Safety Implications of the Use of the Flashing Yellow Arrow for Permissive Left Turns

Requested by
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The Caltrans Division of Research and Innovation (DRI) receives and evaluates numerous research problem statements for funding every year. DRI conducts Preliminary Investigations on these problem statements to better scope and prioritize the proposed research in light of existing credible work on the topics nationally and internationally. Online and print sources for Preliminary Investigations include the National Cooperative Highway Research Program (NCHRP) and other Transportation Research Board (TRB) programs, the American Association of State Highway and Transportation Officials (AASHTO), the research and practices of other transportation agencies, and related academic and industry research. The views and conclusions in cited works, while generally peer reviewed or published by authoritative sources, may not be accepted without qualification by all experts in the field.

Executive Summary

Background

The use of the flashing yellow arrow (FYA) for permissive left turns is relatively new to California, with at least five installations approved under a 2006 Federal Highway Administration (FHWA) Interim Approval memorandum. Inclusion of formal guidance for the optional use of FYA in the 2009 edition of the Manual on Uniform Traffic Control Devices for Streets and Highways (MUTCD) is expected to lead to heightened interest in applying the FYA within California, and Caltrans would like to know more about the safety implications of the use of the FYA for permissive left-turn lanes, particularly at intersections with railroad-preempted traffic signals.

Through examining completed, in-process and planned research related to the use of the FYA for permissive left-turn lanes, this Preliminary Investigation aims to address the following issues:

- The safety implications of the use of the FYA for permissive left-turn lanes, with a particular interest in before-and-after studies.
- Use of the FYA at intersections with a railroad preemption.

Summary of Findings

We reviewed published research and contacted national experts to identify research that is planned or in progress which addresses use of the FYA indication for permissive left turns.

While we report below on before-and-after studies included in NCHRP reports published in 2003 and 2007, we were unable to locate other such studies in the published research. We did locate publications that detail the experience of communities with FYA installations and a project in process that seeks to prepare for upcoming FYA installations by preparing guidelines and training materials. Our research also identified a variety of studies that address driver comprehension of the FYA signal indication.

We were unable to locate research—completed or in progress—that specifically addresses the application of the FYA at intersections with a railroad preemption. However, as a result of our conversations with national experts, the researcher overseeing a pending NCHRP research project is now aware of Caltrans' interest in the application of the FYA at preempted intersections and has indicated that an examination of this type of intersection could be included in the scope of the pending research. The project is expected to get under way in 2011.

Below we summarize specific findings in five topic areas:

- National Guidance.
- Consulting with National Experts.
- Impact of FYA Installations.
- Drivers' Comprehension of the FYA.
- Projects in Process.

National Guidance

- A 2003 NCHRP report, *NCHRP Report 493*, recommends inclusion of the FYA display as an alternative to the circular green indication used in permissive/protected left-turn (PPLT) control and operation, and offers recommendations on how the FYA should be implemented.
- A 2007 follow-up study, *NCHRP Web-Only Document 123*, examines the ability of the FYA indication to improve safety by interpreting crash data with respect to other variables.
    - Results indicate that installation of the FYA indication at sites that currently operate PPLT signal phasing improved safety.
    - Researchers noted an increase in crash frequency at intersections converted from protected-only left-turn control to PPLT with the FYA indication, though crash rates did decrease over time.
    - Insufficient study sites precluded conclusions with regard to conversion of permissive-only sites to PPLT with FYA phasing.
- A 2006 FHWA Interim Approval memorandum provided guidelines for transportation agencies to request experimental approval of the FYA indication for permissive left turns.
- Provisions for the optional use of the FYA are included in the 2009 edition of the MUTCD.

Consulting with National Experts

- None of the national experts we contacted—members of FHWA's MUTCD Team and representatives from relevant TRB and AASHTO committees—are aware of pending projects or research in progress now designed to consider the safety implications of FYA installations at railroad-preempted intersections.
- A pending NCHRP research project, expected to get under way in 2011, could be expanded to consider FYA installations at railroad-preempted intersections in driving simulator experiments.

Impact of FYA Installations

- Conference papers from 2008 and 2009 described FYA installations in Kennewick, WA, and offered recommendations on phasing options, timing elements and detection methods.
- An FYA installation in Jackson County, OR, is described in a 2005 conference paper that includes benefit/cost ratios, citizen comments and comparisons of the FYA display with existing phasing and control devices.

Drivers' Comprehension of the FYA

- To provide baseline information for future studies of the FYA permissive indication, a 2009 report focuses on driver comprehension of the solid yellow change indication that alerts drivers the permissive or protected phase is being terminated.
- A 2008 Missouri DOT report advises undertaking a public information campaign to increase familiarity with the FYA signal prior to and during the implementation process.
- In a 2008 conference paper, researchers described the results of video observation used to analyze drivers' understanding of an FYA installation in St. Louis, MO, concluding that the video observation methodology is superior to questionnaires or simulation. Results indicated that more than 90 percent of the drivers observed understood the meaning of the FYA signal phasing.

- Two 2007 TRB Annual Meeting papers evaluated the impact of two allowable permissive left-turn indications—the FYA and circular green—and comprehension of the solid yellow arrow resulting from exposure to the FYA permissive indication.
- The application of the FYA in specific types of intersections is evaluated in two 2006 publications.
  - In a TRB Annual Meeting paper, researchers concluded that the FYA permissive indication should be used at wide median intersections only after consideration of the safety and operational issues.
  - A journal article describes the results of driving simulator evaluations that indicated the FYA is recommended for use at T-intersections where pedestrian crossings are prevalent.
- Three 2005 publications provide the results of driving simulator studies.
  - A conference paper described the tracking of eye movements to identify scan patterns among drivers completing left turns. Researchers found that 90 percent of drivers first look for the PPLT signal display and then focus on opposing traffic when it is present.
  - Researchers evaluated 12 PPLT signal displays that included only the circular green ball and/or the FYA permissive indication to assess driver comprehension. Findings reported in a journal article indicate a high level of comprehension with no variation between the PPLT displays, which indicates that the FYA is an alternative to the circular green ball permissive indication.
  - A TRB Annual Meeting paper presented results of a study that compared driver comprehension of the circular green indication in a traditional five-section cluster signal configuration with a retrofit display that features the simultaneous display of the circular green with the FYA permissive indication.

Projects in Process

- A project expected to conclude in 2011 prepares for the implementation of the FYA with PPLT operations in Texas with field tests and the development of guidelines and training materials.

Gaps in Findings

The 2007 *NCHRP Web-Only Document 123* provides the most recent before-and-after studies we were able to locate in the published research, and we found no studies specific to the application of FYA at preempted intersections. As previously noted, an NCHRP study expected to begin in 2011 may include an examination of FYA installations at railroad-preempted intersections. A researcher with experience working with NCHRP on previous and pending FYA research is also proposing that NCHRP undertake before-and-after studies that continue the work reported in NCHRP reports published in 2003 and 2007. It is unclear as to when those before-and-after studies might begin.

Next Steps

Caltrans might consider the following in its evaluation of the use of the FYA for permissive left turns:

- Contact states, cities and counties that have a history of FYA use to gather anecdotal and other information about those installations, which may include unpublished before-and-after crash reporting.
  - Transportation agencies in the following locations participated in field trials associated with *NCHRP Report 493*:
    - Montgomery County, MD.
    - Oregon DOT.
    - Jackson County, OR.
    - City of Beaverton, OR.
    - Broward County, FL.
    - City of Tucson, AZ.

- Experimental data reported in *NCHRP Web-Only Document 123* were taken from FYA installations in the following states:
    - California.
    - Colorado.
    - Florida.
    - Michigan.
    - North Carolina.
    - Oregon.
    - Virginia.
    - Washington.
    - Wyoming.

  See *NCHRP Web-Only Document 123* for specific locations.

- Consult with the traffic engineer for the city of Kennewick, WA. FYA installations in Kennewick have been the topic of recent conference papers that offered advice to agencies contemplating or just starting to use the FYA indication.
- Consult with members of FHWA's MUTCD Team with regard to signal phasing for FYA installations, particularly those at railroad-preempted intersections.
- Contact Dr. David Noyce after the TRB Annual Meeting in January 2011 to inquire about the status of the pending NCHRP research project that will evaluate the FYA in shared yellow signal sections and the potential to include an examination of FYA installations at railroad-preempted intersections.

Contacts

During the course of this Preliminary Investigation, we spoke to or corresponded with the following individuals:

National Organizations

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National Committees

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Note: Dr. Noyce co-authored *NCHRP Report 493*, *NCHRP Web-Only Document 123* and other publications cited in this Preliminary Investigation.

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National Guidance

Below we highlight key national publications that evaluate the FYA traffic display in connection with PPLT control and operation, and provide guidance for its use. We begin with a 2003 NCHRP report that recommends inclusion of the FYA in the MUTCD as an allowable alternative display to the circular green indication, and the follow-up NCHRP report published in 2007 that evaluated use of the FYA permissive-only left-turn indication in the field.

The first federal guidelines for the use of the FYA for permissive left turns are reflected in a 2006 FHWA Interim Approval memorandum under which transportation agencies could request approval for an FYA installation. With the publication of the 2009 edition of the MUTCD, which includes specific provisions for the optional use of the FYA for permissive left turns, the 2006 FHWA Interim Approval is no longer in effect.

Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control, *NCHRP Report 493*, 2003.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_493.pdf (report)
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_493WPs/papers.pdf (working papers)

Note: The link to Working Paper 7 is not operational; see Appendix A for this document.

This examination of traffic signal displays for PPLT began with a survey of state and local transportation agencies to identify the signal displays used most often for PPLT control. After making a qualitative assessment of the safety and operational characteristics of each display and analyzing crash data for a more quantitative assessment, the best displays were selected for further study. After identifying the FYA as one of the displays showing promise in the research, pilot installations were made in several cities to assess the display's operation in real-life conditions and identify implementation issues.

The report presents highlights of the research project. More detail is found in the working papers developed for each of the eight study tasks associated with the project (engineering assessment, agency survey, photographic driver study, field traffic operations, field traffic conflict, crash data analysis, driver confirmation study and field implementation).

The following highlights some of the key results of the research project:

- **Driver Comprehension.** Working Paper 7, Driver Study Using Driver Simulator Technology (Confirmation Study), describes the results of an evaluation of driver comprehension using two full-size driving simulators and a video-based static evaluation. A total of 464 drivers participated in the experiment that evaluated 12 PPLT signal displays identified by previous research efforts. Results of the study include:
    - There was no significant difference in drivers correctly interpreting the meaning of the FYA indication as compared to the circular green indication.
    - Drivers' understanding of the FYA display increased with exposure.
    - The FYA display showed a higher fail-safe response compared to the circular green indication.
- **Implementation Issues.** The research team solicited volunteer agencies to implement the FYA for the purpose of identifying implementation issues and overall experience with the FYA display. Working Paper 8 documents the findings of this trial implementation effort undertaken by six participating agencies:
    - Montgomery County, MD.
    - Oregon DOT.
    - Jackson County, OR.
    - City of Beaverton, OR.
    - Broward County, FL.
    - City of Tucson, AZ.

  Project installations used two signal head arrangements—the four-section vertical display and the five-section vertical display. Observations from the project installations include:

- The FYA introduced challenges in working with current conflict monitor designs. In the traditional five-section PPLT operation, it is possible for the circular green indication and the green arrow display to be illuminated simultaneously. However, the FYA and circular green indications cannot illuminate simultaneously because the FYA must be tied to the opposing through movement green indication.
- Before-and-after studies of intersections implementing FYA displays showed no significant changes in conflict rate or follow-up headway data, which indicates good motorist understanding.
- Motorists at the Jackson County, OR, study site were observed to stay at the stop bar during the FYA interval while waiting for a gap in traffic, as compared to normal operation when motorists pull into the intersection while waiting for a gap.

- **Yellow Trap.** The "yellow trap" is commonly referenced in research related to the use of the FYA and PPLT signal control. The report's foreword (page 7 of the PDF) provides a good explanation of this key concern related to PPLT control:

  > A key concern with PPLT control is the "yellow trap," which occurs during the change from permitted left turns in both directions to a lagging protected left turn in one direction. The MUTCD requires that all circular signal indications on an approach to an intersection display the same color. The left-turning driver whose permitted interval is ending may try to sneak through the intersection on the yellow indication, not realizing that the opposing through traffic still has a green indication. To avoid the yellow trap, most agencies do not use leading/lagging PPLT. An innovation known as "Dallas Display" allows this operation without the yellow trap by operating the permissive left turns simultaneously with the opposing through movement. Previous research has shown that this operation reduces delay and improves safety, but is not easily implemented in all situations.

- **Engineering Assessment.** The research team updated an initial engineering assessment to reflect data from the driver confirmation and field implementation studies. The final findings of the project's engineering assessment, which appear on page 10 of the report (page 20 of the PDF), include:
  - The FYA display was shown to offer the highest level of safety.
  - The circular green indication using the Dallas Display and the FYA display was shown to rank "best" in the category of operations.
  - The circular green indication was shown to rank "best" as being implementable.
  - The FYA display was shown to be the best in the category of human factors.
  - The FYA display was shown to have the most versatile characteristics, and the circular green indication was the least versatile.

- **Recommendations.** The report's recommendations begin on page 10 of the report (page 20 of the PDF). Researchers recommend inclusion of the FYA display in the MUTCD as an allowable alternative display to the circular green indication when used in PPLT control/operation, and offer the following with regard to implementation:

  Displays. The four-section, all-arrow display face should be the only display allowed. The only display that justifies an exception to this recommendation is the three-section display face with bi-modal lens. The three-section display face with bi-modal lens should also be allowed given that it operates the same as does the four-section display face. Only one indication shall be illuminated at any time.

  Location. The FYA operation shall only be used in an exclusive signal arrangement. It is recommended, but not required, that the left-turn signal face be placed over the left turn lane.

  Supplemental Signs. Supplemental signing is not warranted with FYA display. Use of supplemental signing is optional.

  Phasing. When used for left-turn treatments, the FYA display shall be tied to the opposing through green indication/display.

The report also recommends a restriction on the use of flashing red indications and a follow-up study that examines FYA installations in the field using before-and-after crash data.

Evaluation of the Flashing Yellow Arrow Permissive-Only Left-Turn Indication Field Implementation, *NCHRP Web-Only Document 123*, 2007.
http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w123.pdf
This report documents the follow-up study undertaken as recommended in *NCHRP Report 493*. Researchers evaluated the ability of the FYA indication to improve safety by interpreting the findings of crash analysis with respect to other variables such as signal phasing, vehicle flow rates, posted speed limits and intersection geometry.

Findings were drawn from the analysis of 50 intersections in which the left-turn FYA indication was installed (three intersections were divided into two sites, resulting in 53 sites) and no other significant changes were known apart from the FYA installation. Only those sites for which one year or more of post-implementation data were available were considered for further analysis. Experimental data were taken from FYA installations in the following states:

- California.
- Colorado.
- Florida.
- Michigan.
- North Carolina.
- Oregon.
- Virginia.
- Washington.
- Wyoming.

See Table 5 on page 42 of the PDF for specific jurisdictions.

Results are reported in three categories that describe conditions at the intersection before the FYA installation:
- Group A—protected/permissive left turn (27 sites).
- Group B—protected-only left turn (21 sites).
- Group C—permissive-only left turn (5 sites).

Researchers' primary findings:

- Installation of the FYA indication at sites that currently operate PPLT signal phasing showed improvements in safety.
- In other locations, the change in left-turn signal phasing (from protected-only to PPLT) had a more significant impact on safety than the change in left-turn indication, although safety appeared to improve over time.

Details of the data analysis follow:

- Safety was improved at the Group A intersections that operated with PPLT phasing before introduction of the FYA display. After FYA implementation:
  - Average annual frequency of total crashes was reduced at 12 of 13 sites.
  - Average annual frequency of left-turn crashes was reduced at all 13 sites.
  - An empirical Bayes analysis found significant reductions at 15 of the 19 intersections available for analysis.
  - Statistical tests showed that sites changed from PPLT to PPLT with an FYA indication had significant decreases in crashes and a positive impact on safety.
- Safety was not improved at the Group B intersections that operated with protected left-turn control before introduction of the FYA display. After FYA implementation:
  - Average annual frequency of total crashes was increased at 12 of 18 sites.
  - Average annual frequency of left-turn crashes was increased at 14 of 18 sites.
  - An average increase in crash frequency of between 0.7 to 1.3 crashes per year for total, left-turn and FYA left-turn crashes was observed within an average period of 24 months after implementation.

    - Statistical analysis of total and left-turn crashes observed at 18 study sites showed that the number of months in the "after" period is significant. As the number of months in the "after" period increase, the crash frequency decreases.

  As the researchers noted, the increase of crash frequency at intersections converted from protected-only left-turn control to PPLT with the FYA indication "is in accordance with previous knowledge that adding a permissive phase to a protected left-turn phase to create PPLT signal phasing will increase crash frequency." Researchers further noted that with time, the crash rates did go down.

- The ability to conduct a complete analysis of the permissive-only left-turn sites (Group C) was limited by the small number of sites in the test group, and researchers offered no conclusions with regard to the conversion of permissive-only sites to PPLT with FYA phasing.

MUTCD—Interim Approval for Optional Use of Flashing Yellow Arrow for Permissive Left Turns (IA-10), FHWA, March 20, 2006.
http://mutcd.fhwa.dot.gov/resources/interim_approval/pdf/ia-10_flashyellarrow.pdf
This memorandum provided interim approval for the optional use of the FYA for permissive left turns at signalized locations. The Interim Approval summarizes key findings of the research represented in the 2003 *NCHRP Report 493* that supported issuance of this Interim Approval:

- The FYA was found to the best overall alternative to the circular green as the permissive signal display for a left-turn movement.
- The FYA was found to have a high level of understanding and correct response by left-turn drivers, and a lower fail-critical rate than the circular green.
- The FYA display in a separate signal face for the left-turn movement offers more versatility in field application. It is capable of being operated in any of the various modes of left-turn operation by time of day, and is easily programmed to avoid the yellow trap associated with some permissive turns at the end of the circular green display.

Part 4, Highway Traffic Signals, Manual on Uniform Traffic Control Devices for Streets and Highways, 2009 Edition, FHWA, December 2009.
http://mutcd.fhwa.dot.gov/pdfs/2009/part4.pdf
Prior to the release of the 2009 edition of the MUTCD, use of the FYA for permissive left turns was considered an experimental application requiring FHWA approval before installation. (See **MUTCD—Interim Approval** above.) With publication of the 2009 edition of the MUTCD, the use of the FYA for permissive left turns is governed by relevant provisions in the MUTCD, and the 2006 Interim Approval has been terminated by FHWA and is no longer in effect. Agencies that installed the FYA for permissive left turns under the Interim Approval are advised to consult the applicable 2009 MUTCD sections and revise installations as necessary to comply with the adopted provisions of the 2009 MUTCD.

Some provisions of interest:

- Section 4D.05, Application of Steady Signal Indications (page 453 of the MUTCD; page 21 of the PDF): Allows the use of an FYA signal before a steady yellow arrow.
- Section 4D.09, Positions of Signal Indications Within a Vertical Signal Face (page 457 of the MUTCD; page 25 of the PDF): Specifies the proper location of flashing yellow and flashing red indications, including:
    - The flashing yellow indication cannot be placed in the same vertical position as the signal section that displays a steady yellow signal indication.
    - The flashing yellow indication shall be placed below the steady yellow signal indication.
- Section 4D.17, Signal Indications for Left-Turn Movements—General (page 465 of the MUTCD; page 33 of the PDF): Begins the discussion of signal indications for left-turn movements.

- Section 4D.20, Signal Indications for Protected/Permissive Mode Left-Turn Movements (page 472 of the MUTCD; page 40 of the PDF): Paragraph 03 provides the requirements associated with use of the FYA using a separate left-turn signal face in a PPLT mode.

Figures related to the position and arrangement of signal faces with the FYA:

- Figure 4D-7, Typical Position and Arrangements of Separate Signal Faces with Flashing Yellow Arrow for Permissive Only Mode Left Turns (page 468 of the MUTCD; page 36 of the PDF).
- Figure 4D-12, Typical Position and Arrangements of Separate Signal Faces with Flashing Yellow Arrow for Protected/Permissive Mode and Protected Only Mode Left Turns (page 473 of the MUTCD; page 41 of the PDF).
- Figure 4D-14, Typical Position and Arrangements of Separate Signal Faces with Flashing Yellow Arrow for Permissive Only Mode Right Turns (page 477 of the MUTCD; page 45 of the PDF).
- Figure 4D-19, Typical Position and Arrangements of Separate Signal Faces with Flashing Yellow Arrow for Protected/Permissive Mode and Protected Only Mode Right Turns (page 482 of the MUTCD; page 50 of the PDF).
- Figure 4D-20, Signal Indications for Approaches with a Shared Left-Turn/Right-Turn Lane and No Through Movement (Sheet 2 of 3) (page 487 of the MUTCD; page 55 of the PDF).
- Figure 4D-20, Signal Indications for Approaches with a Shared Left-Turn/Right-Turn Lane and No Through Movement (Sheet 3 of 3) (page 488 of the MUTCD; page 56 of the PDF).

Consulting with National Experts

We consulted with national experts to gather information about research planned or in progress that relates to the FYA and its application at preempted intersections.

We spoke with representatives from FHWA's MUTCD Team and key national committees that address matters related to traffic control and engineering—the TRB Committee on Traffic Control Devices and the AASHTO Subcommittee on Traffic Engineering—to inquire about research planned or in progress that might address the specific application of the FYA at railroad-preempted intersections.

While none of the national experts we contacted are aware of pending projects or research in progress currently designed to consider the safety implications of FYA installations at railroad-preempted intersections, we did learn about a pending research project that could be expanded to consider this type of intersection in driving simulator experiments.

Below we summarize the results of our discussions.

From FHWA's MUTCD Team

Scott Wainwright, the MUTCD Team member who deals with traffic signals, was unaware of any research using the FYA in conjunction with track clearance at intersections with a railroad preemption.

Bruce Friedman, the MUTCD Team contact for railroad grade crossing issues, said that the FYA display can be considered an advance in the control of signal displays at intersections where there is a preemption. At intersections with a railroad preemption now using the circular green in a five-section signal display, signage is required that indicates no left turn is permitted. With use of the FYA, such signage is no longer required. Permissive left turns at these railroad-preempted intersections are allowed when there is no train; with train passage, a red arrow is displayed for left-turning drivers.

From the National Committees

Erik Maninga, liaison for the AASHTO Subcommittee on Traffic Engineering, referred us to a pending NCHRP project:

> **Evaluation of the Flashing Yellow Arrow (FYA) Permissive Left Turn in Shared Yellow Signal Sections**, NCHRP 20-07/Task 283, Pending.
> http://144.171.11.40/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2763
> The recommended display for the PPLT is a four-section signal head. In some cases, installing a four-section head can be expensive or impossible without significant retrofitting because of vertical clearance issues. As an alternative to the four-section signal head, it is possible to operate the FYA in PPLT in existing three-section heads by installing a bimodal head that allows the yellow left-turn arrow to operate in flashing (permissive) and steady (change) mode. It is not known how well drivers will respond to this application of the three-section head and whether it provides adequate notice that the permissive left turn is ending.
>
> In this pending research project for AASHTO's Standing Committee on Highways, researchers will explore the effectiveness of a three-section PPLT signal display versus a four-section signal display that contains both a FYA section and a steady yellow arrow change interval section.

David Noyce, chair of the TRB Committee on Traffic Control Devices, provided background on this pending project that continues the research documented in *NCHRP Web-Only Document 123*:

> The 2009 edition of the MUTCD specifies the proper location of the FYA as being in a different position in the signal head than the section displaying the steady yellow indication. Such placement requires a four- or five-section signal head.
>
> Before publication of the 2009 edition of the MUTCD, Jackson County, OR, received interim approval from the FHWA to implement a three-section signal head and was among the locations participating in the trial FYA installations examined in *NCHRP Report 493*. From page C64 of *NCHRP Report 493* available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_493.pdf (see page 71 of the PDF):
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> > Since initial implementation in 2001, Jackson County converted five existing exclusive (protected only) left-turn operations to PPLT control with a flashing yellow arrow display. However, in these installations, the County used a three-section vertical display face—the center indication was used for the yellow arrow clearance (following the circular green indication) and the flashing yellow arrow (permissive period) indication. The County pursued this approach to eliminate the costs of a new display face (four-section) and running additional wire cable and to address vertical clearance issues. The County submitted a request to FHWA for approval to implement the three-section arrangement of the flashing yellow arrow display. The request was originally denied by FHWA but later approved by FHWA after FHWA staff reviewed video of the intersection showing the operation. The video showed the adjacent through signals going to yellow at the same time as the flashing yellow arrow changed to a steady yellow arrow in the same section. The ability of left-turn drivers to see the through signals changing to yellow made it less necessary for the change from the flashing yellow arrow to the steady yellow arrow to be positional. Accordingly, FHWA issued a letter authorizing the County to implement the three-section PPLT flashing yellow arrow display.
>
> While the scope of the pending project does not specifically address railroad-preempted intersections, when informed of Caltrans' interest in this application of the FYA, Dr. Noyce indicated that the study's scope could be expanded to include an examination of railroad-preempted intersections using driving simulator experiments. The project is expected to get under way in 2011; further information about the timing of the pending study is expected to be available after the TRB Annual Meeting in January 2011. Dr. Noyce is also proposing that NCHRP move to the next round of before-and-after studies that continue the work reported in *NCHRP Report 493* and *NCHRP Web-Only Document 123*.

Contact information for the individuals referenced above appears on page 5 of this Preliminary Investigation.

Impact of FYA Installations

Below we highlight conference papers that detail experience with FYA installations in Oregon and Washington, including recommendations for phasing options and ways to improve the efficiency of the FYA.

"Five Years of Observations of the Flashing Yellow Arrow Display," John Deskins, Conference Paper AB09H374, *ITE 2009 Annual Meeting and Exhibit: Compendium of Technical Papers*.
Citation at http://tris.trb.org/view.aspx?id=925081
In this paper, the author presented observations and lessons learned in the preparation and implementation of 33 FYA locations throughout the city of Kennewick, WA, including a discussion of phasing options, timing elements and detection methods.

Related document:

- **"Successful Use of the Flashing Yellow Arrow (FYA) and Lessons Learned,"** John Deskins, *ITE 2009 Annual Meeting*.
http://www.ite.org/meetcon/2009AM/Session%2037_John%20Deskins.pdf
This PowerPoint presentation provides graphics and commentary that describe the use of the FYA in the city of Kennewick, WA.

"Methods for Operation and Detection of the Flashing Yellow Arrow Display," John Deskins, Conference Paper AB08H361, *ITE 2008 Annual Meeting and Exhibit: Compendium of Technical Papers*.
Citation at http://tris.trb.org/view.aspx?id=921218
This paper described operational and efficiency benefits of the FYA display and how they are achieved by selection of phasing, timing elements and modified detection methods. The discussion closes with a description of a perceived yellow trap that can sometimes occur with the FYA and how to recognize when it may be a problem.

Related document:

- **"Methods for Operation & Detection of the Flashing Yellow Arrow Display,"** John Deskins, *ITE 2008 Annual Meeting*.
http://www.ite.org/meetcon/2008AM/Session%2036_John%20Deskins.pdf
This PowerPoint presentation addresses time-of-day operations, multiple-phase sequences, detection methods, potential problems and case studies associated with use of the FYA in the city of Kennewick, WA.

"Flashing Yellow Arrow for Protected/Permissive Left Turns at Signalized Intersections," Eric Niemeyer, *ITE 2005 Annual Meeting and Exhibit: Compendium of Technical Papers.*
Citation at http://tris.trb.org/view.aspx?id=762539
This conference paper examined an FYA installation in Jackson County, OR, comparing it to the circular green "doghouse," or cluster, display at a signalized intersection. The author also analyzed several intersections converted from protected-only left-turn operation to PPLT using the FYA. Benefit/cost ratios, citizen comments and observations are used to compare the FYA display with existing phasing and control devices.

Note: Details of Jackson County's experimentation with the FYA also appear in *NCHRP Web-Only Document 123* (see page 37 of the PDF available at http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w123.pdf).

Drivers' Comprehension of the FYA

While published research includes relatively few before-and-after studies that evaluate the impact of the use of the FYA for permissive left turns, driver comprehension of the FYA has been well-examined by researchers. Below we highlight reports, conference papers and journal articles that analyze drivers' reaction to the FYA using surveys, field observations, driving simulators, eye trackers, and computer-based and individual static evaluations.

An Evaluation of Driver Comprehension Related to Solid Yellow Change Indications and the Potential Impact of the Flashing Yellow Arrow Permissive Indication, New England University Transportation Center, Project No. UMAR18-7, November 30, 2009.
http://utc.mit.edu/uploads/files/UMAR18-7.pdf
Researchers focused on the method of alerting drivers that the permissive (FYA) or protected (green arrow) phase is being terminated, seeking to provide a baseline for driver understanding of solid yellow signal indications that can inform future studies of the FYA permissive indication. Results include:

- Correct responses across all displays of the solid yellow indications (circular and arrow) ranged from 34 percent to 83 percent. Researchers noted this was an unexpected result, potentially contradicting the belief that drivers have a high comprehension rate for the solid yellow indication.
- A range of 42 percent to 59 percent of drivers was able to recognize the MUTCD-recommended duration of a yellow light.
- On average, drivers showed a high level of understanding (greater than 80 percent) when identifying what display would come next after the yellow arrow or circular yellow alone; however, drivers showed significant difficulty in comprehending both the meaning and appropriate sequencing of the five-section signal head when presenting combined displays (for example, yellow arrow and circular green).

Assessment of Driver Recognition of Flashing Yellow Left-Turn Arrows in Missouri, Missouri Department of Transportation, Report No. OR08-019, June 2008.
http://ntl.bts.gov/lib/30000/30600/30664/or08019.pdf
Researchers used an April 2008 survey to examine 204 drivers in the area surrounding intersections in Creve Coeur, MO, which use FYA left-turn indications. The survey consisted of six image questions that presented respondents with driving situations and asked the correct way to obey left-turn signals while proceeding through intersections. Results include:

- The "left turn yield on green" indication is better understood than the FYA indication (94 percent and 72.4 percent, respectively).
- More than half of the time, respondents answered *go* rather than *stop* when they did not know the answer was *yield*.
- More experienced drivers scored higher, and exposure to the FYA indication improved correct responses.

Researchers recommended proceeding with caution when installing additional FYA displays in Missouri, and advised undertaking a public information campaign to increase familiarity with the signal prior to and during the implementation process.

"Analysis of Drivers' Reaction to the Flashing Yellow Arrow Signal Design from Field Observation," Pei-Wei Lin, Ganesh Thiagarajan, Danny Atie, *15th World Congress on Intelligent Transport Systems and ITS America's 2008 Annual Meeting*.
Citation at http://tris.trb.org/view.aspx?id=897693
This conference paper reported on a study undertaken to analyze drivers' understanding of FYA display arrangements and indications through a field observation. Using video observation, left-turn drivers' reactions are classified into 16 categories with four phases: solid red arrow, solid yellow arrow, FYA and solid green arrow. The authors used an intersection in St. Louis, MO, to demonstrate the proposed observation and analysis approaches. More than 90 percent of the drivers observed understood the meaning of the FYA signal phasing. The authors concluded that video observation methodology is a better approach than questionnaires or simulation, and provides a more precise gap definition to distinguish safe and unsafe left turns.

“Evaluating the Impact of Two Allowable Permissive Left-Turn Indications,” Michael A. Knodler Jr., David A. Noyce, Donald L. Fisher, *TRB 86th Annual Meeting Compendium of Papers CD-ROM*, Paper #07-2992, 2007.
http://www.topslab.wisc.edu/publications/David/Knodler%20-%20two%20allowable.pdf
The use of the FYA permissive indication as an alternative option to the circular green means that transportation agencies can choose between two permissive indications for use in PPLT applications. Researchers recognized that using two signal indications which provide drivers with the same message has the potential to increase driver error, and sought to identify the likelihood of drivers exposed to both the FYA and circular green incorrectly interpreting the circular green as a protected left-turn indication.

This conference paper described the use of a driving simulator experiment and static evaluations to quantify any change in driver comprehension of circular green indications resulting from exposure to the FYA permissive indication. The results provide little evidence to suggest that the FYA implementation will impact driver comprehension of the circular green. Specific findings include:

- In the simulator, comprehension of the circular green permissive indication following exposure to the FYA permissive indication did not differ significantly from driver comprehension of the circular green before exposure to the FYA.
- In a follow-up static evaluation, drivers exposed to the FYA permissive indication were more likely to give *yield* (correct) responses to the circular green permissive indication.

“An Evaluation of Driver Comprehension of Solid Yellow Indications Resulting from Implementation of Flashing Yellow Arrow,” Michael A. Knodler Jr., David A. Noyce, Kent C. Kacir, Chris L. Brehmer, *TRB 86th Annual Meeting Compendium of Papers CD-ROM*, Paper #07-2293, 2007.
Citation at http://tris.trb.org/view.aspx?id=802137
This research sought to address the question as to whether the FYA results in a change in drivers’ perceived understanding of the solid yellow arrow (SYA) indication. A total of 212 drivers completed an evaluation of the SYA indication in various scenarios. Researchers found no evidence to suggest that the FYA permissive indication may negatively affect drivers’ understanding of the SYA indication.

“Potential Application of Flashing Yellow Arrow Permissive Indication in Separated Left-Turn Lanes,” Michael A. Knodler Jr., David A. Noyce, Kent C. Kacir, Christopher L. Brehmer, *TRB 85th Annual Meeting Compendium of Papers CD-ROM*, Paper #06-2531, 2006.
http://www.topslab.wisc.edu/publications/David/noyce_2006_2635.pdf
As an alternative to protected-only left-turn phasing at wide median intersections, some agencies have implemented a flashing red arrow (FRA) that requires drivers to first stop before accepting a gap in the opposing traffic stream. This research considers the use of the FYA to replace the FRA at exclusive left-turn lanes separated from the adjacent through/right travel lanes by quantifying driver comprehension of the FYA as compared to the FRA.

Researchers used a driving simulator experiment and two static evaluations to examine 264 drivers who responded to 1,260 experimental scenarios. Results presented in this conference paper include:

- The FYA indication was found to have a high driver comprehension on the first exposure.
- The FYA used in this situation resulted in approximately 10 percent of fail-critical errors in drivers’ first exposure to the indication. The FRA results in significantly fewer fail-critical errors than the FYA permissive indication, which is important given the potential of these errors to result in a crash.
- The percentage of fail-critical responses with the FYA permissive indication may indicate a need to initially supplement the FYA indication at wide median locations (through signage or training).

At wide median locations where the use of protected-only left-turn phasing is not desirable, researchers advise that the use of the FYA permissive indication should be used only after consideration of the safety and operational issues.

"Analysis of Driver and Pedestrian Comprehension of Requirements for Permissive Left-Turn Applications," Michael A. Knodler Jr., David A. Noyce, Kent C. Kacir, Christopher L. Brehmer, *Transportation Research Record*, Vol. 1982, 2006: 65-75.
Citation at http://dx.doi.org/10.3141/1982-10
This journal article presents research findings of a follow-up study to *NCHRP Report 493* that targeted the FYA impact on pedestrians. Researchers used a series of dynamic driving simulator and computer-based static evaluations to assess comprehension of the FYA indication in 139 drivers and 100 pedestrians using 5,930 experimental scenarios. Researchers concluded that given the high level of comprehension to yield requirements, the FYA is a recommended indication at T-intersections where pedestrian crossings are prevalent.

"Tracking Driver Eye Movements at Permissive Left-Turns," Michael A. Knodler Jr., David A. Noyce, *Proceedings of the Third International Driving Symposium on Human Factors in Driver Assessment, Training and Vehicle Design,* 2005.
http://drivingassessment.uiowa.edu/DA2005/PDF/21_Knodlerformat.pdf
Researchers created a virtual network of signalized intersections for use in a driving simulator equipped with head and eye tracking equipment. The eye movements of 14 drivers were tracked and the screen was divided into areas of interest that coincided with potential cues used in the completion of a permissive left turn. Results presented in this conference paper include:

- Ninety percent of drivers first look for the PPLT signal display, then focus on opposing traffic when it is present.
- In the absence of opposing vehicles, drivers were more likely to seek out additional cues. Drivers scanning multiple sources at the intersection tended to scan from the right side of the intersection to the left.
- When opposing traffic was present, drivers spent a majority of time focused on opposing traffic and would use this as a base point from which they would glance at other data sources.

"Evaluation of Traffic Signal Displays for Protected-Permissive Left-Turn Control Using Driving Simulator Technology," Michael A. Knodler Jr., David A. Noyce, Kent C. Kacir, Christopher L. Brehmer, *Journal of Transportation Engineering*, Vol. 131, No. 4, April 2005: 270-278.
Citation at http://tris.trb.org/view.aspx?id=754099
In this study, researchers conducted driver comprehension evaluations using driving simulators to determine the safety and effectiveness of 12 PPLT signal displays that differed in permissive indication, arrangement, location and through movement indication. Each PPLT signal display included only the circular green ball and/or FYA permissive indications.

Findings showed a high level of comprehension (91 percent) with no variation between PPLT displays. Researchers note that the lack of significant differences in driver comprehension is itself a significant finding, indicating the FYA is an alternative to the circular green ball permissive indication. Other results include:

- Scenarios with the FYA permissive indication and the green ball/FYA simultaneous permissive indication had significantly more correct responses than displays with the green ball permissive indication.
- Displays with the green ball permissive indication were associated with significantly more fail-critical responses than displays with either the FYA or green ball/FYA permissive indications.
- Displays with the red ball through indication resulted in a significantly lower percent correct response rate than displays with the green ball through indication. The PPLT displays with the red ball through indication also resulted in significantly more fail-critical responses.

"An Evaluation of the Flashing Yellow Arrow Permissive Indication for Use in Simultaneous Indications," Michael A. Knodler Jr., David A. Noyce, Kent C. Kacir, Christopher L. Brehmer, *TRB 84th Annual Meeting Compendium of Papers CD-ROM*, Paper #05-2497, 2005.
http://www.topslab.wisc.edu/publications/David/noyce_2005_2497.pdf
NCHRP Report 493 recommends that the FYA be implemented in an exclusive signal display centered over the left-turn lane. However, most PPLT signal displays use a shared signal head. The implementation of the FYA in the typical PPLT's shared signal head requires that the FYA be displayed simultaneously with the through movement

indication of circular green, circular yellow or circular red. This research addresses the question of driver comprehension of the FYA permissive indication when it is used in such a simultaneous display.

This conference paper described a driving simulator experiment and static evaluations used to compare seven permissive left-turn scenarios featuring the circular green and/or FYA permissive indications. In total, 264 drivers participated in the research, evaluating 3,457 permissive left-turn scenarios. Results include:

- In the driving simulator, the simultaneous indications in the retrofit display (simultaneous indication display) neither improved nor reduced drivers' understanding of the display.
- In a follow-up static evaluation, *yield* responses ranged from a low of 65 percent for the circular green permissive indication in a five-section cluster configuration to a high of 89 percent for the proposed retrofit display.
- The FYA, when displayed as part of a dual indication display, was consistent with all other permissive indication combinations evaluated.

Projects in Process

A project expected to conclude in 2011 prepares for the implementation of the FYA with PPLT operations in Texas with field tests and the development of guidelines and training materials.

"Use of Flashing Yellow Operations to Improve Safety at Signals with Protected-Permissive Left Turn (PPLT) Operations," Texas Southern University, Houston, expected completion date: August 31, 2011.
http://rip.trb.org/browse/dproject.asp?n=23773
This project, sponsored by the Texas Department of Transportation, will develop guidelines for the implementation of the FYA with PPLT display operations in Texas. Among the researchers' tasks leading up to guideline development are field tests at selected intersections and evaluation of the safety performance at test locations. Training strategies and materials for TxDOT personnel will also be developed.

Evaluation of Traffic Signal Displays for Protected-Permissive Left-Turn Control
NCHRP 3-54(2)

DRIVER STUDY USING DRIVING SIMULATOR TECHNOLOGY (CONFIRMATION STUDY)

Working Paper 7

June 2002

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Driver Study Using Driving Simulator Technology

1.0 INTRODUCTION

The left-turn is widely recognized as one of the most difficult maneuvers to safely execute on U.S. roadways (*1*). Safely and efficiently accommodating left-turning vehicles at the approximately 300,000 signalized intersections in the U.S. is also a source of concern for traffic engineers, and this concern has resulted in the use of several unique traffic engineering practices. Although dedicated turn lanes and protected left-turn phases have improved intersection operation and safety, they have done so at the expense of intersection efficiency, as the time provided for an exclusive left-turn phase must be taken away from other critical movements at the intersection. In an effort to minimize this problem, protected/permissive left-turn (PPLT) signal phasing was developed.

PPLT signal phasing provides an exclusive, or protected, phase for left-turns as well as a permissive (permitted) phase during which left-turns can be made if gaps in opposing through traffic allow, all within the same signal cycle (*1*). The theory of PPLT signal phasing is to minimize the exclusive left-turn phase time requirements while increasing the opportunity for left-turn maneuvers. Use of PPLT phasing can increase left-turn capacity and reduce delay, improving the operational efficiency of the intersection.

Although the potential benefits associated with PPLT have been identified, they can only be achieved when PPLT information is correctly presented to the driver. PPLT information is presented to the driver through the illumination of circular- and arrow-shaped indications within a traffic signal display. The meaning of all signal indications is transmitted through a combination of color, shape, orientation and position of the signal display.

The Federal Highway Administration's (FHWA) *Manual on Uniform Traffic Control Devices* (MUTCD) has provided guidance in the selection of signal displays since its first edition in 1935 (*2*). Furthermore, the MUTCD has been adopted as the national standard for traffic control devices in the United States. Because the MUTCD has provided only limited guidance for PPLT applications, a variety of adaptations of PPLT arrangements have been established throughout the country. The variability in PPLT arrangements has contributed to the lack of a uniform national standard for PPLT control (*3*).

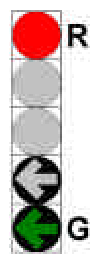
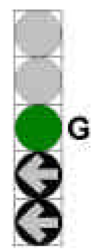
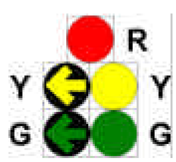
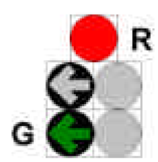
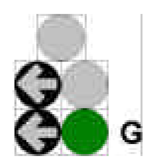
2.0 PROBLEM STATEMENT

Because the MUTCD has provided only limited guidance for PPLT applications, a variety of adaptations of PPLT arrangements and indications have been established throughout the country leading to a lack of uniform national standards. Although many states recommend a five-section signal display for left-turn control, the MUTCD does not require a separate signal display when PPLT signal phasing is used (*2*). Many states have adopted either the five-section cluster (doghouse), horizontal, or vertical display, located overhead between the through and turning lanes, providing a green arrow for the protected phase and a circular green (green ball) for the permissive phase. Typical MUTCD arrangements and indications for PPLT control are shown in Figure 1.

Despite the potential increase in left-turn capacity achieved with PPLT control, problems with PPLT signal phasing, primarily related to the green ball permissive indication, have been identified but not resolved (*1*, *3*). Many traffic engineers believe that the MUTCD green ball permissive indication is adequate and properly presents the intended message to the driver. Other traffic engineers believe that the green ball permissive indication is not well understood and therefore inadequate. The latter belief is based on the argument that left-turn drivers may interpret the green ball permissive indication as a protected indication, creating a potential safety problem.

To overcome this potential problem, traffic engineers have developed at least four variations of the PPLT permissive indication. These variations replace the green ball permissive indication with a flashing red ball, flashing yellow ball, flashing red arrow, or flashing yellow arrow indication. Additionally, variations in signal display arrangement and placement are applied. This variability has led to a myriad of PPLT signal displays and permissive indications throughout the United States that may confuse drivers and lead to inefficient and unsafe operations.

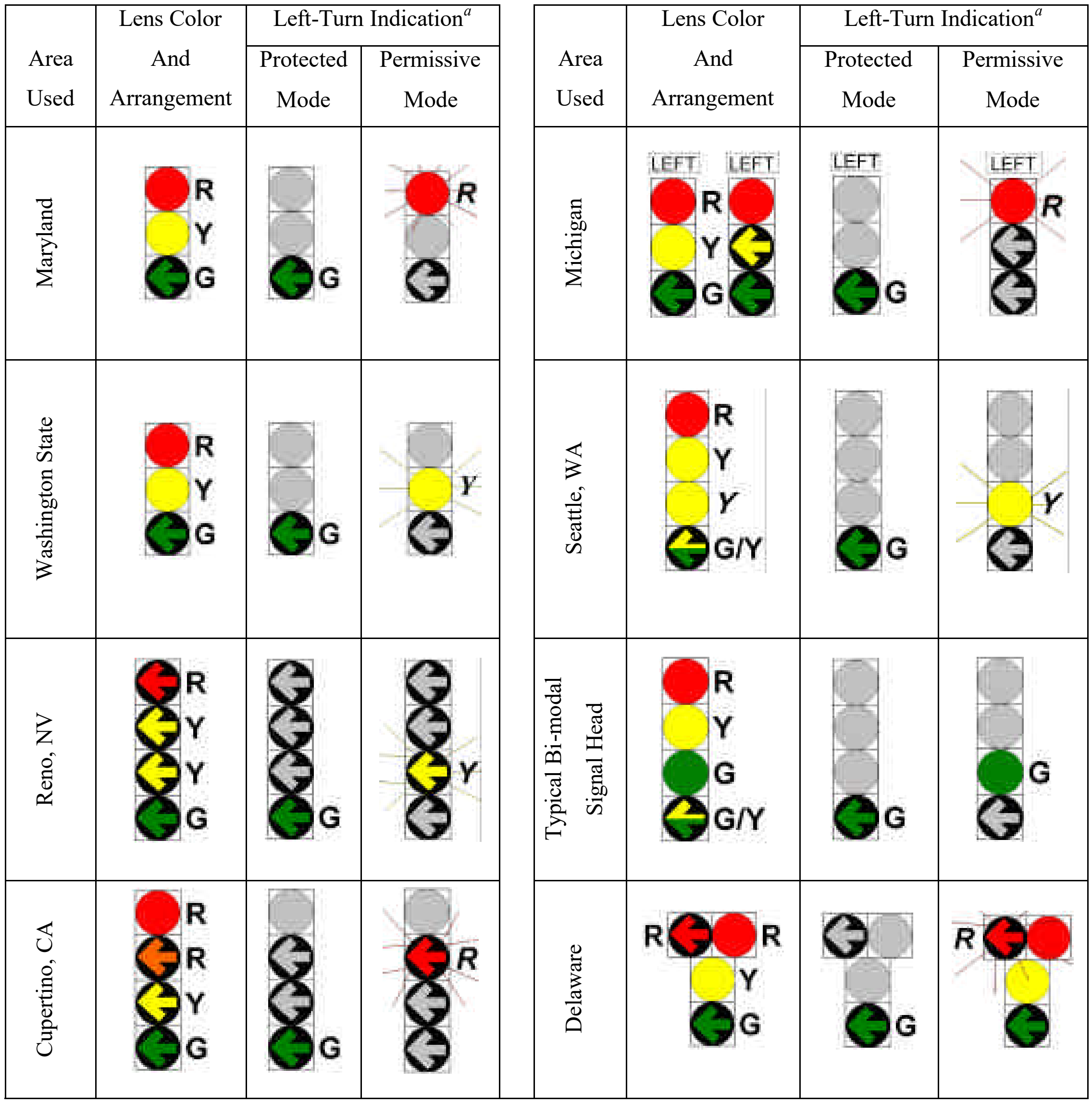
Ongoing research has identified at least seven unique combinations of PPLT signal displays and permissive indications in the United States (*1, 3*). Figure 2 presents several of the unique displays. Displays vary in arrangement, number of signal sections, and in permissive indications, from the three-section vertical display with flashing red ball permissive indication in Michigan, to the four-section vertical display with a flashing yellow ball permissive indication used in Seattle, WA, to the four-section cluster that uses a flashing red arrow permissive indication in Dover, DE (*1*). These unique combinations are in addition to the various arrangements of five-section displays that use the circular green ball for the permissive indication. Additional variations of PPLT control exist in phasing, signal placement, and the use of supplemental signs.

Arrangement	Lens Color and Arrangement	Left-Turn Indication[a]	
		Protected Mode	Permissive Mode
MUTCD 5-Section Horizontal			
MUTCD 5-Section Vertical			
MUTCD 5-Section Cluster			

R = Red Y = Yellow G = Green *R* = Flashing Red *Y* = Flashing Yellow

[a] The indication illuminated for the given mode is identified by the color letter

Figure 1 Typical MUTCD Arrangements and Indications for PPLT Control.



R = Red Y = Yellow G = Green *R* = Flashing Red *Y* = Flashing Yellow

[a] The indication illuminated for the given mode is identified by the color letter

Figure 2 Variations of PPLT Displays (*1*).

Past research has focused on driver comprehension with the objective of identifying display(s), when presented to drivers, that result in acceptable levels of comprehension. Several study methods have been employed. Traditional pen and paper comprehension tests are commonly used in which the driver after observing a PPLT signal display simply marks what he/she believes to be the correct answer the proposed question. The critique of this methodology has focused on the belief that drivers' pen and paper responses may not be consistent with driver's decision-making in the actual driving environment.

To add more realism to driver comprehension experiments, computer technology has been employed by providing static photos of actual driving environments and superimposing PPLT signal displays within them *(1)*. Although this technology is believed to be a major step forward in experimentation, the static nature and lack of dynamic cues may still lead drivers through a different decision process, inconsistent with the actual driving process.

Current technology allows for use of a full-scale dynamic driving simulator as a tool for evaluating driver comprehension by placing drivers in a fully interactive dynamic scenario just as if they were actually driving. To date, a large sample study of drivers' comprehension of various PPLT signal displays using a dynamic full-scale driving environment has not been completed. A need exists to build on this previous research and conduct a comprehensive evaluation of driver comprehension and behavior related to each PPLT signal display and permissive indication in a dynamic driving environment.

3.0 RESEARCH OBJECTIVES

The objective of the NCHRP 3-54 research was to evaluate the safety and effectiveness of selected PPLT signal displays, culminating in the identification of a particular display(s) and permissive indication that operates in all phasing schemes, improves driver comprehension, and improves safety. To meet this objective, driver comprehension evaluations were conducted for a variety of established PPLT signal displays. The driver evaluation described in this working paper was conducted using fully-interactive dynamic driving simulators located in the Human Performance Laboratory on the University of Massachusetts – Amherst (UMass) campus and at the Texas Transportation Institute (TTI). An evaluation of the same PPLT signal displays in a static environment was also completed at both locations to provide comparison data to the simulator experiment as well as to previous research efforts.

It is important to note that this research project will not develop any guidelines, warrants, or recommendations for the use of PPLT phasing. The underlying assumption is that the traffic engineer has decided that PPLT control is the most appropriate left-turn treatment. The goal of this research study is to identify the most effective display(s).

4.0 SIGNAL DISPLAYS

Based on the Phase I research results presented in previous working papers, the NCHRP 3-54(2) research team and project panel identified 12 different PPLT signal displays for further evaluation. The selected displays differ in permissive indication, arrangement, location, and through movement indication. Each of the PPLT signal displays include only the green ball and/or flashing yellow arrow permissive indications. The flashing red and the flashing yellow ball permissive indications were not evaluated in this task. Reasons for not evaluating these permissive indications and the appropriate use of the flashing red indications are presented in the project report.

The green ball permissive indication represents the current state-of-the-practice and the flashing yellow arrow permissive indication represents the most promising alternative based on research finding. Table 1 provides a written list of the PPLT displays evaluated in the driving simulators, and Figure 3 depicts each PPLT signal displays evaluated.

5.0 SCOPE

The scope of this research is limited to driver understanding of PPLT signal displays including the display arrangement, either vertical or cluster, location of the PPLT signal in relation to the left-turn lane, either shared or exclusive, and the permissive indication. Horizontal signal display arrangements were not included in this evaluation. The research focuses on the permissive indication, which has been associated with low levels of driver comprehension. The flashing red permissive indications, red ball and red arrow, as well as the flashing yellow ball permissive indication were not evaluated in this research. Other potential parameters that may effect drivers' understanding of PPLT signal displays such as geometric design issues, signal phasing, and supplemental signage were considered but not included as a detailed component of the simulator evaluation.

Table 1 PPLT Signal Displays for Evaluation

Sc[a]	Left-Turn Display			Through Movement Display		
	Arrangement	Permissive Indication[b]	Location	Arrangement	Permissive Indication[b]	No. of Displays
1	5-section cluster	GB	Shared	3-section vertical	GB	1
2	5-section cluster	GB	Exclusive	3-section vertical	RB	2
3	5-section cluster	FYA	Shared	3-section vertical	GB	2
4	5-section cluster	FYA	Shared	3-section vertical	RB	2
5	5-section cluster	FYA/GB	Exclusive	3-section vertical	GB	2
6	5-section cluster	FYA/GB	Exclusive	3-section vertical	RB	2
7	4-section vertical	FYA	Exclusive	3-section vertical	GB	2
8	4-section vertical	FYA	Exclusive	3-section vertical	RB	2
9	5-section vertical	GB	Exclusive	3-section vertical	GB	2
10	5-section vertical	GB	Exclusive	3-section vertical	RB	2
11	5-section vertical	FYA	Exclusive	3-section vertical	GB	2
12	5-section vertical	FYA	Exclusive	3-section vertical	RB	2

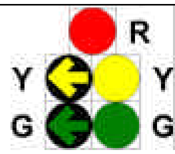
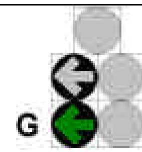
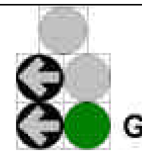
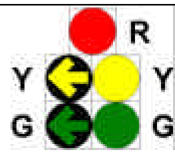
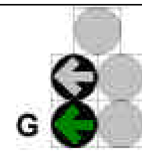
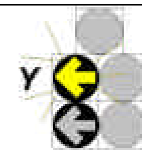
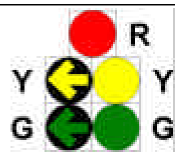
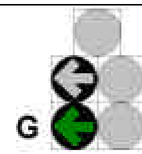
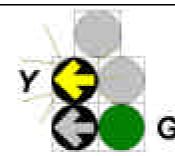
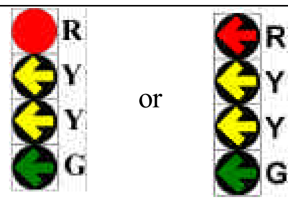
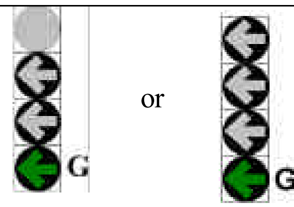
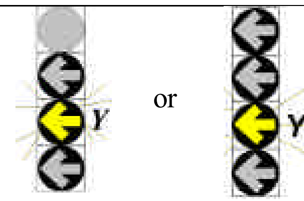
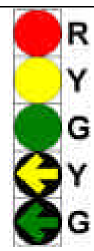
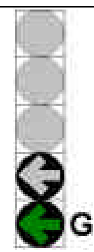
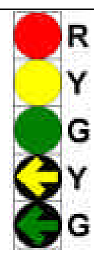
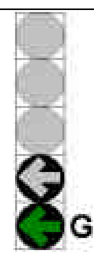
[a] Scenario identification number
[b] Permissive Indication; GB = green ball, FYA = flashing yellow arrow, RB = red ball

6.0 BACKGROUND

A review of the literature pertaining to PPLT signal displays and phasing has been presented in previous working papers and the Interim Report (*1, 3*). Nevertheless, since the research task described in this working paper uses driving simulation as a means of data collection, background information on the use of driving simulation for comprehension and behavior is presented. Additionally, a study of five-section PPLT signal displays using driver simulator technology was recently completed and is relevant to this research.

6.1 Utilization of Driving Simulator Technology

Most agree that the optimal way of evaluating driver behavior and comprehension is to evaluate drivers in an actual driving environment. Although actual field data may be more desirable, it may often times be infeasible. Costs, logistics, and safety associated with implementing traffic control devices in the field for testing most often exceed the resources of the researchers. These limitations led to the need of developing a cost-effective laboratory-based methodology of driver experimentation.

Scenario[a]	Lens Color and Arrangement	Left-Turn Indication[b]	
		Protected Mode	Permissive Mode
1, 2			
3, 4			
5, 6			
7, 8			
9, 10			
11, 12			

R = RED Y = YELLOW G = GREEN *Y* = FLASHING YELLOW

[a] 1, 3, 5, 7, 9, 11 – GB through indication; 2, 4, 6, 8, 10, 12 – RB through indication

[b] The indication illuminated for the given mode is identified by the color letter

Figure 3 PPLT Displays Evaluated in Driver Simulator Experiment.

Driving simulation has recently evolved as one of the best methods for completing driver behavior and driver comprehension research outside of the actual driving environment. Presently, almost 40 known driving simulators are located at research institutes throughout the world (*5)*. The use of simulators allow for multiple variables and scenarios to be evaluated in a relatively short period of time, overcoming the problem with the static evaluations where drivers are not provided with cues and senses that they would normally receive on the roadway. Noyce recommended that a driving simulator be used in future evaluations of driver behavior and comprehension of PPLT signal displays because of the experimental gain associated with the added elements of realism (*1*).

Several studies of drivers and left-turn operations have been completed using simulator technology. Staplin conducted an experiment using driving simulation techniques to evaluate the willingness of drivers to select a left-turn gap in opposing traffic of 30 and 60 mph (*6*). The study recorded driver comprehension information from drivers who were observing either a 20-inch monitor, a large screen video projector, or a large screen cinematic display. For comparison purposes, driver information was also collected in the field. Only the large screen cinematic display corroborated what was occurring in the field, for which the minimum gap length increased as the speed increased. Staplin concluded that higher levels of realism provided more accurate results (*6*).

In a study of driver comprehension of left-turn displays, Szymkowiak used a full-scale driving simulator to test drivers' reaction to a set of 40 different left-turn signal display/sign combinations (*7*). Thirty-two drivers were tested in 40 signalized intersection scenarios (32 test scenarios) in a realistic driving environment that included dynamic opposing traffic. The results indicated better driver comprehension than the Staplin research, which included only static opposing traffic, leading the researchers to conclude that drivers may "benefit from an even more realistic, that is dynamic, environment."

A research study was completed that expanding upon the research efforts of NCHRP 3-54. Smith and Noyce combined five-section displays (horizontal, vertical, and cluster) with yellow and red flashing permissive indications and evaluated driver comprehension with the use of a driving simulator. This study was built on the premise that flashing permissive indications were promising, and five section signal displays were recommended, yet flashing permissive indications in five-section PPLT displays were not previously evaluated in combination.

Using both a driving simulator and a static evaluation instrument (laptop computer), researchers tested driver comprehension of five section displays for five different permissive indications (*4*). Evaluating the green ball, flashing yellow ball, flashing yellow arrow, flashing red ball and flashing red arrow permissive indications, researchers found the flashing yellow ball and arrow permissive indications yielded the highest percent of correct responses. The green ball indication had levels of understanding similar to the flashing yellow ball and flashing yellow arrow, but significantly higher than the flashing red ball and flashing red arrow indications. With the static driver evaluation, researchers concluded that the flashing yellow indications again performed the best; however the green ball had the lowest comprehension level. Drivers completing the static evaluation often assumed the green ball indication provided right-of-way. Driver's permissive indication comprehension is summarized in Figure 4 for both the driving simulator and static evaluations.

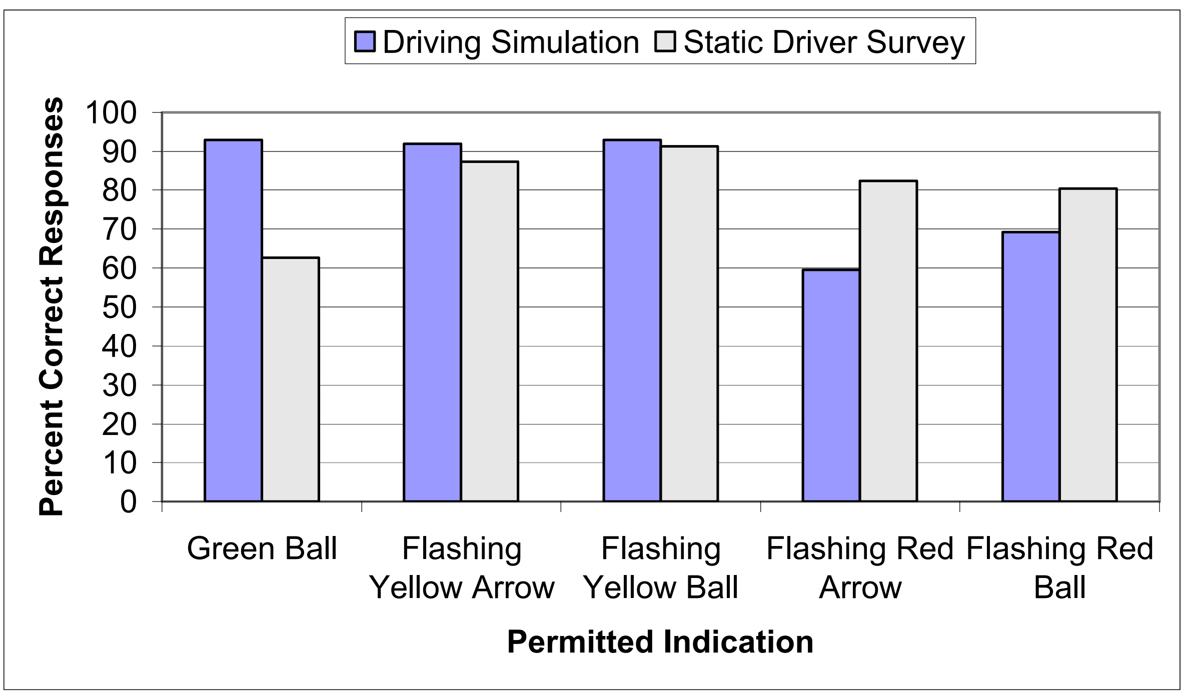


Figure 4 Summary of Smith's Work for Permissive Indications.

The results of this research identified no statistical significance in driver comprehension of PPLT signal displays with arrangement as the independent variable (the five-section horizontal, vertical, and cluster display arrangements were evaluated) (*4)*. Researchers did report that nearly 80 percent of all fail critical responses (drivers assume a left-turn is *protected* with a permissive indication presented) occurred at simulated intersections with a five-section horizontal arrangement.

The Smith and Noyce study also found benefits in the use of simulation by concluding that the driving simulator was effective in the evaluation of driver comprehension of five-section PPLT signal displays (*4)*. They reported differences between the completed static evaluation and the simulation experiment conducted. The added level of realism provided in the simulation experiment appeared to provide drivers with dynamic visual cues found in the roadway environment and was likely responsible for the higher level of comprehension related to the green ball permissive indication. Other recommendations made by the researchers included the length of time drivers should be tested and the need for additional added realism. The simulator experiment required one hour of driving and a one-half hour of follow-up questioning to complete each subject; researchers concluded that drivers became tired during the end of the experiment and should only expected to drive for a period of 30-45 minutes.

One concern with simulator experiments is the potential of simulator sickness, which has been likened to motion sickness. The U.S. Army Research Institute (ARI) for the Behavioral and Social Sciences conducts research to improve the effectiveness of training simulators and simulations (*8)*. The Army uses simulation to assist in the training of soldiers fighting from vehicles. They have recently completed an extensive review on simulator sickness, identifying trends and causes. Although they have identified a number of factors that may trigger the onset of simulator sickness, they believe that ultimately simulator sickness is caused from, "inconsistent information about body orientation and motion received by the different senses, known as the cue conflict theory. For example, the visual system may perceive that the body is moving rapidly, while the vestibular system perceives that the body is stationary" (*8*).

The ARI has evaluated the effects of several of the demographic factors, which may be of importance in the use of simulation in PPLT experiments. ARI reports that age has no significant effect on subjects between the ages of 12 and 50 years old. The literature review also reported that females might be more susceptible to simulator sickness than males (*8)*. Research continues in an effort to determine more specifically what factors cause simulator sickness because of the potential benefits of driving simulation.

7.0 RESEARCH PROCEDURES

The objective of NCHRP 3-54(2) research Task 10 was to evaluate driver's comprehension of the most promising types of PPLT signal displays using full-scale driving simulators at UMass and TTI. The following sections provide a description of the development and administration of the driving simulation experiment and the follow-up static evaluation completed at both universities. Note that the experiment was designed to assure consistency in driving simulator application and data collection. To the extent possible, the research procedure used at UMass and TTI were identical. The exception to this is an initial TTI study in which simulated opposing traffic was programmed differently. Details of the study design and opposing vehicle programming at each location is described in the following sections.

7.1 Simulation and Static Evaluation Experiments

7.1.1 Driving Simulators

Similar driving simulators at UMass and TTI were used to complete the experiment. A fixed-base fully interactive dynamic driving simulator, housed in the Human Performance Laboratory (HPL) on the UMass campus, was used to complete the driving simulation experiment. The vehicle base of the driving simulator is a 1995 four-door Saturn Sedan. Drivers are capable of controlling the steering, braking, and accelerating similar to the actual driving process; the visual roadway adjusts accordingly to the driver's actions. Three separate images are projected to create the "visual world" on a large semi-circular projection screen creating a field-of-view which subtends approximately 150-degrees. The simulator also features a Bose surround audio system, a 60 Hz refresh rate, and a resolution of 1024 x 768 dpi. The UMass driving simulator is pictured in Figure 5.

Designer's Workbench by Coryphaeus Software, Inc. was used to create the simulated roadway environment, including the traffic signal displays. Driving and interaction with other vehicles in the roadway system was programmed with Real Drive Scenario Builder (RDSB) software created by Monterey Technologies, Inc.

Figure 5 UMass Human Performance Lab Driving Simulator.

At TTI, the apparatus used for the experiment was a driving environment simulator (DESi). DESi consisted of three white polypropylene screens (each screen was 2.28 m (90 in) in height and width, a 1995 Saturn SC2 complete vehicle, three image generation PC computers, one data collection PC computer, and three liquid crystal display Proxima 6810 projectors. The driving scene presented to participants was generated by GlobalSim Corporation Hyperdrive software Version 1.2 and projected through three liquid crystal display projectors to the screens at a refresh rate of 30 Hz. The three separate images projected onto the screens were aligned so they appeared as one single image covering a 150 degree field of view horizontally and a 50 degree field of view vertically for the driver. Consistent with the UMass simulator participants sat in the driver's seat of the Saturn, which was positioned in the center of the DESi, from which drivers are capable of controlling the steering, braking, and accelerating similar to the actual driving process. The TTI driving simulator is pictured in Figure 6.

Figure 6 TTI Driving Environment Simulator (DESi)

7.1.2 Development of Simulation

As noted, the PPLT signal displays selected for this research have evolved from previous NCHRP 3-54 tasks. The selected displays were presented in Figure 3 and described in Table 1. One intersection approach was created for each of the 12 experimental PPLT signal displays, and the characteristics of each approach were identical, thus minimizing confounding variability.

Figure 7 depicts a typical PPLT intersection in the UMass driving simulator experiment. Additionally, several intersections that require the driver to turn right, proceed straight, or to turn left on a protected green arrow were included as part of the visual worlds. The additional movements were included to provide experimental variability and reduce the probability of drivers keying in on the nature of the evaluation.

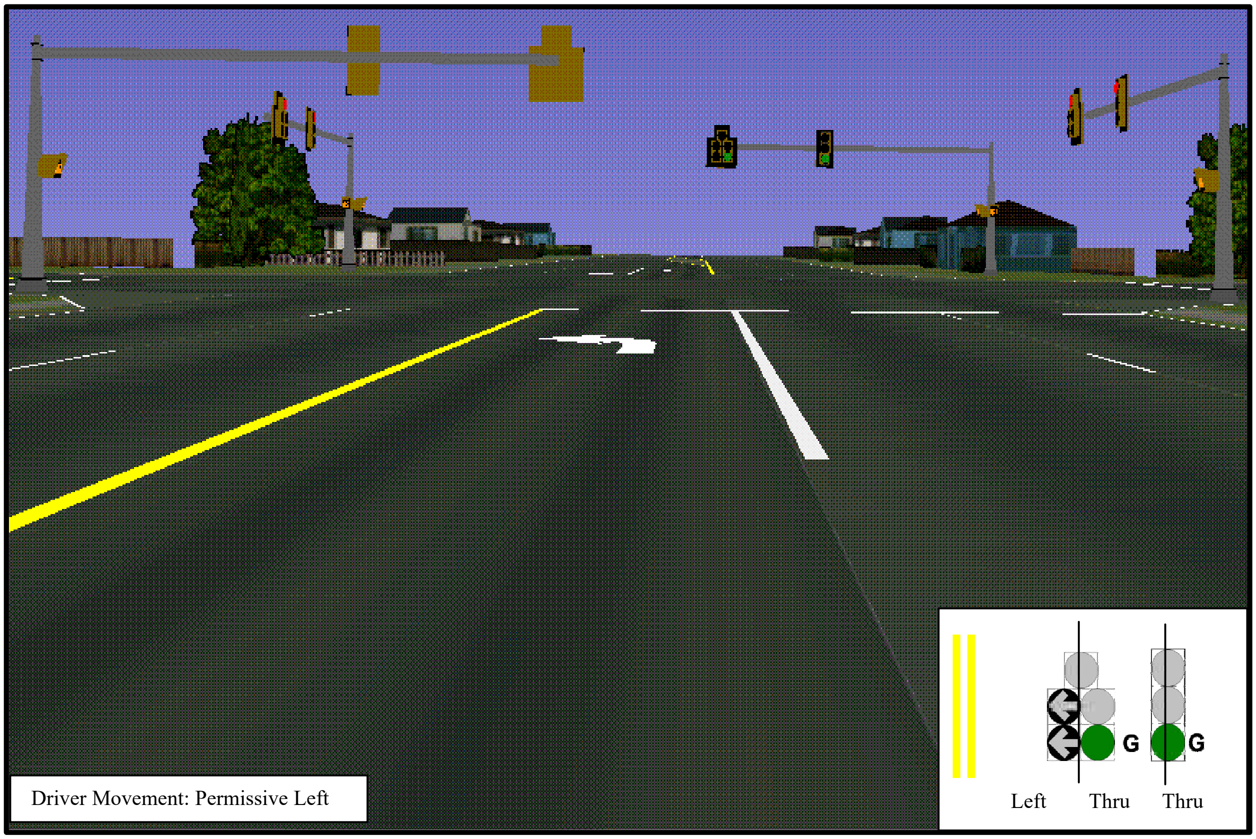


Figure 7 Screen Capture of Typical Intersection in Simulator at UMass.

Additional experimental variability was provided through the creation of multiple driving modules and starting positions. In both the UMass and TTI experiments, four modules were developed, each presenting a different order of the experimental displays. At UMass each module was a continuous loop with drivers starting and ending at the same location after passing through 14 intersections within each module. A summary of signal displays presented to drivers is presented in Table 2. Further, the order in which the modules were driven varied to provide counterbalancing. Specifically, both UMass and TTI used eight module order combinations; therefore, driver one may have seen modules 1 then 2 in the experiment and driver two may have seen module 2 then 1. Similarly at TTI, driver one likely observed modules in the order 1-2-3-4, while driver two would have seen 4-3-2-1. Drivers observed each of the 12 experimental displays only once.

Table 2 Driving Scenarios Encountered by Simulator Drivers in each Module

Scenario	Number of Scenarios Encountered	
	UMass Modules	**TTI Modules**
Experimental PPLT Signal Display	6	3
Protected Left Turn on Green Arrow	2	1
Right-Turn Movement	4	2
Straight (Through) Movement	2	1
TOTAL	14	7

Multiple starting points provided additional experimental variability across drivers. Six different starting points were created in the UMass driving simulator experiment, and three were used in the TTI experiment. The modules could be presented in different orders, which combined with different starting positions within each module, created a number of unique module order and starting point combinations.

Several additional factors were controlled during experimentation:

7.1.2.1 Signal Phasing: All experimental signal displays within the simulation rested in a red ball or arrow indication as drivers approached the intersection. Signal displays changed to the *test* indications as the driver approached the intersection. Approximately 30 meters prior to the intersection stop bar, the PPLT signal display was "triggered" and changed from the red indication to the selected permissive or protected indication. Similarly, the through movement indications either stayed with the red ball indication or changed from a red ball to a green ball indication.

7.1.2.2 Opposing Traffic: Each of the PPLT signal displays were evaluated with opposing traffic at the intersection. Opposing traffic required drivers to simultaneously evaluate the PPLT signal display, traffic movement, and opposing gaps to complete a safe permissive left-turn maneuver. This methodology was used to replicate the decision process required during actual operation of a motor vehicle within the roadway system.

The only difference in the driving simulator experiments at UMass and TTI was the method of introducing the opposing traffic. For simplification, the methods will be referred to as the Release Method of Opposing Traffic (RMOT) and the Continuous Method of Opposing Traffic (CMOT).

The RMOT traffic consistently applied gaps in the opposing traffic at intersections which drivers were required to make a permissive left-turn maneuver. The critical gap concept was used to select the gap sizes. The Highway Capacity Manual indicates that a critical gap value of five and a half seconds for permissive left-turn maneuvers in the design of a four-lane roadway (*9*). Therefore, a gap size was selected below the critical gap that most drivers would not accept (three seconds) and a gap size was selected above the critical gap that most drivers would accept (seven seconds). Providing a consistent sequence of three and seven second gaps prevented gap size selection from being a significant variable in the PPLT analysis.

Six opposing vehicles were used to create the gap sequence. Two vehicles were always positioned at the stop bar in the two through lanes opposing the left-turn driver. The remaining four vehicles were positioned further upstream in a three and seven seconds series of seven-three-seven-seven; therefore, opposing vehicles crossed the intersection seven, 10, 17, and 24 seconds behind the two initially queued opposing vehicles.

A second trigger, similar to that used to change the signal indications, was placed near the left-turn stop bar at each PPLT intersection to release the opposing traffic. By placing the opposing traffic release trigger approximately five feet from the stop bar, left-turn drivers were required to make a decision as to the meaning of the PPLT signal indication and desired action before knowing the actions of the opposing traffic.

At TTI, 116 drivers completed the experiment observing the CMOT traffic. The CMOT method of opposing traffic had the opposing traffic moving as the driver approached the intersection. All gaps in opposing traffic were consistently applied at study intersections. The opposing traffic consisted of three vehicles. As the driver approached the intersection, a trigger located 121 m upstream of the left-turn stop bar released the opposing traffic. At this time the first opposing vehicle was located 290 m downstream of the driver. The opposing vehicle was set to match the speed of the test vehicle. In this setup, the first opposing vehicle approached the intersection, almost mirroring the driver so that they reached the intersection at approximately the same time. The next two vehicles followed behind the initial opposing vehicle three and 10 seconds after the first vehicle; therefore, the driver observed a three and a seven second gap after the initial opposing vehicle had passed.

The remaining 93 drivers at TTI completed the experiment observing the RMOT opposing traffic. Using two methods allowed for an evaluation of opposing traffic impacts on driver comprehension of PPLT signal displays. Using consistent methods allowed for analysis of geographic variability.

7.1.3 Drivers

Two hundred drivers at each location were sought to complete the driving simulator experiment. A desired mix in driver demographics was established in an attempt to represent the *driving population.* Initially, four age groups of drivers were identified. Within each age group, an attempt was made to include an equal number of male and female drivers. The subject pool also included a range of educational and ethnic backgrounds. Target age groups and approximate percentages of drivers in each group are presented in Table 3.

Recruiting drivers to participate in the study was completed through a variety of local mediums, including advertisement on both the UMass and Texas A&M University (TAMU) campuses, through campus and community organizations, and using databases of past experiment participation. Drivers were screened for a valid driver’s license in addition to demographic categorization. It was assumed that driver’s possessing a valid drivers license had 20/40 vision (corrected) or better and had no physical or cognitive limitations that affected their ability to successfully complete the study. General demographic data were recorded.

Table 3 Target Distribution of Drivers by Age Group

Age Group	Age Range	Percent of Total
Group I	Under 24	30
Group II	24 to 44	35
Group III	45 to 65	23
Group IV	Over 65	12

7.1.4 Simulation Experimental Procedure

Drivers were provided an overview of the experimental procedure and asked to sign an Informed Consent Form (per University policy) when they arrived to participate in the simulator experiment. By signing the Informed Consent Form, drivers indicated their understanding of the proposed experiment, a willingness to continue, and that compensation would be provided.

Next, drivers were seated in the simulator and given procedural instructions. Drivers were then asked to fasten their seatbelt, adjust mirrors and adjust the radio as they would in their own vehicle. The objective was to replicate their normal driving environment to the extent possible. Drivers were told that vehicle engine noise will be simulated (along with a small amount of vehicle vibration) and a circulating fan (not used at TTI) will simulate wind through the driver's side window. Drivers who preferred to have a driver side window closed were instructed to do so.

The driving portion of the study began with a practice module that provided the opportunity for drivers to traverse a virtual network and familiarize themselves with the operational characteristics of the simulator vehicle. Subjects were asked to *drive* the simulator vehicle as they would drive their own vehicle. Specifically, drivers were asked to not drive overly conservative nor drive extremely aggressive. At this stage of the study, the driver's well being was closely observed for any early signs of simulator sickness. Drivers who successfully completed the practice course, free of simulator sickness, were permissive to continue with the simulator study.

Following the practice course, drivers completed the experimental modules. In the UMass experiment, drivers completed two modules with each module containing 14 intersections, six of which were study PPLT displays. Two modules were used to present all 12 PPLT displays. In the TTI experiment drivers observed the 12 PPLT signal displays by traversing four modules which each contained six intersections. As described in the previous section, drivers started from different positions within each module and the order of PPLT displays varied in an attempt to provide a desired level of randomness and reduce the effects of learned behavior during the experiment.

To avoid the need for verbal communication during the experiment, drivers were navigated through the modules by guide signs provided on each intersection approach. In addition, drivers were asked to observe speed limit signs (30 mph), providing a higher level of realism and speed control during the experiment. The driving portion of the experiment, including the practice module, required between 15 and 20 minutes to complete.

Drivers' response to each PPLT signal display scenario was manually recorded as correct or incorrect. Incorrect responses were further classified as being fail-safe or fail-critical. A fail-safe response was one in which the driver did not correctly respond to PPLT signal display, but did not infringe on the right-of-way of the opposing traffic. A fail-critical response was an incorrect response in which the driver incorrectly responded to PPLT signal display and impeded the right-of-way of opposing traffic, creating the potential for a crash. Table 4 summarizes the six possible responses in the simulator experiment.

Throughout the study, drivers were asked to *think out loud* and verbally express their thoughts about anything they observed. Two research team members were present to record the results of the simulation, including the responses at each intersection and other driving related factors such as indecision, unnecessary braking, or any pertinent verbal comments made. Each experiment was recorded on videotape allowing the researchers to verify and review the manually collected data. Samples of the data collection sheets used in the experiments are presented in Appendix A.

Table 4 Summary of Possible Driving Simulator Responses

Response Type	Category	Sub-category	Driver Action
1	Correct	—	Yield, go if an acceptable gap in opposing traffic allows
2	Fail-safe	By movement	Stop, instead of yield before proceeding through intersection
3			Stop and remain stopped (must be directed to proceed)
4		By traffic	Stop, wait for all opposing traffic to pass before proceeding (driver did not accept several large gaps)
5	Fail-critical	Non-serious	No visible stop or yield before attempting to proceed through the intersection (avoided conflict by stopping short of opposing traffic)
6		Serious	Go through intersection incorrectly taking the right-of-way from opposing traffic (created crash potential or crashed with opposing traffic)

7.1.5 Video-Based Static Evaluation

After completing the driving portion of the study, drivers were asked to participate in a static evaluation of PPLT signal displays. The static evaluation was administered using videocassette recordings of the screen captures for the 12 PPLT displays. A typical study procedure is pictured in Figure 8.

Each display was shown for 30 seconds during which time the driver was verbally asked the following question and asked to respond with one of the four following choices:

"You encountered this signalized intersection while diving. At this intersection you made a left turn. Considering the left-turn traffic signal lights shown, what do you believe is the appropriate left-turn action?"

- Go, you have the right-of-way;
- Yield, then go if a gap in the opposing traffic exists;
- Stop first, then go if a gap in the opposing traffic exists; or,
- Stop and wait for the appropriate signal.

Figure 8 Setup of Static Evaluation.

Once drivers responded with one of the four possible choices they were asked to indicate their confidence in the answer. Additionally, any comments made by the drivers regarding the displays were manually recorded.

Two presentation modules were used for the static evaluation. The modules varied the order in which the PPLT signal displays were shown to the drivers, with each driver observing only one of the modules. Additionally, the four possible responses were read to the drivers in random order, thus creating eight possible response patterns. These measures were used to provide experimental randomness and counterbalancing.

During breaks in the study, drivers were prompted to complete some remaining paperwork. Specifically, demographic data related to their age, sex, education, and driving experience were recorded. Age was classified into one of four categories as previously specified: under 24, 24 to 45, 45 to 65, or over 65. Driving experience was based on miles driven in the previous year from the following choices:

- 0;
- 1 to 10,000 miles;
- 10,000 to 20,000 miles;
- More than 20,000 miles.

Miles driven was used as a surrogate for driving experience. Those who drove over 20,000 miles were considered very experienced, those who drove less than 10,000 were considered less experienced.

The final demographic question pertained to education. Drivers were asked to indicate the highest level of education they had obtained from the following choices:

- Did not graduate from high school;
- Completed high school;
- Completed some college;
- Have a college degree.

7.2 Compilation of Experimental Results and Data Analysis

Once the data collection process was completed, the results collected from each experimental methodology were compiled and analyzed. The following information was analyzed:

- *Simulator Experiment* - A distribution of correct and incorrect (fail-safe and fail-critical) responses for each PPLT signal display evaluated. The data allowed for a comparison and statistical analysis of each signal display evaluated.
- *Static Evaluation* - A distribution of correct and incorrect (fail-safe and fail-critical) responses for each PPLT signal display evaluated. The data allowed for a comparison and statistical analysis of each signal display evaluated.

Each methodology (driving simulator and static evaluation) was statistically analyzed using similar procedures. The distribution of correct and incorrect responses was used to complete an analysis of variance (ANOVA) to compare driver comprehension related to the 12 selected PPLT signal displays. For each analysis, the 95 percent confidence interval was calculated based on a binomial proportion as follows:

$$\text{95 percent C.I.} = p \pm 1.96\sqrt{\frac{pq}{n}}$$

where: p = sample proportion;

1.96 = value associated with 95 percent confidence level;

$q = 1 - p$; *and,*

n = number of trials.

Minitab© release 13.31 was used to complete the analysis (*10*).

Further analysis was done by considering the effect of each PPLT display components on driver comprehension. Specifically, the permissive indication, display arrangement, location, and through indication were isolated and analyzed for each response. Similarly, demographic data was analyzed simultaneously with the independent variables of both the simulator experiment and static evaluation to determine what, if any, interaction occurs between the parameters and their impact on the independent variables. Additionally, a comparison of results obtained using each methodology was completed to determine the consistency of driver responses.

7.3 Beta Testing Simulator Scenarios

Prior to conducting the experiment, several drivers were recruited to beta test the simulator visual environment. The purpose of the beta test was to practice the research procedure and identify modifications that were only apparent after administering. A total of five drivers participated in the beta test. The beta test resulted in several minor adjustments to the simulated driving environment.

8.0 RESULTS AND ANALYSIS

8.1 Demographics

A total of 464 drivers participated in the experiment. Two hundred thirty-one drivers participated in the study at UMass, and 223 drivers participated at TTI. In both locations some drivers elected not to complete the experiment either during or shortly after the attempting the practice module, reducing the number of full participants to 432. Table 5 presents a summary of the drivers that participated at each location.

Four-hundred thirty-six of the drivers also completed the static evaluation. Each driver completing both driving modules and the static evaluation evaluated 12 PPLT scenarios while driving and 12 PPLT scenarios in the static mode. In total, 4,613 PPLT scenarios were evaluated in the driving simulator experiments with 2,528 scenarios evaluated at UMass and 2,085 scenarios evaluated at TTI. At TTI, 874 PPLT signal display scenarios were observed with the RMOT traffic scheme, and 1,211 PPLT signal display scenarios with the CMOT opposing traffic were evaluated. In the static evaluation 2,590 PPLT scenarios were evaluated at UMass and 2,640 PPLT scenarios were evaluated at TTI for a total 5,230 PPLT scenarios evaluated. Demographics were disaggregated into sex, age, driving experience, and education level. Table 6 provides a breakdown of the driver demographics.

Table 5 Summary of Analyzed Driver by Study Location

Location	Total Drivers	Retired Drivers[a]	Total Drivers Analyzed
UMass	231	8	223
TTI	233	24	209
TOTAL	464	32	432

[a] Opted not to proceed with the experiment during or shortly after the practice module.

Table 6 Breakdown of Driver Demographics

Demographic Category	Level	UMass		TTI	
		Number of Drivers	Percent of Total[a]	Number of Drivers	Percent of Total[b]
Sex	Male	117	52	111	53
	Female	106	48	98	47
Age	Under 24	92	41	65	31
	24 to 45	89	40	84	40
	45 to 65[c]	38	17	41	20
	Over 65[c]	4	2	19	9
Annual Miles Driven	Under 10,000	85	38	60	29
	10,000 to 20,000	110	49	123	60
	More than 20,000	28	13	22	11
Highest Education Level Completed	High School	24	11	21	10
	Some College	79	35	72	35
	College Degree	120	54	114	55

[a] Based on 223 drivers
[b] Based on 209 drivers
[c] Combined for analysis

The 223 drivers that drove the UMass simulator were comprised of 117 males and 106 females. Of the eight drivers who withdrew from the experiment, three were male and five were female. One-hundred eleven males and 98 females drove in the TTI simulator, and of the 24 drivers that withdrew from the experiment five were male and 19 were female.

Initially, four target age groups were desired, with the upper two age groups representing drivers between 45 and 65 and drivers over 65 years of age. Several difficulties were experienced with drivers over the age of 65. Despite aggressive recruiting campaigns, older drivers were significantly more difficult to recruit for the driving experiment. Many older drivers have "computer-phobia" and are reluctant to participate in such experiments. Furthermore, when drivers over the age of 65 did agree to participate, several had difficulty completing the experiment. Six of the eight drivers that elected to withdraw from the UMass experiment before taking part were over the age of 65. Therefore, all drivers over the age of 45 were aggregated for analysis purposes.

As observed in Table 6, the percentages of drivers in the *under 24* and *24 to 45* age categories made up a larger percentage of total participants than the established targets of 30 and 35 percent, respectively. Younger drivers were generally more willing to participate, and considering the campus settings, younger drivers were more plentiful. Therefore, the additional drivers beyond the proposed 200 were generally in the younger age groups.

Recall, the third demographic was associated with the annual miles driven in the previous year. Driving experience was correlated with the number of miles driven. Those who drove over 20,000 miles were considered very experienced, and those who drove less than 10,000 miles were considered less experienced. For analysis purposes, drivers that indicated that they had not driven in the past year, despite possessing a valid driver's license, were included with the *under 10,000* miles group for the analysis.

The final demographic question pertained to education. Of the 432 drivers at UMass and TTI, only two indicated that they had not graduated from high school; therefore these drivers were included with the graduated high school demographic for analysis purposes. Furthermore, over half of the drivers had earned a college degree.

8.2 Driving Simulator (Release Method of Opposing Traffic)

As previously noted, 2,528 scenarios with experimental PPLT signal displays were evaluated at UMass, and 874 experimental scenarios with the RMOT opposing traffic were evaluated at TTI. A statistical comparison of the correct responses in the two data sets was completed to determine if the data sets could be combined for analysis. This analysis is described in the following paragraphs.

Initially, only Response Type 1 was considered as a correct response; however, an argument can be made that drivers making a Response Type 4, the *fail-safe by traffic* response, have not actually committed a driving error. With this response drivers chose to wait for all opposing vehicles to pass before completing the permissive left-turn maneuver despite the presence of several large gaps in the opposing traffic stream. In reality, all these drivers have done is operated the vehicle in the simulated environment in an overly cautious manner. Based on driver comments recorded throughout the experiment, two prevalent explanations as to why drivers elected to wait rather than proceed were noted:

- Drivers were in fact unfamiliar with the vehicle/surroundings and were therefore unsure if they could safely execute the left turn maneuver within the opposing gap provided;
- They were just cautious by nature.

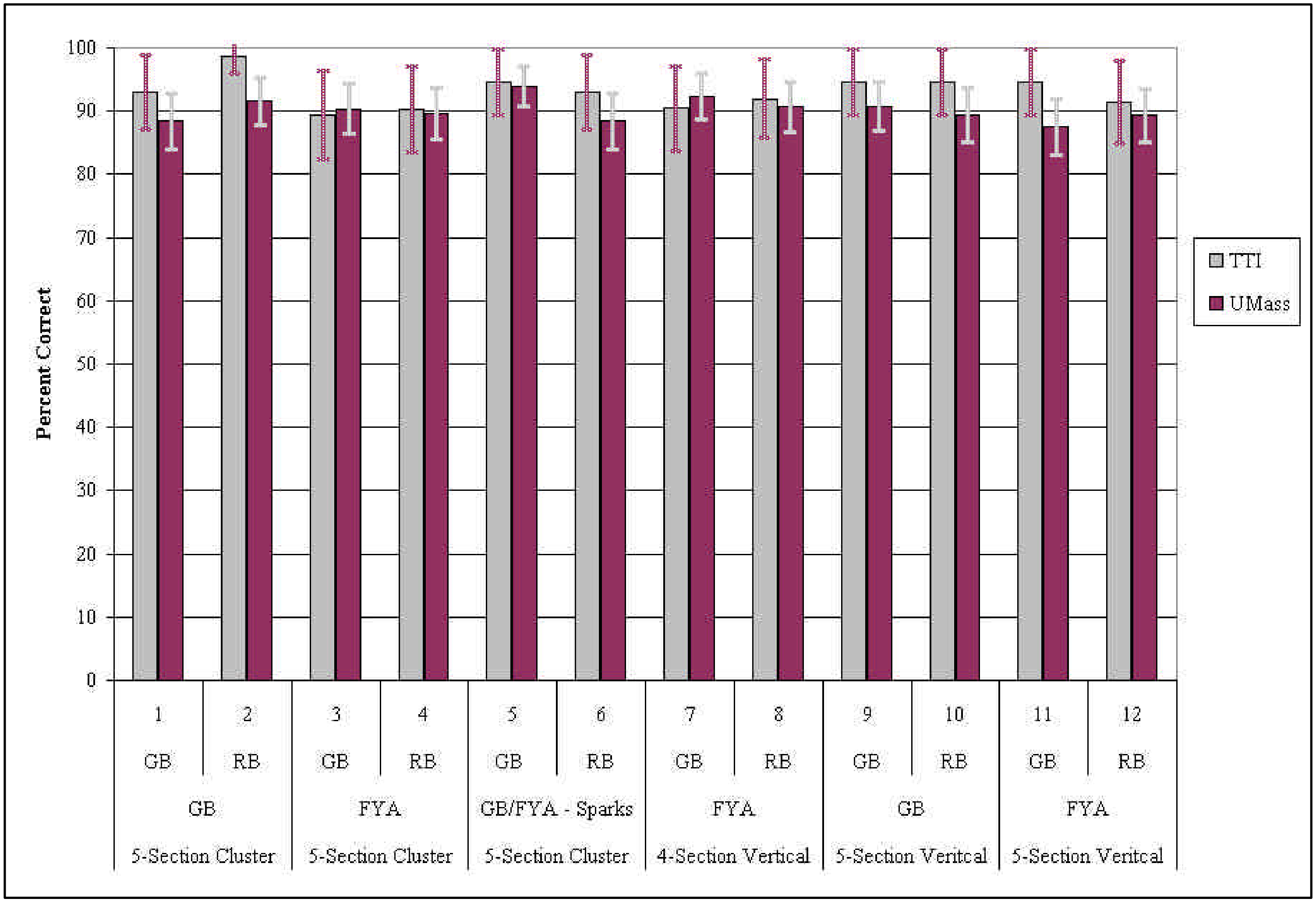
As a result both Response Types 1 and 4 were considered as correct responses.

Correct responses between the two study sites were quite similar. Of the 874 PPLT signal displays evaluated at TTI, 93 percent were correct responses. At UMass, 90 percent of the 2,528 scenarios evaluated contained correct responses. To compare the data sets, the percent of correct responses were cross-analyzed across each of the 12 experimental displays evaluated by geographic region (UMass or TTI). The percentage of correct responses for each of the 12 PPLT signal displays at UMass and TTI are presented in Table 7 (combined) and Figure 9 (separate) with a 95 percent confidence interval. The results of this analysis found that there were no statistically significant differences in the percentage of correct responses across the 12 PPLT signal displays ($p= 0.592$). Based upon this statistical analysis and because the UMass and TTI experiments were procedurally equivalent, the 2,528 scenarios evaluated at UMass and the 874 scenarios evaluated at TTI were combined for all further analysis.

Table 7 Percent of Correct Responses for 12 PPLT Signal Displays in Simulator

Sc[a]	Arrangement[b]	Permissive Indication[c]	Thru Indication[d]	Obser.[e]	Percent Correct[f]	95% C.I.
1	5-section cluster	GB	GB	279	90	4
2	5-section cluster	GB	RB	286	93	3
3	5-section cluster	FYA	GB	282	90	3
4	5-section cluster	FYA	RB	285	90	4
5	5-section cluster	GB/FYA	GB	286	94	3
6	5-section cluster	GB/FYA	RB	279	90	4
7	4-section vertical	FYA	GB	281	92	3
8	4-section vertical	FYA	RB	288	91	3
9	5-section vertical	GB	GB	290	92	3
10	5-section vertical	GB	RB	281	91	3
11	5-section vertical	FYA	GB	289	89	4
12	5-section vertical	FYA	RB	276	90	4

[a] Scenario identification number
[b] PPLT signal display arrangement
[c] Left-turn permissive indication (GB = green ball; RB = red ball)
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Number of Observations – combined study sites
[f] Percent Correct which is Response Type 1 and 4



[a] Scenario identification number
[b] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[c] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[d] PPLT signal display arrangement

Figure 9 Percent Correct for each PPLT Signal Display by Study Location (with 95% C.I.).

Further evaluation of the data was completed considering permissive indication, arrangement, location, and through indication. These results are presented in Table 8. Left turn permissive indications were either green ball (GB), flashing yellow arrow (FYA), or a simultaneous combination (GB/FYA) of the two displays. Arrangements evaluated were five-section cluster, four-section vertical, and five-section vertical. Location was either shared or exclusive and described the location of the PPLT section head. The through indication was either GB or red ball (RB).

The percentage of correct responses by permissive indication ranged from 90 to 92 percent; however, permissive indication was not statistically significant (p = 0.433). Similarly, the arrangement of the PPLT signal display was not significant in determining driver comprehension (p = 0.747). The percentage of correct responses was 91 percent regardless of the through indication, indicating that this variable was not significant (p = 0.716). Location of the PPLT signal display did not have a statistically significant effect on driver comprehension (p = 0.206).

Table 8 Percent Correct by PPLT Display Component

PPLT Display Component	Level	Observations	Percent Correct[a]	95% C.I.	Statistical p-value
Permissive Indication[b]	GB	1136	91	2	0.433
	FYA	1701	90	1	
	GB/FYA	565	92	2	
Arrangement[c]	5-section cluster	1697	91	1	0.747
	4-section vertical	569	91	2	
	5-section vertical	1136	90	2	
Thru Indication[d]	GB	1707	91	1	0.716
	RB	1695	91	1	
Location[e]	Shared	846	90	2	0.206
	Exclusive	2556	91	1	

[a] Response Types 1 and 4
[b] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[c] PPLT signal display arrangement
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Location of PPLT Signal Display

8.2.1 Demographics

Table 9 displays the percent of correct responses, based on the 3,402 scenarios evaluated for each demographic category. Overall, sex was not statistically significant (p = 0.467). Males and females both responded correctly 91 percent of the time. Age was reduced to three different categories. The percent of correct responses varied from 90 percent for the under 24 group to 92 percent for the over 45 group. The percent correct was not statistically significant for the three age groups (p = 0.276).

Analysis considering the interaction effect of age and sex demographics is presented in Table 10. Figure 10 indicates that there was an interaction between age and sex. The interaction implies that there is a relationship between sex and age that has an effect on driver comprehension. Males in the under 24 age group had a higher level of comprehension than females in the same age category; however in the two older age groups (*24 to 45* and *over 45*) females had a higher percentage of correct responses than males. The age variable was not statistically significant within the male demographic, with the correct responses ranging from 90 to 91 percent; however, the age of female drivers was statistically significant (p = 0.016). Females under age 24 had a significantly lower comprehension level than females over age 45.

Table 9 Percent Correct by Demographics

Demographic Category	Level	Number of Observations	Percent Correct[a]	95 % C.I.	Statistical p-value
Sex	Male	1893	91	1	0.467
	Female	1509	91	1	
Age	Under 24	1402	90	2	0.276
	24 to 45	1387	91	1	
	Over 45	613	92	2	
Annual Miles Driven	Under 10,000	1227	89	2	0.013
	10,000 to 20,000	1770	92	1	
	More than 20,000	405	92	3	
Highest Education Level Completed	High School	326	91	3	0.754
	Some College	1228	91	2	
	College Degree	1848	91	1	
Geographic Location	UMass	2,528	90	1	0.012
	TTI	874	93	2	

[a] Response Types 1 and 4

Table 10 Combined Effect of Age and Sex on Percent Correct

Sex	Age	Number of Observations	Percent Correct[a]	95 % C.I.
Male	Under 24	785	91	2
	24-45	784	90	2
	Over 45	324	90	3
Female	Under 24	617	88	3
	24-45	603	93	2
	Over 45	289	95	3

[a] Response types 1 and 4

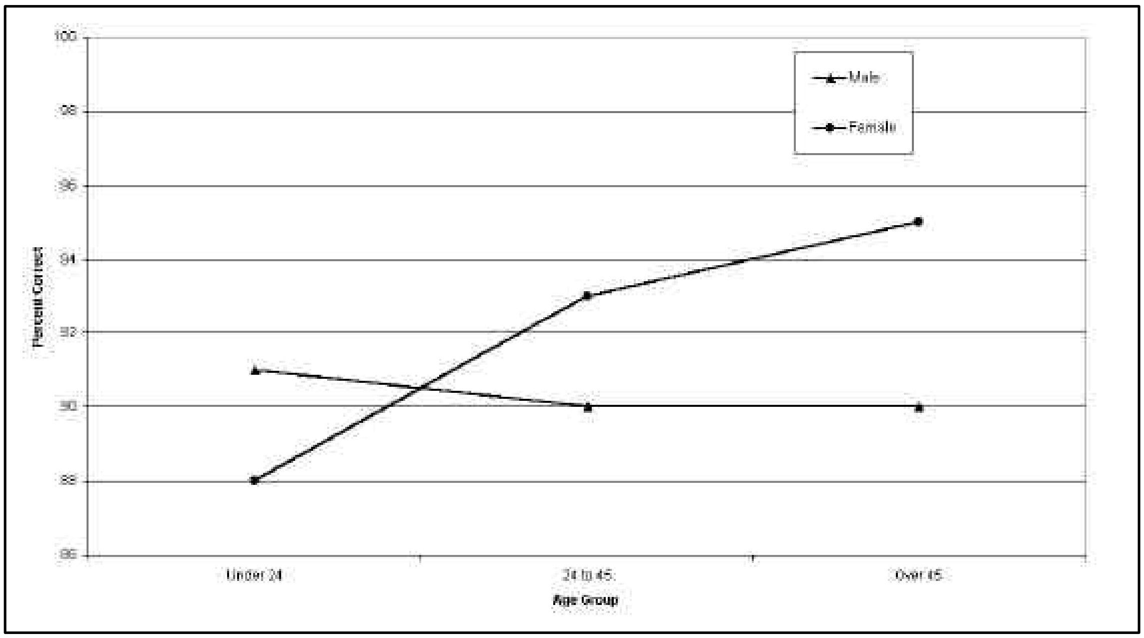


Figure 10 Interaction Plot of Sex and Age

Referring again to Table 9, the results for the demographic of annual miles driven and highest education level completed are shown. Drivers that had driven between 10,000 and 20,000 miles in the previous year had a significantly higher comprehension level than drivers that had driven under 10,000 miles in the previous year (p = 0.013). The highest education level completed by drivers was not statistically significant (p = 0.754) as all three education levels had 91 percent correct responses. Aggregating all responses showed that drivers participating in the simulator study at TTI had slightly more correct responses than drivers participating at UMass.

This difference was significant ($p = 0.012$). However, as previously mentioned, a more appropriate analysis of geographic effects was conducted for each display type and analysis method, which found no geographical differences in the data.

Disaggregating the data into the 12 PPLT signal displays by demographic categories, the percentages of correct responses for all 12 PPLT signal displays with respect to sex are presented in Table 11 and Figure 11. Sex was not significant in determining the percent correct for the PPLT signal displays as values ranged from 87 to 95 percent.

Age was not previously determined to be a significant factor in determining driver comprehension. Disaggregating the data by the proportions of correct responses to each of the 12 PPLT signal displays for each age group yields no significant differences ($p = 0.650$) between any of the age groups. The percentage of correct responses to each PPLT signal display by age group is presented in Table 12 and Figure 12.

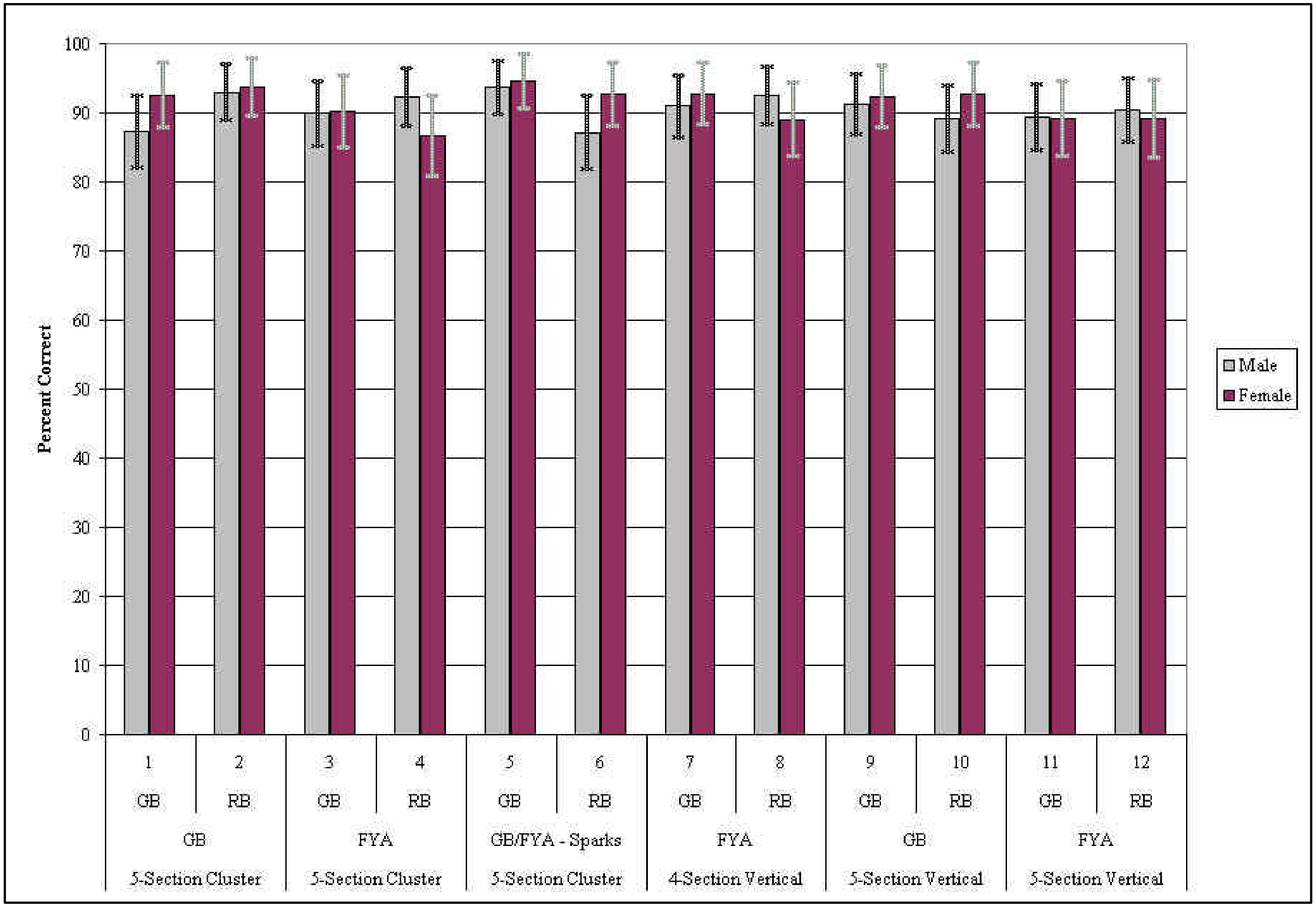
The annual miles driven by drivers had resulted in statistical significance; however, when the annual miles driven demographic was evaluated for each PPLT signal display the results indicated no significant deviations from the mean ($p = 0.719$). Additionally, none of the data sets differed statistically from each other given a 95 percent confidence interval. This data set is displayed in Table 13 and Figure 13.

Similarly, education level was not a significant predictor of percent correct for the overall responses. When the demographic is broken down for each PPLT signal display, driver comprehension was not statistically significant across all PPLT signal-education level combinations. The breakdown of data for education level is presented in Table 14 and Figure 14.

Table 11 Correct Responses for each PPLT Signal Display by Sex

				Sex					
				Male			Female		
Sc[a]	Arr[b]	Per Ind[c]	Thru Ind[d]	Obs[e]	Percent Correct[f]	95% C.I.	Obs[e]	Percent Correct[f]	95% C.I.
1	5-section cluster	GB	GB	158	87	5	121	93	5
2	5-section cluster	GB	RB	157	93	4	129	94	4
3	5-section cluster	FYA	GB	159	90	5	123	90	5
4	5-section cluster	FYA	RB	157	92	4	128	87	6
5	5-section cluster	GB/ FYA	GB	158	94	4	128	95	4
6	5-section cluster	GB/ FYA	RB	156	87	5	123	93	5
7	4-section vertical	FYA	GB	156	91	4	125	93	5
8	4-section vertical	FYA	RB	160	93	4	128	89	5
9	5-section vertical	GB	GB	159	91	4	131	92	5
10	5-section vertical	GB	RB	157	89	5	124	93	5
11	5-section vertical	FYA	GB	160	89	5	129	89	5
12	5-section vertical	FYA	RB	156	90	5	120	89	6

[a] Scenario identification number
[b] PPLT signal display arrangement
[c] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Number of observations
[f] Percent correct



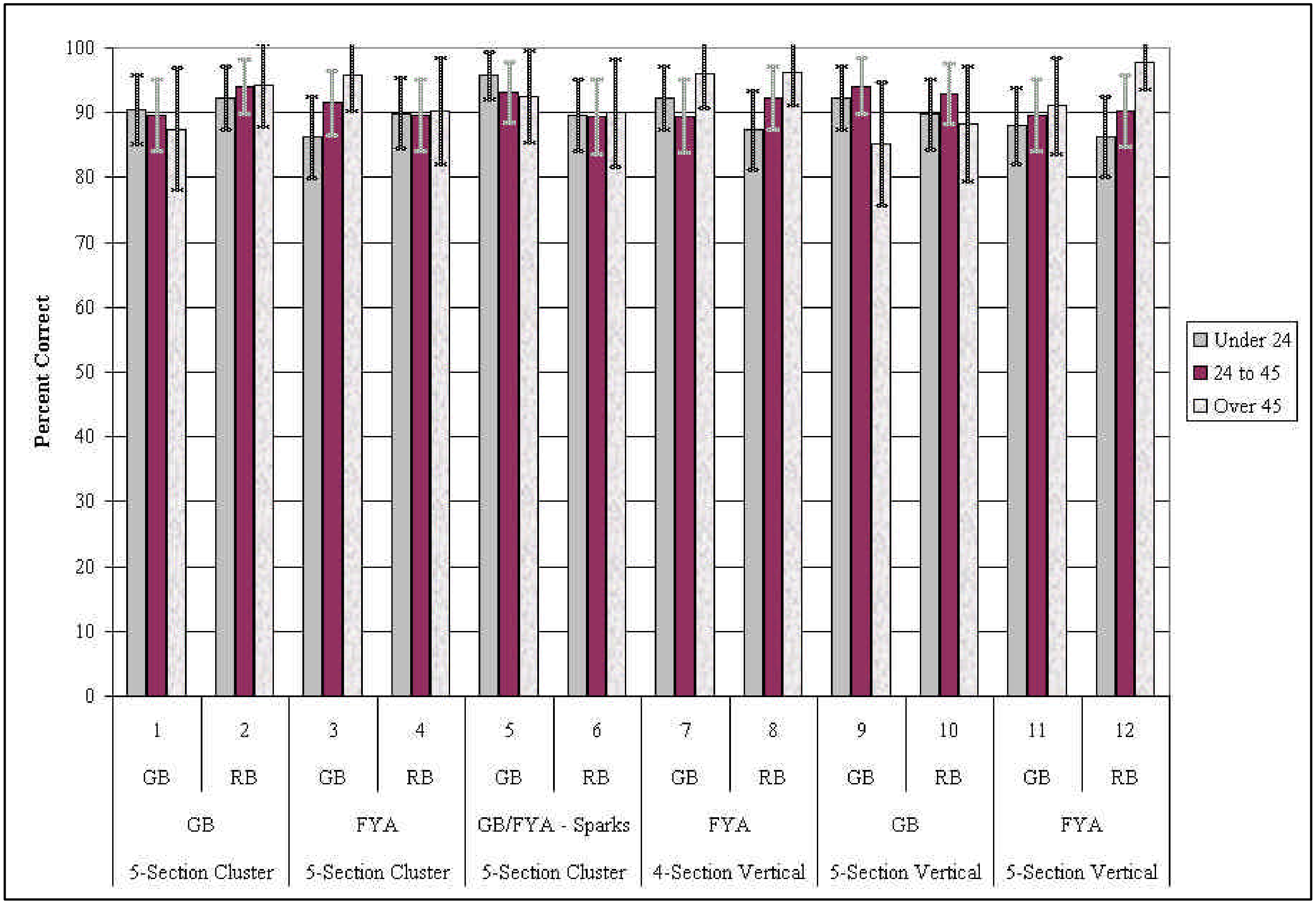
[a] Scenario identification number
[b] Indication for adjacent through lanes
[c] Left-turn permissive indication
[d] PPLT signal display arrangement

Figure 11 Percent Correct for each PPLT Signal Display by Sex (with 95% C.I.).

Table 12 Correct Responses for each PPLT Signal Display by Age

Sc[a]	Arr[b]	Per Ind[c]	Thru Ind[d]	Age Category								
				Under 24			24 to 45			Over 45		
				Obs[e]	%[f]	95% C.I.	Obs[e]	%[f]	95% C.I.	Obs[e]	%[f]	95% C.I.
1	5-section cluster	GB	GB	116	91	5	115	90	6	48	88	9
2	5-section cluster	GB	RB	117	92	5	117	94	4	52	94	6
3	5-section cluster	FYA	GB	116	86	6	118	92	5	48	96	6
4	5-section cluster	FYA	RB	119	90	5	115	90	6	51	90	8
5	5-section cluster	GB/ FYA	GB	116	96	4	117	93	5	53	92	7
6	5-section cluster	GB/ FYA	RB	116	90	6	113	89	6	50	90	8
7	4-section vertical	FYA	GB	116	92	5	114	89	6	51	96	5
8	4-section vertical	FYA	RB	118	87	6	117	92	5	53	96	5
9	5-section vertical	GB	GB	117	92	5	119	94	4	54	85	9
10	5-section vertical	GB	RB	117	90	5	113	93	5	51	88	9
11	5-section vertical	FYA	GB	117	88	6	116	90	6	56	91	7
12	5-section vertical	FYA	RB	117	86	6	113	90	5	46	98	4

[a] Scenario identification number
[b] PPLT signal display arrangement
[c] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Number of observations
[f] Percent correct



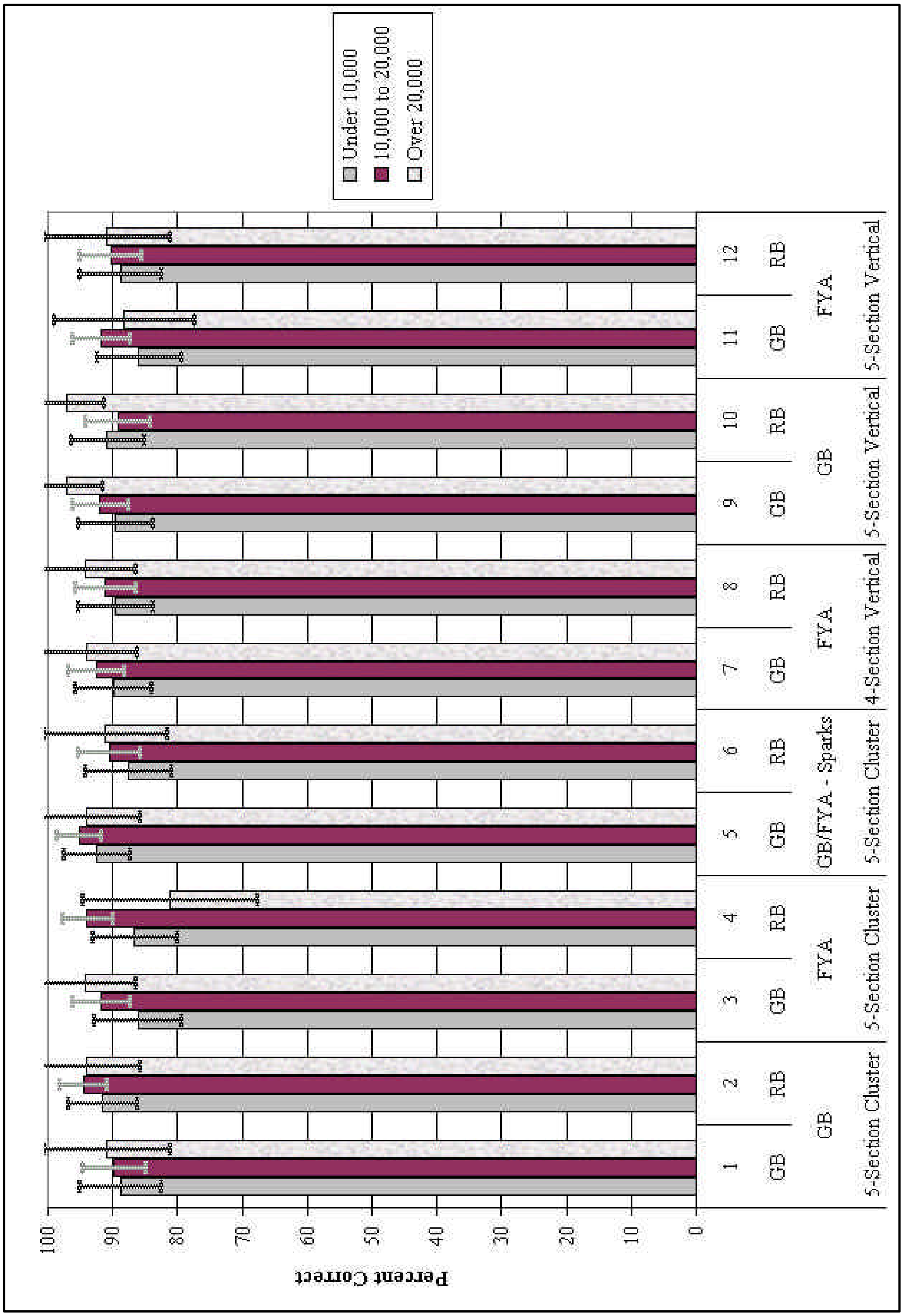
[a] Scenario identification number
[b] Indication for adjacent through lanes
[c] Left-turn permissive indication
[d] PPLT signal display arrangement

Figure 12 Percent Correct for each PPLT Signal Display by Age (with 95 percent CI) in Simulator.

Table 13 Correct Responses for each PPLT Signal Display by Driving Experience

Sc[a]	Arr[b]	Per Ind[c]	Thru Ind[d]	Annual Miles Driven								
				Under 10,000			10,000 to 20,000			Over 20,000		
				Obs[e]	%[f]	95% C.I.	Obs[e]	%[f]	95% C.I.	Obs[e]	%[f]	95% C.I.
1	5-section cluster	GB	GB	98	89	6	148	90	5	33	91	10
2	5-section cluster	GB	RB	106	92	5	147	95	4	33	94	8
3	5-section cluster	FYA	GB	101	86	7	146	92	4	35	94	8
4	5-section cluster	FYA	RB	105	87	7	148	94	4	32	81	14
5	5-section cluster	GB/ FYA	GB	106	92	5	147	95	3	33	94	8
6	5-section cluster	GB/ FYA	RB	97	88	7	148	91	5	34	91	10
7	4-section vertical	FYA	GB	99	90	6	148	93	4	34	94	8
8	4-section vertical	FYA	RB	106	90	6	147	91	5	35	94	8
9	5-section vertical	GB	GB	106	90	6	149	92	4	35	97	6
10	5-section vertical	GB	RB	98	91	6	149	89	5	34	97	6
11	5-section vertical	FYA	GB	107	86	7	148	92	4	34	88	11
12	5-section vertical	FYA	RB	98	89	6	145	90	5	33	91	10

[a] Scenario identification number
[b] PPLT signal display arrangement
[c] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Number of observations
[f] Percent correct



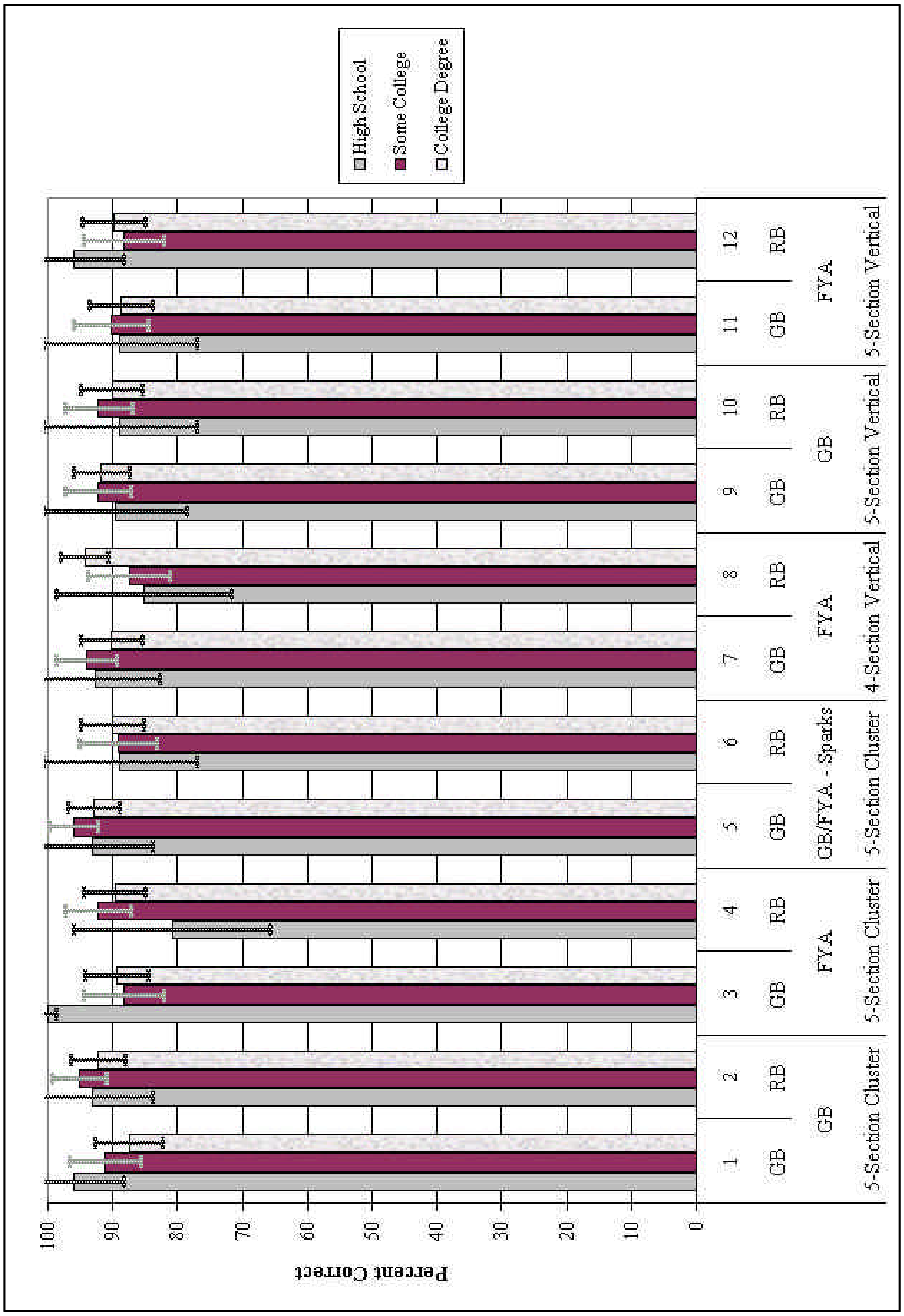
[a] Scenario identification number
[b] Indication for adjacent through lanes
[c] Left-turn permissive indication
[d] PPLT signal display arrangement

Figure 13 Percent Correct for each PPLT Signal Display by Driving Experience (with 95% C.I.).

Table 14 Correct Responses for each PPLT Signal Display by Education

Sc[a]	Arr[b]	Per Ind[c]	Thru Ind[d]	Education Level								
				High School			Some College			College Degree		
				Obs[e]	%[f]	95% C.I.	Obs[e]	%[f]	95% C.I.	Obs[e]	%[f]	95% C.I.
1	5-section cluster	GB	GB	25	96	8	102	91	6	152	88	5
2	5-section cluster	GB	RB	29	93	9	101	95	4	156	92	4
3	5-section cluster	FYA	GB	28	100	1	102	88	6	152	89	5
4	5-section cluster	FYA	RB	26	81	15	104	92	5	155	90	5
5	5-section cluster	GB/ FYA	GB	29	93	9	101	96	4	156	93	4
6	5-section cluster	GB/ FYA	RB	27	89	12	102	89	6	150	90	5
7	4-section vertical	FYA	GB	27	93	10	101	94	5	153	90	5
8	4-section vertical	FYA	RB	27	85	13	104	88	6	157	94	4
9	5-section vertical	GB	GB	29	90	11	103	92	5	158	92	4
10	5-section vertical	GB	RB	27	89	12	102	92	5	152	90	5
11	5-section vertical	FYA	GB	27	89	12	103	90	6	159	89	5
12	5-section vertical	FYA	RB	25	96	8	103	88	6	148	90	5

[a] Scenario identification number
[b] PPLT signal display arrangement
[c] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Number of observations
[f] Percent correct



[a] Scenario identification number
[b] Indication for adjacent through lanes
[c] Left-turn permissive indication
[d] PPLT signal display arrangement

Figure 9 Correct and Responses (with 95 percent CI) in Simulator.

8.2.2 *Analysis of Incorrect Responses*

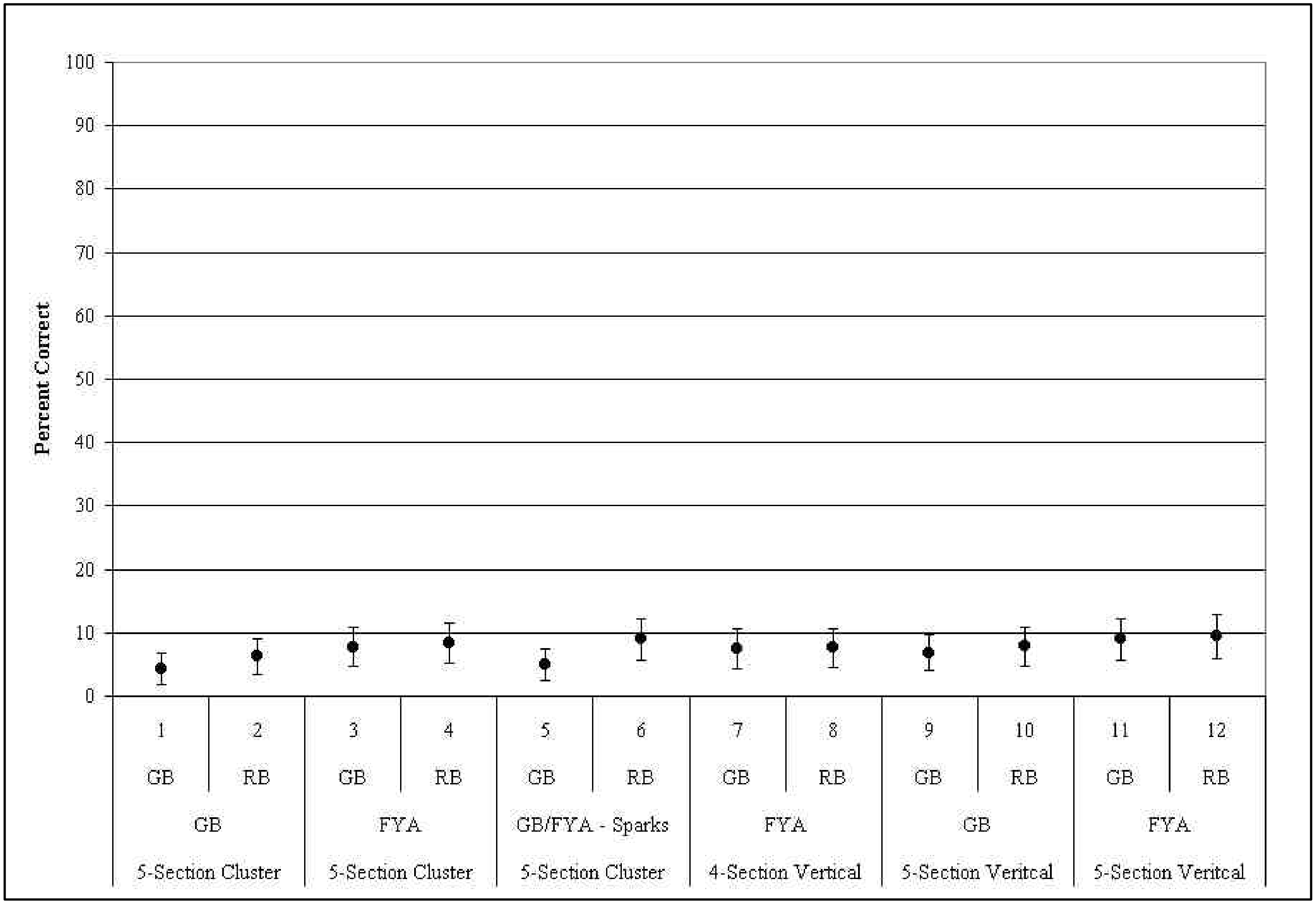
Six possible response types for the simulator experiment were established. Initially, five of the six response types were classified as incorrect responses; however, Response Type 4, which was the *fail-safe by traffic* response, was ultimately considered as a correct response. As shown in Table 4, the remaining incorrect responses were either fail-safe (Response Types 2 or 3) or fail-critical (Response Types 5 and 6). Fail-critical responses were either *non-serious* or *serious*. Refer to Table 4 for further definition of the possible incorrect responses. In the event that multiple incorrect actions were made, all were noted, and the result was classified by the most serious infraction.

The breakdown of incorrect responses is presented in Table 15. Analyzing the *fail-safe by movement responses,* the total percentage of fail-safe responses was two percent. There were statistically significant differences between PPLT signal displays ($p = <0.001$). Specifically, a significant amount of fail-safe by movement responses were observed with scenario one, which is a five-section cluster in a shared location with a green ball permissive indication and adjacent green ball through indication. Across PPLT signal displays, no significant differences were observed in terms of the percentage of *fail-critical non-serious* or *fail-critical serious* responses ($p = 0.606$ and $p = 0.256$, respectively). Furthermore, there were no significant differences when all fail-critical responses were combined for analysis ($p = 0.407$). The percentage of fail-critical errors for each of the 12 PPLT signal displays is presented in Figure 15.

Table 15 Breakdown of Incorrect Responses

Sc[a]	Arr[b]	Per Ind[c]	Thru Ind[d]	Obs[e]	Response Type 2 and 3[f]		Response Type 5[g]		Response Type 6[h]	
					Percent	95% C.I.	Percent	95% C.I.	Percent	95% C.I.
1	5-section cluster	GB	GB	279	6	3	2	2	3	2
2	5-section cluster	GB	RB	286	0	1	3	2	3	2
3	5-section cluster	FYA	GB	282	2	2	2	2	6	3
4	5-section cluster	FYA	RB	285	2	2	3	2	5	3
5	5-section cluster	GB/ FYA	GB	286	1	1	1	1	4	2
6	5-section cluster	GB/ FYA	RB	279	1	1	3	2	6	3
7	4-section vertical	FYA	GB	281	1	1	2	2	5	3
8	4-section vertical	FYA	RB	288	1	1	2	2	6	3
9	5-section vertical	GB	GB	290	1	1	2	2	4	2
10	5-section vertical	GB	RB	281	1	1	4	2	4	2
11	5-section vertical	FYA	GB	289	2	2	2	2	7	3
12	5-section vertical	FYA	RB	276	1	1	2	2	7	3

[a] Scenario identification number
[b] PPLT signal display arrangement
[c] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Number of Observations
[f] *Fail-Safe by Movement Responses*
[g] *Fail-Critical Non-Serious Responses*
[h] *Fail-Critical Serious Responses*



[a] Scenario identification number
[b] Indication for adjacent through lanes
[c] Left-turn permissive indication
[d] PPLT signal display arrangement

Figure 15 Fail-Critical Responses by PPLT Signal Display (with 95 percent CI) in Simulator.

Further analysis was completed using only fail-critical errors as a basis for evaluation, based on the premise that these errors are the most serious and are directly related to driver comprehension of a particular PPLT signal display. Similar to the analysis completed with correct responses, the components of the PPLT display were isolated to determine if they had an impact on the percent of fail-critical errors. The percentage of fail-critical responses for each PPLT display component is presented in Table 16. The percent of fail critical responses by permissive indication ranged from six to eight percent. This difference was not statistically significant (p = 0.133). Similarly, the PPLT signal display arrangement was not associated with statistically significant differences in terms of fail-critical responses (p = 0.325). Additionally, neither the through indication or PPLT signal display location resulted in statistically significant differences (p = 0.134 and p = 0.480, respectively).

Table 16 Effects of PPLT Display Components on Percent of Fail-Critical Responses

PPLT Display Component	Level	Observations	Percent Fail-Crtical[a]	95% C.I.	Statistical p-value
Permissive Indication[b]	GB	1136	6	1	0.133
	FYA	1701	8	1	
	GB/FYA	565	7	2	
Arrangement[c]	5-section cluster	1697	7	1	0.325
	4-section vertical	569	8	2	
	5-section vertical	1136	8	2	
Through Indication[d]	GB	1707	7	1	0.134
	RB	1695	8	1	
Location[e]	Shared	846	7	2	0.480
	Exclusive	2556	8	1	

[a] Response Types 5 and 6
[b] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[c] PPLT signal display arrangement
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Location of PPLT Signal Display

8.2.2.1 Demographics: Demographic variables were again considered, this time to identify any possible effects on the percentage of fail-critical responses. A demographic breakdown of the fail-critical responses is presented in Table 17. Statistically, there was no significant difference in the percentage of fail-critical errors for sex (p =0.815) or education level (p = 0.892). The age demographic was again statistically significant (p = <0.001). Drivers in the over 45 age category had significantly less fail-critical responses than drivers in both the under 24 and 24 to 45 age groups. Statistically significant differences were also observed within the annual miles driven demographic. Specifically, drivers that had driven under 10,000 miles in the previous year made significantly more fail-critical errors than drivers that had driven between 10,000 and 20,000 miles in the previous year.

Analysis combining the age and sex demographics is presented in Table 18, with an interaction plot of the data presented in Figure 16. Figure 16 indicates there is an interaction between the categories (p = <0.001) as the percentage of fail critical responses decreased among males as age increased, yet among females drivers the percentage of fail critical responses was higher for the *24 to 45* age group than the *under 24* age group. Consistent with the trend of fail critical responses among male drivers, the fewest fail critical responses were made by female drivers over the age of 45. The age variable was not statistically significant within both sex categories. In both groups, drivers over the age of 45 made significantly fewer fail-critical responses than drivers younger than them.

Table 17 Demographic Breakdown of Fail-Critical Responses

Demographic Category	Level	Obser[a]	Percent Fail-Critical[b]	95 % C.I.	Statistical p-value
Sex	Male	1893	8	1	0.815
	Female	1509	7	1	
Age	Under 24	1402	9	1	<0.001
	24 to 45	1387	8	1	
	Over 45	613	4	2	
Annual Miles Driven	Under 10,000	1227	9	2	0.032
	10,000 to 20,000	1770	6	1	
	More than 20,000	405	7	2	
Highest Education Level Completed	High School	326	7	3	0.892
	Some College	1228	7	1	
	College Degree	1848	7	1	
Geographic Location	UMass	2,528	9	1	<0.001
	TTI	874	4	1	

[a] Number of Observations
[b] Response Types 5 and 6

Table 18 Combined Effect of Age and Sex on Percent Fail-Critical

Sex	Age	Number of Observations	Percent Correct[a]	95 % C.I.
Male	Under 24	785	7	2
	24-45	784	9	2
	Over 45	324	4	2
Female	Under 24	617	11	2
	24-45	603	6	2
	Over 45	289	3	2

[a] Response types 5 and 6

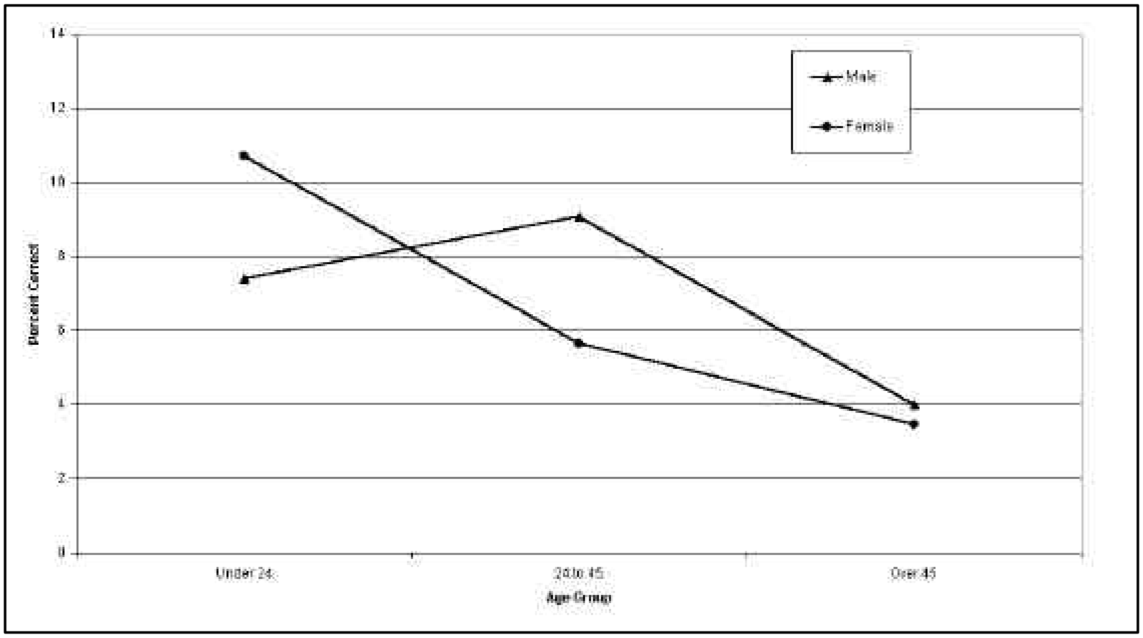


Figure 16 Interaction Plot of Sex and Age for Fail Critical Responses.

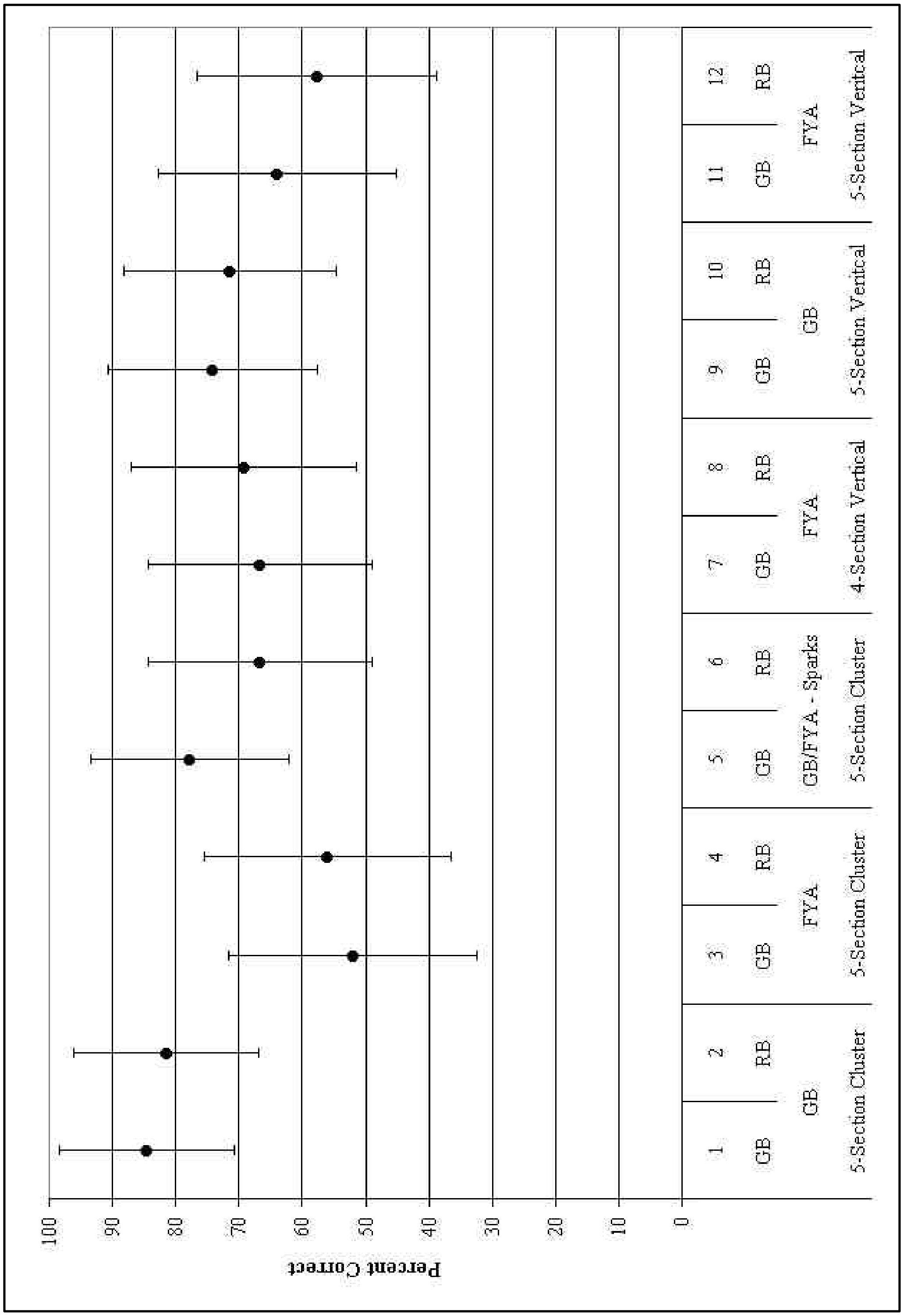
8.2.3 Analysis of First Observed PPLT Display

Based on the balanced design of the experiment each of the PPLT signal displays were equally likely to be the first PPLT display evaluated. Therefore, each of the 316 drivers in this data set had an equally likely chance of observing any of the 12 PPLT signal displays first. Each of the 12 PPLT signal displays was the first observed PPLT signal display by 25 to 28 drivers. Table 19 presents the breakdown of correct, fail-safe, and fail-critical responses at the first PPLT signal display evaluated by each driver. Figure 17 presents the percent of correct responses at the first observed PPLT signal display for the 12 selected signals.

Table 19 Driver Responses at First Observed PPLT Display

Sc[a]	Arr[b]	Per Ind[c]	Thru Ind[d]	Obs[e]	Response Type(s): 1, 4[f] %	1, 4[f] 95% C.I.	2, 3[g] %	2, 3[g] 95% C.I.	5, 6[h] %	5, 6[h] 95% C.I.
1	5-section cluster	GB	GB	26	85	14	4	7	12	12
2	5-section cluster	GB	RB	27	81	15	0	0	19	15
3	5-section cluster	FYA	GB	25	52	20	12	13	36	19
4	5-section cluster	FYA	RB	25	56	19	0	0	44	19
5	5-section cluster	GB/ FYA	GB	27	78	16	0	0	22	16
6	5-section cluster	GB/ FYA	RB	27	67	18	0	0	33	18
7	4-section vertical	FYA	GB	27	67	18	4	7	30	17
8	4-section vertical	FYA	RB	26	69	18	4	7	27	17
9	5-section vertical	GB	GB	27	74	17	0	0	26	17
10	5-section vertical	GB	RB	28	71	17	4	7	25	16
11	5-section vertical	FYA	GB	25	64	19	0	0	36	19
12	5-section vertical	FYA	RB	26	58	19	0	0	42	19

[a] Scenario identification number
[b] PPLT signal display arrangement
[c] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Number of observations
[f] Correct responses
[g] Fail-safe responses
[h] Fail-critical responses



[a] Scenario identification number
[b] Indication for adjacent through lanes
[c] Left-turn permissive indication
[d] PPLT signal display arrangement

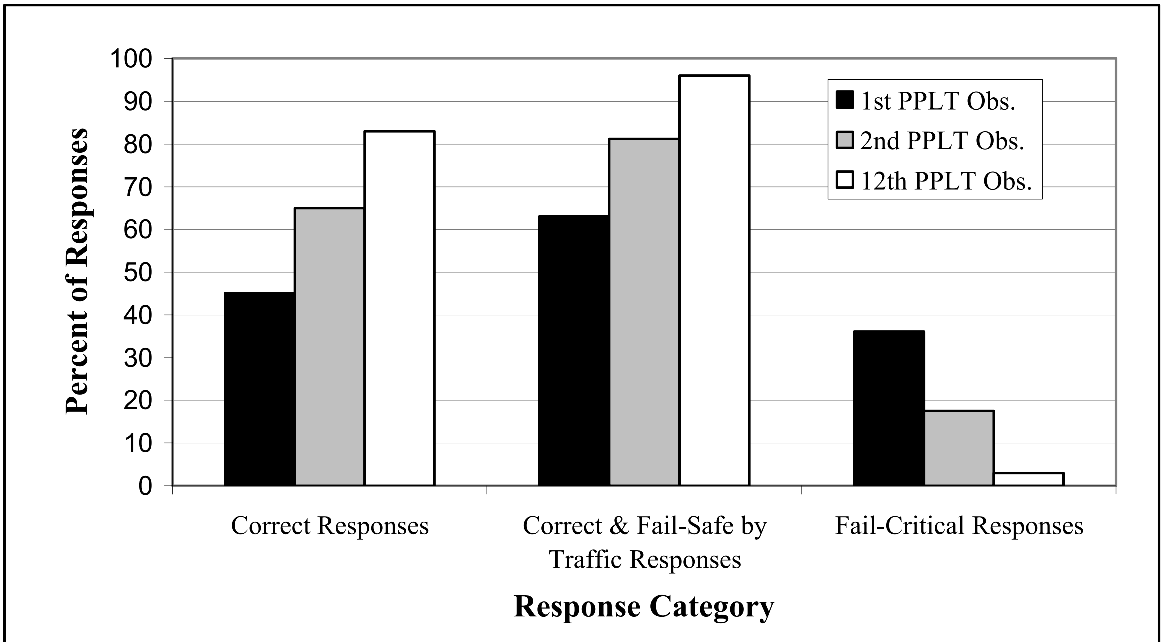
Figure 17 Percent of Correct Responses at First Observed PPLT Signal Display (with 95 % C.I.).

As shown in Figure 17, there is no statistically significant difference in the percentage of correct responses for each of the 12 PPLT signal displays evaluated ($p = 0.261$). The percentage of correct responses at each of the PPLT signal displays ranges from 52 to 85 percent; however, it is important to remember that each display was only observed first somewhere between 25 and 28 times and the smaller sample sizes result in increased confidence intervals.

8.2.4 Driver Learning

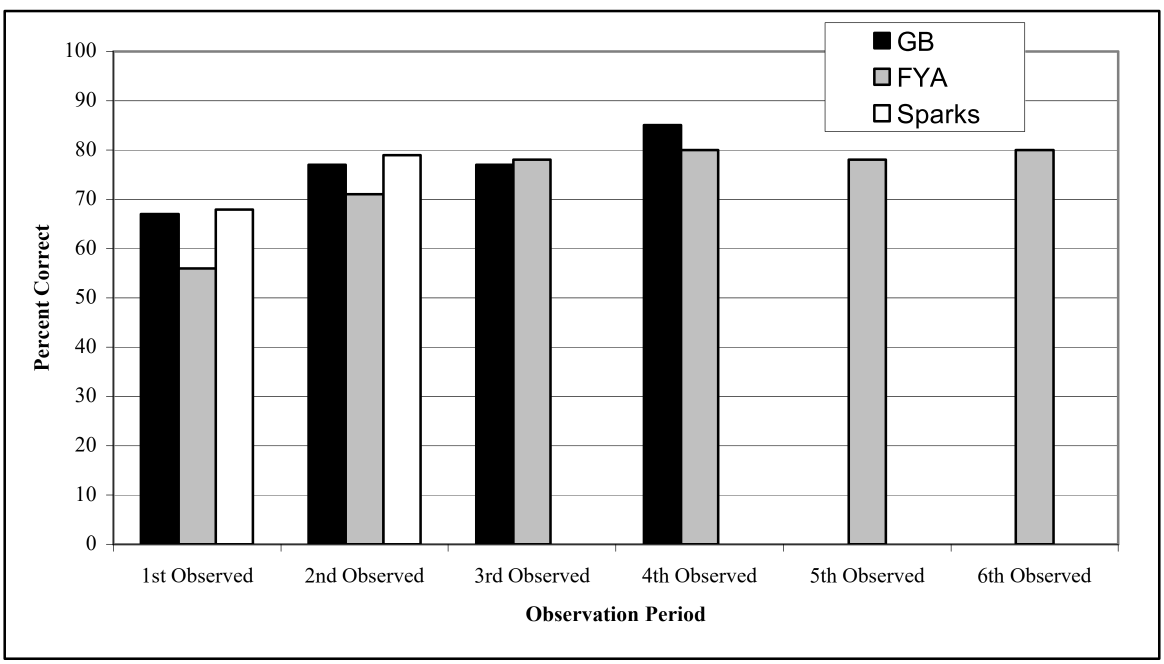
To determine if drivers were *learning* as they completed the simulator experiment, responses were compared at different stages of the experiment. Figure 18 presents the percent of correct responses (Response Type 1 only), combined correct and fail-safe by traffic responses (Response Types 1 and 4), and fail-critical responses (Response Types 5 and 6) at the first, second, and twelfth (final) PPLT signal displays observed by drivers. As seen in Figure 18, driver comprehension at the second observed PPLT signal display was higher than the first observed PPLT signal display for both categories of correct responses. Additionally, driver comprehension at the final PPLT signal display observed was higher than the second observed display. Similar trends are observed when analyzing driver comprehension in terms of fail-critical responses. As presented in Figure 18, drivers made significantly more errors at the first observed PPLT signal display than the second or twelfth observed PPLT signal display.

Similar trends are observed when the data are disaggregated by permissive indication. Figure 19 shows the percentage of correct responses by observation period and permissive indication. For example, drivers observed four PPLT displays with the GB permissive indication, and as seen in Figure 19, the percentage of correct responses was higher at the fourth observed display with a GB than the first. Similarly, the second observed PPLT signal display with the GB/FYA permissive indication resulted in a higher percentage of correct responses than the first observed display with the GB/FYA permissive indication. As seen in Figure 19, the largest increase occurred within displays with the FYA permissive indication. At the first observed display with the FYA permissive indication was 56 percent as compared with 78 percent at the sixth observed display with a FYA permissive indication. After the second observation of the FYA the percentage of correct responses levels off; indicating that any *learning* that may be occurring is likely completed after only two exposures to the permissive indication.



* UMass Data and Response Type 1 only

Figure 18 Trends in Driver Responses by Observation Period.



* UMass Data and Response Type 1 Only

Figure 19 Percent Correct by Permissive Indication and Observation Period.

8.3 Summary of TTI Data (with Continuous Method of Opposing Traffic)

One hundred-sixteen drivers evaluated 1,211 PPLT scenarios in the simulator experiment at TTI with the initial method of opposing traffic. Recall, the opposing vehicles were moving as the driver approached the intersection and arrived at the intersection at the same time as the driver. The percentage of correct responses for each of the 12 PPLT signal displays evaluated are presented with a 95 percent confidence interval in Table 20. Again using the ANOVA model and testing the null hypothesis that all 12 means were equal, a p-value of 0.139 was obtained indicating that the average percent correct for the 12 signal displays were not significantly different.

Table 20 Percent Correct for TTI-Data with CMOT Traffic

Sc[a]	Arrangement[b]	Permissive Indication[c]	Thru Indication[d]	Obser.[e]	Percent Correct[f]	95% C.I.
1	5-section cluster	GB	GB	99	99	2
2	5-section cluster	GB	RB	100	98	3
3	5-section cluster	FYA	GB	101	97	3
4	5-section cluster	FYA	RB	100	96	4
5	5-section cluster	GB/FYA	GB	100	98	3
6	5-section cluster	GB/FYA	RB	104	98	3
7	4-section vertical	FYA	GB	103	99	2
8	4-section vertical	FYA	RB	102	93	5
9	5-section vertical	GB	GB	102	99	2
10	5-section vertical	GB	RB	102	99	2
11	5-section vertical	FYA	GB	98	99	2
12	5-section vertical	FYA	RB	100	98	3

[a] Scenario identification number
[b] PPLT signal display arrangement
[c] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Number of Observations
[f] Percent Correct which is Response Type 1

The percent of correct responses by PPLT display components is presented in Table 21. The percentage of correct responses by permissive indication ranged from 96 to 99 and was statistically significant (p = 0.026) as displays with the GB permissive indication had a significantly higher percentage of correct responses than displays with the FYA permissive indication. The percentage of correct responses for the three types of PPLT signal display arrangements evaluated ranged from 96 to 98 percent; however, this value was not statistically significant (p = 0.336). Similarly, the percent of correct responses was 98 percent when the through indication was green and 96 percent when the through indication was red. This difference in through indications was not significant (p = 0.146). The PPLT signal display location was not a statistically significant variable (p = 0.808).

Table 21 Breakdown of Correct Responses by PPLT Signal Display Component

PPLT Display Component	Level	Observations	Percent Correct[a]	95% C.I.	Statistical p-value
Permissive Indication[b]	GB	403	99	1	0.026
	FYA	604	96	1	
	GB/FYA	204	98	2	
Arrangement[c]	5-section cluster	604	98	1	0.336
	4-section vertical	205	96	3	
	5-section vertical	402	98	1	
Through Indication[d]	GB	603	98	1	0.146
	RB	608	97	1	
Location[e]	Shared	300	97	2	0.808
	Exclusive	911	98	1	

[a] Response Types 1 and 4
[b] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[c] PPLT signal display arrangement
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Location of PPLT Signal Display

The data set was disaggregated further to conduct an analysis of the PPLT signal displays by the demographic variables collected during the experiment. Table 22 presents the percentage of correct responses (Response Types 1 and 4) for each demographic category based on the 1,211 scenarios evaluated at TTI using the initial method of opposing traffic. Overall, sex was not statistically significant (p= 0.609). Males responded correctly 98 percent of the time and females responded correctly 97 percent of the time. Age was reduced to three different categories. The percent of correct responses varied from 95 percent for the under 24 group to 99 percent for the over 24 to 45 age group. The percent correct was statistically significant (p = 0.005).

Referring again to Table 22, the results for the demographic of annual miles driven and highest education level completed are shown. Drivers with a college degree had a significantly higher level of comprehension than drivers with only some college completed (p = 0.007); however, neither group differed significantly from drivers with no college experience. The annual miles driven by drivers was not a statistically significant variable (p = 0.235) as the percent correct ranged from 95 to 98 percent.

Table 22 Percent Correct by Demographics

Demographic Category	Level	Number of Observations	Percent Correct[a]	95 % C.I.	Statistical p-value
Sex	Male	621	98	1	0.609
	Female	590	97	1	
Age	Under 24	397	95	2	0.005
	24 to 45	485	99	1	
	Over 45	329	98	1	
Annual Miles Driven	Under 10,000	307	98	2	0.235
	10,000 to 20,000	776	98	1	
	More than 20,000	128	95	4	
Highest Education Level Completed	High School	110	97	3	0.007
	Some College	446	96	2	
	College Degree	650	99	1	

[a] Response Types 1 and 4

Analysis combining the age and sex demographics is presented in Figure 9. An interaction does exist between sex and age ($p = 0.006$). The age variable was not statistically significant within the male demographic, with the percent correct ranging between 96 and 99 percent. However, within the female demographic, age was statistically significant ($p = 0.017$). Females under the age of 24 had a significantly lower level of comprehension than females in the 24 to 45 age group.

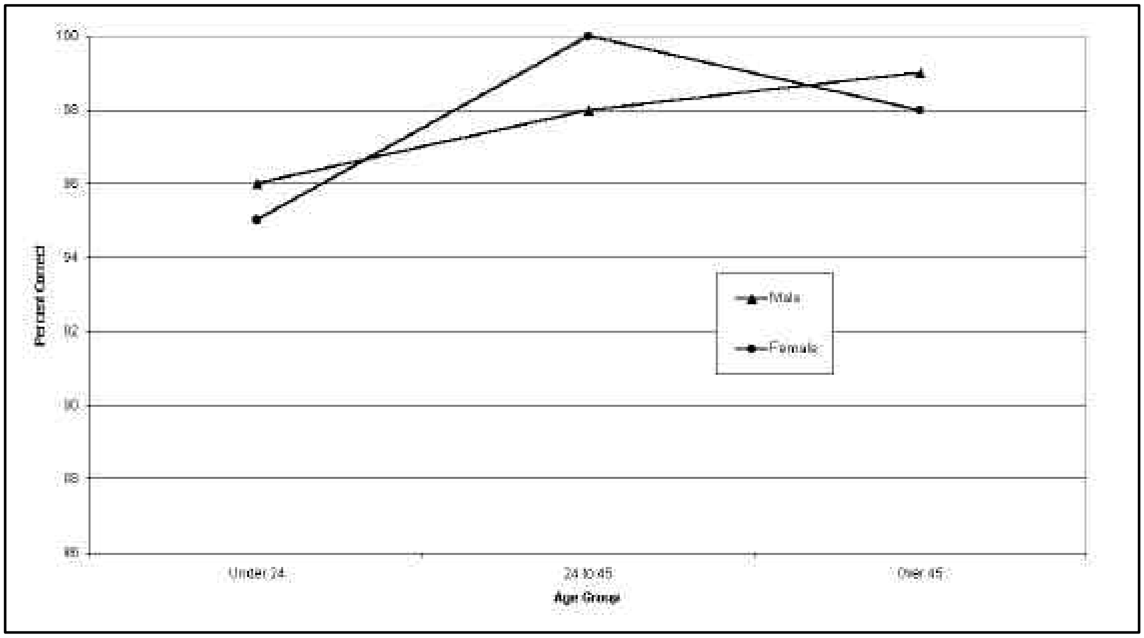
8.3.1 Analysis of Incorrect Responses

Because the *fail safe by traffic* response was been considered as a correct response, there were only four different types of incorrect responses. Table 23 presents the percentages of *fail-safe by movement and fail-critical* responses with a 95 percent confidence interval for the 12 PPLT signal displays. A significant number of fail-safe responses ($p = <0.001$) were observed with PPLT scenario number eight, which is a four-section vertical arrangement in an exclusive location with a FYA permissive indication and adjacent RB indication. No statistically significant differences were observed with respect to the percent of fail-critical errors ($p = 0.750$). Disaggregating the fail-critical errors to fail-critical non-serious (Response Type 5) and fail-critical serious (Response Type 6) did not result in statistically significant differences across PPLT signal displays ($p = 0.898$ and $p = 0.663$, respectively).

Further analysis was completed using only fail-critical errors as a basis for evaluation, based on the premise that these errors are the most serious and are directly related to driver comprehension of a particular PPLT signal display. Table 24 presents the combined fail-critical responses for the various PPLT signal display components.

8.4 Discussion of Opposing Traffic

The previous sections have discussed the simulator evaluation data sets collected using two different methods of opposing vehicles. Recall, 116 drivers completed the experiment at TTI observing the CMOT traffic and 93 drivers observed the RMOT opposing traffic. Each of the 223 drivers at UMass completed the experiment observing the RMOT traffic scheme. The two methods of opposing traffic are described in the experimental design.



* Response Types 1 and 4

Figure 20 Interaction Plot of Sex and Age Demographics for Initial TTI Data Set

Overall the percentage of correct responses (Response Types 1 and 4) was significantly higher for the CMOT data set (p = <0.001). Figure 21 is a breakdown of correct responses at all 12 PPLT signal displays by the method of opposing traffic drivers observed (CMOT or RMOT). As seen in Figure 21, the percentage of correct responses was higher, often significantly, for each PPLT display among drivers that observed the CMOT.

The CMOT resulted in a significantly higher percentage of correct responses and a significantly lower percentage of fail-critical responses. With the CMOT the opposing vehicles in the simulation were arriving at the intersection at the same time as the driver, while with the RMOT traffic scheme the opposing vehicles were stopped at the intersection as the driver approached. The CMOT method provided additional cues from the opposing simulation vehicles, which may have biased drivers that were uncertain of the meaning of the PPLT signal display indication.

Table 23 Percent of Fail-Safe by Movement and Fail-Critical Response for CMOT Data Set

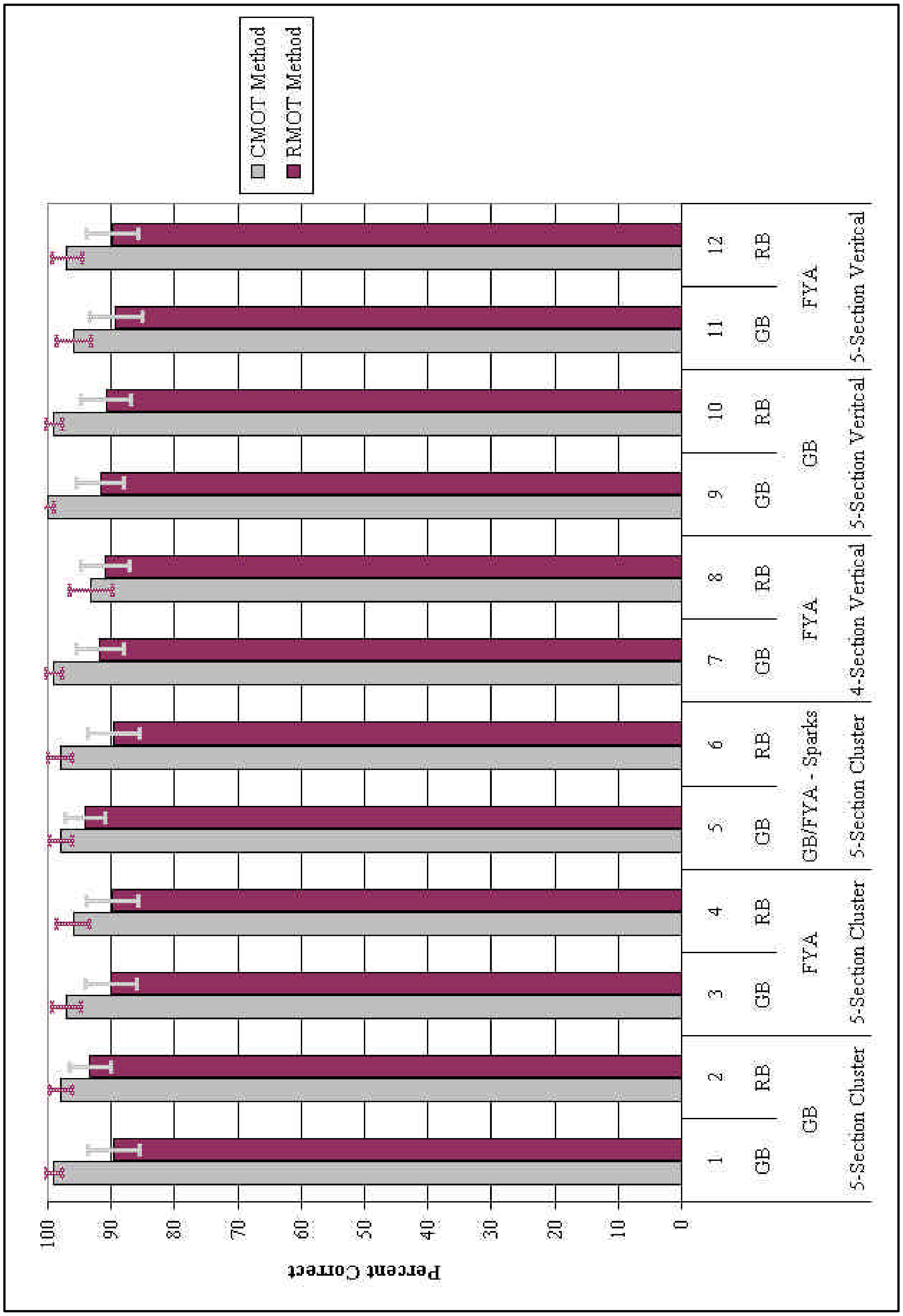
Sc[a]	Arrangement[b]	Per Ind[c]	Thru Ind[d]	Obs[e]	Percent Fail-Safe[f]	95% C.I.	Percent Fail-Critical[g]	95% C.I.
1	5-section cluster	GB	GB	99	0	0	1	2
2	5-section cluster	GB	RB	100	0	0	2	3
3	5-section cluster	FYA	GB	101	0	0	3	3
4	5-section cluster	FYA	RB	100	3	3	1	2
5	5-section cluster	GB/ FYA	GB	100	0	0	2	3
6	5-section cluster	GB/ FYA	RB	104	0	0	2	3
7	4-section vertical	FYA	GB	103	0	0	1	2
8	4-section vertical	FYA	RB	102	6	5	1	2
9	5-section vertical	GB	GB	102	0	0	0	0
10	5-section vertical	GB	RB	102	1	2	0	0
11	5-section vertical	FYA	GB	98	1	2	3	3
12	5-section vertical	FYA	RB	100	1	2	2	3

[a] Scenario identification number
[b] PPLT signal display arrangement
[c] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Number of Observations
[f] Response types 2 and 3
[g] Response types 5 and 6

Table 24 Breakdown of Fail-Critical Responses by PPLT Signal Display

PPLT Display Component	Level	Observations	Percent Fail-Critical[a]	95% C.I.	Statistical p-value
Permissive Indication[b]	GB	403	1	1	0.319
	FYA	604	2	1	
	GB/FYA	204	2	2	
Arrangement[c]	5-section cluster	604	2	1	0.610
	4-section vertical	205	1	1	
	5-section vertical	402	1	1	
Through Indication[d]	GB	603	2	1	0.623
	RB	608	1	1	
Location[e]	Shared	300	2	1	0.766
	Exclusive	911	1	1	

[a] Response Types 5 and 6
[b] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[c] PPLT signal display arrangement
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Location of PPLT Signal Display



[a] Scenario identification number
[b] Indication for adjacent through lanes
[c] Left-turn permissive indication
[d] PPLT signal display arrangement

Figure 21 Percent Correct by Opposing Traffic Method (with 95 percent CI) in Simulator.

8.5 Static Evaluation

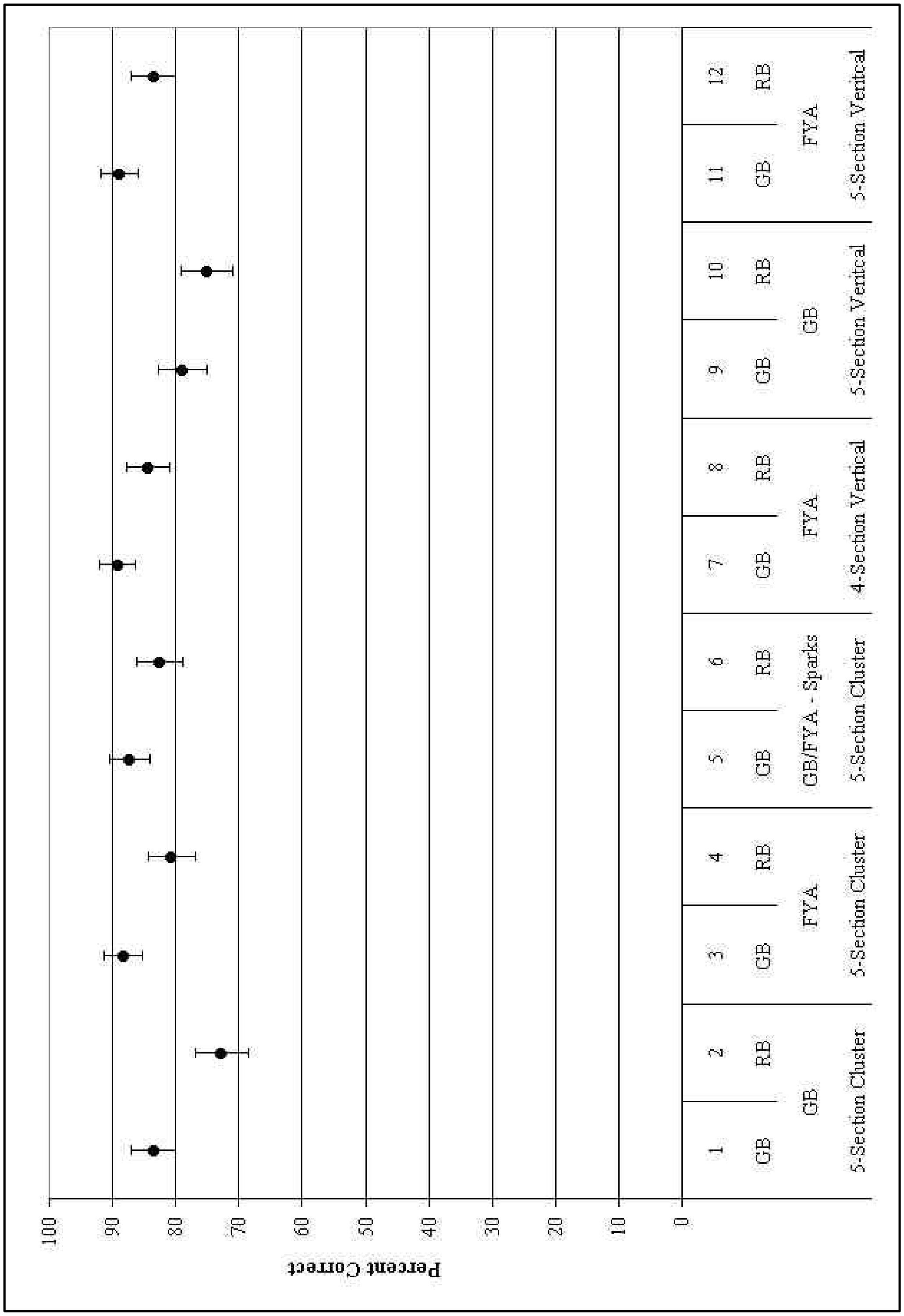
Four-hundred thirty six drivers completed the static evaluation evaluating all 12 scenarios. One driver only evaluated ten scenarios because of an equipment malfunction. In total, 5,230 PPLT signal display scenarios were evaluated. Each driver was asked to respond with one of four choices after viewing the scenario. *Yield, then go if an acceptable gap in the opposing traffic exists* was the correct response for all 12 scenarios; however to be consistent with previous NCHRP evaluations and with the driving simulator evaluation the *stop first, then go if a gap in opposing traffic exists* was also considered a correct response. Driver comprehension was again determined by the percentage of correct responses; however, an analysis of incorrect responses was also completed. Similarly, the components of the PPLT signal displays and demographic variables were isolated to identify any effect on overall driver comprehension.

The percent of correct responses was 83 percent for all 5,230 scenarios evaluated. Correct responses ranged from 73 to 89 percent, and are presented in Table 25 and pictured in Figure 22 for each of the 12 PPLT signal displays. Evaluating the null hypothesis that the percent of correct response for each of the 12 PPLT signal displays were the same, the means were found to be statistically different ($p = <0.001$). In particular, scenarios three (five-section cluster, with FYA permissive indication, and GB through indication), five (five-section cluster, with GB/FYA permissive indication, and GB through indication), seven (four-section vertical, with FYA permissive indication, and GB through indication) and 11 (five-section vertical, with FYA permissive indication, and GB through indication) had significantly high percentages of correct responses. By comparison, displays two (five-section cluster, with GB permissive indication, and RB through indication) and 10 (five-section vertical, GB permissive indication, and RB through indication) had significantly low levels of correct responses.

Table 25 Percent Correct Responses for Static Evaluation

Sc[a]	Arrangement[b]	Per Ind[c]	Thru Ind[d]	Number of Observations	Percent Correct[e]	95 % C.I.
1	5-section cluster	GB	GB	436	83	3
2	5-section cluster	GB	RB	436	73	4
3	5-section cluster	FYA	GB	436	88	3
4	5-section cluster	FYA	RB	435	81	4
5	5-section cluster	GB/ FYA	GB	435	87	3
6	5-section cluster	GB/ FYA	RB	436	83	4
7	4-section vertical	FYA	GB	436	89	3
8	4-section vertical	FYA	RB	436	84	3
9	5-section vertical	GB	GB	436	79	4
10	5-section vertical	GB	RB	436	75	4
11	5-section vertical	FYA	GB	436	89	3
12	5-section vertical	FYA	RB	436	83	3

[a] Scenario identification number
[b] PPLT signal display arrangement
[c] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Both y*ield first* and *stop first* responses



[a] Scenario identification number
[b] Indication for adjacent through lanes
[c] Left-turn permissive indication
[d] PPLT signal display arrangement

Figure 22 Percent of Correct Responses (with 95 percent CI) for Static Evaluation.

Disaggregating the PPLT signal displays into the same four components as before, the data presented in Table 26 are obtained. PPLT signal displays with the GB permissive indication had significantly lower correct responses than PPLT displays with either the FYA or GB/FYA permissive indications. PPLT displays in the four-section vertical arrangement had a significantly higher percentage of correct responses than displays with either the five-section cluster arrangement or the five-section vertical arrangement ($p = 0.003$); however, it should be noted that only the FYA permissive indication was evaluated in a four-section vertical arrangement, and this combination likely attributes for the higher percentage of correct responses. Location of the PPLT display was not statistically significant ($p = 0.170$). A significant difference ($p = <0.001$) was found between displays with the through movement GB and RB, with drivers responding correctly more frequently to displays with the GB through movement.

Table 26 Effects of PPLT Display Components on Percent Correct in Static Evaluation

PPLT Display Component	Level	Observations	Percent Correct[a]	95% C.I.	Statistical p-value
Permissive Indication[b]	GB	1744	78	2	<0.001
	FYA	2615	86	1	
	GB/FYA	871	85	2	
Arrangement[c]	5-section cluster	2614	83	1	0.003
	4-section vertical	872	87	2	
	5-section vertical	1744	82	2	
Thru Indication[d]	GB	2615	86	1	<0.001
	RB	2615	80	2	
Location[e]	Shared	1307	84	2	0.170
	Exclusive	3923	83	1	

[a] Response Types 2 and 3 (*Yield (or Stop First), then go if a gap in opposing traffic exists*)
[b] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[c] PPLT signal display arrangement
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Location of PPLT Signal Display

8.5.1 Demographics

Four demographic categories were isolated using the percent of correct responses as a basis for interpretation. The percentages of correct responses for the various demographic categories are presented in Table 27. In the static evaluation, sex was the only demographic which was not a statistically significant variable (p = 0.208). Within the age demographic, drivers over the age of 45 had a significantly lower percentage of correct responses than drivers in the *24 to 45* and *under 24* age groups (p=<0.001). Drivers that had driven between 10,000 and 20,000 miles in the previous year had a statistically significant higher percentage of correct responses in the static evaluation than drivers from the other driving experience categories (p = <0.001). Additionally, drivers with only a high school diploma had significantly lower driver comprehension levels than drivers in the higher education categories (p = <0.001).

Comparing the geographic regions identified a statistically significant difference in driver comprehension (p = <0.001). Specifically, drivers completing the static evaluation at TTI responded correctly 86 percent of the time, as compared to 79 percent correct responses by drivers at UMass.

Table 27 Demographic Breakdown of Correct Response in Static Evaluation

Demographic Category	Level	Obser[a]	Percent Correct[b]	95 % C.I.	Statistical p-value
Sex	Male	2724	84	1	0.208
	Female	2506	82	1	
Age	Under 24	1908	84	2	<0.001
	24 to 45	2028	86	2	
	Over 45	1294	76	2	
Annual Miles Driven	Under 10,000	1764	81	2	<0.001
	10,000 to 20,000	2818	85	1	
	More than 20,000	648	78	3	
Highest Education Level Completed	High School	552	74	4	<0.0001
	Some College	1884	84	2	
	College Degree	2794	84	1	
Geographic Location	UMass	2640	79	2	<0.001
	TTI	2590	86	1	

[a] Number of Observations
[b] Response Types 2 and 3 (*Yield (or Stop First), then go if a gap in opposing traffic exists*)

8.5.2 Analysis of Incorrect Responses

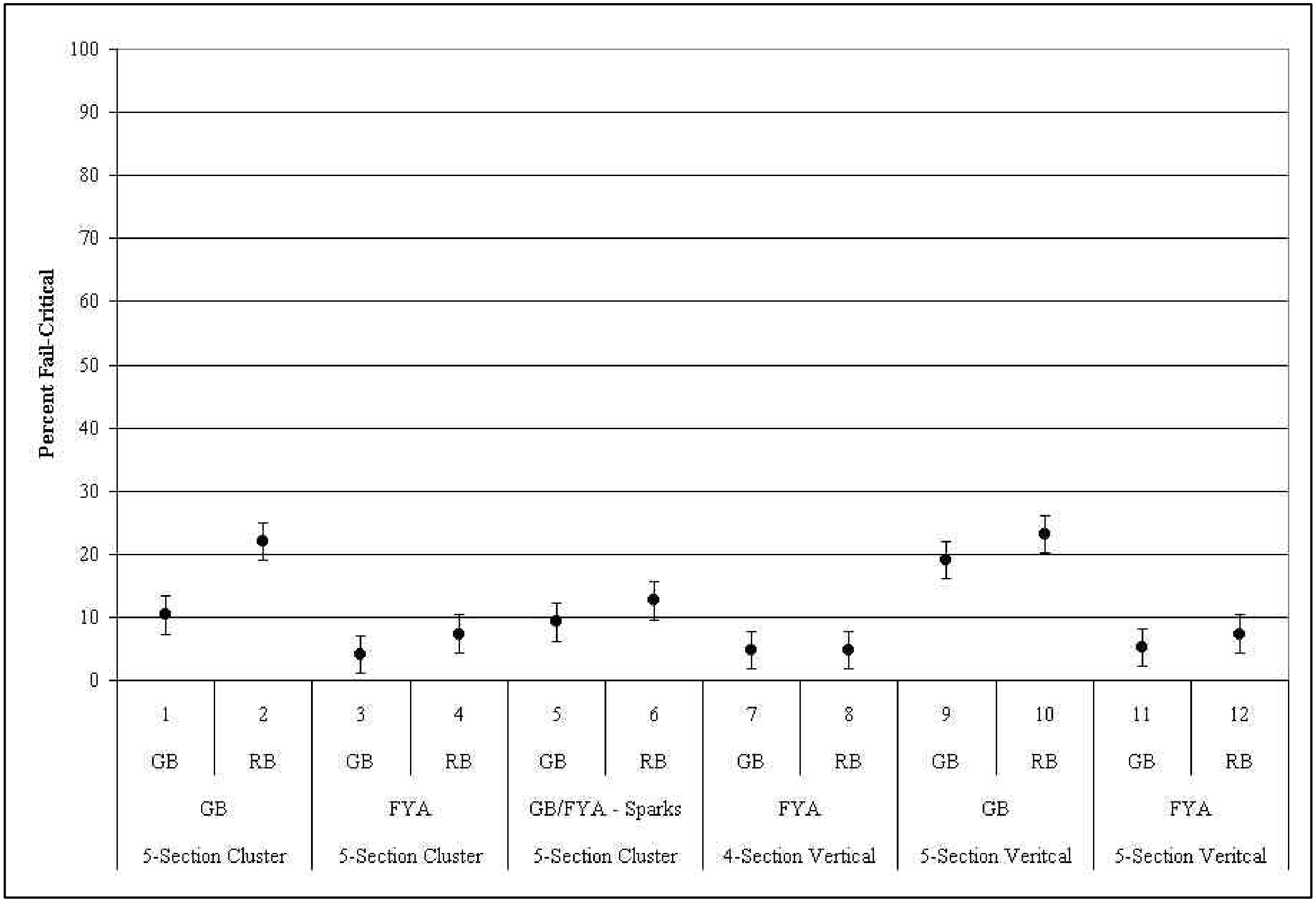
Because the *stop first, then go if a gap in opposing traffic exists* responses were considered correct only two of the four possible response types in the static evaluation were determined to be incorrect. Drivers indicating the choice to *go, you have the right of way* are incorrectly assuming right-of-way in a manner consistent with the fail-critical responses of the driving simulator experiment. The *stop, and wait for the appropriate* signal response demonstrates a lack of understanding that left-turns are permissive provided sufficient gaps in the opposing traffic exist.

A breakdown of all incorrect responses in the static evaluation is summarized in Table 28. For all of the incorrect responses, there were significant differences across the 12 PPLT signal displays (p =<0.001 for each). Figure 23 presents all of the *go, you have the right-of-way* choices for all 12 PPLT displays. As seen from Figure 23, a significantly higher amount of fail-critical responses are generated from three scenarios. Each of these three scenarios include the GB permissive indication. Specifically, displays two (five-section cluster arrangement, GB permissive indication, and RB through indication), nine (five section vertical, GB permissive indication, and GB through indication), and 10 (five section vertical, GB permissive indication, and GB through indication) were each associated with significantly more *go, you have the right-of-way responses.*

Table 28 Breakdown of Incorrect Static Evaluation Responses

Sc[a]	Arrangement[b]	Per Ind[c]	Thru Ind[d]	Obser[e]	Response Type(s)			
					Go[f]		*Stop*[g]	
					Percent of Responses	95% C.I.	Percent of Responses	95% C.I.
1	5-section cluster	GB	GB	436	10	3	6	2
2	5-section cluster	GB	RB	436	22	4	5	2
3	5-section cluster	FYA	GB	436	4	2	8	2
4	5-section cluster	FYA	RB	435	7	2	12	3
5	5-section cluster	GB/ FYA	GB	435	9	3	3	2
6	5-section cluster	GB/ FYA	RB	436	13	3	5	2
7	4-section vertical	FYA	GB	436	5	2	6	2
8	4-section vertical	FYA	RB	436	5	2	11	3
9	5-section vertical	GB	GB	436	19	4	2	1
10	5-section vertical	GB	RB	436	23	4	2	1
11	5-section vertical	FYA	GB	436	5	2	6	2
12	5-section vertical	FYA	RB	436	7	2	9	3

[a] Scenario identification number
[b] PPLT signal display arrangement
[c] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Number of observations
[f] *Go, you have the right-of-way* responses
[g] *Stop and wait for the appropriate signal* responses



[a] Scenario identification number
[b] Indication for adjacent through lanes
[c] Left-turn permissive indication
[d] PPLT signal display arrangement

Figure 23 Percent of Fail-Critical Responses (with 95 percent CI) for Static Evaluation.

8.6 Comparison of Driving Simulator and Static Evaluation

Considering both the driving simulator and static evaluations, 9,905 permissive left-turn scenarios were evaluated. In general, responses in either of the driving simulator data sets were significantly higher than responses in the static evaluation. Table 29 presents a side-by-side comparison of the percentages of correct responses from the combined UMass and TTI data set (with RMOT traffic) and the static evaluation. Table 30 presents the percentages of fail critical responses for the same data sets.

A more direct comparison of responses in the simulator and static evaluations was completed by cross-analyzing individual drivers responses in each methodology. Specifically, drivers' simulator responses were directly compared to their static evaluation responses. The analysis was focused on those drivers who failed critical in the static evaluation. The query was undertaken to determine if drivers' comprehension from the static evaluation was consistent with each driver's action in the dynamic simulation.

There were 353 fail critical responses in the static evaluation for which a direct comparison with the driver's response in the simulator were available. Of the 353 fail critical responses from the static evaluation, drivers had responded correctly in the simulator environment 79 percent of the time. Only 19 percent of the 353 pairs resulted in fail critical responses in both the simulator and static evaluation. Figure 24 presents the number of drivers with fail-critical responses for each of the 12 PPLT signal displays in the static evaluation, and the number of those drivers with fail critical responses with the same display in the simulator.

The results indicate that what drivers say they will do and what they actually do in the driving environment are not always consistent. This is evidence to suggest that the PPLT indication is only one of many elements that the driver takes into account when making left-turn decisions. This result also explains why low level of comprehension related to the green ball permissive indication is not consistent with left-turn crash frequencies.

Table 29 Percent of Correct Responses from Simulator and Static Evaluations

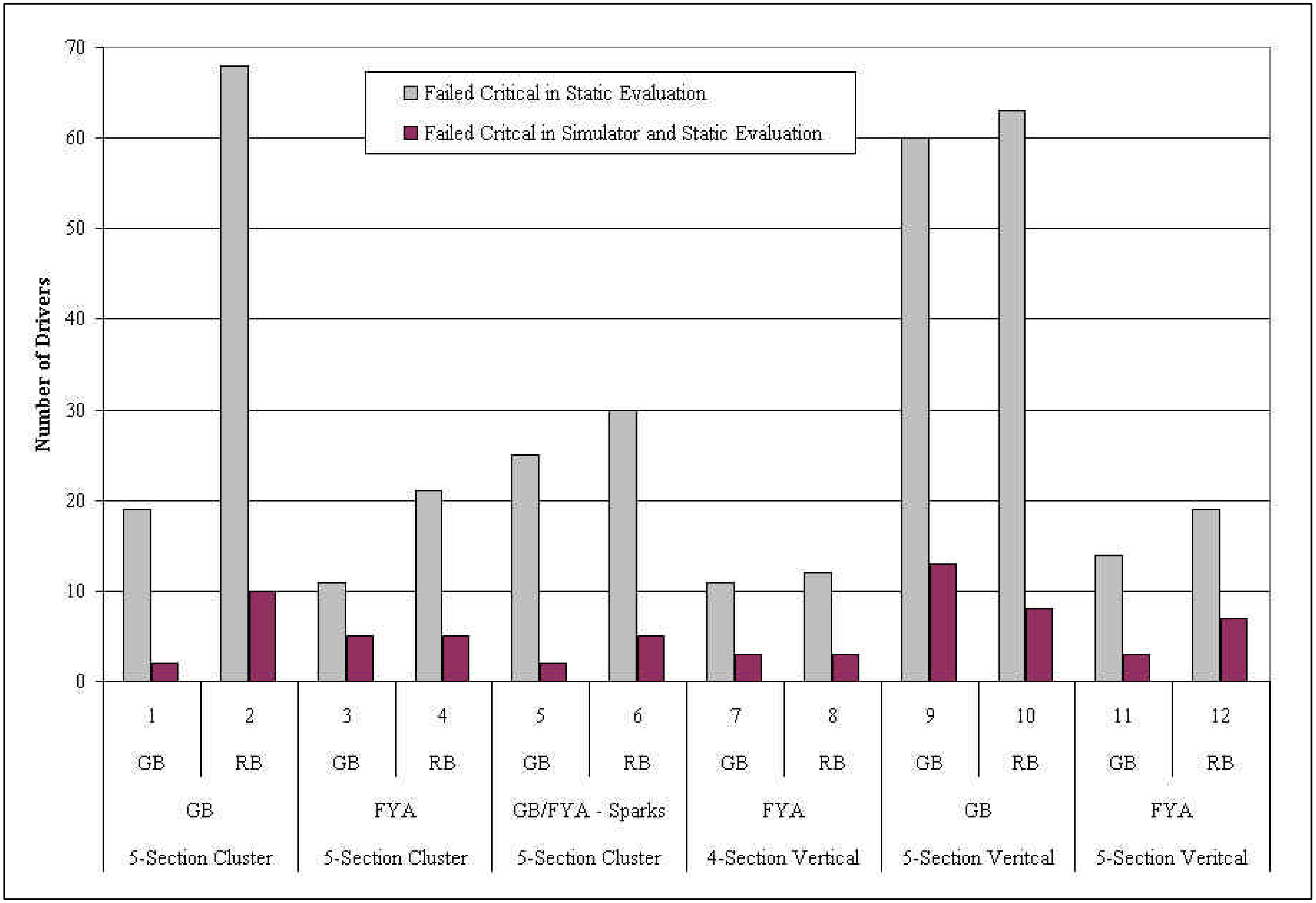
Sc[a]	Arrangement[b]	Per Ind[c]	Thru Ind[d]	Data Set					
				Simulator			Static		
				Obs[e]	Percent Correct[f]	95% C.I.	Obs[e]	Percent Correct[f]	95% C.I.
1	5-section cluster	GB	GB	279	90	4	436	83	3
2	5-section cluster	GB	RB	286	93	3	436	73	4
3	5-section cluster	FYA	GB	282	90	3	436	88	3
4	5-section cluster	FYA	RB	285	90	4	435	81	4
5	5-section cluster	GB/ FYA	GB	286	94	3	435	87	3
6	5-section cluster	GB/ FYA	RB	279	90	4	436	83	4
7	4-section vertical	FYA	GB	281	92	3	436	89	3
8	4-section vertical	FYA	RB	288	91	3	436	84	3
9	5-section vertical	GB	GB	290	92	3	436	79	4
10	5-section vertical	GB	RB	281	91	3	436	75	4
11	5-section vertical	FYA	GB	289	89	4	436	89	3
12	5-section vertical	FYA	RB	276	90	4	436	83	3

[a] Scenario identification number
[b] PPLT signal display arrangement
[c] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Number of observations
[I] Percent correct

Table 30 Percent of Fail Critical Responses from Simulator and Static Evaluations

Sc[a]	Arrangement[b]	Per Ind[c]	Thru Ind[d]	Data Set					
				Simulator			Static		
				Obs[e]	Percent Fail Crit[f]	95% C.I.	Obs[e]	Percent Fail Crit[f]	95% C.I.
1	5-section cluster	GB	GB	279	4	2	436	10	3
2	5-section cluster	GB	RB	286	6	3	436	22	4
3	5-section cluster	FYA	GB	282	8	3	436	4	2
4	5-section cluster	FYA	RB	285	8	3	435	7	2
5	5-section cluster	GB/ FYA	GB	286	5	3	435	9	3
6	5-section cluster	GB/ FYA	RB	279	9	3	436	13	3
7	4-section vertical	FYA	GB	281	7	3	436	5	2
8	4-section vertical	FYA	RB	288	8	3	436	5	2
9	5-section vertical	GB	GB	290	7	3	436	19	4
10	5-section vertical	GB	RB	281	8	3	436	23	4
11	5-section vertical	FYA	GB	289	9	3	436	5	2
12	5-section vertical	FYA	RB	276	9	3	436	7	2

[a] Scenario identification number
[b] PPLT signal display arrangement
[c] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[d] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[e] Number of observations
[f] Percent of fail critical type responses



[a] Scenario identification number
[b] Indication for adjacent through lanes
[c] Left-turn permissive indication
[d] PPLT signal display arrangement

Figure 24 Comparison of Fail Critical Responses in Simulator and Static Evaluation by Driver

9.0 SUMMARY OF FINDINGS

Task 10 of this research study focused on 12 PPLT signal displays identified by previous research efforts where by driver comprehension information was needed before any recommendations could be made. This research study task studied 12 PPLT displays, which are summarized in Table 31. A total of 464 drivers participated in the experiment, yielding 4,613 individual evaluated PPLT scenarios (5,230 PPLT scenarios with the static evaluation). A summary of findings is presented below.

Driver comprehension was evaluated using two full-size driving simulators and a video-based static evaluation. More specifically, driver comprehension was determined from the distribution of correct and incorrect responses for each of the selected PPLT signal displays. Several categories of incorrect responses were used to further evaluate this data. Standard ANOVA techniques were used on all collected data to determine statistical significance.

Table 31 PPLT Signal Displays Evaluated

Sc[a]	Left-Turn Display			Through Movement Display		
	Arrangement	Permissive Indication[b]	Location	Arrangement	Permissive Indication[b]	No. of Displays
1	5-section cluster	GB	Shared	3-section vertical	GB	1
2	5-section cluster	GB	Exclusive	3-section vertical	RB	2
3	5-section cluster	FYA	Shared	3-section vertical	GB	2
4	5-section cluster	FYA	Shared	3-section vertical	RB	2
5	5-section cluster	FYA/GB	Exclusive	3-section vertical	GB	2
6	5-section cluster	FYA/GB	Exclusive	3-section vertical	RB	2
7	4-section vertical	FYA	Exclusive	3-section vertical	GB	2
8	4-section vertical	FYA	Exclusive	3-section vertical	RB	2
9	5-section vertical	GB	Exclusive	3-section vertical	GB	2
10	5-section vertical	GB	Exclusive	3-section vertical	RB	2
11	5-section vertical	FYA	Exclusive	3-section vertical	GB	2
12	5-section vertical	FYA	Exclusive	3-section vertical	RB	2

[a] Scenario identification number
[b] Permissive Indication; GB = green ball, FYA = flashing yellow arrow, RB = red ball

9.1 Driving Simulator

The findings of the driving simulator experiment, including 348 drivers and 3,402 PPLT display evaluations, include:

- In the aggregate, the data also showed a high level of comprehension with no variation between the different PPLT displays tested.
  - Drivers responded correctly 91 percent of the time with no statistical difference between the 12 PPLT displays (Table 13).
- The data showed no statistical difference in driver comprehension when the data was cross-analyzed by permissive indication, arrangement, through indication, and location of the display (Table 14).
  - There was no statistical difference in permissive indication (GB, FYA, GB/FYA), signal head arrangement (five-section cluster, four-section vertical, or five-section vertical), PPLT display location (shared or exclusive), or adjacent through indication (GB or RB)(Table 14). Additionally, there were no significant differences by the various PPLT display components in terms of the percentage of fail critical responses (Table 16).
- The data showed no statistical difference between in driver comprehension when the data was analyzed by sex, age, number of miles driven annually, or education (Table 15).
- The data showed that there is a statistical difference in driver comprehension by sex and age.
  - The data was further cross-analyzed considering of the combined effect of age and sex. In this analysis, there was a statistically significant difference between the three age groups within the female drivers (Table 16).
- The data showed that TTI drivers had a slightly higher level of understanding (overall) as compared to UMass drivers.
  - The data was cross-analyzed between data from TTI and data from UMass (Table 15). This analysis would suggest differences by geographic location. The data shows that the TTI drivers responded correctly 93 percent of the observations, compared to UMass drivers responding correctly 90 percent of the time. The data supports a statistically significant difference ($p=0.012$); however when the data were more appropriately expanded across the 12 experimental PPLT signal displays, there was no statistically significant differences ($p=0.572$).

- o Males and females had statistically equivalent levels of comprehension.
    - There were no statistically significant differences in the percentage of correct or fail critical responses across the 12 PPLT signal displays evaluated.
- o The age demographic resulted in statistically significant differences.
    - Drivers in the over 45 age category had significantly fewer fail critical responses. Overall older drivers were more cautious in the driving simulator experiment often opting to wait for all opposing vehicles to pass before completing the permissive left-turn maneuver.
- o Drivers that had driven between 10,000 and 20,000 miles in the previous year had significantly more correct responses and significantly fewer fail critical responses than drivers with under 10,000 miles driven in the previous year.
- o Education level of the drivers was not statistically significant in determining comprehension levels.
    - However, PPLT scenario three (five-section cluster in a shared location with a FYA permissive indication and GB through indication) had a significantly higher correct response rate by drivers with only a high school diploma than drivers with a higher education level.
- o Analyzing the first observed PPLT display encountered by each of the 316 drivers resulted in some significant differences in comprehension.
    - The percent of correct responses was not significantly different across the 12 PPLT signal displays; however there were significantly more fail critical responses at PPLT scenario three (five-section cluster in a shared location with a FYA permissive indication and GB through indication) than scenario one (five-section cluster in a shared location with a GB permissive indication and GB through indication) when they were the first observed PPLT signal display. Note that the five-section cluster with GB permissive indication and GB through indication is commonly used in both Massachusetts and Texas, and it is reasonable to assume that drivers had encountered this display prior to participating in the experiment.
- o A violation of driver expectancy may have resulted in a higher level of incorrect responses at displays with alternative permissive indications as they were initially observed in the simulator experiment.

- Drivers from Massachusetts and Texas have typically only encountered the GB permissive indication and green arrow protected indication. Based on several drivers' comments as they approached the first displays containing the FYA permissive indication, they initially assumed the indication to be a protected green arrow and assumed the right-of-way. Only after making a fail-critical error did they correctly determine that the display was indeed not a green arrow.

9.2 Static Evaluation

The findings of the video-based static evaluation, considering 436 drivers and 5,230 PPLT displays, include:

- Overall the comprehension was high as 83 percent of 5,230 scenarios were evaluated correctly.
  - The percent of correct responses was 83 percent for all 5,230 scenarios evaluated. Correct responses ranged from 73 to 89 percent and are presented in Table 22 and pictured in Figure 22 for each of the 12 PPLT signal displays. Evaluating the null hypothesis that the percent of correct response for each of the 12 PPLT signal displays were the same, the means were found to be statistically different ($p = <0.001$). In particular, scenarios three (five-section cluster, with FYA permissive indication, and GB through indication), five (five-section cluster, with GB/FYA permissive indication, and GB through indication), seven (four-section vertical, with FYA permissive indication, and GB through indication) and 11 (five-section vertical, with FYA permissive indication, and GB through indication) had significantly high percentages of correct responses. By comparison, displays two (five-section cluster, with GB permissive indication, and RB through indication) and 10 (five-section vertical, GB permissive indication, and RB through indication) had significantly low levels of correct responses.
- A significantly amount of fail critical responses are generated from three scenarios, each of which contain the GB permissive indication.
  - Displays two (five-section cluster arrangement, GB permissive indication, and RB through indication), nine (five section vertical, GB permissive indication, and GB through indication), and 10 (five section vertical, GB permissive indication, and GB

through indication) were each associated with significantly more *go, you have the right-of-way responses.*

- The permissive indication resulted in statistically significant differences of correct and fail critical responses.
    - Displays with the FYA permissive indication and the GB/FYA simultaneous permissive indication had significantly more correct responses than displays with the GB permissive indication (Table 26). Additionally, displays with the GB permissive indication were associated with significantly more fail critical responses than displays with either the FYA or GB/FYA permissive indications.
- PPLT displays with the four-section vertical arrangement had a significantly higher amount of correct responses (Table 26).
    - It is important to note that only the FYA permissive indication was evaluated in this arrangement, and it is likely this combination attributes for the increased percentage of correct responses.
- Displays with the RB through indication resulted in a significantly lower percent correct response rate than displays with the GB through indication.
    - PPLT displays with the RB through indication also resulted in significantly more fail critical responses. This may be attributed to the fact that the practice of using RB through with a permissive left-turn indication is not used in Massachusetts or most of Texas.
- The location of the PPLT signal display did not result in statistically significant differences.
- Divers participating in the experiment at TTI had significantly more correct responses than drivers participating at UMass.
- Statistically significant differences were observed in within age, education, and driving experience demographics.
    - Drivers over the age of 45 had a significantly lower comprehension of the PPLT signal displays. Drivers with only a high school diploma had a significantly lower comprehension than driver with a higher education level. Interestingly, drivers with between 10,000 and 20,000 miles driven in the previous year had significantly more correct responses than both drivers with under 10,000 miles driven and drivers with over 20,000 miles driven in the previous year.

9.3 Driving Simulator and Static Evaluation

Combining results of both the driving simulator experiment and video-based static evaluation has led to the following conclusions:

- Driver comprehension in the simulator experiment was significantly higher than the static evaluation.
    - The results indicate that what drivers say they will do and what they actually do in the driving environment are not always consistent. The biggest inconsistencies occurred for displays with the GB permissive indication. In the simulator experiment, the four scenarios with the GB permissive indication resulted in fail critical responses six percent of the time. By contrast the same four scenarios in the static evaluation resulted in fail critical responses 19 percent of the time.
- Inconsistencies between responses in the driving simulator and static evaluation for displays with the GB permissive indication are cause for concern.
    - Although drivers provided with dynamic cues, which are present in the simulation, are correctly able to interpret the GB permissive indication, there is reason to believe drivers do not have a good understanding of the GB permissive indication. Specifically, drivers observing the GB permissive indication in the static evaluation were more likely to make fail-critical responses. Evidence suggests that the PPLT indication is only one of many elements that the driver takes into account when making left-turn decisions. This result also explains why low level of comprehension related to the green ball permissive indication is not consistent with left-turn crash frequencies.
- In the simulator experiment, the through indication had little effect on driver comprehension, while in the static evaluation the RB through indication resulted in lower comprehension levels.
    - Based on driver comments throughout the entire experiment, drivers often did not observe the through indication in the simulator, but noticed the through indication in the static evaluation.
- Comparing all types of responses in both of the experiments, it can be said that many drivers base their left-turn decision on surrounding traffic, specifically the opposing traffic, instead of the signal indication. This may be due to a lack of driver understanding of the indication.

9.4 Results

The results of this study found that the flashing yellow arrow permissive indication was equally understood (measured in terms of correct responses to questions presented) as the circular green indication. There was no significant difference in drivers correctly interpreting the meaning the flashing yellow arrow indication, compared to the circular green indication. The data demonstrated that drivers understanding of the flashing yellow arrow display increased with exposure. Finally, the flashing yellow arrow display showed a higher fail-safe response compared to the circular green indication. Given the fact that the circular green has higher fail critical rates, with consistent levels of comprehension, one can conclude that the flashing yellow arrow can be beneficial in improving the safety of PPLT.

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