Driver Understanding of the Green Ball and Flashing Yellow Arrow Permitted Indications: A Driving Simulator Experiment

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ABSTRACT

This paper identifies the use of a driving simulator located at the University of Massachusetts to study the green ball and flashing yellow arrow permitted indications in protected/permitted left-turn (PPLT) signal displays. The circular green ball indication is the MUTCD standard to convey the meaning of a permitted [e.g., left-turn] movement at signalized intersections. A key study task in the National Cooperative Highway Research Program (NCHRP) Project 3-54 research (Evaluation of Traffic Signal Displays for the Protected-Permitted Left-Turn Control) is to evaluate the green ball and flashing yellow arrow permitted indications. This paper presents a brief background on the research project and preliminary results of 211 subjects.

INTRODUCTION

The left-turn maneuver is widely recognized by both drivers and traffic engineers as one of the most difficult to safely execute at signalized intersections (*1)*. Driver confusion in and around the approximately 300,000 signalized intersections in the United States is responsible for an increase in both delay and crash potential. Safely and efficiently accommodating left-turning vehicles at signalized intersections is a source of concern for traffic engineers, and this concern has resulted in the utilization of several unique traffic engineering practices. Although dedicated turn lanes and protected left-turn phases have helped to improve intersection operation and safety, it has been at the expense of intersection efficiency; dedicated turn lanes require precious intersection space, while the time provided for an exclusive left-turn phase must be taken away from other critical movements at the intersection. To improve intersection efficiency, protected/permitted left-turn (PPLT) signal phasing was developed.

PPLT signal phasing provides a protected phase for left-turns as well as a permitted phase during which left-turns can be made if gaps in opposing through traffic allow, all within the same signal cycle (*1*). One of the goals of PPLT signal phasing is to minimize the exclusive left-turn phase time requirements while increasing the opportunity for left-turn maneuvers. The utilization of PPLT signal phasing can lead to increased left-turn capacity and reduced 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. As appropriate additional information may be provided to the driver in the form of supplemental signage. 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. In recent years, a variety of adaptations of PPLT arrangements have been established throughout the United States because of concern over driver's understanding of the permitted indication and because the MUTCD has provided only limited guidance for PPLT applications. The variability in PPLT arrangements and indications has contributed to the lack of a uniform national standard for PPLT control (*1)*.

In an effort to evaluate driver's comprehension of the various PPLT signal displays in use, several study methods have been employed. Commonly, pen and paper comprehension tests are used in which the driver simply marks what he/she believes to be the correct answer. The critique of this methodology has focused on the belief that the study responses provided might not be consistent with the decision made in the actual driving environment. To add more realism to the experiment, computer technology has been employed by providing static photos of actual driving environments and superimposing PPLT signal displays within. 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.

This paper describes the use of a full-scale dynamic driving simulator as a tool for evaluating driver comprehension of PPLT signal displays. Driving simulation places drivers in a fully interactive dynamic scenario just as if they were actually driving. To test the effectiveness of the simulator, driver comprehension was evaluated for selected PPLT signal displays using both the driving simulator located in the Human Performance Laboratory on the University of Massachusetts (UMass) campus and a computer-based static survey instrument. A comparison of a data sets collected using the driving simulator and static survey is presented.

BACKGROUND

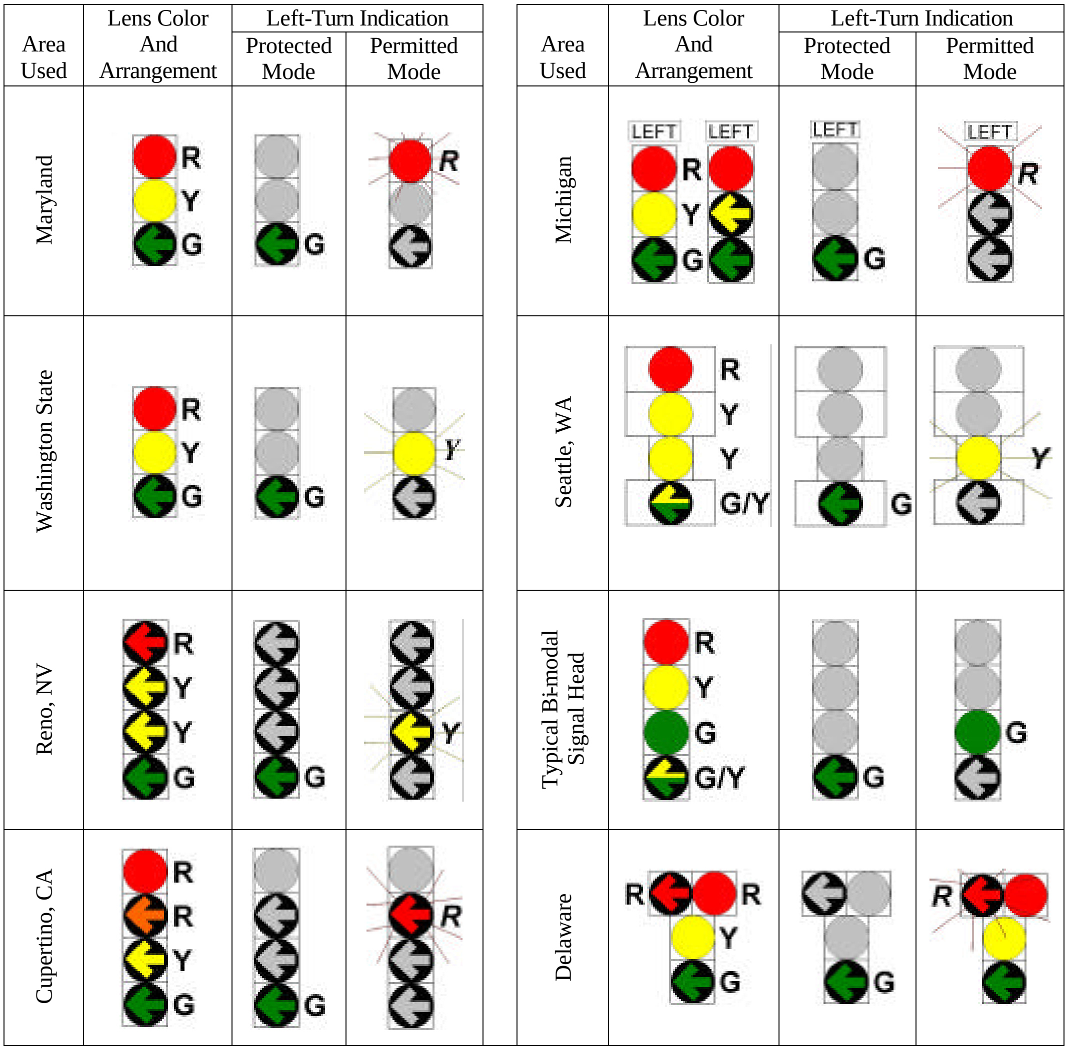
With the usage of PPLT displays to convey intended messages to the drivers at signalized intersections, driver comprehension must be maximized to obtain the potential benefits of PPLT display, including both safety and efficiency. Ongoing research has identified at least seven unique combinations of PPLT signal displays and permitted indications in the United States (*1*). Figure 1 represents several of the unique displays currently used. These unique combinations are in addition to the various arrangements of 5-section displays using the circular green permitted indication. Some transportation professionals have argued that the variability in PPLT display arrangements and the green ball permitted indication may provide a safety problem. This is especially true for the green ball permitted indication because of the potential for confusing it's meaning. In accordance with the MUTCD, a driver with a circular green indication traveling through an intersection has the right-of-way; however, a driver in a left-turn lane with the same circular green indication is required to yield the right-of-way to opposing traffic, and is permitted to proceed should a sufficient gap allow (*2*).

Driving simulation provides a vastly improved mechanism for conducting driver behavior and comprehension research. Presently, at least 40 known driving simulators are located at research institutes throughout the world (*3)*. Although research conducted in the actual driving environment is considered to be optimal, the use of a driving simulator allows for multiple variables and scenarios to be evaluated in a more timely and cost effective manner without losing the *field* credibility.

Several studies with left-turn applications have been conducted using various forms of driving simulation. Staplin conducted an experiment using simulation comparing the willingness of drivers to select a left-turn gap for drivers traveling at 30 and 60 mph (*4*). The study recorded driver information using a 20-inch monitor, a large screen video projector, and a large screen cinematic display. Additionally, he conducted actual field tests for comparative purposes. Staplin found that only the large screen cinematic display corroborated what was occurring in the field, for which the minimum gap length increased as the speed increased. In conclusion, Staplin reported that higher levels of realism provided by the large screen medium provided more accurate results consistent with the driving environment (*4*).

Smith tested driver comprehension of five-section PPLT displays with varying permitted indications using both a driving simulator and a static survey instrument (laptop computer) (*5)*. Smith concluded that the added level of realism provided in the simulation experiment appeared to provide drivers with cues consistent with those found on the roadway. Additionally, drivers often base their left-turn decision on the actions of opposing traffic. The driving simulator was effective in the evaluation of driver comprehension of PPLT signal displays (*5)*.

One concern with simulator experiments is the potential of simulator sickness, which has been likened to motion sickness. The U.S. Army Research Institute for the Behavioral and Social Sciences (ARI) conducts research to improve the effectiveness of training simulators and simulations (*6)*. The Army uses simulation to assist in the training of soldiers fighting from vehicles. They have recently completed an extensive literature 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 it 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" (*6*).



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

* The indication illuminated for the given mode is identified by the color letter

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

RESEARCH PROCEDURES

Development of Simulated PPLT Signalized Intersections

A "visual world" of intersections was developed for use within the driving simulator at UMass. The driving simulator is comprised of a full-sized Saturn Sedan as pictured in Figure 2. Three separate images are projected to create the visual world on three large projection screens that form a large semi-circular wall subtending a 150-degree field-of-view for the driver.

The PPLT signal displays selected for this research have evolved from previous research projects focused on the evaluation of PPLT signals. Ongoing National Cooperative Highway Research Program (NCHRP) 3-54(2) project research identified a set of 12 different PPLT signal displays in which driver comprehension information was desired. The selected displays differed in, arrangement, through movement indication, and placement (signal display placed over center of left-turn lane or between left-turn lane and adjacent through lane). Displays also differed in permitted indication as both the green ball and flashing yellow arrow permitted indications were evaluated. The green ball permitted indication represents MUTCD guidelines, while the flashing yellow arrow permitted indication is one which several traffic engineers have experimented with. Figure 3 provides a visual representation of the PPLT displays evaluated in the driving simulator.

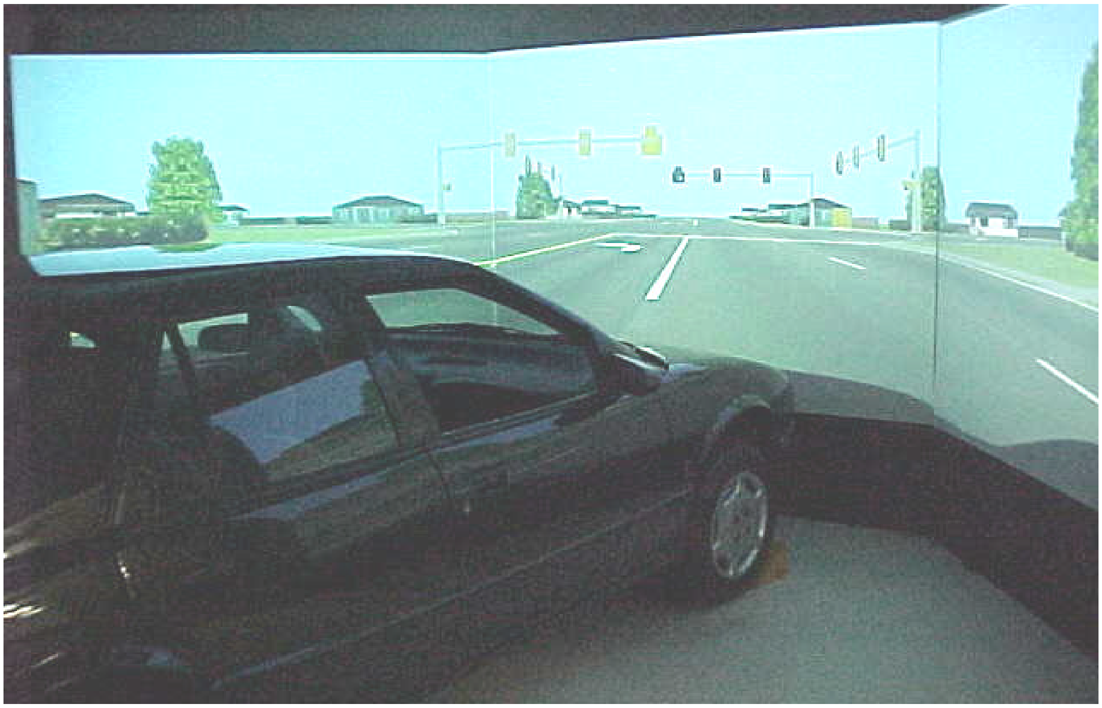


Figure 2 Driving Simulator at UMass

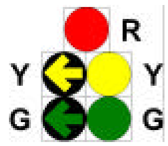
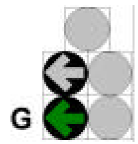
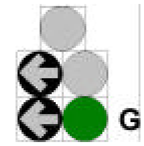
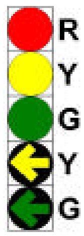
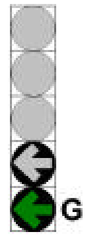
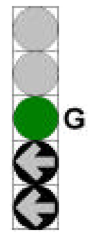
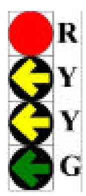
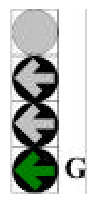
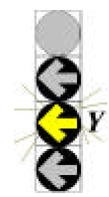
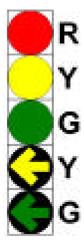
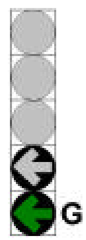
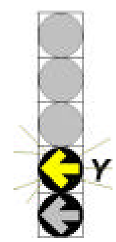
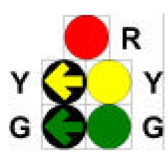
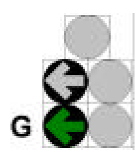
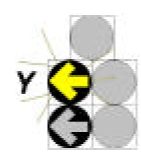
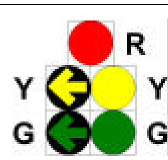
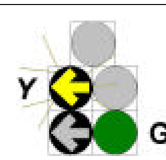
Scenario	Lens Color and Arrangement	Left-Turn Indication*	
		Protected Mode	Permitted Mode
1,2			
3,4			
5,6			
7,8			
9,10			
11,12			

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Figure 3 PPLT Displays to be Evaluated

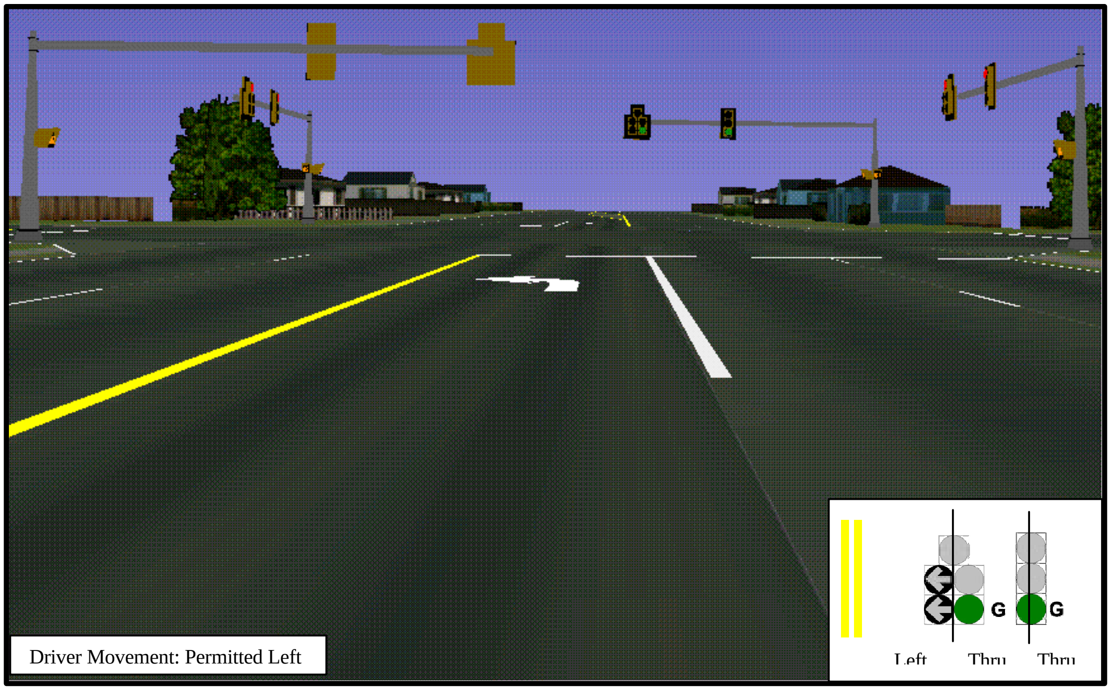

Figure 4 Screen Capture of Typical Intersection in Simulation.

One intersection approach was created for each of the 12 selected PPLT signal displays. Figure 4 depicts a typical intersection in the 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 world. The through and right turn movements were included to provide experimental variability and reduce the probability of the subject driver keying into the nature of the evaluation. Additional variability was provided through the creation of four driving modules and six starting positions. Drivers observed each of the 12 experimental displays once by traversing two of the four modules. The four modules could be presented in eight different orders, and combined with six different starting positions within each module to create 48 unique module order and starting point combinations.

All signal displays within the simulation rested in red (both PPLT and through display showing a red ball indication. Approximately 30 meters prior to the intersection stop bar, the PPLT signal display was "triggered" and changed from a red ball indication to the selected *test* permitted indication. A second trigger was placed at the left-turn stop bar at each PPLT intersection to release the opposing traffic. By placing the opposing traffic release trigger at 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.

Each of the PPLT signal displays were evaluated with opposing traffic at the intersection. The introduction of opposing traffic required drivers to simultaneously evaluate the PPLT signal display, traffic movement, and opposing gaps to complete a safe permitted left-turn maneuver. This methodology was used to replicate the decision process required during actual operation of a motorized vehicle within the roadway system. All gaps in opposing traffic were consistently applied at intersections which drivers were required to make a PPLT maneuver.

Simulator Experiment

Once the consent of subject drivers was given, drivers were seated in the simulator and given a specific set of instructions regarding the procedure. After completing a short practice course, the driver follows a course through two modules. Each module contained 14 intersections, six of which contained study PPLT displays. Two modules were used to present all 12 PPLT displays.

The driver's response to each PPLT signal display scenario was manually recorded. Correct responses were recorded accordingly and incorrect responses were identified as *fail-safe* or *fail-critical*. A *fail-safe* response was one in which the driver did not correctly respond to PPLT signal display arrangement/permitted indication combination, 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 arrangement/permitted indication combination and impeded the right-of-way of opposing traffic, creating the potential for a crash.

Follow-Up Static Survey

After completing the driving modules, drivers were asked to move from the vehicle to a nearby table and chair where they were presented with each of PPLT signal displays in a static mode. The static survey was administered using videocassette recordings of the screen captures for the 12 PPLT displays. Each display was shown for 30 seconds during which time the subject was asked the following question:

"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?"

The subjects were then asked to respond with one of four choices, which were as follows:

- 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.

Elements of randomness and counterbalancing of experimental measures were again implemented at this stage of the experiment. The key difference in this evaluation was the lack of dynamic cues and associated workload of being in the simulated driving environment.

RESULTS

Two hundred eleven subjects participated in the driving simulator experiment at UMass. Each driver observed 12 PPLT displays, generating a total of 2,532 data points from which 2,313 were analyzed. Several data points were lost due to uncompleted experiments or erroneous results. The driver sample was comprised of 108 males and 103 females ranging in age from 18-70.

As noted, three categories (correct, fail-safe, and fail-critical) of driver responses were used to evaluate the results of the simulator experiment. Within the three categories, six potential responses were identified by the research team as summarized in Table 1.

Table 1 Responses at PPLT Displays

Response Number	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		By movement	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 (only a good defensive maneuver prevented a crash)
6		Serious	Go through intersection incorrectly taking the right-of-way from opposing traffic

Figures 5 presents the breakdown of responses to each of the 12 PPLT displays evaluated in the driving simulator experiment. Correct responses ranged from 71 to 79 percent, and the range of *fail-critical* errors was from 5 to 11 percent. Overall the most common type of error was a *fail-safe by traffic* maneuver, which indicates drivers elected to wait for all opposing traffic to pass before proceeding. Although gaps of sufficient size were presented to the drivers, many drivers elected not to proceed. Subject drivers commented that their reason for rejecting all gaps and waiting for all opposing traffic to clear was their uncertainty of the speed of the opposing traffic. Drivers also realized that no potential conflicts existed once the opposing traffic had cleared. Based on this debriefing exercise, it is fair to say that many drivers based their left-turn decision on the opposing traffic stream rather than the PPLT display/indication.

One hundred ninety-six of the 211 drivers also completed the static survey, from which 2,352 PPLT scenarios were evaluated. Drivers were given four possible choices, and a breakdown of responses is shown in Figure 6. Similar to the driving simulator, the correct response for each PPLT display was *yield, then go if a gap in the opposing traffic allows*. Correct responses in the static survey ranged from 51 to 70 percent. The range of *fail-critical* errors was from 3 to 27

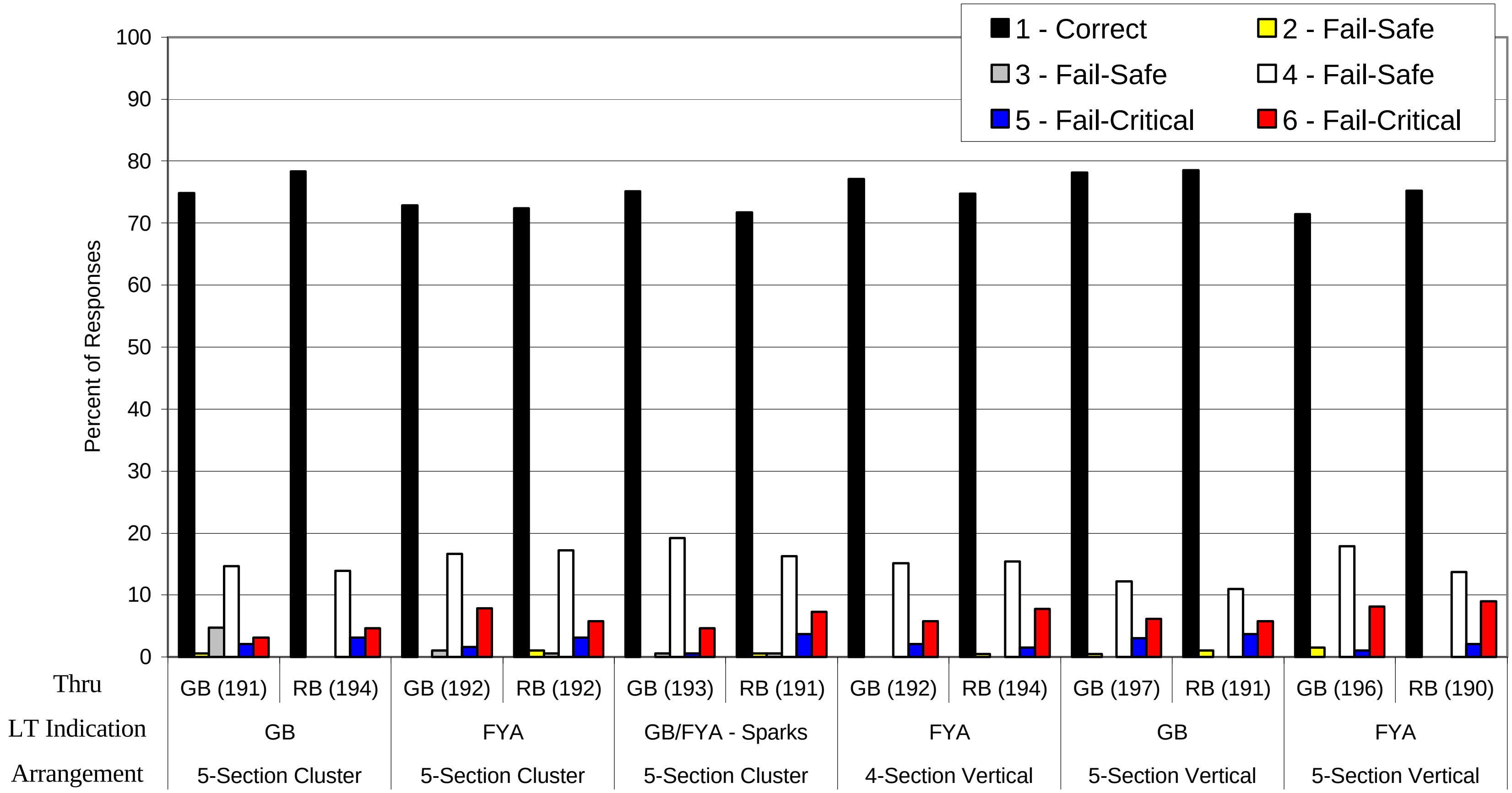

Figure 5 Driving Simulator Results for 211 Subjects.

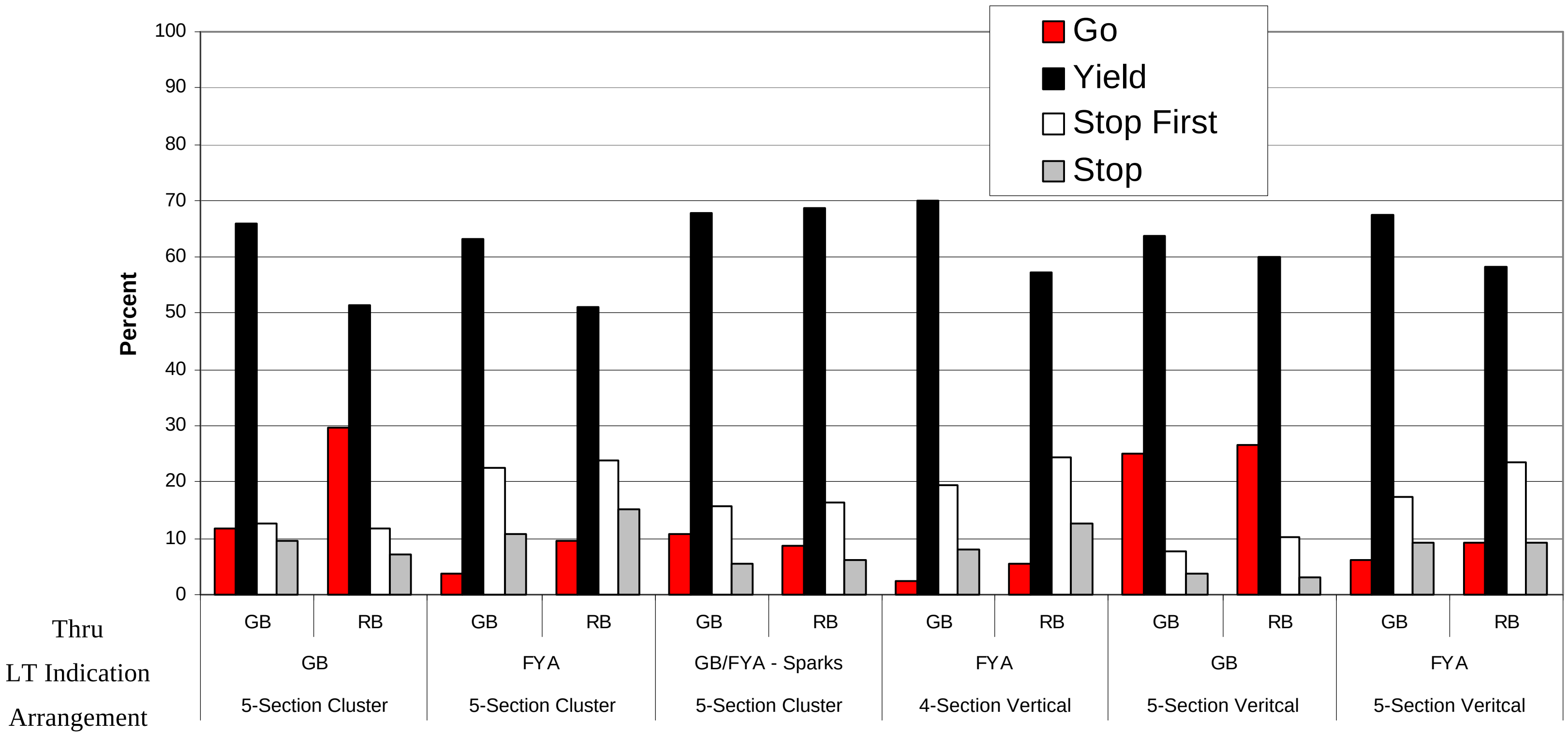

Figure 6 Static Survey Reponses for 196 Subjects.

percent. For each of the displays including a flashing yellow arrow permitted indication, the *stop first, then go if a gap in the opposing traffic allows* choice was the most common error. For displays with the green ball permitted indication, the most common error was the *go, you have the right-of-way* choice, which was classified as a fail-critical error.

Comparing the simulation results with the static survey results the percentage of correct responses was higher in the simulator experiment for each PPLT display evaluated. This suggests that the driving cues provided to the driver in the simulator experiment may have affected drivers' responses to the PPLT displays, better replicating the real-world driving environment.

CONCLUSIONS

Overall the results obtained from this experiment indicate that the driving simulator is an effective method of evaluating driver comprehension of PPLT displays. The percentage of correct results for the driving simulator study were consistently higher than the static survey results which is believed to support the idea that simulator results are more consistent with the actual driving experiment than static based measures. In the driving simulator experiment there was little difference in the levels of driver understanding between the green ball and flashing yellow arrow permitted indications. Further evaluation of selected PPLT signal displays will be completed in the NCHRP Project 3-54(2) final report.

ACKNOWLEDGEMENTS

The work described in this report was completed at the University of Massachusetts using the driving simulator in the Human Performance Laboratory. The evaluation of PPLT signal displays is being conducted as part of NCHRP Project 3-54(2). The project contractor is Kittelson & Associates, Inc. in Portland, OR. Research work on the project is also being conducted at the Texas Transportation Institute (TTI) and Gardner Transportation Systems. Driving simulator data from both UMass and TTI will be analyzed and evaluated for similarities/differences in driver comprehension across geographic regions.

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