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DRIVER COMPREHENSION AND OPERATIONS EVALUATION OF FLASHING YELLOW ARROWS

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A report of the findings of
ICT-R27-97
Evaluation of Flashing Yellow Arrows (FYA) for Protected/Permissive Left-turn (PPLT) Control

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16. Abstract

In spring 2010, the Illinois Department of Transportation initiated an areawide implementation of the flashing yellow arrow (FYA) as the display for the left-turn permissive interval at more than 100 intersections operating with protected/permissive left-turn (PPLT) control in the Peoria, Illinois, area. Bradley University researchers evaluated the effectiveness of FYAs on driver comprehension and traffic operations. A total of 363 drivers completed an online static survey that included seven left-turn scenarios that portrayed the protected and permissive indications of PPLT phasing, with the flashing modes being animated. The results of the survey indicated that drivers had a high comprehension of both the circular green (CG) and FYA permissive left-turn indications. However, the survey results provided evidence of some drivers' misinterpreting the meaning of a permissive left-turn with CG display and incorrectly and unsafely interpreting the meaning as "go" under some circumstances. With supplemental traffic signs present, drivers' understanding of the correct action to take when confronted with a FYA significantly increased, and the percentage of fail-critical, incorrect "go" responses significantly decreased. Before and after field observations, including 128 hours of data collected at 16 study approaches, were collected; and the following variables were investigated: critical gap, left-turn red-light running and yellow-light running, and traffic conflicts. Overall, the findings of this study suggest that drivers in the Peoria, Illinois, area had high comprehension and acceptance of the FYA message. Additionally, the FYA did not appear to have any negative impacts on traffic operations.

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EXECUTIVE SUMMARY

Approximately 27% of all intersection crashes in the United States are associated with left turns, with more than two-thirds occurring at signalized intersections. Various traffic signal control strategies have been implemented to balance concerns about efficiency and safety of left turns. The *Manual on Uniform Traffic Control Devices (MUTCD)* lists four ways to control left-turning traffic at signalized intersections, which include permissive, protected, protected/permissive, and variable left-turn mode.

Several signal indications for the permissive interval of protected/permissive left-turn (PPLT) controlled intersections are currently being used across the United States, including circular green (CG), flashing circular yellow, flashing yellow arrow, flashing circular red, and flashing red arrow. Uniformity of traffic control devices, including traffic signals, is critical in eliciting an appropriate driver action because it allows drivers to recognize and understand the message. The National Committee on Uniform Traffic Control Devices (NCUTCD) expressed concern in the non-uniformity and number of different left-turn permissive indications used throughout the United States and therefore commissioned a study, published in the National Cooperative Highway Research Program (NCHRP) Report 493*,* to evaluate and identify the best signal display for the permissive interval of PPLT control. This 2003 study found that the flashing yellow arrow (FYA) permissive indication is well understood by drivers and recommended its application for permissive left turns. In 2009, the FYA was adopted into the 2009 *MUTCD* after the Federal Highway Administration approved their installation through an interim approval. To date, at least 31 states throughout the United States have begun implementing FYAs for permissive left-turn control, ranging from a dozen installations statewide to several hundred areawide.

In spring 2010, the Illinois Department of Transportation (IDOT) initiated an areawide implementation to integrate the flashing yellow arrow as the display for the left-turn permissive interval at more than 100 intersections operating with PPLT control. Bradley University was retained to perform an effectiveness evaluation of the FYA at these locations. The purpose of this research is to evaluate the effect on safety and operations of upgrading the CG permissive indication to FYA indications at intersections operating with PPLT phasing. The research tasks include performing comprehensive areawide traffic crash analyses, conducting field studies of traffic operations and traffic conflicts, and assessing driver comprehension of the new traffic control through a survey.

To fulfill the research objectives, a driver comprehension survey was conducted, and before and after field studies of traffic operations and traffic conflicts at a sample of 16 study approaches were performed. The findings are documented in this report. A state-of-the-art literature review report was also prepared as a part of this research and is published under a separate title. The comprehensive crash-based evaluation is currently under way and is not included in this report.

DRIVER COMPREHENSION SURVEY

A driver comprehension survey was disseminated to assess Peoria area drivers' understanding of various permissive left-turn indications, and especially the FYA indication. The survey was conducted in two phases: The first phase was disseminated 5 months after the initial implementation of the FYA signals, and the second phase was disseminated 16 months after the first FYAs were operational. A comparison of the survey results of both phases was conducted to determine changes in driver comprehension over time and impacts on a driver's learning curve.

Participating drivers were presented with seven left-turn scenarios that varied, based on left-turn signal display (circular green, flashing yellow arrow, solid green arrow), adjacent through traffic signal display (circular green or circular red), and presence or absence of a supplemental traffic sign. In these seven scenarios, drivers were asked, “If you want to turn left, and you see the traffic signals shown, what would you do?” The available responses were “Go—You have the right-of-way,” “Yield—Wait for a gap,” and “Stop—Wait for signal.” The correct response varied, depending on the scenario.

A total of 363 drivers completed an online survey that included seven left-turn scenarios of the protected and permissive indications of PPLT phasing, with the flashing modes of the FYA indication being animated. The results of the driver comprehension survey revealed the following:

- Participating drivers had very high comprehension of the correct action to take at both the FYA and CG permissive left-turn indications. However, the analysis of the fail-critical responses revealed significantly higher incorrect “go” responses for the CG scenario, compared with the FYA with supplemental sign. These results provide evidence of some drivers’ misinterpreting the meaning of a permissive left-turn with CG display and incorrectly and unsafely interpreting the meaning as “go” under some circumstances.
- Drivers have a significantly higher comprehension of the FYA when the adjacent through traffic has a green signal, as compared to a red signal, regardless of the presence or absence of the supplemental sign. However, this finding was not confirmed in the fail-critical responses because there was no significant difference between the two scenarios with respect to the incorrect and unsafe “go” responses.
- The provision of the supplemental sign at the FYA approaches with text “Left-turn Yield on Flashing Arrow” significantly improved drivers’ understanding of the correct “yield” message, regardless of the color of the adjacent through traffic signal (green or red). This finding was further confirmed by the fail-critical responses, which showed that the FYA with supplemental sign has significantly lower fail-critical “go” responses than the FYA without a supplemental sign.
- When survey participants were asked, “If oncoming traffic has a green light and you wish to turn left permissively, what signal indication best informs you that you must yield to oncoming traffic before completing your turn?” the majority (66%) felt that the FYA presented the best message in a permissive left-turn.

The results of the static driver comprehension survey of correct responses and fail-critical responses provide evidence of heightened driver understanding of the FYA message over the CG. The message of the FYA is further enhanced when the supplemental sign with text “Left-turn Yield on Flashing Arrow” is provided. However, conclusive recommendations regarding the supplemental sign cannot be made based on the results of the static survey alone.

OPERATIONAL ANALYSIS

As a part of this research, intermediate operational measures and traffic conflict data were collected at a sample of test sites to assess the impacts on safety and operations of converting the CG permissive left-turn indication to the FYA. The following variables were used: gap size accepted, red-light running, yellow-light running, and traffic conflicts involving

left-turning vehicles. Traffic conflicts are commonly referred to as “near misses” and are defined as evasive actions taken by drivers to avoid an impending collision. Traffic conflict studies are effective ways to complement traffic crash studies and act as surrogate measures because it may take time until a sufficient amount of traffic crash data can be accumulated. In this research, red-light-running and yellow-light-running events were also quantified to assess the safety impacts of the FYAs. Operational measures specifically related to the left-turn signal were also captured, including traffic volumes and gap-acceptance characteristics.

The operational and traffic conflict studies were conducted for a sample of study approaches selected on the availability of a safe and clear vantage point for the camera, the volume of left-turn traffic carried at the approach, and if enough time was available to collect data in the “before” period, prior to the installation of the FYAs. The “before” data was collected mid-September 2010; beginning in spring 2011, the “after” data was collected at the same intersection approaches during the same weekday peak as collected in the “before” period.

Field data were recorded at 16 study approaches before and after the traffic signals with the FYA for the permissive left-turn indication were installed. It should be noted that the signal operations did not change from the “before” to the “after” periods; the study approaches operated with protected/permissive left-turn phasing. The only change was in the traffic signal’s permissive left-turn indication from CG in the “before” period to FYA in the “after” period.

A total of 128 hours of field data were collected at 16 study approaches, and before and after comparisons were made to assess the impacts of converting the CG permissive left-turn indication to the FYA on operations using the following variables: median gap size accepted, red-light running (RLR), yellow-light running (YLR), and traffic conflicts. The results of the statistical analysis conducted for this study at 95% level of confidence revealed the following:

- No significant differences were observed in the median gap size accepted.
- Only one out of the nine study variables involving RLR and YLR experienced a significant increase (RLR on a per hour basis following the permissive left-turn interval). When exposure variables were considered, the results for RLR were not significant. Overall, the results of this analysis suggest that RLR and YLR, following either the protected interval or the permissive interval of PPLT phasing, is minimally, if at all, affected by the installation of the FYA.
- No significant differences in the traffic conflict experience were observed for any of the traffic conflict variables studied.

Overall, the findings of this study suggest that drivers in the Peoria, Illinois, area have high comprehension and acceptance of the FYA message. Additionally, the FYA does not appear to have any negative impacts on traffic operations. The ultimate impacts of the FYA on safety will be quantified for the Peoria, Illinois, area upon completion of the comprehensive crash-based evaluation.

CONTENTS

LIST OF ACRONYMS

ADT	average daily traffic
ASCE	American Society of Civil Engineers
CG	circular green
CR	circular red
CY	circular yellow
EB	Empirical Bayes
FCR	flashing circular red
FCY	flashing circular yellow
FHWA	Federal Highway Administration
FRA	flashing red arrow
FYA	flashing yellow arrow
IA	interim approval
IDOT	Illinois Department of Transportation
ITE	Institute of Transportation Engineers
LTHO	left-turn head-on
MOE	measures of effectiveness
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
NCUTCD	National Committee on Uniform Traffic Control Devices
PPLT	protected/permissive left-turn
RITA	Research and Innovative Technology Administration
RLR	red-light running
SGA	solid green arrow
TRB	Transportation Research Board
USDOT	United States Department of Transportation
YLR	yellow-light running

CHAPTER 1 INTRODUCTION

Left turns at signalized intersections are widely recognized as being challenging and high-risk maneuvers for drivers. Approximately 27% of all intersection crashes in the United States are associated with left turns, with more than two-thirds occurring at signalized intersections (California Center for Innovative Transportation 2004). Three main sources of conflicts—opposing through traffic, adjacent through traffic, and cross-street vehicular and pedestrian traffic—contribute to the complexity of a left-turn. There are various efficiency and safety concerns related to left turns, making left-turn control an ongoing topic for discussion among traffic engineers. As a result, various traffic signal control strategies have been implemented to address issues that arise from left-turn movements. The *Manual on Uniform Traffic Control Devices (MUTCD)* lists four ways to control left-turning traffic at signalized intersections (Federal Highway Administration 2009):

- Permissive—left-turn may be made after yielding to oncoming traffic and pedestrians.
- Protected—left-turn may be made only when a green arrow signal is displayed.
- Protected/permissive—left-turn movement is presented during both the protected and permissive phases during the same signal cycle.
- Variable left-turn mode—the operating mode changes between protected, permissive, and protected/permissive during different times of the day.

From a safety standpoint, protected-only left-turn phases are desirable because left-turn vehicles have exclusive right-of-way, thus minimizing conflicts with other traffic movements. Protected/permissive left-turn phasing represents a compromise between protected-only phasing and permissive-only phasing. Protected/permissive control has several advantages, "the most important being the reduction in delay for left-turning vehicles achieved by permitting left turns while the opposing through movement has a green indication" *(*Antonucci et al. 2004). Protected/permissive left-turn (PPLT) control provides left-turning vehicles with a protected phase and a permissive phase, all within the same cycle. When applied appropriately, PPLT control has been shown to reduce delays and increase the overall efficiency of an intersection.

Historically, the *MUTCD* has provided limited guidance for PPLT control, particularly regarding the permissive left-turn signal indication *(*American Traffic Safety Services Association/Institute of Transportation Engineers 2001*).* Several signal indications for the permissive phase of PPLT controlled intersections are currently being used across the United States, including the circular green (CG), flashing circular red (FCR), flashing circular yellow (FCY), flashing red arrow (FRA), and flashing yellow arrow (FYA). Uniformity of traffic control devices, including traffic signals, is critical in eliciting an appropriate driver action because it allows drivers more easily to recognize and understand the message. The National Committee on Uniform Traffic Control Devices (NCUTCD) expressed concern in the non-uniformity and number of different left-turn permissive indications used throughout the United States and therefore commissioned a study, published in the National Cooperative Highway Research Program (NCHRP) Report 493 *(*Brehmer et al. 2003*),* to evaluate and identify the best signal display for the permissive interval of PPLT control. This 2003 study found that the flashing yellow arrow (FYA) permissive indication is well understood by drivers and recommended its application for permissive left turns.

In March 2006, the Federal Highway Administration (FHWA) issued a memorandum with the details of the interim approval for new FYA signals. The Office of Transportation Operations reviewed research and considered the FYA to be successful. The memorandum further stated that the Office of Transportation Operations believes the FYA has a low risk of safety concerns and minimal operational concerns. Meetings of the NCUTCD also indicated a consensus in the practitioner community in support of optional use of the FYA. The memorandum also provided the details for the design and operational requirements of the new FYA signal *(*Paniati 2006*)*.The FYA was adopted into the 2009 *MUTCD* after the FHWA approved its installation through an interim approval. To date, at least 31 states throughout the United States have begun implementing FYAs for permissive left-turn control, ranging from a dozen installations statewide to several hundred areawide *(*Rietgraf 2013). Figure 1 illustrates states that have implemented FYA signals for PPLTs. It is important to note that Figure 1 does not specify to what extent the FYAs have been implemented within each state.

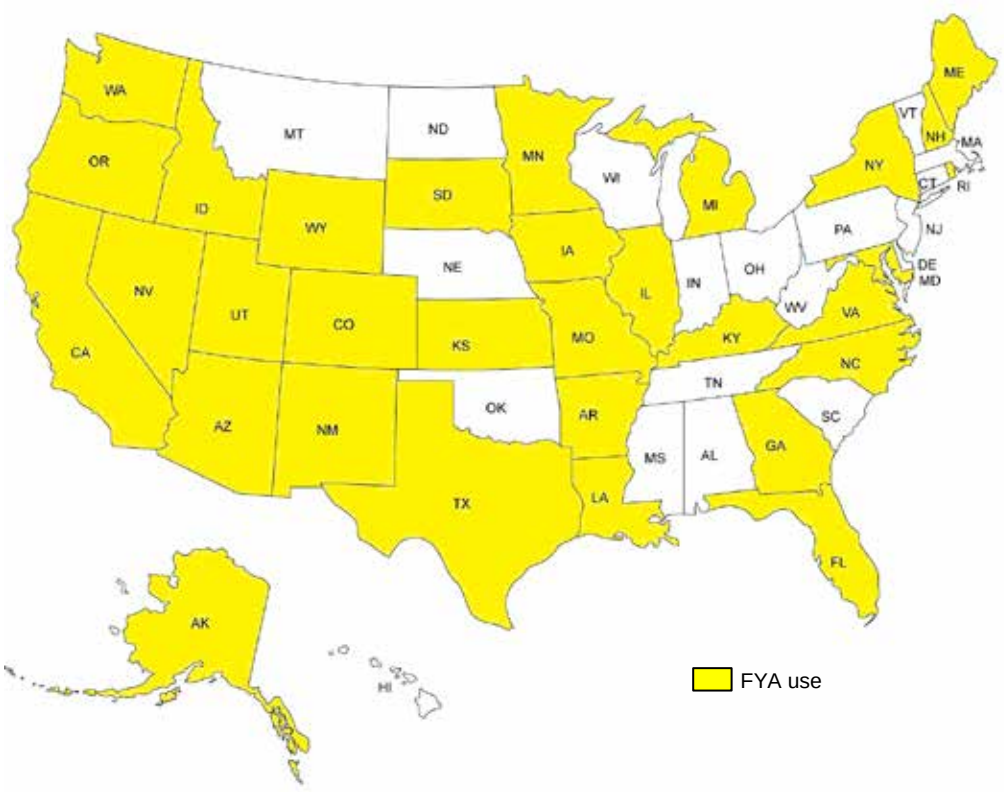


Figure 1. States with signalized intersections operating with left-turn flashing yellow arrows (Source: Rietgraf 2013).

Beginning in spring 2010, the Illinois Department of Transportation (IDOT) installed the FYA signal indication at 112 intersections on state routes with PPLT control in the Peoria, Illinois, area. However, at 16 of these intersections, other safety improvements were also installed, and thus these 16 intersections had to be excluded from the evaluation study because the impacts of the FYAs could not be isolated. Thus, 96 intersections were considered to be eligible for inclusion in the evaluation. The Bradley University research team performed an effectiveness evaluation of the FYA at these locations. The purpose of this research is to evaluate the effect on safety and operations of upgrading the CG

permissive indication to FYA indications at intersections operating with PPLT phasing. The research tasks include performing comprehensive areawide traffic crash analyses, conducting field studies of traffic operations and traffic conflicts, and assessing driver comprehension of the new traffic control through a survey instrument.

The comprehensive crash analyses are currently under way and are not included in this report. The initial research grant was approved for a three-year extension to expand the scope of the research: (a) expand the crash-based effectiveness evaluation to include three years' of "after" data at all the study intersections, (b) develop crash-modification factors for FYAs, (c) conduct statistical analyses, (d) perform economic analysis to quantify the benefit–cost effectiveness of the FYA signal indication, and (e) assist IDOT with implementation planning and/or coordination. The focus of this report is to present the methodologies and results of the driver comprehension, traffic operations, and traffic conflicts analyses.

This report contains the following chapters:

Chapter 2—Summary of the Literature Review

Chapter 3—Driver Comprehension Survey

Chapter 4—Operational Analysis

Chapter 5—Summary and Conclusion

CHAPTER 2 SUMMARY OF THE LITERATURE REVIEW

A comprehensive literature review was conducted to assess the state-of-the-art of PPLT control and signal indications used for the permissive left-turn phase. The search for journal papers, reports and other documents was conducted through web-based queries, as well as queries through specific search engines, such as those of the U.S. Department of Transportation (USDOT), FHWA, Research and Innovative Technology Administration (RITA), the National Transportation Library, the Transportation Research Board (TRB), the Institute of Transportation Engineers (ITE), and American Society of Civil Engineers (ASCE).

More than 30 journal papers, reports, and other published documents were reviewed. These sources reported findings from driver comprehension studies, driving simulator studies, crash-based evaluations, and operational effects of various PPLT control strategies, including the flashing yellow arrow. The extensive literature review is documented in a separate report titled "State-of-the-Art Literature Review on Permissive/Protected Left-Turn Control," published by the Illinois Center for Transportation. It includes details of every paper and research report on the following topics pertaining to PPLT control and FYA:

- Definitions of various PPLT signal indications and types of left-turn control
- NCHRP Report 493 and follow-up studies
- Driver comprehension surveys
- Traffic crash-based studies
- Traffic operations-based studies

The following section provides a summary of the findings from the comprehensive literature review. The majority of research on FYAs was conducted by the authors of NCHRP Report 493 to identify the most suitable traffic signal display for PPLT control. Several conclusions were drawn regarding the FYA permissive indication in NCHRP Report 493 (Brehmer et al. 2003). The conflict study showed that few left-turn conflicts are associated with the PPLT display. The driver confirmation and static follow-up studies showed that the scenarios involving the FYA had a high level of understanding and significantly lower fail-critical rates than the scenarios involving the CG (Brehmer et al. 2003; Knodler et al. 2001; Knodler et al. 2005b). The field implementation study revealed that the change in PPLT display from CG to FYA did not affect driver conflicts or follow-up headway. Observations during the activation of the FYA showed no significant findings. Overall, there was a positive reaction to the FYA from the implementing agencies, the public, and law enforcement (Brehmer et al. 2003). The general recommendations made by the research team of NCHRP Report 493 related to the FYA included (Brehmer et al. 2003):

- The FYA display should be adopted into the *MUTCD* as an alternative PPLT control.
- The four-section, all-arrow display in an exclusive signal arrangement should be used for PPLT control with FYAs.
- The opposing through green indication should be tied to the FYA with optional delay in the start of the FYA.

- Further research should be conducted to gain a better understating of different PPLT displays.

The authors of the NCHRP 493 report, Brehmer, Kacir, Noyce, Manser et al., published several papers in transportation journals documenting their analysis and results from follow-up studies on the impacts of FYAs. Concerning five-section signal arrangements, the FYA and flashing circular yellow (FCY) indications were the best understood in a driving simulation and static follow-up evaluation study. The CG permissive indication had the most fail-critical responses (Noyce and Smith 2003). A retrofitted FYA/CG display was studied and deemed to be acceptable for an interim display (Knodler et al. 2005a). Driver recognition of their yield requirements to pedestrians was not negatively affected by the FYA (Knodler et al. 2006a). FYA use at wide-median locations resulted in high driver comprehension for the FYA, but there was a high percentage of initial fail-critical responses on the first viewing of the FYA (Knodler et al. 2006b). There is little evidence to suggest that installations of the FYA will impact driver comprehension of the CG permissive indication (Knodler et al. 2007a). There is no evidence to suggest that the FYA permissive indication would negatively affect the understanding of the solid yellow arrow (SYA) used in change intervals (Knodler and Fisher 2009; Knodler et al. 2007b).

Additional crash-based, operations-based, and driver understanding survey studies were identified in the literature. A summary of the authors' main conclusions follow. Sites operating with PPLT control before and after implementation of the FYA showed an improvement in safety, while sites that operated with protected-only phasing before the installation of the FYA and switched to PPLT control typically showed an increase in collisions. The authors concluded that the change in phasing from protected-only to PPLT control had a greater impact than the permissive indication change from CG to FYA *(*Noyce et al. 2007; Perez 2010; Pulugurtha et al. 2011; Srinivasan et al. 2011a; Srinivasan et al. 2011b). A study evaluating driver understanding of the FYA in Creve Coeur, Missouri, concluded that area drivers understand the CG with supplemental sign better than the FYA without a sign (Henery and Geyer 2008*)*. An operations-based study determined that 95% of vehicles observed turning left during the FYA permissive indication did so safely *(*Lin et al. 2008*)*. Researchers that conducted a traffic conflict analysis in Texas found that some high-volume intersections operating with the FYA and lead-lag phasing showed an increase in certain types of traffic conflicts (Qi et al. 2011a*)*. The same researchers suggested that louvered signal heads be used to prevent the left-turn drivers from seeing the adjacent through signals would increase FYA comprehension even more. They also surveyed traffic engineers and suggested that the three-section, dual-arrow signal head for FYAs should be used with great caution (Qi et al. 2011a). A crash-based analysis in 2011 concluded that left-turn crash rates did not increase for 14 of 17 study intersections after implementing the FYA. They also commented that lead–lag signal phasing is not recommended with installation of the FYA, due to the "red trap" and "yellow sneakers" crash problems (Qi et al. 2011b).

CHAPTER 3 DRIVER COMPREHENSION SURVEY

The driver comprehension survey was disseminated to assess Peoria area drivers' understanding of various permissive left-turn indications, and especially the FYA indication. The survey was conducted in two phases: The first phase was disseminated 5 months after the initial implementation of the FYA signals, and the second phase was disseminated 16 months after the first FYAs were operational. A comparison of the survey results of both phases was conducted to determine changes in driver comprehension over time and impacts on a driver's learning curve.

To distribute the survey to the targeted general driving population in the Peoria area, the researchers coordinated with local city governments to disseminate the survey by email or to post a link to the survey on the city's website. The cities of Peoria, Washington, Morton, Pekin, and Chillicothe emailed the survey to residents that were members of homeowners associations, while the city of East Peoria posted the survey link on its website. Attempts were made to solicit driver responses in public places, such as at a HyVee grocery store and at the Peoria Civic Center, by setting up a booth equipped with a laptop and Internet connection. However, this method proved to be inefficient for collecting responses, as only 15 drivers were willing to take the survey in the eight hours the booths were set up.

The survey gathered background information on the respondents and assessed their understanding and knowledge of traffic laws associated with permissive left-turn controls by asking how they would respond when confronted with several different types of indications during the protected and permissive left-turn phases. The survey instrument contained general questions on demographic information (age, gender, education level, etc.), driving experience (valid driver's license, annual miles driven, etc.), as well as questions that assessed a driver's understanding and knowledge of traffic laws related to left-turn signals.

Participating drivers were presented with seven left-turn scenarios that varied, based on left-turn signal display (circular green, flashing yellow arrow, solid green arrow), adjacent through traffic signal display (circular green or circular red), and presence or absence of a supplemental traffic sign. A sample screen image of the survey instrument is shown in Figure 2, and the left-turn scenarios that were used in the survey are shown in Figure 3. In these seven scenarios, drivers were asked "If you want to turn left, and you see the traffic signals shown, what would you do?" The available responses were "Go—You have the right-of-way," "Yield—Wait for a gap," and "Stop—Wait for signal." The correct response varied, depending on the scenario.

The participants were also asked the following question: "If oncoming traffic has a green light and you wish to turn left permissively, what signal indication best informs you that you must yield to oncoming traffic before completing your turn?" After completing the survey, participants were redirected to an Illinois Department of Transportation online video that provided background information on the project and explained how to properly drive through an intersection with a flashing yellow arrow (http://www.youtube.com/watch?v=_l3x_Z9Cm-Cg&noredirect=1).

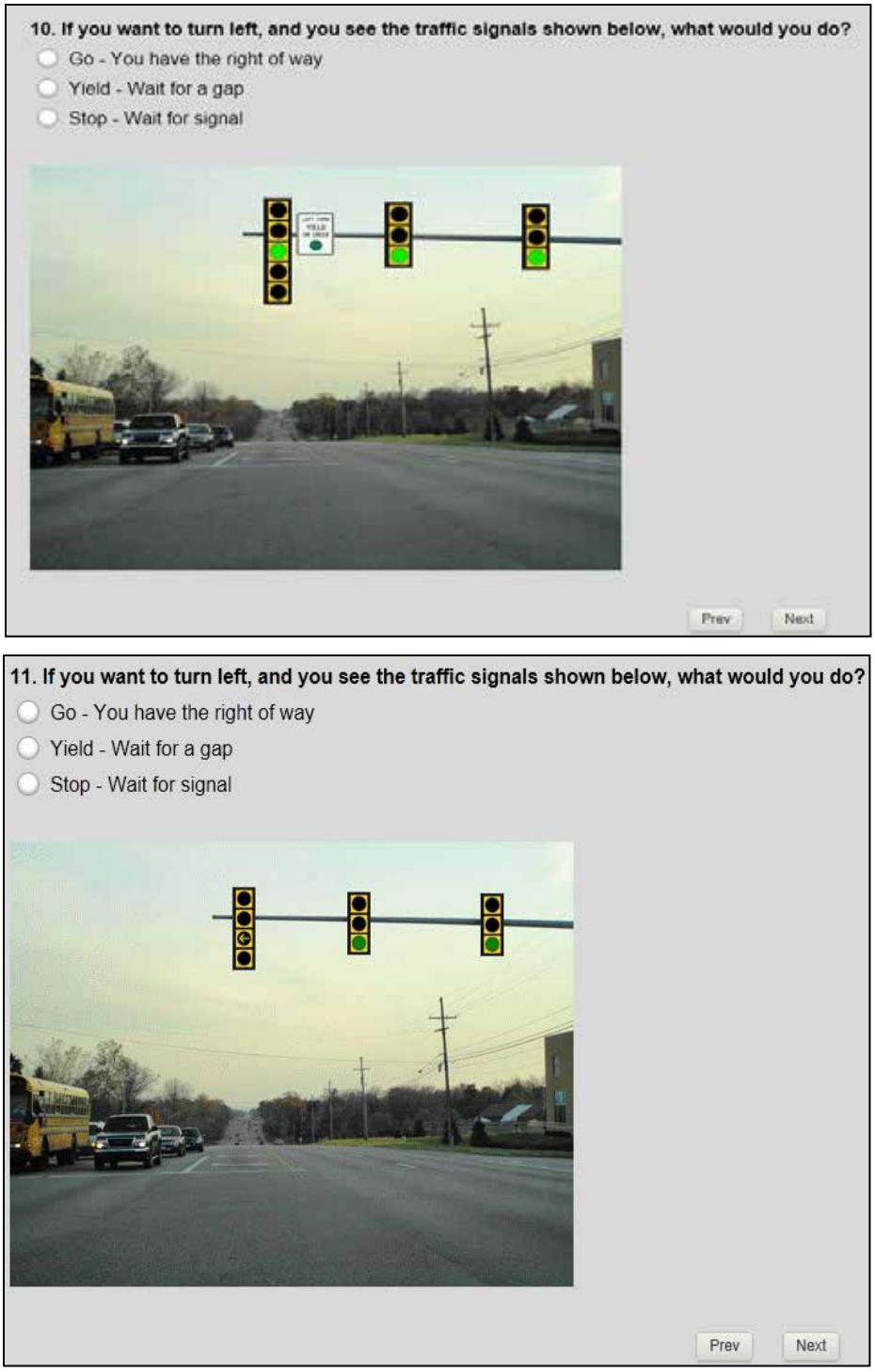


Figure 2. Sample left-turn scenario used in survey instrument.

Left-Turn Scenario	Left-Turn Signal[b]	Adjacent Thru Signals[b]	Supplemental Sign
1			
2			
3[a]			No supplemental sign provided
4[a]			No supplemental sign provided
5			No supplemental sign provided
6[a]			
7[a]			

[a]The image was animated during the survey to replicate the flashing left-turn signal indication.
[b]The indication illuminated for the given scenario is identified by the color letter: R = Red, Y = Flashing Yellow Arrow, G = Green.

Figure 3. Left-turn scenarios used in driver comprehension survey.

3.1 RESULTS OF THE SURVEY—PHASES 1 AND 2

A comparison of the survey results of both phases was conducted to determine changes in driver comprehension over time and impacts on a driver's learning curve. An online survey tool was used to create and administer the survey instrument. A web-link was sent to potential respondents, who then took the survey on a computer, allowing results to be downloaded later. The online nature of the survey allowed the researchers to animate the signal displays to replicate the flashing nature of the FYA indication. The first phase of the driver understanding survey was available for three months, from February to May, 2011: and the second phase of the survey was available for three months, from January to April 2012.

To complete the survey, all respondents were required to be at least 18 years of age (for protection of human subjects in research requirements) and to hold a valid driver's license. Some respondents omitted questions. The following section is a summary of the results obtained from the online survey.

3.1.1 Respondent Characteristics

Participants were asked a series of demographic questions, including:

- What is your age?
- What is your gender?
- Where do you currently reside?
- What is your highest level of education?
- Do you have a valid driver's license?
- On average, how many miles do you drive in a given year?

The demographic characteristics among phase 1 and phase 2 survey respondents were similar, as shown in Table 1. For the phase 1 and phase 2 results combined, the ages of the respondents were relatively consistent throughout all age groups, with the exception of 22- to 25-year-olds. This group was underrepresented in both phases of the survey; and each phase had fewer than half the participants than any other group. For the combined survey results, the mean percentage of respondents from each age group was approximately 14%, with a range of 6 to 19%.The breakdown of participants by gender was nearly equal, with 55% men and 45% women.

The level of education of the survey participants ranged from high school diploma to doctoral degree. The highest percentages of responses were for the categories of "Some College" (31%) and "4-year College Degree" (34%). In terms of the annual number of miles driven, the majority of the participants (57%) indicated that they travel between 10,000 and 20,000 miles a year.

Table 1. Demographic Results from Driver Comprehension Survey

	Phase 1 results		***Phase 2 results***		***Phase 1 & 2 results combined***	
Category	**No. of Drivers**	**% of total**	**No. of Drivers**	**% of total**	**No. of Drivers**	**% of total**
Age (years)						
18–21	28	22%	41	18%	69	19%
22–25	9	7%	11	5%	20	6%
26–35	25	20%	40	17%	65	18%
36–45	16	13%	35	15%	51	14%
46–55	25	20%	33	14%	58	16%
56–65	12	10%	31	13%	43	12%
> 65	11	9%	43	18%	54	15%
Total	126		234		360	
Gender						
Male	68	54%	124	55%	192	55%
Female	57	46%	103	45%	160	45%
Total	125		227		352	
Education						
Less than high school	0	0%	0	0%	0	0%
High school	10	8%	22	9%	32	9%
Some college, no degree	39	31%	73	31%	112	31%
2-year college degree	10	8%	19	8%	29	8%
4-year college degree	46	37%	76	32%	122	34%
Master-level degree	13	10%	36	15%	49	14%
Doctoral-level degree	7	6%	8	3%	15	4%
Total	125		234		359	
Annual Miles Driven						
< 10,000	31	28%	71	30%	102	30%
10,000–20,000	61	55%	136	58%	197	57%
> 20,000	19	17%	26	11%	45	13%
Total	111		233		344	

When the participants were asked where they reside, the majority (90%) indicated that they live in the tri-county area—in Peoria, Tazewell, and Woodford counties, while 10% reside outside of the greater Peoria area (Figure 4). Eight percent of the participants reside in other Illinois counties, including Fulton, Cook, Kendall, Ford, Will, DuPage, and Mason for the phase 1 responses; and Fulton, Macon, McLean, Lake, Cook, DuPage, and Marshall for phase 2. The 2% residing out of state live in Pennsylvania, Minnesota, and Missouri for the phase 1 responses; and for phase 2, they live in Wisconsin, Colorado, and Missouri.

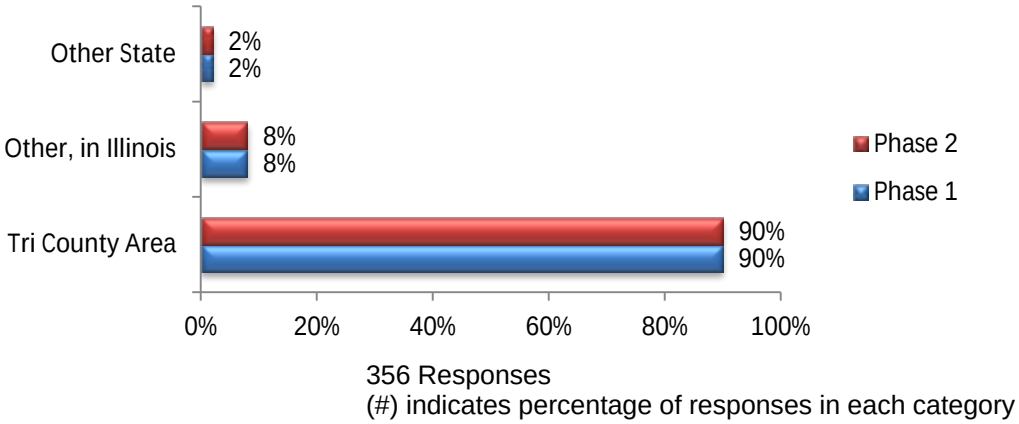


Figure 4. Survey responses by area of residence.

Participants were asked if they noticed a difference in left-turn signal operations, and the results are shown in Figure 5. A vast majority of the phase 1 (76%) respondents indicated that they noticed that left-turn signals are being operated differently in the area. Of the remaining responses, 18% had taken no notice and 7% were unsure. Eleven months after the phase 1 survey was administered, drivers were once again asked if they noticed a difference in the way left-turn signals were operated; and phase 2 yielded similar results. A higher percentage of phase 2 respondents (83%) noticed that left-turn signals were operating differently in the area. Of the remaining responses, 11% had not noticed a difference, and 5% were unsure.

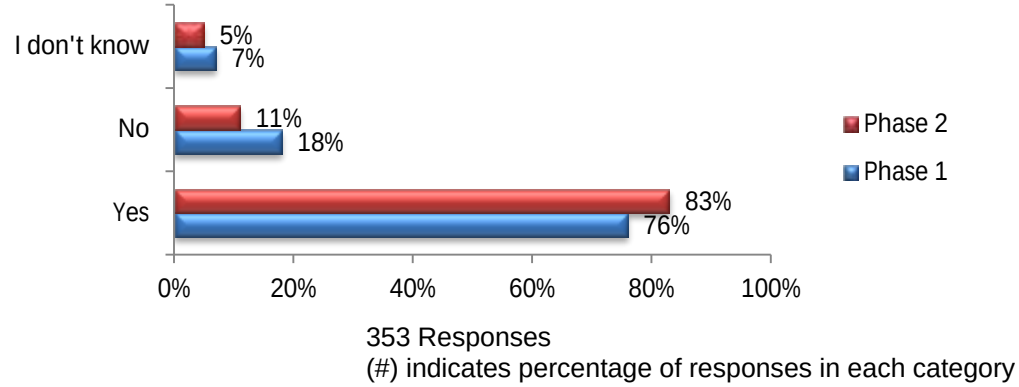
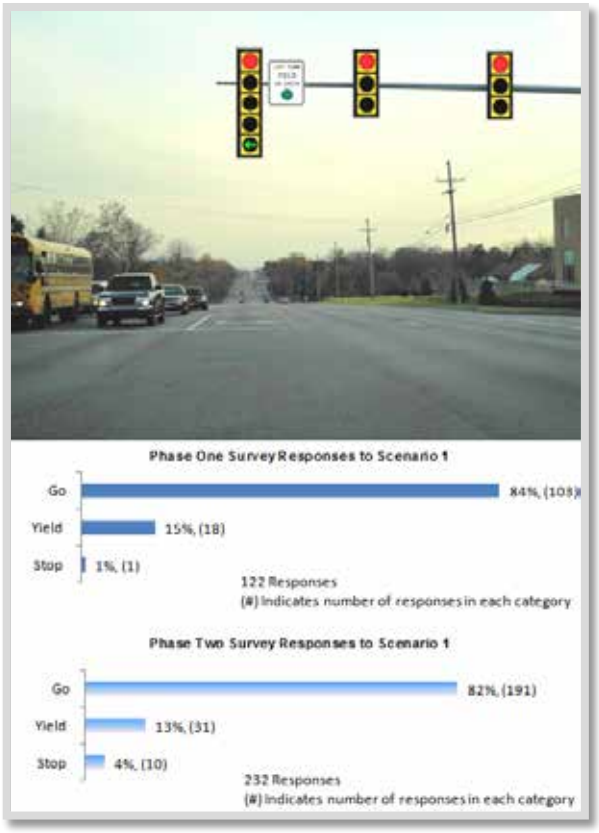


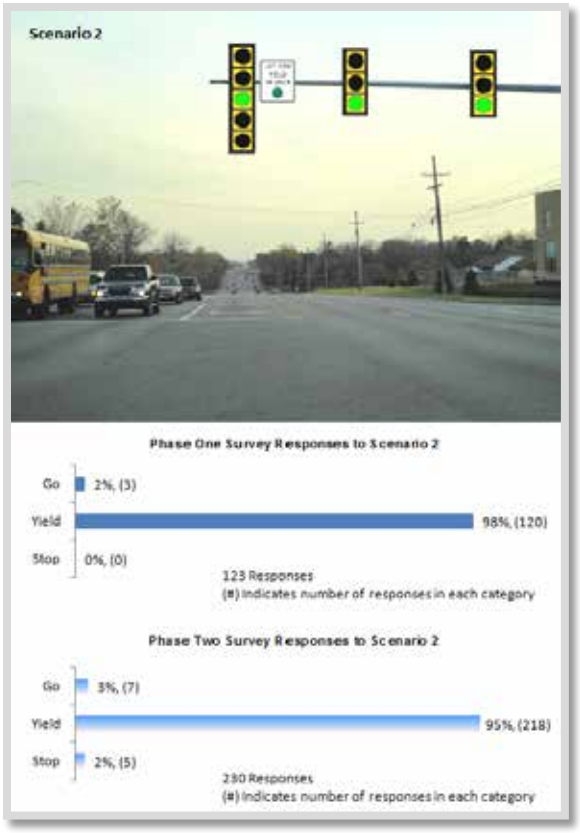
Figure 5. Survey response for noticing a change in left-turn signal operation.

3.1.2. Survey Results—Left-Turn Scenarios

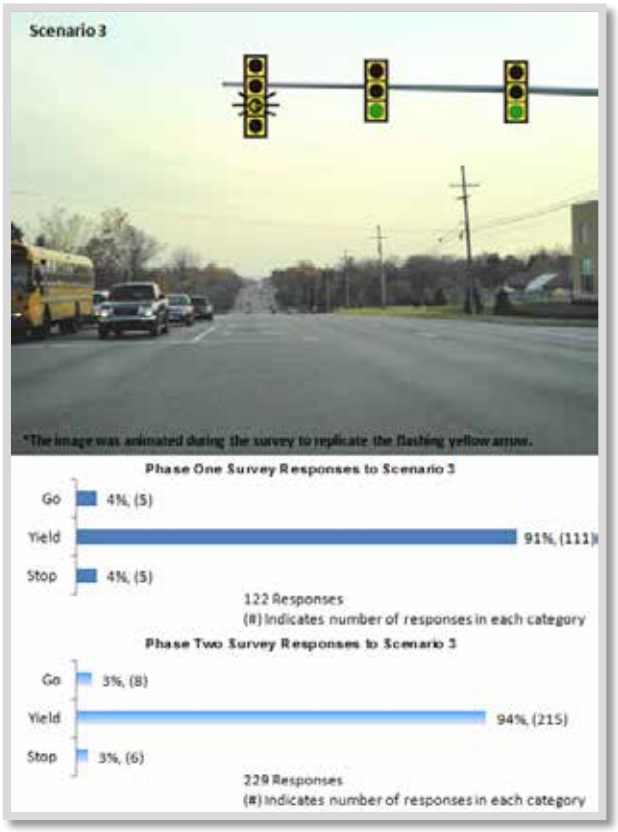
The main purpose of the survey was to evaluate driver understanding of the different protected/permissive left-turn controls being used throughout the Peoria area. Participants of the survey were presented with seven different scenarios (previously illustrated in Figure 3) and were asked, “If you want to turn left, and you see the traffic signals shown below, what you would do?” A static picture was displayed; and participants were given the options to “Go—you have the right-of-way,” “Yield—wait for a gap,” or “Stop—wait for signal.” Although the picture was static, the flashing mode of the signal indication was animated, where applicable. The correct response varied, depending on the scenario. The specific responses to each of the seven left-turn scenarios by phase are shown in Figure 6.



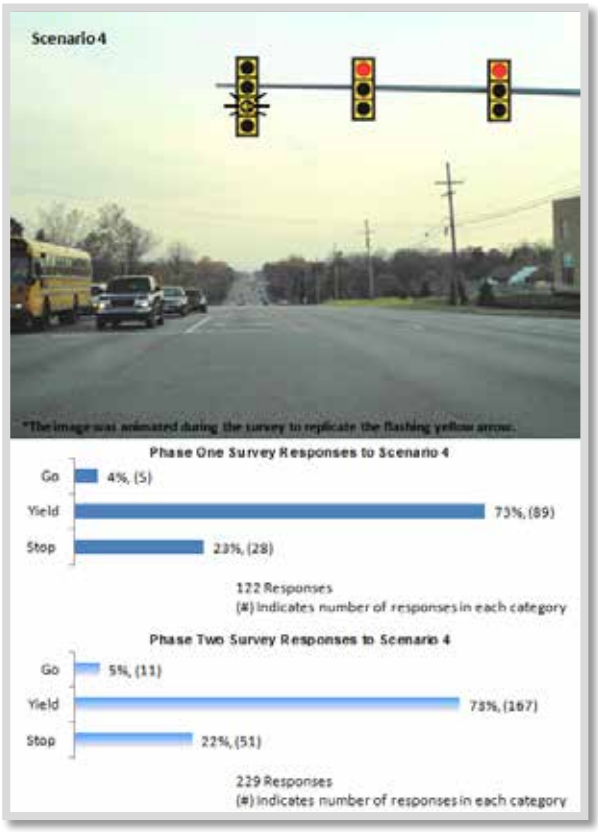
Left-Turn Scenario 1



Left-Turn Scenario 2

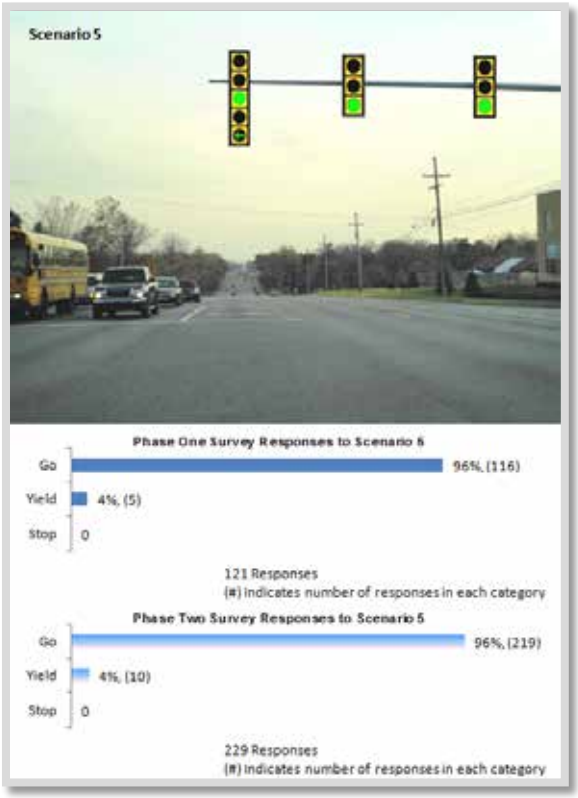


Left-Turn Scenario 3

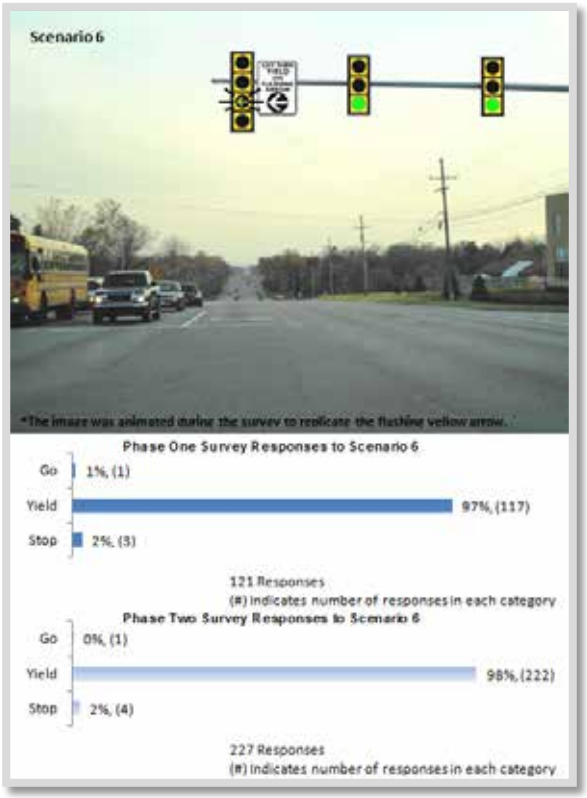


Left-Turn Scenario 4

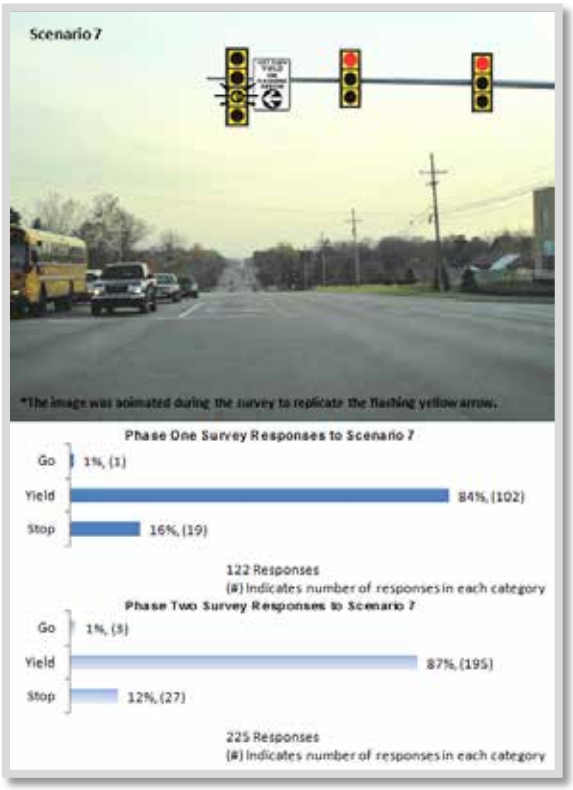
Figure 6. Survey responses for the seven left-turn scenarios by phase.
(continues)



Left-Turn Scenario 5



Left-Turn Scenario 6



Left-Turn Scenario 7

Figure 6 (continued). Survey responses for the seven left-turn scenarios by phase.

For the seven questions pertaining to the left-turn scenarios, the percentage of correct responses and fail-critical responses were analyzed. A fail-critical response occurred when a driver confronted with a permissive CG or FYA left-turn indication incorrectly selected the “go” response instead of “yield.”

The percentage of correct responses did not vary by more than three percentage points among the phase 1 and phase 2 responses, as shown in Figure 7. The percentage of fail-critical responses between phase 1 and phase 2 varied by less than one percentage point. Results of the chi-square test indicated that statistically there was no difference between the phase 1 and phase 2 correct and fail-critical responses. Thus, the drivers’ responses were combined for the phase 1 and phase 2 results. Although 363 participants responded to the survey, a range of 347 to 354 responses were received, depending on the question, as some participants may have skipped questions.

The total population age 18 and older in the greater Peoria area is approximately 220,500. Using Equation 1, the number of desired responses to the survey can be calculated. To be representative of the target driving population in Peoria, with a 5% margin of error, a sample size of 383 participants is considered ideal. In this research, 363 participants age 18 years and older responded to the survey, which corresponds to a margin of error slightly higher than 5% (5.15% margin of error).

$$n = \frac{M}{\left[\frac{(E/1.96)^2 \times (M-1)}{p \times q}\right] + 1}$$

Equation 1

Where

E = Margin of error
p = Percentage found in the sample (assumed as 50% where the standard error of a percentage is the greatest).
q = 100 – p
n = Size of the sample
M = Size of the population to be sampled

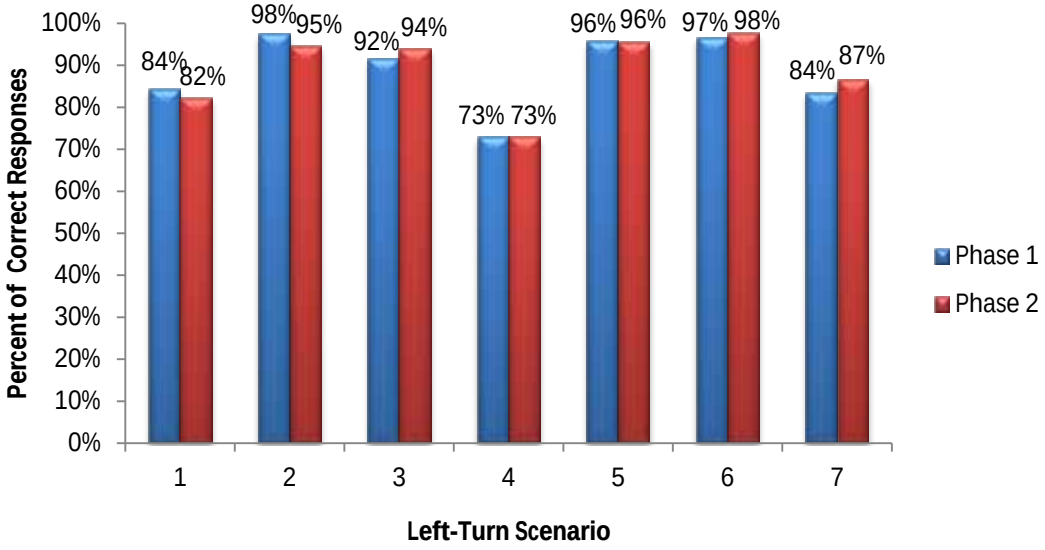


Figure 7. Percent correct response rate by phase for the left-turn scenarios.

The correct response varied, depending on the scenario as shown in Figure 8. For scenarios 1 and 5, “go” is the correct response because a protected left-turn phase was displayed (solid green arrow). Scenario 1 involved an exclusive left-turn phase with a red signal displayed for the adjacent through traffic, while scenario 5 displayed a split phase where both the left-turning and through vehicles at the approach had the right-of-way (adjacent through traffic signal displayed a green indication). The correct response for scenarios 2, 3, 4, 6, and 7 is “yield.” Scenario 2 used the CG permissive left-turn indication with supplemental sign. Four scenarios (3, 4, 6, and 7) involved the FYA indication to examine the effects of the presence or absence of supplemental signs, and the color of the adjacent through signal indication being red or green.

It should be noted that scenarios 4 and 7 present a relatively new traffic operation that was not available for PPLT phasing using the CG indication for the permissive interval. In this operation, the left-turn signal portrays a FYA and the adjacent through traffic has a red light, while both the opposing through and the opposing left-turn vehicles have green signal indications and exclusive right-of-way.

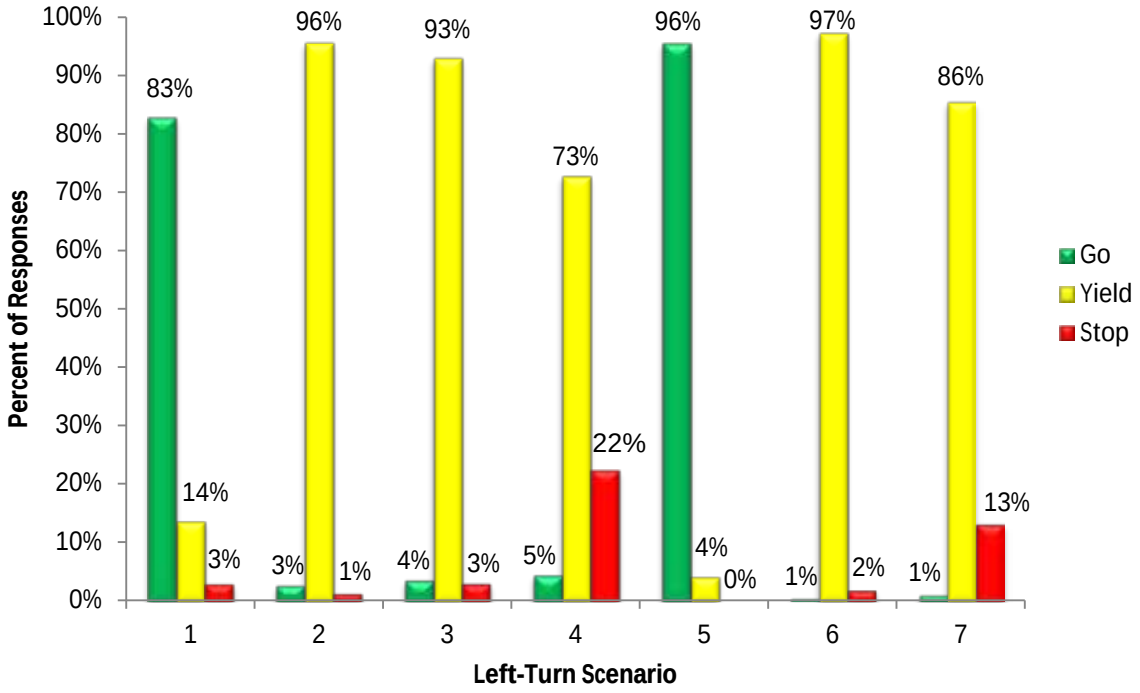


Figure 8. Survey results for left-turn scenarios: Go, Yield, Stop responses for both phases combined.

As part of this survey, the research team asked the participants if they had encountered a FYA in their driving experiences prior to the survey. The participants were also asked to give the location they encountered the signal if they had. The results are presented in Figure 9.

A majority of the respondents (71%) who participated in the first phase of the survey had encountered a flashing yellow arrow prior to the survey, and 29% had not. By the time

the second phase of the survey was distributed, the percentage of respondents who had encountered the flashing yellow arrow before had risen to 77%. All but one respondent had encountered the flashing yellow arrow control in the Peoria tri-county area. The one unique respondent had previously encountered the flashing yellow arrow in Creve Coeur, Missouri.

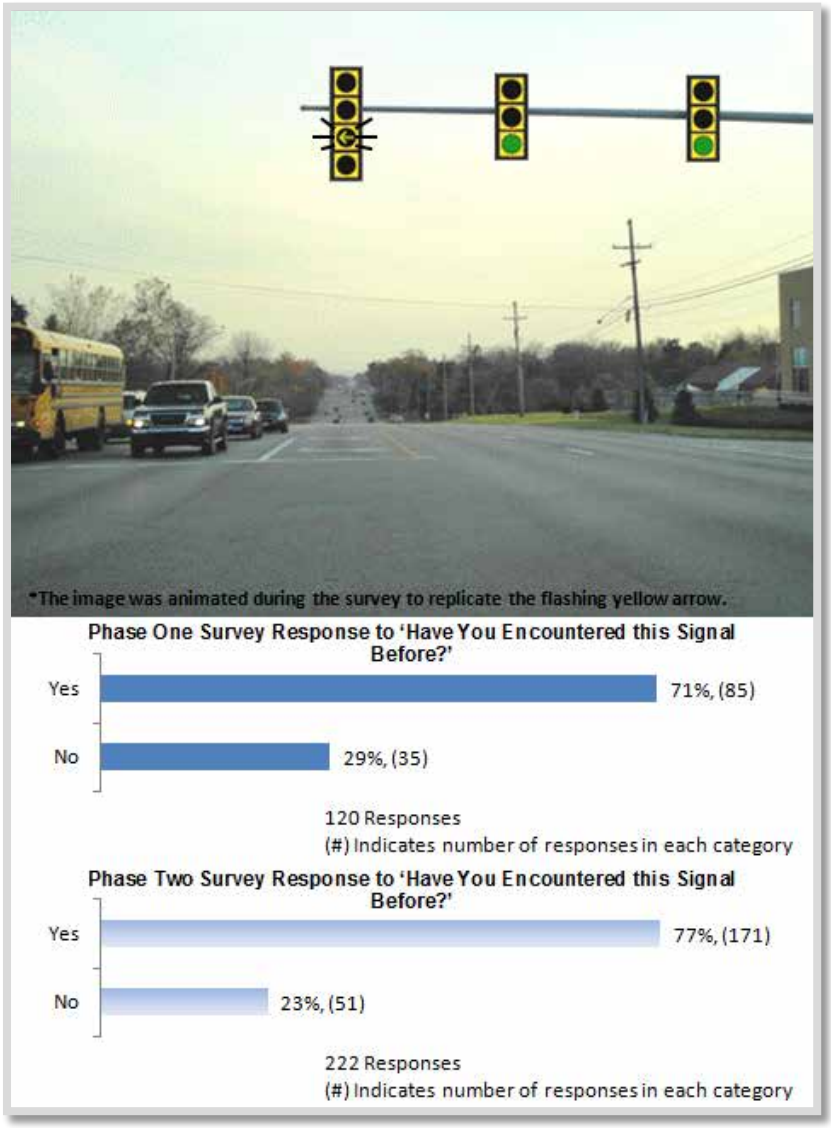


Figure 9. Survey response to "Have you encountered this signal before?"

Participants were asked, "If oncoming traffic has a green light and you wish to turn left permissively, what signal indication best informs you that you must yield to oncoming traffic before completing your turn?" The majority of participants felt that the FYA presented the best message in a permissive left-turn (66% of participants from both phases). This figure compared with 27% of participants who believed that the CG indication sends the best message in a permissive left-turn scenario. Figure 10 shows the survey responses by indication and by phase.

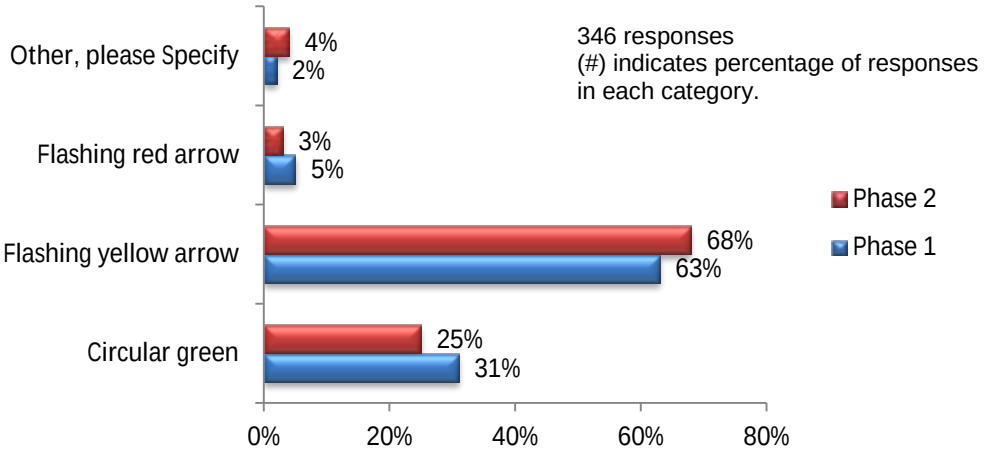


Figure 10. Survey response to "Which PPLT control sends the best message?"

As illustrated in Figure 10, a majority of respondents in the phase 1 and phase 2 surveys (63 and 68%, respectively) felt that the flashing yellow arrow control sends the best message in regards to yielding to oncoming traffic when attempting to make a left-turn. The second highest response was that the circular green display sent the clearest message: 31% in phase 1, which decreased to 25% in phase 2. Three to 5% of the respondents in phases 1 and 2 felt that the flashing red arrow was the best message. Participants were able to specify other types of indications, and the following are their responses:

- Both the flashing yellow arrow and the circular green indication, but install them with consistency throughout the area
- Flashing green arrow with a descriptive sign
- Solid green arrow
- Flashing green arrow
- Solid yellow arrow with sign
- All of the above

3.2 STATISTICAL ANALYSIS OF SURVEY RESULTS

Statistical analyses were conducted to assess driver understanding of certain scenarios. Specifically, interest centered on investigating whether the FYA was a better understood message, as compared to the CG; whether the supplemental sign had an impact on driver understanding of the FYA; and whether the signal indication displayed for the adjacent through traffic had an impact on driver understanding of the FYA. The following scenarios were compared for correct responses and fail-critical responses:

- Scenario 2 vs. 6—Comparison of CG with sign to FYA with sign when adjacent through signals are green
- Scenario 2 vs. 3—Comparison of CG with sign to FYA without sign when adjacent through signals are green

- Scenario 6 vs. 3—Comparison of FYA with sign to FYA without sign when adjacent through signals are green
- Scenario 7 vs. 4—Comparison of FYA with sign to FYA without sign when adjacent through signals are red
- Scenario 6 vs. 7—Comparison of FYA with green adjacent through signals to FYA with red adjacent through signals when the supplemental signs are present
- Scenario 3 vs. 4—Comparison of FYA with green adjacent through signals to FYA with red adjacent through signals when the supplemental signs are not present
- Scenarios 3 and 4 vs. 6 and 7—Comparison of FYA without sign to FYA with sign, regardless of adjacent through indication
- Scenarios 3 and 6 vs. 4 and 7—Comparison of FYA with adjacent through green indication and FYA with adjacent through red indication, regardless of signage

Statistical testing was performed to determine if there were significant differences in the proportion of correct and fail-critical driver responses to the scenarios being compared. The z-test for proportions was used to determine the significance of the observed differences at a 95% level of confidence. The z-calculated values were derived using the data collected in the survey, using Equation 2 for each of the scenario comparisons. A one-tailed test was used because the effect of the FYA on the direction of the measures of effectiveness could be inferred, based on the results of past studies. The results of the statistical analyses are shown in Table 2.

$$z_{Calculated} = \frac{P_1 - P_2}{\sqrt{p(1 - p)(\frac{1}{N_1} - \frac{1}{N_2})}}$$ Equation 2

Where

P_1 = Proportion of correct responses in the first scenario being compared

P_2 = Proportion of correct responses in the second scenario being compared

N_1 = Number of total responses in the first scenario being compared

N_2 = Number of total responses in the second scenario being compared

X_1 = Number of correct responses in the first scenario being compared

X_1 = Number of correct responses in the second scenario being compared

p = Estimate of the overall proportion = $(N_1P_1 + N_2P_2)/(N_1 + N_2)$

Table 2. Results of the Statistical Analysis of the Driver Survey Responses for the Comparisons of the Various Left-Turn Scenarios

	Correct Responses			Fail-Critical Responses		
Comparison of Driver Responses	$z_{calculated}$	P-value (significance level)	Statistically significant?	$z_{calculated}$	P-value (significance level)	Statistically significant?
Scenario 2 vs. Scenario 6	-1.21	0.1131	No	2.30	0.0107	Yes
Scenario 2 vs. Scenario 3	1.64	0.0505	No, but very close	-0.65	0.2578	No
Scenario 6 vs. Scenario 3	2.78	0.0027	Yes	-2.84	0.0023	Yes
Scenario 7 vs. Scenario 4	4.12	< 0.0001	Yes	-2.70	0.0035	Yes
Scenario 6 vs. Scenario 7	5.6	< 0.0001	Yes	-0.83	0.2033	No
Scenario 3 vs. Scenario 4	7.02	< 0.0001	Yes	-0.57	0.2843	No
Scenario 6 and 7 vs. Scenario 3 and 4	4.81	< 0.0001	Yes	-3.89	0.0001	Yes
Scenario 3 and 6 vs. Scenario 4 and 7	8.89	< 0.0001	Yes	-0.86	0.1949	No

The results of the statistical analysis of the correct and fail-critical driver responses from the driver comprehension survey for the left-turn scenario comparisons revealed the following:

- No significant differences were found in correct driver responses of the FYA and CG, regardless of whether or not a supplemental sign was used at the FYA approach. However, the analysis of the fail-critical responses revealed significantly higher incorrect “go” responses for the CG scenario, compared to the FYA with supplemental sign.
- Regardless of the color of the adjacent through traffic signal (green or red), the provision of the supplemental sign at the FYA approaches significantly improved drivers’ understanding of the correct “yield” message. This finding was further confirmed by the fail-critical responses, which showed that the FYA with supplemental sign has significantly lower fail-critical “go” responses than the FYA without a supplemental sign.
- Drivers have a significantly higher comprehension of the FYA when the adjacent through traffic has a green signal, as compared to a red signal, regardless of the presence or absence of the supplemental sign. However, this finding was not confirmed in the fail-critical responses because there was no significant difference between the two scenarios with respect to the incorrect and unsafe “go” responses.

CHAPTER 4 OPERATIONAL ANALYSIS

As a part of this research, intermediate operational measures and traffic conflict data were collected at a sample of test sites to assess the impacts on operations and safety of converting the CG permissive left-turn indication to the FYA. The following variables were used: median gap size accepted (critical gap), red-light running, yellow-light running, and traffic conflicts involving left-turning vehicles. Traffic conflicts are commonly referred to as "near misses" and are defined as evasive actions taken by drivers to avoid an impending collision. Traffic conflict studies are effective ways to complement traffic crash studies and act as surrogate measures because it may take time until a sufficient amount of traffic crash data can be accumulated. In this research, red-light-running and yellow-light-running events were also quantified to assess the safety impacts of the FYAs. Operational measures specifically related to the left-turn signal were also captured, including traffic volumes and gap-acceptance characteristics.

The operational and traffic conflict studies were conducted for a representative sample of study approaches and represent 17% of the total intersection approaches that were eligible to be studied (i.e., 16 sample intersections out of 96 total eligible FYA intersections). These approaches were selected based on the availability of a safe and clear vantage point for the camera, the volume of left-turn traffic carried at the approach, and if enough time was available to collect data in the "before" period, prior to the installation of the FYAs. It should be noted that the "before" data was collected prior to mid-September 2010, which was before the anticipated project start date of this research grant (December 1, 2010) for many of the study approaches. Thus, the Bradley University research team began the data collection for the "before" period at a sample of intersection approaches in the Peoria area prior to being awarded a contract, as a part of independent, unfunded research efforts.

Beginning in spring 2011, the "after" operational and traffic conflict data were collected at the same intersection approaches during the same weekday peak as collected in the "before" period. This method enabled ample time for the FYAs to be installed throughout the Peoria area and for drivers to acclimate to the new traffic control.

Field data were recorded at 16 study approaches before and after the traffic signals with the FYA for the permissive left-turn indication were installed. It should be noted that the signal operations did not change from the "before" to the "after" periods; the study approaches operated with protected/permissive left-turn phasing. The only change was in the traffic signal's permissive left-turn indication from CG in the "before" period to FYA in the "after" period. The characteristics of the 16 study sites are shown in Table 3.

Table 3. Description of Sites Included in the Operational Analysis

Left-turn Approach	Intersection Name	Roadway Laneage	Intersection ADT (vpd[a])	Speed Limit (mph[b])	Average Peak Hour Volumes (vph[c])			
					Left-turn		Opposing Thru	
					Before	After	Before	After
WB War Memorial	War Memorial &	5 Lanes	20,600	50	72	67	881	738
	Willow Knolls	3 Lanes		25				
WB War Memorial	War Memorial &	5 Lanes	43,200	45	157	159	441	460
	Prospect	5 Lanes		35				
EB War Memorial	War Memorial &	5 Lanes	29,500	45	338	327	640	654
	Big Hollow	3 Lanes		45				
EB War Memorial	War Memorial &	5 Lanes	41,600	45	85	124	668	675
	Sheridan	5 Lanes		30				
WB War Memorial	War Memorial &	5 Lanes	26,650	45	35	23	778	820
	Brandywine	3 Lanes		30				
NB Knoxville	Knoxville &	5 Lanes	25,800	45	133	170	796	800
	Northpoint	3 Lanes		25				
NB Knoxville	Knoxville &	5 Lanes	31,350	35	91	74	628	804
	McClure	5 Lanes		30				
NB Court	Court &	5 Lanes	24,800	35	106	119	770	801
	Valle Vista	3 Lanes		NM				
EB Court	Court &	5 Lanes	18,525	45	63	77	814	688
	Barney	2 Lanes		NM				
EB Farmington	Farmington &	3 Lanes	21,800	40	366	353	113	197
	Sterling	2 Lanes		45				
WB Washington	E. Washington &	5 Lanes	21,950	40	56	56	310	330
	Illini	3 Lanes		30				
EB IL98	IL98 &	3 Lanes	11,225	45	39	40	98	76
	Main	2 Lanes		35				
NB Main	Main &	5 Lanes	29,725	35	38	34	499	460
	Highland	4 Lanes		25				
WB BUS 24	BUS 24 &	5 Lanes	19,625	35	75	75	532	546
	Wilmor	3 Lanes		25				
WB BUS 24	BUS 24 &	5 Lanes	25,100	45	73	72	733	735
	Cummings	3 Lanes		45				
SB 5th	Margaret &	3 Lanes	12,775	30	159	155	152	148
	5th	2 Lanes		30				

NOTE: NM = speed limit is not marked.
[a]vpd = vehicles per day
[b]mph = miles per hour (NOTE: 1 mph = 1.61 km/h)
[c]vph = vehicles per hour

4.1. DATA COLLECTION METHODOLOGY

Four hours of data were collected at each of the 16 study approaches during both of the analysis periods; thus, this evaluation includes a total of 128 hours of data, with 64 hours of “before” field observations and 64 hours of “after” field observations. The data were collected in two-hour increments during the morning (AM), midday, or evening (PM) peaks on weekdays in summer/fall 2010 for the before period and on weekdays in summer/fall 2011 for the after period. To minimize seasonal variation or hourly/weekday traffic fluctuations between the before and after periods, data at each site were collected during the same season (summer or fall), during the same peak period, and on the same day of the week.

To collect the data accurately, video cameras were carefully positioned at the intersection approaches so that the left-turn stop bar, signal disposition, driver brake lights, and opposing through traffic were visible. The video cameras were placed inconspicuously at the intersection approaches (inside the data collector’s vehicle), so that most drivers were not aware that their driving behavior was being monitored. Thus, the location of the video camera did not influence driver behavior.

Following the data collection, each video was carefully reviewed in the laboratory; and data for the operational variables, traffic conflicts, and traffic volumes were extracted. Specifically, data for the following measures of effectiveness (MOE) were extracted, summarized, and analyzed in this evaluation study:

- Size of critical gap accepted by a left-turning driver during the permissive left-turn interval.
- Left-turning vehicles entering the intersection late (last 2 seconds) in the yellow interval that follows the permissive left-turn interval of PPLT phasing (referred to as YLR following permissive). It should be noted that as per the Illinois Vehicle Code, drivers in Illinois are allowed to enter the intersection during the yellow interval.
- Left-turning vehicles entering the intersection after the onset of the red signal indication that follows the permissive left-turn interval of PPLT phasing (referred to as RLR following permissive).
- Left-turning vehicles entering the intersection late in the yellow or after the onset of the red indications that follow the protected left-turn interval of PPLT phasing (referred to as YLR and RLR following protected).
- Left-turn traffic conflicts, including backing in the left-turn lane, left-turn head-on conflicts, left-turn opposing right turn, left-turn same direction, erratic driver movements, excessive braking, lane-change conflicts, and left-turn pedestrian conflicts.

The measures of effectiveness for YLR, RLR, and traffic conflicts were analyzed on an hourly basis, as well as by rates, to account for the exposure factor of traffic volumes on a “per 100 left-turning vehicles” and a “per 1,000 opposing through vehicles” basis. Table 4 shows the before and after comparison for the five measures of effectiveness on an hourly basis at each of the study sites.

Table 4. Before and After Comparison of the Operational and Safety Measures by Site

	Median Gap (Critical Gap) Size Accepted		Average YLR Following Permissive Per Hour		Average RLR Following Permissive Per Hour		YLR & RLR Following Protected Per Hour		Average Traffic Conflicts[a] Per Hour	
Study Site at Intersection	Before (CG)	After (FYA)	Before (CG)	After (FYA)	Before (CG)	After (FYA)	Before (CG)	After (FYA)	Before (CG)	After (FYA)
War Memorial & Willow Knolls Ct.	8	9	0.25	0.00	0.00	0.00	0.00	0.00	1.25	0.50
War Memorial & Prospect	10	6	3.25	2.75	0.25	0.25	4.00	2.00	0.75	0.25
War Memorial & Big Hollow	8	6	4.50	4.25	0.00	1.75	25.25	1.00	1.00	0.75
War Memorial & Sheridan	8	7	1.50	1.25	0.00	0.00	1.25	6.00	0.25	0.25
War Memorial & Brandywine Ct.	8	7	0.75	1.00	0.00	0.75	0.00	0.25	0.25	0.25
Knoxville & Northpoint	8	9	1.00	0.75	0.25	0.00	0.50	4.50	0.25	0.75
Knoxville & McClure Ct.	10	8	1.50	2.00	0.00	0.00	2.75	2.00	0.25	0.00
Court & Valle Vista	10	9	0.75	1.00	0.00	0.25	2.00	1.25	0.50	1.00
Court & Barney	8	8	1.50	1.50	0.75	0.50	0.25	0.50	0.00	0.50
Farmington & Sterling	12	10	5.00	11.25	0.75	2.75	5.00	12.25	0.00	0.25
E. Washington & Illini	9	11.5	1.25	1.50	0.00	0.25	0.50	0.25	0.25	0.25
IL98 & Main	7	9	0.75	1.75	0.25	0.50	0.00	0.25	0.25	0.50
Main & Highland	9	9	1.25	1.50	0.00	0.00	0.50	0.00	0.00	0.25
BUS 24 & Wilmor	9	6	0.75	1.25	0.00	0.00	1.75	0.75	0.25	0.75
BUS 24 & Cummings	8	9	1.00	0.00	0.00	0.00	1.00	0.75	0.50	0.50
Margaret & 5th	5	9	0.25	0.75	0.00	0.00	24.25	19.5	7.75	0.75

[a] Traffic conflicts included backing in the left-turn lane, left-turn head-on, left-turn opposing right turn, left-turn same direction, erratic driver movements, excessive braking, lane-change, and left-turn pedestrian conflicts.

4.1.1 Left-Turn Gap Acceptance

Gap-acceptance characteristics were analyzed as a part of this research to assess the impacts on traffic operations and capacity during the FYA permissive interval compared to the CG interval. Gap-acceptance measures were also used to assess driver understanding of the PPLT signal displays and indications.

Drivers making a left-turn movement during the permissive interval may proceed if there is an acceptable gap in the opposing traffic stream. *Gap acceptance* is defined as the time headway in the opposing traffic stream that left-turn drivers are willing to turn through during the permissive left-turn phase. The median time headway between two successive vehicles in opposing traffic streams accepted by left-turn drivers during the permissive left-turn phase is referred to as the *critical gap*. As per the *Highway Capacity Manual,* a critical gap is considered to be 4 seconds for a driver making a left-turn from a major road to a minor road (HCM 2000). Median critical gaps accepted were assessed in this research.

4.1.2 Left-Turn Red-Light Running and Yellow-Light Running

Red-light-running and yellow-light-running events were quantified as a part of this research to assess the safety impacts of the FYAs. Red-light running was observed when a left-turning vehicle crossed the stop bar and continued through an intersection, after the onset of the red light. A yellow-light-running event was observed when a left-turning vehicle crossed the stop bar and completed the turning movement during the last 2.0 seconds of the yellow change interval.

For the RLR and YLR analysis, 64 hours of before data and 62 hours of after data were used. Two hours of the after data could not be extracted accurately at one of the approaches because the traffic signals became obscured and were not visible in the video.

RLR and YLR were analyzed for the following phases: yellow-light runners following the permissive phase, red-light runners following the permissive phase, and yellow- and red-light runners following the protected phase. Yellow- and red-light runners following the protected phase were combined for analysis because during the before period, a red arrow was not displayed between the protected and permissive left-turn phases.

Three exposure variables were used to analyze RLR and YLR: average per hour, average per 100 left-turn vehicles, and average per 1,000 opposing through vehicles.

4.1.3 Left-Turn Traffic Conflicts

Traffic conflict studies are effective ways to complement traffic crash studies and act as surrogate measures because it may take time until a sufficient amount of “after” crash data can be accumulated. Traffic conflicts are commonly referred to as “near misses” and are defined as evasive actions taken by drivers to avoid an impending collision. Seven traffic conflict types, (six of which are shown in Figure 11) were analyzed as a part of this research:

- Backing in the left-turn lane—places vehicles behind the lead vehicle in danger of a rear-end crash
- Left-turn head-on conflicts—turning vehicle executes the left-turn movement placing the opposing through vehicle in danger of a left-turn head-on collision
- Left-turn opposing right turn—a vehicle making a permissive left-turn executes the turn in front of a vehicle in the opposing direction making a right turn

- Left-turn same direction—the first vehicle slows to make a left-turn and places the second following vehicle in danger of a rear-end collision
- Erratic driver movements—vehicles swerving or excessive braking
- Lane-change conflicts—a vehicle begins a merge into a different lane but sees a second vehicle and has to swerve back into the original lane
- Left-turn pedestrian—a bicycle or pedestrian is crossing a street in front of a vehicle that has the right-of-way, causing the vehicle to brake or swerve to avoid a collision

It should be noted that left-turn lane overflow was not considered, as the camera locations at some intersections did not allow for this type of conflict to be observed.

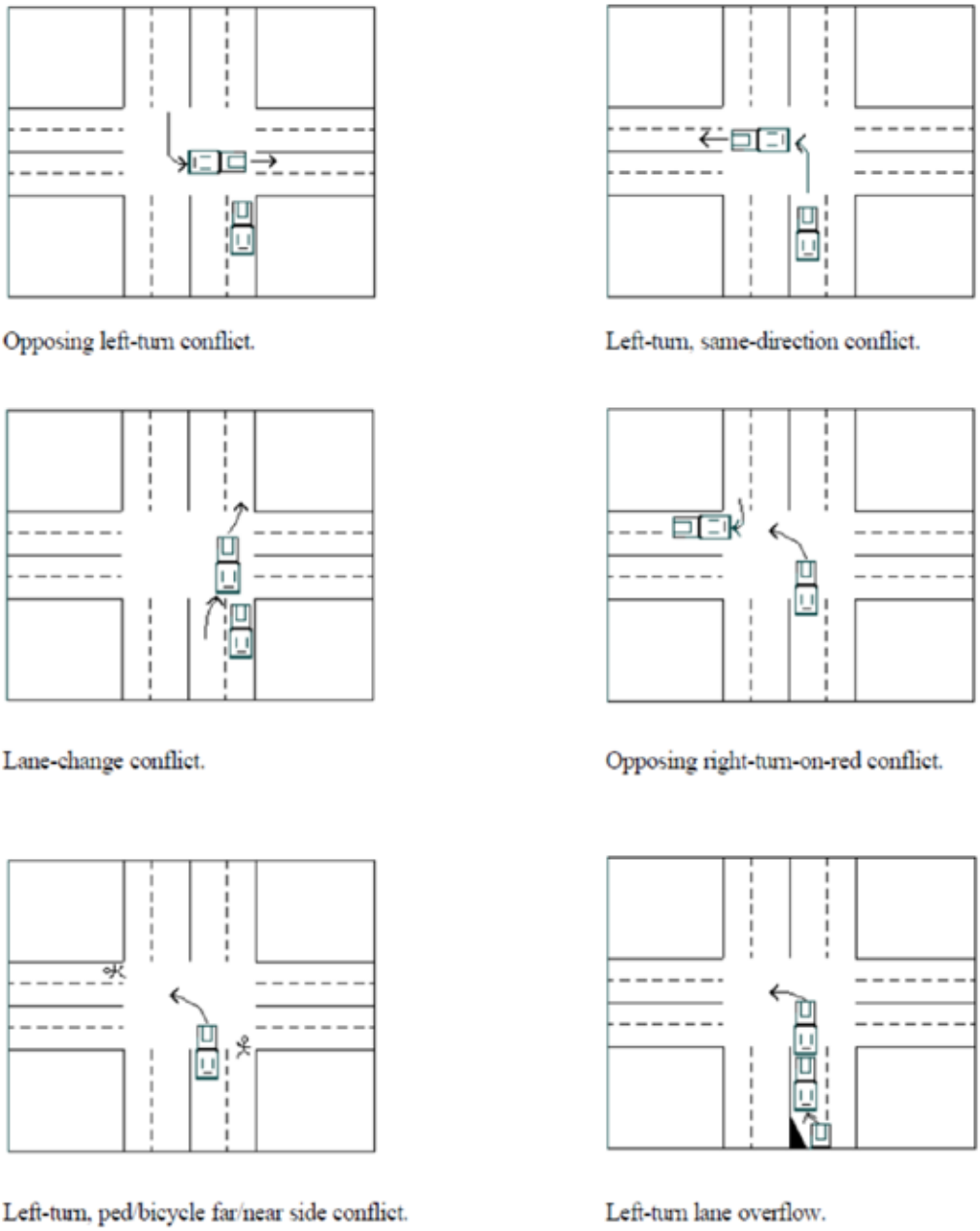


Figure 11. Traffic conflict types.

4.2. STATISTICAL ANALYSIS OF OPERATIONAL DATA

After all data were extracted, statistical analyses were performed on the measures of effectiveness to determine if the implementation of the FYA had a statistically significant effect on traffic operations (gap acceptance) and safety (RLR, YLR, and traffic conflicts). The statistical analyses were performed on an individual-site basis, as well as an aggregate basis using data for all 16 sites combined. Because the population variance is not known and will be estimated by the sample variance, the sampling distribution used for the

statistical analysis is the t-distribution. Two equations for the t-test are available, one that assumes equal variances (Equation 3) and one that assumes unequal variances (Equation 4) among the two data sets to be compared. In order to determine which equation should be used for the t-statistic, an F-test is conducted first to validate assumptions regarding homogeneity (i.e., whether variances could be assumed to be equal or unequal in the test of means).

Equation 3—Population variance unknown but assumed equal:

$$t = \frac{(\overline{X_1} - \overline{X_2}) - d_0}{S_p \sqrt{\frac{1}{n_1} + \frac{1}{n_2}}} \qquad S_p^2 = \frac{(n_1 - 1)S_1^2 + (n_2 - 1)S_2^2}{n_1 + n_2 - 2} \qquad \text{degrees of freedom} = n = n_1 + n_2 - 2$$

Equation 4—Population variance unknown and assumed to be unequal:

$$t = \frac{(\overline{X_1} - \overline{X_2}) - d_0}{\sqrt{\frac{S_1^2}{n_1} + \frac{S_2^2}{n_2}}} \qquad \text{degrees of freedom} = n = \frac{(s_1^2 / n_1 + s_2^2 / n_2)^2}{[\frac{(s_1^2 / n_1)^2}{(n_1 - 1)} + \frac{(s_2^2 / n_2)^2}{(n_2 - 1)}]}$$

Where

$\bar{X}$ = Sample mean

S^2 = Estimate of variance

n = Sample size (number of observations)

To test the homogeneity of the variance, the F-test can be used, which is simply the ratio of the two variances of the samples, where the larger of the two variances is used in the numerator (Equation 5).

$$F = \frac{s_1^2}{s_2^2}$$ Equation 5

The null (H_o) and alterative (H_a) hypotheses used in the analysis of variance and the F-statistic are as follows:

Null and alterative hypotheses for the test of variance:

$$H_o : \sigma_1^2 = \sigma_2^2$$
$$H_a : \sigma_1^2 \neq \sigma_2^2$$

The critical values for the F-test are based upon the F distribution and are determined by the degrees of freedom and a 95% level of confidence (LOC) or alpha equal to 0.05. If the calculated F value exceeds the critical F value, the assumption of homogeneity fails. If the calculated F-test value is less than the critical F value, the assumption of homogeneity is valid.

Based on the results of the F-test of variance, the appropriate t-test of means was used at a 95% LOC or a = 0.05. A two-tailed t-test was used because the effect of the FYA on the direction of the measures of effectiveness (gap size accepted, YLR, RLR, and traffic conflicts) could not be inferred or hypothesized (i.e., test for difference in either direction—for either an increase or a decrease in the random variable).The null and alternative hypotheses used in the test of means with the t-statistic are shown below. The calculated t-values and associated p-values were determined. The p-value is the lowest level of significance at which the calculated value of the test statistic is significant. Thus, for a two-tailed test if the p-value is less than 0.05 (or 2 ´ a/2 = 2 ´ 0.025 = 0.05), then the null hypothesis is rejected and the finding is significant. If the p-value is greater than 0.05 a significant difference in the MOE between the before and after periods was not observed.

Null and alterative hypotheses for the test of means:

$$H_o : \mu_{Before} = \mu_{After}$$

$$H_a : \mu_{Before} \neq \mu_{After}$$

The results of the statistical analysis for the five measures of effectiveness are shown in Table 5.

Table 5. Results of Statistical Analysis of Operational MOE – Test of Means

	Median/Mean		Standard Deviation			
Measures of Effectiveness	Before (CG)	After (FYA)	Before (CG)	After (FYA)	p-value	Significant Difference[a]
Gap Size Accepted (Median)	8.56	8.28	1.55	.1.55	.611	No
YLR Following Permissive (Mean)						
Average per hour	1.58	2.05	1.80	2.96	0.284	No
Average per 100 LT vehicles	1.58	2.10	1.85	3.56	0.307	No
Average per 1000 opposing thru vehicles	5.39	4.15	11.04	6.33	0.438	No
RLR Following Permissive (Mean)						
Average per hour	0.14	0.44	0.39	0.86	0.016	Yes, Increase
Average per 100 LT vehicles	0.15	0.44	0.53	1.20	0.080	No
Average per 1000 opposing thru vehicles	0.66	0.86	2.14	1.88	0.591	No
YLR and RLR Following Protected (Mean)						
Average per hour	4.33	3.29	8.18	5.75	0.411	No
Average per 100 LT vehicles	2.46	2.11	3.90	3.86	0.585	No
Average per 1000 opposing thru vehicles	16.73	7.27	40.31	16.45	0.086	No
Traffic Conflicts (Mean)						
Average per hour	0.84	0.47	2.03	0.72	0.166	No
Average per 100 LT vehicles	0.76	0.65	1.48	1.32	0.674	No
Average per 1000 opposing thru vehicles	3.85	0.92	13.11	1.64	0.081	No

[a]Based on two-tailed t-test at 95% LOC

Overall, the results of the statistical analysis revealed one significant finding from before and after comparison of the five measures of effectiveness. Red-light running following the permissive phase experienced a significant increase in RLR per hour from 0.14 RLR per hour to 0.44 RLR per hour, a difference of 0.3 RLR per hour, or 3 RLR in 10 hours. Because a consistent trend was not observed among the all three exposure variables for RLR (per hour, per 100 left-turning vehicles, per 1,000 opposing through vehicles), it is not conclusive that the observed increase in RLR per hour is attributable to the FYAs. The results for the median gap size accepted and the YLR following the permissive phase showed no significant difference resulting from the installation of the FYA. The results of RLR and YLR following the protected phase showed no significant changes in occurrence when the permissive left-turn display was converted to the FYA. Traffic conflicts were studied at the 16 test sites to provide a preliminary indication of safety. The results of the conflict analysis did not reveal any overall statistically significant differences.

CHAPTER 5 SUMMARY AND CONCLUSION

In spring 2010, IDOT initiated an areawide implementation of the FYA as the display for the left-turn permissive interval at more than 100 intersections operating with PPLT control in the Peoria, Illinois, area. Bradley University researchers performed an effectiveness evaluation of the FYA at the approaches where no other geometric or operational changes were made. The purpose of this study was to evaluate the effectiveness of upgrading the CG permissive indication to the FYA indication at intersections operating with PPLT phasing on safety and operations. The overall project research tasks include performing a comprehensive areawide traffic crash analyses at 164 approaches of 86 study intersections, assessing driver comprehension of the new traffic control through a survey instrument, and conducting before and after field studies of traffic operations and traffic conflicts. The comprehensive crash-based evaluation is currently under way and is not included in this report.

5.1 DRIVER COMPREHENSION SURVEY

A total of 363 drivers completed an online survey that included seven left-turn scenarios of the protected and permissive indications of PPLT phasing, with the flashing modes of the FYA indication being animated. The results of the driver comprehension survey revealed the following:

- Participating drivers had very high comprehension of the correct action to take at both the FYA and CG permissive left-turn indications. However, the analysis of the fail-critical responses revealed significantly higher incorrect “go” responses for the CG scenario, compared with the FYA with supplemental sign. These results provide evidence of some drivers misinterpreting the meaning of a permissive left-turn with CG display and incorrectly and unsafely interpreting the meaning as “go” under some circumstances.
- Drivers have a significantly higher comprehension of the FYA when the adjacent through traffic has a green signal, as compared to a red signal, regardless of the presence or absence of the supplemental sign. However, this finding was not confirmed in the fail-critical responses because there was no significant difference between the two scenarios with respect to the incorrect and unsafe “go” responses.
- The provision of the supplemental sign at the FYA approaches with text “Left-turn Yield on Flashing Arrow” significantly improved drivers’ understanding of the correct “yield” message, regardless of the color of the adjacent through traffic signal (green or red). This finding was further confirmed by the fail-critical responses, which showed that the FYA with supplemental sign has significantly lower fail-critical “go” responses than the FYA without a supplemental sign.
- When survey participants were asked, “If oncoming traffic has a green light and you wish to turn left permissively, what signal indication best informs you that you must yield to oncoming traffic before completing your turn?” the majority (66%) felt that the FYA presented the best message in a permissive left-turn.

The results of the static driver comprehension survey of correct responses and fail-critical responses provide evidence of heightened driver understanding of the FYA message

over the CG. The message of the FYA is further enhanced when the supplemental sign with text “Left-turn Yield on Flashing Arrow” is provided. However, conclusive recommendations regarding the supplemental sign cannot be made based on the results of the static survey alone.

5.2 OPERATIONAL AND SAFETY EVALUATION

A total of 128 hours of field data were collected at 16 study approaches; and before and after comparisons were made to assess the impacts of converting the CG permissive left-turn indication to the FYA on operations using the following variables: median gap size accepted, red-light running, yellow-light running, and traffic conflicts. The results of the statistical analysis conducted for this study revealed the following:

- No significant differences were observed in the median gap size accepted.
- Only one out of the nine study variables involving RLR and YLR experienced a significant increase (RLR on a per hour basis following the permissive left-turn interval). When exposure variables were considered, the results for RLR were not significant. Overall, the results of this analysis suggest that RLR and YLR, following either the protected interval or the permissive interval of PPLT phasing, are minimally, if at all, affected by the installation of the FYA.
- No significant differences in the traffic conflict experience were observed for any of the traffic conflict variables studied.

Overall, the findings of this study suggest that drivers in the Peoria, Illinois, area have high comprehension and acceptance of the FYA message. Additionally, the FYA does not appear to have any negative impacts on traffic operations. The ultimate impacts of the FYA on safety will be quantified for the Peoria, Illinois, area upon completion of the comprehensive crash-based evaluation.

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APPENDIX A SURVEY INSTRUMENT

Left turns at signalized intersections are widely recognized as being challenging maneuvers for drivers. There are various ways to control left turn movements with signals. Protected only left turns may be made when a green arrow signal indication is displayed. Permissive left turns may be made after yielding to oncoming traffic and pedestrians at intersections where they are allowed.

Research sponsored by the Illinois Center for Transportation (ICT) and the Illinois Department of Transportation (IDOT) is being conducted through the Civil Engineering and Construction Department at Bradley University to learn about how drivers respond to various types of left turn traffic signals. We hope to gather information that may help people in the future by making intersections safer.

You are being asked to participate in this research study by completing the following survey. You must be 18 years of age or older to participate. The data will be gathered anonymously and no identifying information will be collected. Your participation is voluntary and you may skip any question or exit the survey at any time. This survey should take 5 minutes to complete.

Your input is very much appreciated.

If you have any questions regarding this study please feel free to contact Dr. Kerrie Schattler, Associate Professor of Civil Engineering, Bradley University at kschattler@bradley.edu or 309-677-2779. You may also contact Dr. Ross Fink, Chair of the Committee on the Use of Human Subjects in Research (CUHSR), Bradley University at rf@bumail.bradley.edu or 309-677-2271.

***1. Clicking below indicates that I have read the description of the study and I agree to participate.**

- I Agree.
- I Disagree.

2. What is your age?

- < 18 years
- 18 - 21 years
- 22 - 25 years
- 26 - 35 years
- 36 - 45 years
- 46 - 55 years
- 56 - 65 years
- > 65 years

3. What is your gender?

- Male
- Female

4. Where do you currently reside?

- Tri-County area (Peoria, Tazwell, or Woodford counties)
- Other, please specify (City, State)

5. What is your highest level of education?

- Less than high school
- High school
- Some college - no degree
- 2 year college degree
- 4 year college degree
- Master-level degree
- Doctoral-level degree

6. Do you have a valid driver's license?

- No
- Yes, in Illinois
- Yes in other state, please specify

7. On average, how many miles do you travel in a given year?

- Less than 10,000 miles
- Between 10,000 and 20,000 miles
- More than 20,000 miles

8. Have you noticed a change in the way left turn signals are operated in the Peoria area?

- Yes
- No
- I don't know

9. If you want to turn left, and you see the traffic signals shown below, what would you do?

- Go - You have the right of way
- Yield - Wait for a gap
- Stop - Wait for signal

10. If you want to turn left, and you see the traffic signals shown below, what would you do?

- Go - You have the right of way
- Yield - Wait for a gap
- Stop - Wait for signal

11. If you want to turn left, and you see the traffic signals shown below, what would you do?

- Go - You have the right of way
- Yield - Wait for a gap
- Stop - Wait for signal

12. If you want to turn left, and you see the traffic signals shown below, what would you do?

- Go - You have the right of way
- Yield - Wait for a gap
- Stop - Wait for signal

13. If you want to turn left, and you see the traffic signals shown below, what would you do?

- Go - You have the right of way
- Yield - Wait for a gap
- Stop - Wait for signal

14. If you want to turn left, and you see the traffic signals shown below, what would you do?

- Go - You have the right of way
- Yield - Wait for a gap
- Stop - Wait for signal

15. If you want to turn left, and you see the traffic signals shown below, what would you do?

- Go - You have the right of way
- Yield - Wait for a gap
- Stop - Wait for signal

16.Have you ever encountered the signal shown below?

- Yes
- No

If yes, please indicate the location (city, intersection).

17. If oncoming traffic has a green light and you wish to turn left permissively, what signal indication best informs you that you must yield to oncoming traffic before completing your turn?

- Circular green
- Flashing yellow arrow
- Flashing red arrow
- Other, please specify


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