Improving Left-Turn Safety Using Flashing Yellow Arrow Permissive Indications

David A. Noyce, Ph.D., P.E.
University of Wisconsin – Madison
1210 Engineering Hall
1415 Engineering Drive
Madison, WI 53706
noyce@engr.wisc.edu

ABSTRACT

Significant variability exists in the application of protected/permissive left-turn (PPLT) signal displays throughout the United States. PPLT signal phasing provides a protected phase for left-turns as well as a permissive phase during which left-turns can be made if gaps in opposing traffic allow, all within the same signal cycle. Although the intent of the Manual on Uniform Traffic Control Devices (MUTCD) is to provide a national standard, only general guidance is provided in the selection and use of PPLT signal displays. Additionally, the MUTCD does not require a separate PPLT signal display for PPLT signal phasing. Consequently, PPLT signal displays have been implemented in a variety of configurations throughout the United States.

PPLT signal phasing and corresponding displays can be found at approximately 29 percent of signalized intersections in the United States. The five-section cluster is the most common arrangement, used at approximately 63 percent of all PPLT intersections, but is not uniformly applied in placement, location, and use of supplemental signs. Within each PPLT signal display, the MUTCD requires a green arrow for the protected left-turn movement and a circular green indication for the permissive movement.

Problems with driver's comprehension of PPLT signal displays have been identified but not resolved. Specifically, the permissive (circular green) phase is a concern for many traffic engineers. The problem lies in the fact that drivers traveling through an intersection displaying a circular green indication may proceed straight through, with all other vehicles yielding the right-of-way. Drivers turning left with a circular green indication are required to yield the right-of-way to opposing vehicles before proceeding. Therefore, the circular green indication has been challenged on the premise that it provides two different messages. The safety of left-turn drivers requires that the permissive phase be an unambiguous signal display arrangement and/or indication because of its unique turning requirements.

To improve driver comprehension, traffic engineers in California, Delaware, Michigan, and Washington, among others, have replaced the circular green permissive indication with one of several unique indications. These unique indications include a flashing circular yellow, a flashing circular red, a flashing yellow arrow, and a flashing red arrow. Each of these permissive indications has been used in either a three-section or four-section signal display.

Research has shown that flashing permissive indications may lead to a higher level of driver comprehension and improve safety at PPLT intersections. Additionally, results of a national study have concluded that flashing yellow arrow permissive indications provide driver

Proceedings of the 2003 Mid-Continent Transportation Research Symposium, Ames, Iowa, August 2003.

comprehension and safety benefits. Work is currently underway on making the flashing yellow arrow indication an accepted/approved indication in the MUTCD.

Key words: driver behavior—driving simulation—left-turn safety—protected/permissive—signal display

INTRODUCTION

The flexibility provided by the Manual on Uniform Traffic Control Devices (MUTCD) has led to multiple signal display arrangements and indications for Protected/Permissive Left-Turn (PPLT) applications (*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 for the permissive phase. Problems with PPLT signal phasing, primarily related to the circular green permissive indication, have been identified but not resolved (*2*, *3*).

Many traffic engineers believe that the MUTCD circular green permissive indication is adequate and properly presents the intended message to the driver. Other traffic engineers believe that the circular green permissive indication is not well understood and therefore inadequate. The latter belief is based on the argument that left-turn drivers may interpret the circular green 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 circular green permissive indication with a flashing circular red, flashing circular yellow, 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 left-turn operations.

Variability in left-turn control led the National Cooperative Highway Research Program (NCHRP) to introduce project 3-54; a study of the various aspects of PPLT signal phasing. The objective of the NCHRP 3-54 project was to evaluate the safety and effectiveness of different signal displays and phasing for PPLT control through laboratory and field studies. Conducted over a seven-year period, NCHRP 3-54 is the most comprehensive study of PPLT displays to date. The research project identified current practice, studied driver understanding of known protected and permissive displays in the United States, analyzed crash data, analyzed operational data, and conducted a confirmation study using a full-scale driving simulator and several field installations to study driver understanding of the most promising permissive displays (*4, 5*). The results of a driver behavior and comprehension study included in NCHRP 3-54 are presented in the following sections.

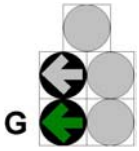
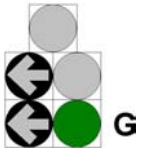
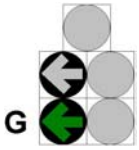
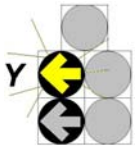
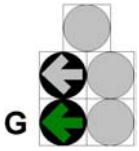
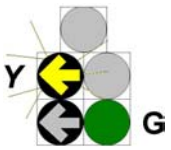
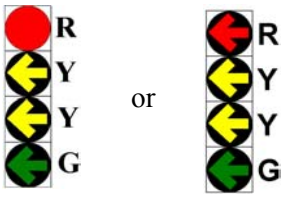
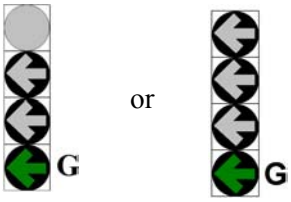
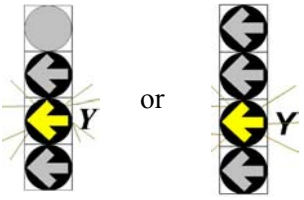
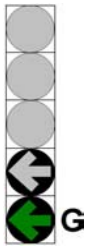
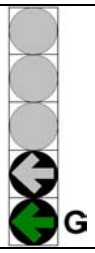
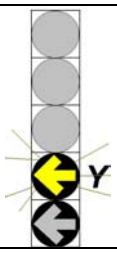
RESEARCH OBJECTIVES

The objective of the research task described was to evaluate the safety and effectiveness of selected PPLT signal displays through a driver behavior and comprehension evaluation. The study was conducted using full-scale fixed-base 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 tasks.

METHODOLOGY

Twelve different PPLT signal displays were identified for evaluation (*4, 6*). The selected displays differ in permissive indication, arrangement, location, and through movement indication. Each of the PPLT signal displays included only the circular green and/or flashing yellow arrow

permissive indications. The circular green 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 finding (*2 - 5*). Figure 1 depicts each of the PPLT signal displays evaluated.

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 – Circular green through indication; 2, 4, 6, 8, 10, 12 – circular red through indication

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

FIGURE 1. PPLT Displays Evaluated in Driving Simulator Experiment

The UMass and TTI driving simulators are pictured in Figure 2. Both simulators 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.

Development of Simulation

One intersection approach was created for each of the 12 experimental PPLT signal displays; the characteristics of each approach were identical 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. Further experimental variability was provided by creating multiple driving modules and starting positions. All experimental signal displays within the simulation rested in a circular red or arrow indication as drivers 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 remained red or changed from a circular red to a circular green indication.

Each of the PPLT signal displays was evaluated with opposing traffic at the intersection. Six opposing vehicles were used to create a predetermined 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 five 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.

FIGURE 2. UMass and TTI Driving Simulators Used in 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. 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 the PPLT signal indication, but did not infringe on the right-of-way of opposing traffic. A fail-critical response was an incorrect response in which the driver incorrectly responded to the PPLT signal indication and impeded the right-of-way of opposing traffic, creating the potential for a crash.

Video-Based Static Evaluation

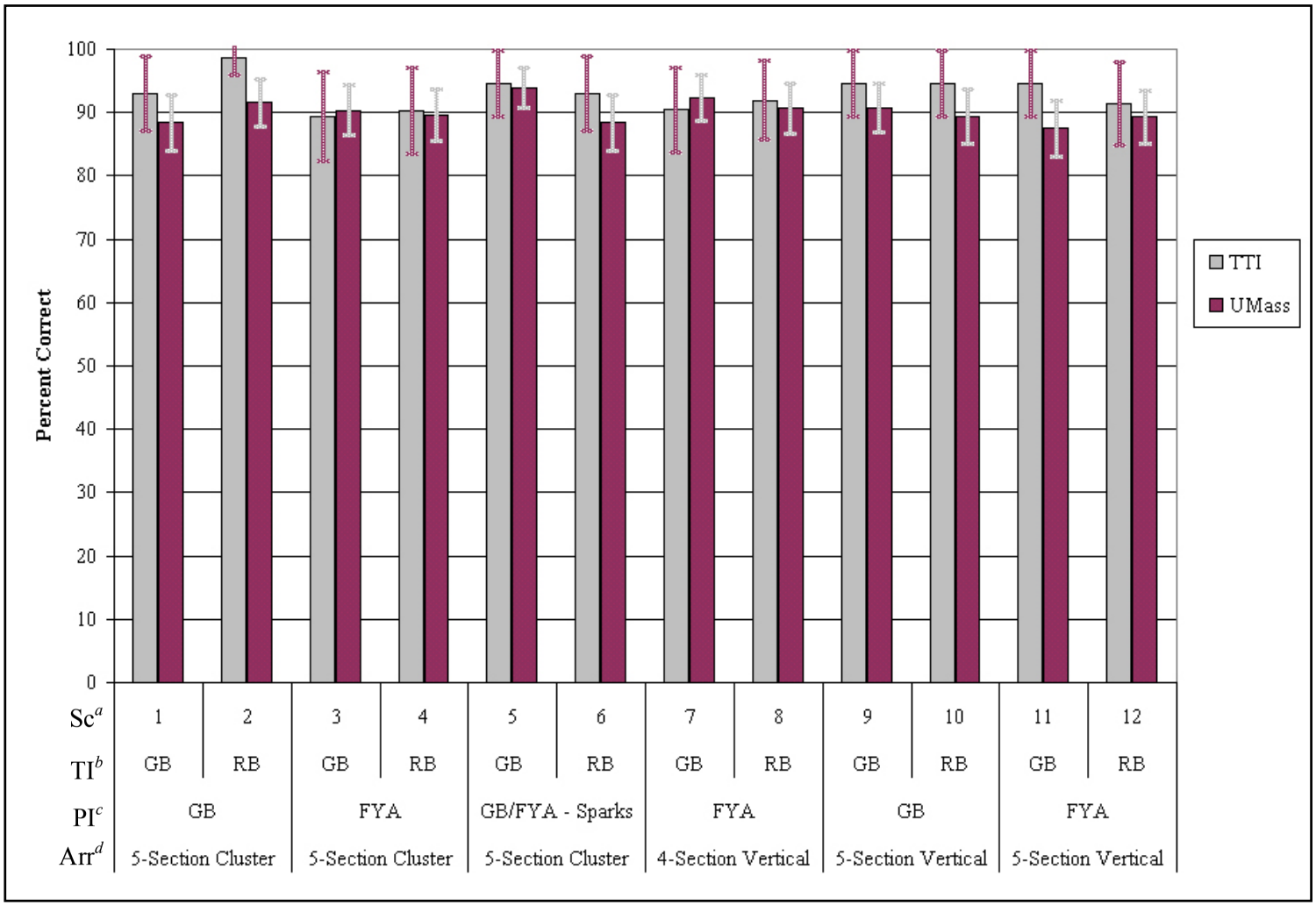
After completing the driving portion of the study, drivers were asked to participate in a static evaluation of PPLT signal displays. The static evaluation was administered using videocassette recordings of screen captures for the 12 PPLT displays. Each display was shown for 30 seconds during which time the driver verbally indicated how they would react. Data were recorded and combined with the driving simulator data to complete the analysis. An analysis of variance (ANOVA) procedure was used to evaluate and compare driver comprehension related to the 12 selected PPLT signal displays (7). For each analysis, the 95 percent confidence interval was calculated based on a binomial proportion.

RESULTS

Two hundred twenty-three drivers at UMass evaluated 2,528 scenarios with experimental PPLT signal displays; 93 drivers at TTI evaluated 874 scenarios. 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 UMass and TTI data 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 circular green (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 circular green or circular red (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 were 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 ($p = 0.206$).



[a] Scenario identification number
[b] Indication for adjacent through lanes (GB = circular green; RB = circular red)
[c] Left-turn permissive indication (GB = circular green; 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.)

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	1,136	91	2	0.433
	FYA	1,701	90	1	
	GB/FYA	565	92	2	
Arrangement[b]	5-section cluster	1,697	91	1	0.747
	4-section vertical	569	91	2	
	5-section vertical	1,136	90	2	
Thru Indication[c]	GB	1,707	91	1	0.716
	RB	1,695	91	1	
Location[d]	Shared	846	90	2	0.206
	Exclusive	2,556	91	1	

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

Analysis of Incorrect Responses

A significant amount of fail safe by movement responses were observed with scenario one; a five-section cluster in a shared location with a circular green permissive indication and adjacent circular green 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 ($p = 0.407$).

Static Evaluation

Four hundred thirty-six drivers completed the static evaluation. 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. *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 completed. Similarly, the components of the PPLT signal displays and demographic variables were isolated to identify any effect on overall driver comprehension.

Correct responses ranged from 73 to 89 percent 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 flashing yellow arrow permissive indication, and circular green through indication), five (five-

section cluster, with circular green/flashing yellow arrow permissive indication, and circular green through indication), seven (four-section vertical, with flashing yellow arrow permissive indication, and circular green through indication) and 11 (five-section vertical, with flashing yellow arrow permissive indication, and circular green through indication) had significantly high percentages of correct responses. By comparison, displays two (five-section cluster, with circular green permissive indication, and circular red through indication) and 10 (five-section vertical, circular green permissive indication, and circular red through indication) had significantly low levels of correct responses.

PPLT signal displays with the circular green permissive indication had significantly lower correct responses than PPLT displays with either the flashing yellow arrow or circular green/flashing yellow arrow 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 ($p = 0.003$).

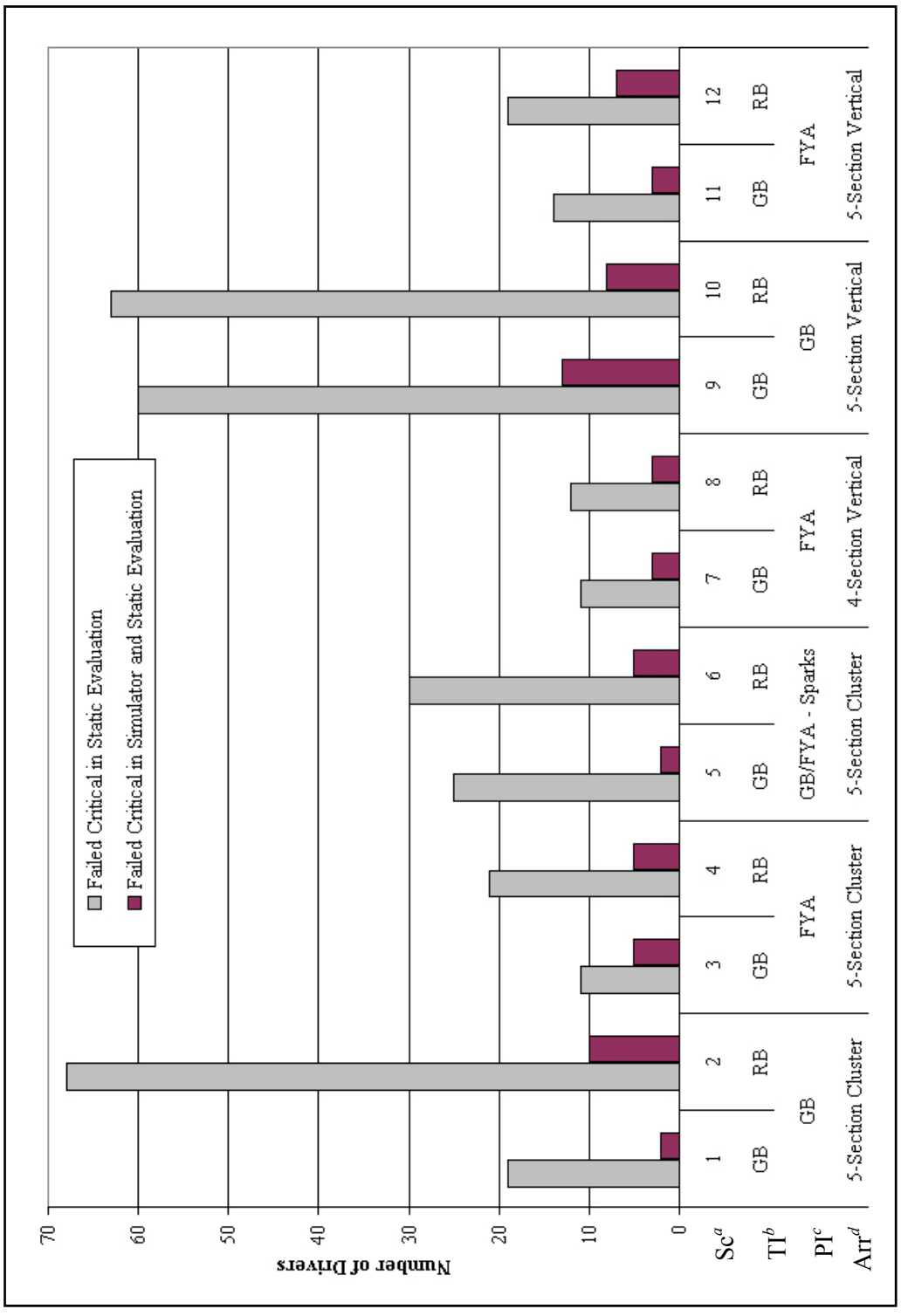
Location of the PPLT display was not statistically significant ($p = 0.170$). A significant difference ($p = <0.001$) was found between displays with the through movement circular green and circular red, with drivers responding correctly more frequently to displays with the circular green through movement.

Analysis of Incorrect Responses

An analysis of incorrect responses yielded statistically significant differences across the 12 PPLT signal displays ($p = <0.001$). A significantly higher number of fail-critical responses were generated from three scenarios, each including the circular green permissive indication. Specifically, scenarios two (five-section cluster arrangement, circular green permissive indication, and circular red through indication), nine (five section vertical, circular green permissive indication, and circular green through indication), and 10 (five section vertical, circular green permissive indication, and circular green through indication) were each associated with significantly more *go, you have the right-of-way responses.*

Comparison of Driving Simulator and Static Evaluation Results

There were 353 fail-critical responses in the static evaluation for which a direct comparison with the driver's response in the simulator was 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 4 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.



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

FIGURE 4. Comparison of Fail-Critical Responses in Simulator and Static Evaluation by Driver

SUMMARY OF FINDINGS

The findings of the driving simulator study showed that 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. 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 circular green permissive indication.

Overall, the permissive indication resulted in statistically significant differences of correct and fail-critical responses. Scenarios with the flashing yellow arrow permissive indication and the circular green/flashing yellow arrow simultaneous permissive indication had significantly more correct responses than displays with the circular green permissive indication. Additionally, displays with the circular green permissive indication were associated with significantly more fail-critical responses than displays with either the flashing yellow arrow or circular green/flashing yellow arrow permissive indications. PPLT scenarios with the four-section vertical arrangement had a significant amount of correct responses; however, only the flashing yellow arrow permissive indication was evaluated in this arrangement.

Displays with the circular red through indication resulted in a significantly lower percent correct response rate than displays with the circular green through indication. PPLT displays with the circular red through indication also resulted in significantly more fail-critical responses. This may be attributed to the fact that conflicting signal indications (red and green), even when not in the same signal display, are confusing to drivers. The location of the PPLT signal display did not result in statistically significant differences.

SUMMARY OF RELATED RESEARCH

As a result of the research described above, and as part of the NCHRP 3-54 project, field implementation of experimental flashing yellow arrow PPLT displays were completed in cooperation with six volunteer agencies located around the country. In September 2000, Montgomery County, Maryland became the first agency to implement the flashing yellow arrow permissive indication. Maryland's installation was subsequently followed by the City of Tucson, AZ; Jackson County, OR; the Oregon Department of Transportation; the City of Beaverton, OR; and Broward County, FL. Figure 5 illustrates the flashing yellow arrow permissive indication used in Woodburn, Oregon.

The research study and field implementation effort has identified several benefits of the flashing yellow permissive indication in a four-section vertical, all arrows, display including:

- Left-turn confusion is significantly reduced, especially related to shared signal heads;
- No supplemental sign with PPLT operation is required;
- All types of phasing can be operated by time of day (protected only, permissive only, protected/permissive, or permissive/protected);
- The display works at all signalized intersections;

- No louvers or precise head placements are required;
- The display can be mounted by pole, span wire, or median mount;
- The display can use a bi-modal lens in a three section display;
- The display can be used for right-turns;
- The "yellow trap" is eliminated when the flashing yellow arrow display is logically tied to the opposing through movement green indication.

FIGURE 5. Four-Section Vertical Flashing Yellow Arrow Permissive Indication

Based on the findings of all research tasks, the flashing yellow arrow indication was well understood in almost all deployment cases. Analysis of the research data suggest that the flashing yellow arrow indication is at least as safe as the circular green indication. Where deployed, the flashing yellow arrow indication was favored by almost all of the traffic engineers, field technicians, and citizens when compared to the traditional circular green PPLT indication. The flashing yellow arrow indication and display was found to have a high level of understanding, and a lower fail critical rate as compared to the circular green permissive indication. Hence, a significant safety improvement. The flashing yellow arrow display offers more versatile field application features (for example, it can be operated in a variety of operational modes by time-of-day, implemented on any signal mount, and any intersection configuration) as compared to the circular green indication.

Given these very favorable results, it is recommended that the flashing yellow arrow display be included in the MUTCD as an allowable alternative display to the circular green indication when

used in PPLT control/operation. The four-section, all arrow display face should be the only display allowed, with the exception of a three-section display face with bi-modal lens (other potential variations including a five-section head are identified for consideration). Ideally, the flashing yellow arrow operation shall only be used in an exclusive signal arrangement. When used for left-turn treatments, the flashing yellow arrow shall be tied to the opposing through-green indication/display.

ACKNOWLEDGEMENTS

This research was conducted as a component of NCHRP 3-54(2) contracted by Kittelson & Associates, Inc., Portland, OR.

REFERENCES

1. *Manual on Uniform Traffic Control Devices*. Federal Highway Administration, U.S. Department of Transportation, Washington, DC, 2000.

2. Noyce, D.A. *Development of a Uniform Traffic Signal Display for Protected/Permitted Left-Turn Signal Displays*. Ph.D. Dissertation, Texas A&M University, College Station, TX, 1998.

3. Kittelson & Associates, and the Texas Transportation Institute. *Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control*. NCHRP 3-54(2), Interim Report, FHWA, U.S. Department of Transportation, Washington, DC, 1999.

4. Kittelson & Associates, *Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control*. NCHRP 3-54(2), 2nd Interim Report, FHWA, U.S. Department of Transportation, Washington, DC, 2002.

5. Kittelson & Associates, *Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control*. NCHRP 3-54(2), Final Report, FHWA, U.S. Department of Transportation, Washington, DC, 2003.

6. Smith, C.R. *An Evaluation of Five-Section Protected/Permitted Left-Turn Signal Displays Using Driving Simulator Technology.* Master's Thesis, University of Massachusetts, Amherst, MA, 2000. Change to Noyce paper

7. Mendenhall, W., Beaver, R.J, and B. M. Beaver. *Introduction to Probability and Statistics,* 10th edition. Duxbury Press, Pacific Grove, 1999.