dual-arrow vertical
5	4 pedestrians (2 each side)	3 vehicles	4-section vertical
6	1 pedestrian *away* from subject	9 vehicles	4-section vertical
Grid 2			
1	1 pedestrian *toward* the subject	No vehicles	3-section dual-arrow vertical
2	No pedestrians	3 vehicles	3-section dual-arrow vertical
3	1 pedestrian *toward* the subject	9 vehicles	4-section vertical
4	No pedestrians	No vehicles	4-section vertical
5	4 pedestrians (2 each side)	3 vehicles	3-section dual-arrow vertical
6	1 pedestrian *away* from subject	9 vehicles	3-section dual-arrow vertical
Grid 3			
1	1 pedestrian *away* from subject	3 vehicles	4-section vertical
2	No pedestrians	9 vehicles	3-section dual-arrow vertical
3	1 pedestrian *toward* the subject	No vehicles	4-section vertical
4	1 pedestrian *away* from subject	3 vehicles	3-section dual-arrow vertical
5	4 pedestrians (2 each side)	9 vehicles	4-section vertical
6	1 pedestrian *away* from subject	No vehicles	3-section dual-arrow vertical
Grid 4			
1	No pedestrians	9 vehicles	4-section vertical
2	1 pedestrian *toward* the subject	3 vehicles	4-section vertical
3	1 pedestrian *away* from subject	No vehicles	4-section vertical
4	4 pedestrians (2 each side)	9 vehicles	3-section dual-arrow vertical
5	No pedestrians	3 vehicles	4-section vertical
6	4 pedestrians (2 each side)	No vehicles	3-section dual-arrow vertical

Four different types of scenarios involving pedestrians were presented to the subjects: intersections with no pedestrians; one pedestrian walking towards; one pedestrian walking away from; and four pedestrians walking away from and towards the test vehicle (two pedestrians in each direction).

According to the Institute of Transportation Engineers (ITE) *Transportation Planning Handbook*, one of the most common pedestrian crashes is the vehicle turn/merge conflict type (Meyer, 2009). This conflict type occurs when a pedestrian and vehicle collide while the vehicle is conducting, preparing or has just completed a turning movement. In 2006, in an educational course on pedestrians and bicyclist safety, the FHWA reported that this crash type occurred in 9.8% of all pedestrian crashes, and 18% of these crash types resulted in serious or fatal injuries (FHWA, 2006). Due to these findings, the simulated pedestrians were positioned to the left of the driver, so that each subject would have to maneuver through the pedestrians' walking paths. An illustration of this type of pedestrian/vehicle crash is shown in Figure **3.8:** . The walking speeds of all simulated pedestrians were 3.5 feet per second, which is the suggested design speed found in Chapter 4E of the 2009 edition of MUTCD (FHWA, 2009).

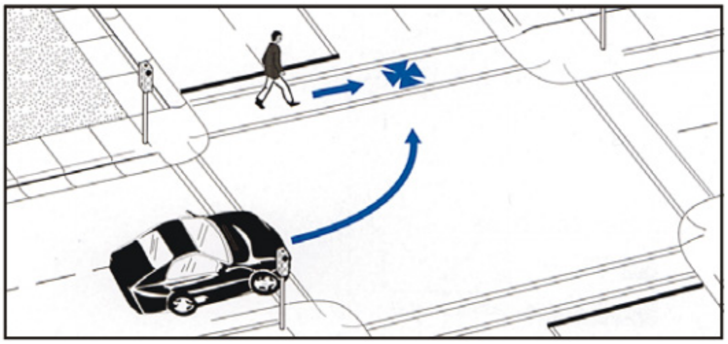


Figure 3.8: Vehicle Left-Turn/Merge Pedestrian Crash Type (FHWA)

When approaching each intersection, the driver was exposed to three different sets of opposing vehicle volumes: zero, three or nine vehicles. Vehicles were released at an average saturation headway of two seconds, based on the FHWA's *Traffic Signal Timing Manual* (FHWA, 2009) and engineering judgment. When converted, this headway results in an average saturation flow rate of 1,800 vehicles per hour of green per lane. The first three to four headways were randomly generated within certain ranges that considered the reaction time to the green indication, replicating the start-up lost time. Figure 3.9 shows a graphical representation from Roess, Prassas and McShane (2004) of the start-up lost time ($\Sigma\Delta_i$) and saturation headway (h). Acceleration of the simulated vehicles were randomly generated within a range that averaged to 5.2 feet per second squared, the acceleration characteristic of a typical passenger vehicle found in the ITE *Traffic Engineering Handbook* (Kraft, 2009) for a speed range between 40 and 50 mph.

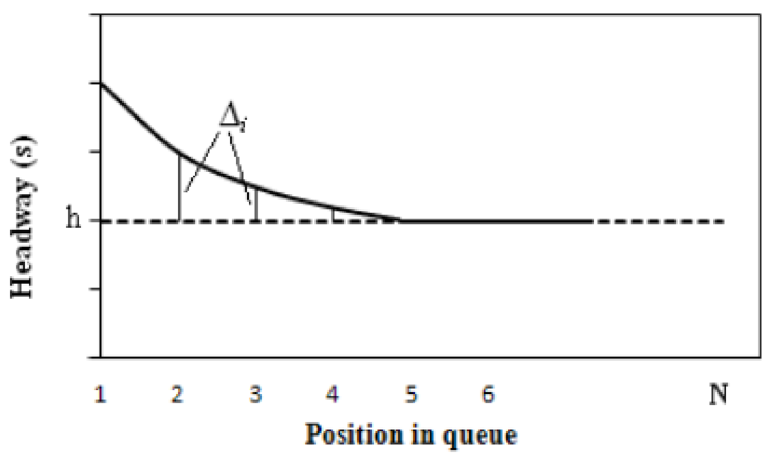


Figure 3.9: Graphical Representation of Start-up Lost Time and Saturation Headway (Roess, Prassas and McShane, 2004)

Subjects were initially exposed to red signals throughout their approach to an intersection. Programmed sensors within close proximity to the signals then triggered the intersection control scripts when the change interval to FYA should be completed, based on the position of the subject's vehicle. This was programmed so that the drivers would be presented with the FYA relatively quickly as soon as they come to a complete stop. However, in some cases, depending on the deceleration rate, subjects come to more of a rolling stop (<5 mph) before the permissive FYA indication. **Error! Reference source not found.** shows an intersection operating the three-section, dual-arrow signal configuration in operation and moments after the nine-vehicle queue had been released.

Figure 3.10: Simulator Screen Capture Showing Nine Queued Vehicles Being Released

3.7 SIMULATOR VALIDATION

To validate driver performance in the simulator, video data were collected at one of the modeled intersections (Southwest Murray Boulevard and Walker Road in Beaverton, OR) for a 48-hour period between Sept.18-20, 2012. This intersection was chosen because it was the only one of the six modeled intersections that had its original FYA signal-timing logic intact and was consistent with our study. All of the other intersections had the signal timing logic modified to eliminate the pedestrian-FYA conflict. Two video cameras were temporarily attached in an inconspicuous manner to the signal pole on the western corner of the intersection. The video cameras provided footage to a DVR that was housed in a weatherproof container on top of the housing for the pedestrian signal head that was attached to the same signal pole. The DVR footage was reviewed and analyzed at a later date. The video cameras captured footage side-by-side, eliminating the need to sync the video. They provided separate views, allowing continuous observation as a vehicle proceeded with its left turn from where it was stationed in the left-turn bay until it had exited the intersection and passed the crosswalk at the end of its turning movement (notice the overlap in the images of Figure 3.11, where the white SUV is shown twice).

Figure 3.11: Screen Capture of the Video Data Collection, Looking NE (Left) and SE (Right)

To confirm that the simulator environment was similar to the actual modeled intersections, researchers investigated whether vehicles would stop in a similar fashion, which would indicate that the user in the simulator had a real-world experience. Because stopping locations were needed to validate the simulator, vehicles that encountered either opposing traffic or pedestrians in the conflicting crosswalk while turning during the FYA phase were recorded. Vehicles that entered during the FYA but did not have to slow down for anything other than the actual turn were not considered. From the footage, it was possible to observe where the vehicle stopped in the left-turn bay relative to the crosswalk (before, in or after the crosswalk); the type of stop performed (full stop, stop and creep, creep and stop, or creep); the number of pedestrians and their crossing direction (towards or away from the vehicle); and the relative amount of opposing traffic (typical rush hour, medium-high traffic, low traffic, or no traffic). These validation data are analyzed in Section 4.5.

4 RESULTS AND DISCUSSION

Out of the 648 possible permissive left-turn maneuvers performed by the 27 subjects, 620 were deemed acceptable for further analysis.

4.1 POST-DRIVE SURVEY AND DRIVER UNDERSTANDING

Upon completion of the simulator experiment, subjects were asked to complete a questionnaire that related to comprehension of the FYA indication. The results of the comprehension questions can be found in Table 4.1. The response to the first question (*If you want to turn left and are presented with the flashing yellow arrow, would you: A) Go. You have the right of way. B) Yield. Wait for a gap. C) Stop. Then wait for a gap. D) Stop. Wait for the signal.*) suggests that most drivers perceived the FYA message correctly (i.e., yield and then wait for a gap). No subjects thought that the FYA gave them the right-of-way or that they must stop and wait for the next signal. All of the subjects who tested correctly understood that, when presented with the FYA, they must yield to both opposing vehicles and pedestrians.

Table 4.1: Driver Response to Questionnaire

If you want to turn left and are presented with a flashing yellow arrow, would you:		
Possible Responses	***Number of Participants***	***Percentage of Participants***
Go. You have the right of way.	0	0%
Yield. Wait for a gap.	24	89%
Stop. Then wait for a gap.	3	11%
Stop. Wait for the signal.	0	0%
If you want to turn left and are presented with a flashing yellow arrow, to whom are you required to yield?		
Opposing vehicles	27	100%
Pedestrians	27	100%
Cross-street vehicles	5	19%
None of the above	0	0%

4.2 DATA REDUCTION

After the experiment, driver fixations for each subject were analyzed by Area of Interest (AOI) polygons with the ASL Results Plus software suite that was provided with the ASL Mobile Eye-XG equipment. For this process, researchers watched each collected approach video (approximately 24 per subject) and drew AOI polygons on individual video frames in a sequence separated by intervals of approximately five to 10 frames. Once the researcher manually moved each AOI, an "Anchor" was created within the software. The distance and size differences of the AOIs between these Anchors was interpolated by the Results Plus software, to ensure that all fixations on the interested objects (i.e., pedestrians, signals and opposing vehicles) were captured. Examples of the different AOIs are shown in Figure 4.1, in which the subject is at a stop line waiting for an appropriate moment to make a left-turn maneuver. At this particular moment in time, the subject is fixating on the pedestrian walking towards their direction (left edge of the figure identified by a blue rectangular AOI and green cross hairs). This figure also shows heat maps (red-yellow circular patterns) for the other AOIs in the field of view.

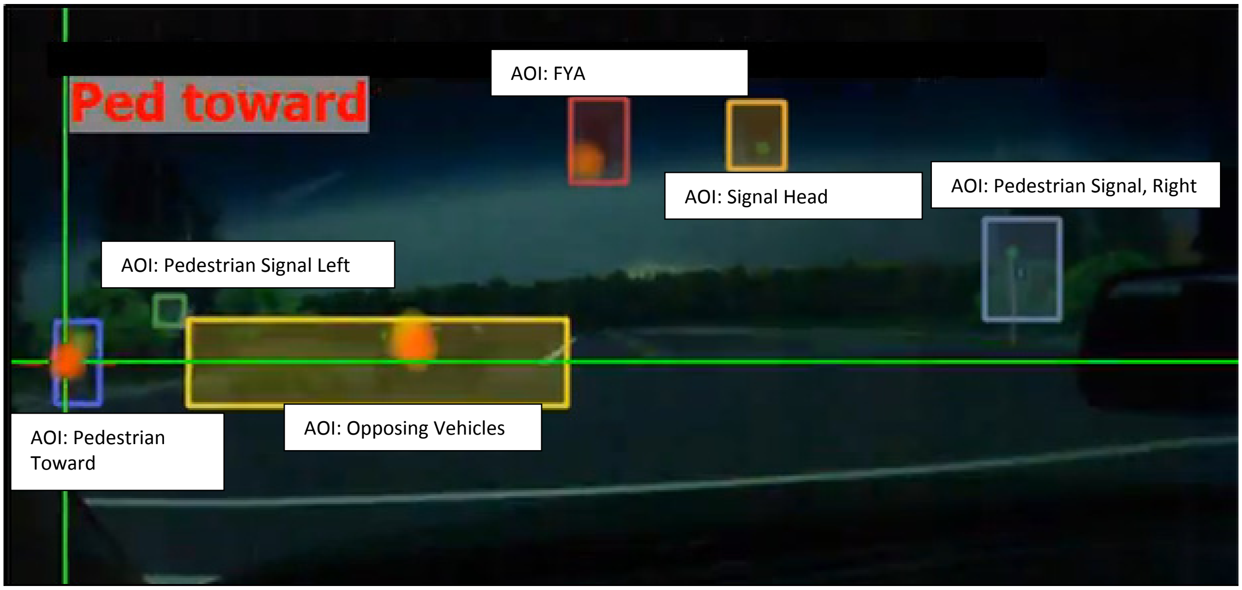


Figure 4.1: Subject at Stop Line Fixating on AOIs

Another example of a subject fixating on an AOI (in this case, a crossing pedestrian walking away from the subject) is shown in Figure 4.2. This figure exemplifies the vehicle turn/merge conflict type, in which the permissive left-turn movement is initiated while the pedestrian is still obstructing the vehicle's path (see Section 3.6). Immediately after the left-turn movement has been completed, the analysis is complete for that particular intersection. The objects of concern for these research questions all exist before the maneuver is complete.

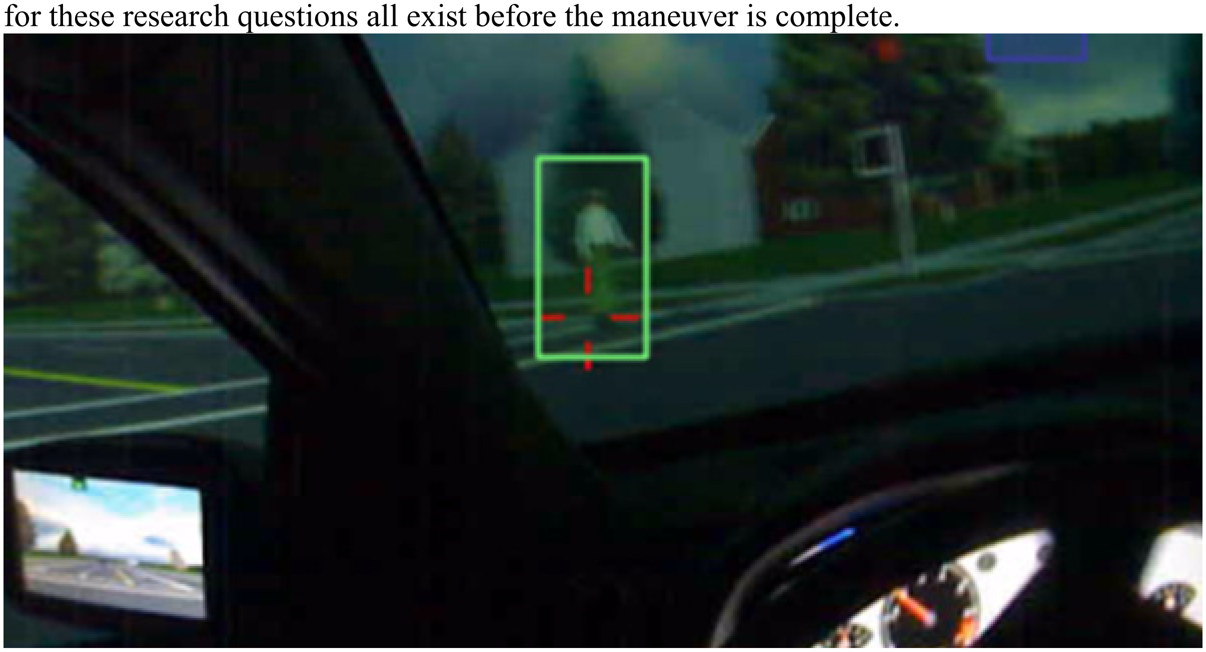


Figure 4.2: Subject Fixation on Crossing Pedestrian Walking Away During Left-Turn Maneuver

Once the AOIs were coded for each individual video file, the ASL Results Plus software was used to output spreadsheets of all of the fixations and their corresponding AOIs. Fixations outside of coded AOIs were universally defined as OUTSIDE and were not used for further analysis. Researchers exported these .txt spreadsheets and imported them into different analysis packages (e.g., Excel and R) for further analysis. An example of a portion of one subject's summary data set provided by the Results Plus software at a single approach with opposing vehicles and a pedestrian walking toward the subject can be found in Table 4.2. This table summarizes the fixations during a single 30-second approach video and includes the number of fixations, total fixation durations, average fixation durations, and time of the first fixation within each AOI created during one intersection approach and left-turn maneuver. Saccades were not exported and analyzed. A 30-second approach video was analyzed for every subject at every intersection.

Table 4.2: Example AOI Summary Table, Subject 00001

AOI Name	Description	Fixation Count	Total Fixation Duration	Average Fixation Duration (s)	First Fixation Time (s)
Bay	Left-turn bay at intersection	4	6.416	0.273	7.663995
FYA	FYA signal head	7	8.593	0.209	7.601724
Opposing Veh	Opposing vehicle queue at intersection	17	29.194	0.292	7.628364
Ped Towards	Pedestrian(s) walking towards the subject	4	6.154	0.87	7.928397
Ped Away	Pedestrian(s) walking away from the subject	2	3.077	0.34	8.433225
Ped Area	Areas where pedestrians could be expected when no pedestrians are present	N/A	N/A	N/A	N/A
Ped Signal Lt	Left-side pedestrian signal	2	0.37	2.178	8.152173
Ped Signal Rt	Right-side pedestrian signal	0	0	0	N/A
OUTSIDE	Any other area	29	46.498	0.272	7.615044

AOIs included the left-turn bay that the subjects merged into from the left through lane; FYA signal; opposing vehicles in the queue; pedestrians walking away from the subject; pedestrians walking toward the subject; pedestrian signals on the left and right; and a pedestrian area when no pedestrians are present.

The average total fixation duration (ATFD) was selected as the primary measure to describe the visual search task across the AOIs considered most germane to this study. The use of the ATFD as a performance measure makes the data more susceptible to outliers than it might otherwise be. For example, a driver who does not fixate on an individual AOI could decrease the ATFD of that AOI, whereas an abnormally high value would increase the ATFD. However, the ATFD is a commonly used measure for analyzing the glance data for driving subjects.

4.3 PRELIMINARY DATA ANALYSIS

Reduction of the eye-tracking video data allowed researchers to perform various descriptive statistics and statistical tests. Although several performance measures were available for analysis, the total fixation duration was considered to be one of the most directly applicable variables for this research. Therefore, for each scenario, the ATFDs from all subjects were collected for each AOI.

Table 4.3: AOI Fixations by Intersection

Intersection Information					ATFD (s)							
Scenaior	*No. Crossing Ped. and Direction*	*No. Opposing Vehicles*	*FYA Config.*	*No. Obser-vations*	*Bay*	*FYA*	*Opp. Veh.*	*Ped Toward*	*Ped Away*	*Ped Signa l Lt*	*Ped Signa l Rt*	*Ped Area*
Grid 1-1	1 Ped Away	3	3-Section	24	2.405	2.132	3.73	0.89	N/A	0.019	0.036	N/A
Grid 1-2	None	None	3-Section	24	2.521	2.255	N/A	N/A	N/A	0.083	0	0.62

Grid 1-3	4 (2 each side)	None	4-Section	25	2.18	2.336	N/A	2.014	1.911	0.223	0.004	N/A
Grid 1-4	1 Ped Away	9	3-Section	26	2.348	1.487	7.102	0.718	N/A	0.036	0	N/A
Grid 1-5	4 (2 each side)	3	4-Section	26	2.403	1.709	2.816	1.68	1.095	0.052	0	N/A
Grid 1-6	1 Ped Towards	9	4-Section	26	1.858	1.507	6.3	N/A	1.177	0.104	0.014	N/A
Grid 2-1	1 Ped Away	None	3-Section	27	2.465	1.483	N/A	2.56	N/A	0.164	0	N/A
Grid 2-2	None	3	3-Section	27	2.33	1.377	4.173	N/A	N/A	0.068	0.004	0.4
Grid 2-3	1 Ped Away	9	4-Section	26	1.19	1.838	6.095	1.04	N/A	0	0	N/A
Grid 2-4	None	None	4-Section	26	2.229	1.911	N/A	N/A	N/A	0.108	0	0.422
Grid 2-5	4 (2 each side)	3	3-Section	26	2.219	0.981	3.197	1.475	1.419	0.072	0	N/A
Grid 2-6	1 Ped Towards	9	3-Section	26	2.502	1.669	6.455	N/A	0.887	0.108	0	N/A
Grid 3-1	1 Ped Towards	3	4-Section	25	2.705	2.007	3.37	N/A	1.365	0.108	0.006	N/A
Grid 3-2	4 (2 each side)	9	3-Section	25	2.907	1.711	7.808	N/A	N/A	0.041	0.006	0.276
Grid 3-3	1 Ped Away	None	4-Section	25	2.206	1.94	N/A	2.58	N/A	0.138	0.012	N/A
Grid 3-4	1 Ped Towards	3	3-Section	25	2.321	1.204	4.326	N/A	1.583	0.166	0	N/A
Grid 3-5	4 (2 each side)	9	4-Section	25	2.43	1.863	5.773	0.875	0.852	0.096	0	N/A
Grid 3-6	1 Ped Towards	None	3-Section	25	2.504	2.121	N/A	N/A	2.266	0.338	0.024	N/A
Grid 4-1	None	9	4-Section	26	2.608	1.816	7.621	N/A	N/A	0.13	0.009	0.273
Grid 4-2	1 Ped Away	3	4-Section	27	2.601	1.731	3.99	1.636	N/A	0.019	0	N/A
Grid 4-3	1 Ped Towards	None	4-Section	27	2.293	2.177	N/A	N/A	2.534	0.278	0	N/A
Grid 4-4	4 (2 each side)	9	3-Section	27	1.423	1.473	5.773	0.833	0.663	0	0	N/A
Grid 4-5	None	3	4-Section	27	2.004	1.221	4.945	N/A	N/A	0.126	0	0.299
Grid 4-6	4 (2 each side)	None	3-Section	27	2.128	1.622	N/A	2.425	2.287	0.214	0	N/A

Figure 4.3 shows the ATFD values for AOIs at an intersection that presented the driver with no pedestrians, no opposing vehicles, and a four-section vertical FYA signal display. This particular intersection is the most basic of all intersections shown to the subjects. It consists of the signal configuration that is standard with the 2009 MUTCD and, therefore, was considered as the control case in the study. The 95% confidence intervals (CIs) were constructed around the mean ATFDs (whisker bars in Figure 4.3).

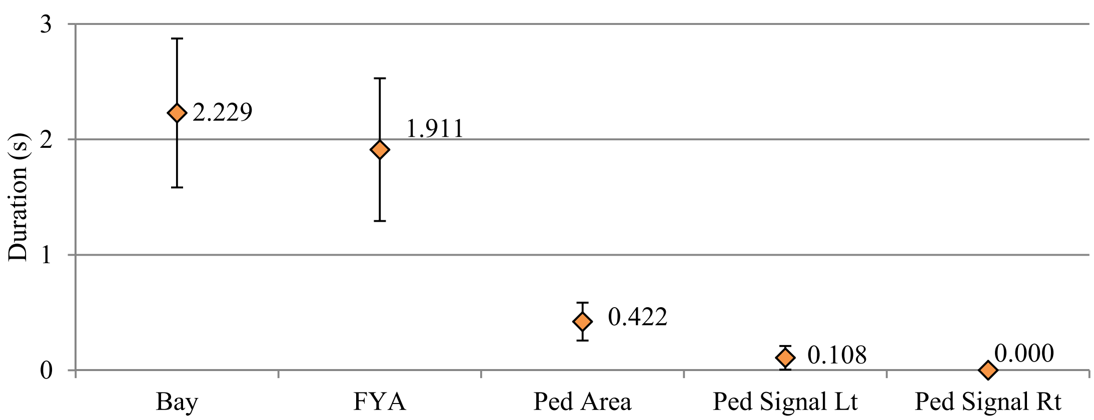


Figure 4.3: ATFDs with 95% CIs for Control Case (Four-Section FYA, No Vehicles, No Pedestrians)

Figure 4.4 shows the ATFDs from all subjects at an intersection with nine opposing vehicles, four pedestrians (two walking away from and two walking towards the subject), and a three-section FYA signal display. This case includes the greatest number of experimental variables. It is the most visually complex case when compared to the control case described in Figure 4.3. Appendix A contains figures showing the ATFDs and 95% CIs for all 24 experimental scenarios.

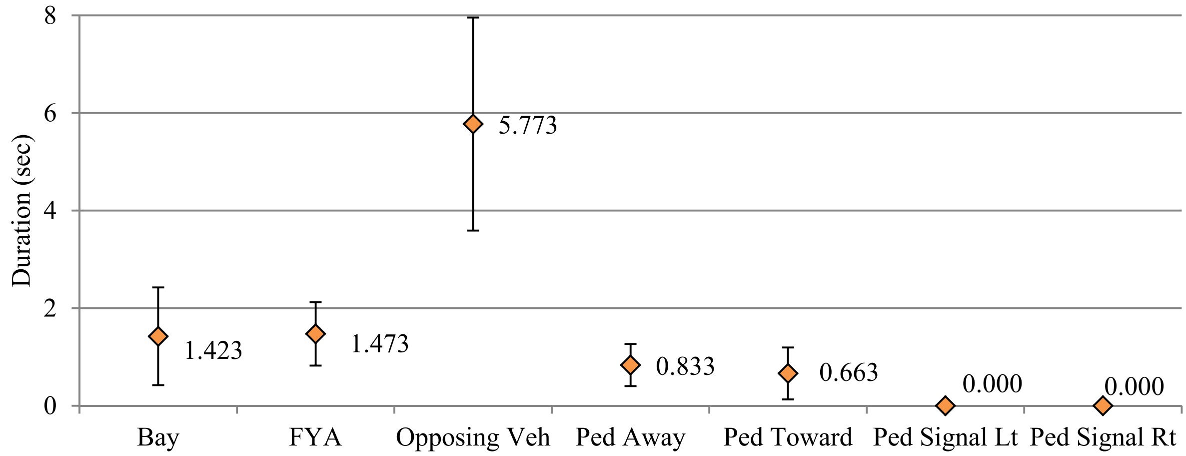
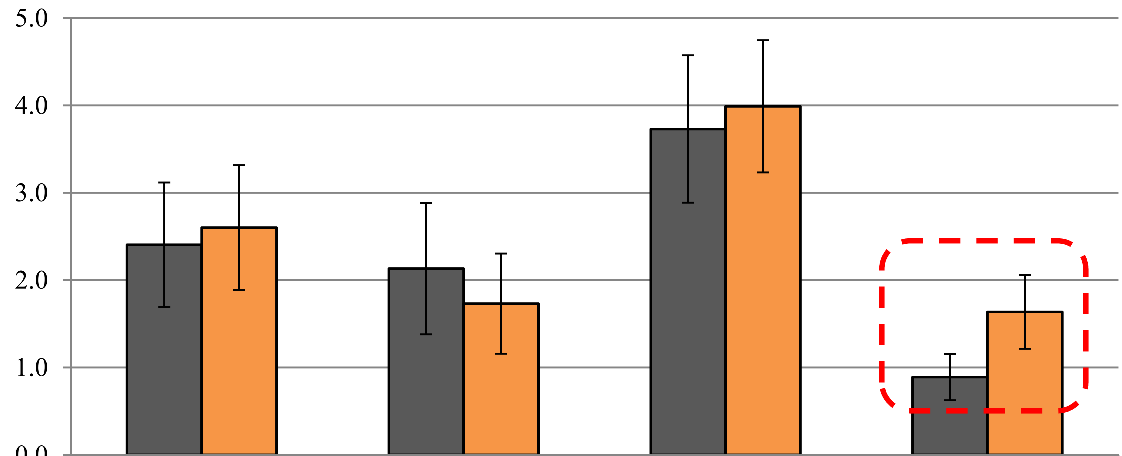


Figure 4.4: ATFD with 95% CIs for Most Visually Complex Case (Three-Section FYA, Nine Vehicles, Four Pedestrians)

Figure 4.5 shows the ATFDs of four AOIs for two experimental scenarios in which all factors were kept constant (one pedestrian walking towards and three opposing vehicles) except for the signal configuration (three- vs. four-section). As described in Chapter 3, Grid 1-1 represents the intersection with the three-section, dual-arrow configuration, whereas Grid 4-2 represents the intersection with the 2009 MUTCD standard four-section, vertical signal configuration. The graphical comparison shows that the ATFDs of pedestrians walking towards the subject and the 95% CIs do not overlap. This finding suggests that when presented with a four-section FYA signal, drivers spend more time fixating on the position of the pedestrians (1.6 seconds) than they do when presented with a three-section FYA signal (0.9 seconds). A two-sample Welch's *t*-test (determined by a two-sample F-test) resulted in a two-tailed *P*-value of 0.008 for this comparison.



	Bay	FYA	Opposing Veh	Ped Toward
Grid 1-1	2.405	2.132	3.730	0.890
Grid 4-2	2.601	1.731	3.990	1.636

Figure 4.5: Bar Plots of ATFD (s) for Two Similar Intersections with Different Signal Configurations

4.4 STATISTICAL ANALYSIS

4.4.1 Pedestrian Direction of Travel

For the first set of statistical analyses, the dataset was split by the three pedestrian levels described by the first null hypothesis found in Section 3.1:

> ***H_0****: There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with pedestrians walking towards, away or from both sides.*

The three resulting groups (pedestrians walking towards, away or from both sides) consisted of six experimental scenarios each. This grouping allowed researchers to isolate the impact of individual variable levels. For example, a possible test could determine the difference between the ATFDs on the FYA AOI between intersections with a pedestrian walking towards the subject (Ped Toward) and intersections with a pedestrian walking away from the subject (Ped Away). Figure 4.6 shows the ATFDs on AOI by pedestrian group.

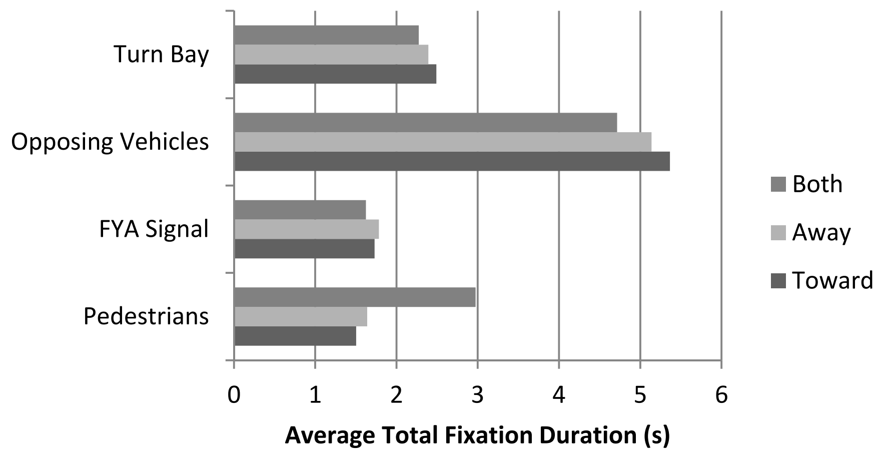


Figure 4.6: Bar Plot of ATFDs at All Intersections, According to Pedestrian Case

To determine whether the ATFD was actually different between specific cases, F-tests were initially conducted to assess if the variances of the two samples were equal. Analysis of variance (ANOVA) was used to determine whether any of the ATFDs differed with pedestrians walking towards, away or from both sides (R software, 2012). Finally, family-wise comparisons were made. In these comparisons each pedestrian case was compared against the remaining pedestrian cases. In order to account for the increased possibility for errors while making multiple comparisons, the p-values shown were calculated using Tukey's Honest Significant Difference (HSD). Table 4.4 presents the results of these tests, with statistically significant P-values shown in bold.

Table 4.4: ANOVA Analysis of ATFDs for Pedestrian Cases

AOIs	**Pedestrian direction of travel**			**ANOVA**	**Tukey's HSD multiple comparisons for pedestrian cases**		
	Toward	Away	Both	All	Toward vs. Away	Toward vs. Both	Away vs. Both
	ATFD (s)			*P*-value	*P*-value	*P*-value	*P*-value
Pedestrians	1.504	1.639	2.974	**< 0.001**	0.489	**< 0.001**	**< 0.001**
FYA Signal	1.730	1.783	1.625	0.704	0.958	0.848	0.689
Opposing Vehicles	5.365	5.138	4.715	0.281	0.848	0.259	0.564
Turn Bay	2.491	2.392	2.274	0.564	0.877	0.533	0.831

The ANOVA analysis showed that only fixations on pedestrians had significant differences in the ATFDs. Family-wise comparison revealed no significant difference between the Ped Toward and Ped Away cases. This finding suggests that fixation durations do not change depending on what direction a single pedestrian is walking in the crosswalk. The only vehicle/pedestrian conflict being tested is that of the turn/merge movement described in Section 3.6. The ATFD for the pedestrian AOIs was statistically different when there was a single pedestrian walking toward the subject versus when two pedestrians were coming from both sides (Ped Both). This result was also found between the Ped Away and Ped Both independent variables. No other significant differences were found with 95% confidence.

4.4.1.1 No Fixations on Pedestrians

When assessing pedestrian-vehicle conflicts during permissive left-turn operations, it is important to determine whether drivers neglect to scan for the presence of pedestrians in or adjacent to the crosswalk.

***H_0**: There is no difference in the proportion of drivers who fixate on areas where pedestrians are or may be present during permitted left-turn maneuvers at signalized intersections operating the FYA when pedestrians are present or not in the crosswalk.*

Individual driver fixation behavior was examined to determine whether failures to scan for pedestrians took place. As depicted in Table 4.5, for all levels of pedestrian activity, a measurable portion of subjects did not fixate on pedestrians.

Table 4.5: Pedestrian AOI Summary Table

Ped Cases	Total (n)	Drivers Who Did Not Look		Drivers Who Looked	
		n	%	n	%
Towards	152	10	6.6%	142	93.4%
Away	150	6	4.0%	144	96.0%
Both	309	16	5.2%	293	94.8%
None	158	62	39.2%	96	60.8%

For the levels of pedestrian activity considered, drivers failed to fixate on pedestrians in the cross walk for 4-7% of the intersection scenarios tested. Comparisons of the proportions between each pedestrian case were made with proportions tests in the R statistical software (Table 4.6). For cases in which pedestrians were present, there was no evidence that the two proportions were different for each of the three comparisons ($P > 0.05$). Although no statistically significant differences were found between the number of drivers who "did not look" across the three pedestrian cases, the fact that the percentage who "did not look" exceeded zero is a finding of this research.

Table 4.6: Proportions Analysis of Pedestrian AOI Comparisons

Comparisons	Difference in Proportion of Drivers	95% CI	*P*-value
Toward vs. Away	2.6%	(-8.3%, 3.1%)	0.457
Both vs. Toward	1.4%	(-6.5%, 3.7%)	0.690
Both vs. Away	1.2%	(-0.3%, 5.7%)	0.748
None vs. Toward	32.6%	(23.4%, 41.9%)	< 0.001
None vs. Away	35.2%	(26.3%, 44.1%)	< 0.001
None vs. Both	34.1%	(25.6%, 42.5%)	< 0.001

At intersections that did not have a crossing pedestrian (Case = None), fixations in the general direction of the pedestrian area were recorded. As expected, a large number of subjects did not fixate on areas where pedestrians could be expected compared to the number of subjects that failed to fixate on pedestrians when they were present. The results of the data analysis supported this assumption ($P < 0.001$ for every comparison involving the Ped Area AOI).

4.4.2 Opposing Vehicle Volumes

For the next series of analysis, the influence of vehicles was considered. The three vehicular volume levels were as described within the second null hypothesis found in Section 3.1:

> ***H_0**: There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with zero, three or nine opposing vehicles.*

Three groups of eight experimental scenarios each were considered, including intersections with zero, three or nine opposing vehicles. Figure 4.7 shows the ATFDs on different AOIs as a function of opposing vehicle volume.

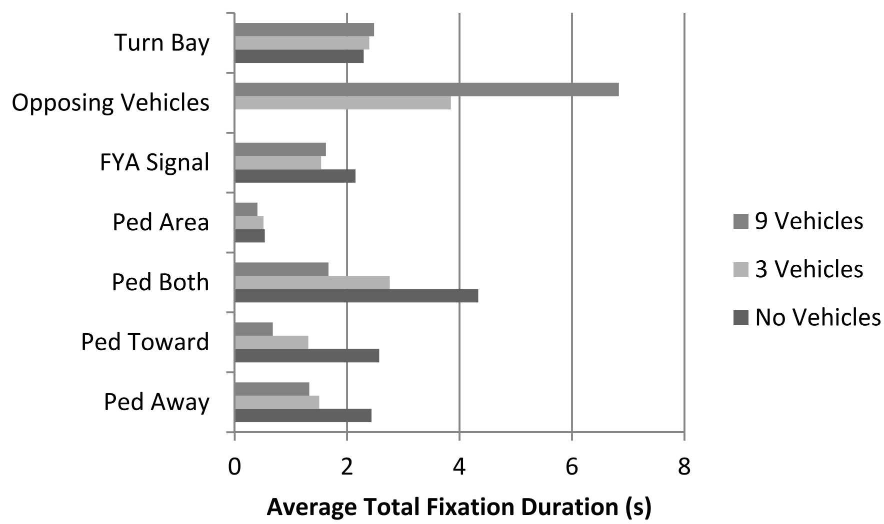


Figure 4.7: Bar Plot of ATFDs at All Intersections, According to Opposing Vehicle Volume

An ANOVA test in the R software package was used to determine whether any significant difference existed between the groupings. The different levels of other variables were compared against one another with Tukey's HSD for multiple comparisons. The results of these statistical analyses appear in Table 4-7, together with the ATFDs for each variable. The comparison of opposing vehicles was different from the other comparisons described. Because a driver cannot fixate on a nonexistent vehicle, only two conditions were tested and multiple comparisons were not required. A two-sided Welch's two-sample *t*-test was used for this comparison.

At intersections with no opposing vehicles compared to all intersections with three opposing vehicles, statistically significant differences (with 95% confidence) were found between the Ped

Away, Ped Toward, Ped Both, and FYA Signal AOIs. This result suggests that the fixation durations do change when there is a low volume of opposing vehicles present compared to when there are no opposing vehicles present. Similar results were found when intersections with no vehicles were compared to intersections with nine opposing vehicles. Significant differences existed between the Ped Toward, Ped Both and Opposing Veh variables when comparing intersections with only three opposing vehicles to intersections with nine. Some of these results were anticipated. For example, one can assume that when the released opposing queue has nine vehicles, more time will be spent fixating on these vehicles than when there are only three vehicles being released.

Table 4.7: ANOVA Analysis Comparing Locations of Differing Opposing Vehicular Volume

AOIs	Mean Opposing Vehicle Volume			ANOVA	Tukey's HSD multiple comparisons		
	No Veh	3 Veh	9 Veh	All	No Veh vs. 3 Veh	No Veh vs. 9 Veh	3 Veh vs. 9 Veh
	ATFD (s)			*P*-value	*P*-value	*P*-value	*P*-value
Ped Away	2.435	1.504	1.328	**< 0.001**	**< 0.001**	**< 0.001**	0.762
Ped Toward	2.570	1.310	0.678	**< 0.001**	**< 0.001**	**< 0.001**	**0.037**
Ped Both	4.334	2.758	1.670	**< 0.001**	**< 0.001**	**< 0.001**	**0.010**
Ped Area	0.536	0.512	0.404	0.145	0.964	0.333	0.511
FYA Signal	2.150	1.538	1.622	**0.012**	**0.001**	**0.007**	0.880
Opposing Vehicles	N/A	3.845	6.833	N/A	N/A	N/A	**< 0.001**†
Turn Bay	2.296	2.394	2.479	0.313	0.842	0.554	0.882

†No multiple comparisons required. The *P*-value reflects a two-sided Welch's two-sample *t*-test. Significant *P*-values are shown in bold type.

4.4.3 Type of Signal Display

The next set of analyses involved comparing all intersections operating the MUTCD standard four-section vertical FYA signal configuration to those operating the three-section, dual-arrow vertical FYA signal configuration as described by the fourth null hypothesis found in Section 3.1:

> ***H_0***: *There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with a four-section vertical or a three-section, dual-arrow vertical configuration.*

Two groups, each with 12 experimental scenarios of different FYA configurations, were examined. Figure 4.8 shows the ATFD results on different AOIs according to the FYA configuration.

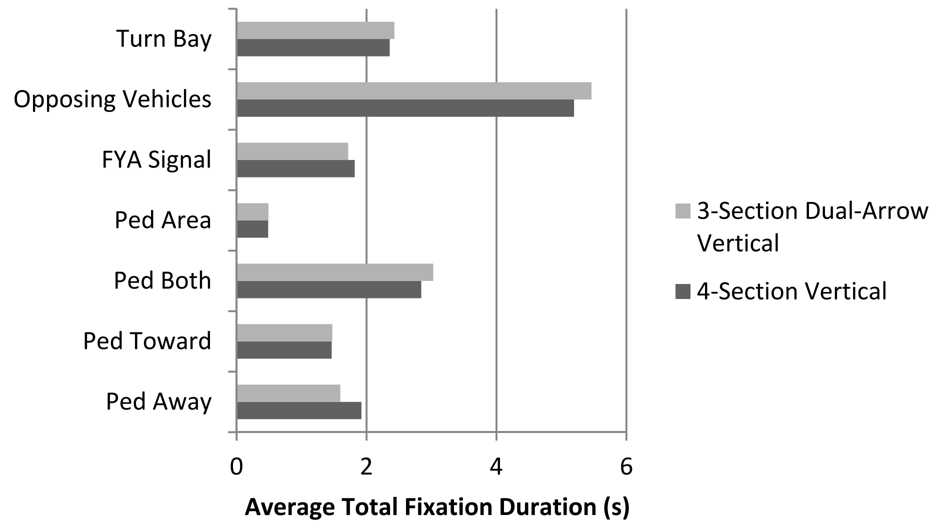


Figure 4.8: Bar Plot of ATFDs at All Intersections, According to FYA Signal Configuration

The 2009 MUTCD does allow the three-section signal configuration, in instances where height restrictions exist. This analysis is of interest to practicing engineers because of the cost differential between the different configurations. According to traffic engineers in Washington County, OR, the three-section signal costs $790 per signal head, whereas the four-section signal costs $1,540. These amounts include materials and labor for installation. These values are based on 21 upgrades of three-section signals and 340 upgrades of four-section signal heads. Although this difference may not seem drastic, when hundreds of conversions are considered (such as they were in Washington County), the additional $800 per signal, time and equipment required became a legitimate concern.

Two-sample, two-sided Welch's *t*-tests were used to determine whether the ATFDs on specific AOIs varied when subjects were confronted with the three-section versus four-section configurations. A summary of these *t*-tests is shown in Table 4.8. No statistically significant differences were identified between the three- or four-section signal configurations. Comparisons were made on a per-intersection basis, in which all variables except signal configuration were held constant. The only statistical difference was found between two intersections that each had one pedestrian walking toward the subject and three opposing vehicles but different signal configurations (Figure 4.5). In this instance, as described earlier within this section, the subjects fixated on the three-section signal longer than the four-section signal, thereby fixating less on the crossing pedestrians.

Table 4.8: Two-sample t-Test of ATFDs Comparing AOIs with Four- vs. Three-Section Signals

AOIs	Signal Configuration		Welch's t-test
	Four-section	Three-section	Four-Section vs. Three-Section
	ATFD (s)		*P*-value
Ped Away	1.923	1.596	0.132
Ped Toward	1.465	1.474	0.965
Ped Both	2.844	3.027	0.588
Ped Area	0.485	0.492	0.929
FYA Signal	1.819	1.718	0.484
Opposing Vehicles	5.196	5.463	0.374
Turn Bay	2.359	2.429	0.676

4.4.4 Pedestrian Lane Position When Driver Turns

The eye-tracking video was used to capture the position of pedestrians in the crosswalk when the drivers initiated their permitted left-turn maneuvers. Initiation of the permitted left was determined by looking at the driver's hands on the steering wheel. This view was readily available from the eye-tracking video. The location of the pedestrian was determined through visual inspection of the scene camera video from the eye tracker. Pedestrian position was classified by one of six Pedestrian Location Numbers (PLNs), as show in Figure 4.9. Due to the nature of the head-mounted eye tracker, it was not always possible to see the pedestrian in the video. PLNs were only included in the data analysis if the scene camera record provided a clear line of sight to the pedestrian.

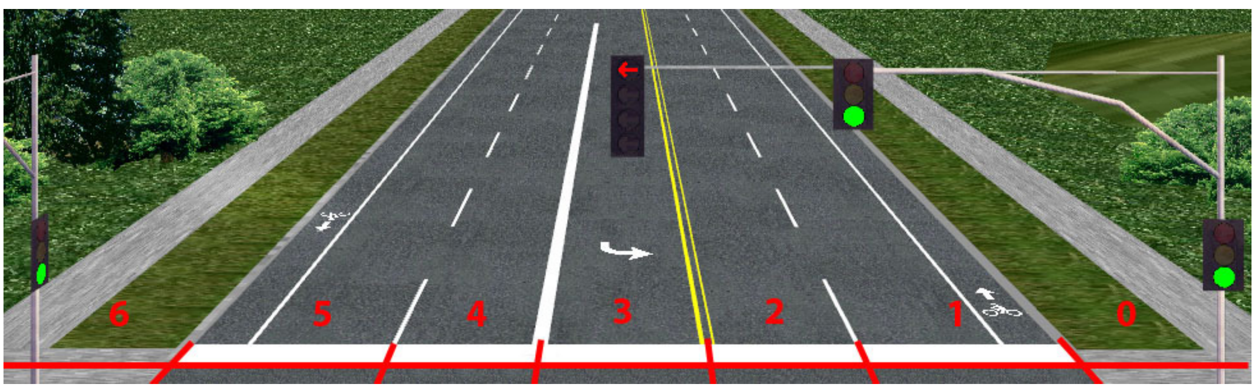


Figure 4.9: PLNs when Driver Initiates a Left Turn

The PLN does not translate directly to distance, due to the inclusion of the bike lanes adjacent to PLNs 1 and 5 and the classification of positions 0 and 6 as anything beyond the location of the curb.

4.4.4.1 Number of Opposing Vehicles

In the first analysis of the pedestrian position, the data set was aggregated by vehicle volume, as described by the third null hypothesis found in Section 3.1:

$\boldsymbol{H_0}$: *There is no difference in the location of the pedestrian in the crosswalk when the driver initiates a permitted left-turn maneuver at signalized intersections operating the FYA with zero, three or nine opposing vehicles.*

The pedestrians were split into four groups: those walking away from the driver when no other pedestrians are present (Away Only); those walking away from the driver when other pedestrians are walking towards the driver (Both Away); those walking towards the driver when no other pedestrians are present (Towards Only); and those walking towards the driver when other pedestrians are walking away from the driver (Both Towards).

ANOVA tests were run with the R statistical software to determine if any differences existed within pedestrian groups between the different levels of opposing traffic (No Veh, 3 Veh, and 9 Veh). In all cases, the ANOVA showed a statistical difference (Table 4.9). For further comparison, family-wise p-values were computed with Tukey's HSD, which revealed a significant difference in pedestrian position, across all pedestrian cases, when comparing 9 Vehicles to 3 Vehicles and 9 Vehicles to No Vehicles. No significant difference was found when comparing 3 Vehicles to No Vehicles.

Table 4.9: Pedestrian Location by Opposing Vehicles

Pedestrian Case	**Mean Ped Lane Position at Turn**	**ANOVA**	**Tukey's HSD multiple comparisons for pedestrian cases**					
		All	9 Veh vs. 3 Veh		9 Veh vs. No Veh		3 Veh vs. No Veh	
		P-value	*P*-value	Diff (PLN)	*P*-value	Diff (PLN)	*P*-value	Diff (PLN)
Away Only	0.873	< 0.001	< 0.001	-1.042	< 0.001	-1.091	0.925	-0.049
Both Away	0.940	< 0.001	< 0.001	-0.923	< 0.001	-0.758	0.539	0.165
Toward Only	3.256	0.007	0.021	1.314	0.005	1.546	0.667	0.232
Both Towards	4.776	< 0.001	< 0.001	1.359	< 0.001	1.485	0.891	0.126

The difference in PLN clearly shows that there was a large significant difference in pedestrian location when comparing 9 Vehicles to 3 Vehicles and 9 Vehicles to No Vehicles. These differences ranged from 0.8 to 1.1 PLN closer to the destination curb when pedestrians were walking away from the driver when nine vehicles were present.

When pedestrians were walking towards the driver, these differences ranged between 1.3 and 1.5 PLN closer to the destination curb when nine opposing vehicles were present. The fact that pedestrians were closer to their destination curb when nine opposing vehicles were present is probably due to the fact that the driver must wait for the opposing vehicles to clear the intersection before making a permitted turn. As a result of this situation, the opposing traffic is the controlling factor for when the driver initiates his or her turn. No significant difference was seen between 3 Vehicles and No Vehicles, which suggests that low levels of opposing traffic are not a significant influence as to when driver initiates the permitted left turn.

4.4.4.2 Type of Signal Display

In the second analysis of the pedestrian position, the data set was split by signal display, as described by the fifth null hypothesis found in Section 3.1:

***H_0**: There is no difference in the location of the pedestrian in the crosswalk when the driver initiates a permitted left-turn maneuver at signalized intersections operating the FYA with a four-section vertical or a three-section, dual-arrow vertical configuration.*

Pedestrians were split into the same groups as before (Away Only, Both Away, Towards Only and Both Towards). Figure 4.10 shows the average PLNs for different pedestrian groups by FYA configuration.

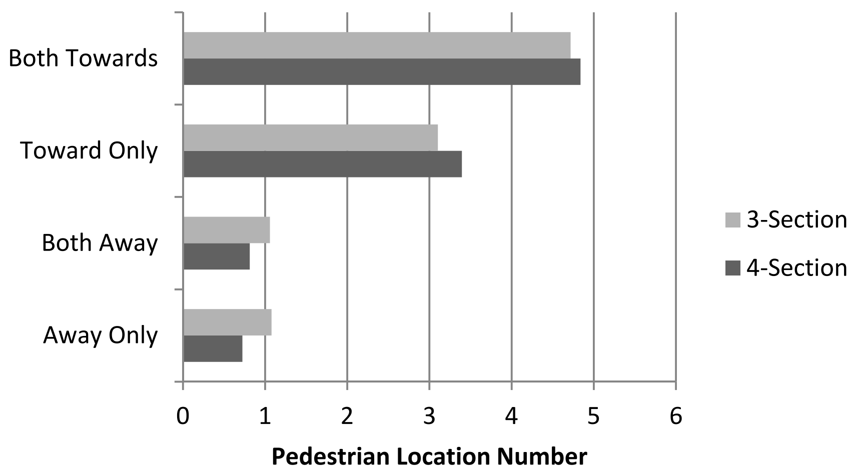


Figure 4.10: Bar Plot of PLNs, According to FYA Signal Configuration

Welch's two-sample, two-tailed *t*-tests by the R software package revealed only one significant difference (Table 4.10). For the Away Only case, the pedestrian location was 0.36 PLN closer to the destination curb in the presence of a four-section signal display as compared to the three-section display ($\alpha = 0.05$). The Both Away case had $P = 0.091$ (shown in italic font in Table 4.10). Although not significant with 95% certainty, this result could possibly become significant if more data were available.

Table 4.10: Pedestrian Location by Signal Configuration

Pedestrian Direction	**Signal Configuration**		**Welch's *t*-test**
	Four-section	Three-section	Four-section vs. Three-section
	Average PLN		*P*-value

Away Only	0.724	1.079	**0.007**
Both Away	0.813	1.058	*0.091*
Toward Only	3.395	3.103	0.277
Both Towards	4.838	4.718	0.665

4.5 SIMULATOR VALIDATION

By utilizing video footage collected in the field (discussed in detail in Section 3.7), driver behaviors between the field and the simulator were compared. The goal of this process was to validate that the simulator closely reflected actual driving conditions. Of the vehicles observed turning left during the FYA while also performing some form of a stop (from a full stop to a creep) during their maneuver, 179 were from the field and 509 were from the simulator. To validate the simulator, the stopping locations of the vehicles as they turned left were compared to the field-observed data. If a vehicle did not come to a complete stop, in either the field or the simulator, then the position that the vehicle reached its lowest speed was considered as its stopping location. Stopping locations were grouped into three common locations: before the first crosswalk, in the first crosswalk, or in the intersection. The results of the stopping location comparison are shown in Figure 4.11 and Table 4.11. The sample size of each group of observations is displayed within each respective bar. A chi-square test for goodness of fit, assuming that the field data show the expected distribution of driver behaviors, indicated that the simulator and field-observed proportions were different ($P = 0.0012$). Although the differences were statistically significant, there was still some similarity in the proportions. The values for In Crosswalk and Before Crosswalk had very similar proportions, and an After Crosswalk stop appeared to be more likely to occur in the field than in the simulator.

Table 4.11: Comparison of Stopping Positions for Simulator vs. Field

	Sample	**Before Crosswalk**	**In Crosswalk**	**After Crosswalk**	**Total**
Observed	Field	120	26	33	179
	Simulator	368	84	57	509
Row Percent	Field	67%	15%	18%	
	Simulator	72%	17%	11%	

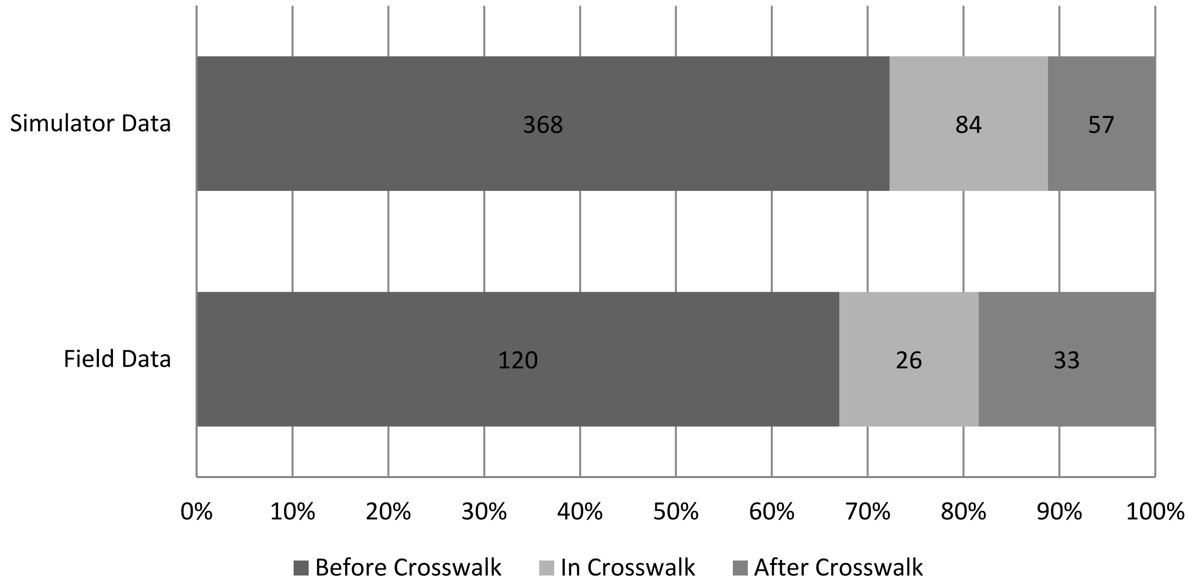


Figure 4.11: Comparison of Left-Turning Vehicle Stopping Locations in Field vs. Simulator

The various stopping patterns were analyzed in the simulator and field data. Stopping patterns were categorized into four groups: vehicles that came to a complete stop and waited to proceed (Full Stop), those that came to a stop and then proceeded by creeping forward (Stop & Creep), those that crept forward and eventually came to a stop (Creep & Stop), and those that continually crept throughout their turn before completing the movement (Creep). The results of the type of stop comparison are shown in Figure 4.12 and Table 4.12. The sample size of each group of observations is displayed within each respective bar. The values for Stop & Creep, Creep & Stop, and Creep had very similar proportions, and a Full Stop appeared to be more likely to occur in the field than in the simulator. A chi-square test for goodness of fit, assuming that the field data show the expected distribution of driver behaviors, confirmed that the simulator and field-observed proportions were different (P <0.001).

Table 4.12: Comparison of Stopping Patterns for Simulator vs. Field

	Sample	Creep	Creep & Stop	Stop & Creep	Full Stop	Total
Observed	Field	18	14	25	122	179
	Simulator	83	58	122	246	509
Row Percent	Field	10%	8%	14%	68%	
	Simulator	16%	11%	24%	48%	

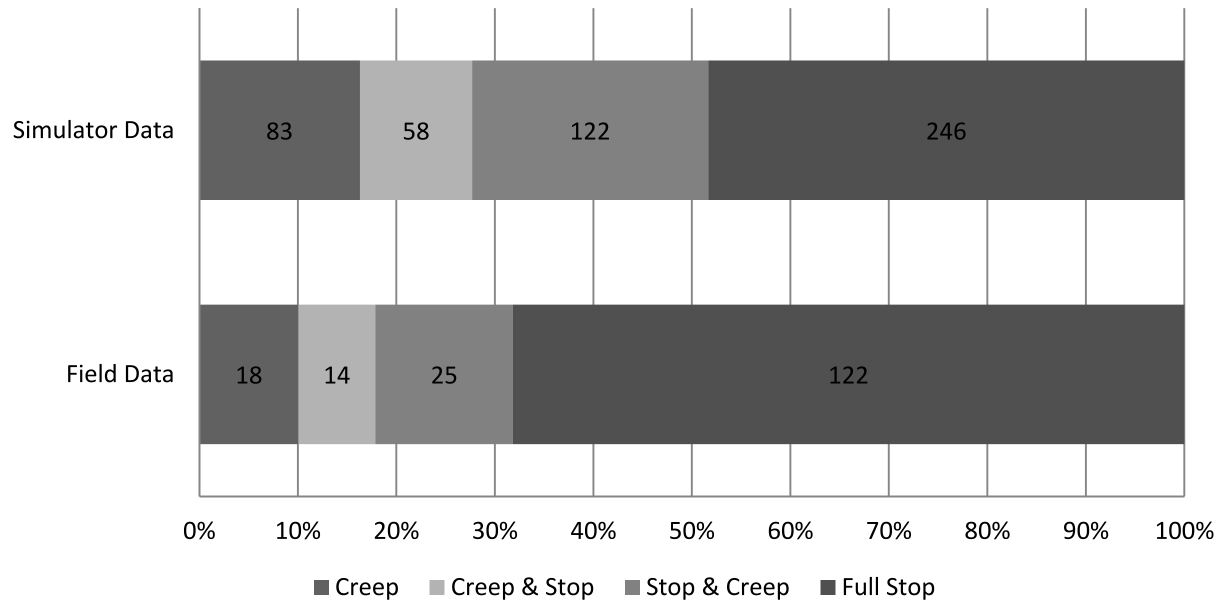


Figure 4.12: Comparison of Left-Turning Vehicle Stopping Patterns for Field vs. Simulator

There are clear reasons for why the simulator and field data stopping positions differed. One reason concerns the amount of opposing traffic that the driver was exposed to while turning left. In the simulator, the approaching volumes were carefully controlled. Drivers experienced no opposing traffic, three opposing vehicles, and nine opposing vehicles at equal rates (one-third of their left-turns, respectively). These observations were placed in the categories of Zero, Low, and Medium, respectively. The field observations took place in a suburban setting, often with large numbers of opposing vehicles. In the field, observations of left turns with no opposing vehicles, about 1–5 opposing vehicles, about 6–15 opposing vehicles, and ≥16 opposing vehicles were placed into the categories of Zero, Low, Medium, and High, respectively. These categories of opposing traffic for the field and simulator are presented in Figure 4.13. Left-turning vehicles in the field often experienced a High amount of opposing vehicles, whereas the simulator was never programmed to display more than nine opposing vehicles. There were also very few instances of no opposing vehicles for drivers in the field, whereas the simulator provided that type of a scenario at one-third of the intersections that the driver turned left.

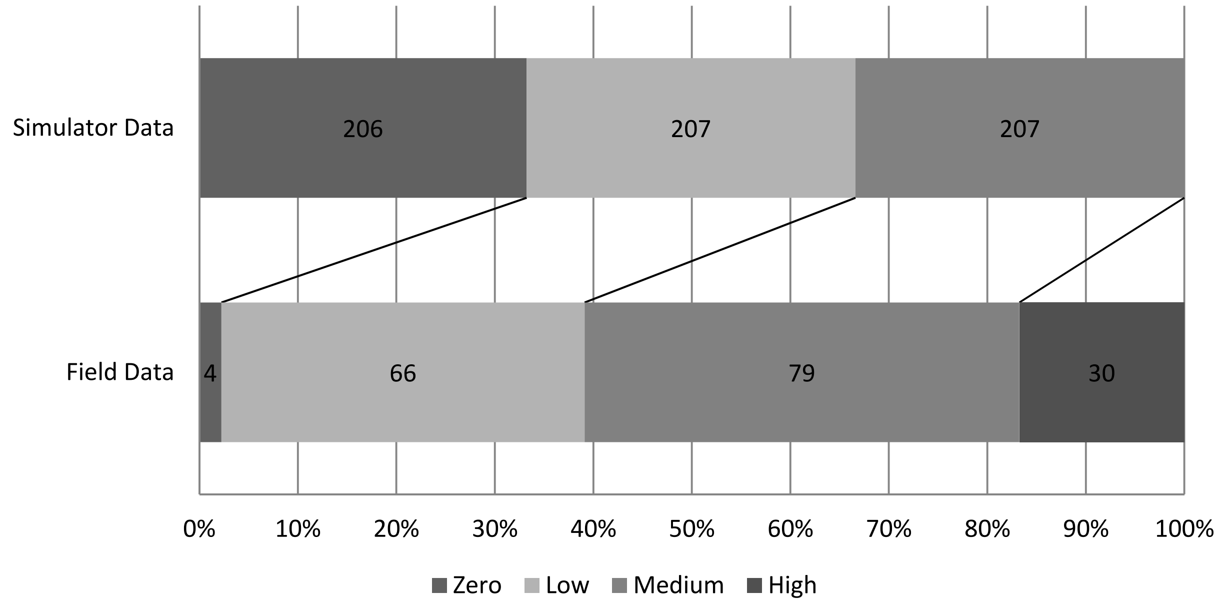


Figure 4.13: Left-Turning Vehicle Observations and Amount of Opposing Traffic for Field vs. Simulator

The second difference between the field and the simulator concerns the number of pedestrians that the driver experienced as they turned left. The field only had four instances of a pedestrian located anywhere within the crosswalk as the vehicle crossed the path of the crosswalk, whereas the simulator scenarios often exposed the driver to pedestrians: sometimes walking away from the driver, sometimes walking towards the driver, and sometimes crossing in both directions. To collect meaningful data about the presence of pedestrians, it was understood that this part of the experiment could not be similar to the field, as it would require an excessive number of simulation runs to create the number of interactions with pedestrians necessary to be able to make confident statements. The large difference in relation to pedestrian interactions between the field and simulator can be observed in Figure 4.14.

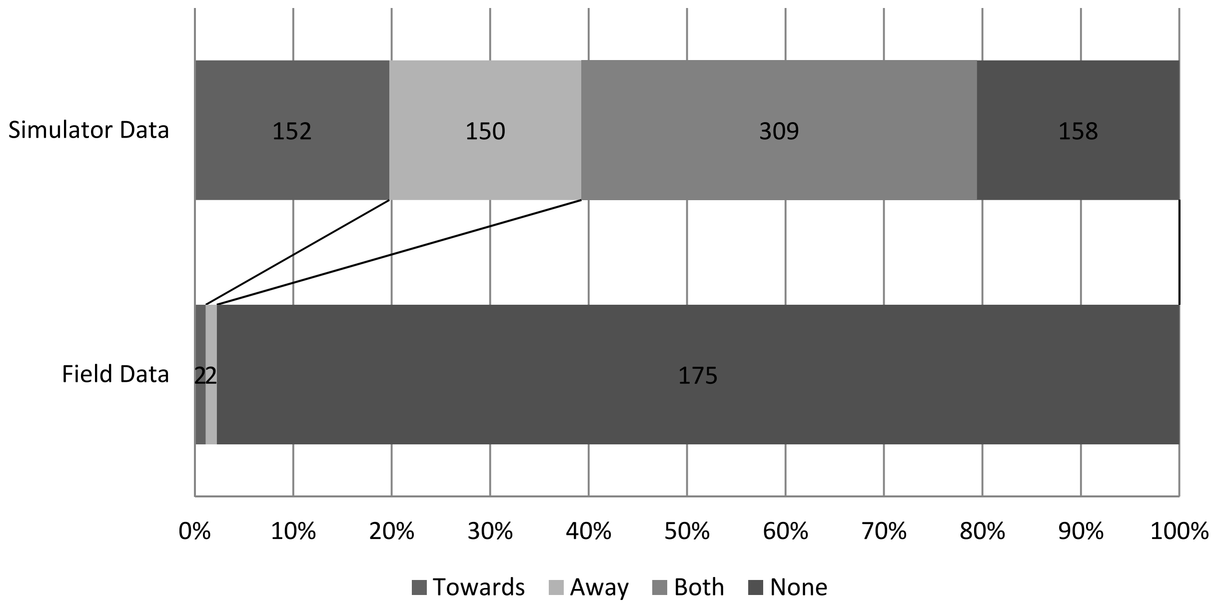


Figure 4.14: Presence and Direction of Pedestrians in the Conflicting Crosswalk for the Field vs. Simulator

5 CONCLUSIONS

Transportation facilities, when designed appropriately, attempt to provide a balance between safety and efficiency while acknowledging the implications of their design on their most vulnerable users. Pedestrians are considered to be among the most vulnerable users of signalized intersections. When in the crosswalk at intersections without protected left-turn phasing, pedestrians are particularly at risk from left-turning vehicles. Although legally required to yield to opposing through vehicles and pedestrians until an acceptable gap is present, it is not uncommon for drivers to fail to observe pedestrians due to other demands on the driving task.

5.1 RESEARCH OBJECTIVES

The research objective of this project was to measure the differences in driver behavior for making permissive left turns at FYA displays. The research explored how average total glance duration and fixation patterns change when presented with different levels of pedestrian volumes, opposing vehicle volumes, and signal configuration types. Six null hypotheses were tested with the driving simulator experimental design:

1) ***H_0***: *There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with pedestrians walking towards, away or from both sides.*

2) ***H_0***: *There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with zero, three or nine opposing vehicles.*

3) ***H_0***: *There is no difference in the location of the pedestrian in the crosswalk when the driver initiates a permitted left-turn maneuver at signalized intersections operating the FYA with zero, three or nine opposing vehicles.*

4) ***H_0***: *There is no difference in the total duration of driver fixations during permitted left-turn maneuvers at signalized intersections operating the FYA with a four-section vertical or a three-section, dual-arrow vertical configuration.*

5) ***H_0***: *There is no difference in the location of the pedestrian in the crosswalk when the driver initiates a permitted left-turn maneuver at signalized intersections operating the FYA with a four-section vertical or a three-section, dual-arrow vertical configuration.*

6) ***H_0***: *There is no difference in the proportion of drivers who fixate on areas where pedestrians are or may be present during permitted left-turn maneuvers at signalized intersections operating the FYA when pedestrians are present or not in the crosswalk.*

5.2 SIGNIFICANT FINDINGS

Section 4.4.1 compared the three pedestrian levels, including cases with pedestrians walking towards the subject, away from the subject, and from both sides of the crosswalk, in the simulated environment. The following significant findings were observed:

- Statistically significant differences ($P < 0.05$) in the ATFDs were found on crossing pedestrians and opposing vehicles between all of the Ped Toward and Ped Both intersections.

- Significant differences in the ATFD on crossing pedestrians were found between the Ped Away and Ped Both intersections.

These results suggest that when there are *more pedestrians* present (four for the Ped Both intersections), drivers focus more of their attention on these crossing pedestrians than when there are minimal pedestrians present (one in the Ped Away and Ped Toward cases).

Section 4.4.2 focused on the vehicular volume levels, specifically intersections with zero, three or nine opposing vehicles. The following findings were observed:

- ATFD was statistically different for all pedestrian levels when subjects were confronted with No Vehicles vs. 3 Vehicles vs. 9 Vehicles, except between 3 Vehicles and 9 Vehicles in the case with pedestrians walking away from the driver. This finding suggests that the opposing volume of vehicles released from the queue affects the focus of subjects on pedestrians. A greater number of opposing vehicles results in less time fixating on pedestrians.

- The ATFD on the opposing traffic was significantly different when there were 3 Vehicles vs. 9 Vehicles.

Section 4.3.2.1 focused on the position of the pedestrians, as described by the lane location when the driver initiates the left-turn (PLN), within the cross walk when the driver initiates a permitted left turn with different vehicle volumes, specifically intersections with zero, three or nine opposing vehicles. The following findings were observed:

- Statistically significant differences ($P < 0.05$) were found in the PLN for all pedestrian cases between 9 Vehicles and 3 Vehicles or No Vehicles.

Section 4.4.3 focused on the FYA signals themselves, specifically comparing locations operating the MUTCD standard four-section vertical vs. the three-section, dual-arrow vertical signal. The analysis suggests that there is no statistically significant difference of ATFD between any variable at all intersections with the four-section and all intersections with the three-section signal. However, in terms of individual intersection comparisons and as shown in Figure 4.5, there was one instance in which a significant difference ($P = 0.008$) was found between the ATFD on pedestrians of two intersections that were almost identical, consisting of Ped Away and 3 Vehicles, with the only differences being the signal configurations. These results suggest that:

- When presented with three opposing vehicles and a four-section FYA signal, drivers spend more time fixating on the position of a pedestrian walking towards them (1.6 s) than they do when presented with a three-section FYA signal (0.9 s).

Section 4.3.2.2 focused on the position of the pedestrians, as described by the PLN, within the crosswalk when the driver initiates a permitted left turn with different signal configurations, specifically the MUTCD standard four-section vertical vs. the three-section, dual-arrow vertical signal. The following findings were observed:

- Statistically significant differences ($P < 0.05$) in the PLN were found for pedestrians walking away from the driver, with no other pedestrians present, between the four- and three-section signal configurations.

This result shows that, for certain situations, pedestrian safety could be positively enhanced by the use of the 4-section display.

Section 4.3.1.4 showed that 7% of drivers failed to fixate on pedestrians walking toward their vehicle; 4% failed when pedestrians were walking away from their vehicle; and 5% failed to fixate on pedestrians walking in both directions. These percentages are alarming and suggest that these specific subjects focused on other variables at the intersections and failed to focus on the most vulnerable road users, pedestrians. In cases where there were no pedestrians present, fixations in the direction of the pedestrian area were collected. The results showed that 39% of all subjects failed to fixate on these areas for any potential crossing or queued pedestrians.

Finally, driver behaviors in the simulator and a selected intersection in the field were compared. Drivers who stopped their vehicles during their left turns were grouped into three common locations of their stops: before the first crosswalk, in the first crosswalk or in the intersection. The proportions of the stopping positions among drivers in the field and simulator were significantly different, although reasonably similar given the differences in opposing traffic and pedestrian activity between the field and the simulated environment. The stopping patterns (i.e., Full Stop, Stop & Creep, Creep & Stop, and Creep) were also significantly different. This result is readily explained by the differences in opposing traffic presented to drivers.

5.3 FUTURE WORK

This research provides insights into the eye glance and fixation patterns of drivers and how they are affected by different variables introduced through a simulated environment. Additional future work could make the dataset and results even more robust:

- As the subject recruitment for this research was primarily from a university population, there was an overrepresentation of the younger population. A larger, more diverse sample size could result in more significant findings that more closely match the driving population.

- Further analyses could be performed on the current dataset, not only from the eye-tracking data but also from the speed and position data of the simulator itself. Examples include fixation sequence (what areas of interest do drivers look at first, second, third, etc.), acceleration and deceleration comparisons when presented with different variables, and the location of the crossing pedestrians when subjects start the turning movement.

- Increasing the number of variables experienced by the tested subjects could also lead to additional results and findings.

Insight has been gained into the position of the pedestrian within the crosswalk when drivers initiate a permissive turn at the FYA. Further study could improve the following findings:

- An effect on PLN by opposing vehicle volume was seen at intersections with 9 Vehicles and 3 Vehicles, and with 9 Vehicles and No Vehicles, but no effect was seen at intersections with 3 Vehicles and No Vehicles. Further study could help determine at what opposing vehicle volume effects are seen on PLN.

- An inconclusive, but suggestive, effect on PLN was noted between the three- and four-section signal displays for pedestrians walking away from the driver (and other pedestrians walking towards the driver). A larger data set could help determine whether a relationship truly exists.

5.4 IMPLICATIONS FOR PRACTICE

After the incorporation of the FYA at hundreds of traffic signals in Washington County, OR, the number once source of complaints became pedestrian-vehicle conflicts. Engineers from Washington County and the research team have hypothesized that the conflict is created when permissive left-turning vehicles fail to yield to the conflicting pedestrian movement. A lack of fixations on likely pedestrian locations suggests that drivers indeed may not even be searching for pedestrians in the conflicting crosswalk.

Any permissive movement at a signalized intersection has the potential to increase efficiency to the detriment of safety by increasing the potential number of conflicts between movements. A more conservative operational approach would involve the separation of the pedestrian phase from the FYA phase to promote pedestrians at the intersection. This separation would allow the pedestrian to cross the approach fully before the FYA indication is displayed, thereby reducing potential conflicts. While the pedestrian phase is being served, the parallel through movements are simultaneously given a circular green.

During traditional FYA operations, in which the FYA is displayed alongside the circular green and pedestrian phases, the left-turning vehicles are required to yield to the queued opposing vehicular movements. Therefore, it is unlikely that the left-turning vehicles would be able to utilize the beginning of the FYA phase when operated simultaneously with the through, right-turning and pedestrian movements. At some intersections, the safety gained by running the pedestrian phase separately from the FYA phase may offset any loss of efficiency of vehicle throughput. Furthermore, this approach could be combined with the leading pedestrian interval to provide additional safety features for pedestrians.

Ultimately Washington Country developed and implemented new logic in the Voyage traffic controller software to eliminate the pedestrian conflict with the permissive left turning vehicle.

This logic has been adopted at every 2070 traffic signal cabinet. They have also elected to use the gap dependent features and the FYA by time of day to reduce vehicle to vehicle crashes and balance the desire for safety and efficiency at their signalized intersections.

REFERENCES

Agent, Kenneth R. "Guidelines for the use of protected/permissive left-turn phasing." *ITE Journal* 57, no. 7 (1987): 37-42.

Agent, Kenneth R., and R. C. Deen. "Warrants for left-turn signal phasing." *Transportation Research Record: Journal of the Transportation Research Board,* 737 (1979): 1-10.

Bella, Francesco. "Driving simulator for speed research on two-lane rural roads." *Accident Analysis and Prevention* 40, no. 3 (2008): 1078-1087.

Benioff, Barry, Thayer Rorabaugh, Frederick C. Dock, Cynthia Carson, and R. Henry Mohle. *A Study of Clearance Intervals, Flashing Operation, and Left-Turn Phasing at Traffic Signals. (Publication No. FHWA-RD-78- 48.,* Washington, D.C.: U.S. Department of Transportation, 1980.

Brehmer, Chris L., Kent C. Kacir, David A. Noyce, and Michael P. Manser. *NCHRP Report 493: Evaluation of Traffic Signal Displays for Protected-Permissive Left-Turn Control*. Washington, D.C.: Transportation Research Board, 2003.

Cinnamon, Jonathon, Nadine Schuurman, and S. Morad Hameed. "Pedestrian Injury and Human Behaviour: Observing Road-Rule Violations at High-Incident Intersections." *PLoS ONE* 6, no. 6(2011): e21063.

Dewar, Robert E., and Paul L. Olson. *Human Factors in Traffic Safety*. 2nd ed. Tucson, AZ: Lawyers & Judges Publishing Co., 2007.

David, N. A., and J. R. Norman. *Motor Vehicle Accidents in Relation to Geometric and Traffic Features of Highway Intersections: Volume II*, *Research (Publication No. FHWA-RD-76-129)*. Washington, D.C.: U.S. Department of Transportation, 1975.

Fayish, Aaron C., and Frank Gross. "Safety Effectiveness of Leading Pedestrian Intervals Evaluated by a Before-After Study with Comparison Groups." *Transportation Research Record: Journal of the Transportation Research Board*, 2198 (2010): 15–22.

Federal Highway Administration. *Federal Highway Administration University Course on Bicycle and Pedestrian Transportation. Lesson 3: Pedestrian and Bicyclist Safety. (Publication No. FHWA-HRT-05-133)*. Washington, D.C.: U.S. Department of Transportation, July 2006.

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

Federal Highway Administration. *Traffic Signal Timing Manual*. Washington, D.C.: U.S. Department of Transportation, 2009.

Godley, Stuart T., Thomas J. Triggs, and Brian N. Fildes. "Driving simulator validation for speed research." *Accident Analysis & Prevention* 34, no. 5 (2002): 589-600.

Hatfield, Julie, and Susanne Murphy. “The Effects of Mobile Phone Use on Pedestrian Crossing Behaviour at Signalised and Unsignalised Intersections.” *Accident Analysis & Prevention* 39, no. 1(2007): 197-205.

Hauer, Ezra. “Left-Turn Protection, Safety, Delay, and Guidelines: A Literature Review.” Draft. 2004. http://turnlanes.net/files/Hauer_LeftTurn_2004.pdf (accessed 12 Dec 2012)

Hurwitz, David S., Haizhong Wang, Michael A. Knodler, Daiheng Ni, and Derek Moore. "Fuzzy Sets to Describe Driver Behavior in the Dilemma Zone of High-Speed Signalized Intersections." *Transportation Research Part F: Traffic Psychology and Behaviour* 15, no. 2 (2012): 132-143.

Keegan, Owen, and Margaret O’Mahony. “Modifying Pedestrian Behaviour.” *Transportation Research Part A: Policy and Practice* 37, no. 10 (2003): 889-901.

Kittelson & Associates, Inc. (2011). *Going Green by Flashing Yellow.* Presented at the Transportation Education Series, Portland, Oregon, November 9th.

Knoblauch, Richard L., Martin T. Pietrucha, and Marsha Nitzburg. “Field Studies of Pedestrian Walking Speed and Start-Up Time.” *Transportation Research Record: Journal of the Transportation Research Board*, 1538 (1996): 27-38.

Knodler, Michael A., and David A. Noyce. “Tracking Driver Eye Movements at Permissive Left-Turns.” Presentation at the Third International Driving Symposium on Human Factors in Driving Assessment, Training, and Vehicle Design, Rockport, ME, 2005.

Knodler, Michael A., David A. Noyce, Kent C. Kacir, and Chris L. Brehmer. “Driver Understanding of the Green Ball and Flashing Yellow Arrow Permitted Indications: A Driving Simulator Experiment.” Presentation at the ITE Conference, Chicago, IL, 2001.

Knodler, Michael A., David A. Noyce, Kent C. Kacir, and Chris L. Brehmer. “Evaluation of Traffic Signal Displays for Protected-Permissive Left-Turn Control Using Driving Simulator Technology.” *Journal of Transportation Engineering* 131, no. 4 (2003): 270-278.

Knodler, Michael A., David A. Noyce, Kent C. Kacir, and Chris L. Brehmer. “Evaluation of Flashing Yellow Arrow in Traffic Signal Displays with Simultaneous Permissive Indications.” *Transportation Research Record: Journal of the Transportation Research Board*, 1918 (2005): 46-55.

Knodler, Michael A., David A. Noyce, Kent C. Kacir, and Chris L. Brehmer. “Analysis of Driver and Pedestrian Comprehension of Requirements for Permissive Left-Turn Applications.”

Transportation Research Record: Journal of the Transportation Research Board, 1982 (2006): 65-75.

Kraft, Walter H., ed. *Traffic Engineering Handbook.* 6th ed. Washington, D.C.: Institute of Transportation Engineers, 2009.

Lord, Dominique. "Analysis of Pedestrian Conflicts with Left-Turning Traffic." *Transportation Research Record: Journal of the Transportation Research Board*, 1538 (1996): 61-67.

Lord, Dominique, Alison Smiley, and Antoine Haroun. "Pedestrian Accidents with Left-Turning Traffic at Signalized Intersections: Characteristics, Human Factors and Unconsidered Issues." Presentation at the 77th Annual Transportation Research Board Meeting, Washington, D.C., 1998. http://safety.fhwa.dot.gov/ped_bike/docs/00674.pdf (accessed 12 Dec 2012)

MacGregor, Carolyn, Alison Smiley, and Wendy Dunk. "Identifying Gaps in Child Pedestrian Safety: Comparing What Children Do with What Parents Teach." *Transportation Research Record: Journal of the Transportation Research Board*, 1674 (1999): 32-40.

Meyer, Michael D., ed. *Transportation Planning Handbook*. 3rd ed. Washington, D.C.: Institute of Transportation Engineers, 2009.

National Safety Council. "Understanding the distracted brain: Why driving while using hands-free cell phones is risky behavior." White paper, Washington D.C., March 2010. http://distracteddriving.nsc.org (accessed 12 Dec 2012)

Neuman, Timothy R., Ronald Pfefer, Kevin L. Slack, Kelly Kennedy Hardy, Douglas W. Harwood, Ingrid B. Potts, Darren J. Torbic, and Emilia R. Kohlman Rabbani. *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan. Volume 5: A Guide for Addressing Unsignalized Intersection Collisions*. Washington, D.C.: Transportation Research Board, 2003.

Noyce, David A., Casey R. Bergh, and Jeremy R. Chapman. *NCHRP Report 123: Evaluation of the Flashing Yellow Arrow Permissive-Only Left-Turn Indication Field Implementation.* Washington, D.C.: Transportation Research Board, 2007.

Noyce, David A, Daniel B. Fambro, and Kent C. Kacir. "Traffic Characteristics of Protected/Permitted Left-Turn Signal Displays." *Transportation Research Record: Journal of the Transportation Research Board*, 1708 (2000): 28-39.

Noyce, David A., Daniel B. Fambro, and Kent C. Kacir. "Traffic Conflicts Associated with Protected/Permitted Left-Turn Signal Displays." Presentation at the 79th Annual Meeting of the Transportation Research Board, Washington, D.C., January, 2000.

Noyce, David A., and Kent Kacir. "Drivers' Understanding of Protected-Permitted Left-Turn Signal Displays." *Transportation Research Record: Journal of the Transportation Research Board*, 1754 (2001): 1-10.

Oregon Department of Transportation. *Traffic Signal Policy and Guidelines*. May, 2006
Oregon State University. *Driving Simulator*. 2011. Retrieved from Driving and Bicycling Research Lab: http://cce.oregonstate.edu/research/drivingsimulator/DrivingSim.php

Regan, Michael A., John D. Lee, and Kristie L. Young, eds. *Driver Distraction: Theory, Effects, and Mitigation*. CRC Press, 2008.

Roess, Roger P., Elena S. Prassas, and William R. McShane. *Traffic engineering*. New Jersey: Pearson/Prentice Hall, 2004.

Shinar, David. *Traffic Safety and Human Behavior*. Emerald Group Publishing, Ltd., 2008.

Srinivasan, Raghavan, Gerald Ullman, Melisa Finley, and Forrest Council. "Use of Empirical Bayesian Methods to Estimate Crash Modification Factors for Daytime Versus Nighttime Work Zones." *Transportation Research Record: Journal of the Transportation Research Board* 2241, no. 1 (2011): 29-38.

Smith, Christopher R., and David A. Noyce. "An Evaluation of Five-Section Protected/Permitted Left-Turn Signal Displays Using Advanced Driving Simulator Technology." Paper presented at the Institute of Transportation Engineers Annual Meeting and Exhibit, Nashville, Tennessee, August 6-9, 2000.

Törnros, Jan. "Driving Behaviour in a Real and a Simulated Road Tunnel—A Validation Study." *Accident Analysis & Prevention* 30, no. 4 (1998): 497-503.

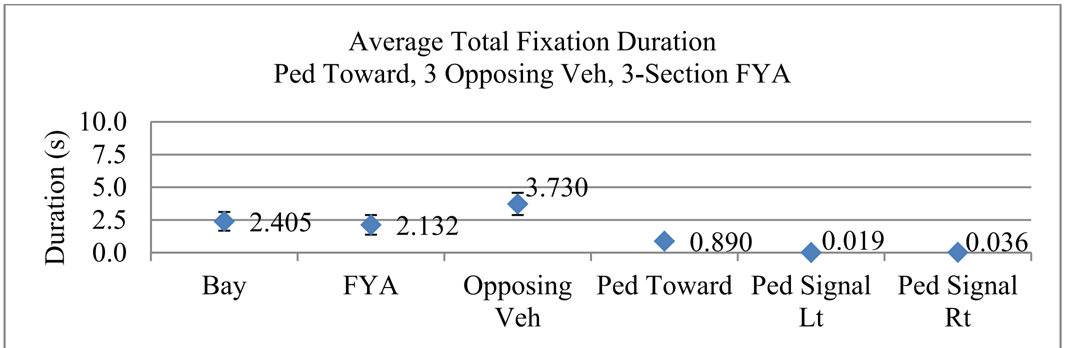
Upchurch, Jonathan. "Comparison of left-turn accident rates for different types of left-turn phasing". *Transportation Research Record: Journal of the Transportation Research Board* 1324 (1991): 33-40.

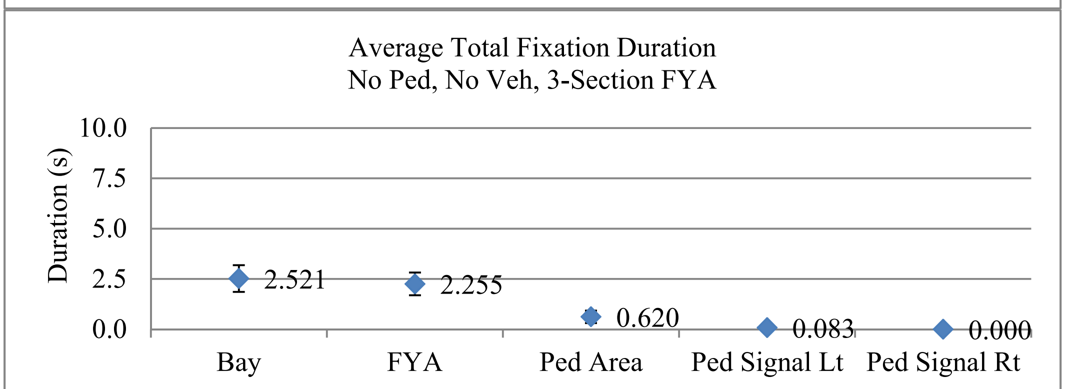
Van Houten, Ron, Richard A. Retting, Charles M. Farmer, and Joy Van Houten. "Field Evaluation of a Leading Pedestrian Interval Signal Phase at Three Urban Intersections." *Transportation Research Record: Journal of the Transportation Research Board* 1734, no. 1 (2000): 86-92.

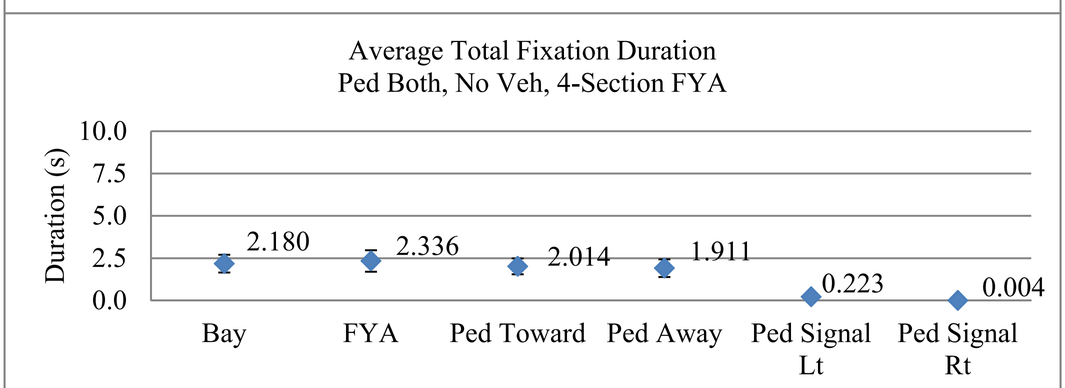
Wang, Wuhong, Hongwei Guo, Ziyou Gao, and Heiner Bubb. "Individual Differences of Pedestrian Behaviour in Midblock Crosswalk and Intersection." *International Journal of Crashworthiness* 16, no. 1 (2011): 1-9.

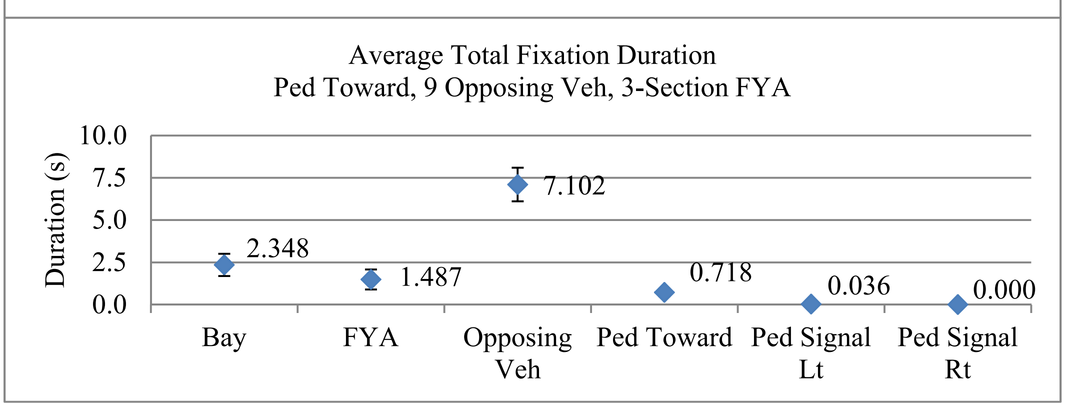
Warren, D. L. "Accident Analysis of the Left Turn Phasing." *Public Roads* 48, no. 4, (1985): 121-127.

6 APPENDIX


Average Total Fixation Duration
Ped Toward, 3 Opposing Veh, 3-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
2.405
2.132
3.730
0.890
0.019
0.036
Bay
FYA
Opposing Veh
Ped Toward
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
No Ped, No Veh, 3-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
2.521
2.255
0.620
0.083
0.000
Bay
FYA
Ped Area
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
Ped Both, No Veh, 4-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
2.180
2.336
2.014
1.911
0.223
0.004
Bay
FYA
Ped Toward
Ped Away
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
Ped Toward, 9 Opposing Veh, 3-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
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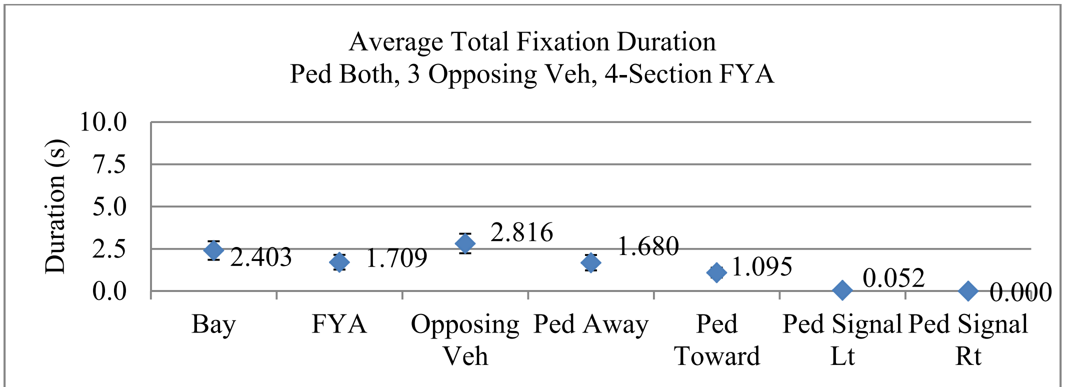
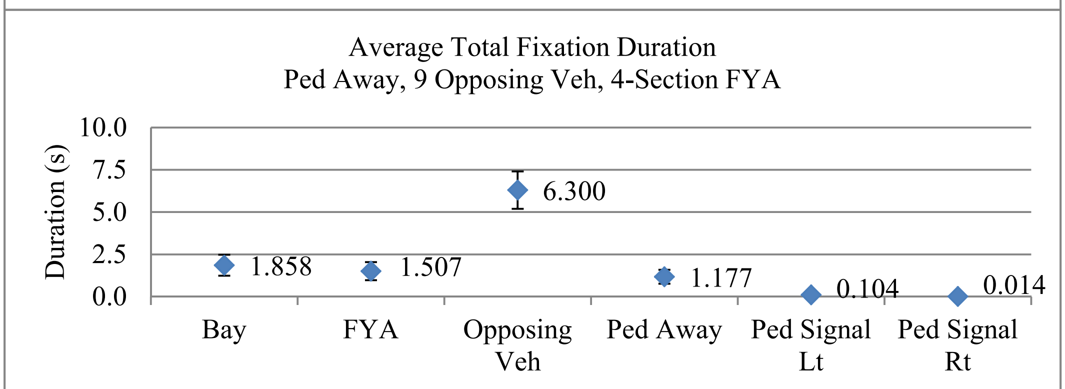
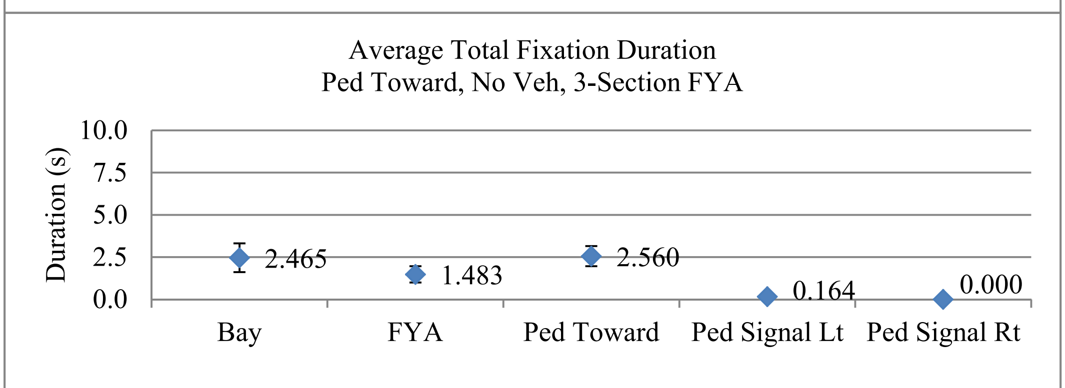
1.487
7.102
0.718
0.036
0.000
Bay
FYA
Opposing Veh
Ped Toward
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
Ped Both, 3 Opposing Veh, 4-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
2.403
1.709
2.816
1.680
1.095
0.052
0.000
Bay
FYA
Opposing Veh
Ped Away
Ped Toward
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
Ped Away, 9 Opposing Veh, 4-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
1.858
1.507
6.300
1.177
0.104
0.014
Bay
FYA
Opposing Veh
Ped Away
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
Ped Toward, No Veh, 3-Section FYA
Duration (s)
10.0
7.5
5.0
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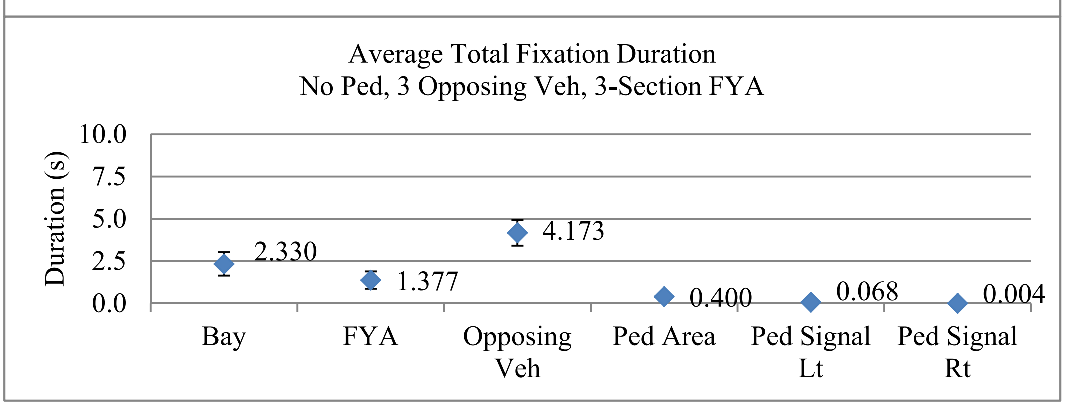
1.483
2.560
0.164
0.000
Bay
FYA
Ped Toward
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
No Ped, 3 Opposing Veh, 3-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
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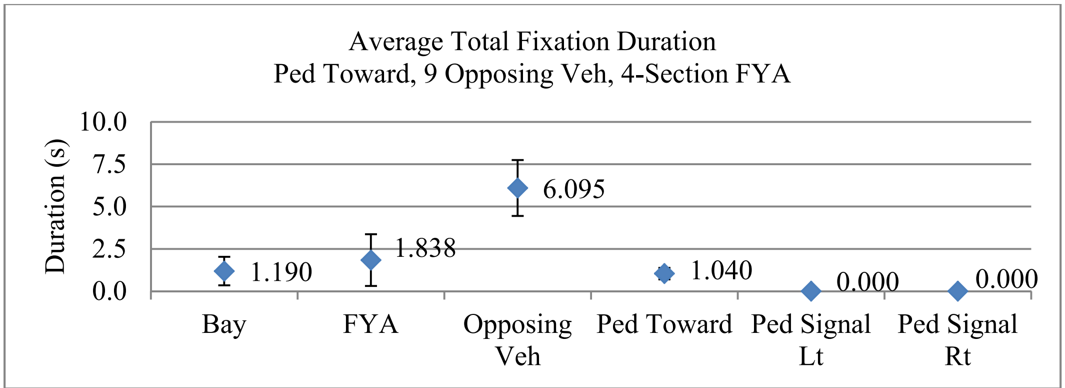
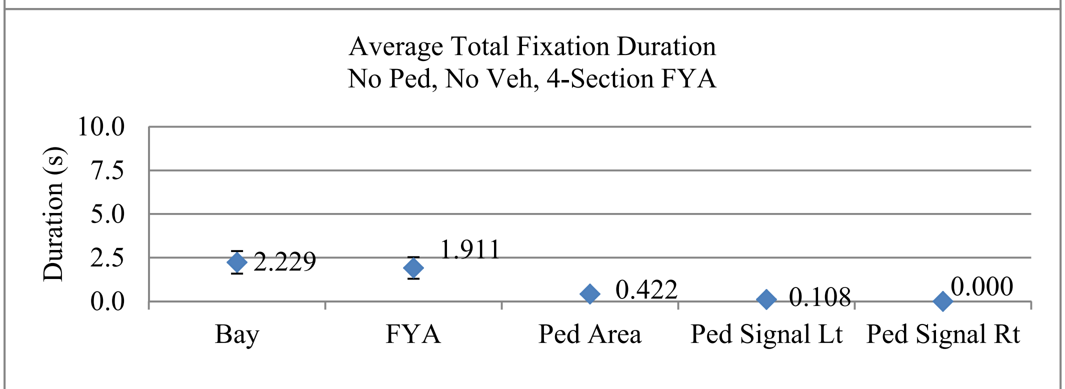
1.377
4.173
0.400
0.068
0.004
Bay
FYA
Opposing Veh
Ped Area
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
Ped Toward, 9 Opposing Veh, 4-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
1.190
1.838
6.095
1.040
0.000
0.000
Bay
FYA
Opposing Veh
Ped Toward
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
No Ped, No Veh, 4-Section FYA
Duration (s)
10.0
7.5
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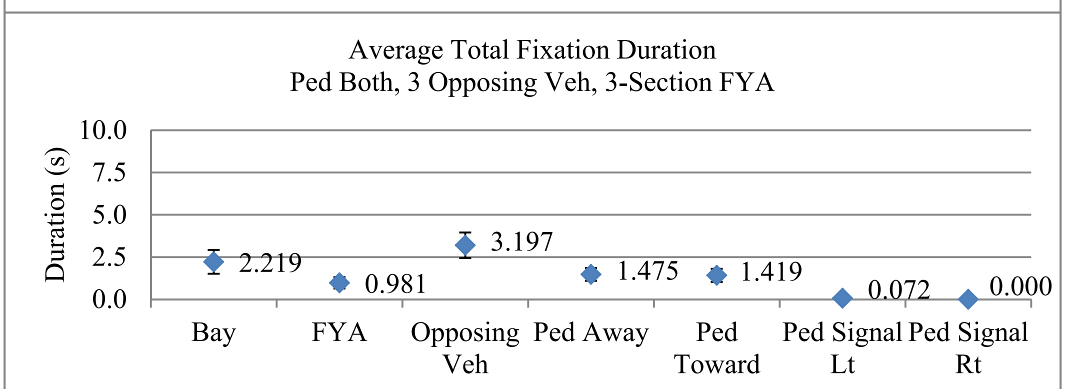
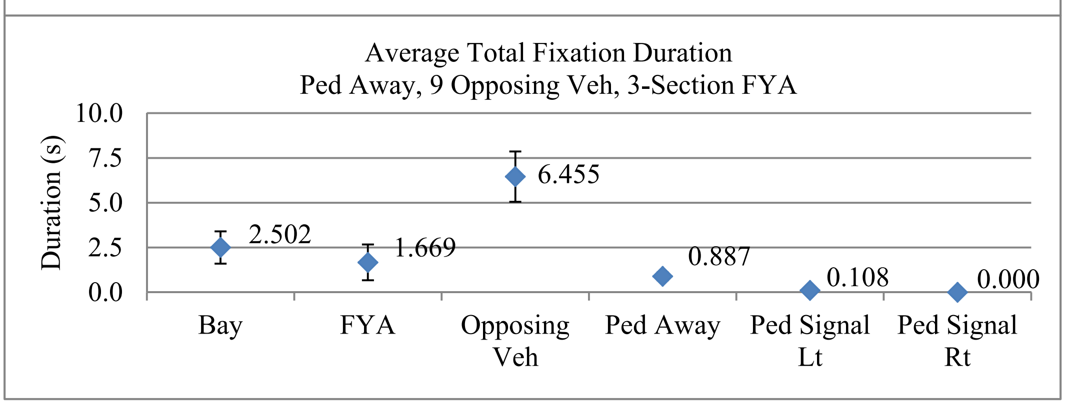
2.5
0.0
2.229
1.911
0.422
0.108
0.000
Bay
FYA
Ped Area
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
Ped Both, 3 Opposing Veh, 3-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
2.219
0.981
3.197
1.475
1.419
0.072
0.000
Bay
FYA
Opposing Veh
Ped Away
Ped Toward
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
Ped Away, 9 Opposing Veh, 3-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
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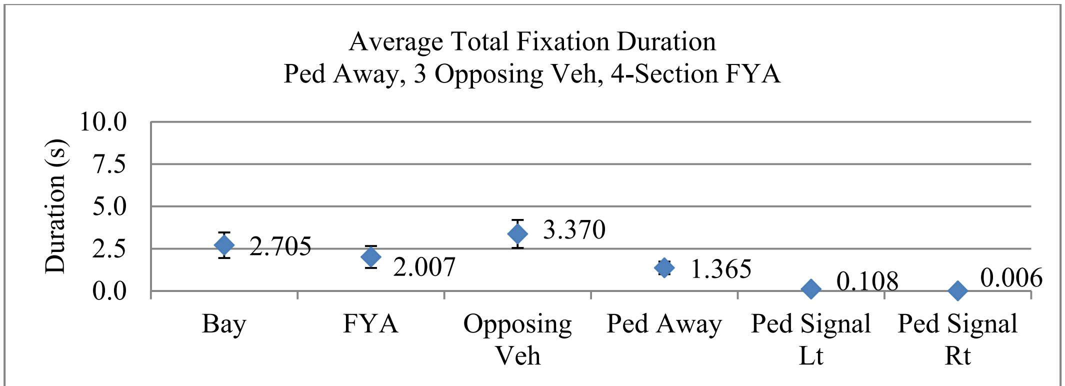
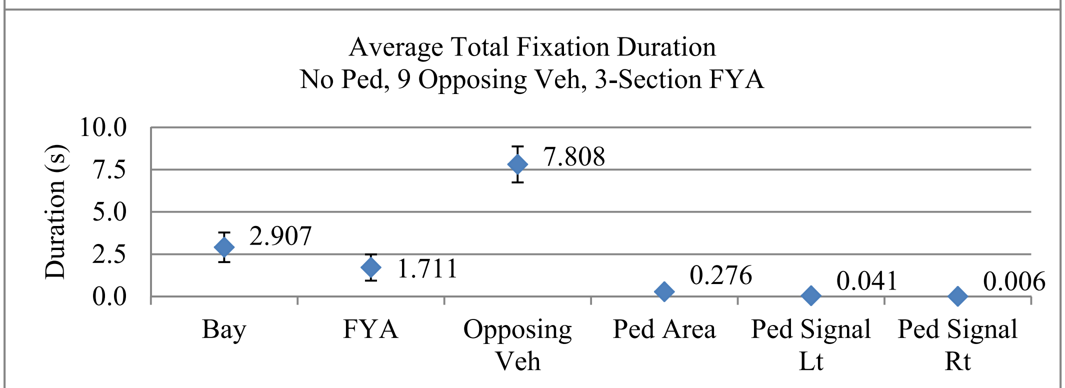
1.669
6.455
0.887
0.108
0.000
Bay
FYA
Opposing Veh
Ped Away
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
Ped Away, 3 Opposing Veh, 4-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
2.705
2.007
3.370
1.365
0.108
0.006
Bay
FYA
Opposing Veh
Ped Away
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
No Ped, 9 Opposing Veh, 3-Section FYA
Duration (s)
10.0
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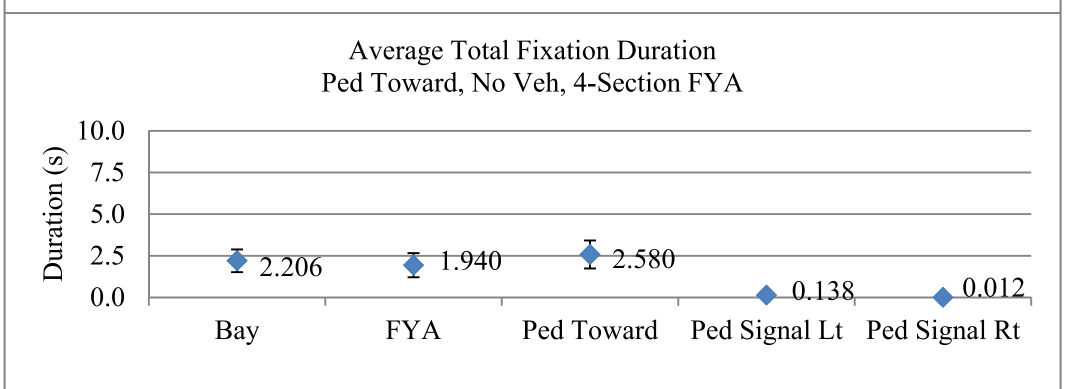
5.0
2.5
0.0
2.907
1.711
7.808
0.276
0.041
0.006
Bay
FYA
Opposing Veh
Ped Area
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
Ped Toward, No Veh, 4-Section FYA
Duration (s)
10.0
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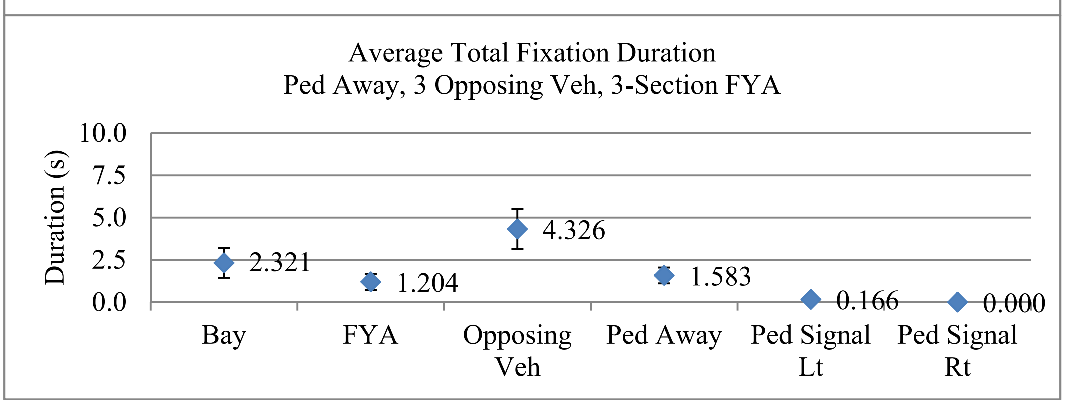
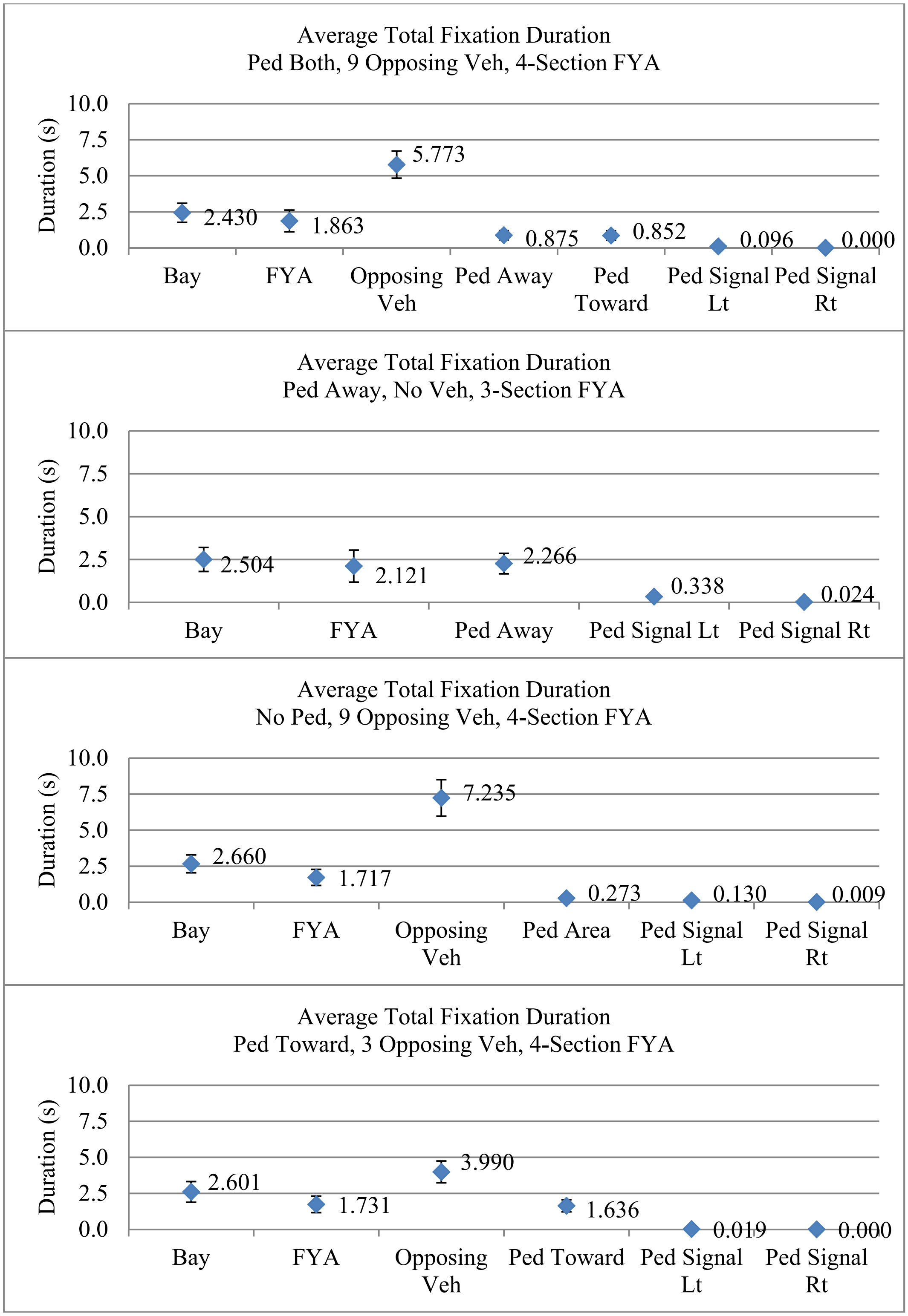
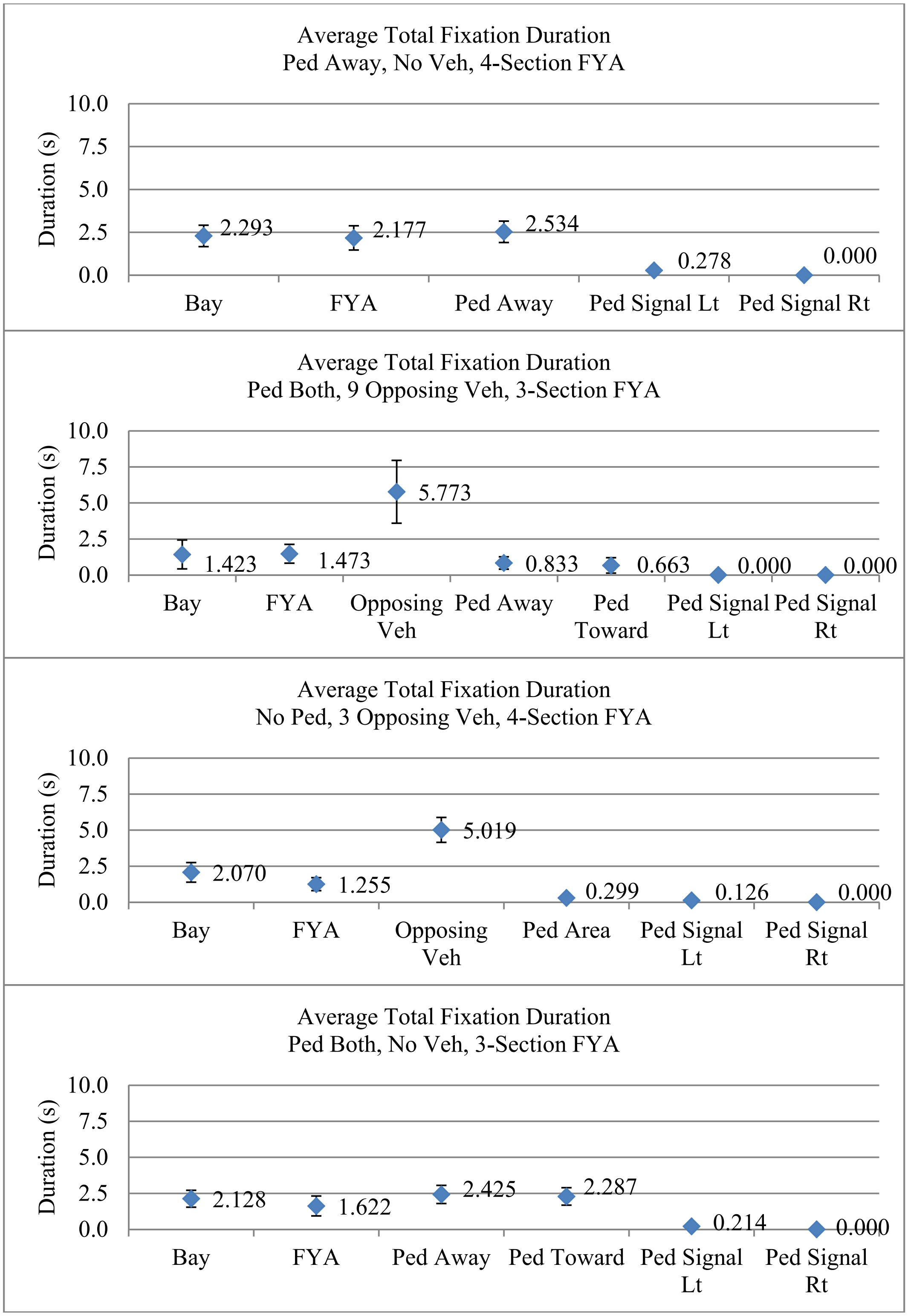
5.0
2.5
0.0
2.206
1.940
2.580
0.138
0.012
Bay
FYA
Ped Toward
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
Ped Away, 3 Opposing Veh, 3-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
2.321
1.204
4.326
1.583
0.166
0.000
Bay
FYA
Opposing Veh
Ped Away
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
Ped Both, 9 Opposing Veh, 4-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
2.430
1.863
5.773
0.875
0.852
0.096
0.000
Bay
FYA
Opposing Veh
Ped Away
Ped Toward
Ped Signal Lt
Ped Signal Rt
Average Total Fixation Duration
Ped Away, No Veh, 3-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
2.504
2.121
2.266
0.338
0.024
Bay
FYA
Ped Away
Ped Signal Lt
Ped Signal Rt
Average Total Fixation Duration
No Ped, 9 Opposing Veh, 4-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
2.660
1.717
7.235
0.273
0.130
0.009
Bay
FYA
Opposing Veh
Ped Area
Ped Signal Lt
Ped Signal Rt
Average Total Fixation Duration
Ped Toward, 3 Opposing Veh, 4-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
2.601
1.731
3.990
1.636
0.019
0.000
Bay
FYA
Opposing Veh
Ped Toward
Ped Signal Lt
Ped Signal Rt



Average Total Fixation Duration
Ped Away, No Veh, 4-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
2.293
2.177
2.534
0.278
0.000
Bay
FYA
Ped Away
Ped Signal Lt
Ped Signal Rt
Average Total Fixation Duration
Ped Both, 9 Opposing Veh, 3-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
1.423
1.473
5.773
0.833
0.663
0.000
0.000
Bay
FYA
Opposing Veh
Ped Away
Ped Toward
Ped Signal Lt
Ped Signal Rt
Average Total Fixation Duration
No Ped, 3 Opposing Veh, 4-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
2.070
1.255
5.019
0.299
0.126
0.000
Bay
FYA
Opposing Veh
Ped Area
Ped Signal Lt
Ped Signal Rt
Average Total Fixation Duration
Ped Both, No Veh, 3-Section FYA
Duration (s)
10.0
7.5
5.0
2.5
0.0
2.128
1.622
2.425
2.287
0.214
0.000
Bay
FYA
Ped Away
Ped Toward
Ped Signal Lt
Ped Signal Rt

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