POTENTIAL APPLICATION OF THE FLASHING YELLOW ARROW PERMISSIVE INDICATION IN SEPARATED LEFT-TURN LANES

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ABSTRACT

A recommendation of National Cooperative Highway Research Program Report 493 was that a flashing yellow arrow (FYA) permissive indication is an acceptable and recommended application for permissive left-turns. Consideration being given to the adoption of the FYA permissive indication has led to a number of additional studies to evaluate the potential scenarios in which the FYA may be effectively used. An example of this is in wide median intersections where the left-turn lane and corresponding signals are separated from the adjacent lane(s) containing the through and right-turn movements. Left-turn maneuvers from signalized intersections with these geometric features typically operate with protected only left-turn phasing and separate signal displays as drivers cannot see the adjacent through movement signals; however, some transportation professionals have implemented a flashing red arrow (FRA) that requires drivers to first stop before accepting a gap in the opposing traffic stream.

This research quantified driver comprehension of the FYA permissive indications as compared to the FRA indication for use at exclusive left-turn lanes separated from the adjacent through/right travel lanes. The research comprised three primary tasks, including a driving simulator experiment, and two static evaluations and resulted in 264 drivers responding to 1,260 experimental scenarios. The results of this research led to several relevant findings.

The FYA indication was found to have a high driver comprehension on the first exposure. Nevertheless, the FYA in this situation did result in approximately 10 percent of fail critical errors in driver's first exposure to the indication. The large number of drivers who interpreted the FRA as a yield condition is consistent with previous evaluations and indicates an incorrect comprehension of the indication as drivers facing a FRA would be required to stop first. At wide median locations were the use of protected only left-turn phasing is not desirable, the use of the FYA or FRA permissive indications should be used only after consideration of the safety and operational issues common to the initial implementation.

Keywords: Protected / Permissive Signal Control, Left-Turns, Driving Simulation, Traffic Operations, Signal Phasing

INTRODUCTION

The overarching goals of providing high levels of mobility and intersection efficiency, while simultaneously assuring the highest level of safety, often result in competing interests at signalized intersections. The conflict is magnified in the consideration of left-turn movements, where traffic streams are required to cross paths. Protected left-turn control, where left-turning drivers have the right-of-way only on selected phases, provides for the safety of left-turning vehicles, but does not maximize intersection efficiency because some available gaps in the opposing traffic stream are not used for left-turns. Conversely, permissive left-turn control allows left-turn drivers to complete their maneuver assuming sufficient gaps in the opposing traffic exists; however, this is often associated with increased potential for crashes. Protected/permissive left-turn (PPLT) signal phasing provides both a protected phase and a permissive phase all within the same signal cycle, and attempts to balance the competing interests of intersection safety and operational efficiency (1). In recent years, much attention has been given to the application of PPLT signal phasing in use at over 300,000 U.S. signalized intersections.

National Cooperative Highway Research Program (NCHRP) Report 493 was a comprehensive, national research study to evaluate operational advantages and safety aspects of various left-turn controls at signalized intersections (2). The comprehensive research project, which evaluated all elements of protected/permissive left-turn (PPLT) signal displays, was based on several identified problems, in particular, the recommended permissive indication (2). In accordance with the Federal Highway Administration's (FHWA) *Manual on Uniform Traffic Control Devices* (MUTCD), which provides guidance regarding the use of traffic signal displays, a circular green (CG) indication is the recommended visual message for communicating a permissive left-turn indication to drivers (3).

Contrary to drivers making a through movement, the CG indication implies that drivers wishing to complete a left-turn must first yield to oncoming traffic and accept a gap in the opposing traffic stream. While some argued that the CG permissive indication was adequate, others argued that a *unique* indication was needed because drivers, particularly those in a left-turn lane, may interpret the CG as a protected indication, resulting in improper left-turn movements and a situation with high crash potential. For this reason, the permissive indication became the primary focus of NCHRP research (2). A resulting recommendation of the NCHRP research project was that a flashing yellow arrow (FYA) permissive indication provided a viable alternative to the CG permissive indication. Therefore the research team recommended that the FYA permissive indication be included in the MUTCD (2).

The consideration being given to the adoption of the FYA permissive indication has led to a series of follow-up studies evaluating the many potential scenarios in which the FYA may be effectively used (4, 5). An example of this is in wide median intersections where the left-turn lane and corresponding signals are separated from the adjacent lane(s) containing the through and right-turn movements. Currently, left-turn maneuvers from signalized intersections with these geometric features typically operate with protected only left-turn phasing. An example of this is presented in Figure 1. In an attempt to improve operational efficiency, some transportation professionals have implemented a flashing red arrow (FRA) indication allowing drivers to accept available gaps in the opposing traffic stream after stopping. Left-turn are thus accommodated both during the green phase as well as with the FYA.

FIGURE 1 Example wide median intersection where left-turn traffic is separated from adjacent through traffic.

PROBLEM STATEMENT

Wide intersection configurations, where the left-turn lane is separated from the adjacent through and right-turn lanes, create a scenario in which left-turn drivers are unable to see the adjacent through movement signal indications. In most cases, protected-only left-turn signal phasing is used. In an attempt to provide phasing less restrictive than protected-only at this type of application, several agencies have used a FRA indication. While functional, the FRA inherently poses a number of problems related to efficiency and compliance. With the FRA drivers would be required to stop first before proceeding, similar to stop sign, which potentially degrades operational efficiency. Conversely, if drivers operate in a yield format, they are violating the intended meaning of the FRA, which may have safety related consequences at other intersections where flashing red control is employed.

Some wide median applications such as the example cited in Figure 1 could be operated more efficiently with PPLT. The traditional CG permissive indication is not desirable in this application due to driver’s potential to incorrectly assume the right-of-way when viewing the CG. The NCHRP 493 report recommended an alternative FYA permissive indication; however, application of the FYA in a wide median environment was not reviewed in exhaustive detail through the previous research effort (2). For this reason, there is a need to determine the potential feasibility for using the FYA in separated left-turn lanes.

The resulting research question is as follows:

Is the FYA as effective as the flashing red arrow (FRA) indication currently used for permissive control at wide intersections where the left-turn lane is separated from the adjacent through lanes?

EXPERIMENTAL METHODOLOGY

The intent of this research was to quantify driver's comprehension of the FYA permissive indications as compared to the FRA indication for use at exclusive left-turn lanes separated from the adjacent through/right travel lanes. The research comprised three primary tasks, including a dynamic driving simulator experiment, a follow-up static evaluation, and an independent static evaluation administered in both Massachusetts and Wisconsin. The purpose of the static evaluation was to assess driver's pure comprehension of the permissive indications, and the two locations were selected to provide geographic variability and coincided with research team member locations. The dynamic evaluation was used to assess driver comprehension in a more dynamic environment complete with many of the cues associated with real world driving. The details of these evaluations and a description of the driving simulator and static evaluation instrument used are discussed in the following sections.

Signal Displays for Evaluation

The evaluation needed to compare typical FRA applications with the proposed FYA at wide median intersections. It was necessary to evaluate driver comprehension of both indications under the same scenarios. In total, four permissive applications, presented in Figure 2, were evaluated at wide intersections and featured either the FYA or FRA permissive indication. Although the study was focused on driver's comprehension of the selected indications at wide median intersections, additional displays were included in the experiment to provide comparison information, variability in what drivers observed, and to counterbalance the objective functions. A reasonable assumption of the research was that drivers were not familiar with either the FYA or FRA as part of a regular signal cycle, and in particular, to represent a permissive indication. The standard permissive indication, in both Massachusetts and Wisconsin, is the circular green permissive indication; however, in separated left-turn lanes in both states the standard left-turn phasing would be protected only (i.e., drivers are only able to make a left-turn on a protected green arrow indication).

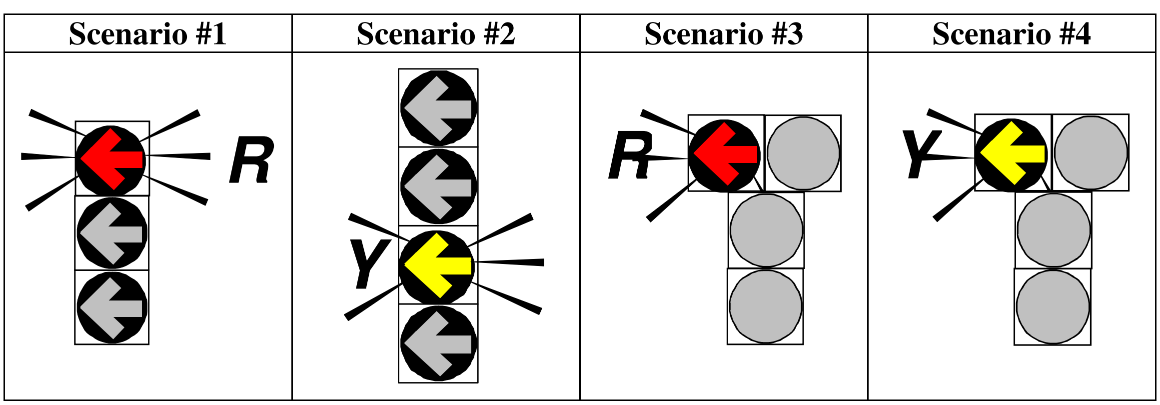

FIGURE 2 Permissive displays evaluated at wide median applications.

Driving Simulator Experiment

The initial experimental methodology was a dynamic driving simulator experiment completed in the Human Performance Laboratory (HPL) at the University of Massachusetts – Amherst (UMass). The driving simulator used was a full-scale, fixed-base fully-interactive 1995 Saturn sedan. Drivers were capable of controlling the steering, braking, and accelerating similar to the actual driving process; the visual roadway adjusted accordingly to the driver's actions. The visual field-of-view, which subtends 150-degrees, was projected by three separate images in a semi-circular fashion. The driving simulator and a sample of a simulated scenario are presented in Figure 3.

FIGURE 3 Driver simulator vehicle and configuration (left) and sample simulated visual world (right).

Development of Simulated Environment

A virtual network of intersections was created for use in the research experiment. Each driver participating in the experiment completed (i.e., drove) a course consisting of two scenario modules with 14 total intersections. Each driving module was a continuous loop with multiple starting positions. Allowing drivers to start at different positions provided appropriate counterbalancing and assured that each of the four experimental scenarios (or protected indication scenarios) was equally likely to be presented first to drivers. As mentioned, the 14 simulated intersections contained FYA, FRA, and an array of protected left-turn, through movement, or right turn phasing concepts. The benefits of these non-left-turn intersections were to provide experimental variability, to reduce the probability of drivers keying in on the nature of the evaluation, and to provide a more realistic driving environment. For this task, the dependent variables at the experimental intersections included drivers' comprehension of the permissive signal displays presented previously in Figure 2.

Operational Characteristics of Simulation

The operational characteristics within the simulation were consistent at all experimental intersections. Specifically, signal displays within the simulation rested in either a prohibited red (circular or arrow) or a protected left-turn (green arrow) indication as drivers approached the intersection. The signal displays then changed to the test indications once the driver was approximately 30 meters prior to the intersection stop bar. Each PPLT signal display was evaluated with opposing traffic at the intersection, to more accurately simulate the real world driving environment and require drivers to evaluate the left-turn indication and traffic movement simultaneously.

All gaps in the opposing traffic stream were consistently applied at the four experimental intersections and consistent with previous research (2, 5). Two vehicles were positioned at the stop bar in the two through lanes opposing the left-turn driver. The remaining four were positioned further upstream in a specified gap sequence. Gaps were set at three and seven seconds in a series of 7-3-7-7; therefore, opposing vehicles crossed the intersection seven, 10, 17, and 24 seconds behind the two initially queued opposing vehicles. The critical gap concept was used to select the gap sizes, which for this intersection design would be a recommended value of approximately five seconds per the Highway Capacity Manual (6). To assure that gaps were not a critical variable in the analysis, unacceptable gaps sizes less than the critical gap (three seconds) and acceptable gap sizes greater than the critical gap (seven seconds) were selected (6).

Recording Driver Responses

Driver comprehension was based on driver's responses at each of the experimental intersections. Driver actions were recorded through the driving simulator; specific driver actions indicating their comprehension of each intersection scenario was manually recorded by researchers. Correct responses were recorded based upon drivers yielding the right-of-way; the presence of the initially queued opposing traffic forced drivers to stop first, which would be consistent with a correct response at a FRA, and as a result, the correct responses were identical in the simulated environment. Incorrect maneuvers/responses were classified as fail-safe or fail-critical in a manner consistent with previous research (2, 4). A fail-safe response is one in which the driver did not correctly respond to the signal display arrangement/permissive indication combination, yet 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 signal display and impeded the right-of-way of opposing traffic, thus creating the potential for a crash.

Static Evaluations

After completing the dynamic driving simulator experiment, each driver immediately completed a follow-up computer-based static evaluation. Additionally, over 100 subjects in both Madison, Wisconsin and Amherst, Massachusetts were recruited to complete the computer-based static evaluation in what was labeled an independent static experiment. The static evaluation instrument presented drivers with various traffic signal displays in realistic background photos and allowed for the signal indications to flash as required. A sample computer-based static evaluation scenario is presented in Figure 4. For each signal display, drivers were asked to respond with one of four choices to the following question:

"If you want to turn left and you see the traffic signal lights shown, you would?"

- Go, you have the right-of way;
- Yield, wait for a gap;
- Stop, then wait for a gap; or,
- Stop, wait for signal.

As part of the static evaluation, drivers observed the PPLT scenarios previously presented in Figure 2. Based upon the scenarios, drivers would assume that they were the first vehicle in the queue waiting to complete their left-turn maneuver. As with the simulator experiment, drivers observed additional scenarios in the static evaluation beyond the experimental wide median intersections. In total, each driver observed 29 scenarios as part of the static evaluation. The static evaluation instrument was designed such that the order in which the scenarios were presented was completely randomized across drivers, and it also allowed for all the driver responses to be downloaded to a spreadsheet file.

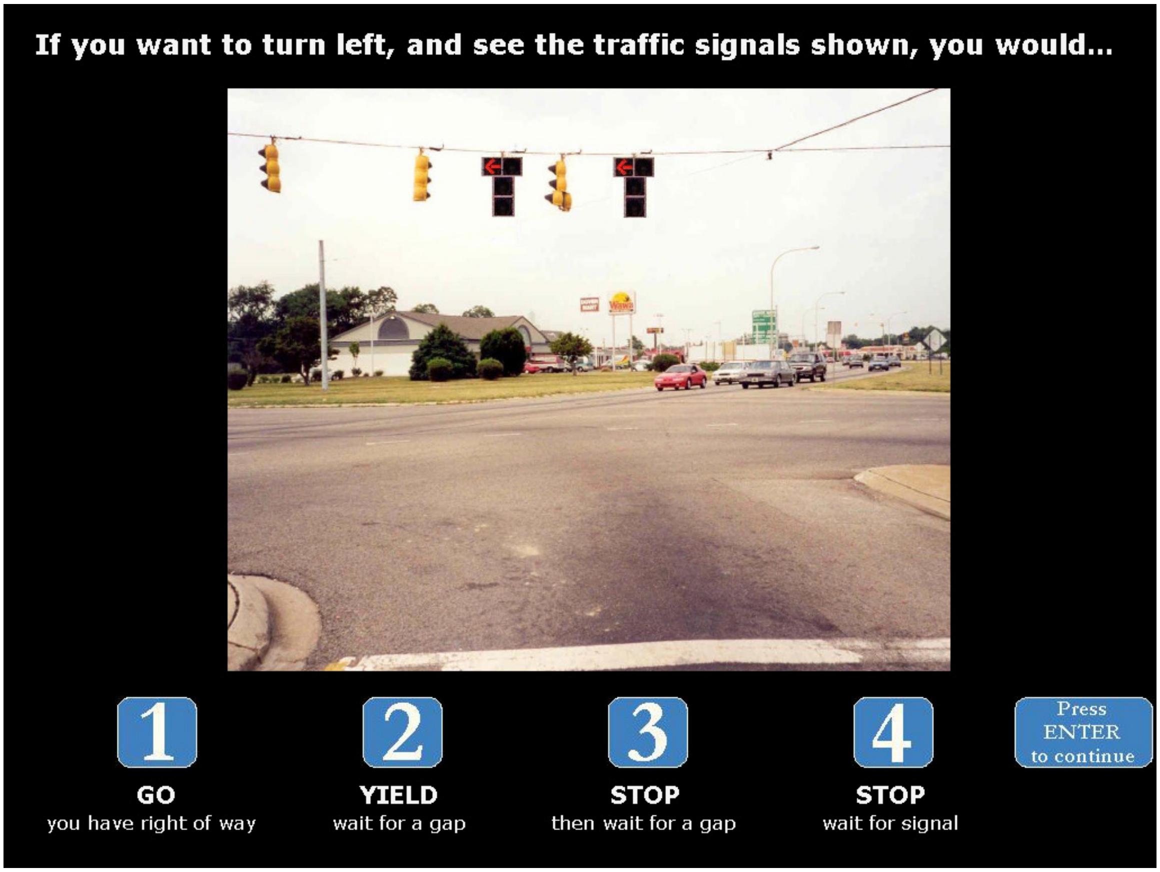

FIGURE 4 Sample of the static evaluation scenarios.

RESEARCH RESULTS

A total of 264 drivers participated in the experiment, with 54 drivers participating in the dynamic driving simulator experiment and follow-up static evaluation and 210 drivers participating in the independent static evaluation. Of the 210 independent static evaluation drivers, 101 completed the experiment in Massachusetts and 109 completed the evaluation in Wisconsin. Six drivers participating in the simulator experiment elected not to complete the simulation as a result of simulator induced discomfort or time constraints, yet all 54 managed to fully complete the follow-up static evaluation. In total, 200 experimental scenarios were evaluated in the driving simulator, with 50 responses recorded for each of the scenarios presented in Figure 2. With respect to the static evaluations, there were 220 and 840 experimental responses for the follow-up and independent static evaluations, respectively. Demographics were disaggregated into sex, age, driving experience, and education level as summarized in Table 1. Driving experience was correlated to the number of miles driven in the previous year, and education was based upon the highest level of education completed by the participating driving.

TABLE 1 Breakdown of Driver Demographics

		Driving Simulator and Follow-Up Static		Independent Static Evaluation			
				Massachusetts		Wisconsin	
Category	Level	No. of Drivers	% of Total[a]	No. of Drivers	% of Total[b]	No. of Drivers	% of Total[c]
Gender	Male	27	50	48	48	67	61
	Female	27	50	53	52	42	39
Age	Under 25	21	39	31	31	70	64
	25 to 44	27	50	40	40	36	33
	Over 44	6	11	30	30	3	3
Annual Miles Driven	Under 10,000	16	30	42	42	64	59
	10,000 to 20,000	20	37	34	34	38	35
	More than 20,000	18	33	25	25	7	6
Highest Education Level	High School	3	6	17	17	6	6
	Some College	12	22	42	42	64	59
	College Degree	39	72	42	42	39	36

[a] Percent of sample based on 54 drivers in simulator evaluation
[b] Percent of sample based on 101 drivers in Massachusetts
[c] Percent of sample based on 109 drivers in Wisconsin

Driving Simulator Experiment

In the driving simulator experiment, four experimental scenarios were considered in the wide median intersection analysis. Driving simulator responses were classified as follows to allow comparison with the static evaluations:

- Go – the driver incorrectly perceived the right-of-way and either crashed or narrowly avoided a crash;
- Yield – the driver yielded the right-of-way to opposing vehicles before selecting a gap in opposing traffic; note that the presence of the initially appeared opposing traffic

would force drivers to stop as part of the yield maneuver, and as a result in the simulator this would be the correct response for both the FRA and FYA scenarios;

- Stop first – the driver stopped at the left-turn lane stop bar and waited for all opposing vehicles to pass before proceeding; note that this response was also considered to be correct; or
- Stop and wait – the driver stopped at the left-turn stop bar and waited even after all opposing vehicles had cleared waited as if waiting for the signal to change. Drivers had to be instructed to proceed, but were instructed to continue doing that which they believed to be appropriate at future intersections.

Figure 5 presents the breakdown of driver responses from the driving simulator experiment. A series of chi-square analyses were completed to identify statistically significant responses at a 95 percent confidence level. Based upon the data presented in Figure 5, the following results can be reported:

- There were significantly more *yield* responses at the two FYA scenarios as compared to the FRA scenarios.
- There were no statistically significant differences between the percentages of *yield* responses for the FYA in a four-section vertical configuration versus the FYA in a four-section "T" configuration.
- There were no statistically significant differences in the percentage of *yield* responses and *stop first* responses observed at the three-section vertical configuration with FRA permissive indication versus the FRA in a four-section cluster configuration.
- A total of ten fail-critical (*go*) responses were observed at the two scenarios with FYA permissive indications. It should be noted that all but one of the fail critical responses occurred on the very first FYA scenario observed by a particular driver. Alternatively, no fail-critical responses were observed at the FRA scenarios. This result was statistically significant.
- In 16 instances drivers observing a FRA permissive indication had to be instructed to proceed after allowing all opposing traffic to pass and remaining stopped as if waiting for a change of the signal. This response was not observed at either scenario with the FYA permissive indications.

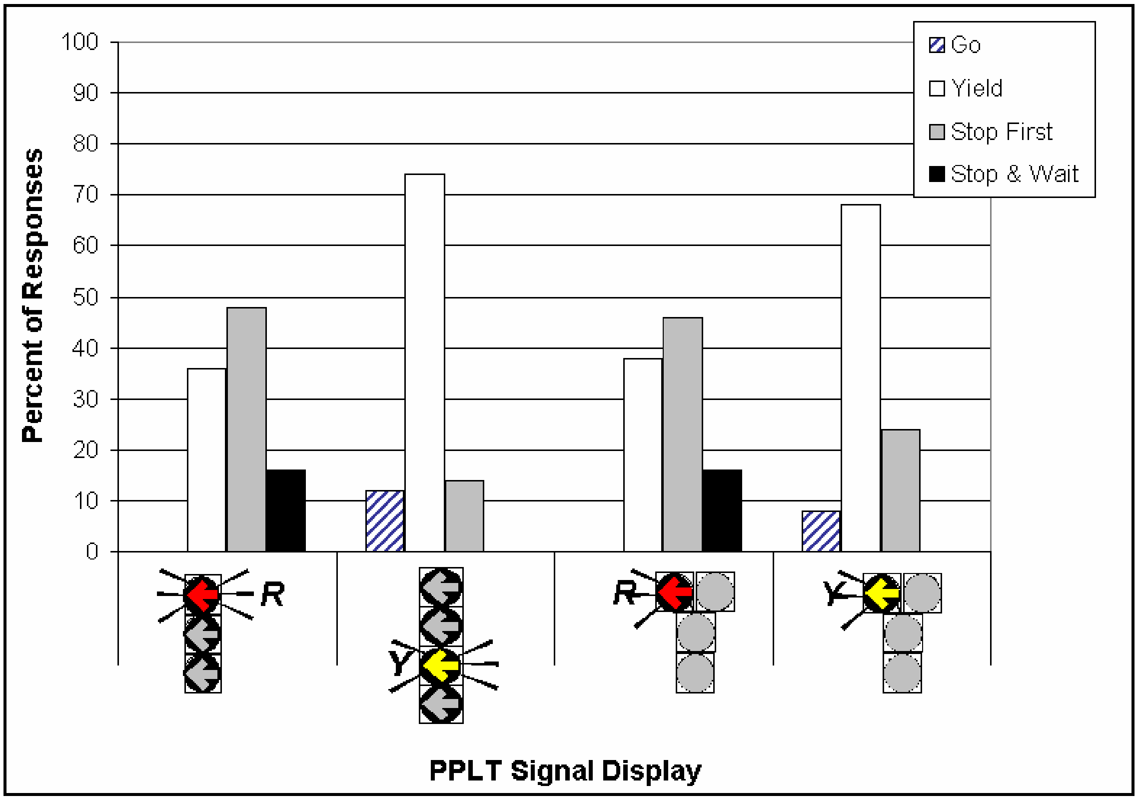

FIGURE 5 Breakdown of driver responses for driving simulator experiment.

Follow-Up Static Evaluation

The follow-up static evaluation responses presented in Figure 6 resulted in similar findings to that of the simulator study as follows:

- There were significantly more *yield* responses at the FYA scenarios than at the FRA scenarios, while at the FRA scenarios there were statistically higher percentages of *stop first* responses.
- There was no statistically significant difference between the *yield* responses at the FYA scenarios as compared to the *stop first* responses at the FRA scenarios.
- Combining the *yield* and *stop first* responses results in nearly identical levels of correct responses for all four scenarios ranging between 91 and 93 percent correct.
- Six of the seven *go* responses occurred at the FYA scenarios (with three for each scenario), and the seventh *go* response occurred at the FRA in a three-section vertical configuration.
- Consistent with the simulator, *stop and wait* responses were mostly observed at the two FRA scenarios (eight of 11 were at FRA scenarios with four observed at each FRA scenario); however, this difference was not statistically significant.

A query of simulator and follow-up static evaluation responses was undertaken to track drivers' fail-critical responses based upon the premises that these would be of greatest concern given their crash potential. To complete the query, all fail-critical responses from the simulator were matched with that driver's response to the same scenario in the follow-up static evaluation.

Of the six fail-critical responses at the FYA permissive indication in a four-section vertical configuration, drivers later responded correctly on four instances and responded *stop first* on another instance. Only one diver responded *go* in both cases. For the four-section cluster configuration with a FYA permissive indication, three of the four drivers making a fail-critical error later responded correctly in the follow-up static evaluation, and the last driver again responded incorrectly by choosing a *go* response.

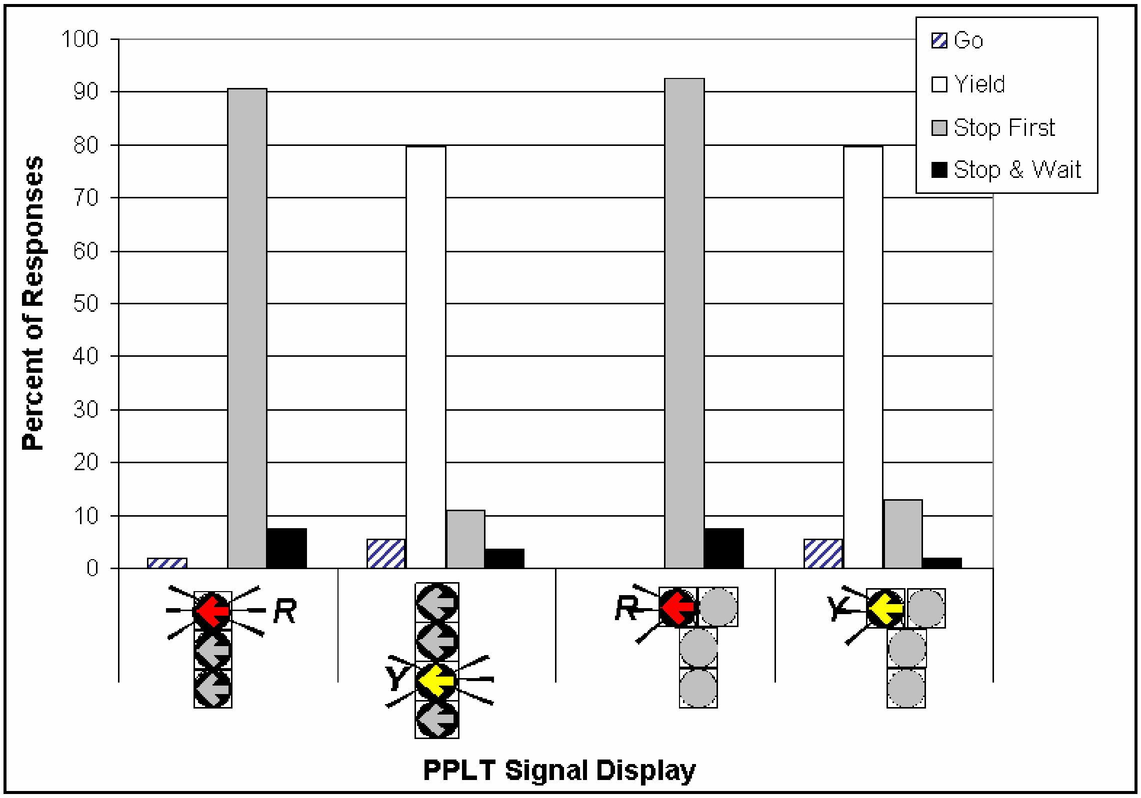

FIGURE 6 Breakdown of driver responses for follow-up static evaluation.
Independent Static Evaluation

In the independent static evaluation, the trend in responses was statistically identical between Massachusetts and Wisconsin. As a result, driver responses were aggregated and a breakdown of driver responses for the four signal display scenarios is presented in Figure 7. Responses are consistent with both the simulator and follow-up static evaluations with the following results:

- The percentage of *yield* responses for the FYA scenarios at 62 (FYA in four-section vertical configuration) and 61 percent (FYA in four-section cluster configuration) are equivalent to the *stop first* responses for the FRA scenarios (62 percent for FRA in three-section vertical configuration and 61 percent for FRA in four-section cluster configuration).
- There was a statistically significant higher percentage of *go* responses for the FYA scenarios than the FRA scenarios. In contrast, there was also a statistically higher percentage of *stop and wait* responses for the FRA scenarios than the FYA scenarios.
- If the *stop first* and *yield* responses are both considered to be correct, the percentage of correct responses is higher for the two FYA scenarios than for the two FRA scenarios; however, this difference was not statistically significant.

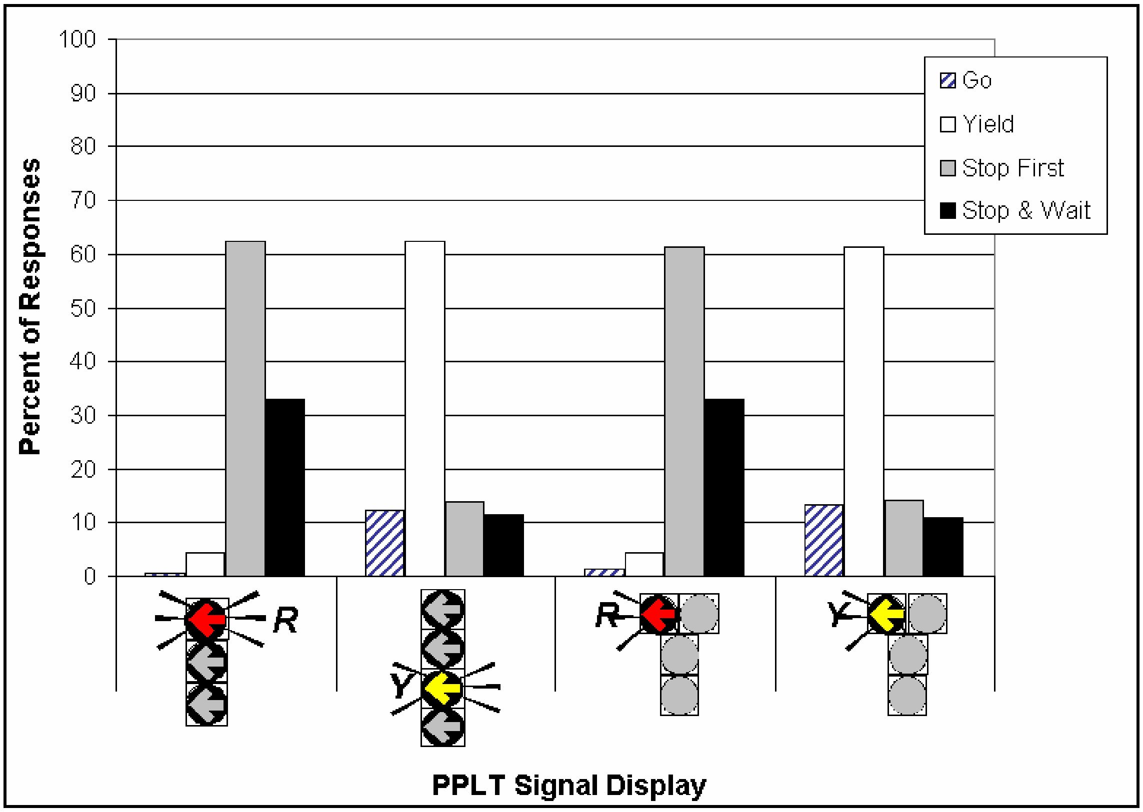

FIGURE 7 Breakdown of driver responses from independent static evaluation.

Summary

The results of the dynamic driving simulator experiment led to several statistically significant findings, including a significantly higher percentage of yield responses observed for the two scenarios with a FYA permissive indication in the dynamic simulator evaluation. There were no statistically significant differences between the percentages of *yield* responses for the two different configurations of the FYA. No statistically significant differences existed in the percentage of *yield* responses and *stop first* responses observed at the three-section vertical configuration with FRA permissive indication versus the FRA in a four-section cluster configuration. Additionally, a significantly higher percentage of fail-critical (go responses) were observed at the two scenarios with FYA permissive indications as compared to the FRA scenarios. In fact, there were no fail-critical errors at the two scenarios with the FRA permissive indication. Nevertheless, a statistically significant higher percentage of stop and wait responses were observed at the FRA scenarios (drivers were waiting for the appropriate signal and had to be directed to proceed). When drivers made a fail-critical error (assumed the right of way) at a FYA scenario, it had the potential to result in either a crash or near miss. Driver's not comprehending the FRA remained stopped at the left-turn stop bar waiting for a change in signal. Also noteworthy is the number of driver's yielding at the FRA, when in fact they are legally required to stop.

In the follow-up static evaluation, the findings were similar. Significantly more *yield* responses were observed at the FYA scenarios than at the FRA scenarios, while at the FRA scenarios there were statistically higher percentages of *stop first* responses. From a statistical perspective, there is no difference between the *yield* responses at the FYA scenarios when compared with the *stop first* responses at the FRA scenarios. Combining the *yield* and *stop first* responses resulted in nearly identical levels of correct responses for all four scenarios ranging between 91 and 93 percent. When drivers made an error in the static evaluation, there were differences amongst scenarios. Specifically, six of the seven *go* (fail-critical) were associated with FYA scenarios. Consistent with the simulator, *stop and wait* responses were mostly observed at the two FRA scenarios (eight of 11 were at FRA scenarios with four observed at each FRA scenario); however, this difference was not statistically significant.

The independent static evaluation provided still more significant findings, which were consistent with both the dynamic driving simulator and follow-up static evaluations. Specifically, the percentage of *yield* responses for the FYA scenarios (62 percent for the FYA in four-section vertical configuration and 61 percent for the FYA in four-section cluster configuration) are statistically equivalent to the *stop first* responses for the FRA scenarios (62 percent for FRA in three-section vertical configuration and 61 percent for FRA in four-section cluster configuration). There were significantly more *go* responses for the FYA scenarios than the FRA scenarios; however, there was a statistically higher percentage of *stop and wait* responses for the FRA scenarios than the FYA scenarios. If the *stop first* and *yield* responses are both considered to be correct, the percentage of correct responses is highest, 76 percent for both FYA scenarios, as compared to 67 and 66 percent correct for the two FRA scenarios; however, this difference is not statistically significant at the 95 percent confidence level. Thus, there was no difference in driver comprehension across displays.

CONCLUSIONS AND RECOMMENDATIONS

The FYA indication has a high percentage of driver comprehension on the first exposure with a rate comparable to that seen in NCHRP Report 493, however, there is some concern over the initial percentage of fail-critical responses at wide median intersections. Wide median intersections provide a unique scenario for drivers. The percentage of fail critical responses in the simulator and static environments with the FYA permissive indication may indicate a need to initially supplement the FYA indication at wide median locations (i.e., signage, training). Nevertheless, drivers participating in the research had no previous experience or training with the FYA, and in all but one case, responded correctly on the next exposure.

The FRA results in significantly fewer fail-critical errors than the FYA permissive indication, which is important given the potential of these errors to result in a crash. The large number of drivers who interpreted the FRA as a yield condition is consistent with previous evaluations and also indicates an incorrect comprehension of the indication as drivers facing a FRA would be required to stop first (similar to stop sign control) (1). The FYA has operational benefits over the FRA as drivers are not legally required to stop. A larger number of left-turn vehicles are able to accept the same large gaps decreasing follow-up headways and increasing the operational efficiency and capacity of the left-turn lanes.

It is reasonable to assume that protected only phasing offers the safest alternative at wide median intersections; however, when a permissive indication is desired there is some potential for the FYA permissive indication to be effectively used.

The FYA offers a new tool to traffic engineers and, as documented by NCHRP 493, is widely understood by drivers. While the FYA shows great potential and has been implemented successfully in several jurisdictions across the U.S., it should be more widely implemented and accepted before being introduced in wide median applications. Although some drivers interpreted the FYA to be a ‘go’ response, the authors believe that may be in part attributed to the simulated environment, interpretation of opposing gaps, and first exposure to the display. In contrast, although the FRA display appears to work safely and has been implemented in wide median applications, the FRA does not appear to be well understood. Drivers exhibit a tendency to incorrectly assume a yield condition at wide median FRA applications – creating the potential for drivers to misinterpret the meaning of a flashing red at installations where a stop is absolutely necessary for safety reasons. This dilution effect has been previously identified. At wide median locations were the use of protected only left-turn phasing is not desirable, the use of the FYA or FRA permissive indications should be used only after consideration of the safety and operational research results presented.

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