Analysis of Driver and Pedestrian Comprehension of Requirements for Permissive Left-Turn Applications

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Operations engineers commonly program traffic signal controllers to serve the pedestrian movement at the same time as the parallel vehicular through movement. This requires drivers completing a permissive left-turn movement to yield to opposing vehicles and pedestrians before selecting an appropriate gap. To minimize the potential safety problem, it is critical that drivers and pedestrians understand the permissive left-turn signal indications. The recently completed NCHRP Report 493 identified that a flashing yellow arrow (FYA) permissive indication provided a preferred alternative to the existing circular green permissive indication and recommended that the FYA permissive indication be included in the Manual on Uniform Traffic Control Devices. This paper presents research findings of a follow-up study that targeted the FYA impact on pedestrians, including driver comprehension of the need to yield to pedestrians and pedestrians’ recognition of appropriate crossing opportunities. Driver and pedestrian comprehension of the FYA indication was evaluated with a series of dynamic driving simulator evaluations and computer-based static evaluations. In total, 139 drivers and 100 pedestrians were evaluated in 5,930 experimental scenarios. The FYA permissive indication can be safely and effectively used at intersections with pedestrian activities. Given the high level of comprehension to yield requirements, the FYA is a recommended indication at T-intersections where pedestrian crossings are prevalent. Fewer than half the pedestrians understood correct crossing procedures when pedestrian signal heads were not present, and pedestrian comprehension of the walking requirements under a flashing “don’t walk” were quite low in all scenarios evaluated.

Although walking is the oldest mode of transportation, accommodating pedestrians in the transportation system is often of low priority. Increased pedestrian and vehicle exposure is often associated with a relatively high risk of injury or death on the existing networks of streets and highways. Specifically, the interaction of pedestrians with motor vehicles results in the greatest potential for injury or death when a crash occurs. As a result, pedestrian safety remains a critical concern in the United States. In 2003, there were 4,749 pedestrian fatalities and approximately 70,000 pedestrian injuries caused by motor vehicle crashes (1).

Much emphasis on highway transportation has historically focused on increasing the safety and mobility of motor vehicles. Nevertheless, ensuring consistency with the goals of providing a safe and efficient transportation system for all users, accommodating pedestrians at signalized intersections has become the focus of numerous research efforts (2, 3). Such studies have attempted to quantify the magnitude and characteristics of pedestrian crashes and identify the traffic and roadway characteristics associated with these events. One area where the potential for conflict between vehicles and pedestrians is magnified occurs at signalized intersections.

In an effort to improve operational efficiency, a common method of incorporating pedestrian phasing at signalized intersections is to allow pedestrians to move simultaneously with parallel traffic. For example, a pedestrian wishing to move north to south would be permitted to cross (i.e., receive the walk indication) while northbound-southbound traffic is moving (except during protected left-turn phases). Currently, drivers making a permissive left-turn movement are required to yield to opposing vehicles, select a gap in opposing traffic, and yield to pedestrians who are lawfully crossing the intersection parallel with through-moving traffic. In accordance with the FHWA Manual on Uniform Traffic Control Devices (MUTCD), a circular green (CG) indication is the recommended visual message for communicating a permissive left-turn indication to drivers (4).

The recently completed NCHRP Report 493 was a comprehensive, national research study to evaluate operational advantages and safety aspects of various left-turn controls at signalized intersections (5). The research evaluated the operational, safety, and human factor issues related to protected-permissive left-turn (PPLT) signal phasing. The recurring major problem, and focus of the NCHRP report, was based on the CG permissive indication. Results of the research indicated that the flashing yellow arrow (FYA) performed as well as or better than the CG and was a viable alternative to the CG permissive indication. Therefore, the research team recommended that the FYA permissive indication be included in the MUTCD (5). The consideration being given to adopting the FYA permissive indication (possibly as soon as the 2008 MUTCD) has led to additional research questions that warrant further consideration.

PROBLEM STATEMENT

By allowing pedestrians to move parallel with traffic, drivers making a permissive left-turn, which is typically communicated to a driver with a CG indication, are required to yield to pedestrians who are
lawfully crossing an intersection parallel with through-moving traffic. Research is needed to determine whether drivers observing a FYA permissive indication are aware of their requirement to yield the right-of-way to pedestrians. Driver comprehension of the FYA regarding pedestrians is also significant at intersections with three approaches (T-intersections).

An additional question related to potential implementation of the FYA centers around pedestrian comprehension. Specifically, there is a need to evaluate pedestrian comprehension related to FYA permissive indication. This is of particular concern when no pedestrian signals are present and pedestrians must safely select appropriate crossing intervals.

The resulting research questions associated with the evaluation of driver and pedestrian comprehension related to the FYA permissive indication are as follows:

- Do drivers facing an FYA indication comprehend that they are required to yield to pedestrians?
- Similarly, do pedestrians comprehend Walk opportunities at a FYA permissive indication when no pedestrian signals are present?

**EXPERIMENTAL METHODOLOGY**

The evaluation of pedestrian implications of the FYA included comprehension evaluations from both a driver and a pedestrian perspective. Specifically, two static evaluation instruments were designed and administered. Additionally, a driving simulator experiment was created to address driver comprehension of the need to yield the right-of-way to pedestrians when facing a permissive left-turn indication.

**Driver Comprehension of Pedestrian Requirements at FYA**

Three components to the evaluation of driver comprehension of the requirements to yield the right-of-way to pedestrians at permissive left-turn applications were considered:

- A driving simulator experiment,
- A follow-up computer-based static evaluation for drivers completing the simulator experiment, and
- An independent static evaluation for drivers not participating in the simulator experiment.

**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. The driving simulator used was a full-scale, fixed-base fully interactive 1996 Saturn sedan. Drivers were capable of controlling the steering, braking, and accelerating similar to the actual driving process; the visual roadway adjusted according to the driver’s actions. The visual field-of-view, which subtends 150°, was projected by three separate images in a semicircular fashion. The driving simulator and a sample of a simulated scenario are presented in Figure 1.

A virtual network of intersections was created for the HPL driving simulator. Each driver participating in the experiment completed a driving course consisting of multiple driving modules, each containing 14 total intersections. With starting positions being varied, appropriate counterbalancing was provided to ensure that each PPLT scenario was equally likely to be presented first to drivers. In addition to the experimental intersections, drivers were required to traverse several additional intersections. The rationale for including additional intersections requiring drivers to complete a protected left-turn maneuver, proceed straight, or turn right was to provide experimental variability and reduce the probability of drivers keying in on the nature of the evaluation.

Several different intersection scenarios were evaluated. Intersection geometry varied; three scenarios included standard four-leg intersections and two were three-leg intersections (T-intersections). The five permissive scenarios included in the driving simulator evaluation are presented in Figure 2. As noted, drivers completed two driving modules as part of the experiment. Although pedestrians were present in the first module, they were always walking along the...
sidewalk and were never attempting to cross the intersection at any point. The second module required drivers to make decisions about the need to yield to pedestrians.

Each scenario was presented twice to each driver, once with and once without crossing pedestrians. All scenarios included the presence of opposing traffic. Specifically, two opposing vehicles were queued at the opposing stop bar and were released as the left-turn indication changed from stop to permissive mode as the driver approached the left-turn lane stop bar. After queued vehicles were cleared, the next vehicle in the opposing traffic stream did not cross the intersection stop bar until 20 s after the two initial vehicles cleared. Drivers were not informed of the opposing vehicles’ movements until a decision on their left-turn maneuver was made. This method of opposing traffic allowed for an evaluation of the driver’s comprehension of yield requirements. In scenarios with pedestrian crossings, pedestrians crossed the street parallel with through traffic and in conjunction with left-turn traffic (i.e., subject drivers). To evaluate the driver’s comprehension of the requirement to yield to pedestrians, the pedestrians crossed right after the two initial opposing vehicles cleared.

Driver responses were manually recorded, with the focus being whether drivers correctly yielded to pedestrians, and were aggregated into three general categories as follows:

- Correct. Driver recognized the need to yield to the pedestrian; the driver waited in the travel lane for the pedestrian to cross before beginning the left-turn maneuver.
- Fail-safe. Driver began to make a left-turn maneuver but slowed to allow the pedestrian to cross the street, essentially stopping in the opposing travel lane. (This situation would have had the potential to become dangerous if opposing traffic were approaching.)
- Fail-critical. Driver did not yield the right-of-way to the pedestrian, as evidenced by one or more of the following criteria:
  - Driver sped up or swerved to miss the crossing pedestrian (typically passing in front of the crossing pedestrian at a high rate of speed);
  - Driver slammed on the brakes to avoid hitting the crossing pedestrian; and
  - Driver would have hit the pedestrian; however, the pedestrian was removed in the simulation to avoid an actual crash.

**Static Evaluations**

A static evaluation was developed and administered to all drivers completing the simulator experiment. The static evaluation was designed to evaluate drivers’ comprehension of the requirement to yield the right-of-way to pedestrians when observing a FYA permissive indication. To expand the number of observations, an additional 100 drivers completed the static evaluation outside the driving simulator environment. In total, 25 scenarios, including nine with permissive left-turn indications, were evaluated. The permissive indication displays are presented in Figure 3.

An additional variable related to the type of pedestrian presence was introduced. Specifically, each of the 25 displays was evaluated with no pedestrians, with a pedestrian waiting to cross, and with a visually impaired pedestrian (with dog guide) waiting to cross. The rationale for including different background images was to determine whether drivers’ recognition of the requirement to yield to pedestrians was affected by the presence or type of pedestrian present. The signal–pedestrian presence combination resulted in 75 total scenarios, too many to present to any single driver. As a result, the static evaluation instrument was designed to present 25 randomly selected scenarios from the total 75 to each driver.

Consistent with previous study questions, drivers were asked to respond appropriately given their intentions of completing a left turn. The initial question and responses were presented as follows: “If you want to turn left, and see the traffic signals shown, would you?”

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

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**FIGURE 2** Permissive scenarios evaluated in driving simulator experiment.
If drivers selected “yield, then go,” they were presented a follow-up question asking them to select all appropriate responses for the following question: “If you want to turn left, and see the traffic signals shown, to whom are you required to yield?”

- Opposing vehicles,
- Pedestrians,
- Cross-street vehicles, or
- None of the above.

More than one response could be selected with the follow-up question. A sample of the static evaluation (left-turn driver perspective) scenario and possible follow-up scenario for “yield” responses is presented in Figure 4.

**Pedestrian Comprehension of the FYA Permissive Indication**

This component of the research was completed using only a computer-based static evaluation from the perspective of a pedestrian waiting to cross the roadway. The evaluation presented several pedestrian crosswalk situations with various signalization alternatives and asked pedestrians about specific elements of the crossing. Specifically, pedestrians were asked to respond to the following question: “You are standing on the curb waiting to cross. Given the traffic signals shown, are you permitted to walk?”

- Yes,
- No,
- Or
- Not sure.

Scenarios included combinations of signalization with and without pedestrian signal displays. In total, seven permissive left-turn signal displays were evaluated from a pedestrian perspective, both without pedestrian signals present and with a flashing “don’t walk” indication. The “don’t walk” indication was the upraised hand, consistent with the MUTCD. The permissive indications evaluated in this pedestrian static evaluation are presented in Figure 5, and a sample static evaluation scenario is presented in Figure 6. The intent was to determine whether pedestrians were able to determine appropriate walk opportunities in the absence of pedestrian signals.

In addition, the evaluation included other combinations of signal indication scenarios, including, circular red (CR), circular yellow (CY), solid yellow arrow as well as assorted variations of “walk” (walking person symbolizing walk), “don’t walk,” flashing “don’t
walk,” and no-pedestrian-signal-head scenarios. Each pedestrian observed all 30 scenarios developed.

The resulting data from the static evaluation were a compilation of pedestrian responses to the various permissive scenarios. When the flashing “don’t walk” signal was illuminated, the correct response was not to cross, and when no pedestrian signal display was present, pedestrians were permitted to cross. A $\chi^2$ analysis across permissive scenarios was completed for both flashing “don’t walk” and no-pedestrian-signal display scenarios.

**RESEARCH RESULTS**

Driver and pedestrian comprehension of the FYA indication was evaluated at or near the pedestrian crosswalks. A total of 139 drivers participated in the experiment, with 36 drivers participating in the dynamic driving simulator experiment and follow-up static evaluation and 103 drivers participating in an independent static evaluation. The simulator data were consistently monitored after every 12 subjects because of the time and costs associated with a simulator study.
After 36 drivers had completed the dynamic evaluation, the results were consistent and subject recruitment was halted. One hundred pedestrians completed the pedestrian comprehension static evaluation. Table 1 presents a breakdown of general demographics from each evaluation methodology. All drivers and pedestrians participating in the experiment did so in Massachusetts where the predominant permissive indication is the CG in a five-section cluster arrangement. In total, 180 PPLT scenarios were evaluated in the driving simulator, 176 PPLT scenarios were evaluated in the follow-up static evaluation, and 2,575 PPLT scenarios were evaluated in the independent static evaluation. Pedestrians completing the static evaluation evaluated a total of 3,000 scenarios.

![FIGURE 5 Permissive indications evaluated in pedestrian perspective static evaluation.](image)

![FIGURE 6 Sample scenario from pedestrian comprehension static evaluation.](image)
Driving Simulator and Follow-Up Static Evaluation Results

The driving simulator analysis on driver’s comprehension and behavior related to parallel pedestrian movements and opposing vehicles. Figure 7 presents the driver responses for the five permissive displays evaluated in the driving simulator. A 95% confidence interval is indicated in Figure 7 for each response (represented by the vertical line segment). There were no statistically significant differences in responses for any display type. When all 180 simulator responses (five scenarios by 36 drivers) were combined, the percentage of correct responses was statistically lower than the percentage of fail-safe responses.

Figure 8 presents the follow-up static results for the same five scenarios evaluated in the driving simulator. As before, the 95% confidence interval is represented by the vertical line segment for the “yield” responses only. There was no statistically significant difference in the percentage of “yield” responses between scenarios at standard four-leg intersections. Nevertheless, there are statistically significant differences between the two T-intersection scenarios as the FYA scenario had significantly more “yield” as well as “stop and wait” responses. Conversely, the scenario with the CG permissive indication was associated with a statistically significant higher percentage of “go” responses.

Independent Driver Comprehension Static Evaluation

Each participating driver responded to a random sample of 25 scenarios from the database of 75 total scenarios that were described...
previously, including nine scenarios with different combinations of permissive indications and background scenarios (no pedestrian, pedestrian, and visually impaired pedestrian). At each permissive scenario, the correct response for drivers was to yield, regardless of the background scenario. Recall that drivers selecting “yield” were prompted with a follow-up question asking to whom they were to yield. At the standard (four-leg) intersection, drivers were also required to yield to opposing vehicles. At the two T-intersection scenarios, there were no opposing vehicles and hence no yield to vehicles was required. The reason for including a T-intersection was to evaluate driver comprehension of the unopposed scenario.

Because there were no statistically significant differences in the percentage of “yield” responses, regardless of the background image presented, data were combined for analysis purposes. That is, there was no difference in the percentage of “yield” responses at the PPLT signal displays regardless of whether the background image had no pedestrians, a pedestrian, or a visually impaired pedestrian. Figure 9 presents the breakdown of driver responses for each permissive display for the combined set of background images. Figure 10 presents a summary of responses for drivers completing the follow-up question. At the seven standard four-leg intersections, the following was observed:

- The scenario that featured a CR and FYA displayed simultaneously in a five-section cluster configuration had a significantly lower percentage of “yield” responses than all other scenarios except the one featuring a CY–FYA displayed simultaneously in a five-section cluster.

- Each scenario (CG in a five-section cluster and FYA in a four-section vertical when the adjacent through is CG) had a significantly higher percentage of “yield” responses than the scenarios featuring the four scenarios with all combinations of FYA permissive with CY or CR through indications.

- There were no statistically significant differences in the percentage of “go” responses at the seven scenarios from standard intersections.

- According to results of the follow-up question, approximately 73% of all drivers responding “yield” indicated some level of requirement to yield to pedestrians.

For the two scenarios at T-intersections, the following was observed:

- The percentage of “yield” responses was statistically higher for the FYA scenario, as were the “stop first” and “stop and wait” responses.

- By comparison, the percentage of “go” for the CG scenario was statistically higher than for the FYA scenario.

Pedestrian Comprehension Static Evaluation

One hundred pedestrians completed the computer-based static evaluation. Figure 11 presents the breakdown of correct responses in the static evaluation. In the absence of pedestrian signal heads, it would be permissible for pedestrians to cross the street when the pedestrian is facing a permissive left-turn signal indication. As indicated in Figure 11, the highest percentage of pedestrians responding “yes” occurred when the CG was presented in a five-section cluster configuration. Statistically, this scenario resulted in significantly more “yes” responses than all other displays ($p < .001$). There were no statistically significant differences in “yes” responses across all six scenarios featuring a FYA permissive indication.

For scenarios featuring the flashing “don’t walk” message, the correct response in this situation would be “no,” as pedestrians should not walk on the flashing “don’t walk” indication if they have not already left the curb. Statistically, there was no significant difference in pedestrian responses across all displays ($p = .504$).

CONCLUSIONS AND RECOMMENDATIONS

Measuring comprehension for drivers and pedestrians using a dynamic simulator evaluation and follow-up static evaluation resulted in several important findings. Data for 36 drivers completing the
dynamic simulator evaluation and follow-up static evaluation lead to the following conclusions:

- Using generalized correct responses and responses that resulted in fail-safe or fail-critical conditions, there was no statistically significant difference within responses for the five scenarios evaluated in the dynamic driving simulator evaluations.
- Combining all 180 simulator responses (five scenarios by 36 drivers), the percentage of “yield” responses (i.e., correct responses) was statistically lower than the percentage of fail-safe responses, demonstrating a low driver comprehension of the requirement to yield to pedestrians when the pedestrian was legally within the crosswalk, regardless of the signal display.
- No statistically significant difference in “yield” responses existed between scenarios at standard four-leg intersections in the follow-up static evaluation.
- There are statistically significant differences between the two T-intersection scenarios as the FYA scenario had significantly more “yield” as well as “stop and wait” responses. Conversely, the CG scenario, which drivers may be more familiar with, was associated with a statistically significant higher proportion of “go” responses.

In the independent static evaluation completed by 103 drivers, three background images and nine permissive scenarios were evaluated. Specifically, drivers’ responses did not differ significantly when the background image contained no pedestrians, a pedestrian, or a visually impaired pedestrian with a dog guide; however, this result is likely attributed to drivers being unable to specifically identify a visually impaired pedestrian as such. When combining driver responses for all three background image types, statistically significant findings are evident. At the seven standard four-leg intersections, the following was observed:

- The scenario featuring a CR–FYA displayed simultaneously in a five-section cluster configuration had a significantly lower percentage of “yield” responses than all other scenarios except the one featuring a CY–FYA displayed simultaneously in a five-section cluster.
- The scenarios with a CG permissive indication in a five-section cluster and the scenario with a FYA in a four-section vertical when the adjacent through is CG each had a significantly higher percentage of “yield” responses than four scenarios containing all combinations of the FYA permissive with CY or CR through indications.
- For the seven scenarios, there were no statistically significant differences in the percentage of “go” responses.
- According to results of the follow-up question, about 73% of all drivers responding “yield” indicated some level of requirement to yield to pedestrians.

For the two scenarios at T-intersections, the following was observed:

- The percentage of “yield” responses was statistically higher for the FYA scenario, as were the “stop first” and “stop and wait” responses.
- By comparison, the percentage of “go” for the CG scenario was statistically higher than for the FYA scenario.

From a pedestrian perspective, a static evaluation of 100 participants resulted in several interesting findings. Specifically, in the absence of pedestrian signal heads, pedestrians were more likely to identify acceptable crossing opportunities when facing a CG permissive indication. Nevertheless, fewer than half the pedestrians understood correct crossing procedures without pedestrian heads. Approximately one in four pedestrians indicated they could leave the curb and walk on the flashing “don’t walk” signal.
Several further points of discussion can be disseminated from the research conclusions:

- Implementation of the FYA will not negatively affect drivers’ recognition of the need to yield to pedestrians. Surprisingly, driver comprehension of the yield-to-pedestrian requirements was higher in a static environment than in the simulator, unlike previous research efforts in which drivers benefited from additional cues provided in the simulator environment (6, 7). This result may reflect real-world driving behavior instead of pure driver comprehension.

- After evaluating driver comprehension at T-intersections, the CG permissive indication is associated with a high number of “go” responses, whereas the FYA is associated with significantly more “yield” responses.

- The results indicate that, in the absence of pedestrian signal heads, pedestrians were more likely to identify acceptable crossing opportunities when facing a CG permissive indication. This result may simply be a result of previous exposure. Specifically, it is likely that pedestrians participating in the experiment have previously been exposed to a crossing parallel with traffic while facing a CG with no pedestrian signals. By comparison, it is reasonable to assume that pedestrians participating in the experiment have never encountered an FYA permissive indication.

- Approximately one in four pedestrians indicated they could walk on the flashing “don’t walk” signal regardless of the permissive indication, which further documents the problem that pedestrians do not understand the meaning of the flashing “don’t walk” signal. The opportunity to cross is not intuitively recognized by pedestrians facing...
an FYA or CG permissive indication; however, this may be a result of the static nature of the evaluation. In the field, pedestrians have the opportunity to observe several phases of the signal cycle and more accurately assess when conflicting vehicles will be moving and when it is a safe time for them to cross. Nevertheless, pedestrian comprehension and recognition of crossing opportunities, particularly in the absence of pedestrian signals, should continue to be investigated, regardless of the left-turn permissive indication used.

The resulting recommendation of this research is that the FYA permissive indication can be used effectively at intersections with pedestrian activities. Although both driver and pedestrian comprehension of the pedestrian signal indications were not ideal, the FYA did not degrade current operational characteristics. Researchers believe that, with additional experience, drivers and pedestrians will find the FYA a more effective and safe permissive indication. Given the high level of comprehension to the yield requirements, the FYA is a recommended indication at T-intersections where pedestrian crossings are prevalent.

ACKNOWLEDGMENTS

This research was completed as a continuation of NCHRP 3-54 awarded to Kittelson & Associates, Inc. The University of Massachusetts–Amherst driving simulator used in the research effort was established, in part, by a grant from the National Science Foundation Engineering Infrastructure Program to Donald L. Fisher.

REFERENCES