AN ABSTRACT OF THE THESIS OF

Halston Tuss for the degree of Master of Science in Civil Engineering presented on September 21, 2012.

Title: Pedestrian Safety at Signalized Intersections Operating the Flashing Yellow Arrow.

Abstract approved: ____

David S. Hurwitz

At signalized intersections, pedestrians are considered to be amongst the most vulnerable. When in the crosswalk at intersections without protected left-turn phasing, pedestrians are particularly at risk from left-turning vehicles. Until recently, a wide variety of indications were in use across the US to indicate a permissive left-turn condition to the driver. In Oregon, the Flashing Yellow Arrow (FYA) has been used to indicate the permissive left-turn condition for approximately 10 years. With the addition of the FYA in the 2009 MUTCD, it is likely that its use will continue to increase nationally. Though many operational and safety issues have been studied about the FYA indication, this research proposes to fully investigate factors that influence driver behavior in the context of the permissive left-turn conflict with pedestrians. Specifically, the research seeks to study driver glance behavior to identify reasons why drivers are, “looking at but not seeing” pedestrians in or near the crosswalk or not searching for the presence of pedestrians at all.

Pedestrian Safety at Signalized Intersections Operating the Flashing Yellow Arrow

by
Halston Tuss

A THESIS

submitted to

Oregon State University

in partial fulfillment of
the requirements for the
degree of

Master of Science

Presented September 21, 2012
Commencement June, 2013

Master of Science thesis of Halston Tuss presented on September 21, 2012

APPROVED:

Major Professor, representing Civil Engineering

Head of the School of Civil and Construction Engineering

Dean of the Graduate School

I understand that my thesis will become part of the permanent collection of Oregon State University libraries. My signature below authorizes release of my thesis to any reader upon request.

Halston Tuss, Author

ACKNOWLEDGEMENTS

I am sincerely grateful for the guidance I have received from all the professors I have had the chance to work with at Oregon State University. I would like to extend a special thank you to my advisor, Dr. David Hurwitz, whose knowledge, advice, and encouragement has been the most influential factor in my success. There is no doubt I would not have accomplished as much as I have without all of his help.

I would like to thank my family and friends for supporting me throughout my pursuit of a great education. I am very thankful for all the opportunities I have been given. I would like to thank my fellow graduate students who have helped with this research and given me support; Raul Avelar, Lacy Brown, Pat Marnell, Derek Moore, Josh Swake, Isaac Talley, and Jianfei Zheng.

Additionally, I would like to thank the members of my committee, Dr. David Hurwitz, Dr. Kate Hunter-Zaworski, Dr. Haizhong Wang, and Dr. Marc Norcross, for all their help in making this project successful.

TABLE OF CONTENTS

Page

1 Introduction 1

2 Literature Review 3

2.1 PPLT Signal Phasing and the MUTCD 3

2.2 PPLT Driver Challenges 4

2.3 Initial Simulator and Conflict Studies Supporting FYA 5

2.4 FYA Field Validation and Crash Modeling 7

2.5 Driving Behavior 8

2.5.1 Driver Comprehension 8

2.5.1 Survey Research on FYA Comprehension 8

2.5.1 Driving Simulation Research on FYA Comprehension 9

2.6 Pedestrian Behavior 10

2.6.1 Leading Pedestrian Interval 10

2.6.2 Driver Inattention...11

2.6.3 Pedestrian Activity...11

2.6.4 Young and Elderly Pedestrians...12

2.6.5 Pedestrian Gender Differences 13

2.6.6 Group Behavior 13

3 Methodology 15

3.1 Research Objectives..15

3.2 Driving Simulator 17

3.2.1 OSU Simulator Description..17

TABLE OF CONTENTS (Continued)

Page

3.2.2 Driving Simulator Validation 18

3.2.3 Driving Simulator Validation for Left Turn Research 19

3.3 Eye Glance Data 20

3.4 Subject Recruitment and Sample Size 21

3.5 Procedure 22

3.6 Scenario Layout and Intersection Control 24

4 Results and Discussion 30

4.1 Post-drive questionnaire and driver understanding..................................30

4.2 Data Reduction...31

4.3 Data Analysis and Results 33

4.3.1 Pedestrians 35

4.3.2 Vehicles 37

4.3.3 Signal Display..38

4.3.4 No Fixations on Pedestrians...40

5 Conclusions 42

5.1 Research Objectives Review..42

5.2 Significant findings...43

5.3 Future work...44

6 References 46

7 APPENDIX 49

LIST OF FIGURES

Figure Page

Figure 1 Typical Position and Arrangements of Shared Signal Faces for PP Left-Turns (*MUTCD, 2009*).. 3

Figure 3 - Examples of other PPLT indications used before MUTCD recommendations 5

Figure 4 - 4-section configuration and 3-section dual-arrow configuration 16

Figure 5 - Driving Simulator Operator Workstation.. 18

Figure 6 - Oregon State Driving Simulator... 18

Figure 7 – OSU researcher demonstrating both the Mobile Eye XG glasses and mobile recording unit 21

Figure 8 – Eye tracking calibration image shown on driving simulator screen.... 23

Figure 9 - Grid layout 25

Figure 10 - 3-section dual-arrow signal configuration and pedestrian walking toward subject 27

Figure 11 - Vehicle turn/merge pedestrian crash type (FHWA).......................... 28

Figure 12 - Graphical representation of start-up lost time and saturation headway 28

Figure 13 - Intersection showing FYA operation and queued vehicles being released 29

Figure 14 - Subject at stop line fixating on AOIs 31

Figure 15 - Subject fixation on crossing pedestrian walking away during left turn maneuver 32

Figure 16 – ATFD with 95% CIs of case with a 4-section FYA, no vehicles, and no pedestrians.. 34

Figure 17 – ATFD with 95% CIs of case with a 3-section FYA, 9 vehicles, and pedestrians from both sides.. 34

Figure 18 - Graphical comparison between two similar intersections with different signal configurations.. 35

LIST OF TABLES

Table Page

Table 1 – Subject demographics 22

Table 2 - Grid and intersection layout 26

Table 3 - Driver Response to Questionnaire 30

Table 4 – Example of raw fixation data and AOI summary table 33

Table 5 - Statistics summary table comparing the locations of differing pedestrian volumes 36

Table 6 - Statistics summary table comparing locations of differing opposing vehicular volume 38

Table 7 - Statistics summary table comparing locations with 4-section signal vs. locations with 3-section signal 40

Table 8 – Pedestrian AOI summary table 40

Table 9 - Proportions analysis of pedestrian AOI comparisons 41

IMPROVED PEDESTRIAN SAFETY AT SIGNALIZED INTERSECTIONS OPERATING THE FLASHING YELLOW ARROW

1 INTRODUCTION

Use of the flashing yellow arrow (FYA) has gained momentum in Oregon and across the country as research and field implementation continues to demonstrate its effectiveness relative to alternative permissive left-turn indications. In 2003, NCHRP Report 493, "Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control," performed a comprehensive evaluation of protected/permissive left-turn (PPLT) alternatives and arrived at the recommendation to include the FYA in future editions of the MUTCD (*Brehmer et al., 2003*). In 2007, Noyce et al. evaluated the FYA permissive left-turn indication by summarizing all relevant research in this area, arriving at the same conclusion. The MUTCD now includes guidelines for FYA operation (*2009*).

The Oregon Department of Transportation (ODOT) was an early adopter and a national leader in the application of the FYA indication for 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. Washington County, Oregon has taken this further, replacing protected operation with FYA PPLT operation. At some locations, operation of the FYA has been halted at several signalized intersections in Washington County, Oregon due to reports of a high number of conflicts between pedestrians and permissive left-turning vehicles. 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 more conservative method to increase pedestrian safety may be accomplished through the complete separation of the pedestrian phase and the FYA phase. This would allow the pedestrian phase to fully complete before displaying the FYA, which would reduce potential conflicts. While the pedestrian phase is being served, the parallel through movements are simultaneously given a Circular Green (CG) – which is when the FYA phase would have also been displayed if it had not been separated from the pedestrian phase.

During traditional FYA operations (where the FYA is displayed alongside the CG 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 could be combined with the leading pedestrian interval to provide additional safety features for pedestrians.

2 LITERATURE REVIEW

2.1 PPLT Signal Phasing and the MUTCD

The MUTCD provides guidance for multiple arrangements of shared signal faces for PPLT movements (*2009*). Included configurations consist of the five-section cluster (commonly referred to as the "dog house"), and three and four-section vertical and horizontal arrangements all of which include a solid green arrow (SGA) for the protected phase and a CG permissive indication. The MUTCD does allow dual-arrow signal displays, where, for example, green arrow (GA) indications and yellow arrow (YA) indications are given from the same signal head, however this signal is only permitted at locations that have signal head height limitations (*2009*). Today, many locations operate dual-arrow configurations against MUTCD standards; however the Federal Highway Administration (FHWA) does not have a mandated compliance period for separated signal faces, section 4D.20 of the 2009 MUTCD (FHWA, 2009). Approved MUTCD PPLT configurations can be found in Figure 1.

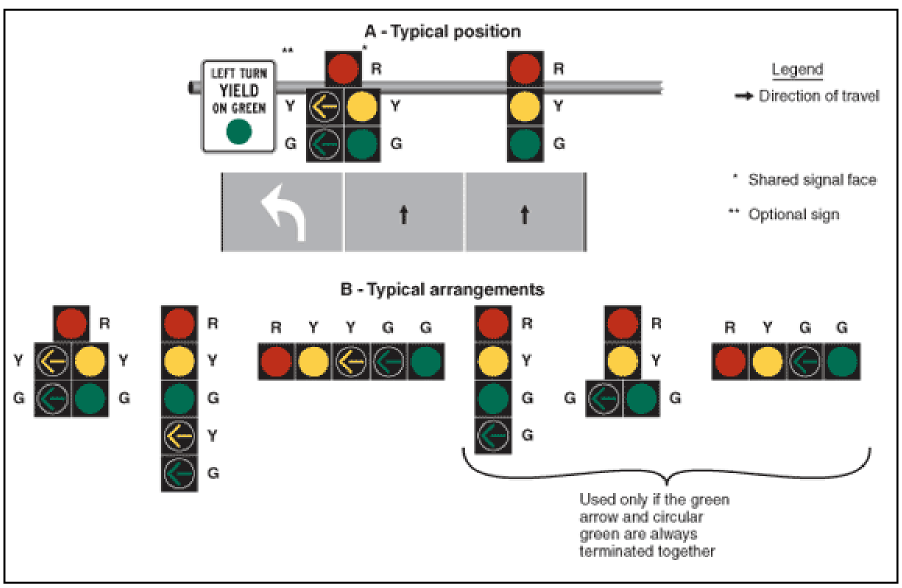


Figure 1 Typical Position and Arrangements of Shared Signal Faces for PP Left-Turns (*MUTCD, 2009*)

While 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 the inclusion of the FYA indication in the

MUTCD, PPLT signal phasing indicated this permitted movement with the CG indication and used a SGA indication for the protected phase (*2009*). It has been hypothesized that the CG indication (also used to give the right of way in the through and right turning lanes) may lead to poor driver comprehension as the same indication provides a different message depending on the particular movement being performed by the driver (i.e. through movement or permissive left-turn) (*Knodler et al., 2005*). An example of the traditional PPLT with CG signal configuration compared to the current PPLT with FYA configuration is shown in Figure 2.

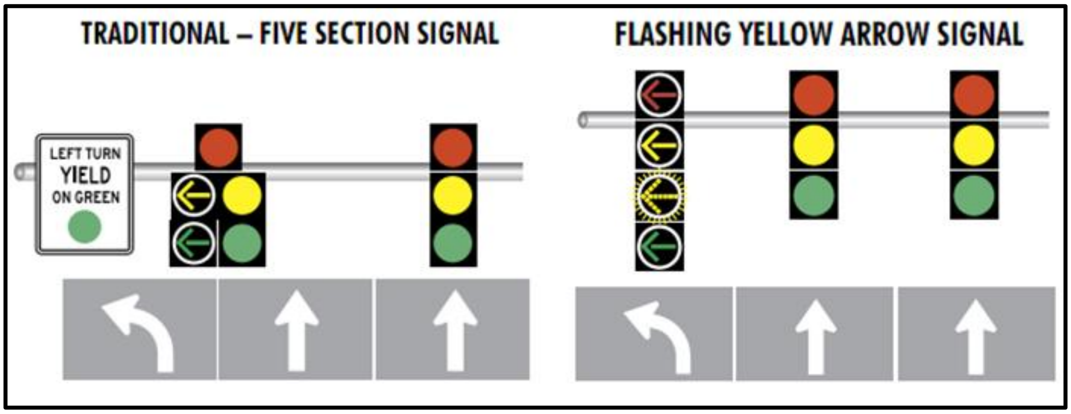


Figure 2 - Example of traditional PPLT signal configuration vs. FYA PPLT signal configuration (*ODOT, 2012*)

2.2 PPLT Driver Challenges

The work documented in NCHRP Report 493 recognized that two independent tasks are performed by the driver in order to accept or reject an adequate gap. The first task is to acknowledge and process the message being provided by the left-turn indication (whether that includes a CG or a FYA), while the second task is to analyze the opposing vehicles and 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, leading to a reduction in efficiency and/or safety at the intersection.

Choosing the appropriate time to enter the intersection requires the driver to accurately assess the gaps in the conflicting traffic streams. However, drivers usually have difficulties when attempting to judge the size of the gaps (both time and distance) and can occasionally choose to proceed into the intersection when oncoming vehicles are too close or traveling too fast, thus increasing the likelihood of a severe crash (*Neuman et al., 2003*). Additionally, high traffic volumes and/or travel speeds on the major approaches may result in relatively fewer usable gaps for turning or crossing maneuvers from the minor approach, thus increasing delay and wait times and reducing intersection capacity (*Gluck et al., 1991*). Therefore, gap acceptance behavior is particularly crucial to both the safety and operational performance of signalized intersections operating the FYA.

2.3 Initial Simulator and Conflict Studies Supporting FYA

Before the FYA indication became the standard replacement of CG 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. These indications included the flashing red arrow (FRA), flashing circular yellow (FCY), and flashing circular red (FCR) in addition to the FYA. Examples of these permissive left-turn indications are shown in Figure 3. While not uniform, these indications were developed to improve driver comprehension and safety during PPLT operations. The variety of different indications communicating 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.

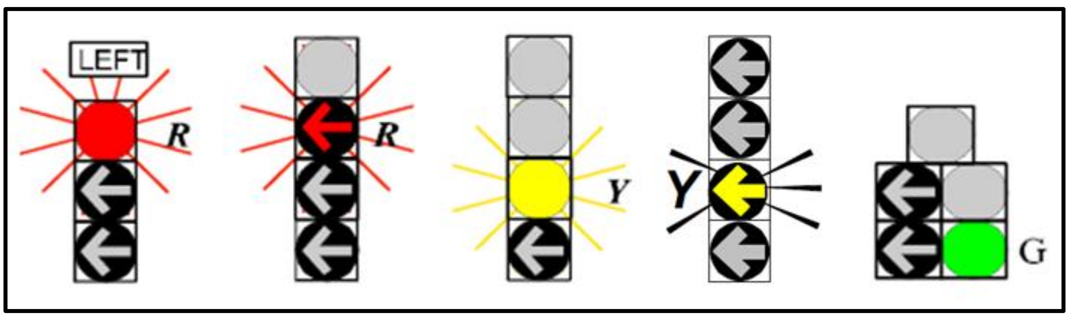


Figure 3 - Examples of other PPLT indications used before MUTCD recommendations

Using the Arbella Human Performance Laboratory (HPL) driving simulator lab at the University of Massachusetts Amherst (UMass Amherst) in 2000, Smith and Noyce tested 34 drivers resulting in 991 responses collected from indication scenarios in order to understand the difference in driver comprehension of five different permissive left-turning signal head configurations. The researchers found that the percent of correct responses for the CG, FYA, and FCY indications were relatively equal, with a difference of one percent, but outperformed the FRA and FCR indications by an average of 28.2 percent. Smith and Noyce also found that the different types of five-section PPLT signal display configurations (vertical, horizontal, and cluster) had negligible effect on the percent of correct responses (*Smith and Noyce, 2000*).

Noyce et al. collected 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 in 2000. In their analysis, they found no statistically significant difference in saturation flow rate due to the PPLT displays with 95% confidence or start-up lost time between different types of PPLT signal displays at locations across the country, which included CG, FYA, FCY, FRA, and FCR. They concluded that any minor differences observed could be attributed to the different traffic operations and driver behaviors at each geographical area studied (*2000*). Noyce et al. also explored traffic conflicts associated with PPLT signal displays and found that, with 95% confidence, there was no statistical difference in conflict rates, which were very low, for the different PPLT signal displays. Due to the low conflict rates during this research, no conclusions were made on the safety effects of operating the different PPLT signal displays (*2000*).

This preliminary work by Noyce and Knodler provided significant evidence that FYA indication should be used when replacing CGs for permitted left-turn movements. In 2003, NCHRP Report 493, "Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control," performed a comprehensive evaluation of PPLT alternatives and arrived at the recommendation to include the FYA in future editions of the MUTCD as an allowable alternative display to the CG during PPLT operation, but only in an exclusive signal for the left-turn lane. Additionally, NCHRP Report 493 recommended that the use of a flashing red indication should be restricted for use during PPLT operation (*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 during the Circular Yellow (CY) operations for the through movement. Knodler et al. observed that when presented with a five-section cluster signal configuration, where both the left-turn FYA and the through movement CY are located in the same signal house, some drivers would completely stop in the left-turn lane and had to be directed to proceed by the researchers (*2005*). The researchers also observed that when drivers were presented with a four-section vertical exclusive left-turn signal configuration and a separate signal for the through lane, there were a greater percentage of drivers who yielded during the permissive left-turn phase (*Knodler et al., 2005*).

2.4 FYA Field Validation and Crash Modeling

Locations that converted to PPLT phasing with FYA indications from a protected only left-turn phase experienced greater efficiency but reduced safety. The FHWA expected around a 60 percent increase in crash frequency due to conversions at locations that exclusively operated protected left-turning movements with a GA (*KAI, 2011*). This conclusion is supported by Srinivasan et al., who conducted research to develop Crash Modification Factors (CMF) for treatments at signalized intersections in 2011. Treatments analyzed included the installation of the FYA at intersections that had protected only, permissive only, and protected/permissive left turn operations previously. Crash data was collected for 39 total locations, five in Kennewick, Washington and 34 in Oregon primarily in the Portland metropolitan area. The analysis by Srinivasan et al. found that for the locations with a protected before condition, the CMF for a FYA was 2.043 for left-turn crashes at the intersection. This translates to an increase in crashes of 49 percent, however a CMF of 0.734 was found for FYA treatments at locations that had PPLT or permissive only operation in the before condition (*Srinivasan et al., 2011*).

With current traffic controllers, time of day operation can be established based on changes in roadway demand. For example, during peak hours a roadway may have high vehicular and/or pedestrian volumes, leading to an inadequate frequency of usable gaps in traffic to make a permissive left-turn maneuver. With the adaptive controller PPLT operation can be turned off during these hours, and then turned back on during off peak hours or when there are low instances of pedestrian volumes (*KAI, 2011*).

With PPLT control, if the left-turns are operated as lead-lag, a “yellow trap” conflict may result. The yellow trap occurs when the driver of a left-turning vehicle is presented a CY after a CG permissive indication is provided and erroneously assumes that the opposing through traffic is simultaneously presented a CY. 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 CG, the yellow trap is completely eliminated without any additional traffic control devices, leading to a reduction in right angle crashes (*Brehmer et al., 2003*).

2.5 Driving 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 it does when involved in individual tasks performed separately. The brain can only contribute to a limited number of tasks simultaneously and once drivers attempt to multitask their ability to do either task is degraded (*Regan, Lee & Young, 2008*).

2.5.1 Driver Comprehension

It is important to establish a working definition for 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." Thus it is clearly important for the driver to immediately understand the message of any traffic control device because any delay or misinterpretation may result in driver error (*Dewer 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 percent, and lower fail-critical rates. Fail-critical response in this research done by Noyce and Kacir is defined as incorrectly assuming left-turn priority. Their findings suggest that the CG indication, which received a 50.4 percent correct response rate, may in fact lead to confusions due to its dual purpose during PPLT phasing (*Noyce and Kacir, 2001*). This conclusion was also supported in the work done by Smith and Noyce in 2000 using a driving simulator to evaluate five section PPLT signal displays. They determined that in order for a PPLT signal display to be effective it needed to be understood by nearly all drivers, experienced and inexperienced, and found that the FYA fulfilled this requirement (although results showed a slightly higher correct response rate, with a difference of approximately 1 percent, with CG indications). (*2000*). While the research conducted by Smith and Noyce showed that there is little difference in driver comprehension between the CG and FYA indications, both indications had much higher correct response rates than the FRA and FCR indications with differences of about 33 and 23 percent, respectively (*2000*).

2.5.3 Driving Simulation Research on FYA Comprehension

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 (*2005*). Eleven subjects were tested resulting in the evaluation of 66 simulated intersection interactions. Knodler and Noyce found that 90 percent of the drivers initially focused on the PPLT before focusing on the opposing through traffic to find an adequate gap. Interestingly, it was determined that 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 primarily focus 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 (*2005*).

In 2003, Knodler et al. conducted a driver simulator experiment followed by a questionnaire of the subjects, to evaluate 12 experimental PPLT signal displays. The experiment included 432 drivers split between simulators located at the UMass Amherst (223 drivers) and the Texas Transportation Institute (TTI) (209 drivers). In the experiment, left-turn permissive indications included the CG, FYA, and a combination of both CG and FYA and were presented on a five-section cluster, five-section vertical, or four-section vertical signal configuration. Overall, with the 432 subjects in the simulator, Knodler et al. found that scenarios with the FYA indication and the CG/FYA combination indications had more correct responses than scenarios operating only the CG ($p < 0.001$) (*2003*). This was also supported by a separate survey given concurrently to 436 subjects by Knodler et al. ($p < 0.001$) (*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 where the driver recognized the need to yield to the pedestrian, a “fail-safe” response where the driver began to make the maneuver but eventually noticed the pedestrian and allowed the pedestrian to cross, and a "fail-critical" response where the driver did not yield to the pedestrian in any way. It should be noted that the fail-critical response for this experiment is defined differently than the study in 2001 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.

2.6 Pedestrian Behavior

The 2009 MUTCD states that vehicles presented with the FYA must yield to opposing traffic, as well as pedestrians in the crosswalk (*MUTCD, 2009*); however, in many situations the driver workload is elevated and drivers often fail to scan for pedestrians while performing permissive left-turns (*Lord et al., 1998*). This is particularly an issue in suburban settings where the expectation for encountering pedestrians is lower. From the pedestrian's perspective, a walk signal is presented, signifying that they have the right-of-way (ROW) to cross, and likely expect 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 ROW confusion that contributes to the pedestrian/left-turning vehicle conflict is to use advanced signal software logic to provide an exclusive leading pedestrian interval. This modification may help mitigate the conflict (*Fayish and Gross, 2010*); however this increased safety comes at the cost of decreased vehicular throughput. It is critical to understand when this alternative should be applied, as 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, pedestrians yielding the ROW to vehicles while crossing the intersection dropped by 60 percent (*Van Houten, 2000*). In a related example, 85 percent of pedestrian conflicts with left-turning vehicles at four-leg signalized intersections occurred during the last half of the green phase, suggesting 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 Driver Inattention

As mentioned in subsection 1.3 Driver Behavior, the driver may be so attentive to the FYA indication and the demands of vehicle control during the required maneuver that they may not notice pedestrians, or that they may even, “look but not see” any pedestrians – even though pedestrians may be present. The National Safety Council describes inattention as "cognitive distraction 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.

2.6.3 Pedestrian Activity

In addition to the driver behavior and comprehension, it is important to characterize pedestrian behaviors. Pedestrian behavior at signalized intersections can be unpredictable and their actions are quite varied (*Cinnamon, 2011*). In a 1971 study of 2,157 pedestrian collisions that occurred in 13 US cities, police records indicated that 34 percent of the collisions were the result of pedestrians abruptly entering the roadway (darting out) at mid-block locations, as compared to seven percent of the collisions being the result of a vehicle attending to oncoming traffic and not noticing the pedestrian (*Shinar, 2007*).

Similarly, when a pedestrian does comply with the walk indication, they tend to walk slower than the pedestrians initiating their crossing during either the FDW or the DW indications (*Knoblauch, 1996*) – as 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, increasing the chance that they will become involved in a conflict in situations where pedestrians do not have an exclusive phase and vehicles are allowed to turn across their path (after yielding to pedestrians). This information is relevant to our simulation; however, other work also observed 9,808 pedestrian crossings at seven urban 4-leg signalized intersections in Vancouver, BC where 13 percent of pedestrians entered the crosswalk illegally (during the FDW or DW phase) (*Cinnamon, 2011*). The 13 percent non-compliance rate consisted of 9.8 percent of pedestrians (this ranged from 7.2 percent to 15.8 percent at the intersection of Broadway and Commercial) who had entered during the FDW phase, and 3.2 percent of pedestrians (ranged from 0.5 percent to 9.7 percent at the intersection of Hastings and Gore) who had entered during the DW phase (*Cinnamon, 2011*).

Pedestrian behavior is highly variable, even within the same city, and is likely dependent on numerous factors at each individual intersection. One of the most significant reasons for non-compliance are signal timing plans that include an unnecessarily excessive amount of pedestrian delay. The longer pedestrians wait, the more likely they will violate the pedestrian signal (*Wang, 2011*).

2.6.4 Young and Elderly Pedestrians

It is intuitive that young and elderly pedestrians act much differently than average adult pedestrians; therefore, it is of particular interest to look at the differences between these groups. For example, 67 percent of elderly pedestrians aged 55 and older (10 out of 15 people) had been observed through video to wait at a signalized crossing (located in Dublin) until they received a walk sign, compared to 44 percent of those aged 15-24 (54 out of 123 people) at the same signal (*Keegan, 2003*). Rather than choosing to non-comply, one reason many elderly pedestrians wait to cross may be slower walking speeds, which lead to greater exposure and therefore risk. For the 15^{th} percentile of pedestrians, young adults walk 4.1 ft/s or less, while elderly people walk 3.2 ft/s or less (*Knoblauch, 1996*). As an entire population, the 15^{th} percentile of pedestrians walk 3.5 ft/s or less (*Knoblauch, 1996*) – which is the current speed used when timing walk phases (*MUTCD, 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), child pedestrians were observed to be less likely to search for traffic at signalized intersections (48 percent of the time), as compared to unsignalized intersections (*MacGregor, 1999*), likely due to a false sense of security provided by the cross walk. It was also observed in the same community that when children were accompanied by an adult, the children made fewer visual searches than when unaccompanied (*MacGregor, 1999*) – likely because they relinquished decision making to the adult.

2.6.5 Pedestrian Gender Differences

The differences in pedestrian behaviors between genders are also significant. In general, the research concludes that males violate traffic rules more often. For example, 61 percent of females (98 out of 160 people) were observed through video to have waited for the walk signal at the same signalized intersection located in Dublin that was mentioned previously, while 38 percent of males (61 out of 161 people) were observed to have waited for the same walk signal (*Keegan, 2003*).

When a pedestrian uses a cell phone while crossing an intersection, female behavior tends to be influenced more than male behavior. It was observed that males crossed at slower speeds while using a cell phone (*Hatfield, 2007*), 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 crossing 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 (*Hatfield, 2007*).

2.6.6 Group Behavior

Group behavior also has an effect on pedestrian crossing behavior, as pedestrians in groups are more likely to violate the signal. Once one person commits to violating the signal others tend to follow suit (*Wang, 2011*), where they may not have violated the signal had they been crossing the intersection as an individual. 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 (those that appeared to be under 65 years old) that crossed as an individual had a mean speed of 5.04 ft/s and a 15^{th} 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 15^{th} percentile speed of 3.86 ft/s. Older pedestrians (those that appeared to be 65 years old or older) that crossed as an individual had a mean speed of 4.15 ft/s and a 15^{th} 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 15^{th} percentile speed of 3.12 ft/s (*Knoblauch 1996*).

When walking, groups and individual pedestrians proceed at different speeds, however, both groups and individuals experience similar start-up times before beginning their actual walking movement. Younger pedestrians experience a 1.93 second mean start-up time as an individual as well as part of a group, while older pedestrians experience a mean start-up time of 2.43 seconds when walking as an individual, and 2.5 seconds when walking with a group (*Knoblauch, 1996*).

It can be seen that pedestrian behavior is quite variable and slightly unpredictable, and when combined with the confusion of motorists with the FYA it leads to potentially serious conflicts between pedestrians and motorists at intersections that have implemented the FYA. However, when looking at specific types of pedestrians, their actions are more predictable, allowing for an accurate representation to be modeled in a simulated environment. This relatively accurate depiction of pedestrians is necessary to produce quality data when observing motorist’s eye movements.

3 METHODOLOGY

This research fully investigates the influence of three factors related to the permissive left-turn vehicle conflict with pedestrians: opposing traffic volumes, pedestrian volumes, and signal display configurations. Though many operational and safety issues regarding the implementation of the FYA indication have been studied. Specifically, the research seeks to study driver glance behavior to identify the fundamental causes of the permissive left-turning vehicle conflict with pedestrians. The researchers hypothesize that drivers are either, “looking at but not seeing” pedestrians in or near the crosswalk or not looking for the presence of pedestrians at all.

This research includes experimental tasks in the driving simulator and 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 and elements of those intersections (approach widths, lane configurations, signal head configurations, and adjacent land use) were modeled in the OSU driving simulator. The study took place in the recently established Oregon State University Driving Simulator, a high fidelity one dimensional motion base 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. 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 Objectives

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 4-section vertical or 3-section vertical with a dual-arrow lens configuration.

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

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

According to the 2009 MUTCD, a 3-section signal face using a dual-arrow signal section can only be used at intersections with signal head height limitations. Although the MUTCD does stipulate that if a 3-section signal face is used, only a solid green arrow and FYA can be used in the dual-arrow signal section. Upon extensive literature review, it was found that little to no research has been conducted to specifically determine the operational and safety effects of using 3-section dual-arrow configurations versus 4-section signal configurations, both configurations shown in Figure 4. While several dual-arrow configurations exist, for example in Jackson County, OR the dual-arrow signal section operates a solid yellow arrow and FYA, this research will only focus on the 3-section dual-arrow that is provided by the 2009 MUTCD.

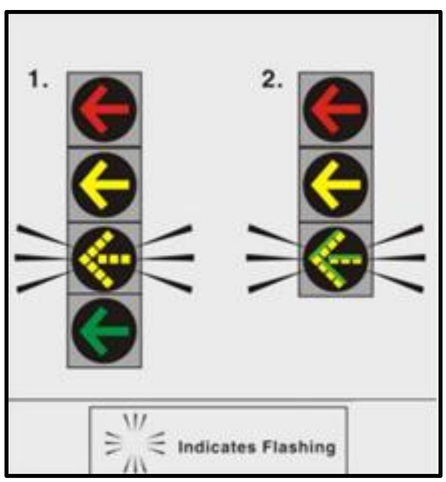


Figure 4 - 4-section configuration and 3-section dual-arrow configuration

The MUTCD does not elaborate on why a 3-section dual-arrow signal can only be used if height limitations are experienced. Due to the considerable difference in costs between 3-section dual-arrow (estimated by Washington County engineers to be $1,156 including materials and labor) and 4-section configurations ($1,458), it was decided to test the safety effects of the two configurations. At an estimated $300 difference, or greater, across hundreds of signal conversions, this cost difference is drastic. This leads to a third null hypothesis:

***H_0**: There is no difference in the total duration driver fixations during permitted left turn maneuvers at signalized intersections operating the FYA with 4-section or 3-section vertical with a dual-arrow display.*

Furthermore, the 2009 MUTCD states that if a separate left-turn signal is used in PPLT operations above the left-turn lane, then a CG indication shall not be used. This is important because in some cases prior to FYA operation, intersections would use a 5-section doghouse configuration shared by the left turn lane and through lane that would now have to be replaced.

It was also of interest to see if drivers do indeed fixate on pedestrians. If the subjects tested in the simulator fail to fixate on a crossing pedestrian at any time during the approach and turning movement, this could lead to concerning results. A related hypothesis is as follows:

***H_0**: There is no difference in the total duration of driver fixations 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 base simulator. The simulator consists of a full 2009 Ford Fusion cab mounted on top of 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 events (*Oregon State University, 2011*). Researchers build the environment and track subject drivers at the operations station shown in Figure 5, which is out of view from subjects within the vehicle.

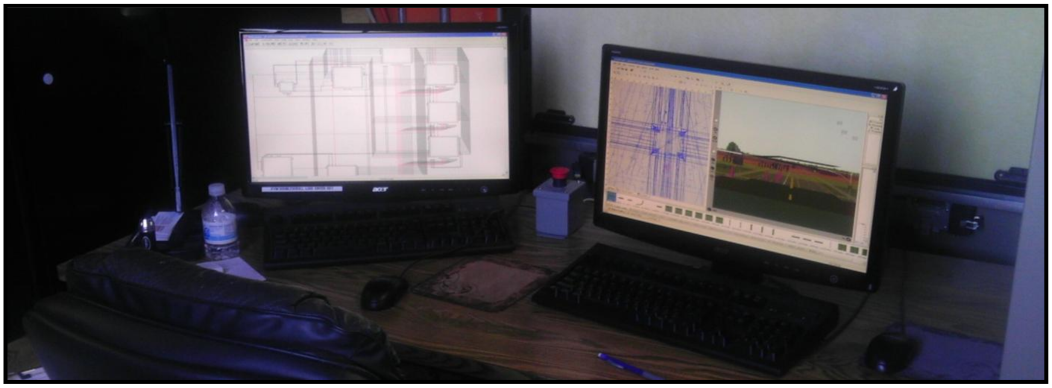


Figure 5 - Driving Simulator Operator Workstation

Three liquid crystal on silicon projectors with resolution of 1400 x 1050 are used to project a 180°x40° front view, these front screens measure to 11 ft by 7.5 ft. 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 Hz. The ambient sounds around the vehicle are modeled with a surround sound system, as well as sound internal to the vehicle. The OSU driving simulator is pictured in Figure 6.

Figure 6 - Oregon State Driving Simulator

3.2.2 Driving Simulator Validation

Validation of a driving simulator can occur on one of two levels, either absolute or relative, 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 from those observed in the real world. A simulator becomes absolutely validated when the magnitude of these differences is not significantly different.

It has been repeatedly found (*Godley et al., 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 in which drivers could perceive their speed in both a real world environment and a driving simulator. It was found that drivers consistently travelled about 5 mph faster in the simulated environment compared to the real world, which was consistent with the findings of Godley (*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, since 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 is obtained: however it is necessary that relative validity is established (*Tornos, 1998*).

3.2.3 Driving Simulator Validation for Left Turn Research

Knodler et al. conducted a simulator experiment with 211 subjects that resulted in 2313 data points and determined that a driving simulator is an effective way to evaluate PPLT signals and that it is more accurate than static evaluations (*2001*). 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.

In an effort to identify 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 either focused, when the driver fixates on an object or area for a second or longer, or a glance, when the driver fixates for less than a second.

3.3 Eye Glance Data

Eye tracking data was collected using the Mobile Eye-XG platform from Applied Science Laboratories, the equipment is shown in Figure 7. The advanced Mobile Eye-XG allows the user to not only have unconstrained eye movement but also unconstrained head movement, generating a sampling rate of 30 Hz and an accuracy of 0.5 to 1.0 degree. The subject's gaze is 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 where fixations are points that are focused on during a short period of time and saccades are when the eye moves to another point. The Mobile Eye-XG system records a fixation when the subject's eyes have paused in a certain position for more than 100 milliseconds. Quick movements to another position, saccades, are not recorded directly but instead are calculated based on the dwell time between fixations. For this research, these saccades or dwell times were not analyzed due to the research questions being considered.

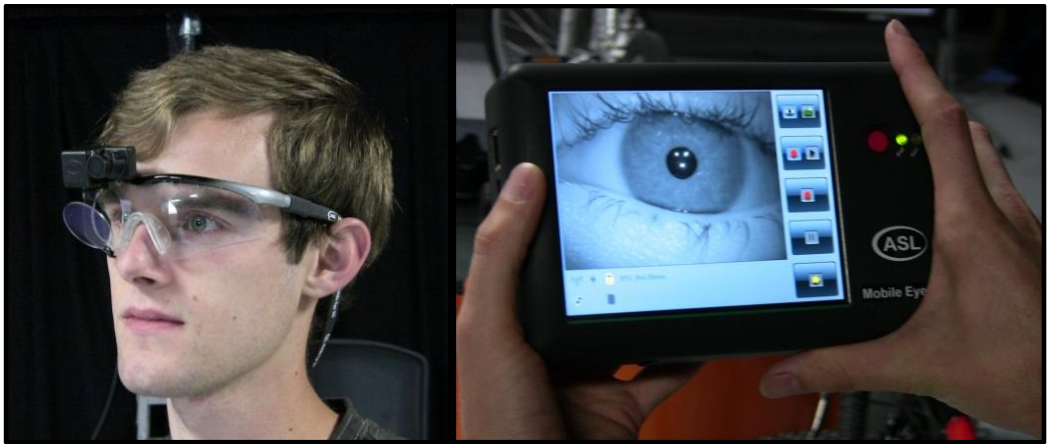


Figure 7 – OSU researcher demonstrating both the Mobile Eye XG glasses and mobile recording unit

3.4 Subject Recruitment and Sample Size

Participants in this study were selected from the 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.

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 possess a valid driver 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. While it was desired to vary the age of the participants it was not a requirement of this particular effort.

Throughout the entire study, information related to the participants was kept under double lock security in conformance with accepted IRB procedures. Each participant was randomly assigned a number to remove any uniquely identifiable information from the recorded data. Demographic information collected from the subject population can be found in Table 1. There was an over-representation of college aged students, resulting in a relatively low average age. In total, 38drivers participated in the test; however 8 were not able to complete the test due to simulator sickness or eye tracker calibration failures. A total of 30 subjects had completed the experiment; however data was lost from 3 subjects resulting in a final count of 27 subjects.

Table 1 – Subject demographics

How many years have you been a licensed driver?		
Possible Responses	***Number of Participants***	***Percentage of Participants***
0-5 years	12	40%
6-10 years		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%
Gender		
Male	14	52%
Female	13	48%
Age		
Minimum	***Average***	***Maximum***
18	25.8	67

3.5 Procedure

Selected participants were invited to meet a researcher in the OSU Driving Simulator Office (Rm 206A, Graf Hall) on the OSU Campus. At this time, the participants were given the informed consent document and provided the opportunity to carefully read the entire document and ask any necessary clarifying questions. The researchers also summarized each section of the consent document aloud to reduce any confusion.

Participants were also informed of the potential risk of simulator sickness during this process and that they could stop participating in the experiment at any time without any monetary penalty.

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, the subjects were allowed to adjust seat, mirror, and steering wheel position so 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 similar short turning movements at intersections, which is accepted in the literature as a possible contributor to simulator sickness. This also provided the opportunity to assess the likelihood that a subject would experience simulator sickness during further experimentation. If it was determined that the possibility of simulator sickness was low, and that the subject was able to successfully drive within the virtual environment, the researchers calibrated the subject's eyes to points on the screen from their position in the driver's seat. The calibration image shown during the test can be found in Figure 8. If the eye tracking equipment was not able to calibrate to the subject's eyes, which depended on eye position and other physical attributes, then the experiment was not continued.

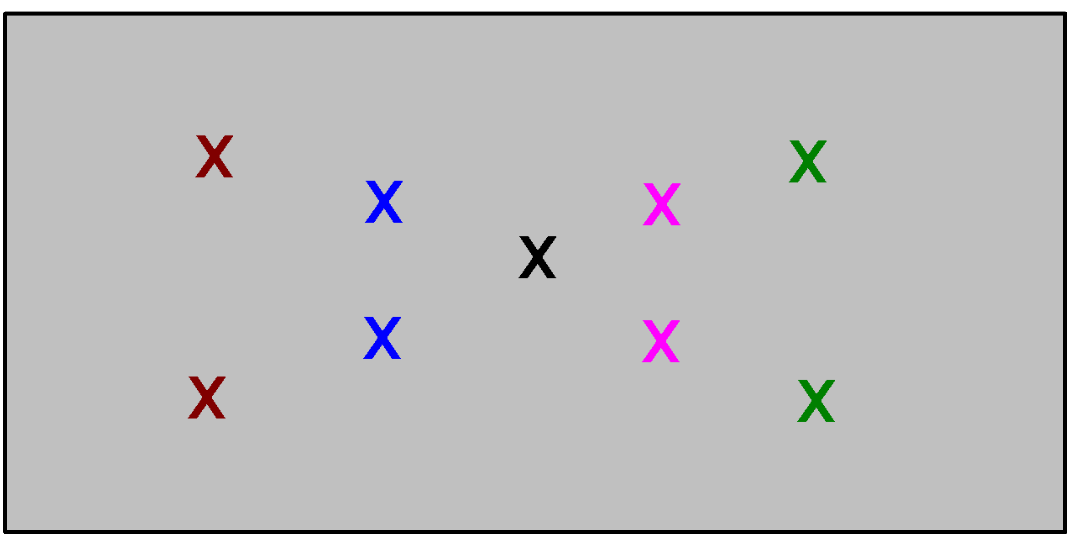


Figure 8 – Eye tracking calibration image shown on driving simulator screen

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

3.6 Scenario Layout and Intersection Control

Simulator software, 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 can 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. In an effort to reduce the chances of simulator sickness, the driving scenario was split into four grids of six intersections each, as shown in Figure 9. This allowed the subjects the opportunity to take small breaks between scenarios instead of forcing them to maneuver through all intersections without a break. It also allowed for the researchers to introduce one distractor question in between each grid. The distractor questions included:

- 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 5 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.

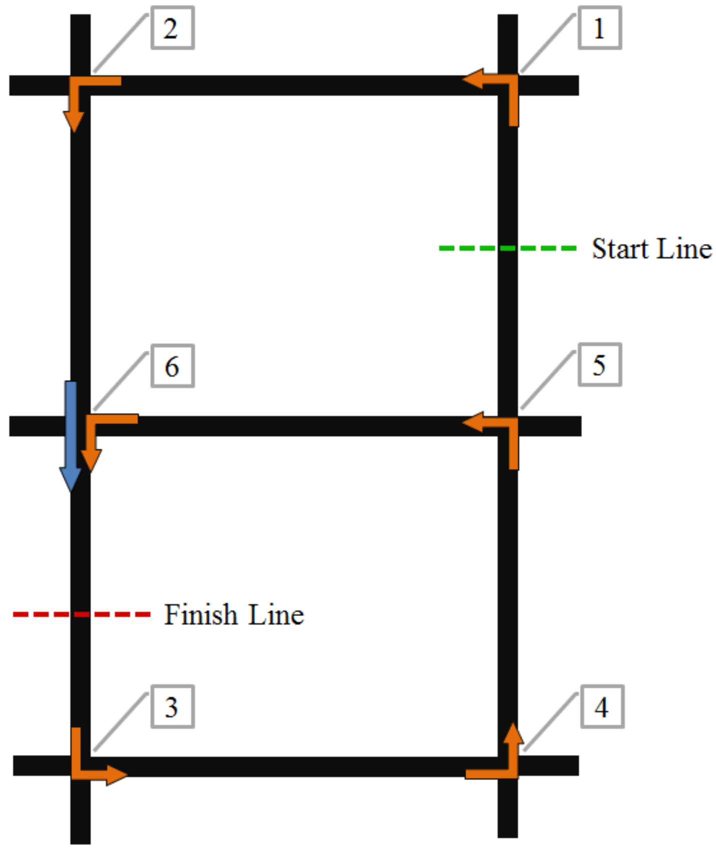


Figure 9 - Grid layout

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 4-section vertical or the 3-section vertical dual-arrow configuration. Other experimental variables included combinations of crossing pedestrians and opposing vehicular volume. Tangent sections between intersections measure approximately 1650 ft, with 12 ft lanes and 4 ft bike lanes. Figure 10 shows an example of an intersection with no opposing vehicles, a pedestrian walking toward the subject, and a 3-section dual-arrow vertical signal. In total, 24 different combinations of these variables were presented to the driver when approaching the intersections. These combinations are shown in Table 2. 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 included a posted speed limit of 45 mph.

Table 2 - Grid and intersection layout

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

Figure 10 - 3-section dual-arrow signal configuration and pedestrian walking toward subject

Four different types of scenarios involving pedestrians were presented to the subjects. These included intersections with no pedestrians, one pedestrian walking toward the test vehicle, one pedestrian walking away from the test vehicle and a case with four pedestrians, two walking away and two walking towards. According to the ITE Transportation Planning Handbook, one of the most common pedestrian crashes is described as the vehicle turn/merge conflict type (2009). This conflict type describes when a pedestrian and vehicle collide while the vehicle is conducting, preparing, or has just completed a turning movement. In 2006, for an educational course on pedestrians and bicyclist safety, the Federal Highway Administration (FHWA) found that this crash type occurred in 9.8 percent of all pedestrian crashes and 18 percent of these crash types had resulted in serious or fatal injuries. Due to these findings, the simulated pedestrians were positioned to the left of the driver, so that each subject would have to make maneuvers through the walking paths of the pedestrians. A figure of this type of pedestrian and vehicle crash type is shown in Figure 11. The walking speeds of all simulated pedestrians were 3.5 ft/s, which is the suggested design speed found in chapter 4E of the 2009 edition MUTCD.

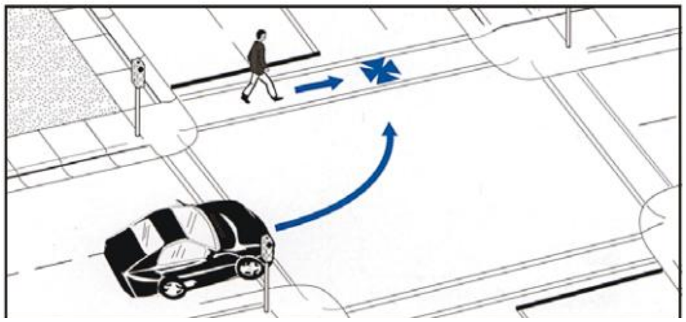


Figure 11 - Vehicle turn/merge pedestrian crash type (FHWA)

When approaching each intersection, the driver was exposed to three different sets of opposing vehicle volumes; no vehicles, three vehicles, and nine vehicles. Vehicles were released using an average saturation headway of two seconds, which is based on the FHWA Traffic Signal Timing Manual and engineering judgment (2009). When converted, this headway results in an average saturation flow rate of 1800 vehicles per hour of green per lane. The first three to four headways were randomly generated within certain ranges that had taken into account the reaction time to the FYA indication, replicating start-up lost time. Figure 12 shows a graphical representation from Roess, Prassas & McShane of both the start-up lost time ($\Sigma\Delta_i$) and saturation headway (h) (2010). Acceleration of the simulated vehicles were also randomly generated within a range that averaged to 5.2 ft/s^2, the acceleration characteristic of a typical passenger vehicle found in the ITE Traffic Engineering Handbook for a speed range between 40 and 50 mph (2009).

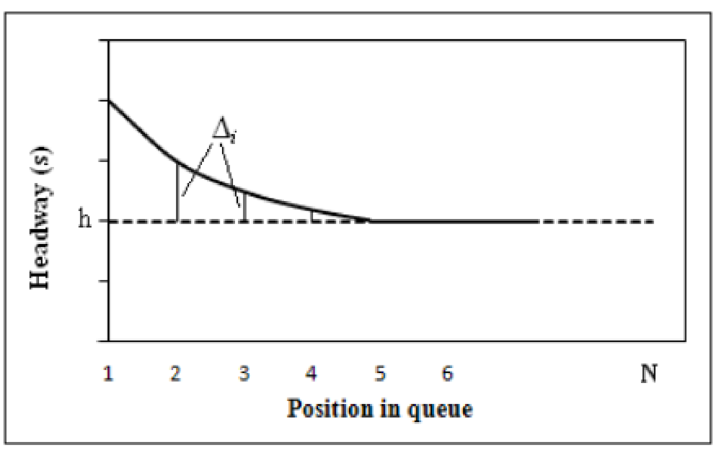


Figure 12 - Graphical representation of start-up lost time and saturation headway

Subjects were 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 (under 5 mph) before the permissive FYA indication. Figure 13 shows an intersection operating the 3-section dual-arrow signal configuration in operation and moments after the 9 vehicle queue had been released. This intersection also has a pedestrian walking away from the subject that is being blocked by the Blue SUV shown in the far left.

Figure 13 - Intersection showing FYA operation and queued vehicles being released

4 RESULTS AND DISCUSSION

Of the 38 subjects who participated in the experiment, 8 could not complete the experiment due to simulator sickness, and 3 subjects were removed due to failed data acquisition from the eye tracking video. This resulted in 27 experimental subjects. In total, out of the possible 648 permissive left turn maneuvers performed by the 27 subjects, 620 were deemed acceptable for further analysis.

4.1 Post-drive questionnaire 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 3. The response to the first question (If you want to turn left, and are presented with the flashing yellow arrow you would: 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 perceive the FYA message correctly i.e. yield and then wait for a gap. No subjects thought the FYA gave them the right of way or that they must stop and wait for the next signal. All of the subjects tested correctly understood that when presented with the FYA, they must yield both opposing vehicles and pedestrians.

Table 3 - Driver Response to Questionnaire

If you want to turn left, and are presented with a flashing yellow arrow, you would:		
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?		
Possible Responses	***Number of Participants***	***Percentage of Participants***
Opposing vehicles	27	100%
Pedestrians	27	100%
Cross-street vehicles	5	19%
None of the above	0	0%

4.2 Data Reduction

Using the ASL Results Plus software suite provided with the ASL Mobile Eye-XG equipment, researchers were able to analyze each subject's fixations using Area of Interest (AOIs) polygons after the experiment. This process required researchers to watch each approach video that was collected effectively (approximately 24 per subject) and draw these AOI polygons on individual video frames in a sequence separated by intervals measuring approximately 5 to 10 frames. Once the researcher manual moves each AOI, an "Anchor" is created within the software. The distance and size difference of the AOIs between these Anchors is interpolated by the Results Plus software to ensure that all fixations on the interested objects, in this case pedestrians, signals, opposing vehicles, are captured. An example of the different AOIs can be found in Figure 14, in this image the subject is at the stop line waiting for an appropriate moment to make the left turn maneuver. At this particular moment in time, the subject is fixating on the pedestrian walking towards their direction (Centered 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) indicating that the subject had just previously fixated on the opposing vehicles being released and the FYA signal before that.

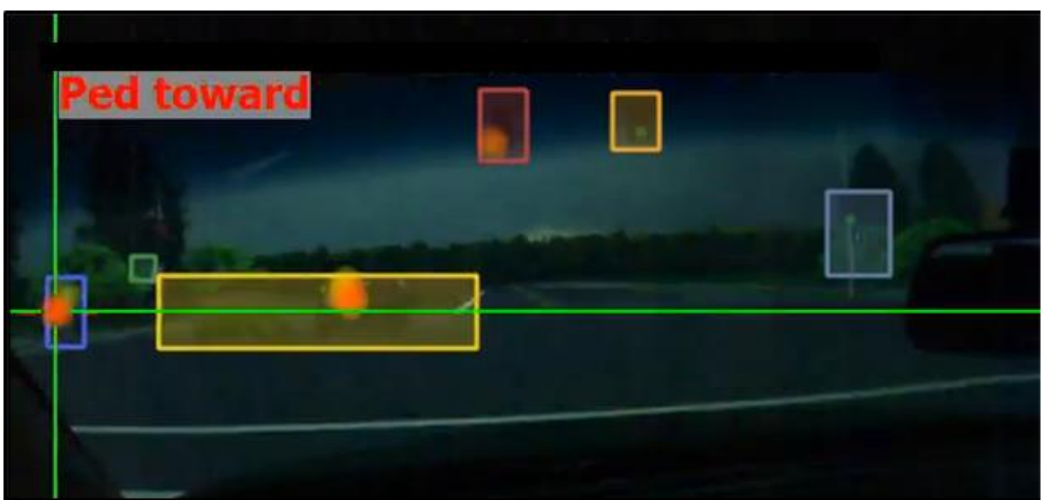


Figure 14 - Subject at stop line fixating on AOIs

Another example of a subject fixating on an AOI, in this case the crossing pedestrian walking away from the subject, can be found in Figure 15. This figure exemplifies type of pedestrian-vehicle conflict being explored as the permissive left turn movement is initiated while the pedestrian was still obstructing the path of the vehicle; defined by the FHWA as a vehicle turn/merge conflict type as was described in 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.

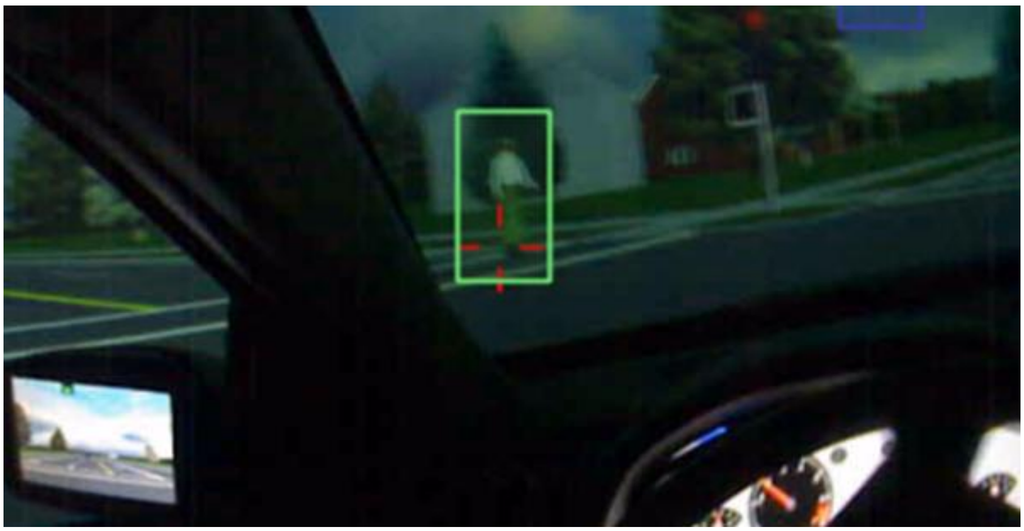


Figure 15 - Subject fixation on crossing pedestrian walking away during left turn maneuver

Once the AOIs have been coded for each individual video file, ASL Results Plus is used to output spreadsheets of the all fixations and their corresponding AOIs. Fixations outside of coded AOIs were universally defined as OUTSIDE and were not used further in the analysis. Researchers exported these .txt spreadsheets and imported them into different analysis packages such as excel and R for further analysis. An example of a portion of one subject's 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. This table is a summary of the fixations during a single 30 second approach video and includes the number of fixations, total fixation durations, average fixation durations, and time of first fixation within each AOI created during one intersection approach and left turn maneuver. Saccades, quick eye movements where no fixations are made by the subject, were not exported and analyzed.

Table 4 – Example of raw fixation data and AOI summary table

AOI Name	Fixation Count	Total Fixation Duration	Average Fixation Duration	First Fixation Time
Bay	9	3.4	0.378	15.02
FYA	7	3.11	0.444	16.02
Opposing Veh	8	2.72	0.34	24.34
OUTSIDE	27	6.19	0.229	14.29
Ped Towards	1	0.2	0.2	29.72

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

4.3 Data Analysis and Results

The reduction of the eye tracking video data allowed researchers to perform a variety of descriptive statistics and statistical tests. Several performance measures were available to analyze, for this research however, total fixation duration was one of the most directly applicable. For each scenario, an average of the total fixation duration from all subjects was collected for each AOI. Figure 16 shows the average total fixation duration (ATFD) for AOIs at an intersection that presented the driver with no pedestrians, no opposing vehicles, and a 4-section vertical FYA signal display. This particular intersection is the most basic of all intersections shown to the subjects and consists of the signal configuration standard from the 2009 MUTCD, and therefore considered the control case. 95% confidence intervals were constructed around the ATFDs, examples of which can be seen in Figure 16. The 95% CI describes that we are 95% confident that the true mean exists within the specified interval.

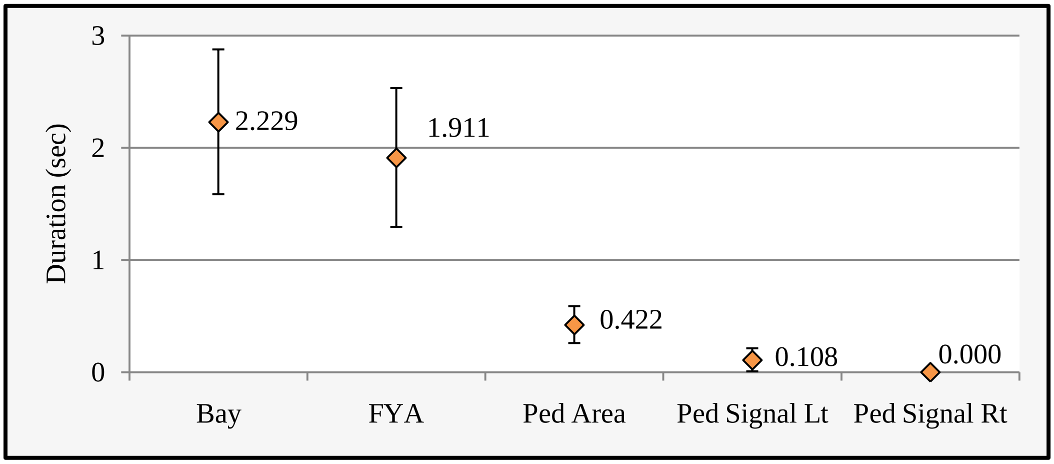


Figure 16 – ATFD with 95% CIs of case with a 4-section FYA, no vehicles, and no pedestrians

Figure 17 shows the ATFD from all subjects at an intersection with nine opposing vehicles, two pedestrians walking away from the subject, two pedestrians walking toward the subject, and a 3-section FYA signal display. This case includes the highest levels of the experimental variables, the most visually complex case when compared to the control case described in Figure 16. The ATFD and 95% CIs figures, like the two shown, for all 24 experimental scenarios can be found in Appendix 7.

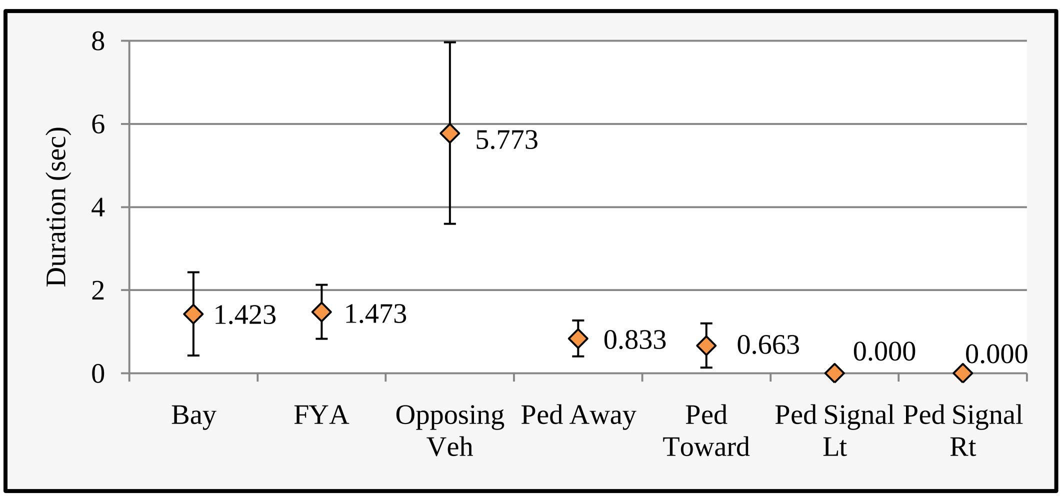
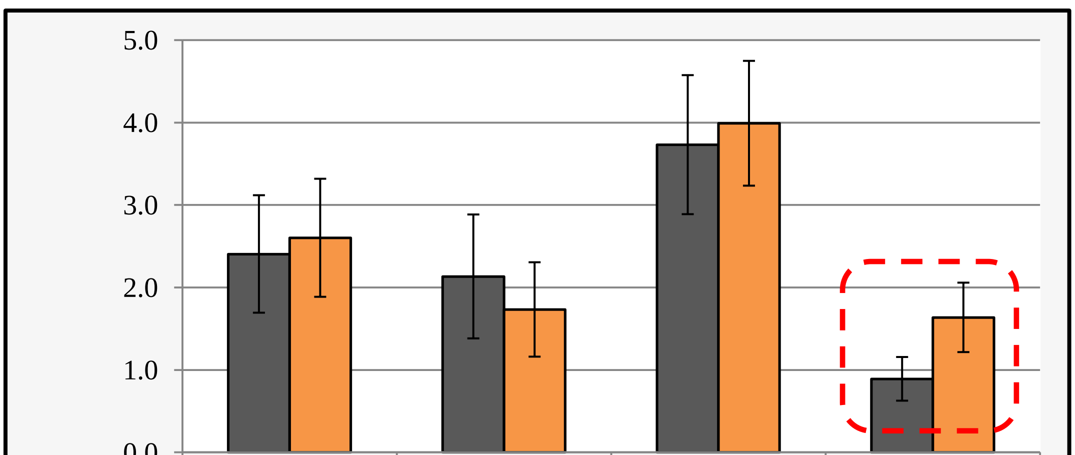


Figure 17 – ATFD with 95% CIs of case with a 3-section FYA, 9 vehicles, and pedestrians from both sides

Upon further consideration, useful graphical comparisons can be performed based on the ATFD and the corresponding 95% CIs. For example, Figure 18 shows the ATFD on four

AOIs for two experimental scenarios where all factors are kept constant (1 pedestrian walking toward and 3 opposing vehicles) except for the signal configuration (3-section versus 4-section). As described in the Methods Chapter, Grid 1-1 represents the intersection with the 3-section dual-arrow while Grid 4-2 represents the intersection with the 2009 MUTCD standard 4-section vertical signal configuration. The graphical comparison shows that, with 95% confidence, the ATFD on the pedestrians walking toward the subject are significantly different due to the fact that the 95% CIs do not overlap. This suggests that when presented with a 4-section FYA signal, drivers spend more time fixating on the position of the pedestrians (1.6s) than they do when presented with a 3-section FYA signal (0.9s). To further confirm this observation, a two sample t-test assuming unequal variances (determined by a two-sample F-test) resulted in a one tail p-value of 0.003.



	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 18 - Graphical comparison between two similar intersections with different signal configurations

4.3.1 Pedestrians

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 driver fixations during permitted left turn maneuvers at signalized intersections operating the FYA with pedestrians walking towards, away, or from both sides.*

This resulted in three groups (pedestrians walking towards, away or from both sides) consisting of six experimental scenarios each. This allowed researchers to isolate the impact of individual variable levels. For example, one possible test could determine the difference between the total fixation durations on the FYA AOI between intersections with a pedestrian walking toward the subject (*Ped Toward*) and intersections with a pedestrian walking away from the subject (*Ped Away*). To find if the ATFD is in fact different between specific cases, F-tests were initially conducted to assess if the variance of the two samples were equal. However, after running both the two-sample t-test assuming equal variance and unequal variance, the resulting p-values were so similar that significant different conclusions were not affected by the equal variance assumption. Therefore, the two sample one tail t-test assuming unequal variance was selected as this is the more conservative of the two statistical tests. Table 5 presents the results of these t-tests. In order for two variables to be statistically different with 95% confidence, the resulting p-values have to less than 0.05.

Table 5 - Statistics summary table comparing the locations of differing pedestrian volumes

	Pedestrian direction of travel			**Two sample one tail t-test assuming unequal variance for ped cases**					
Areas of Interest	Toward	Away	Both	***Toward*** vs ***Away***		***Toward*** vs ***Both***		***Away*** vs ***Both***	
	ATFD (sec)			p-value	Sig	p-value	Sig	p-value	Sig
Pedestrians	1.504	1.639	2.974	0.200	No	< 0.001	**Yes**	< 0.001	**Yes**
FYA Signal	1.720	1.787	1.617	0.375	No	0.282	No	0.198	No
Opposing Vehicles	5.365	5.138	4.690	0.292	No	0.046	**Yes**	0.152	No
Turn Bay	2.443	2.361	2.272	0.352	No	0.191	No	0.328	No

Between the *Ped Toward* and *Ped Away* cases, no statistically significant differences were found. This suggests that fixation durations do not change depending on what direction a single pedestrian is walking in the crosswalk. Recount that the only vehicle/pedestrian conflict being tested is that of the turn/merge movement described in Section 3.1. It was found that the ATFD for the pedestrian AOIs was statistically different when there was a single pedestrian walking toward the subject versus two pedestrians from both sides (*Ped Both*). This result was also found between the *Ped Away* and *Ped Both* independent variables. The only other significant difference found with 95% statistical significance was the ATFD of the opposing vehicle AOIs between the *Ped Toward* and *Ped Both* cases.

4.3.2 Vehicles

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

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

This resulted in three groups consisting of eight experimental scenarios each; including intersections with no opposing vehicles, three vehicles, and nine vehicles. The various levels of the other variables were tested against one another using two sample one tail t-tests assuming unequal variance. The results from these t-tests appear in Table 6 along with the ATFD for each variable. At all intersections with no opposing vehicles compared to all intersections with 3 opposing vehicles, statistically significant differences (with 95% confidence) were found between the *Ped Away*, *Ped Toward*, *Ped Both*, and *FYA signal* AOIs. This suggests that 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 comparing intersections with no vehicles and intersections with 9 opposing vehicles, in addition to a statistical difference between ATFD on the pedestrian areas when there were no pedestrians present (*Ped Area*). The t-tests show that statistical differences existed between the *Ped Away*, *Ped Toward*, *Ped Both*, and *Opposing Veh* variables when comparing intersections with only 3 opposing vehicles to intersections with 9. Some of these results were anticipated, for example one can assume that when the released opposing queue has 9 vehicles more time will be spent fixating on these vehicles then when there are only 3 vehicles being released.

Table 6 - Statistics summary table comparing locations of differing opposing vehicular volume

	Opposing Vehicle Volume			**Two sample one tail t-test assuming unequal variance**					
Areas of Interest	No Veh	3 Veh	9 Veh	***No Veh*** vs ***3 Veh***		***No Veh*** vs ***9 Veh***		***3 Veh*** vs ***9 Veh***	
	ATFD (sec)			p-value	Sig	p-value	Sig	p-value	Sig
Ped Away	2.405	1.474	1.032	< 0.001	**Yes**	< 0.001	**Yes**	0.013	**Yes**
Ped Toward	2.570	1.285	0.652	< 0.001	**Yes**	< 0.001	**Yes**	< 0.001	**Yes**
Ped Both	4.334	2.835	1.677	< 0.001	**Yes**	< 0.001	**Yes**	< 0.001	**Yes**
Ped Area	0.517	0.350	0.275	0.065	No	0.010	**Yes**	0.185	No
FYA Signal	1.973	1.542	1.601	0.003	**Yes**	0.015	**Yes**	0.351	No
Opposing Veh	N/A	3.837	6.784	N/A		N/A		< 0.001	**Yes**
Turn Bay	2.314	2.380	2.437	0.352	No	0.240	No	0.375	No

4.3.3 Signal Display

The next set of analyses involved comparing all intersections operating the MUTCD standard 4-section vertical FYA signal configuration to those operating the 3-section vertical with dual-arrow FYA signal configuration as described by the third null hypothesis found in Section 3.1:

***H_0**: There is no difference in the total duration driver fixations during permitted left turn maneuvers at signalized intersections operating the FYA with 4-section or 3-section vertical with a dual-arrow display.*

The 2009 MUTCD does allow the 3-section signal configuration, but only 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, Oregon the 3-section signal costs $1,156 per intersection while the 4-section signal costs $1,458. These amounts include materials and labor for installation. While this may not seem like a drastic difference when considering a single installation, when hundreds of conversions are considered, such as they were in Washington County, the additional $300 per signal, as well as the added time and equipment required became a legitimate concern.

Once again, two sample one tail t-tests were used to determine if the ATFD on specific AOIs varied when subjects were confronted with the 3-section versus 4-section configurations. A summary of these t-tests are shown in Table 7. No statistically significant differences for any of the experimental variables presented to the subjects when looking at all intersections. Furthermore, comparisons were made on a per intersection basis where all variables were held constant except for the signal configuration. The only statistical difference was found between two intersections that both had 1 pedestrian walking toward the subject and 3 opposing vehicles but different signal configurations, these two intersections are compared graphically in Figure 18. In this instance, as described earlier within this section, the subjects fixated on the 3-section longer than the 4-section therefore fixating less on the crossing pedestrians.

Table 7 - Statistics summary table comparing locations with 4-section signal vs. locations with 3-section signal

	Signal Configuration		**Two sample one tail t-test assuming unequal variance**	
Areas of Interest	4-section	3-section	***4-section*** vs ***3-section***	
	ATFD (sec)		p-value	Significant
Ped Away	1.707	1.570	0.263	No
Ped Toward	1.589	1.417	0.238	No
Ped Both	2.809	3.081	0.196	No
Ped Area	0.331	0.429	0.116	No
FYA Signal	1.808	1.602	0.059	No
Opposing Vehicles	5.133	5.490	0.114	No
Turn Bay	2.354	2.400	0.372	No

4.3.4 No Fixations on Pedestrians

When assessing pedestrian-vehicle conflicts during permissive left turn operations, it is important to determine if drivers neglect to scan for the presence of pedestrians in or adjacent to the crosswalk. Individual driver fixation behavior was examined to determine if failures to scan for pedestrians took place. As depicted in Table 8, for all levels of pedestrian activity a measurable portion of subjects did not scan for pedestrians.

Table 8 – Pedestrian AOI summary table

Ped Cases	**Did not look**		**Looked**	
Towards	13	8%	142	92%
Away	8	5%	146	95%
Both	17	11%	139	89%
None	56	35%	105	65%

Table 9 - Proportions analysis of pedestrian AOI comparisons

Comparisons	Difference	95% CI	p-value
Toward vs Away	3.2%	(-2.4%, 8.8%)	0.264
Both vs Toward	2.5%	(-4.0%, 9.1%)	0.453
Both vs Away	5.7%	(-0.3%, 11.7%)	0.063
None vs Toward	26.4%	(17.8%, 34.9%)	< 0.001
None vs Away	29.6%	(21.4%, 37.7%)	< 0.001
None vs Both	23.9%	(15.1%, 32.7%)	< 0.001

It was determined that for the levels pedestrian activity considered, drivers failed to fixate on pedestrians in the cross walk for 5 to 11 percent of the intersection scenarios tested. Comparisons of the proportions between each pedestrian case were made with proportions tests and can be found in Table 9. There was no evidence that the two proportions were different, for each of the three comparisons (p-value > 0.05). While no statistical differences between the number of "did not look" occurrences between the three pedestrian cases is not statistically different, the fact that the percentage of "did no look" exceeds zero is concerning.

At the intersections that did not have a crossing pedestrian, the fixations in the general direction of the pedestrian area were recorded. As expected, there were a high number of subjects that did not fixate on these areas where pedestrians could be expected compared to the number of subjects that failed to fixate on pedestrians when they were present. The data analysis supports this assumption with p-values under 0.001 for every comparison involving the *Ped Area* AOI.

5 CONCLUSIONS

Transportation facilities, when designed appropriately, attempt to provide a balance between safety and efficiency while acknowledging the design implications on their most vulnerable users. At signalized intersections, pedestrians are considered to be amongst the most vulnerable. When in the crosswalk at intersections without protected left-turn phasing, pedestrians are particularly at risk from left-turning vehicles. Though 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 detect and appropriately respond to the presence of pedestrians.

5.1 Research Objectives Review

This research was aimed at better understanding what fundamental mechanism contributes to why drivers sometimes fail to observe pedestrians. More specifically, when drivers are presented with the FYA for a permissive left turn, how do fixation durations change when as levels of pedestrian volumes, opposing vehicle volumes, and type of signal configuration are varied. Three null hypotheses were tested in the OSU driving simulator.

1. H_0: *There is no difference in the total duration 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 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 total duration driver fixations during permitted left turn maneuvers at signalized intersections operating the FYA with 4-section or 3-section vertical with a dual-arrow display.*

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 when pedestrians are present or not in the crosswalk.*

A driving simulator experiment was conducted in which a sample of 27 drivers was collected representing 620 permissive left turn maneuvers. The following subsections highlight the most meaningful research findings.

5.2 Significant findings

The results found in section 4.3.1 compare the three levels of the pedestrian variable designed in the simulated environment, which includes cases with a pedestrian walking toward the subject, cases with a pedestrian walking away from the subject, and pedestrian from both sides of the crosswalk. Significant findings include:

- Statistically significant differences (p-value < 0.05) were found in the average total fixation duration (ATFD) on crossing pedestrians and opposing vehicles between all of the *Ped Toward* intersections and *Ped Both* intersections.
- Additionally, 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 (4 in the *Ped Both* scenarios) drivers do in fact focus more of their attention on these crossing pedestrians than when there are minimal pedestrians present (1 in the *Ped Away* and *Ped Toward* cases).

Section 4.3.2 focuses on the vehicular volume levels, specifically intersections with *No Vehicles*, *3 Vehicles*, and *9 Vehicles*. Findings include:

- ATFD was found to be statistically different for all pedestrian levels when subjects were confronted with *No Vehicles* vs. *3 Vehicles* vs. *9 Vehicles* suggesting that the opposing volume of vehicles released from the queue affects the focus of subjects on pedestrians drastically. Greater number of opposing vehicles results in less time fixating on pedestrians.
- When subjects were exposed to scenarios with no pedestrians and with 9 opposing vehicles, subjects would spend less time fixating on locations that could have pedestrians than if there were no vehicles (p-value = 0.015).

- It was also found that the ATFD on the opposing traffic was significantly different when there were 3 vehicles as compared to 9 vehicles.

The results presented in section 4.3.3 were concerned with the FYA signals displays, specifically comparing locations operating the MUTCD standard 4-section vertical vs. intersections with the 3-section dual-arrow vertical signal. It can be argued that the MUTCD standard is not supported based on the measure of ATFD, and due to costs, the 3-section vertical configuration could be considered an optional choice. The analysis supports this, showing that no significant difference of ATFD between any variable at all intersections with the 4-section and at all intersections with the 3-section signal. However, researchers looked at individual intersection comparisons and, as shown in Figure 18, there was one instance where a significant difference (p-value = 0.003) was found between the ATFD on pedestrians of two scenarios, *Ped Toward* and *3 Vehicles*, with the only differences being the signal configurations suggesting that:

- When presented with 3 opposing vehicles and a 4-section FYA signal, drivers spend more time fixating on the position of a pedestrian walking away (1.6s) than they do when presented with a 3-section FYA signal (0.9s).

The number of subjects who failed to fixate on pedestrians crossing the roadway was also collected. It was found that 8 percent of the subjects failed to fixate on pedestrians walking toward their vehicle, 5 percent failed when pedestrians were walking away from the subject’s vehicle, and 11 percent failed to fixate on pedestrians in the *Ped Both* cases. These percentages are alarming, it suggests that these specific subjects focus on other variables given at the intersections and fail to focus on the most vulnerable road users, pedestrians. In cases where there were no pedestrians present, fixations in the direction of a pedestrian area was collected. 35 percent of all subjects failed to fixate on these areas for any crossing or queued pedestrians.

5.3 Future work

This research has provided unique insight into the driver’s eye fixation patterns and durations. The influence of pedestrian, vehicle and display variables were successfully studied in a simulated driving environment a part of this experiment. With that said, there is additional work that could be conducted to advance this line of research:

- As this research was conducted on campus, there was an over-representation of relatively younger drivers in the sample population. A larger, more diverse sample size could result in more adoptable results.
- Further analyses could be performed on the current dataset, not only from the eye tracking data but also from the speed and position data from 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 the different variables, and the location of the crossing pedestrians when subjects start the turning movement.
- Increasing the number of different variables experienced by the tested subjects could also lead to meaningful results and findings.

6 REFERENCES

Brehmer, C. L., Kacir, K. C., Noyce, D. A., and Manser, M. P. (2003). "Evaluation of Traffic Signal Displays for Protected-Permissive Left Turn Control." *NCHRP Report 493*.

Cinnamon, J., Schuurman, N., and Hameed, S. M. (2011). "Pedestrian Injury and Human Behaviour: Observing Road-Rule Violations at High-Incident Intersections." *PLoS ONE*, 6(6), e21063.

Fayish, A. C., and Gross, F. (2010). "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, 15–22.

FHWA. (2006). "Federal Highway Administration University Course on Bicycle and Pedestrian Transportation. Lesson 3: Pedestrian and Bicyclist Safety." U.S. Department of Transportation.

FHWA. (2009). "Manual on Uniform Traffic Control Devices." U.S. Department of Transportation.

FHWA. (2009). "Traffic Signal Timing Manual." U.S. Department of Transportation.

Gluck, J. S., Levinson, H. S., Stover, V. G., N.C.H.R.P., Officials, A.A. of S.H. and T., and Board, N.R.C. (U.S.). T.R. (1999). *Impacts of Access Management Techniques*. Transportation Research Board.

Hatfield, J., and Murphy, S. (2007). "The Effects of Mobile Phone Use on Pedestrian Crossing Behaviour at Signalised and Unsignalised Intersections." *Accident Analysis & Prevention*, 39(1), 197-205.

Houten, R., Retting, R., Farmer, C., and Houten, J. (2000). "Field Evaluation of a Leading Pedestrian Interval Signal Phase at Three Urban Intersections." *Transportation Research Record: Journal of the Transportation Research Board*, 1734, 86-92.

Institute of Transportation Engineers. (2009). "Transportation Planning Handbook." 3rd ed. 974-976.

Institute of Transportation Engineers. (2009). "Traffic Engineering Handbook." 6th ed.

Kittelson & Associates, Inc. (2011). *Going Green by Flashing Yellow.* Portland: Washington County, Oregon.

Keegan, O., and O'Mahony, M. (2003). "Modifying Pedestrian Behaviour." *Transportation Research Part A: Policy and Practice*, 37(10), 889-901.

Knoblauch, R., Pietrucha, M., and Nitzburg, M. (1996). "Field Studies of Pedestrian Walking Speed and Start-Up Time." *Transportation Research Record: Journal of the Transportation Research Board*, 1538, 27-38.

Knodler, M. A., and Noyce, D. A. (2005). "Tracking Driver Eye Movements at Permissive Left-Turns." University of Iowa, Iowa City, Rockport, Maine, 9p.

Knodler, M., Noyce, D., Kacir, K., and Brehmer, C. (2006). "Analysis of Driver and Pedestrian Comprehension of Requirements for Permissive Left-Turn Applications." *Transportation Research Record: Journal of the Transportation Research Board*, 1982, 65-75.

Knodler, M. A., Noyce, D. A., Kacir, K. C., and Brehmer, C. L. (2001). "Driver Understanding of the Green Ball and Flashing Yellow Arrow Permitted Indications: A Driving Simulator Experiment." ITE, Chicago, Illinois.

Knodler, M., Noyce, D., Kacir, K., and Brehmer, C. (2005). "Evaluation of Flashing Yellow Arrow in Traffic Signal Displays with Simultaneous Permissive Indications." *Transportation Research Record: Journal of the Transportation Research Board*, 1918, 46-55.

Knodler, M. A., Noyce, D. A., Kacir, K. C., and Brehmer, C. L. (2003). "Evaluation of Traffic Signal Displays for Protected-Permissive Left-Turn Control Using Driving Simulator Technology." *Journal of Transportation Engineering*, 131(4), 270-278.

Lord, D., Smiley, A., and Haroun, A. (1998). "Pedestrian Accidents with Left-Turning Traffic at Signalized Intersections: Characteristics, Human Factors and Unconsidered Issues." *77th Annual Transportation Research Board Meeting, Washington, DC.*

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

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

National Safety Council. (2010). "Understanding the distracted brain: Why driving while using hands-free cell phones is risky behavior." *[White paper]*.

Neuman, T.R., Pfefer, R., Slack, K.L., Kennedy, K., Harwood, D., Potts, I., Torbic, D., Kohlman, E. (2003). "Guidance for Implementation of the AASHTO Strategic Highway Safety Plan - Volume 5: A Guidance for Addressing Unsignalized Intersections Collisions." *NCHRP Report 500, National Cooperative Highway Research Program, Transportation Research Board*.

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

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

Noyce, D. A., Fambro, D. B., and Kacir, K. C. (2000). "Traffic Conflicts Associated with Protected/Permitted Left-Turn Signal Displays." *Transportation Research Record: Journal of the Transportation Research Board*, 00-1698.

Olson, P. L., and Dewar, R. E. (2002). Human Factors in Traffic Safety. Lawyers & Judges Publishing Company.

Oregon Department of Transportation. (2006). "Traffic Signal Policy and Guidelines."

Oregon State University. (2011). *Driving Simulator*. Retrieved from Driving and Bicycling Research Lab: http://cce.oregonstate.edu/research/drivingsimulator/DrivingSim.php

Qi, Y., Yuan, P., Chen, X., and Zhang, M. (2012). "Safety of Flashing Yellow Arrow Indication with Protected Permissive Left-Turn (PPLT) Operation." *91st Annual Transportation Research Board Meeting, Washington, DC.*

Qi, Y., Zhang, M., Wang, Y., and Chen, X. (2012). "Safety Performance of Flashing Yellow Arrow Signal Indication." *91st Annual Transportation Research Board Meeting, Washington, DC.*

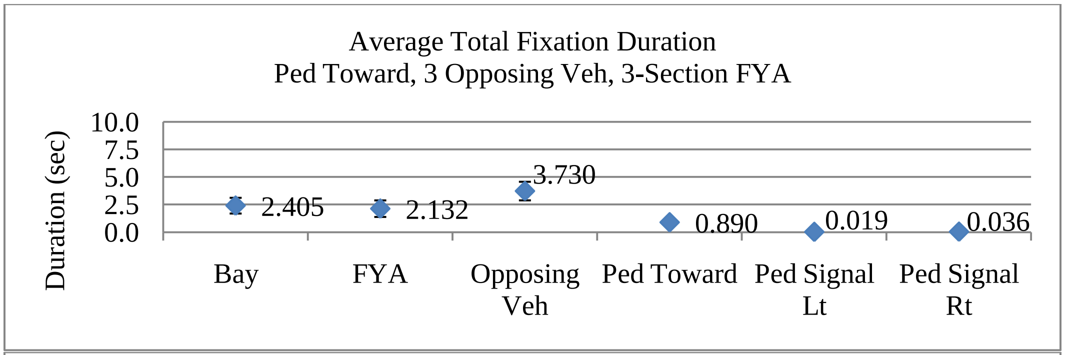
Regan, M. A., Lee, J. D., and Young, K. L. (2008). *Driver Distraction: Theory, Effects, and Mitigation*. CRC Press.

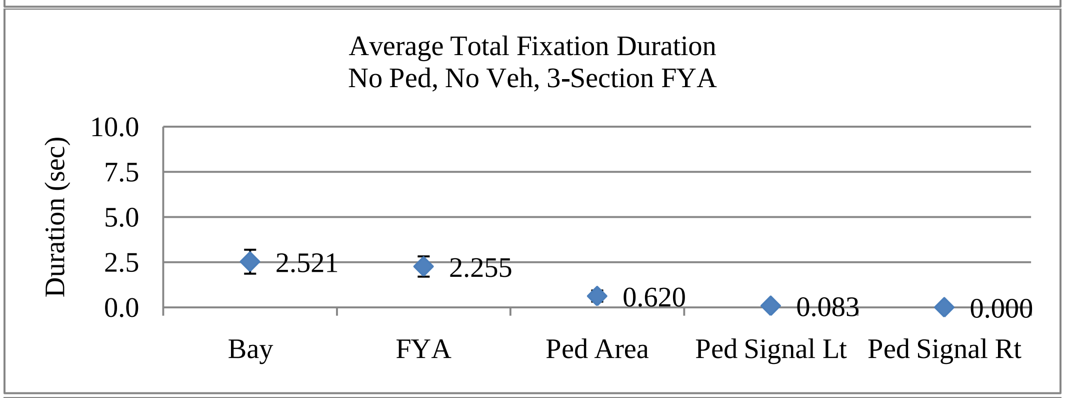
Shinar, D. (2007). *Traffic Safety and Human Behavior*. Emerald Group Publishing Limited.

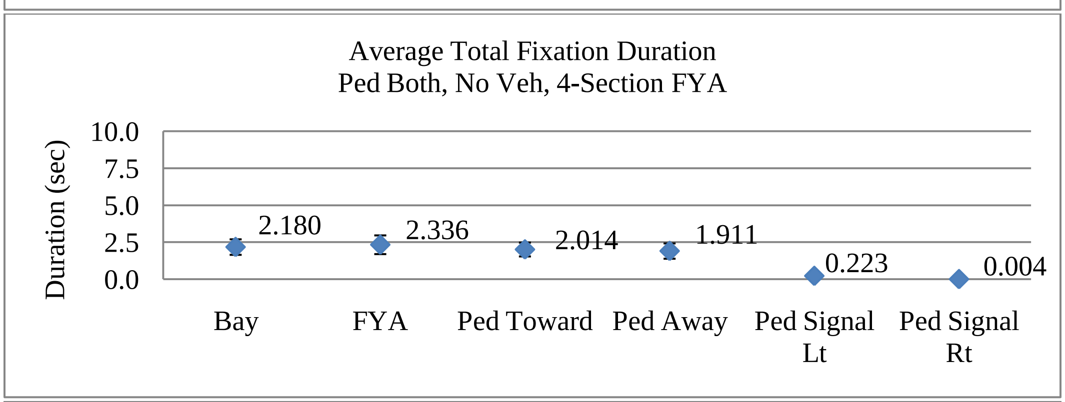
Smith, C. R., and Noyce, D. A. (2000). "An Evaluation of Five-Section Protected/Permitted Left-Turn Signal Displays Using Advanced Driving Simulator Technology." *Institute of Transportation Engineers*, Institute of Transportation Engineers, 23p.

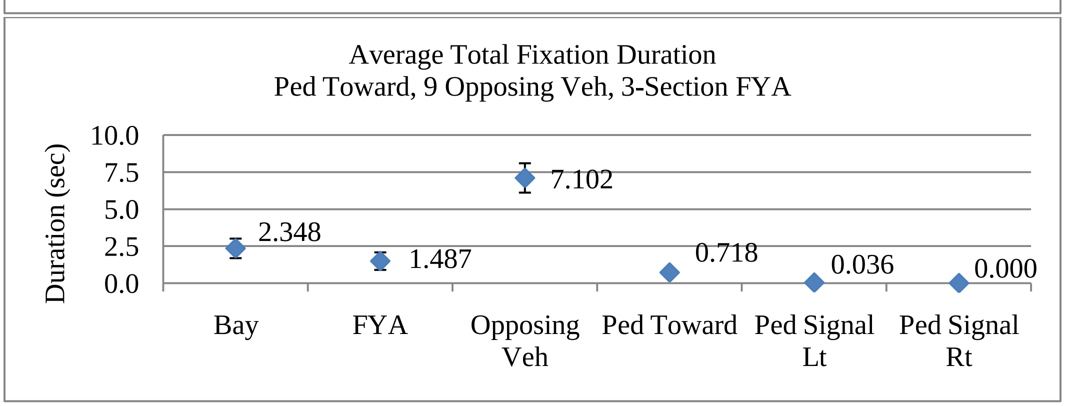
Wang, W., Guo, H., Gao, Z., and Bubb, H. (2011). "Individual Differences of Pedestrian Behaviour in Midblock Crosswalk and Intersection." *International Journal of Crashworthiness*, 16(1), 1-9.

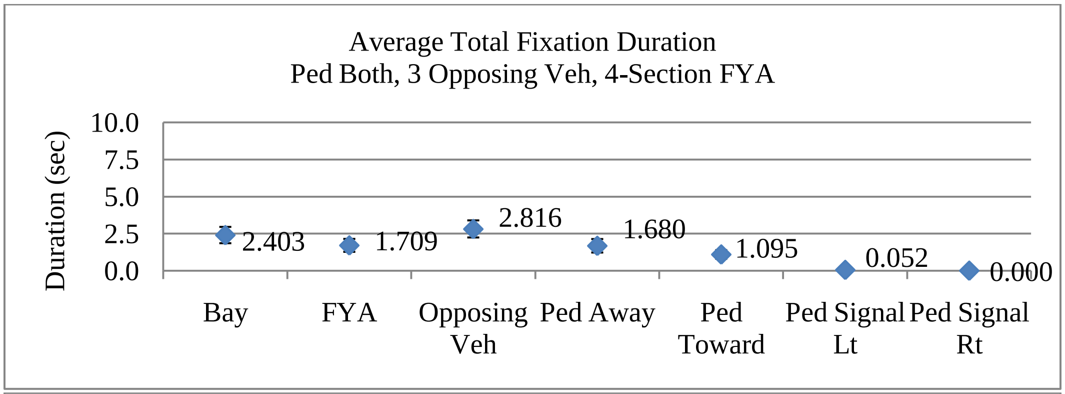
7 APPENDIX

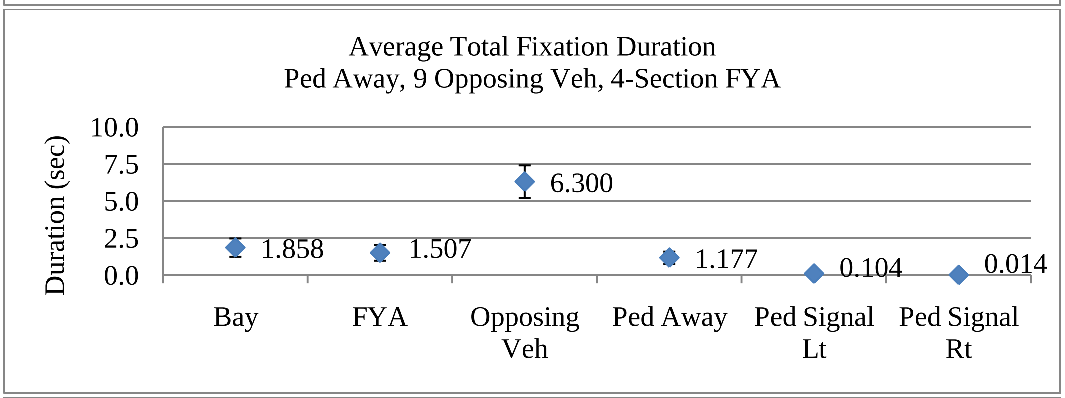

Average Total Fixation Duration
Ped Toward, 3 Opposing Veh, 3-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.405
2.132
3.730
0.890
0.019
0.036
Bay
FYA
Opposing Veh
Ped Toward
Ped Signal Lt
Ped Signal Rt

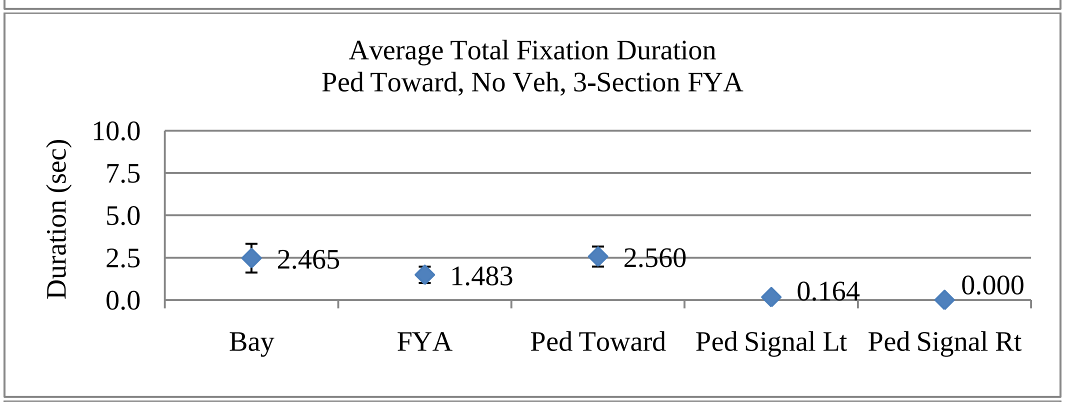

Average Total Fixation Duration
No Ped, No Veh, 3-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.521
2.255
0.620
0.083
0.000
Bay
FYA
Ped Area
Ped Signal Lt
Ped Signal Rt

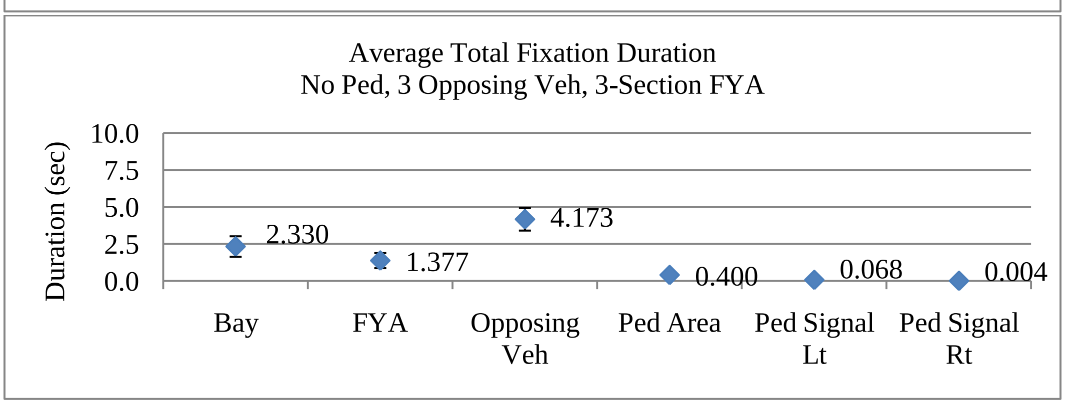

Average Total Fixation Duration
Ped Both, No Veh, 4-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.180
2.336
2.014
1.911
0.223
0.004
Bay
FYA
Ped Toward
Ped Away
Ped Signal Lt
Ped Signal Rt

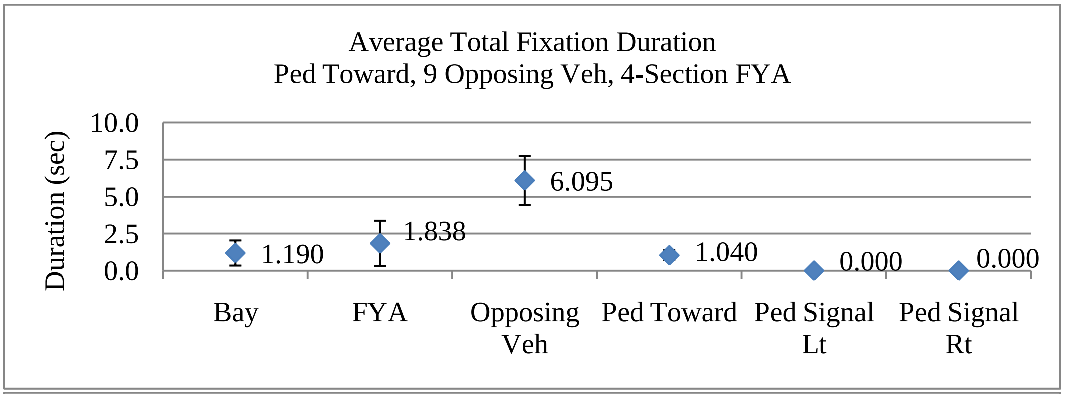

Average Total Fixation Duration
Ped Toward, 9 Opposing Veh, 3-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.348
1.487
7.102
0.718
0.036
0.000
Bay
FYA
Opposing Veh
Ped Toward
Ped Signal Lt
Ped Signal Rt

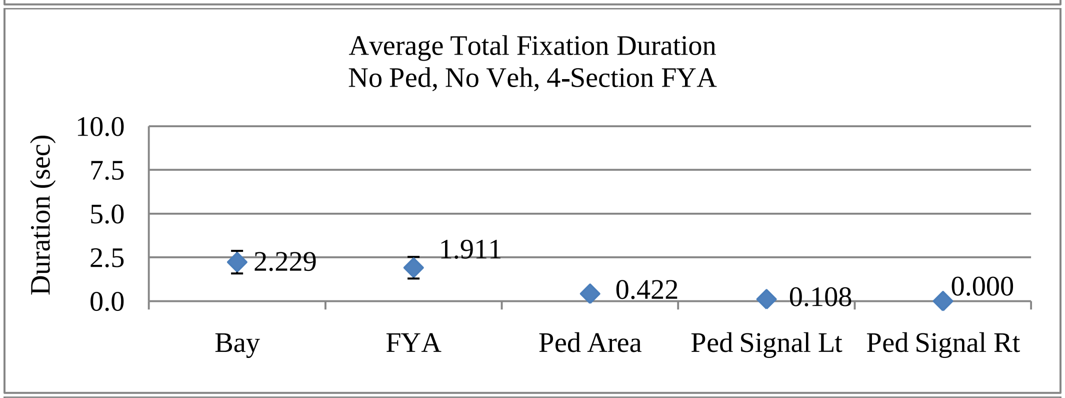

Average Total Fixation Duration
Ped Both, 3 Opposing Veh, 4-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.403
1.709
2.816
1.680
1.095
0.052
0.000
Bay
FYA
Opposing Veh
Ped Away
Ped Toward
Ped Signal Lt
Ped Signal Rt

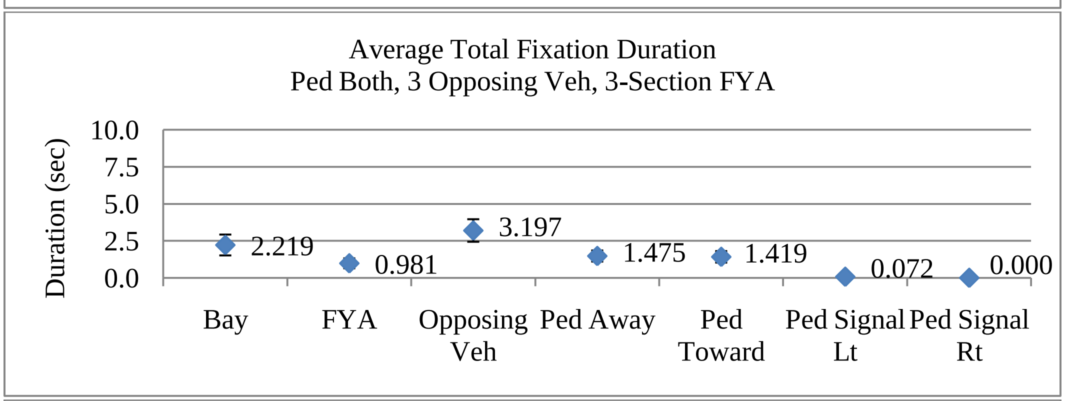

Average Total Fixation Duration
Ped Away, 9 Opposing Veh, 4-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
1.858
1.507
6.300
1.177
0.104
0.014
Bay
FYA
Opposing Veh
Ped Away
Ped Signal Lt
Ped Signal Rt

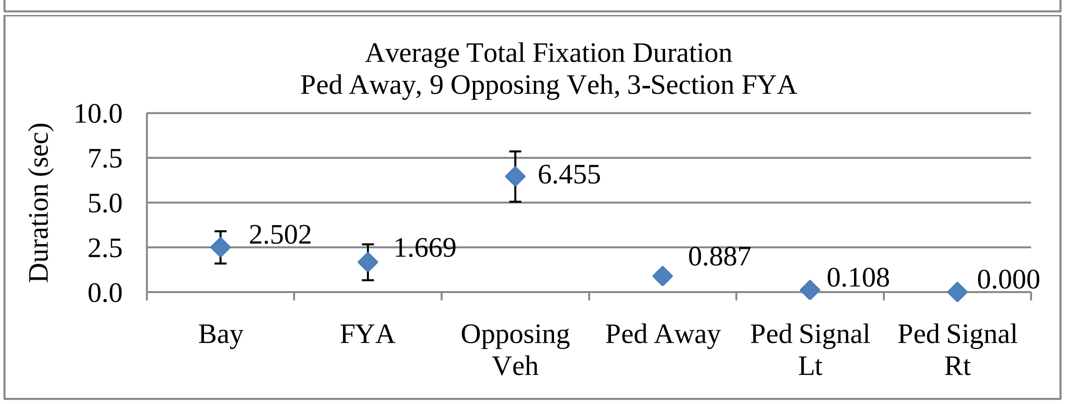

Average Total Fixation Duration
Ped Toward, No Veh, 3-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.465
1.483
2.560
0.164
0.000
Bay
FYA
Ped Toward
Ped Signal Lt
Ped Signal Rt

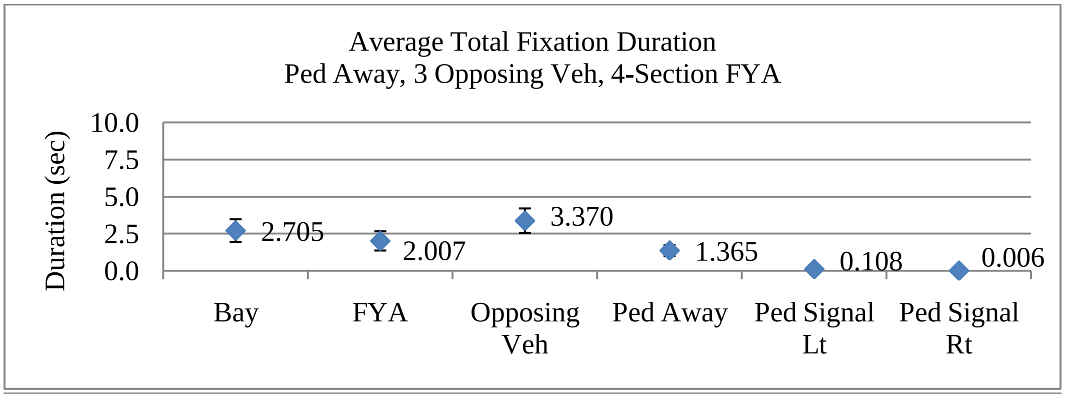

Average Total Fixation Duration
No Ped, 3 Opposing Veh, 3-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.330
1.377
4.173
0.400
0.068
0.004
Bay
FYA
Opposing Veh
Ped Area
Ped Signal Lt
Ped Signal Rt

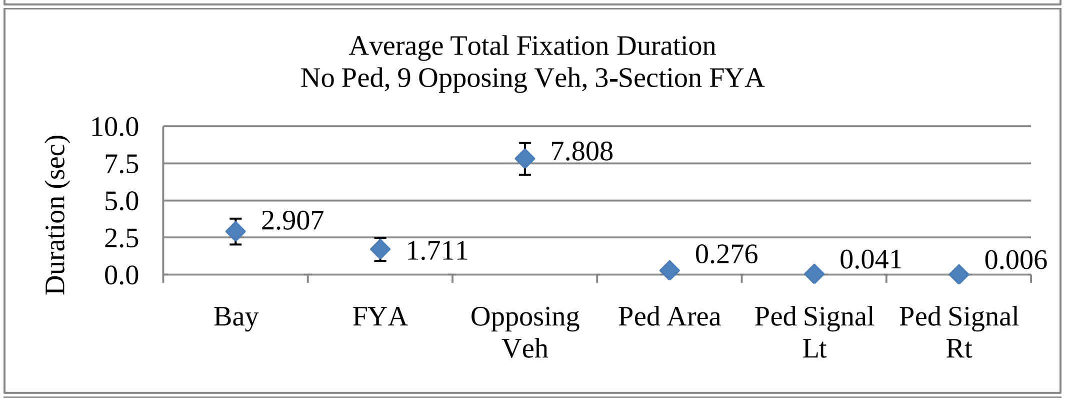

Average Total Fixation Duration
Ped Toward, 9 Opposing Veh, 4-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
1.190
1.838
6.095
1.040
0.000
0.000
Bay
FYA
Opposing Veh
Ped Toward
Ped Signal Lt
Ped Signal Rt

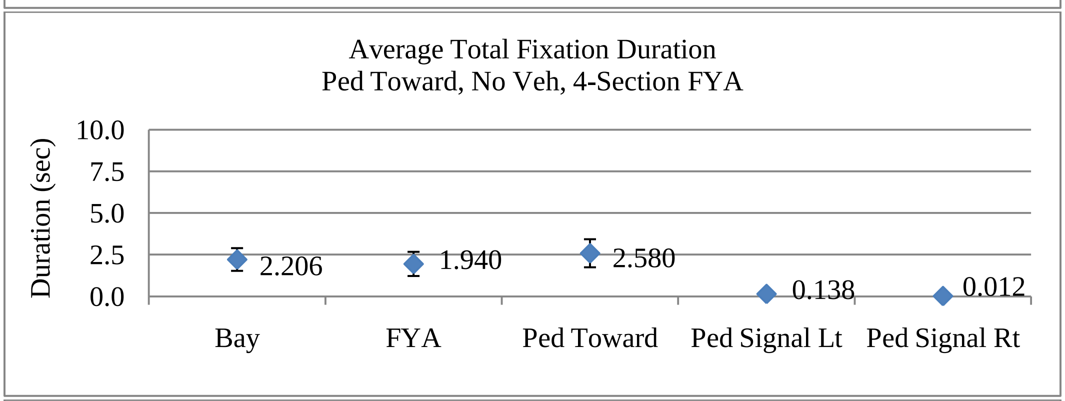

Average Total Fixation Duration
No Ped, No Veh, 4-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.229
1.911
0.422
0.108
0.000
Bay
FYA
Ped Area
Ped Signal Lt
Ped Signal Rt

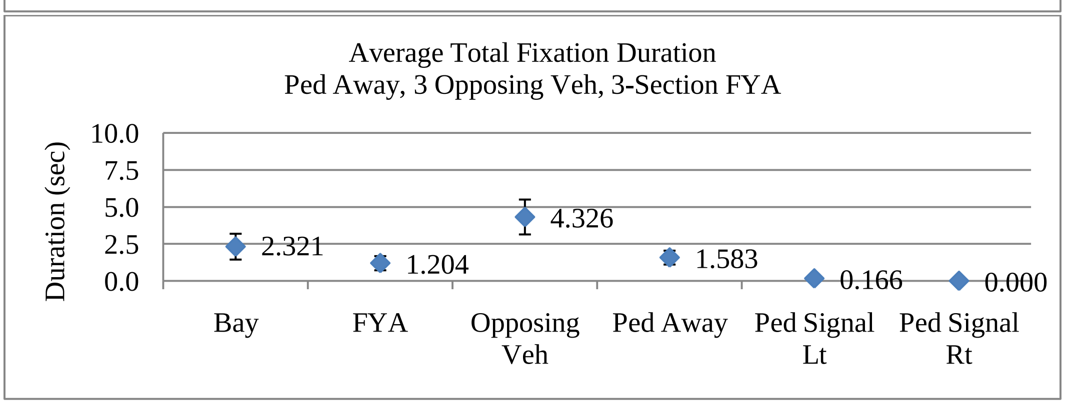

Average Total Fixation Duration
Ped Both, 3 Opposing Veh, 3-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.219
0.981
3.197
1.475
1.419
0.072
0.000
Bay
FYA
Opposing Veh
Ped Away
Ped Toward
Ped Signal Lt
Ped Signal Rt

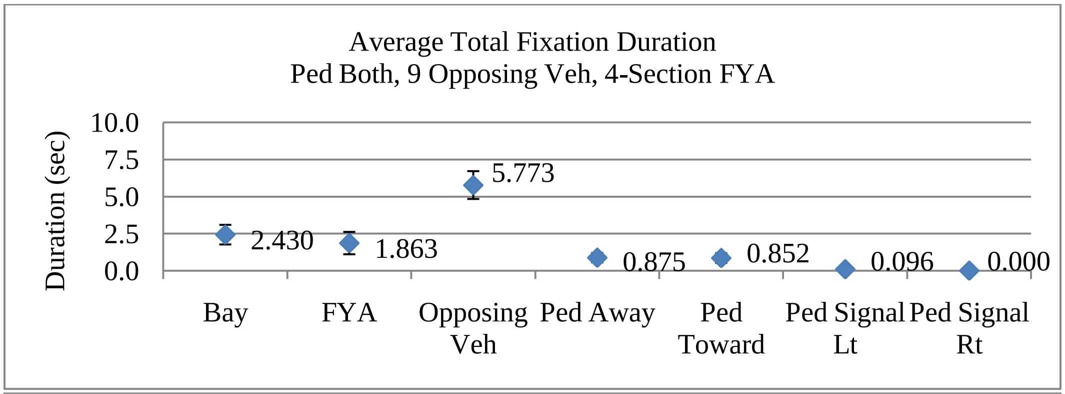

Average Total Fixation Duration
Ped Away, 9 Opposing Veh, 3-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.502
1.669
6.455
0.887
0.108
0.000
Bay
FYA
Opposing Veh
Ped Away
Ped Signal Lt
Ped Signal Rt

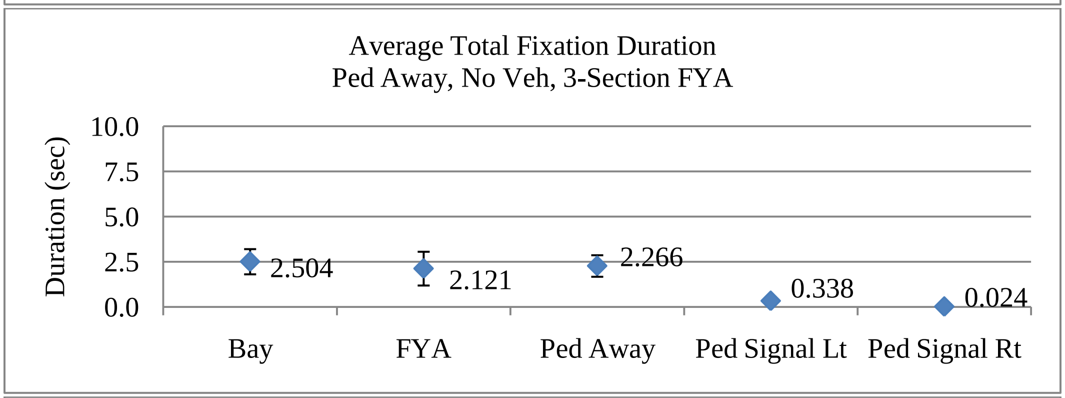

Average Total Fixation Duration
Ped Away, 3 Opposing Veh, 4-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.705
2.007
3.370
1.365
0.108
0.006
Bay
FYA
Opposing Veh
Ped Away
Ped Signal Lt
Ped Signal Rt

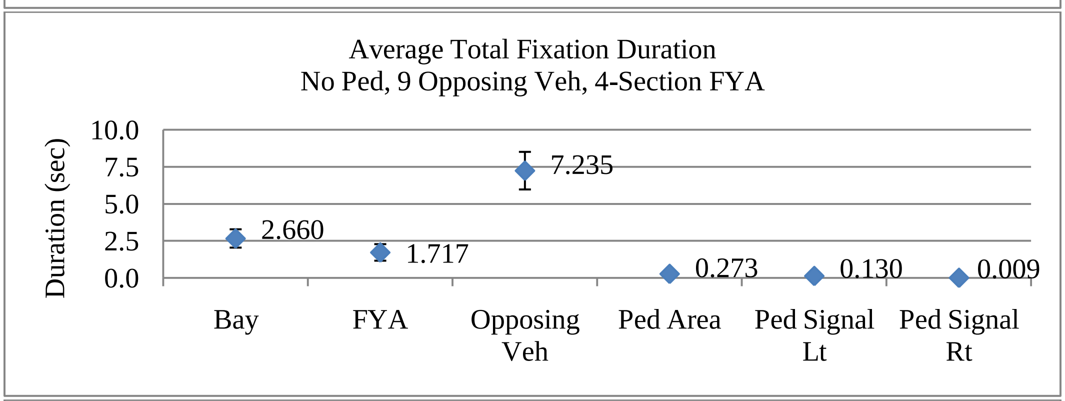

Average Total Fixation Duration
No Ped, 9 Opposing Veh, 3-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.907
1.711
7.808
0.276
0.041
0.006
Bay
FYA
Opposing Veh
Ped Area
Ped Signal Lt
Ped Signal Rt

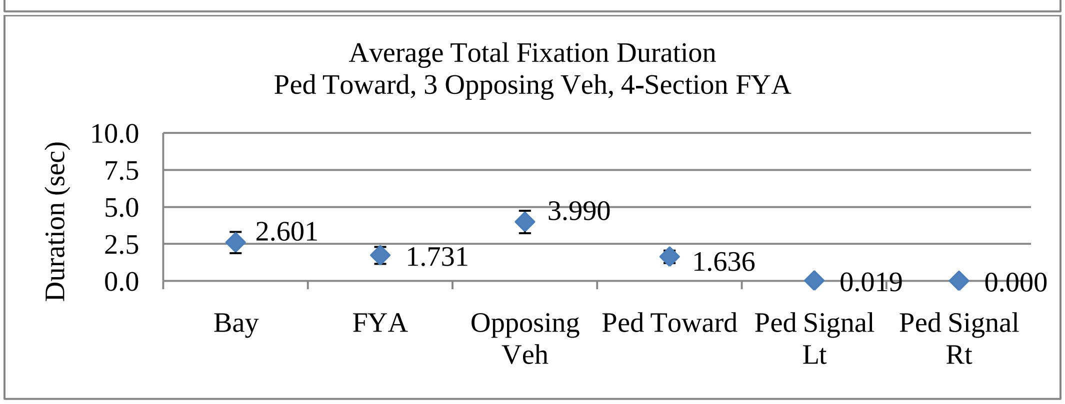

Average Total Fixation Duration
Ped Toward, No Veh, 4-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.206
1.940
2.580
0.138
0.012
Bay
FYA
Ped Toward
Ped Signal Lt
Ped Signal Rt

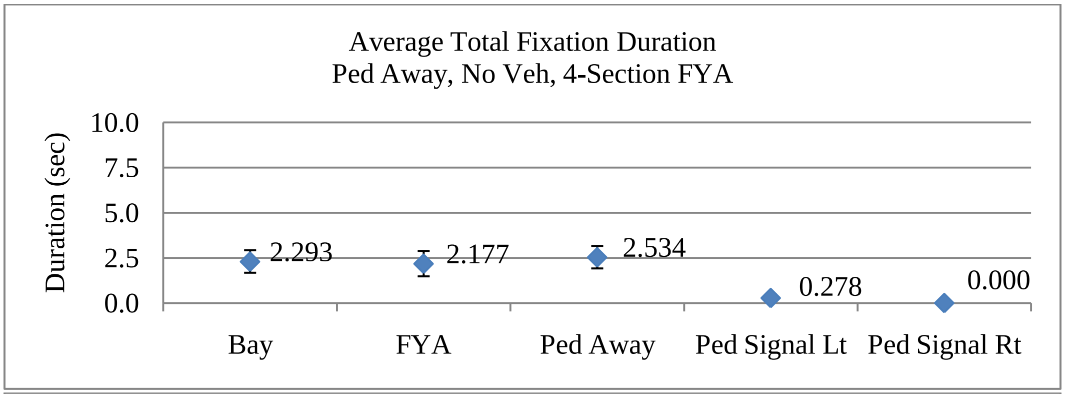

Average Total Fixation Duration
Ped Away, 3 Opposing Veh, 3-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.321
1.204
4.326
1.583
0.166
0.000
Bay
FYA
Opposing Veh
Ped Away
Ped Signal Lt
Ped Signal Rt

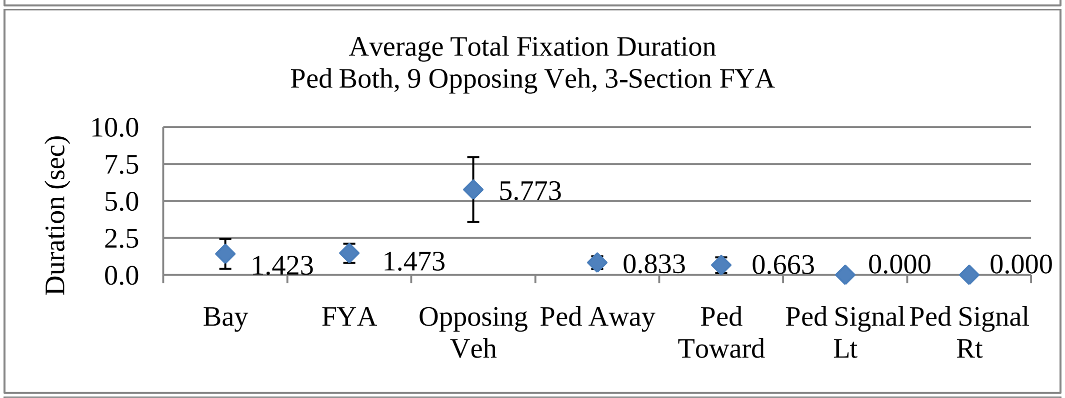

Average Total Fixation Duration
Ped Both, 9 Opposing Veh, 4-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.430
1.863
5.773
0.875
0.852
0.096
0.000
Bay
FYA
Opposing Veh
Ped Away
Ped Toward
Ped Signal Lt
Ped Signal Rt

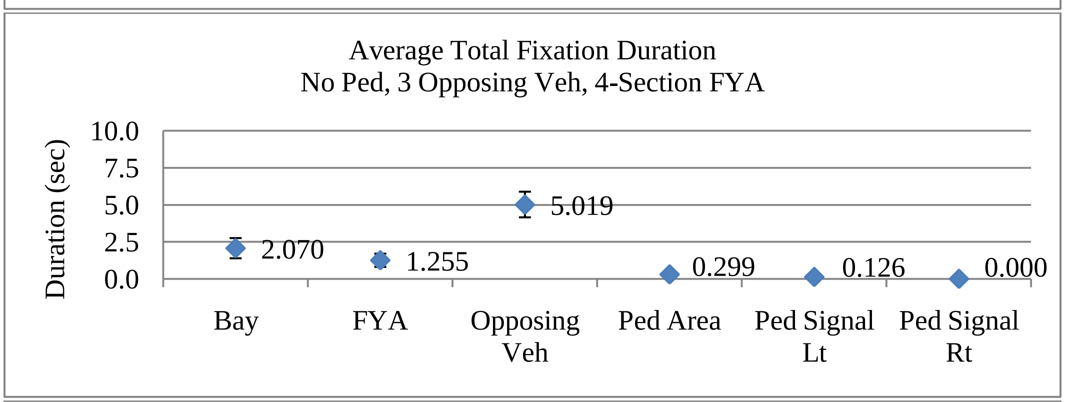

Average Total Fixation Duration
Ped Away, No Veh, 3-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.504
2.121
2.266
0.338
0.024
Bay
FYA
Ped Away
Ped Signal Lt
Ped Signal Rt

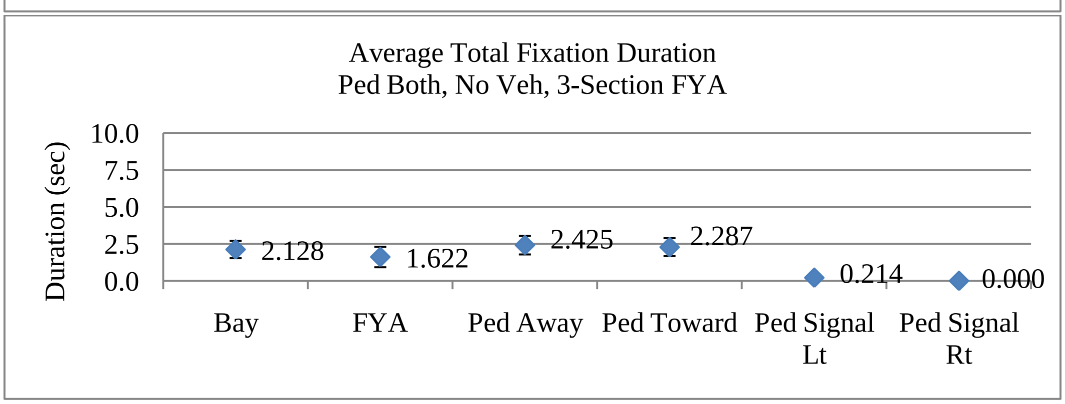

Average Total Fixation Duration
No Ped, 9 Opposing Veh, 4-Section FYA
Duration (sec)
10.0
7.5
5.0
2.5
0.0
2.660
1.717
7.235
0.273
0.130
0.009
Bay
FYA
Opposing Veh
Ped Area
Ped Signal Lt
Ped Signal Rt


Average Total Fixation Duration
Ped Toward, 3 Opposing Veh, 4-Section FYA
Duration (sec)
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 (sec)
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 (sec)
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 (sec)
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 (sec)
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