AN EVALUATION OF FIVE-SECTION PROTECTED/PERMITTED LEFT-TURN SIGNAL DISPLAYS USING ADVANCED DRIVING SIMULATOR TECHNOLOGY

by

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INTRODUCTION

One relatively new type of left-turn signal phasing designed to minimize the protected left-turn phase time requirements, while increasing the opportunity for left-turn maneuvers, is protected/permitted left-turn (PPLT) phasing (*1*). 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 traffic allow, all within the same signal cycle. Consequently, PPLT signal phasing can improve operational efficiency by increasing left-turn capacity and reducing delay at signalized intersections.

The positive attributes of PPLT phasing are presented to the driver through the use of traffic signal displays. Traffic signal displays illuminate circular- and arrow-shaped indications to allow different traffic maneuvers through the intersection. The meaning of each indication is transmitted to the driver by its color, shape, orientation, and position within the traffic signal display. The Manual on Uniform Traffic Control Devices (MUTCD) is the current source for guidelines on the use of traffic signal displays (*2*). According to the MUTCD, proper use of traffic signal displays can improve the overall capacity, efficiency, and safety of an intersection.

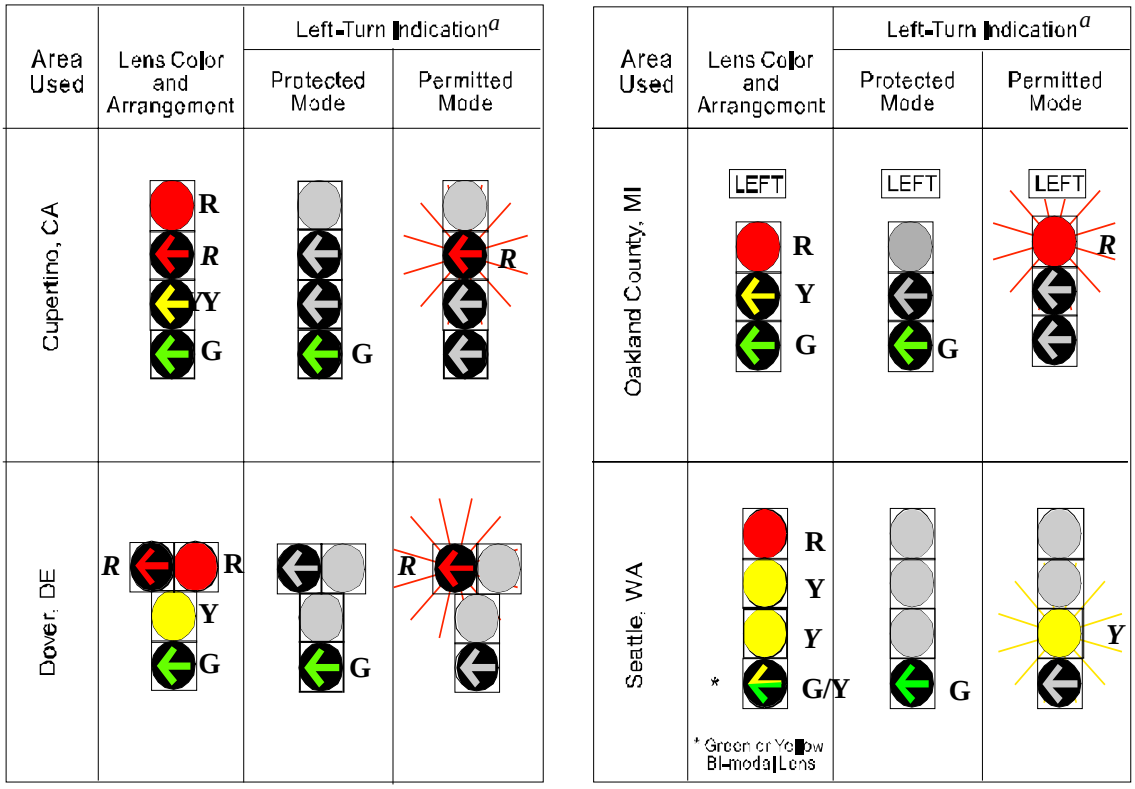
PROBLEM STATEMENT

Although the intent of the 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 (*2*). Consequently, PPLT signal displays have been implemented in a variety of configurations throughout the United States.

Most jurisdictions using PPLT signal phasing have adopted a five-section PPLT signal display in either a horizontal, vertical, or cluster arrangement. Included in the PPLT signal display is a green arrow indication for the protected left-turn phase and a circular green (ball) indication for the permitted phase.

The combination of PPLT signal phasing with the arrangements and indications described has led to concern over driver's understanding of PPLT signal displays. Specifically, the permitted (green ball) phase is a concern for traffic engineers. Most traffic engineers in the United States have adopted the green ball indication for the permitted left-turn phase; however, the green ball can convey different meanings in different situations. Those receiving the green ball when turning right or traveling straight through an intersection have the right-of-way, yet during the permitted left-turn movement, those receiving the green ball must yield to the opposing through movement (*2*). Therefore, the PPLT green ball indication has been challenged on the premise that the permitted phase needs a separate distinguishable indication because of its unique turning requirements.

Since the green ball indication may be confusing to drivers during the permitted left-turn phase, other indications may more clearly present the intended message. Therefore, traffic engineers in Delaware, Michigan, and Washington, among others, have replaced the green ball permitted indication with one of several different permitted phase indications including a flashing yellow ball, a flashing red ball, a flashing yellow arrow, or a flashing red arrow. Each of these permitted indications has been used in either a three-section or four-section signal display as shown in Figure 1.



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

[a] The indication illuminated for the given mode is identified by the letter R (red) and G (green).

Figure 1 Variations in PPLT Signal Display (2)

The use of different permitted indications has created considerable variability in PPLT display usage throughout the U.S. Variability in signal display indications associated with permitted left-turn phasing can lead to high levels of driver confusion and may not effectively convey the appropriate driver action. Recent studies have indicated that flashing red or yellow (ball or arrow) permitted indications may overcome the problems associated with the green ball permitted indication and lead to a higher level of driver understanding at PPLT intersections (*1, 3, 4*). For example, Noyce found that all flashing indications had higher correct response rates than the green ball permitted indication (*1*). Analysis of serious error rates (fail-critical) produced similar results with the highest serious error rate being 25 percent for the green ball permitted indication.

Current applications of the PPLT flashing permitted indications include only three- and four-section signal displays. If a system wide change to a flashing permitted indication is to be considered, the flashing indications must also be effective in five-section displays, since the five-section display is the most commonly used. In fact, the five-section cluster display is used at approximately 63 percent of all PPLT signal displays in the United States (*1*). No research has been completed to evaluate driver understanding of all permitted indication types in five-section PPLT signal displays. Therefore, the objective of this research was to investigate and evaluate driver understanding of both the green ball and flashing permitted indications within five-section PPLT signal displays.

DRIVING SIMULATOR

The driving simulator at the University of Massachusetts used in this research is a mid-level *Real Drive* simulator manufactured by Illusion Technologies, Inc. Since the vehicle is an actual Saturn sedan, a driver operates the controls of the Saturn just as he or she would on the road. A photo of the driving simulator is shown in Figure 2.

The visual world is displayed on a screen in front of the vehicle. The visual display subtends 60 degrees in the horizontal direction and 30 degrees in the vertical direction. As the driver turns the wheel, brakes, or accelerates, the roadway that is visible to the driver changes appropriately. The images themselves are updated 30 times a second within the computing system. The sound system for the simulator consists of three speakers, two located on the left and right sides of the car and one, a sub-woofer, located in front of the car. The system provides realistic road, wind and other vehicle noises with appropriate direction, intensity and Doppler shift. The hardware and software described was able to create an exact replica of many different intersection and left-turn conditions using PPLT signal phasing and provided the visual world for this research.

Figure 2 Driving Simulator at the University of Massachusetts, Amherst

RESEARCH PROCEDURES

A set of 15 unique PPLT signal displays was created in the driving simulator environment. These 15 different displays were the result of some combination a five-section signal display arrangement (horizontal, vertical, or cluster) and permitted indication (flashing yellow arrow, flashing yellow ball, flashing red arrow, flashing red ball, or steady green ball). The flashing permitted indications replaced the green ball permitted indication within each arrangement.

Each of the 15 different display arrangement/permitted indication combinations were tested with the presence of opposing traffic. When the driver arrived at the intersection, the opposing traffic was at a distance such that the subject driver did not know, simply by looking at the opposing traffic, whether this opposing traffic was going to stop or continue through the intersection. The driver was then required to base his/her left-turn decision only on the five-section PPLT signal display arrangement and indication present in the intersection. The driver's left-turn decision represented whether

he/she understood the intended message conveyed by the five-section PPLT signal display arrangement and indication.

The five-section cluster PPLT signal display arrangement and permitted indication combinations were also tested with no opposing traffic present. Results from trials containing no opposing traffic helped to define the influence that opposing traffic had on drivers' left-turn decisions, although these results are not within the scope of this paper. With the addition of the five five-section cluster PPLT signal display arrangement/permitted indication combinations with no opposing traffic, each driver was evaluated in a total of 20 different five-section PPLT signal display arrangement/permitted indication scenarios.

A total of 24 intersections were presented in each of four modules, including 10 PPLT intersections. Right-turn and through movements were also presented to introduce a higher level of realism into the research and to prevent driver learning during the testing period.

The driver's response to each PPLT scenario was recorded for correctness. Incorrect responses were broken into two different categories, fail-safe and fail-critical. A fail-safe response is one in which the driver does not correctly respond to the five-section PPLT signal display arrangement/permitted indication combination, but does not infringe on the right-of-way of the opposing traffic. A fail-critical response is an incorrect response in which the driver incorrectly responds to the five-section PPLT signal display arrangement/permitted indication combination and impedes on the right-of-way of the opposing traffic creating the potential for a crash. Figure 3 presents all possible fail-safe and fail-critical responses.

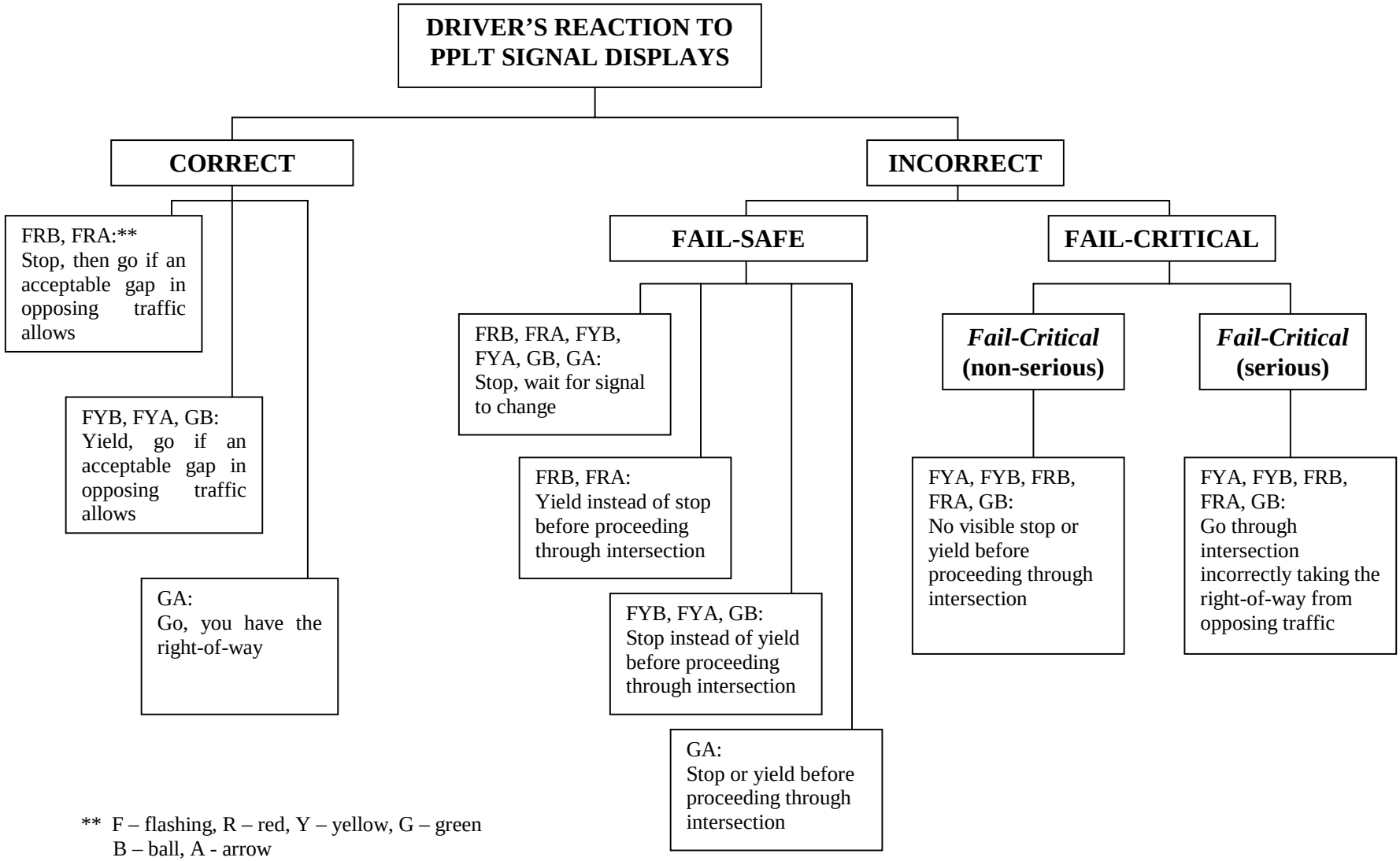


Figure 3 Response Categories for Driver Actions in Simulator Experiment

RESEARCH RESULTS

A total of 34 drivers completed all or part of the driving simulation task. Table 1 shows the driver demographics, number of observations and percent correct responses for permitted indication scenarios containing opposing traffic. In total, 991 responses were collected from permitted indication scenarios with opposing traffic. A correct response was given for 81.3 percent of the 991 responses.

Table 1 - Summary of Driver Demographics, Observations, and Response Rates

Demographic Category	Level	Number of Drivers	Number of Observations	Percent Correct Responses
Gender	Male	17	510	85.3
	Female	17	481	77.1
Age	24 or younger	17	510	81.0
	25 to 45	12	360	86.1
	Over 45	5	121	68.6
Highest Level of Education Completed	Less Than College Degree	19	556	79.1
	College Degree or Greater	15	435	84.1
Miles Driven in the Past Year	< 10,000	10	286	72.4
	10,000 to 20,000	20	585	83.2
	> 20,000	4	120	93.3
	Total	**34**	**991**	**81.3**

Table 2 presents the overall number of observations and percentage of correct responses for all five-section PPLT signal display arrangement and permitted indication combinations. The combination of the five-section horizontal arrangement and flashing yellow ball permitted indication was the most understood with a 97.0 percent correct response rate. The next most understood combination was the horizontal arrangement with flashing yellow arrow permitted indication (93.9 percent correct response rate). The combination of the five-section cluster arrangement and flashing red arrow permitted indication had a correct response rate of 60.6 percent followed only by the five-section vertical arrangement with the flashing red arrow permitted indication with a 57.6 percent correct response rate. Note that the flashing red arrow indication had the lowest correct response rate for all arrangements.

The average correct response rate for the horizontal, vertical, and cluster five-section PPLT signal display arrangements tested were very similar, 84.3, 81.0, and 78.0 respectively. The difference in results was found not to be statistically significant ($p = 0.116$). Nevertheless, the results suggest that the cluster arrangement may have a lower level of driver understanding than the horizontal and vertical arrangements.

Figure 4 presents the percent correct responses for the permitted indications. The difference in the percentage of correct responses for the permitted indications was statistically significant ($p = 0.0001$). The results in Figure 4 suggest that the green ball, flashing yellow arrow, and flashing yellow ball had significantly a higher level of driver understanding than flashing red arrow and flashing red ball. There was no significant difference among PPLT signal display arrangements.

Table 2 Number of Observations and Percent Correct Responses to Arrangement/Indication Combinations

Display	Permitted Signal Indication	Number of Observations	Percent Correct Responses
5-Section Vertical	Green Ball	66	92.4
	Flashing Yellow Arrow	66	92.4
	Flashing Red Arrow	66	57.6
	Flashing Yellow Ball	66	92.4
	Flashing Red Ball	67	70.1
5-Section Horizontal	Green Ball	100	93.0
	Flashing Yellow Arrow	66	93.9
	Flashing Red Arrow	66	60.6
	Flashing Yellow Ball	66	97.0
	Flashing Red Ball	66	72.7
5-Section Cluster	Green Ball	32	93.8
	Flashing Yellow Arrow	66	89.4
	Flashing Red Arrow	66	60.6
	Flashing Yellow Ball	66	89.4
	Flashing Red Ball	66	65.2
Total		**66**	**81.3**

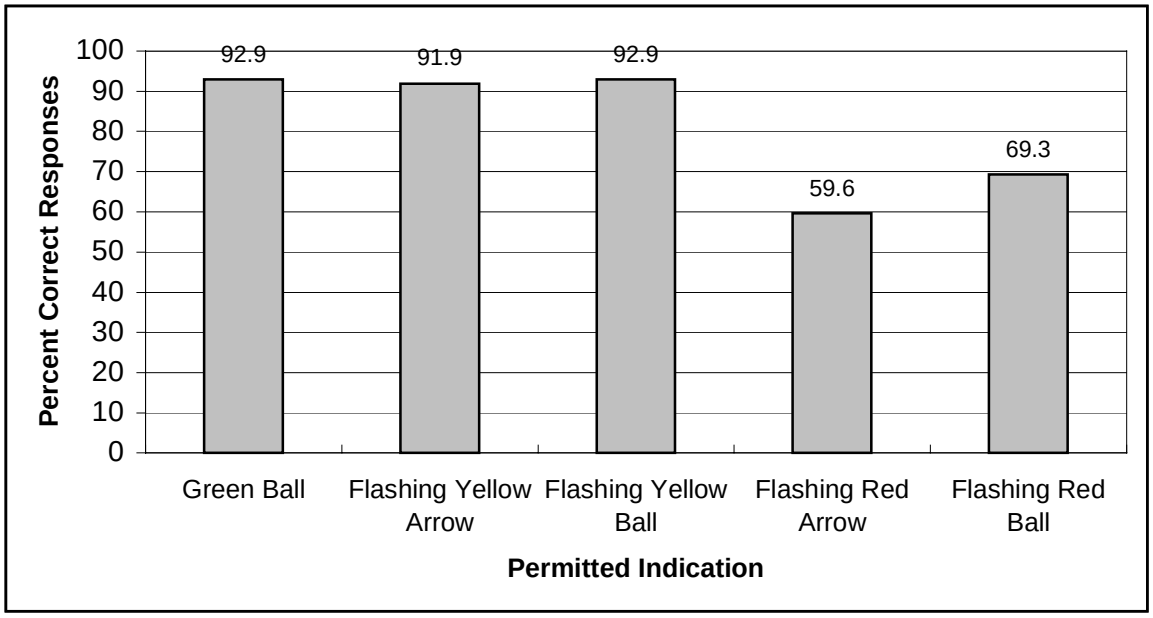


Figure 4 Percent Correct Responses to Permitted Indications

DEMOGRAPHICS

Gender

The correct response rate for male drivers was 85.3 percent as compared with a 77.1 percent for female drivers. This difference was statistically significant ($p = 0.001$). As shown in Figure 5, male drivers consistently had a higher correct response rate than female drivers in all PPLT arrangements and permitted indications except the green ball permitted indication in the five-section horizontal display. Considering all display configurations, male drivers (93.1 percent) and female drivers (92.7 percent) had nearly identical levels of understanding with the green ball permitted indication. Significant differences in driver understanding between male and female drivers existed with all other permitted indications. There was no difference in driver understanding considering arrangement.

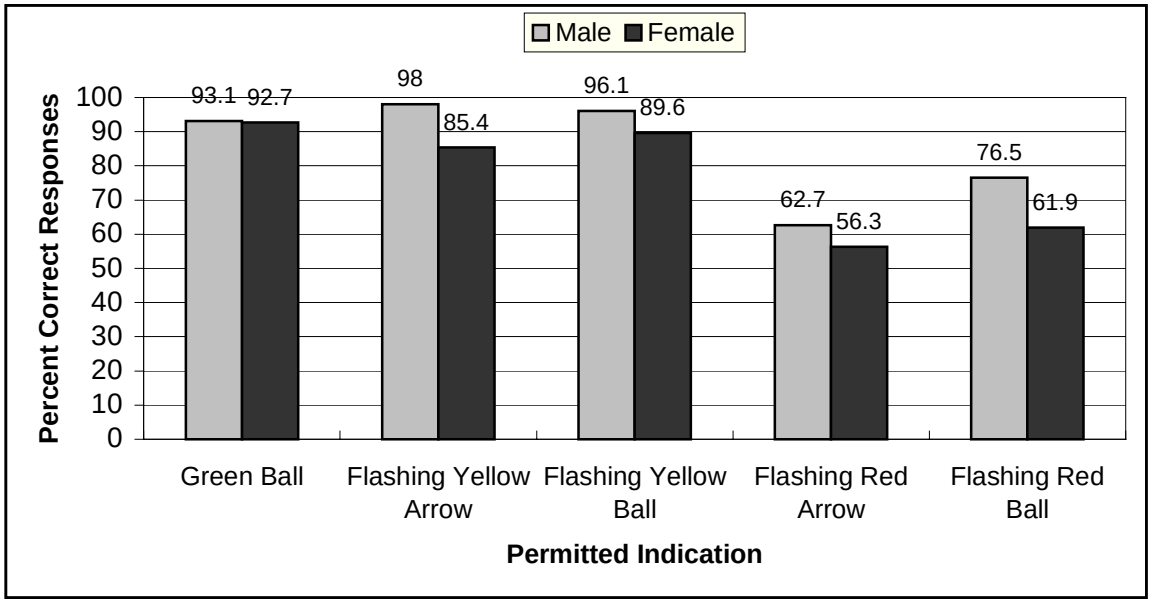


Figure 5 Percent Correct Responses to Permitted Indications by Gender

Age

Figures 6 and 7 present the percentage of correct responses for the five-section arrangements and permitted indications, respectively, by age. The difference in the percentage of correct responses for age was found to be statistically significant ($p = 0.0001$). Note that *older* drivers were grouped as ages 45 and above to balance group sizes.

The data presented in Figures 6 and 7 suggest that drivers between the ages of 25 and 45 had an overall slightly higher understanding of PPLT signal displays than drivers under the age of 24. Additionally, drivers over the age of 45 appear to have a much more difficult time understanding PPLT signal displays than drivers under the age of 45, especially when a flashing red ball or flashing red arrow permitted indication is used.

Several trends become apparent when analyzing the permitted indication data considering age. First, drivers older than 45 years of age appear to understand the green ball, flashing yellow arrow, and flashing yellow ball much better than the flashing red arrow and flashing red ball. No drivers over 45 years of age incorrectly responded to the flashing yellow arrow indication. Second, drivers younger than 24 years of age have a similar, yet not as drastic, relationship amongst display/indication combinations. Correct response rates for the green ball, flashing yellow arrow, and flashing yellow ball were approximately 87.0 percent while the correct response rate for the flashing red ball and flashing red arrow were 54.9 percent. Third, drivers between the ages of 24 and 45 had a much more stable pattern of correct responses. They ranged from a high of 93.1 percent for the green ball to a low of 81.9 for both the flashing red arrow and flashing red ball.

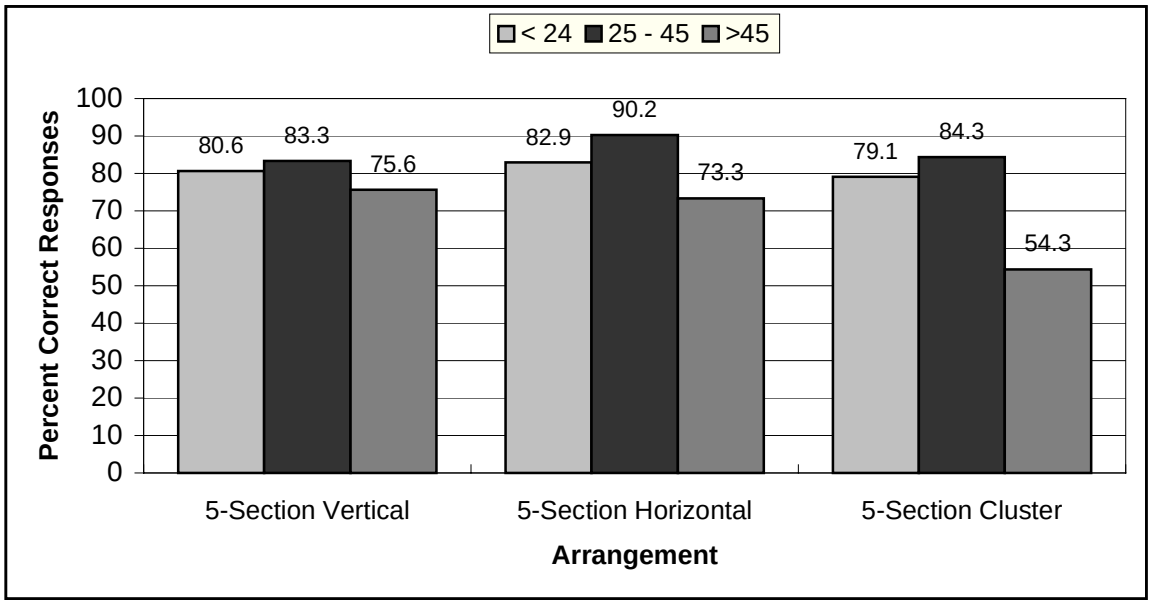


Figure 6 Percent Correct Responses to Five-Section Arrangements by Age

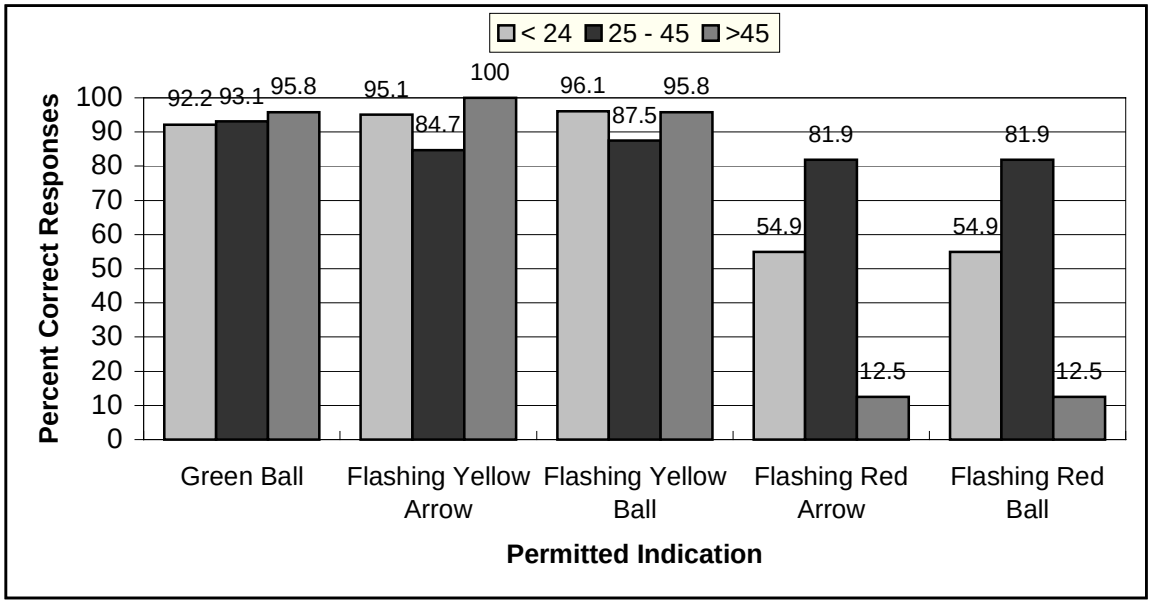


Figure 7 Percent Correct Responses to Permitted Indications by Age

Education

Figure 8 represents the percentage correct responses when comparing permitted indications. The difference in the percentage of correct responses for highest level of education completed was statistically significant ($p = 0.045$).

The flashing red arrow and flashing red ball had correct response rates much lower than the other indications. This result is consistent with the previous demographic factors considered. One interesting trend does appear in Figure 8. The drivers with a college degree understood the flashing red arrow and flashing red ball much better than the drivers with no college degree; however, drivers with less than a college degree better understood the flashing yellow arrow and flashing yellow ball. All drivers appeared to understand the green ball indication equally well.

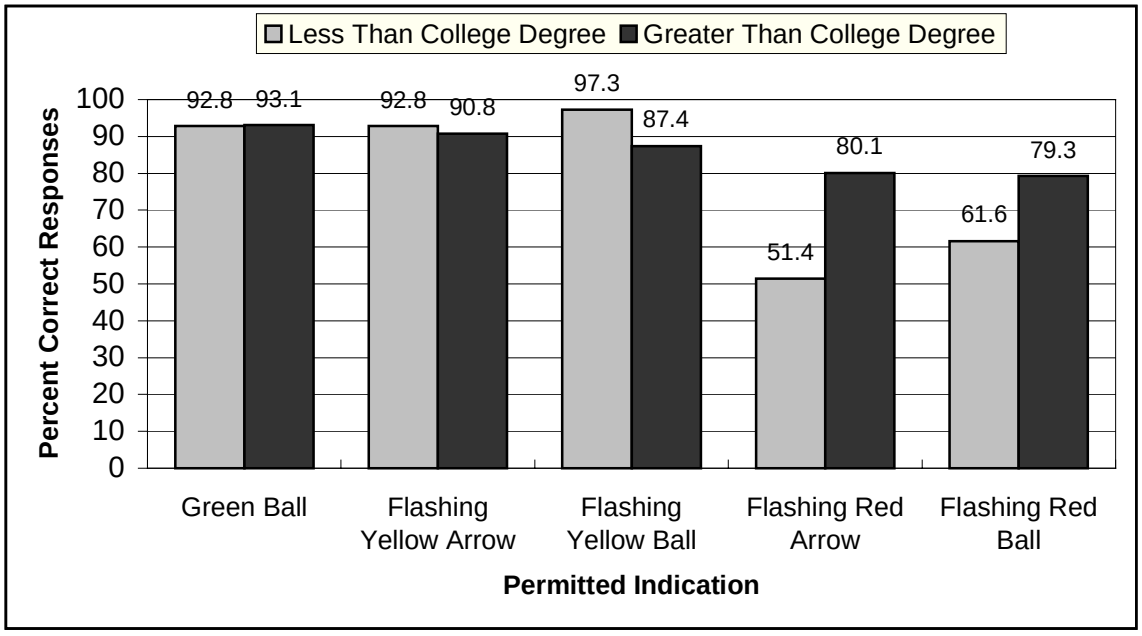


Figure 8 Percent Correct Responses to Permitted Indications by Education

Annual Miles Driven

Figures 9 and 10 represent the percentage correct responses for the five-section arrangements and permitted indications, respectively. The difference in percentage of correct responses for annual miles driven was statistically significant ($p = 0.0001$).

The data suggest that drivers with a higher number of annual miles driven may have a better understand PPLT signal displays. The percentage of correct responses increases by approximately 10 percent for each additional 10,000 miles driven. Additionally, drivers reporting over 20,000 miles driven in the past year had the highest percentage of correct responses across all three arrangements evaluated and four of the five permitted indications evaluated.

A very obvious trend becomes apparent when analyzing Figure 9. The drivers reporting over 20,000 miles driven in the past year had a higher level of understanding than the drivers reporting between 10,000 and 20,000 miles driven. In turn, drivers reporting between 10,000 and 20,000 miles driven in the past year had a higher level of understanding than the drivers reporting less than 10,000 miles driven in the past year. The five-section vertical was the most understood for the drivers reporting over 20,000 miles driven while drivers reporting less than 20,000 miles driven best understood the five-section horizontal.

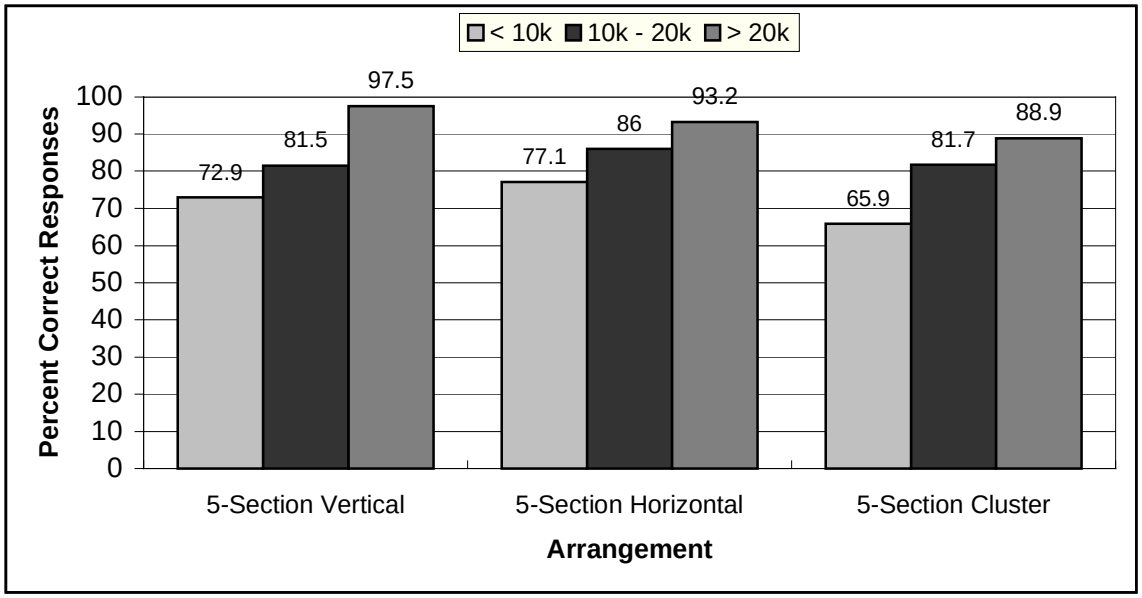


Figure 9 Percent Correct Responses to Five-Section Arrangements by Annual Miles Driven

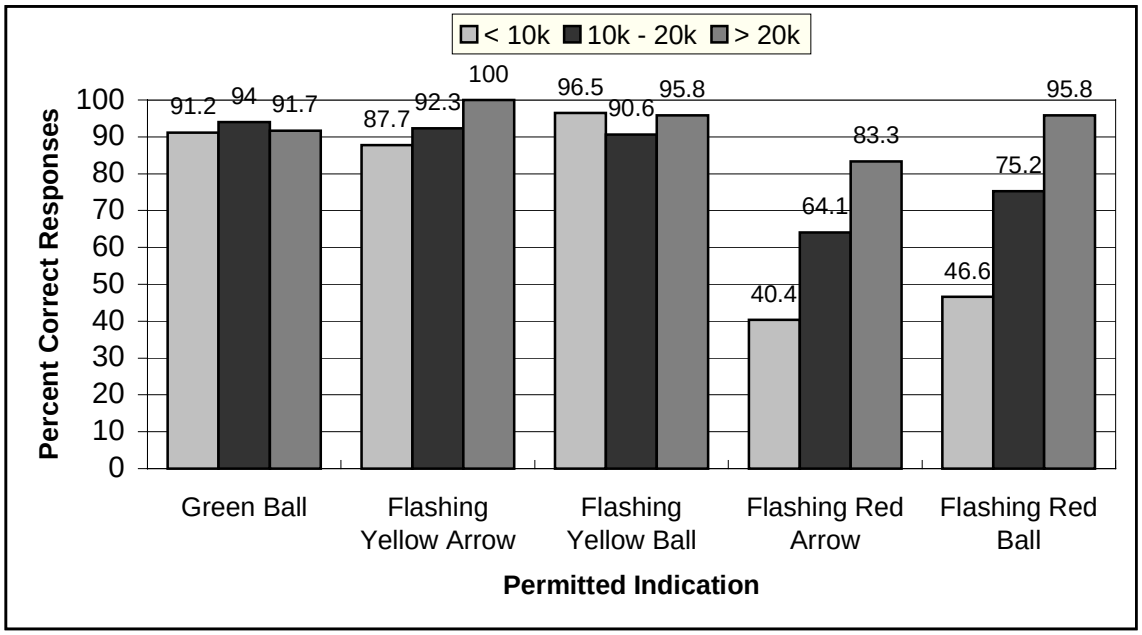


Figure 10 Percent Correct Responses to Permitted Indications by Annual Miles Driven

Only one significant trend becomes apparent when analyzing permitted indications considering annual miles driven. Drivers reporting less than 10,000 miles driven annually had a significantly lower level of driver understanding with the flashing red ball and flashing red arrow indications ($p = 0.0001$). The average correct response rate was approximately 43 percent for the flashing red indications and over 90 percent for the green ball, flashing yellow ball, and flashing yellow arrow permitted indications. A similar trend occurs with the drivers reporting between 10,000 and 20,000 miles driven annually. The average correct response rate was approximately 70 percent for the flashing red ball and flashing red arrow indications and was approximately 92 percent for the green ball, flashing yellow ball, and flashing yellow arrow permitted indications.

Analysis of Incorrect Responses

Since the overall percentage of correct responses for all drivers was 81.3 percent, 18.7 percent of the time an incorrect response was given. Recall the incorrect responses could be, fail-safe, fail-critical (non-serious), and fail-critical (serious). Table 3 shows

the number of observations and percentage of incorrect responses for all PPLT signal display arrangement and permitted indication combinations.

Of the 18.7 percent of incorrect responses given, 15.6 percent were fail-safe. A fail-safe response indicates the driver is not completely sure of the correct response and errors and tends not to have a large safety impact on the intersection and other drivers on the roadway, but most often only increases intersection delay. The data in Table 3 inversely follows trends discussed in the analysis of correct responses. The fail-safe responses to the flashing red ball and flashing red arrow permitted indications tend to be much higher than the green ball, flashing yellow ball, or flashing yellow arrow permitted indications. Additionally, the five-section cluster and five-section vertical arrangements tended to produce higher fail-safe responses than the five-section horizontal arrangement.

Table 3 Number of Observations and Percent Incorrect Responses to Arrangement/Indication Combinations

Display	Permitted Signal Indication	Fail-Safe		Fail Critical (non-serious)		Fail-Critical (serious)		Total
		Observ.	Percent	Observ.	Percent	Observ.	Percent	
5-Section Vertical	Green Ball	1	1.5	4	6.1	0	0.0	7.6
	Flashing Yellow Arrow	3	4.5	2	3.0	0	0.0	7.5
	Flashing Red Arrow	26	39.4	2	3.0	0	0.0	42.4
	Flashing Yellow Ball	4	6.1	1	1.5	0	0.0	7.6
	Flashing Red Ball	19	28.4	1	1.5	0	0.0	29.9
5-Section Horizontal	Green Ball	2	2.0	3	3.0	2	2.0	7.0
	Flashing Yellow Arrow	2	3.0	1	1.5	1	1.5	6.0
	Flashing Red Arrow	23	34.8	1	3.0	1	1.5	39.3
	Flashing Yellow Ball	2	3.0	0	0.0	0	0.0	3.0
	Flashing Red Ball	18	27.3	0	0.0	0	0.0	27.3
5-Section Cluster	Green Ball	0	0.0	2	6.3	0	0.0	6.3
	Flashing Yellow Arrow	4	6.1	3	4.5	0	0.0	10.6
	Flashing Red Arrow	25	37.9	1	1.5	0	0.0	39.4
	Flashing Yellow Ball	4	6.1	2	3.0	1	1.5	10.6
	Flashing Red Ball	22	33.3	1	1.5	0	0.0	34.8

The most common fail-safe response to the permitted indications was drivers yielding instead of stopping for the flashing red ball and flashing red arrow indications. This result is not surprising considering many drivers on the actual roadway tend to anticipate intersections where they will be required to stop and look ahead for oncoming traffic. If no traffic is present, drivers will not come to a complete stop and slowly roll into a turn or through the intersection.

The fail-critical (non-serious) responses were the second highest source of incorrect responses although they were much less than the fail-safe incorrect responses. Fail-critical (non-serious) accounted for 2.5 percent of all responses and 13.3 percent of the incorrect responses. Table 3 shows that the green ball permitted indication produced the most fail-critical (non-serious) responses. The green ball indication was followed by the flashing yellow ball and flashing yellow arrow permitted indications with the flashing red ball and flashing red arrow indications producing the fewest fail-critical (non-serious) responses. As with the fail-safe responses, the five section vertical and cluster arrangements produced higher fail-critical (non-serious) responses than did the five section horizontal PPLT signal display arrangement.

Drivers may have committed more fail-critical (non-serious) responses at a green ball permitted indication due to the green ball being used in the majority of PPLT signal displays throughout the United States and, in particular, the Amherst, Massachusetts area. Drivers would tend to be more comfortable with the green ball permitted indication then with any other permitted indication and make their response decision quickly allowing them to accelerate prior to the left-turn. The higher percentage of correct responses for the five-section horizontal arrangement may be due to drivers' caution and lack of experience with this display type. Drivers approached this arrangement slowly as they made a decision on their response and, in turn, yielded correctly to the PPLT display.

The final incorrect response, fail-critical (serious), is believed to have the largest safety impact of the three incorrect responses. This response, therefore, is of most concern to the authors. Recall that during a fail-critical (serious) response, a driver goes through an intersection incorrectly, taking the right-of-way from the opposing vehicles. In total, there were only 5 out of 991 responses, or 0.5 percent, that were fail-critical (serious). All fail-critical (serious) responses were produced by drivers under the age of 24, with less than a college degree. Three female subjects produced four of the five fail-critical (serious) responses, all with the horizontal five-section PPLT signal display present. The green ball permitted indication was the only indications producing more than one fail-critical (serious) response.

CONCLUSIONS

The comparison of the percentage of correct responses to the five-section PPLT signal display arrangement and permitted indication combinations found that gender, age, education, and annual miles driven were all statistically significant variables. In general, male drivers had a higher understanding of PPLT signal displays than female drivers. Drivers between the ages of 25 and 45 consistently performed at a higher correct response rate than drivers both under the age of 25 and over the age of 45. When considering highest level of education completed, those having a college degree displayed a higher level of understanding than those having less than a college degree. Finally, drivers that reported driving over 20,000 miles in the past year had a higher level of understanding than drivers that reported driving between 10,000 and 20,000 miles in the past year. In turn, drivers that reported driving between 10,000 and 20,000 miles in the past year had a higher level of understanding than drivers that reported driving less than 10,000 miles in the past year.

The type of five-section PPLT signal display arrangement has very little effect on the percent of correct responses for the permitted left-turn maneuver. The five-section cluster arrangement had the lowest correct response rate, 78.0, while the five-section horizontal arrangement, has the highest correct response rate, 84.3 percent. These

differences were not statistically significant. This finding was consistent with previous research results (*3, 4*).

The type of permitted indication used in five-section PPLT signal displays had a significant effect on driver understanding of the permitted left-turn maneuver. Overall, the green ball, flashing yellow ball, and flashing yellow arrow were the most understood (92.9, 92.9 and 91.9 correct response rate, respectively), while the flashing red ball and flashing red arrow were the least understood (69.3 and 59.6 correct response rate, respectively). This finding was consistent with previous research results (*3*).

When combining five-section PPLT signal display arrangements and permitted indications, the five-section horizontal arrangement with a flashing yellow ball permitted indication had the highest level of driver understanding with a 97.0 percent correct response rate. The five-section vertical arrangement with a flashing red arrow permitted indication produces the lowest correct response rate at 57.6 percent. Table 4 shows a group rank order of five-section PPLT signal display arrangement and permitted indication combinations by correct response rate.

The type of five-section PPLT signal display arrangement did have an effect on the percent of fail-critical (serious) responses to the permitted movement through intersection while the type of permitted indication did not have any effect. The five-section horizontal arrangement produced 80.0 percent of the fail-critical (serious) responses during the research while the remaining 20.0 percent came from the five-section cluster arrangement. The five-section vertical arrangement produced no fail-critical (serious) responses.

Drivers have a higher understanding of flashing ball permitted indications than flashing arrow indications. The percentage of correct responses for flashing ball permitted indications was 81.1 percent while the percentage correct responses for flashing arrow indications was 75.7 percent.

Table 4 Group Rank Order of Arrangement/Indication Combinations by Percent Correct Response Rates

Group Rank Order	Display	Permitted Signal Indication	Percent Correct Responses
1	5-Section Horizontal	Flashing Yellow Ball	97.0
2	5-Section Horizontal	Flashing Yellow Arrow	93.9
	5-Section Cluster	Green Ball	93.8
	5-Section Horizontal	Green Ball	93.0
	5-Section Vertical	Green Ball	92.4
	5-Section Vertical	Flashing Yellow Arrow	92.4
	5-Section Vertical	Flashing Yellow Ball	92.4
3	5-Section Cluster	Flashing Yellow Arrow	89.4
	5-Section Cluster	Flashing Yellow Ball	89.4
4	5-Section Horizontal	Flashing Red Ball	72.7
	5-Section Vertical	Flashing Red Ball	70.1
5	5-Section Cluster	Flashing Red Ball	65.2
6	5-Section Horizontal	Flashing Red Arrow	60.6
	5-Section Cluster	Flashing Red Arrow	60.6
7	5-Section Vertical	Flashing Red Arrow	57.6

RECOMMENDATIONS

Although the findings presented tend to focus on the highest percentage of correct responses, another important element can be observed in the results. For a PPLT signal display to be considered for uniform application, it must be effective in several key demographic areas; novice *and* older drivers, drivers with low levels of education, and inexperienced drivers. The research results show that the flashing yellow indications have the potential to fulfill these requirements, while performing as good or better that the green ball indication. Since arrangement (horizontal, vertical, cluster) of the five-section displays was found to be insignificant in driver understanding, the flashing yellow arrow and flashing yellow ball permitted indications in any arrangement may overcome the problems identified with the green ball permitted indication. Since the use of a flashing yellow ball permitted indication creates several undesirable operational issues, it is recommended that the flashing yellow arrow permitted indication be further evaluated

as a potential alternative to the green ball permitted indication. Current activities with NCHRP research project 3-54(2) may fulfill this recommendation.

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