Evaluation of Traffic Signal Displays for Protected-Permissive Left-Turn Control Using Driving Simulator Technology

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ABSTRACT

The objective of this research was to determine the safety and effectiveness of selected protected/permissive left-turn (PPLT) signal displays through driver comprehension evaluations. Driver evaluations were conducted using full-scale, fixed-based, fully-interactive driving simulators located at the University of Massachusetts and the Texas Transportation Institute. PPLT displays were also evaluated in a static environment to provide comparison data.

The 12 experimental PPLT signal displays differed in permissive indication, arrangement, location, and through movement indication. Each of the PPLT signal displays included only the green ball and/or flashing yellow arrow permissive indications. The green ball permissive indication represented the current state-of-the-practice and the flashing yellow arrow permissive indication represented the most promising alternative based on previous research findings.

Driver comprehension was determined from the distribution of correct and incorrect responses. Findings from the driving simulator study showed a high level of comprehension (91 percent) with no variation between PPLT displays tested. No statistically significant difference in driver comprehension existed when the data were cross-analyzed by permissive indication, arrangement, through indication, and location of the display. The lack of significant differences in driver comprehension is in itself a significant finding, indicating the flashing yellow arrow is a viable alternative to the green ball permissive indication.

Correct responses in the static evaluation ranged from 73 to 89 percent, with the flashing yellow arrow permissive indication outperforming the green ball. Responses in the driving simulator data sets generally exhibited significantly higher correct response rates than the static evaluation, indicating that what drivers say they will do and what they actually do in the driving environment are not always consistent.

Keywords: Protected/Permissive Left-Turn, Driving Simulation, Safety, Signal Display, Driver Behavior

INTRODUCTION

Because the Manual on Uniform Traffic Control Devices (MUTCD) provides limited guidance for protected/permissive left-turn (PPLT) applications, a variety of adaptations of PPLT arrangements and indications have been established throughout the U.S. (*1*). Many states have adopted either the five-section cluster (doghouse), horizontal, or vertical display, providing a green arrow for the protected phase and a circular green (green ball) for the permissive phase. Problems with PPLT signal phasing, primarily related to the green ball permissive indication, have been identified but not resolved (*2*, *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 PPLT permissive indications. 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 U.S. that may confuse drivers and lead to inefficient and unsafe operations.

Past research has focused on driver comprehension with the objective of identifying which display(s), when presented to drivers, 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 drivers' 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 *(2)*. 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 scenario just as if they were actually driving. To date, a large sample study of drivers' comprehension of various PPLT signal displays using a driving simulator has not been completed.

RESEARCH OBJECTIVES

The objective of this research was to evaluate the safety and effectiveness of selected PPLT signal displays through driver comprehension evaluations. The driver evaluation described in this paper was conducted using driving simulators located at the University of Massachusetts – Amherst (UMass) 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.

SIGNAL DISPLAYS

Twelve different PPLT signal displays were identified for further evaluation (*4*). 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 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 previous research finding. Figure 1 depicts each of the PPLT signal displays evaluated.

BACKGROUND

The literature pertaining to PPLT signal displays and phasing has been well documented as part of National Cooperative Highway Research Program (NCHRP) project 3-54 (*2, 3*). NCHRP 3-54(2) is an on-going research project with the objective of evaluating the safety and effectiveness of different signal displays used with PPLT control.

A recent study of five-section PPLT signal displays using driver simulator technology provided additional insight (*5*). 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 (*5*). Evaluating the green ball, flashing yellow ball, flashing yellow arrow, flashing red ball and flashing red arrow permissive indications, 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 a protected movement. Furthermore, the 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.

METHODOLOGY

The objective of this research was to evaluate driver's comprehension of the most promising types of PPLT signal displays using full-scale driving simulators. Presently, almost 40 known driving simulators are located at research institutes throughout the world (*6).* Several studies of drivers and left-turn operations have been completed using simulator technology (*7, 8*).

Similar driving simulators at UMass and TTI were used to complete the experiment. Both simulators used were fixed-base fully-interactive dynamic driving simulators in which 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. The vehicle base of both driving simulators is a four-door Saturn sedan. Three separate images are projected to a

large semi-circular projection screen creating a "visual world" field-of-view which subtends approximately 150-degrees. The UMass and TTI driving simulators are each pictured in Figure 2.

Development of Simulation

One intersection approach was created for each of the 12 experimental PPLT signal displays depicted in Figure 1. The characteristics of each approach were identical, thus minimizing confounding variability.

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. Further experimental variability was provided by creating 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, six with experimental displays, within each module. At TTI, each module had six intersections, half of which were experimental displays. Drivers observed each of the 12 experimental displays only once by traversing two modules at UMass and all four modules at TTI.

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 indication either stayed with the red ball indication or changed from a red ball to a green ball indication.

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 operations.

Opposing traffic was presented in predetermined gaps. Six opposing vehicles were used to create this 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 approximately four feet from the left-turn stop bar at each PPLT intersection to release the opposing traffic. This trigger position required drivers to make a decision as to the meaning of the PPLT signal indication and desired action before knowing the actions of the opposing traffic.

Simulation Experimental Procedure

Following completion of a practice course, used to orient drivers to the simulator vehicle, drivers completed the experimental modules. 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' responses to each PPLT signal display scenario were 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.

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 screen captures for the 12 PPLT displays. Each display was shown for 30 seconds during which time the driver was verbally asked the following question:

"You encountered this signalized intersection while driving. 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?"

Drivers were then asked to respond with one of the four following choices:

- 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.

The data were recorded and combined with the driving simulator data to complete the analysis.

Compilation of Experimental Results and Data Analysis

A distribution of correct and incorrect (fail-safe and fail-critical) responses from each experimental methodology were compiled and analyzed. Each methodology (driving simulator and static evaluation) was statistically analyzed using similar procedures. An analysis of variance (ANOVA) procedure was used to evaluate and 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 (*9*).

Further analysis was done by considering the effect of each PPLT display component on driver comprehension. Specifically, the permissive indication, display arrangement, location, and through indication were isolated and analyzed for each response. Additionally, an analysis of the effects of driver comprehension by demographic variables, including sex, age, driving experience, and education levels was completed. Also completed was a comparison of results obtained using each methodology to determine the consistency of driver responses.

RESULTS AND ANALYSIS

Demographics

A total of 464 drivers participated in the experiment. Two hundred thirty-one drivers participated in the study at UMass, and 233 drivers participated at TTI. Potential participants were screened for sex and age (under 25, 25 to 45, or over 45) to assure a representative sample of drivers similar to the driving population. Eight subjects at UMass and 24 subjects at TTI elected to retire from the experiment leaving 432 drivers for analysis.

Originally, researchers wanted to explore the effects of two different opposing traffic strategies, by using one method of opposing traffic at UMass and a second at TTI. After the first 116 subjects at TTI were run, a decision was made to use the same opposing traffic strategies at both study sites. Therefore, 116 drivers at TTI were evaluated separately and are not included within this analysis. The statistical analysis described was based on the results of 223 drivers at UMass and 93 drivers at TTI.

Driving Simulator

Drivers at UMass evaluated 2,528 scenarios with experimental PPLT signal displays, and similarly drivers at TTI evaluated 874 scenarios. Overall, drivers at UMass responded correctly to the PPLT scenarios presented 90 percent of the time compared to 93 percent at TTI. The percentage of correct responses for each of the 12 PPLT signal displays at UMass and TTI are presented in Figure 3. Note that the vertical line segment at the top of the solid bars in Figure 3 represents a 95 percent confidence interval for the results. To compare the data sets, the percent of correct responses was cross-analyzed across each of the 12 experimental displays evaluated by geographic location. The analysis found 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 analysis.

Further evaluations of the data were completed considering independent variables of which the PPLT display is comprised, including the permissive indication, arrangement, location, and through indication. These results are presented in Table 1. Left turn permissive indications were either green ball (GB), flashing yellow arrow (FYA), or a simultaneous combination (GB/FYA) of the two displays referred to as the Sparks display. Arrangements evaluated were either five-section cluster, four-section vertical, or 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, the differences in correct responses as a result of permissive indications was not statistically significant ($p = 0.433$). Similarly, the arrangement of the PPLT signal display was not significant in determining driver comprehension ($p= 0.747$), nor was the through indication ($p = 0.716$) or the location of the PPLT signal display ($p = 0.206$).

Analysis of Incorrect Responses

The incorrect responses were either *fail-safe by movement* or fail-critical. Fail-safe by movement responses occurred when drivers did not correctly respond to PPLT signal display, but did not infringe on the right-of-way of the opposing traffic. Specifically this type of error was a result of drivers stopping and waiting at a permissive indication and waiting for the indication to change before proceeding, often times waiting until researchers ultimately instructed them to continue with the experiment. Fail-critical responses were either *non-serious* or *serious.* A fail-critical non-serious response was one in which no visible stop or yield was made before attempting to proceed through the intersection was made; drivers avoided conflict by stopping short of opposing traffic. Fail-critical serious responses occurred when drivers went through the intersection incorrectly taking the right-of-way from opposing traffic, creating a crash potential. In the event that multiple incorrect actions were made, all were noted, and the result was classified by the most serious infraction.

The summary of incorrect responses is presented in Table 2. In total, fail-safe by movement responses accounted for on average two percent of the responses at each of the experimental displays. 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 ($p = 0.407$).

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 3.

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 ($p = 0.325$), nor were the through indication or PPLT signal display location which did not result in statistically significant differences ($p = 0.134$ and $p = 0.480$, respectively).

Driver Demographics

The analysis was expanded to evaluate the effects of driver demographics on driver comprehension. Specifically, driver comprehension was evaluated based on sex, age, driving experience, and education level. Male and female drivers were stratified into three age groups: under 25, 25 to 45, and over 45. Driving experience was correlated to the number of miles driven in the previous year. Those who drove over 20,000 miles were considered very experienced and those with under 10,000 were considered less experienced. The final

demographic pertained to education. Drivers were asked to indicate the highest level of education they had obtained.

Table 4 presents the overall percent of correct responses, based on the 3,402 scenarios evaluated for each demographic category. Evaluating each of the 12 PPLT signal displays by demographic category found:

- Sex was not significant in determining the percent correct for the PPLT signal displays as values ranged from 87 to 95 percent;
- The proportions of correct responses to each of the 12 PPLT signal displays for each age group yields no significant differences between any of the age groups ($p = 0.650$);
- Annual miles driven demographic provided no significant deviations from the mean ($p = 0.719$). Additionally, none of the data sets differed statistically; and
- Education level was not a significant predictor of percent correct for the overall

Static Evaluation

Four hundred thirty six drivers completed the static evaluation viewing all 12 scenarios. One driver only evaluated 10 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. 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 Figure 4 for each of the 12 PPLT signal displays. A statistically significant difference in driver comprehension was found considering each of the 12 PPLT signal displays, ($p = <0.001$). 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.

Again considering permissive indication, arrangement, location, and through indication as independent variables, the data presented in Table 5 were 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 ($p = 0.003$). 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.

Analysis of Incorrect Responses

A breakdown of incorrect responses yielded statistically significant differences across the 12 PPLT signal displays ($p = <0.001$). Figure 5 presents all of the *go, you have the right-of-way* choices for all 12 PPLT displays. As seen in Figure 5, a significantly higher amount of fail-critical responses are generated from three scenarios. Each of these three scenarios includes the GB permissive indication. Specifically, scenarios 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.*

Comparison of Driving Simulator and Static Evaluation Results

Correct responses in the driving simulator data sets were generally significantly higher than responses in the static evaluation. A direct comparison of responses in the simulator and static evaluations was completed by cross-analyzing individual driver's responses in each methodology. 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 6 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 at the same display in the simulator.

SUMMARY OF FINDINGS

The findings of the driving simulator study 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. No statistically significant difference in driver comprehension was found when the data were cross-analyzed by the PPLT display components including, the permissive indication, arrangement, through indication, and location of the display. Additionally, there were no significant differences by the various PPLT display components in terms of the percentage of fail-critical responses. Analyzing driver comprehension by demographic categories of sex, age, driving experience, and education resulted in no statistically significant findings. The lack of significant differences documented in

this study is in itself a significant finding. The results indicate that the flashing yellow arrow is a viable alternative to the green ball permissive indication.

The results of the video-based static evaluation found that 83 percent of 5,230 scenarios were evaluated correctly. Correct responses ranged from 73 to 89 percent. This result was found to be statistically significant ($p = <0.001$). 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 significant amount of fail-critical responses were generated from three scenarios, each of which contains the GB permissive indication. Scenarios 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.*

Overall, the permissive indication resulted in statistically significant differences of correct and fail-critical responses. Scenarios with the FYA permissive indication and the GB/FYA simultaneous permissive indication had significantly more correct responses than displays with the GB permissive indication. 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 scenarios with the four-section vertical arrangement had a significant amount of correct responses; however, only the FYA permissive indication was evaluated in this arrangement, and it is likely this combination that accounts 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 simultaneous conflicting signal indications (green and red), which even when not in the same signal display, is confusing to drivers. The location of the PPLT signal display did not result in statistically significant differences.

The results of the simulator study and static evaluation indicate 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 the low level of comprehension reported in previous research related to the green ball permissive indication is not consistent with left-turn crash frequencies. What drivers say they will do and what they actually do in the driving environment are not always consistent.

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FIGURES AND TABLES

FIGURE 1 PPLT Displays Evaluated in Driver Simulator Experiment.
FIGURE 2 UMass and TTI Driving Simulators used in the Experiment.
FIGURE 3 Percent Correct for each PPLT Signal Display by Study Location (with 95% C.I.).
FIGURE 4 Percent of Correct Responses (with 95 percent C.I.) for Static Evaluation.
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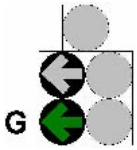
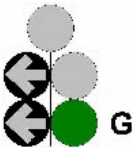
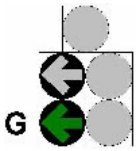
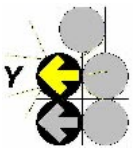
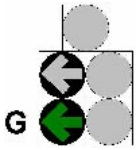
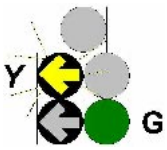
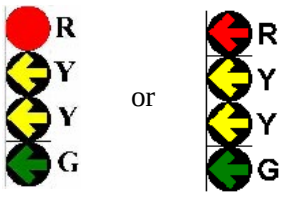
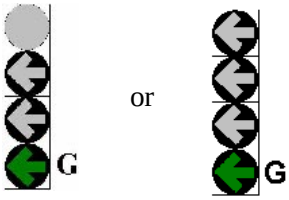
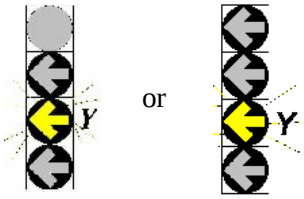
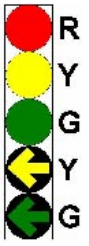
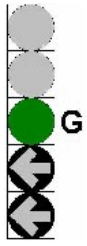
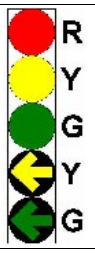
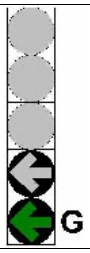
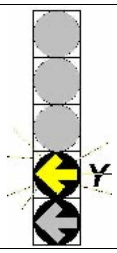
FIGURE 6 Comparison of Fail-Critical Responses in Simulator and Static Evaluation by Driver

TABLE 1 Percent Correct by PPLT Display Component
TABLE 2 Effects of PPLT Display Components on Percent of Fail-Critical Responses
TABLE 3 Breakdown of Incorrect Responses
TABLE 4 Overall Percent Correct in Simulator by Demographic Category
TABLE 5 Effects of PPLT Display Components on Percent Correct in Static Evaluation

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			

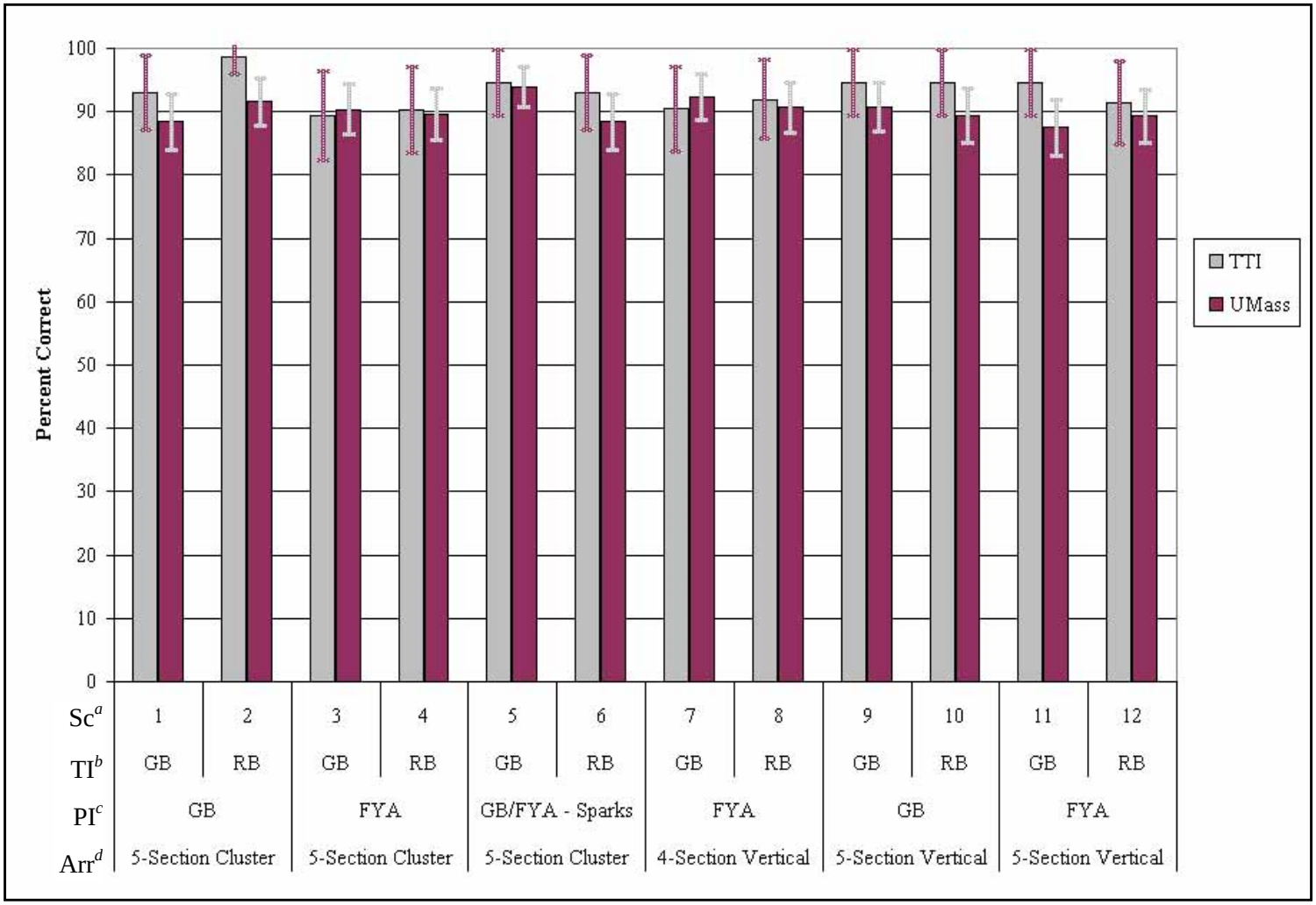
R = RED Y = YELLOW G = GREEN *Y* = FLASHING YELLOW

[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

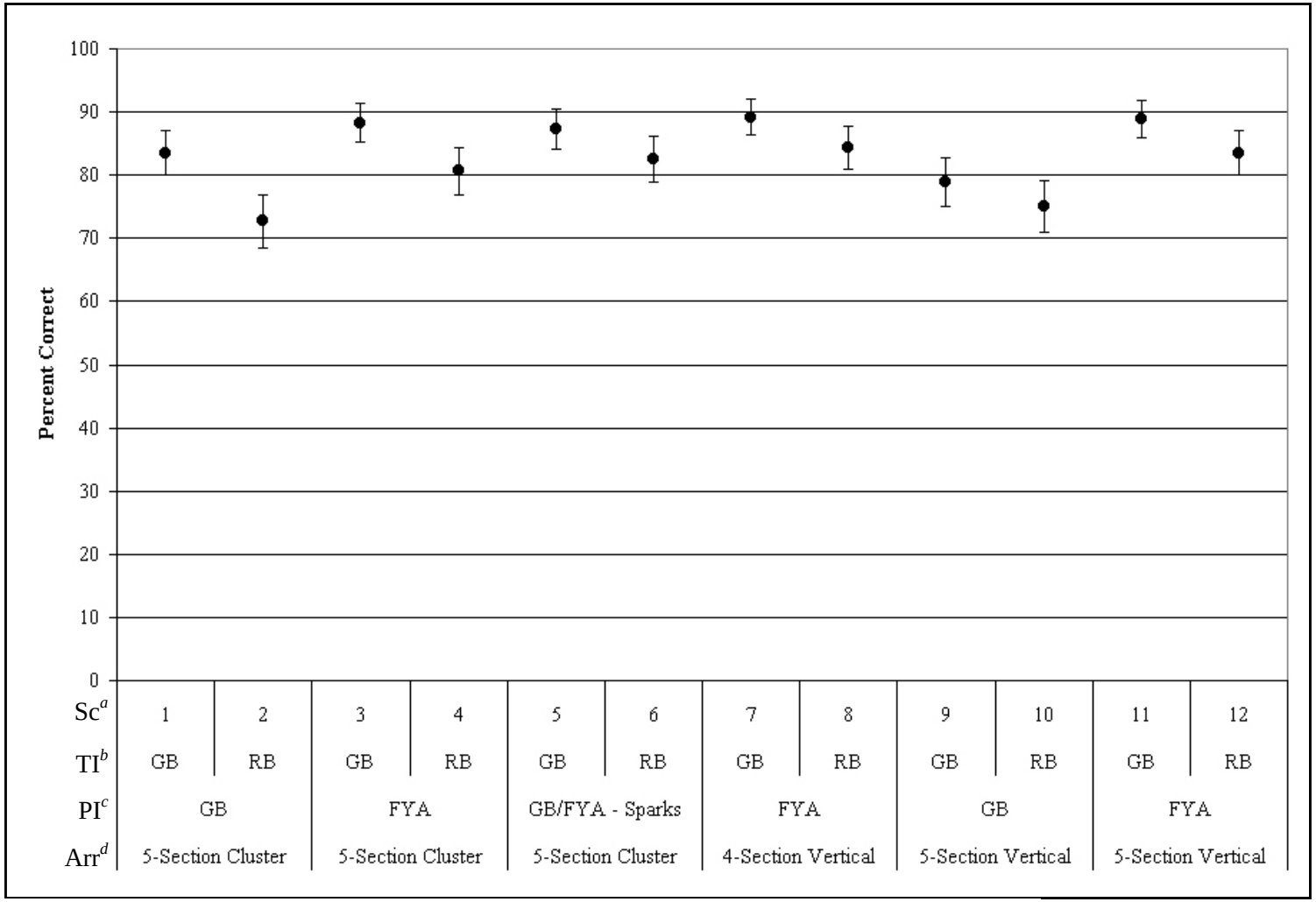
FIGURE 1 PPLT Displays Evaluated in Driver Simulator Experiment.

FIGURE 2 UMass and TTI Driving Simulators used in the Experiment.



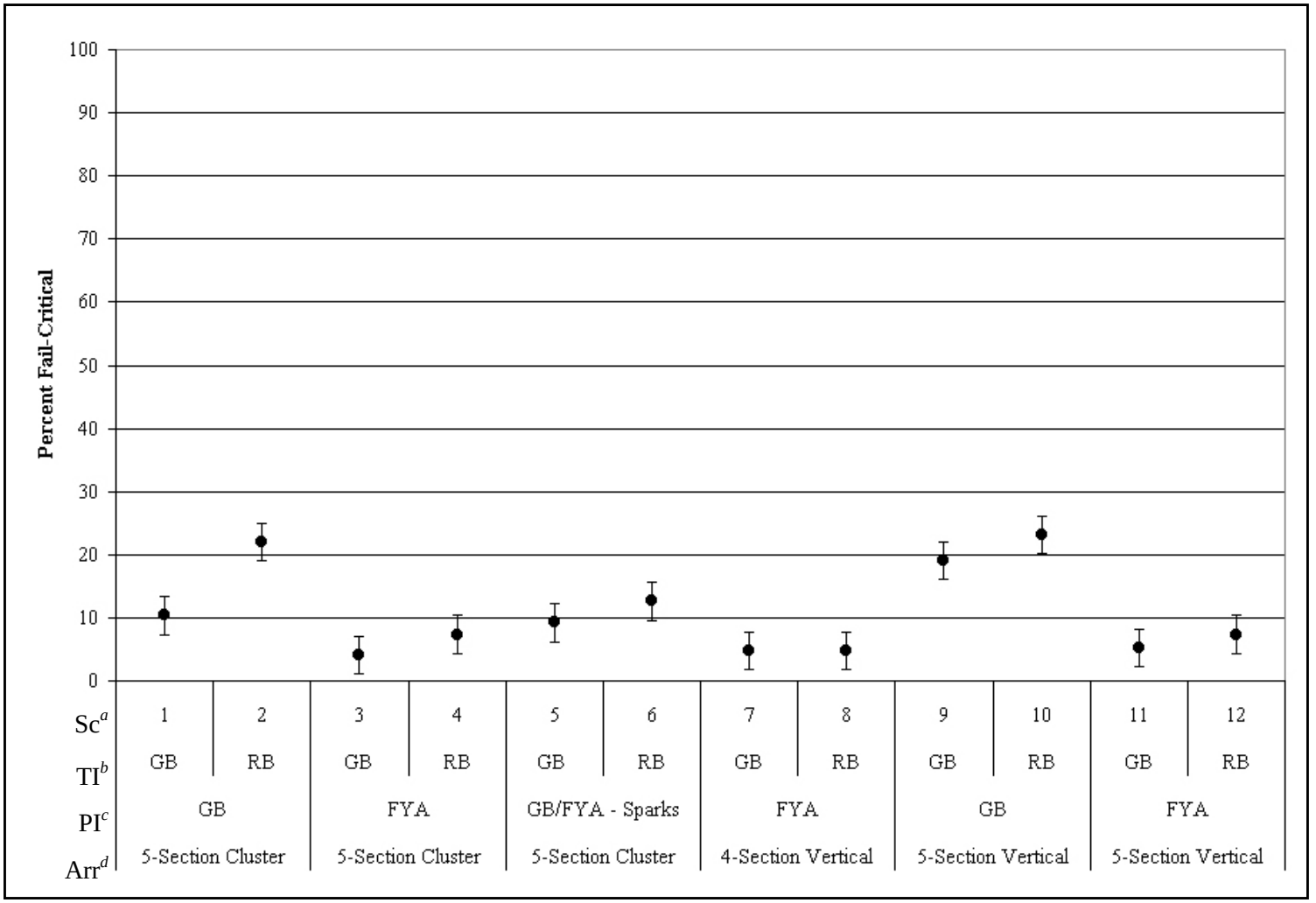
[a] Scenario identification number
[b] Indication for adjacent through lanes (GB = green ball; RB = red ball)
[c] Left-turn permissive indication (GB = green ball; FYA = flashing yellow arrow)
[d] PPLT signal display arrangement

FIGURE 3 Percent Correct for each PPLT Signal Display by Study Location (with 95% C.I.).



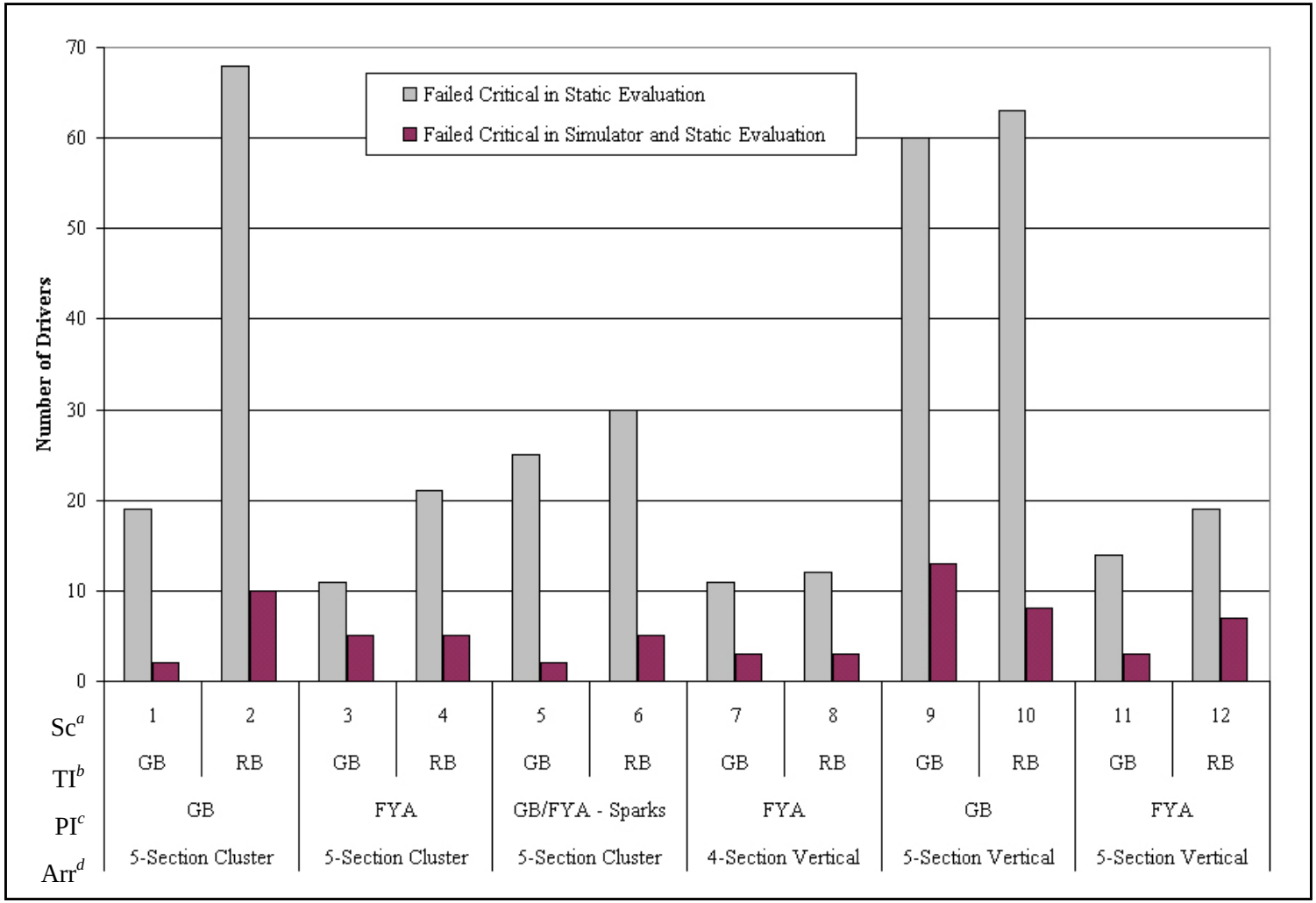
[a] Scenario identification number
[b] Indication for adjacent through lanes
[c] Left-turn permissive indication
[d] PPLT signal display arrangement

FIGURE 5 Percent of Correct Responses (with 95 percent C.I.) for Static Evaluation



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

FIGURE 5 Percent of Fail-Critical Responses (with 95 percent C.I.) for Static Evaluation.



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

FIGURE 6 Comparison of Fail-Critical Responses in Simulator and Static Evaluation by Driver

TABLE 1 Percent Correct by PPLT Display Component

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

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

TABLE 2 Effects of PPLT Display Components on Percent of Fail-Critical Responses

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

[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

TABLE 3 Breakdown of Incorrect Responses

Sc[a]	Arr[b]	Per Ind[c]	Thru Ind[d]	Obs[e]	Fail-Safe by Movement Responses		Fail-Critical Non-Serious Responses		Fail-Critical Serious Responses	
					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

TABLE 4 Overall Percent Correct in Simulator by Demographic Category

Demographic Category	Level	Number of Observations	Percent Correct	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	
	TTI	874	93	2	

TABLE 5 Effects of PPLT Display Components on Percent Correct in Static Evaluation

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

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