CIVIL ENGINEERING STUDIES
Illinois Center for Transportation Series No.13-004
UILU-ENG-2013-2017
ISSN: 0197-9191

STATE-OF-THE-ART LITERATURE REVIEW ON PERMISSIVE/ PROTECTED LEFT-TURN CONTROL

Prepared By
Kerrie L. Schattler
Jessica A. Lund
Bradley University

Research Report No. FHWA-ICT-13-004

A synthesis of
ICT-R27-97
Evaluation of Flashing Yellow Arrows (FYA) for Protected/Permissive Left-Turn (PPLT) Control

Illinois Center for Transportation

June 2013

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-ICT-13-004		

4. Title and Subtitle State-of-the-Art Literature Review on Permissive /Protected Left-Turn Control	5. Report Date June 2013
	6. Performing Organization Code
7. Author(s) Kerrie L. Schattler and Jessica A. Lund	8. Performing Organization Report No. ICT-13-004 UILU-ENG-2013-2017
9. Performing Organization Name and Address Illinois Center for Transportation Department of Civil & Environmental Engineering University of Illinois at Urbana-Champaign 205 N. Mathews Ave., MC-250 Urbana, IL 61801	10. Work Unit No. (TRAIS) 11. Contract or Grant No. R27-97
12. Sponsoring Agency Name and Address Illinois Department of Transportation Bureau of Materials and Physical Research 126 E. Ash Street Springfield, IL 62704	13. Type of Report and Period Covered 14. Sponsoring Agency Code

15. Supplementary Notes

16. Abstract

In spring 2010, the Illinois Department of Transportation 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 protected/permissive left-turn (PPLT) control. Bradley University was retained to perform an effectiveness evaluation of the FYA at these locations. The purpose of this research was to evaluate the effect on safety and operations of upgrading the circular green permissive indication to FYA indications at intersections operating with PPLT phasing. The research tasks included 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.

To fulfill the research objectives, a comprehensive state-of-the-art literature review was conducted; the findings are documented in this report. The purpose of the literature review was to document the current knowledge and research findings involving PPLT control, and specifically, studies involving FYA indications. 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. This report provides a synthesis of the state-of-the-art on various left-turn traffic control strategies.

17. Key Words	18. Distribution Statement
flashing yellow arrow, left-turn control, permissive left-turn interval	No restrictions. This document is available to the public through the National Technical Information Service, Springfield, Virginia 22161

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of Pages	22. Price
Unclassified	Unclassified	72	

Form DOT F 1700.7 (8-72) **Reproduction of completed page authorized**

ACKNOWLEDGMENT, DISCLAIMER, MANUFACTURERS' NAMES

This publication is based on the results of ICT-R27-97, **Evaluation of Flashing Yellow Arrows (FYA) for Protected/Permissive Left-Turn (PPLT) Control.** ICT-R27-97 was conducted in cooperation with the Illinois Center for Transportation; the Illinois Department of Transportation (IDOT), Division of Highways; and the U.S. Department of Transportation, Federal Highway Administration (FHWA).

The research team is thankful for the assistance provided by the project's Technical Review Panel (TRP) members and other IDOT staff throughout the progress of this project.

Members of the TRP are the following:

Randy Laninga, Chair, IDOT

Kyle Armstrong, IDOT

Joe Monroe, IDOT

David Piper, IDOT

Sean Coyle, IDOT

Maureen Addis, IDOT

Dean Mentjes, FHWA

Tom Hufnagle, IDOT

Juan David Pava, IDOT (BMPR)

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 used across the United States, including circular green, 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 appropriate driver action because it allows drivers to recognize and understand the message. The National Committee on Uniform Traffic Control Devices (NCUTCD) expressed concern about the non-uniformity and number of different left-turn permissive indications used throughout the United States. In response they commissioned a study, published as the National Cooperative Highway Research Program (NCHRP) Report 493, to evaluate and identify the best signal display for the permissive interval of PPLT control. The 2003 study found that the flashing yellow arrow (FYA) permissive indication is well understood by drivers and was recommended for permissive left turns. In 2009, the FYA was adopted into the *MUTCD* after the Federal Highway Administration (FHWA) permitted 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 to several hundred statewide.

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 was to evaluate the effect on safety and operations of upgrading circular green permissive indications to FYA indications at intersections with PPLT phasing. The research tasks included 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 comprehensive literature review was conducted, and the findings are documented in this report. The purpose of the literature review was to document current knowledge and research findings involving PPLT control, and specifically, studies involving FYA indications.

LEFT-TURN–RELATED CRASHES IN PEORIA TRI-COUNTY AREA

To quantify the extent of the left-turn crash experience in the Peoria, Illinois area, a trend analysis over time was conducted as a part of this research. Traffic crashes from the years 2007 through 2010 in the Peoria tri-county area (Peoria, Tazewell, and Woodford counties) were analyzed using the Illinois statewide computerized database to determine the trend of total signalized intersection crashes and left-turn head-on (LTHO) crashes. The results are shown in Table E-1.

This analysis revealed that 23.8% of all signalized intersection crashes in the Peoria area are LTHO, which is a considerable portion of the crashes. The installation of FYAs is expected to reduce the number of LTHO crashes, and if found to be effective, will have a substantial impact on safety at Peoria area intersections.

Table E-1. Average Annual Total and LTHO Crashes by County in the Tri-County Area

Type of Crash	Peoria County	Tazewell County	Woodford County	Total Tri-County Area
Average Annual Total Crashes (crashes/year)	5,484	2,952	594	9,031
Average Annual Crashes at Signalized Intersections (crashes/year)	1,099	548	17	1,664
Average Annual LTHO Crashes at Signalized Intersections (crashes/year)	286	106	5	397
Percentage of LTHO crashes of Total Crashes at Signalized Intersections	**26.0%**	**19.3%**	**29.4%**	**23.8%**

LITERATURE REVIEW SYNTHESIS

A comprehensive literature review was conducted to assess the effectiveness of PPLT control and signal indications used for permissive left-turn intervals. 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 following is a summary of the authors' results and findings.

The authors of the NCHRP Report 493, Brehmer, Kacir, Noyce and Manser, as well as Knodler, Bergh, Chapman, and others, published several papers in transportation journals documenting their analysis and results published in NCHRP Report 493, as well as follow-up studies on the impacts of FYAs. The following conclusions were drawn regarding FYA permissive indications (Brehmer et al. 2003; Noyce and Smith 2003; Knodler et al. 2001; 2005b):

- In the photographic driver survey, out of the circular green (CG), flashing circular yellow (FCY), flashing circular red (FCR), and flashing yellow arrow (FYA), the CG permissive indication had the lowest percentage of correct responses for all indications (50%), and the FCY and FCR had the highest percentage of correct responses.
- In the field traffic operations study, follow-up headways were higher for the flashing red displays than the other displays, probably a result of legal requirements in the vehicle code that state a vehicle must first stop.
- The traffic conflict study showed that few left-turn conflicts are associated with the PPLT display.
- The driver confirmation and static follow-up surveys showed that the scenarios involving the FYA had a high level of driver understanding and significantly lower fail-critical rates than the scenarios involving the CG display.

- 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. There was a mostly positive reaction to the FYA from the implementing agencies, the public, and law enforcement.

The authors also made the following recommendations (Brehmer et al. 2003; Kacir, Brehmer, and Noyce 2003a, 2003b):

- 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.
- Flashing red indications (circular and arrow) should be limited to certain situations in which a complete stop is recommended for left-turning traffic during the permissive interval.
- If there is widespread use of the flashing red indications for PPLT control, the meaning and effectiveness of the indication may be undermined.

Several follow-up studies from the authors of NCHRP Report 493 are also presented in this report. The following conclusions were drawn from these studies:

- Concerning five-section signal arrangements, the FYA and FCY indications were 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 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, Noyce, and Fisher 2007).
- 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 at. 2007).

Additional crash-based, operations-based, and driver comprehension studies were reviewed and presented in this literature review report. A summary of the various authors' conclusions from these studies is as follows:

- 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 installation of the FYA and switch 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, Bergh, and Chapman 2007b; Perez, 2010; Pulugurtha, Agurla, and Khader 2011; Srinivasan, Lyon, et al. 2011; Srinivasan Gross, et al. 2011).
- A study evaluating driver understanding of the FYA in Creve Coeur, Missouri, concluded that area drivers understand the CG with a supplemental sign better than the FYA without a sign (Henery and Geyer 2008). However, these findings were not supported by statistical analysis and were based on a sample size of 204 drivers.
- An operations-based study determined that 95% of vehicles observed turning left during the FYA permissive indication did so safely (Lin, Thiagarajan, and Atie 2008).
- A study conducted in Texas found that some high-volume intersections operating with the FYA and lead-lag left-turn phasing showed an increase in certain types of traffic conflicts (Qi, Yuan et al. 2011). They concluded that the FYA indication was well understood by drivers based on driver survey results. They suggested that louvered signal heads be used to prevent the left-turn drivers from seeing the adjacent through signals, especially when lead-lag left-turn phasing is used (Qi, Yuan et al. 2011).
- 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. (Qi, Zhang et al. 2011).

CONTENTS

LIST OF ACRONYMS

AADT	average annual daily traffic
ADT	average daily traffic
ASCE	American Society of Civil Engineers
CG	circular green
CR	circular red
CMF	crash modification factors
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
IDOT	Illinois Department of Transportation
ITE	Institute of Transportation Engineers
LTHO	left-turn head-on
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
NCUTCD	National Committee on Uniform Traffic Control Devices
NHTSA	National Highway Traffic Safety Administration
PPLT	protected/permissive left-turn
RFP	request for proposal
RITA	Research and Innovative Technology Administration
SGA	solid green arrow
SPF	safety performance function
SRA	solid red arrow
TRB	Transportation Research Board
TTI	Texas Transportation Institute
UMass	University of Massachusetts
USDOT	United States Department of Transportation

CHAPTER 1 INTRODUCTION

Left turns at signalized intersections are widely recognized as being challenging and high-risk maneuvers for drivers. Vehicles turning left may be subjected to conflicts with three main sources of traffic: opposing through traffic, same-direction through traffic, and cross-street vehicular and pedestrian traffic. Using data available from 1998, it can be estimated that 23.8% of all crashes occurring at signalized intersections in the United States were left-turn–related (calculated based on data from Smith and Najm 2001; National Highway Traffic Safety Administration 1999). Others have estimated that 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).

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 of a 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.

PPLT control exists throughout the country in different forms with varying signal display arrangements, placements, and permissive signal indications because the *MUTCD* has historically provided limited guidance for PPLT control (ATSSA, 2001). Several signal indications for the permissive interval 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 for their intended application is critical in eliciting an appropriate driver action from the motoring public. The use of uniform traffic control devices, including traffic signals, simplifies the tasks of the road user because they allow drivers to recognize and understand the message more easily. This in turn, reduces the motorists’ response times and improves their ability to take the desired driving action.

The National Committee on Uniform Traffic Control Devices (NCUTCD) had long expressed concern about the non-uniformity and number of different indications for PPLT control used throughout the United States and its potential for confusing drivers traveling across state boundaries. In addition, some professionals felt that drivers making a permissive left-turn may interpret the widely used CG permissive display incorrectly. In most traffic signal applications, a CG indication means “look both ways and proceed with caution” or simply “go.” Although drivers have generally learned the meaning of the CG for permissive lefts (to yield and then proceed if a gap in oncoming traffic is available), some researchers felt that if taken out of proper context, the CG message may be misinterpreted by some drivers, thus contributing to safety problems. To address these concerns, the National Cooperative Highway Research Program (NCHRP) commissioned a study, published in Report 493 (Brehmer et al. 2003) to evaluate and identify the best signal display for PPLT control. The NCHRP Report 493, titled *Evaluation of Traffic Signal Displays for Protected/Permissive Left-turn Control,* found that the FYA permissive indication is well understood by drivers; and the authors 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, and that meetings of the NCUTCD indicated a consensus in the practitioner community in support of optional use of the FYA. Interim approval was granted to any jurisdiction that submitted a written request to the Office of Transportation Operations. The memorandum also provided the details for the design and operational requirements of the new FYA signal (Paniati 2006). The FYA was then adopted into the 2009 *MUTCD* after FHWA allowed FYAs to be installed on an interim-approval basis. To date, at least 31 states throughout the United States have begun implementing FYAs for permissive left-turn control, as shown in Figure 1 (Rietgraf 2013). It should be noted however, that there is a wide variation in the magnitude of the implementation of FYAs, ranging from a dozen to several hundred statewide. Additionally, these implementations may have been initiated by local agencies within the highlighted states shown in Figure 1 and/or by the state department of transportation.

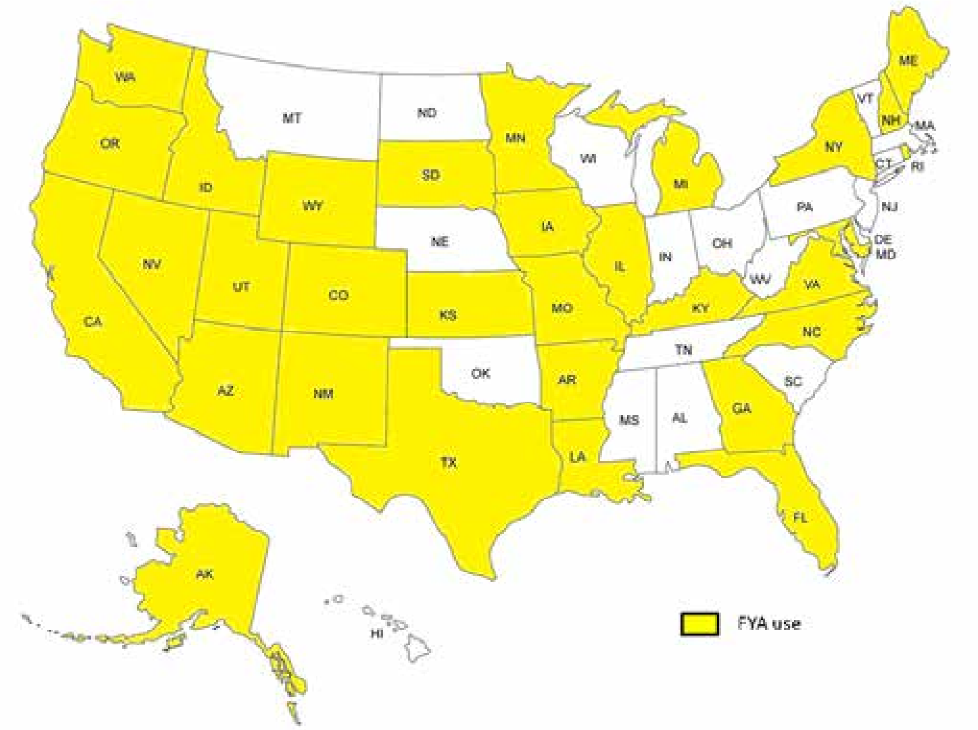


Figure 1. States operating the FYA at signalized intersections (Source: Rietgraf 2013).

1.1 ANALYSIS OF AREAWIDE LEFT-TURN CRASHES

According to the National Highway Traffic Safety Administration (NHTSA), in 1998 there were a total of 1,250,000 signalized intersection–related crashes in the United States (NHTSA 1999). A paper published in 2001 analyzed the 1998 crash data to define the problem of left-turn and crossing-path crashes in the United States. The authors reported 229,000 left-turn head-on (LTHO) crashes at signalized intersections in 1998 (Smith and Najm 2001). The statistics cited imply that 18.3% of all crashes occurring in 1998 in the United States at signalized intersections were LTHO crashes.

The LTHO crash type is of particular interest to this research because it often occurs during the permissive left-turn phase. An LTHO crash is a specific crash type that falls into the broad category of “left-turn related crashes”. An LTHO crash is one in which a left-turning vehicle collides with a vehicle proceeding straight from the opposite direction. Figure 2 shows an example of an LTHO crash.

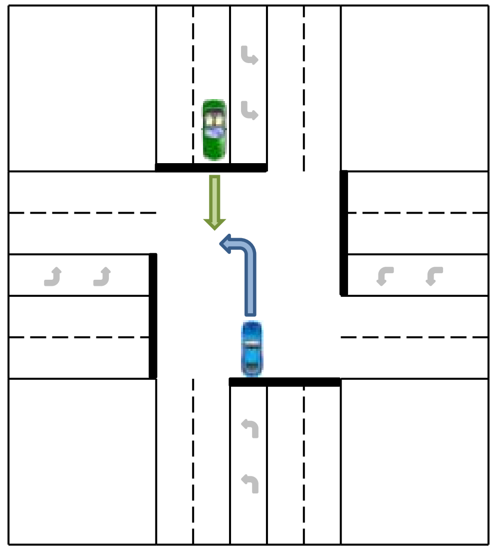


Figure 2. An example of an LTHO crash.

It should be noted that it is challenging to compile nationwide statistics on LTHO crashes because of the differences in crash-type coding and reporting among states. For example, in Illinois there is no official crash-type designation for recording an LTHO crash on the crash report form. An LTHO crash is typically coded as a “turning” crash; however, a “turning” crash can include any crash involving at least one vehicle in the process of completing a turning maneuver (right or left), making it difficult to isolate the LTHO crash type in Illinois directly. By contrast, in Michigan there is a specific LTHO crash type used in the reporting process.

Traffic crashes from the years 2007 through 2010 in the Peoria tri-county area (Peoria, Tazewell, and Woodford counties) in Illinois were analyzed using the statewide computerized database to determine the trend of total signalized intersection crashes and LTHO crashes. The total number of crashes at signalized intersections by year and county is shown in Figure 3.

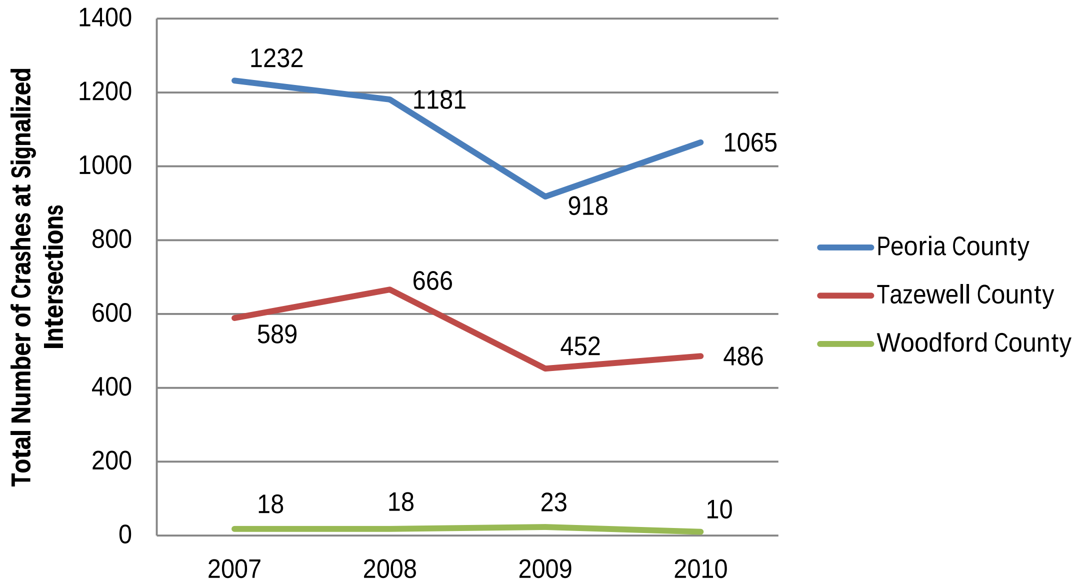


Figure 3. Signalized intersection crashes in the tri-county area, 2007–2010.

These crashes were then sorted by crash type. As mentioned, LTHO crashes are typically coded as "turning" crashes in Illinois. All crashes that reported the crash type as "turning" were further analyzed by each vehicle's maneuver prior to the crash. Only crashes that reported one vehicle as "turning left" and the other as "straight ahead" were considered to be LTHO crashes. The number of LTHO crashes at signalized intersections by year in the tri-county area are shown in Figure 4.

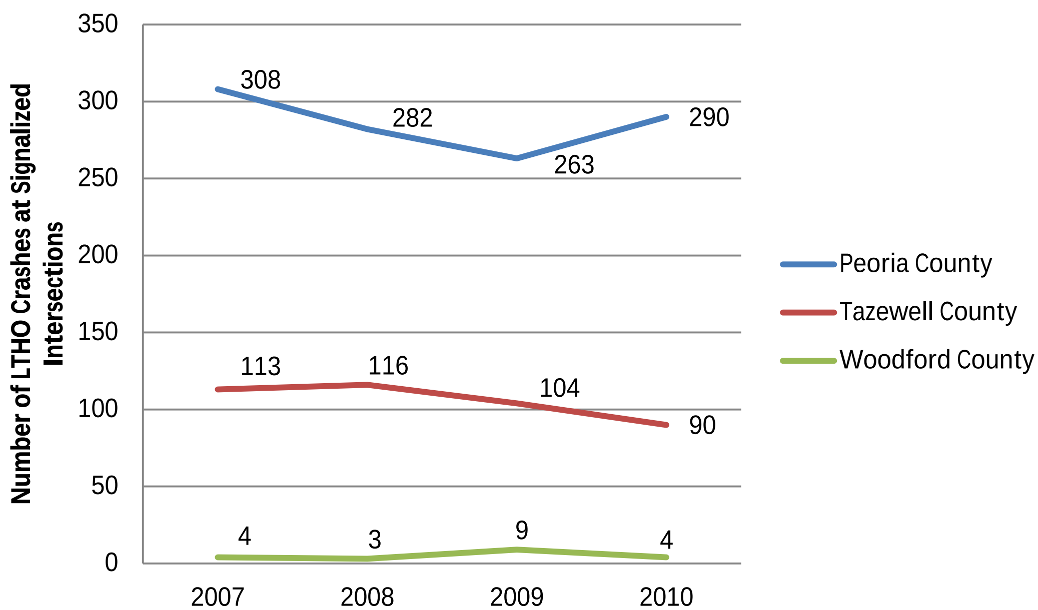


Figure 4. LTHO crashes at signalized intersections in the tri-county area, 2007–2010.

Table 1 provides a summary of the average annual total crashes, signalized intersection crashes, and LTHO crashes for the tri-county area.

Table 1. Average Annual Total and LTHO Crashes by County in the Tri-County Area

Type of Crash	Peoria County	Tazewell County	Woodford County	Total Tri-County Area
Average Annual Total Crashes (crashes/year)	5,484	2,952	594	9,031
Average Annual Crashes at Signalized Intersections (crashes/year)	1,099	548	17	1,664
Average Annual LTHO Crashes at Signalized Intersections (crashes/year)	286	106	5	397
Percentage of LTHO crashes of Total Crashes at Signalized Intersections	**26.0%**	**19.3%**	**29.4%**	**23.8%**

For the years 2007 through 2010, LTHO crashes averaged 23.8% of the total crashes at signalized intersections for the entire tri-county area. For Peoria County, LTHO crashes accounted for 26.0% of all crashes at signalized intersections.

The percentage of LTHO crashes of total crashes at signalized intersections from year to year was determined and is shown in Figure 5.

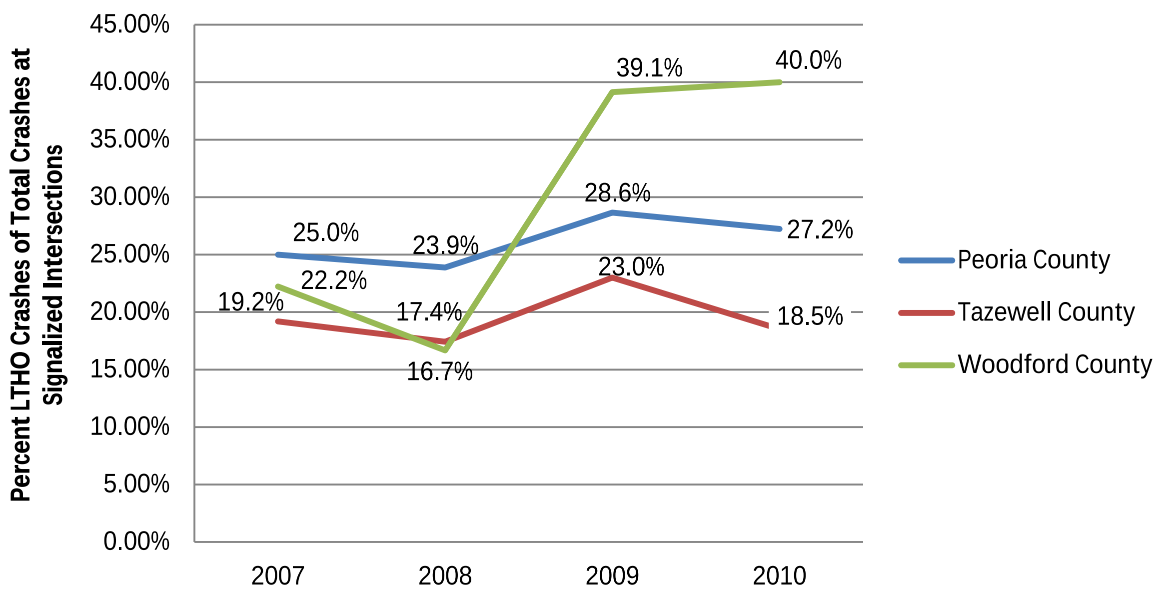


Figure 5. Percentage of LTHO crashes of total crashes at signalized intersections in the tri-county area, 2007–2010.

1.2 PURPOSE

Beginning in the spring of 2010, the Illinois Department of Transportation (IDOT) installed the FYA signal indication on state routes at more than 100 intersections with PPLT control in the Peoria, Illinois, area. 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 comprehensive literature review was conducted and the findings are documented in this report. The purpose of the literature review is to document the current knowledge and research findings involving PPLT control and, specifically, studies involving FYA indications.

CHAPTER 2 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 interval. 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 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), 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 literature review is organized into the following sections:

- 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 meanings of left-turn signal indications, types of left-turn control, and phasing sequences are discussed throughout the literature review. Definitions and schematics are presented in section 2.1 Definitions as a reference.

2.1 DEFINITIONS

Chapter 4D of the *MUTCD,* "Traffic Control Signal Features," defines the meaning of various signal indications and appropriate vehicular responses. The definitions, as stated in the *MUTCD,* for four permissive signal indications are presented below for the flashing yellow arrow, circular green, flashing circular red, and flashing red arrow indications (Section 4D.04) (Federal Highway Administration 2009). Diagrams of typical signal arrangements are presented to illustrate the four permissive left-turn indications, as shown in Figures 6 through 9, respectively.

Flashing Yellow Arrow
"Vehicular traffic, on an approach to an intersection, facing a flashing YELLOW ARROW signal indication, displayed alone or in combination with another signal indication, is permitted to cautiously enter the intersection only to make the movement indicated by such arrow, or other such movement as is permitted by other signal indications displayed at the same time.

"Such vehicular traffic, including vehicles turning right or left or making a U-turn, shall yield the right-of-way to:

a. Pedestrians lawfully within an associated crosswalk, and
b. Other vehicles lawfully within the intersection.

“In addition, vehicular traffic turning left or making a U-turn to the left shall yield the right-of-way to other vehicles approaching from the opposite direction so closely as to constitute an immediate hazard during the time when such turning vehicle is moving across or within the intersection.” (Federal Highway Administration 2009)

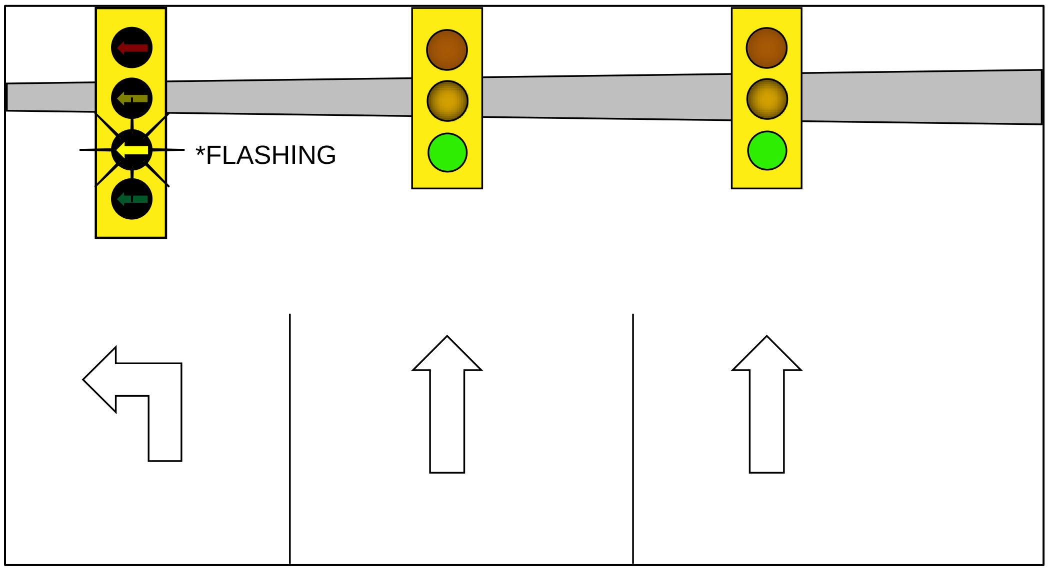


Figure 6. Typical permissive left-turn signal using flashing yellow arrow indication.

Circular Green

“Vehicular traffic facing a CIRCULAR GREEN signal indication is permitted to proceed straight through or turn right or left or make a U-turn movement except as such movement is modified by lane-use signs, turn prohibition signs, lane markings, roadway design, separate turn signal indications, or other traffic control devices.

“Such vehicular traffic, including vehicles turning right or left or making a U-turn movement, shall yield the right-of-way to:

a. Pedestrians lawfully within an associated crosswalk, and

b. Other vehicles lawfully within the intersection.

“In addition, vehicular traffic turning left or making a U-turn movement to the left shall yield the right-of-way to other vehicles approaching from the opposite direction so closely as to constitute an immediate hazard during the time when such turning vehicle is moving across or within the intersection.” (Federal Highway Administration 2009)

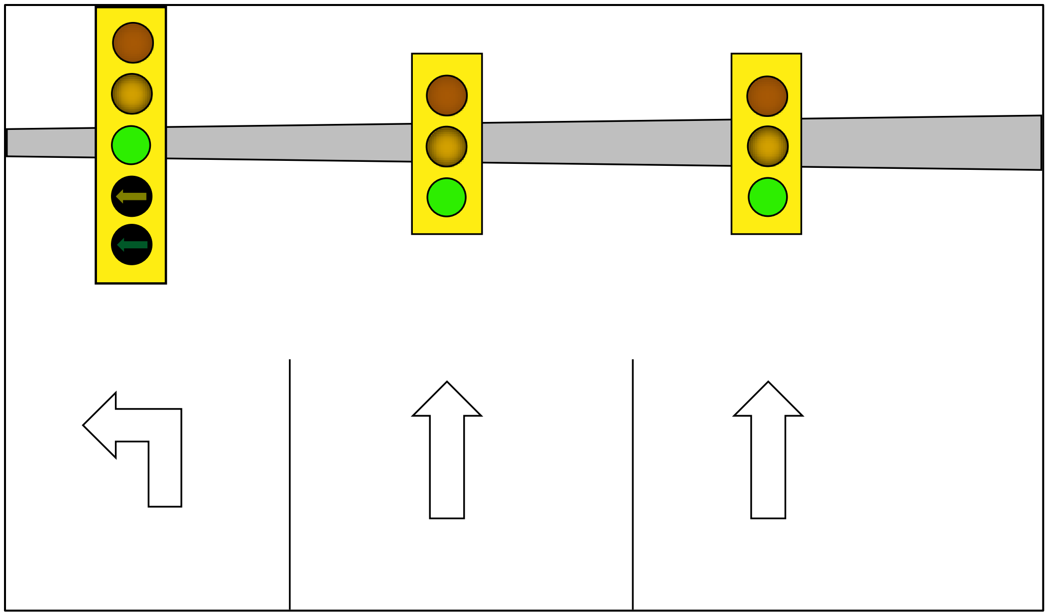


Figure 7. Typical permissive left-turn signal using circular green signal indication.

Flashing Circular Red
"Vehicular traffic, on an approach to an intersection, facing a flashing CIRCULAR RED signal indication shall stop at a clearly marked stop line; but if there is no stop line, before entering the crosswalk on the near side of the intersection; or if there is no crosswalk, at the point nearest the intersecting roadway where the driver has a view of approaching traffic on the intersecting roadway before entering the intersection. The right to proceed shall be subject to the rules applicable after making a stop at a STOP sign." (Federal Highway Administration 2009)

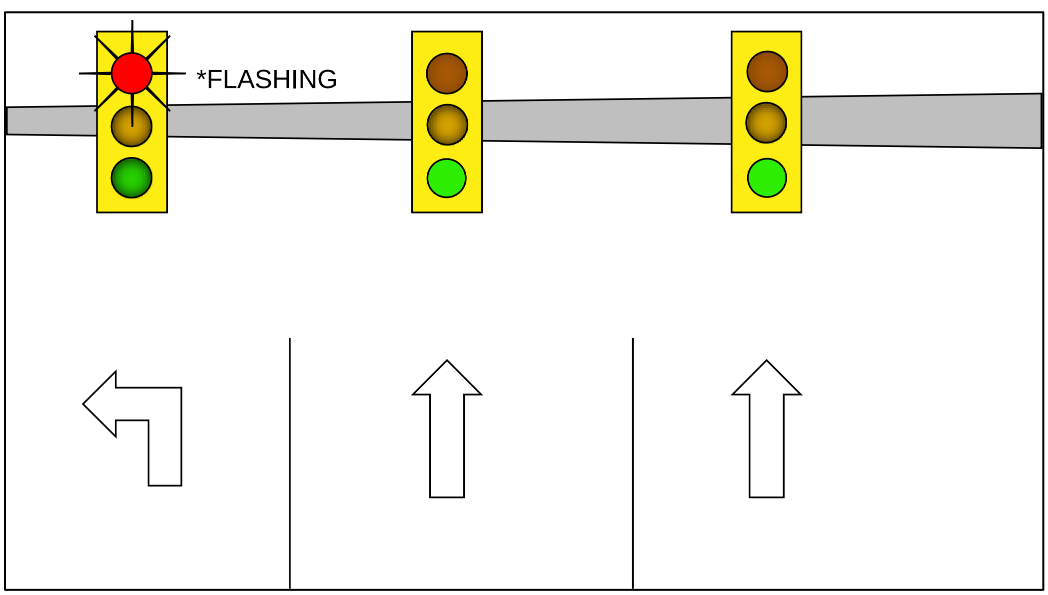


Figure 8. Typical permissive left-turn signal using flashing circular red indication.

Flashing Red Arrow
"Vehicular traffic, on an approach to an intersection, facing a flashing RED ARROW signal indication if intending to turn in the direction indicated by the arrow shall stop at a clearly marked stop line; but if there is no stop line, before entering the crosswalk on the near side of the intersection; or if there is no crosswalk, at the point nearest the intersecting roadway where the driver has a view of approaching traffic on the intersecting roadway before entering the intersection. The right to proceed with the turn shall be limited to the direction indicated by the arrow and shall be subject to the rules applicable after making a stop at a STOP sign." (Federal Highway Administration 2009)

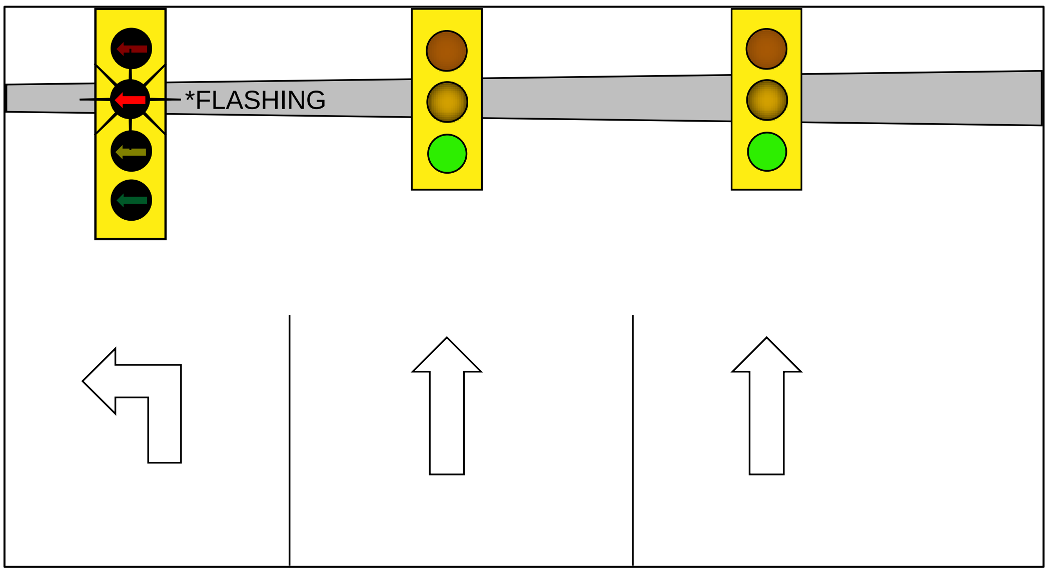


Figure 9. Typical permissive left-turn signal using flashing red arrow indication.

2.1.1 Types of Left-Turn Control

The left-turn movement can be protected-only, permissive-only, or protected/permissive.

- In protected-only control, left-turn drivers can make their turn only during an exclusive left-turn phase, in which they have the right-of-way. Drivers may proceed only to turn left on a green left-turn arrow (Figure 10a).
- During permissive-only control, left-turn drivers must first yield to oncoming traffic and pedestrians before initiating their left-turn (Figure 10b).
- Protected/permissive left-turn control includes both a protected left-turn phase and a permissive left-turn interval within the same cycle. Examples of variations of phasing plans with PPLT control are shown in Figure 11.

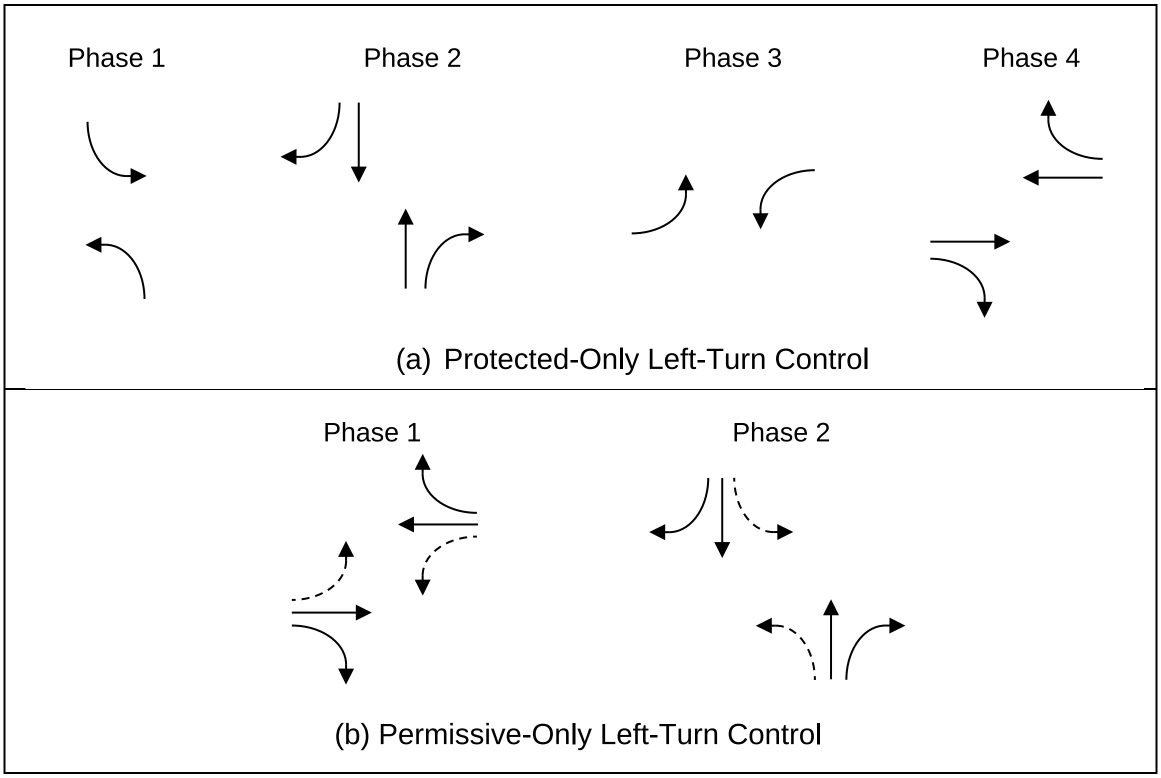


Figure 10. Left-turn control phasing diagrams for (a) protected-only left-turn control and (b) permissive-only left-turn control.

2.1.2 Phasing Sequence

The sequence of protected and permissive left-turn phases in PPLT control varies. Each type of phasing sequence described is shown in Figure 11.

- Lead left-turn sequence: moves both of the opposing left turns before the through movements (Figure 11a)
- Lag left-turn sequence: moves both of the opposing left turns after the through movements (Figure 11b)
- Lead-lag sequence: Opposing left turns move separately from each other but simultaneously with their associated through phase (Figure 11c).

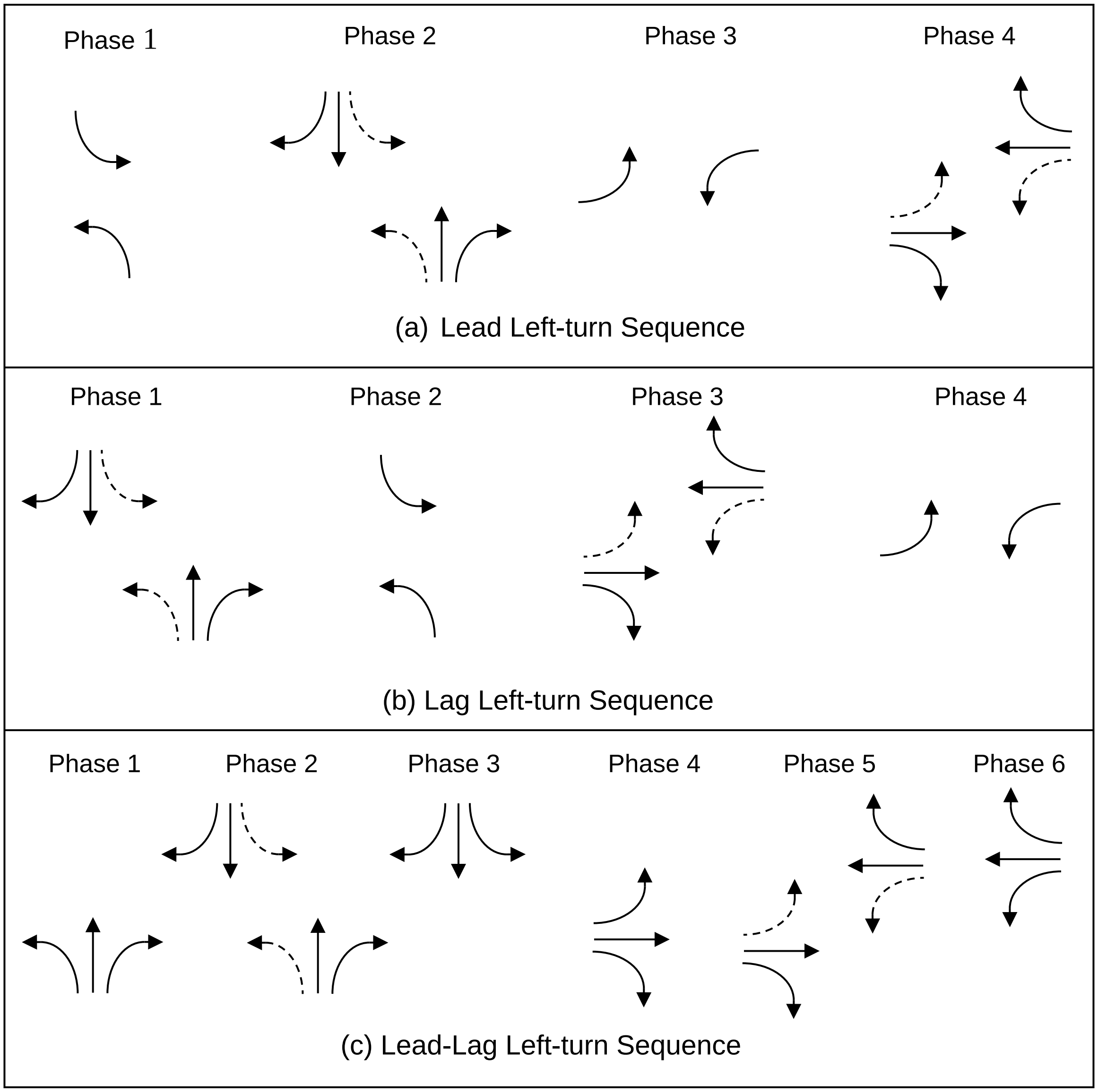


Figure 11. Phasing sequences for PPLT control (a) lead left-turn sequence, (b) lag left-turn sequence, and (c) lead-lag left-turn sequence.

2.1.3 Left-Turn Yellow Trap

When the lead-lag sequence is used with PPLT control, a phenomenon exists called the yellow trap. The yellow trap is a potentially hazardous situation that occurs when the signal changes from a permissive phase to a lagging protected phase in one direction (as shown in Phase 2 and 3 for example in Figure 11c). A driver attempting to complete a left-turn during the permissive phase may become “trapped” in the intersection when his/her permissive indication changes to yellow for the change interval. This driver will see that the adjacent through lanes also receive a yellow signal and may believe (incorrectly) that the opposing through traffic is also seeing the yellow change interval. The driver may make the left-turn, not knowing that the opposing through traffic actually has a green through indication and a protected left-turn indication. Potential for traffic conflict exists between the “sneaker” left-turn vehicle and the opposing through traffic that does not stop. Figure 12 further shows the left-turn yellow trap scenario.

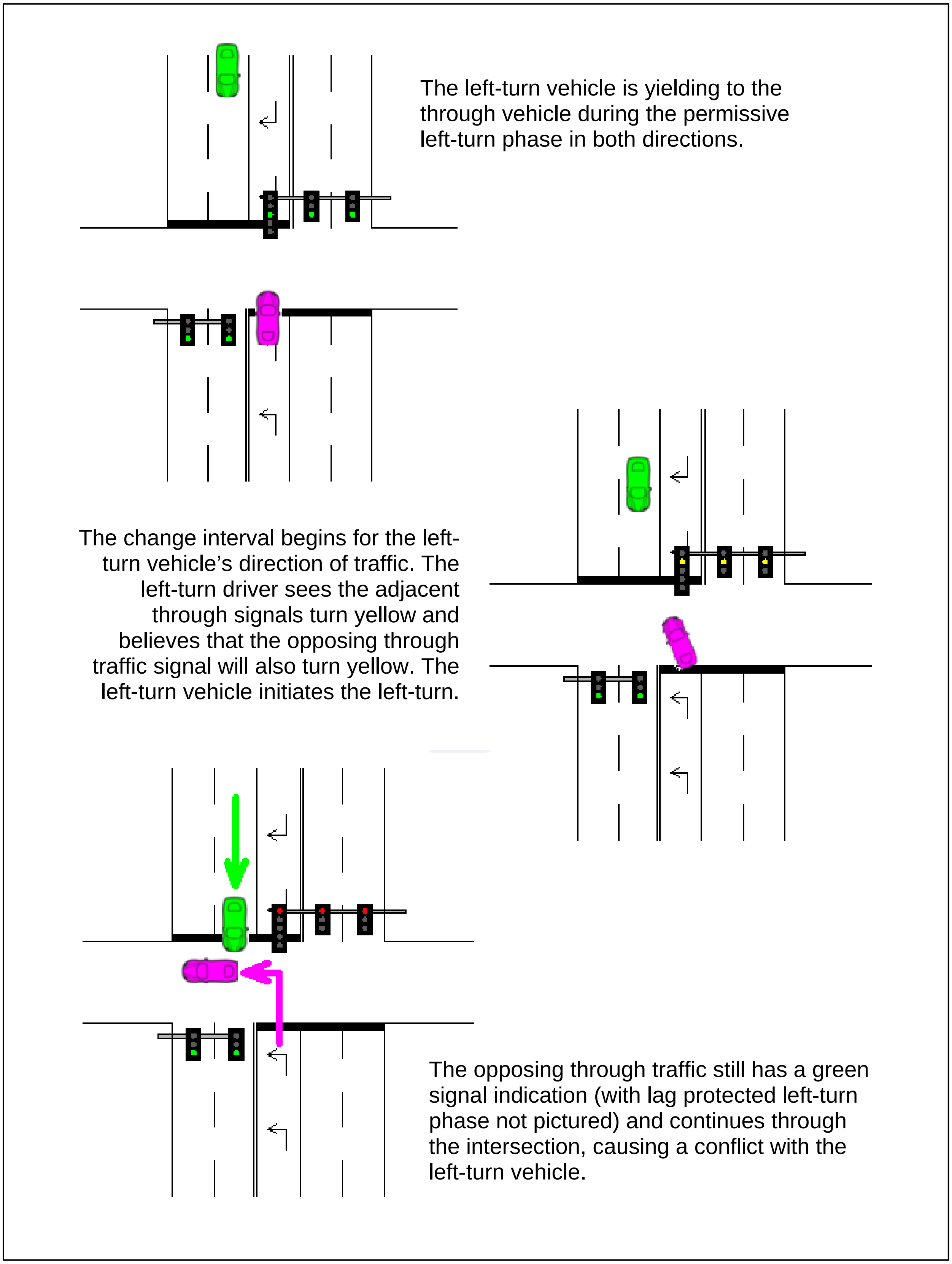


Figure 12. The left-turn yellow trap scenario illustrated using a CG permissive left-turn indication.

2.2 NCHRP REPORT 493 AND FOLLOW-UP STUDIES

The authors of the NCHRP Report 493 (2003), Brehmer, Kacir, Noyce, and Manser, along with Knodler, Bergh, Chapman, and others, published several papers in transportation journals documenting their analysis and results from the NCHRP Report 493, as well as follow-up studies on the impacts of FYAs. This section presents summaries of those authors' findings in chronological order.

2.2.1 NCHRP Report 493 Methodology and Findings

The National Cooperative Highway Research Program conducted research in response to the need for a comprehensive national study to evaluate safety and operational implications of the various left-turn indications used in different states. The results of this research are presented in NCHRP Report 493 *Evaluation of Traffic Signal Displays for Protected/ Permissive Left-Turn Control*, which was completed in 2003 (Brehmer et al.).

Extensive research was conducted as part of NCHRP 493 to identify the most suitable traffic signal display for PPLT control. The objective of the project was to examine the effectiveness of several PPLT signal displays and permissive indications, by conducting the necessary field studies and laboratory tests. This project spanned seven years, and the report includes a literature review, current practice survey, photographic driver survey, field traffic operations study, field traffic conflict study, crash-data analysis, driver confirmation study, and field implementation study (Brehmer et al. 2003; Kacir, Brehmer, and Noyce 2003b).

The NCHRP 493 research team sought through their research to identify a display/indication that would provide the following characteristics:

- A clear distinction between protected and permissive left turns
- Minimal driver confusion
- A reduction in the incidence of left-turning drivers assuming the right-of-way
- Elimination of the yellow trap
- Allowance for protected-only and permissive-only operation by time of day
- No need for supplemental signing
- No need for special lenses or louvers.

The recommendations of this research ultimately led to the revision of the *MUTCD* to include the FYA as an allowable indication for the permissive left-turn interval. The following are general recommendations made by the research team of NCHRP Report 493:

- 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.

- Flashing red indications (circular and arrow) should be limited to certain situations in which a complete stop is recommended for left-turning traffic during the permissive interval.
- If there is a widespread use of the flashing red indications for PPLT control, the meaning and effectiveness of the indication may be undermined.

The various tasks performed as a part of NCHRP Report 493 are discussed further in the following sections.

2.2.1.1 Current Practice Survey

The objective of the current practice survey was to identify and quantify the various PPLT displays, design, and phase sequencing used in the United States. A 15-question survey was disseminated to collect general information about the extent agencies used PPLT displays; the arrangement, location, and indications used; special techniques to avoid the yellow trap; and local laws affecting the use of PPLT displays.

The authors analyzed the survey responses from 168 agencies. It was discovered that 29% of all signalized intersections were reported to use PPLT signal phasing. The five-section cluster arrangement (Figure 13) was the predominant arrangement in 34 states, which accounted for 63% of all reported PPLT signal displays.

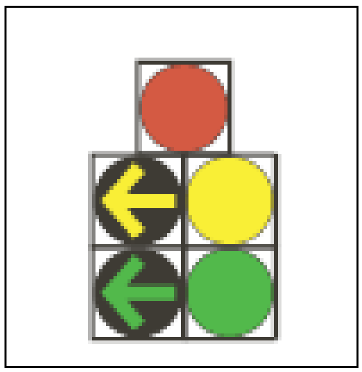


Figure 13. Five-section cluster signal head arrangement (adapted from Brehmer et al. 2003).

The CG permissive indication was used by 165 out of 168 agencies. Other permissive indications used included the FCY, FYA, FCR, and FRA. It was also found that 49% of agencies always use supplemental signs, and 34% of agencies sometimes use supplemental signs for permissive indications. The majority of PPLT controlled signalized intersections used lead phasing (83%). The authors then commented on the various signal displays in use across the nation (Brehmer et al. 2003).

2.2.1.2 Photographic Driver Survey

A photographic driver survey was conducted to evaluate the various PPLT signal displays that exist in the United States. The objective of the survey was to collect data on driver understanding of different PPLT signal indications with varying display arrangements. Approximately 300 drivers participated in each of eight different geographic locations across the United States, totaling more than 2,400 participants. All participants were licensed drivers. The study was conducted primarily at driver licensing facilities (Brehmer et al. 2003).

A self-explanatory, computer-based survey was used to collect data on driver understanding of the different PPLT signal indications and displays. The various permissive indications tested were the FYA, FRA, FCY, FCR, and CG. Photographs of actual intersections were used as the background images to make the survey more realistic. Survey participants were provided with 30 randomly chosen scenarios selected from 200 unique scenarios. The time taken for the participants to respond to each of the survey questions was recorded and served as an alternative measure of driver understanding. For each scenario, survey participants were asked, “If you want to turn left, and you see the traffic signals shown, you would….” For each question presented, the following options were given: go, yield and wait for a gap, stop then wait for a gap, and stop. Participants could also choose not to respond (Brehmer et al. 2003). In addition to the scenarios, participants were also presented with certain demographic questions. An example of the survey screen presented to participants is shown in Figure 14.

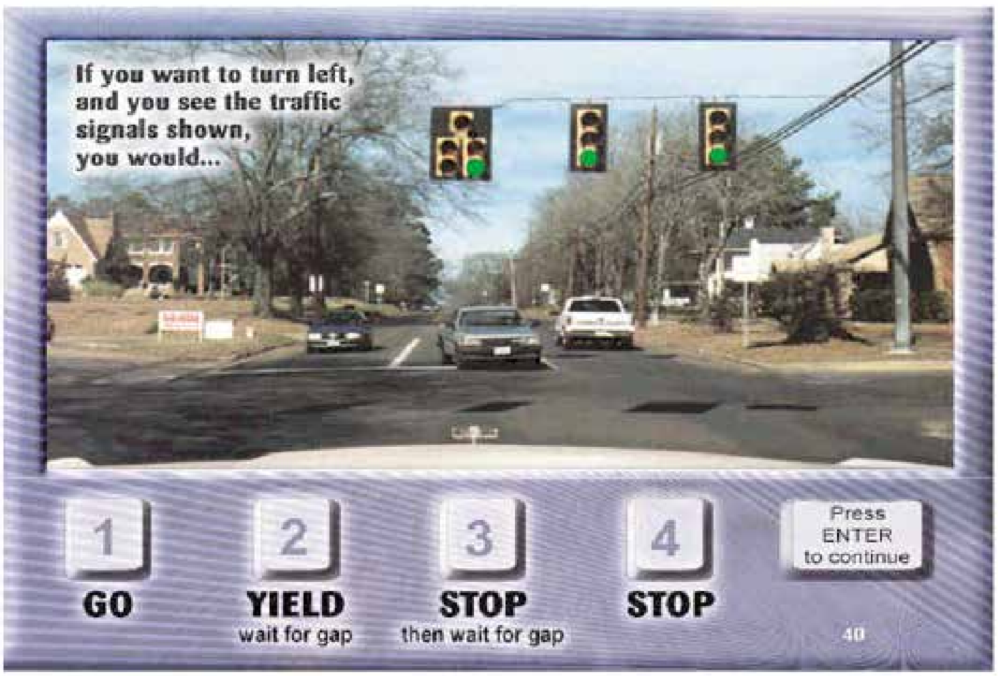


Figure 14. Sample photographic driver survey question (Source: Brehmer et al. 2003).

The photographic driver survey led to several findings about PPLT control. A 95% level of confidence was used for all statistical analyses:

- The CG indication had the lowest percentage of correct response at 50%.
- Males had a statistically higher percentage of correct responses than females.
- Participants age 65 and over had a statistically lower percentage of correct response than ages 24–44, with an extremely low correct response rate associated with the CG permissive indication. However, out of all age groups, participants age 65 and over had the highest correct response rate for the FCR, FCY, and FYA.
- In general, the flashing permissive indications (FCY, FYA, FCR, and FRA) had a lower average response time.

- The flashing permissive indications were found to be better understood by drivers, compared with solid indications for permissive left turns (such as the CG indication). The circular displays were better understood than arrow displays for permissive left-turn movements, as shown in Figure 15.

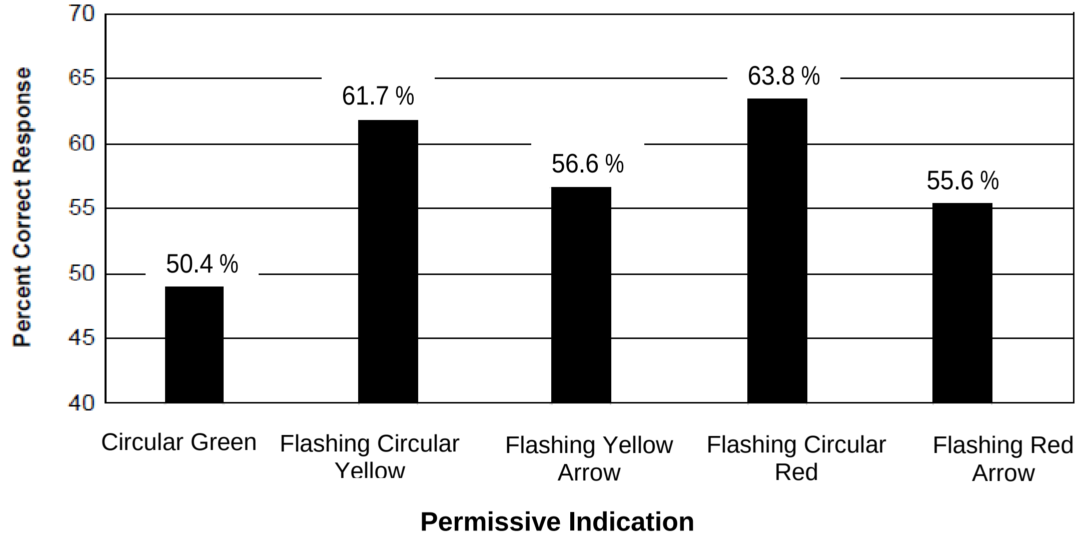


Figure 15. Percentage of correct responses for the permissive indications in PPLT signal displays (adapted from Brehmer et al. 2003).

2.2.1.3 Field Traffic Operations Study

A traffic operations study was also conducted as a part of NCHRP Report 493 before the FYAs had been installed. The authors analyzed saturation flow rates, lost time, response time, and follow-up headway to quantify capacity and delay effects of the various PPLT displays used in the United States at the time of this study—the CG, FCY, FRA, and FCR indications (Brehmer et al. 2003). The specific PPLT displays and geographic regions used in the observational study are shown in Figure 16.

Eight geographical locations were selected based on their use of the PPLT control displays shown in Figure 16. Three intersections in each city were studied except in Dallas, where five intersections were examined. The 26 total intersections were considered typical; however, they had differing PPLT display arrangements and corresponding permissive indications. Traffic operations at each intersection were recorded on video for eight hours, and vehicle headways were extracted in the office using a computer program.

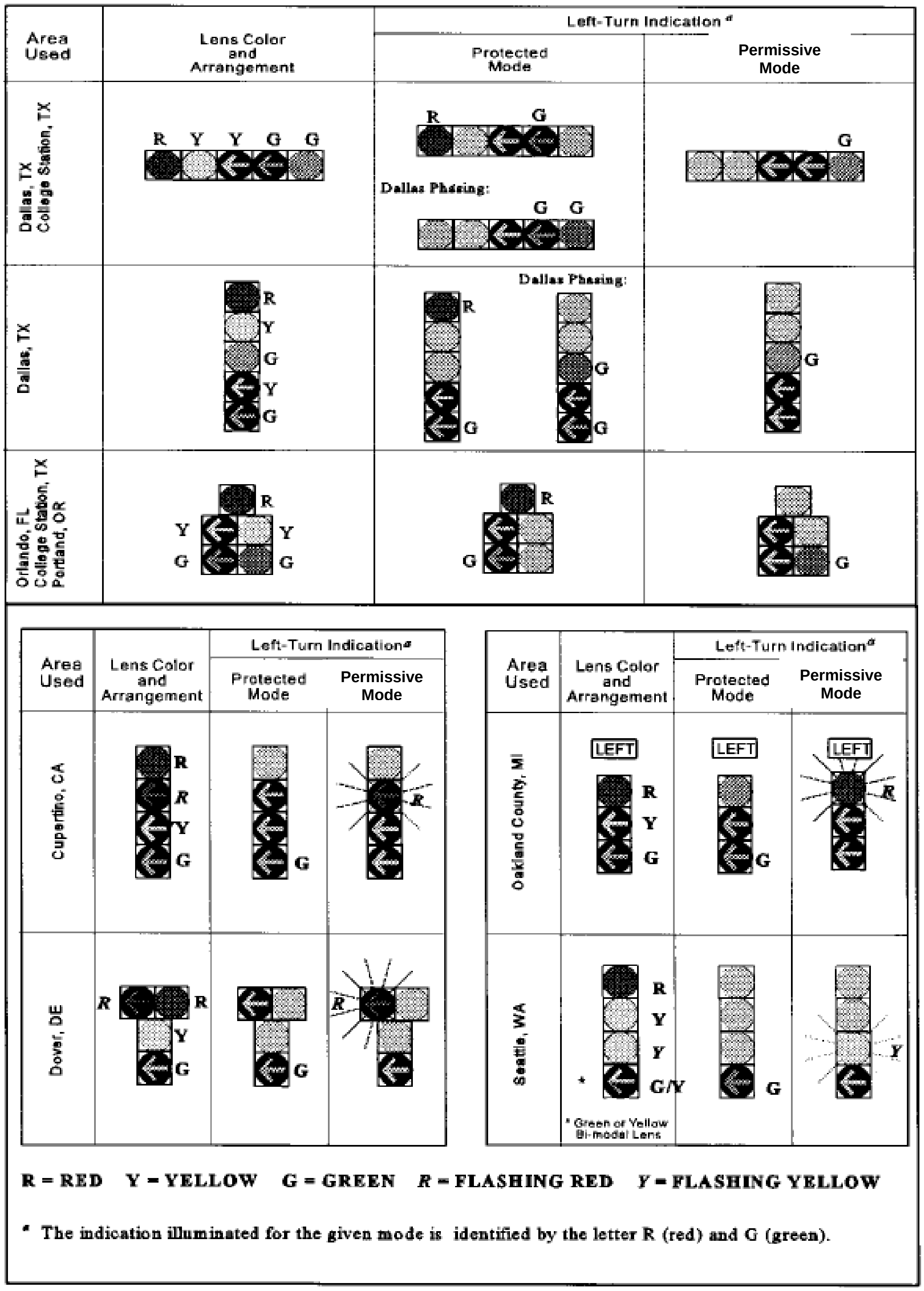


Figure 16. PPLT displays evaluated during the field traffic operations study at various locations in the United States (adapted from Noyce and Smith 2003).

Response time, start-up lost time, and headway data were collected for the protected left-turn movements. The saturation flow rates were collected for both the through movement and the protected left-turn movement. Follow-up headway data were collected for the permissive left-turn movement. Follow-up headway data for the permissive phase were limited because only a few instances were observed in which more than one vehicle made a left-turn in the same gap (Brehmer et al. 2003).

The key findings from the field traffic operations study are summarized below (Noyce and Smith 2003):

- The differences in average saturation flow rates were due to differences in the driver behavior at each location. The type of PPLT signal display was not a contributor.
- The type of PPLT signal display did not significantly influence start-up lost time. The difference in start-up lost time was primarily due to the difference in PPLT phasing. The lag phasing is predictable, and drivers began their movements earlier.
- The response time was significantly influenced primarily by the phasing sequence; the type of PPLT signal display had a correlation as well.
- Differences in follow-up headway were significantly affected by the type of PPLT signal display. The follow-up headway was higher for the flashing red displays than for the other displays. This difference was most likely due to the legal requirements in the vehicle code. Drivers legally had to stop first for the flashing red indications and not for the other types.

2.2.1.4 Field Traffic Conflict Study

The purpose of the field traffic conflict study was to quantify left-turn conflict and event rates for different PPLT signal displays and indications. The authors defined a traffic conflict as one or more drivers taking evasive action to avoid a collision. A traffic event was defined as an unusual, dangerous, or illegal non-conflict maneuver, such as red-light-running, backing, or hesitating. Twenty-four of the 26 intersections that were used in the operations study were used for the conflict study. A total of 11 hours of videotaped data was reviewed at each of the 24 intersections (Brehmer et al. 2003).

Traffic conflicts were categorized into the following four types and are shown in Figure 17 (Brehmer et al. 2003):

- Type 1—opposing left-turn conflicts
- Type 2—left-turn/same-direction conflicts
- Type 3—lane-change conflicts
- Type 4—secondary conflicts (i.e., opposing right-turn-on-red conflicts, conflicts with pedestrians/bicycles, or conflicts resulting from lane overflow)

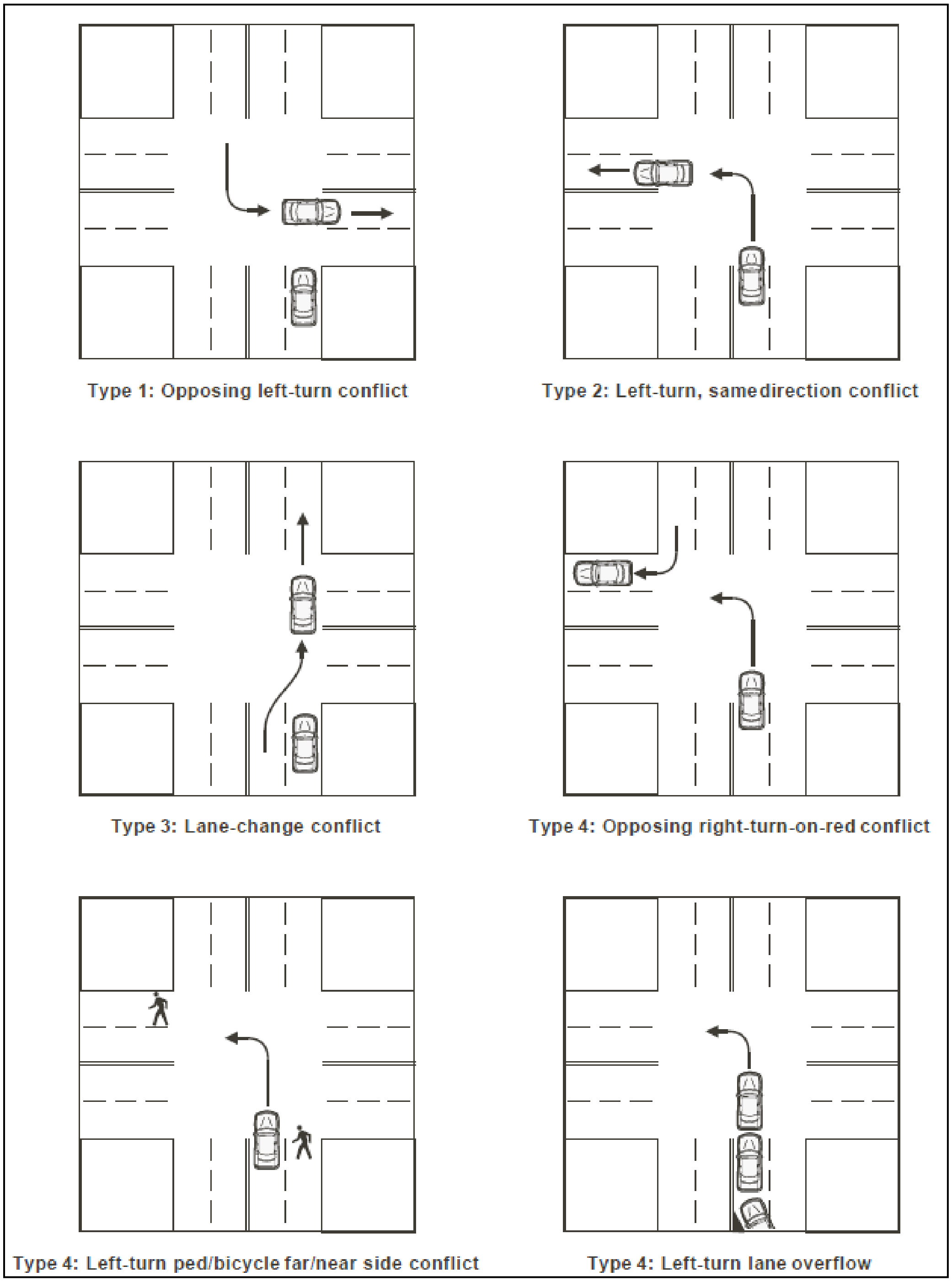


Figure 17. Left-turn traffic conflicts types used in the field traffic conflict study (Source: Brehmer et al. 2003).

Few left-turn conflicts were found to be associated with the PPLT display. There were 166 total conflicts: 155 Type 1 conflicts, nine Type 2 conflicts, two Type 3 conflicts, and zero Type 4 conflicts. Aggressive driving appeared to be the cause of 146 of the 155 Type 1 conflicts (drivers continued to turn on the yellow and all-red change and clearance intervals following the protected left-turn phase). The remaining nine Type 1 conflicts occurred when drivers assumed the right-of-way during a permissive phase (eight of those were during a CG permissive indication, and one was during an FRA permissive indication). The Type 2 conflicts occurred when a driver hesitated to make a left-turn during the permissive phase, causing a conflict with the following vehicle. The Type 3 conflicts were due to driver error and not a lack of understanding of the PPLT signal display (Brehmer et al. 2003).

Traffic events were categorized into the following four types (Brehmer et al. 2003):

- Type 1—driver hesitation on protected left-turn
- Type 2—driver hesitation on permissive left-turn
- Type 3—driver going through a circular red (CR) indication
- Type 4—driver backing out of the intersection back into the left-turn lane

Most of the left-turn events were related to hesitation at the onset of the green indication. There were 242 total events: 147 Type 1 events, 53 Type 2 events, five Type 3 events, and 37 Type 4 events. There was increased uncertainty (more Type 1 events) with the five-section horizontal arrangement with the green arrow and circular red indications shown. Type 2 events were not related to the arrangement, phasing, or indication. Numerous red-light-running events were noted, but Type 3 was recorded only when the action was clearly a function of driver misunderstanding. There was no pattern observed among the five Type 3 events. Of the 37 Type 4 events, 33 were associated with flashing indications (driver entered the intersection, not did not have an opportunity to turn, and backed up) (Brehmer et al. 2003).

2.2.1.5 Crash-Data Analysis

The objective of the crash-data analysis was to determine and compare left-turn crash rates associated with various PPLT displays. The most recent three years of crash data were requested for the same 24 intersections studied in the traffic conflict study. The research team was also able to gather crash data from volunteer agencies via the current practice survey for intersections using the CG permissive indication (Brehmer et al. 2003).

The authors calculated the following crash rates:

- Average number of crashes per year per intersection
- Average number of crashes per year per 100 left-turn vehicles
- Average number of crashes per year per 100,000 left-turn × opposing through vehicles
- Average rate for the intersection based on only left-turn crashes

The rankings of the various crash rates were not entirely consistent, but the intersection operating with the FCY permissive indication was consistently high in the rankings (low crash rates), while the College Station location using the CG permissive indication was consistently low in the rankings (high crash rates). No correlation was found between the crash rate analysis and the conflict study results (Brehmer et al. 2003).

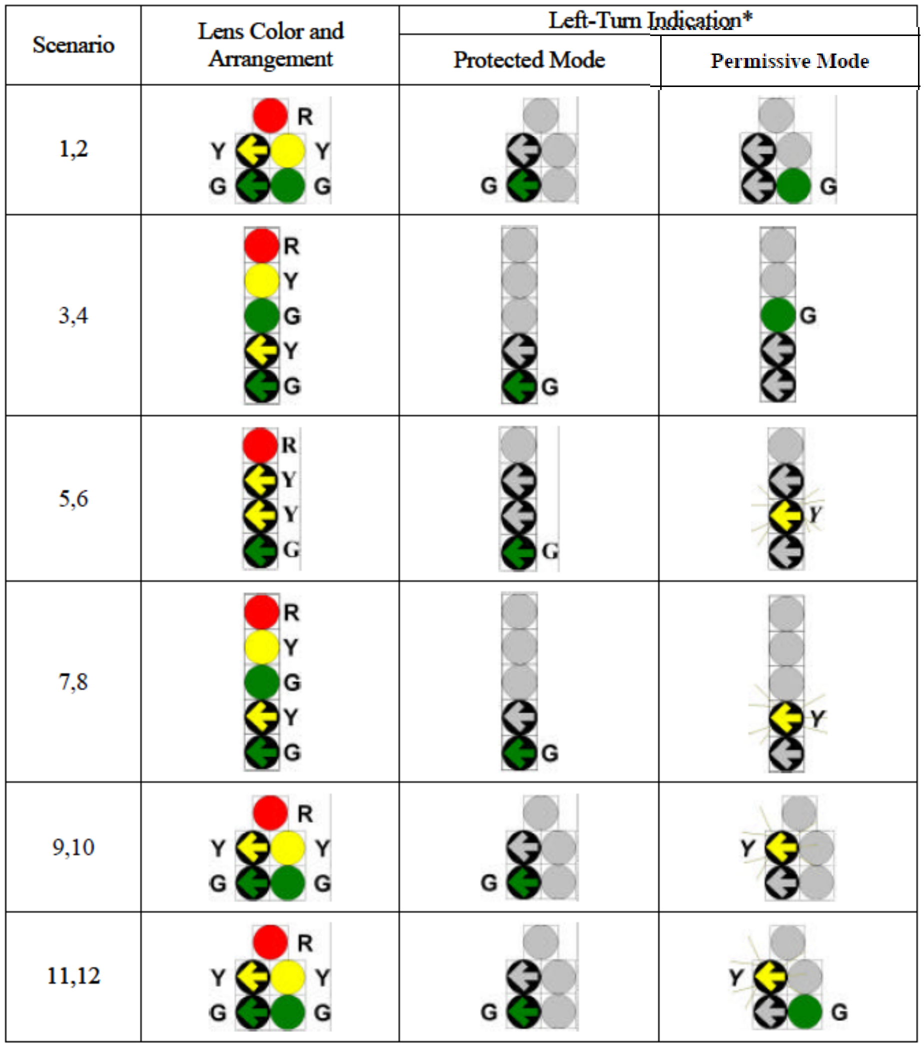
The authors received crash data from 135 intersections from six agencies that responded to the agency survey. The average crash rate for each intersection was calculated; however, no meaningful trends in this data were identified.

2.2.1.6 Driver Confirmation Study

Driving simulators provide a dynamic driving environment to test subjects and can greatly improve the quality of driver comprehension and response data. Driving simulators include control, guidance, and navigation tasks to replicate actual roadway driving conditions. Driver behavior data can be obtained from simulator experiments without subjecting participants to unsafe conditions associated with real driving environments. Driver simulators can be used to conduct experiments under many different conditions without having to implement them in the field (Noyce and Smith 2003). The authors of NCHRP 493 used full-scale, fixed-base driving simulators to collect driver comprehension data.

A 2001 paper discusses preliminary results of the research conducted as part of NCHRP 493, in which the CG was evaluated against the FYA as permissive left-turn displays using a driving simulator (Knodler et al. 2001). These indications were chosen for the evaluation because one of the key tasks of the NCHRP 493 research was to compare the current standard CG permissive indication with the recently introduced FYA permissive indication.

The researchers identified 12 different PPLT signal displays to include in their study. These displays differed in arrangement, through movement indication, placement, and permissive indication. Figure 18 shows the various displays that were evaluated. Intersections involving through and right-turn movements were also created in the virtual environment for the participants to travel through. This aspect would create more variability in the study and keep drivers from “keying in” on the nature of the study (Knodler et al. 2001).



R = RED Y = YELLOW G = GREEN *Y* = FLASHING YELLOW
* The indication illuminated for the given mode is identified by the color letter

Figure 18. PPLT displays evaluated (adapted from Knodler et al. 2001).

An additional objective of the preliminary study was to test the effectiveness of the driving simulator as a study method. Driving simulators at the University of Massachusetts (UMass) were used to create a visual driving environment (Knodler et al. 2001). This simulator was a fixed-base, fully interactive simulator, as pictured in Figure 19, along with a nearly identical driving simulator at Texas Transportation Institute (TTI) used by the authors in NCHRP Report 493 and in later studies.

Figure 19. Typical driving simulators used in NCHRP 493 research (UMass on the left and TTI at Texas A&M on the right) (Source: Brehmer et al. 2003).

Four driving modules with six starting positions were created to provide a more random order in which participants viewed each PPLT scenario. Each participant observed the 12 experimental displays once by traveling through two of the four modules. There were14 intersections in each module, six of which were study PPLT displays. The participants completed a short practice course to get better oriented with the simulator controls.

All signal displays rested in the red indication until the simulator car was approximately 100 feet from the intersection. At that time, the PPLT display was triggered and changed to the test permissive indication. There was a second trigger at the stop bar to release the opposing through traffic. This way, the left-turn drivers had to make a decision as to the meaning of the PPLT signal indication and the desired action before knowing the actions of opposing traffic. The opposing traffic traveled in predetermined gaps that were consistent from intersection to intersection.

The driver response was manually recorded as correct, fail-safe, or fail-critical. Fail-safe responses were incorrect responses, but the driver did not infringe upon the right-of-way of the opposing through traffic; usually, the driver stopped and waited for the indication to change and had to be prompted to continue. Fail-critical responses occurred when the driver created a crash potential by impeding on the right-of-way of the opposing through traffic by going through the intersection (Knodler et al. 2001; Noyce 2003). Drivers used guide signs throughout the course for navigation to minimize verbal communication with the researchers during the test runs. Drivers were also asked to obey the speed limit signs to make sure the situation was more realistic (Knodler et al. 2005b; Noyce 2003). An example of the screen display at one of the test intersections is shown in Figure 20.

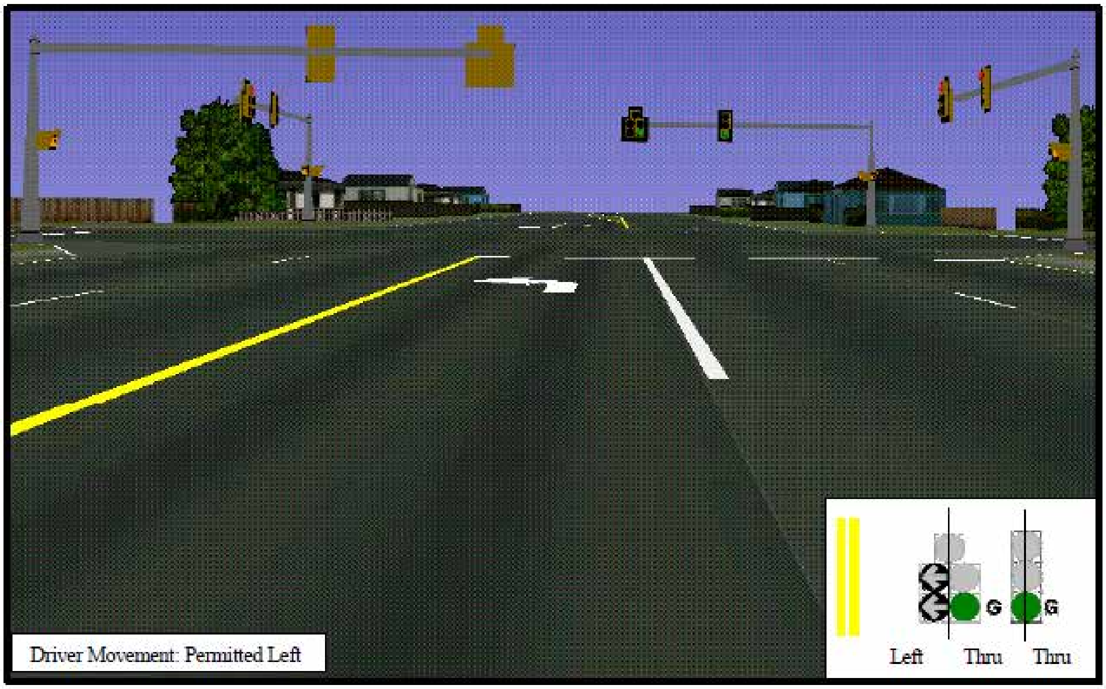


Figure 20. An example of the driving simulator display at one of the PPLT test intersections (Source: Knodler et al. 2001).

Two-hundred and eleven drivers, ages 18 to 70, participated in the preliminary driver simulation study. Correct responses ranged from 71% to 79%, while fail-critical responses ranged from 5% to 11%. The most common error was a fail-safe error when drivers decided to wait for all opposing traffic to pass before proceeding with their left-turn even though sufficient gaps were present in the opposing traffic stream. The authors suggest that many drivers based their left-turn decision on opposing traffic rather than the PPLT display.

After completing the driving simulation, the participants were presented with videocassette recordings of screen captures for the 12 PPLT displays. Each was shown for 30 seconds and the driver was asked the following question: “You encountered this signalized intersection while driving. At this intersection you made a left-turn. Considering the left-turn traffic signal lights shown, what do you believe is the appropriate left-turn action?

- Go, you have the right-of-way.
- Yield, then go if a gap in the opposing traffic exists.
- Stop first, then go if a gap in the opposing traffic exists.
- Stop and wait for the appropriate signal.

This static follow-up driver survey was important for comparison purposes to the data gathered from the driver simulator study (Knodler et al. 2001).

There were 196 participants in the static follow-up survey. Correct responses ranged from 51% to 70%, and fail-critical responses ranged from 3% to 27%. The most common error for each FYA display was the “stop first, and then go” option (fail-safe), while the most common error for each CG display was “go,” which is a fail-critical response.

Overall, the results indicate that the driving simulator is an effective method of evaluating driver comprehension of PPLT displays. The percentage of correct results for the driving simulator study was consistently higher than the static follow-up survey results. The authors say this supports the idea that simulator results are more consistent with actual driving than static-based evaluations. The driver is presented with more cues with which to make a decision in the driving simulator. The absence of these cues in the static survey leads to discrepancies in responses. Drivers may respond differently in the driving simulator than they did for the same scenario in the static evaluation. This study helped to reveal that what drivers say they are going to do and what they actually do in a real-life situation may be inconsistent. Also, there was little difference found in driver understanding between the CG permissive indication and the FYA in the driving simulator study (Knodler et al. 2001).

Further evaluation of driver comprehension based on driving simulator and static follow-up survey results was completed and presented in NCHRP 493. Twelve different PPLT displays (shown in Figure 21) were used in both the simulator study and the static follow-up evaluation. The displays differed according to the following characteristics (Knodler et al. 2005b; Noyce 2003):

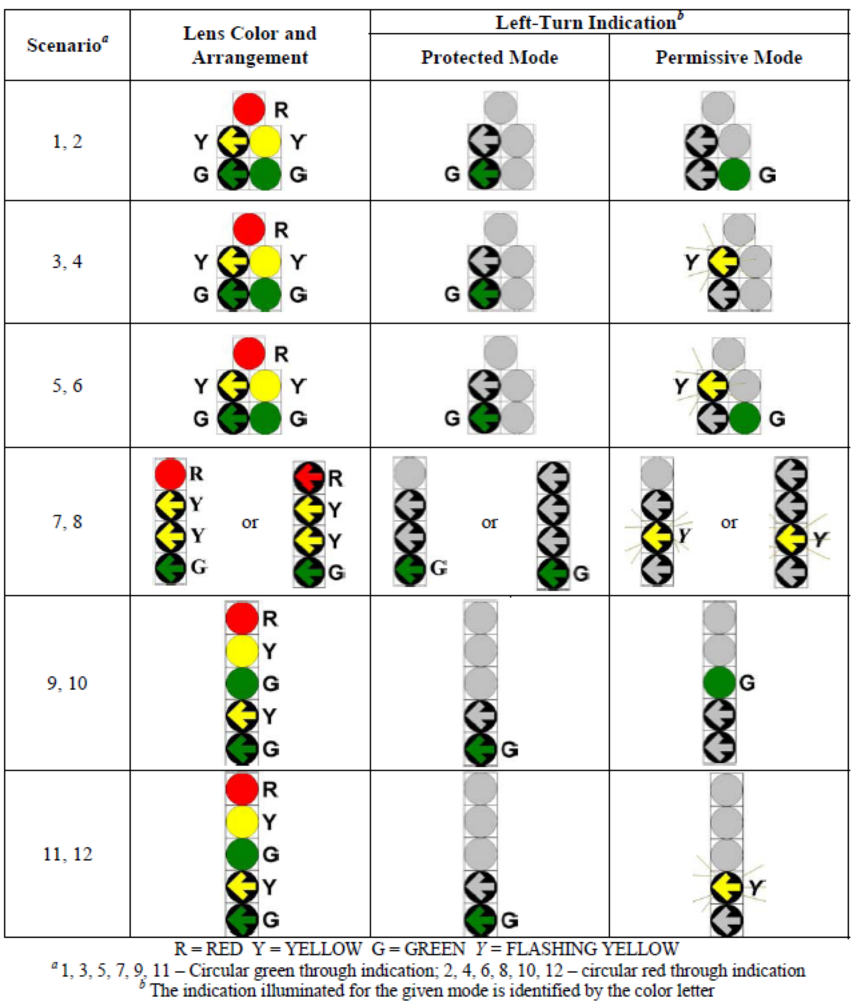
- The left-turn permissive indication was the CG, FYA, or the combination of CG and FYA displayed simultaneously in a five-section cluster arrangement (shown in Figure 21 under scenarios 5 and 6 in the permissive mode, from here on referred to as FYA/CG).
- The signal arrangement was the five-section cluster, four-section vertical, or five-section vertical.
- The location of the PPLT section head was either a shared or exclusive signal.
- The through traffic indication was either CG or CR.

The driving simulator experiment was designed similarly to the aforementioned driving simulator study. The driving simulators at UMass and TTI were used to administer the experiment to participants. Driver responses at the test intersections were categorized as either correct or incorrect. The incorrect responses were broken down further into fail-safe responses and fail-critical responses. More than 3,400 responses were collected from 432 participating drivers.

Overall, 91% of the responses to the simulator scenarios were correct, meaning that the PPLT displays from this experiment were associated with high levels of driver comprehension. There was no statistical difference observed in the responses among the 12 PPLT displays tested. The driver comprehension data were cross-analyzed by display components, including the arrangement, permissive and through indications, and location. There was no statistical difference observed in driver comprehension from this cross-analysis. Furthermore, the cross-analysis results showed no significant difference between fail-critical responses. When the driver comprehension data were analyzed by demographic categories, there was no significant difference observed in overall correct responses. The authors state this lack of difference illustrates that the FYA permissive indication is a feasible alternative to the CG permissive indication (Knodler et al. 2005b; Noyce 2003).

For the static follow-up evaluation, 432 participants were shown 30 seconds of videotaped data of each of the 12 different PPLT displays under investigation. The drivers were asked the same question and presented with the same choices as drivers in the preliminary study.

Out of all the scenarios evaluated by drivers as part of the static follow-up evaluation, an average of 83% was evaluated correctly, with individual scenario responses ranging from 73% to 89%. Both the “yield” and “stop first, then go” responses were considered correct. There was a significant difference in correct and fail-critical responses observed when the permissive indication component was isolated. The scenarios involving the FYA permissive indication and the FYA/CG simultaneous indication yielded a significantly higher number of correct responses compared with the scenarios involving the CG permissive indication. Furthermore, a significantly higher number of fail-critical responses was observed for the scenarios associated with the CG permissive indication than scenarios with the FYA or FYA/CG permissive display. A significantly higher number of correct responses was observed for the display with the four-section vertical arrangement than the other two arrangements. The authors noted that only the FYA was evaluated in the four-section vertical arrangement, and that this likely accounts for the higher percentage of correct responses (Knodler et al. 2005b; Noyce 2003).



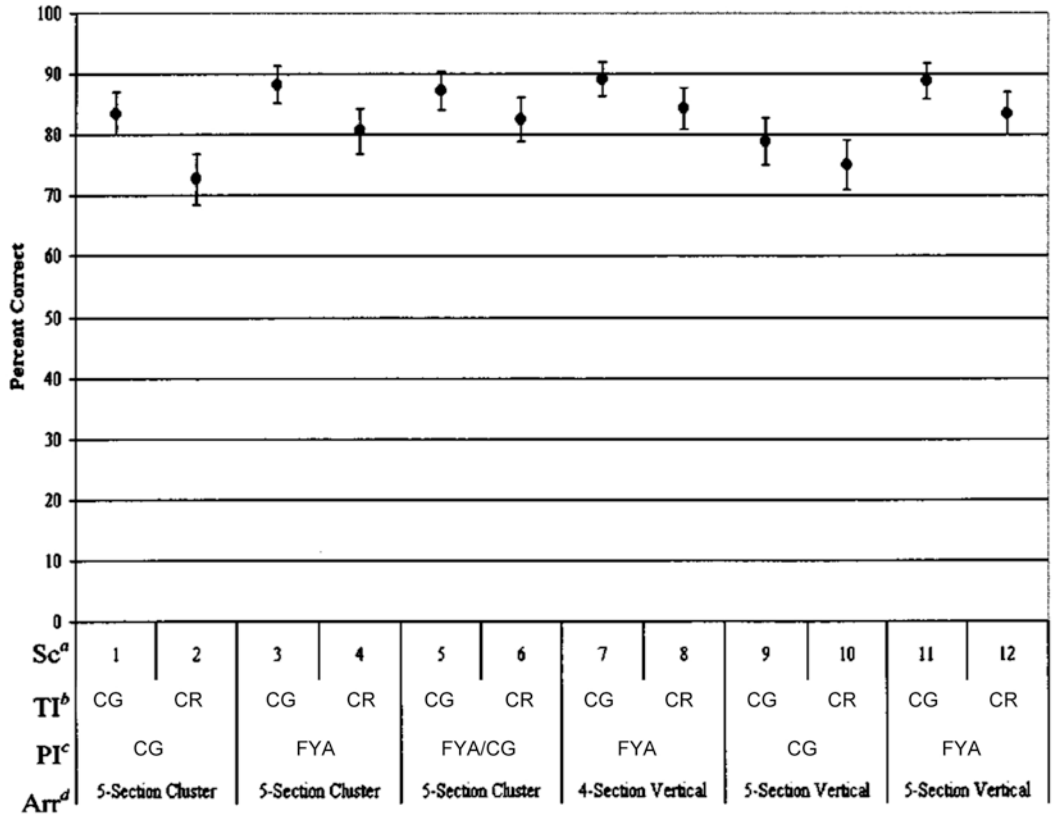
R = RED Y = YELLOW G = GREEN *Y* = FLASHING YELLOW

[a] 1, 3, 5, 7, 9, 11 – Circular green through indication; 2, 4, 6, 8, 10, 12 – circular red through indication

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

Figure 21. PPLT displays tested in driving simulator and static follow-up evaluation studies (Source: Noyce 2003).

It was also found that PPLT displays with the CG through indication were associated with a significantly higher correct response rate when compared with the displays with the CR through indication. The fail-critical responses were also significantly higher for PPLT displays with CR through indications than displays with CG through indications. The authors indicate that this shows that simultaneous conflicting indications (green and red), even when used in different signal displays, can cause driver confusion. It was also found that there were no significant differences resulting from the location of the PPLT display, being either shared or exclusive (Knodler et al. 2005b; Noyce 2003). Figure 22 shows the results from the static follow-up evaluation.



[a]Sc = scenario identification number; [b]TI = indication for adjacent through lanes; [c]PI = left-turn permissive indication; [d]Arr = protected/permissive left-turn signal display arrangement.

Figure 22. Percentage of correct responses for static follow-up evaluation by scenario (adapted from Knodler et al. 2005b).

When comparing the simulator results with the static follow-up evaluation results, the authors found that the simulator responses generally had significantly more correct responses than the static evaluation. Individual driver responses were analyzed further. There were 353 fail-critical responses in the static evaluation for which a corresponding response in the simulator was available. Of those responses, the participants responded correctly in the same scenario in the simulator 79% of the time. Only 19% of the 353 had an incorrect response in both the simulator and static evaluation for that scenario. The authors suggest that what drivers say they will do and what they actually do are not always consistent.

The authors conclude that the FYA permissive indication has a high level of driver comprehension and lower fail-critical rates than the CG permissive indication. They also state that the PPLT indication is only one of many things a driver takes in consideration when in the simulator or real world. This circumstance is why there were significant findings in the static follow-up evaluation when drivers had only the indication to consider, versus the simulator where drivers could use other information to make a correct decision, even when they did not comprehend the signal meaning (Knodler et al. 2005b; Noyce 2003).

2.2.1.7 Field Implementation Study

The project panel for NCHRP 493 approved a field implementation study of FYAs to gain insight on the real-world applications of this PPLT display. The objective of this study was to assess any issues related to FYAs and to collect safety and cost data from their implementation (Brehmer et al. 2003).

At the time of this study, the FYA had not been adopted into the *MUTCD.* A request for proposal (RFP) for an implementation plan was issued by the research team in August 2000 that sought volunteer transportation agencies for this research. This situation meant that all agencies interested in installing FYA signals for this experiment were required to obtain approval from FHWA. Field data were collected at study and control intersections with very specific characteristics and signal displays used. The intersections that were chosen for evaluation were right-angle, level-grade intersections that operated with PPLT phasing. In terms of geometric and operational features, the study intersections were considered typical. The study intersections were converted from a CG permissive indication to an FYA. The researchers also asked for data on similar intersections that would not receive the improvement to use as control sites. The research team contacted more than 35 agencies across the United States, and six were involved in the field implementation study.

Members of the research team, with the help of local jurisdictions, collected 16 hours of video data before and after the FYA signal displays were installed at each study site. The video data were used for conducting a traffic conflict study and to quantify follow-up headway.

The data were analyzed with a focus on conflicts directly related to left-turn movements through the intersection. The targeted conflict data for this analysis included instances in which drivers hesitated while making left turns and instances in which drivers failed to yield to opposing through traffic during the permissive phase. These conflicts were used as an indication of driver comprehension of left-turn signal indications. The results from the conflict study show that the change in PPLT display did not contribute to added driver conflicts: There was only negligible difference noted between before-installation and after-installation conflict data.

The video data were also used to quantify follow-up headway during the permissive phase. There was a limited amount of data because instances when more than one vehicle turned in the same gap during a permissive phase were scarce; however, the authors concluded, based on the data available, that the change in PPLT display from CG to FYA had a negligible impact on follow-up headway.

The research team visited six of the study intersections during the activation of the FYA indication. They did this to conduct casual field observations for signs of initial driver confusion before the video data were collected. No unusual findings were observed. The majority of drivers did not show any confusion and drove through the intersection as though there were no difference.

All the transportation agencies that participated in this implementation stage also took part in a post-implementation survey that identified issues related to the change in PPLT display, cost information, and stakeholders' support for the FYA indication. FYAs received a positive response overall from volunteering agencies. The implementation cost and associated labor hours were found to be relatively low. The most commonly reported problem was overcoming the current design of controllers and conflict monitors. The research team assumed that this would not be a problem in the future because the logic would continue to improve. The authors also noted that the FYA would be easier to implement because suppliers are becoming more and more aware of this new signal control. Overall, the public responded in a positive manner to the FYAs. Support was also shown by local law enforcement; however, because the indication was not included in the *MUTCD* at the time of the project, county commissioners and city council members showed slight hesitation. Most agencies that did not participate cited lack of resources as the reason.

2.2.1.8 Conclusions and Recommendations of NCHRP 493

The authors concluded that the FYA exhibited a high understanding and lower fail-critical rates than the CG permissive indication. The field implementation showed that the FYA was well understood, at least as safe as the CG, and well accepted by engineers and the public.

The FYA was also cited as having the following operational advantages (Noyce, Fambro, and Kacir 2003):

- Eliminates the yellow trap when tied to the opposing through movement
- Eliminates the need for louvers or optically shielded display faces
- Can be used at all intersection configurations
- Does not require supplemental signing
- Provides flexibility in signal phasing operation (protected-only, permissive-only, or protected/permissive)
- Provides flexibility in phasing by time of day

The authors of NCHRP 493 recommended that the FYA display be incorporated into the *MUTCD* as an allowable alternative display to the CG when used in PPLT operation. They also recommended that the four-section, all-arrow display be used for the signal arrangement, that the signal should be located over the left-turn lane, and that the FYA be logically tied to the opposing through green indication. The authors also suggested that follow-up studies be conducted after enough time has passed for an implementation period to acquire before and after crash data.

The last major recommendation was that the use of flashing red indications should be restricted to locations where an engineering study has identified that drivers must come to a complete stop before proceeding on the permissive interval. Many drivers have interpreted the FCR and FRA just like an FYA indication; they do not stop but simply yield. Using flashing red indications when they are not necessary will dilute the "stop first" meaning (Noyce, Fambro, and Kacir 2003).

2.2.2 Follow-Up Studies to NCHRP 493

The authors of NCHRP 493 continued research regarding the FYA after the publication of NCHRP 493 in 2003. The details of these follow-up studies are discussed in this section in chronological order.

2.2.2.1 Five-Section PPLT Signal Display Arrangements

One study conducted by Noyce and Smith aimed to evaluate the best understood permissive indication among the FYA, FCY, FRA, FCR, and CG, using variations of five-section signal head arrangements. Three display arrangements were examined, including the five-section horizontal, five-section vertical, and five-section cluster arrangements. The five-section cluster arrangement was the most widely used in the United States for PPLT control at the time the study was conducted. Three arrangements, combined with five permissive left-turn indications (FYA, FCY, FRA, FCR, and CG), created 15 unique combinations that were evaluated (Noyce and Smith 2003).

The simulator study used a full-scale, fixed-base driving simulator. The study was conducted in a similar manner as the driving simulator studies conducted as a part of NCHRP 493. The drivers' responses were categorized as either correct or incorrect, with incorrect responses being further categorized into fail-safe, fail-critical (serious), and fail-critical (non-serious). A fail-critical serious response was one in which the driver impeded opposing traffic right-of-way, creating the potential for a crash. Fail-critical non-serious responses resulted in an incorrect stop or yield but did not impede opposing traffic (Noyce and Smith 2003).

Thirty-four (34) participants completed the simulator study, and a total of 991 responses were collected from the permissive indication scenarios. The overall rate of correct responses was 81.3%. The average percentages of correct responses for the different arrangements were not significantly different; however, there were statistically significant differences in the percentage of correct responses based on permissive indication. The CG, FYA, and FCY had significantly higher comprehension rates than the FRA and the FCR. The combination of the horizontal arrangement and the FCY had the highest comprehension, at a 97% correct response rate. The vertical arrangement with the FRA had the lowest comprehension, at a 57.6% correct response rate. The FRA and FCR had much higher fail-safe response rates than the other permissive indications. The most common fail-safe response was a driver yielding instead of stopping for the FCR and FRA. The CG had the most fail-critical (non-serious) responses. The authors believe this is because the drivers were more comfortable with this indication and made their decision about what to do quickly, usually accelerating into their turn. It was also found that the cluster and vertical arrangements had a higher fail-critical (non-serious) rate than the horizontal arrangement. The authors believe that the drivers lacked experience with the horizontal arrangement; and so they took a more cautious and slower approach, usually deciding to yield correctly (Noyce and Smith 2003).

The static survey used animated PPLT displays that were superimposed on photos of intersections taken from the driver's perspective. All 15 scenarios were shown with opposing traffic. The participants were presented with a similar question (What do you believe is the appropriate left-turn action?) and response choices (go, yield, stop first, stop and wait) as participants in NCHRP 493 static studies.

The static survey, like the driving simulator study, found that the type of permissive indication had a significant effect on driver comprehension and that the type of arrangement did not have a significant effect. The FYA and FCY were the best understood indications in both the static evaluation and the simulator study. The biggest difference between the static survey and the simulator study was the rate of correct responses for the green and red indications (refer to Figure 23). The static survey had significantly more incorrect responses for the CG indication than the driver simulator study. It was suggested that the drivers in the simulator used other surrounding cues to help decide their course of action, while the responses to the static survey had to be solely based on the indication (because surrounding cues were absent). The FCR and FRA had higher comprehension in the static survey than in the driver simulator study. There were also more fail-critical (serious) responses in the static survey than in the driver simulator study resulting from the lack of surrounding cues (Noyce and Smith 2003).

The authors concluded that arrangement of the five-section signal did not have a significant effect on driver comprehension, while the type of permissive indication did. The FYA and FCY had the best correct response rates in both the simulator study and the static survey. They also stated that some drivers misinterpret the CG for a protected indication but make their decision in a real-life situation based on other surrounding information (Noyce and Smith 2003).

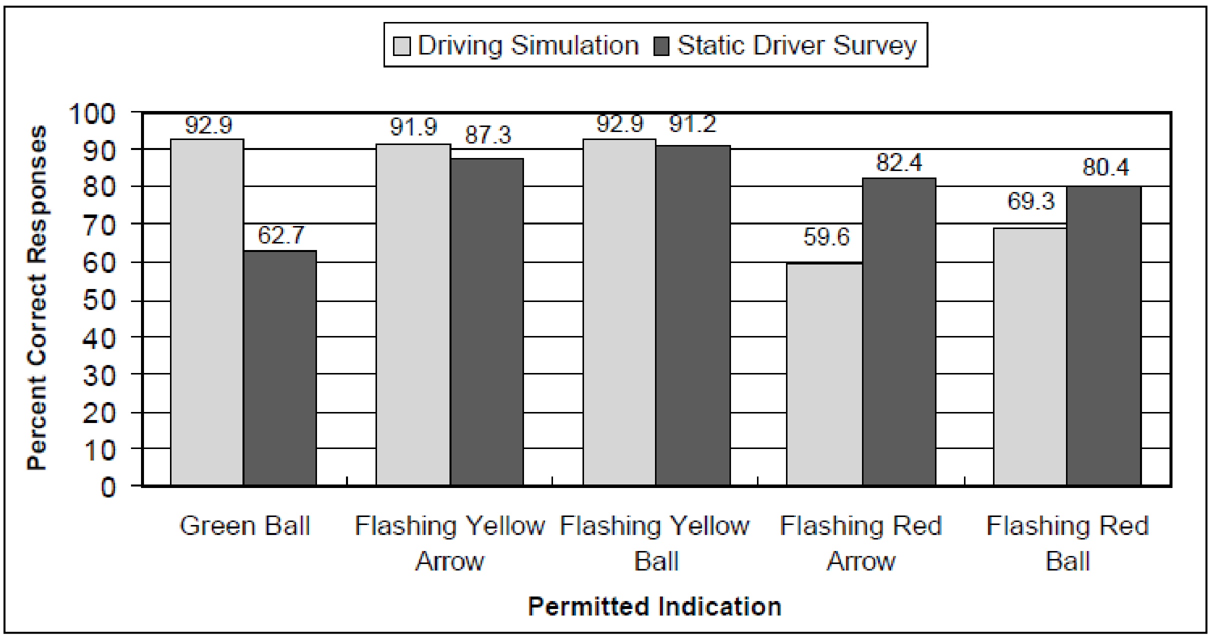


Figure 23. Comparison of correct responses in simulation and static survey using five-section signal heads (adapted from Noyce and Smith 2003).

2.2.2.2 Using the FYA with Simultaneous Permissive Indications

The most common PPLT signal arrangement used in the United States in 2005 was the five-section cluster arrangement. Since the *MUTCD* requires that all circular indications displayed on all signal faces on the same approach be the same, the FYA must be simultaneously displayed with the circular through indication if the five-section cluster arrangement is to be used. In 2005, researchers saw the need to quantify driver comprehension of the FYA in a five-section cluster arrangement when simultaneously displaying the through indication. Because many intersections using PPLT control had this five-section cluster arrangement, it was necessary to evaluate if this type of signal, retrofitted with an FYA, would be understood by drivers. The researchers also aimed to compare the driver comprehension of the FYA/CG cluster display with the current CG standard, as well as with the exclusive four-section vertical FYA signal suggested by NCHRP 493. The authors' evaluation methodology included a driving simulator study and a static evaluation (Knodler et al. 2005a).

The simulator experiment used the driving simulator located at UMass. The methodology used in the simulator experiment and static follow-up study was similar to the process used in studies previously discussed (refer to section 2.2.1.6) (Knodler et al. 2005a). In addition to the static follow-up survey, additional responses were gathered in an independent static survey that polled drivers in Massachusetts and Wisconsin.

The signal displays tested are presented in Figure 24. The displays using the circular yellow (CY) indication had to be analyzed separately because of the conditions under which the driver would approach the intersection in the driving simulator. For all signal displays except the ones involving the CY indication, the simulation rested in either a red or a protected left-turn and changed to the test permissive indication. The two scenarios testing the CY rested in a permissive indication and changed to the CY indication. Because the preceding indication was permissive in these cases, it would not be reasonable to assume that there would be a queue of vehicles in the opposing through lanes like there was in the other scenarios; therefore the CY scenarios were analyzed independently.

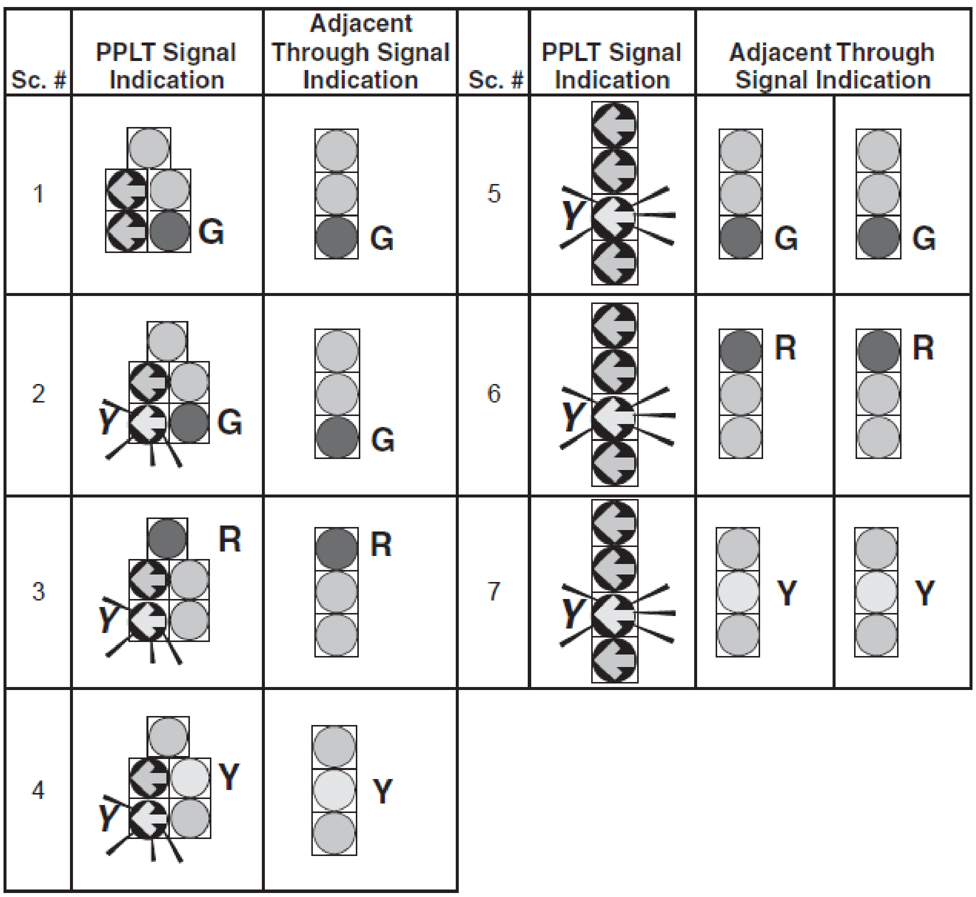


Figure 24. PPLT signal displays studied using the retrofitted five-section cluster, the CG cluster, or the FYA four-section vertical arrangement (Source: Knodler et al. 2005a).

Fifty-four people participated in the simulator study. Results showed that drivers' understanding of permissive indications was not affected by the type of PPLT display. This was demonstrated by the lack of statistical differences between "yield" responses and combined "yield" and "stop first" responses across all scenarios. However, drivers displayed a high level of comprehension to the FYA, as shown in Figure 25 (b, c, d, and e), despite being unfamiliar with this permissive indication prior to participating (Knodler et al. 2005a).

The same 54 drivers that completed the driving simulation study completed the follow-up static evaluation. The results demonstrated that the retrofit display (FYA/CG) helped improve drivers' understanding of permissive indications, compared with the CG. The percentage of "yield" responses varied from 65% for the five-section cluster with CG permissive indication to 89% for the retrofit display (Figure 26, a vs. c). The "yield" responses were found to be statistically different at a 95% level of confidence for these two scenarios (FYA/CG vs. CG). When "yield" and "stop first" responses were both assumed to be correct responses, the retrofit display again had significantly more correct responses than the five-section cluster with CG permissive indication (Knodler et al. 2005a).

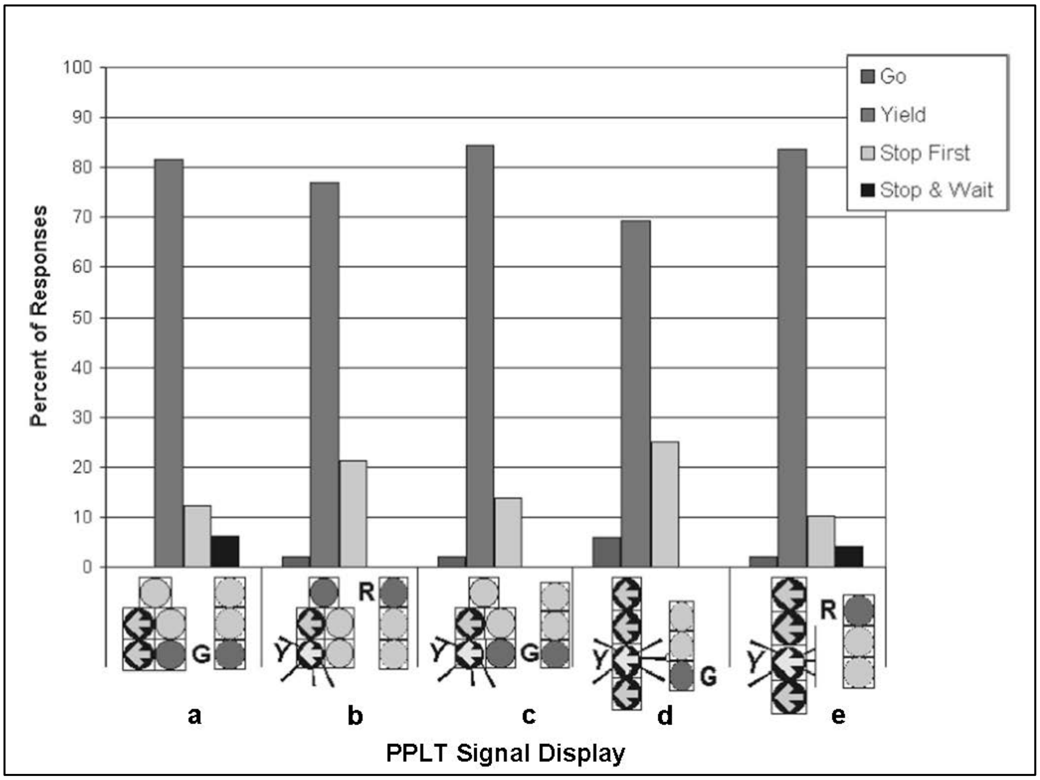


Figure 25. Breakdown of driver responses from driving simulator study (Source: Knodler et al. 2005a).

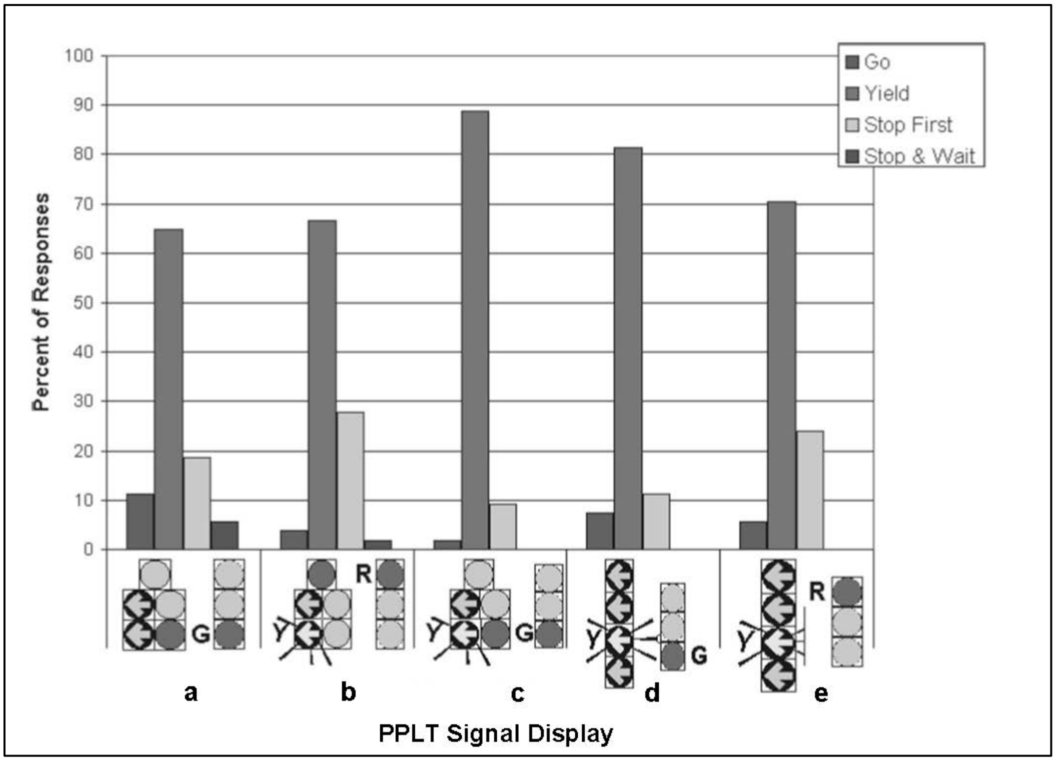


Figure 26. Breakdown of responses from the follow-up static evaluation (Source: Knodler et al. 2005a).

Additional participants completed the static evaluation independently of the simulator study in Massachusetts and Wisconsin. The independent static evaluation used a similar format, question, and response choices as the previous studies. A total of 29 scenarios were viewed by an additional 210 drivers in Massachusetts and Wisconsin. Using a chi-square analysis, it was found that the independent static evaluation responses from Massachusetts and Wisconsin contained statistically significant differences. Therefore, these two subsets of data were analyzed independently (Knodler et al. 2005a).

- In Massachusetts, the FYA/CG retrofitted display had more “yield” responses than all others except for the FYA four-section vertical display when the adjacent through signal displayed a CG (Figure 27 d); however, the differences were not statistically significant. If both “yield” and “stop first” responses were assumed to be correct, the retrofit display and the FYA four-section vertical display (with adjacent CG through indication) had statistically more correct responses than the CG permissive display. The FYA permissive indication simultaneously displayed with a CR through indication in a five-section cluster arrangement (FYA/CR) had significantly more “stop and wait” responses than both the FYA/CG display and the FYA four-section vertical arrangement with adjacent CG through indication display (Figure 27, b vs. c and d).
- In Wisconsin, the CG permissive display had a significantly higher correct response rate (when “yield” and “stop first” responses were combined) than the FYA/CR display (Figure 28, a vs. b). The percentage of “yield” responses for the FYA vertical display with CG through indication was significantly higher than for the FYA/CR display (Figure 28, d vs. b).

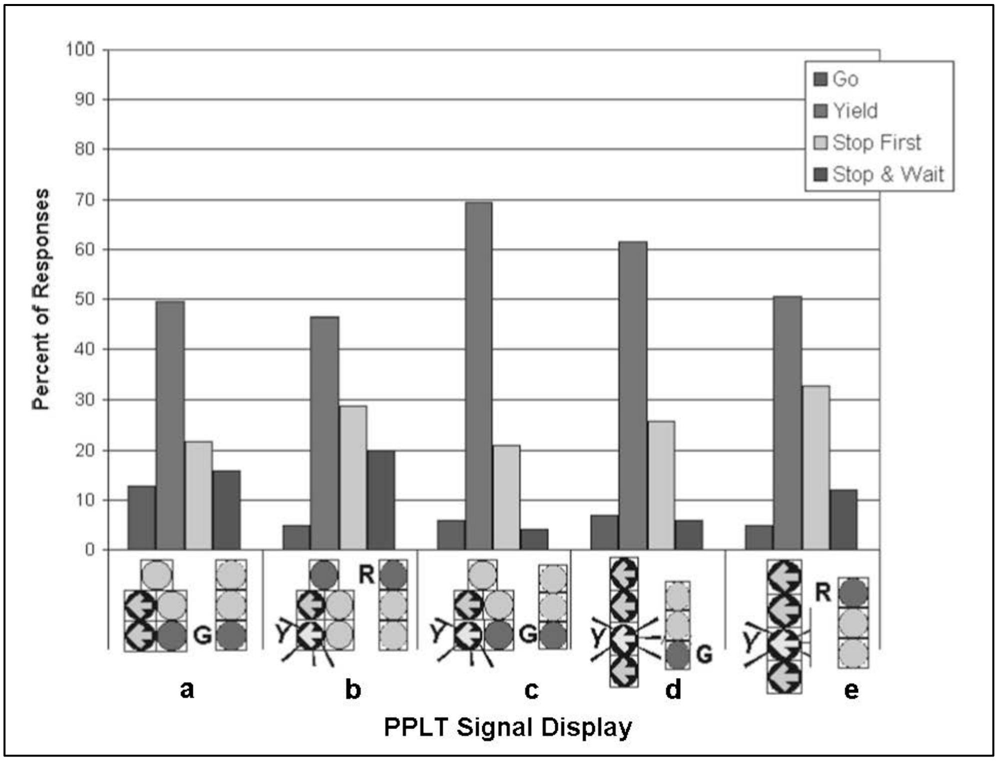


Figure 27. Breakdown of responses from the Massachusetts independent static evaluation (Source: Knodler et al. 2005a).

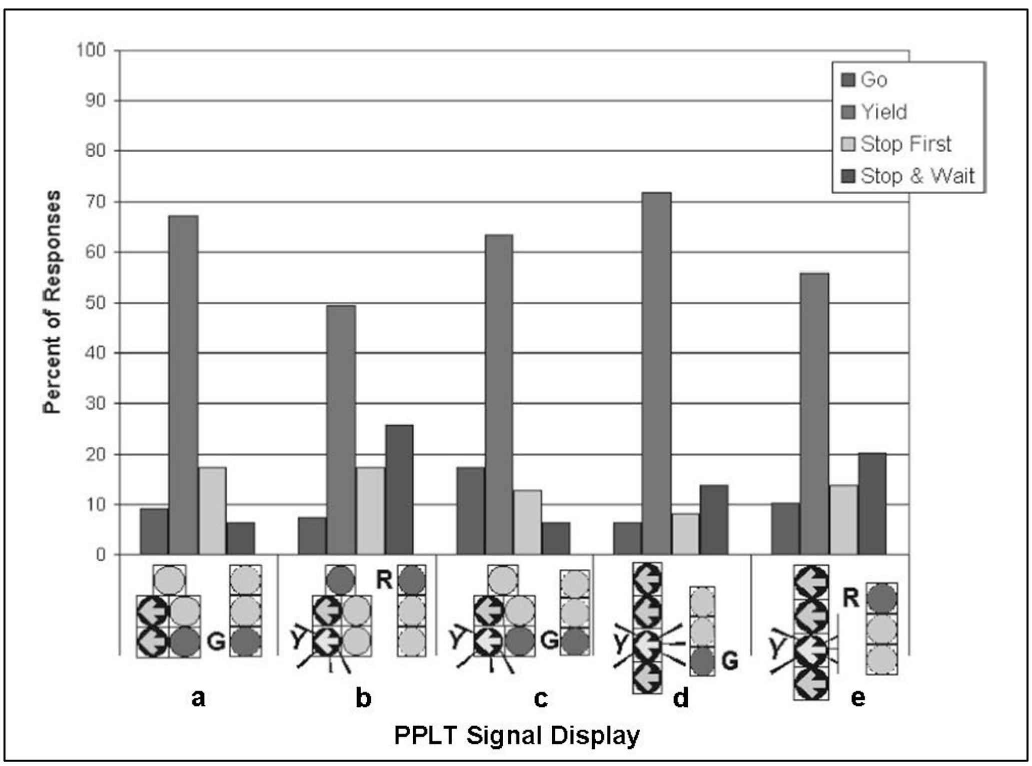


Figure 28. Breakdown of responses from the Wisconsin independent static evaluation (Source: Knodler et al. 2005a).

The two FYA with CY through indication displays had to be presented differently in the simulator experiment, and fail-critical responses were not recorded. For both the follow-up and independent static evaluations (Figure 29), the percentage of “yield” responses was higher for the FYA vertical display with adjacent CY through indication than for the FYA permissive indication with simultaneous CY through indication in a five-section cluster arrangement (FYA/CY); however, this difference was statistically significant only in the Massachusetts independent static evaluation. When “yield” and “stop first” responses were both considered correct, there were no statistically significant differences between the vertical and the cluster arrangements in the follow-up or in the independent static evaluations (Knodler et al. 2005a).

Overall, the results of this research were consistent with the previous research that supported the inclusion of the FYA in the *MUTCD* because of high driver comprehension. The retrofit display (FYA/CG) was found to improve drivers’ comprehension of the permissive indication, compared with the CG permissive display. The conflicting message of the CR and FYA indications shown simultaneously in retrofit signals supports the use of four-section vertical signal heads, but this research showed that using the retrofit five-section cluster as an interim display in transition to the four-section vertical signal does not affect driver comprehension (Knodler et al. 2005a).

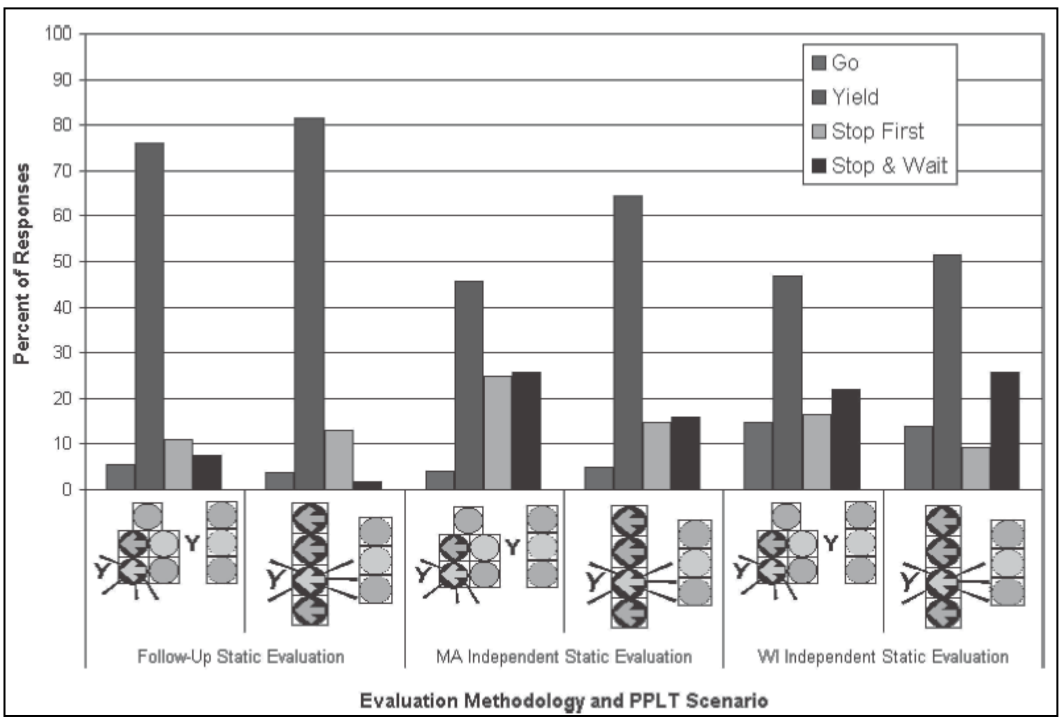


Figure 29. Breakdown of the responses for the scenarios involving the CY through indication (Source: Knodler et al. 2005a).

2.2.2.3 Pedestrians and the FYA

A study conducted by Knodler et al. in 2006 aimed to gain an understanding of pedestrian behavior at intersections with FYA permissive indications. Pedestrian movements are designed to run parallel with vehicular traffic. Drivers completing a permissive left-turn movement are required to yield to oncoming through traffic and pedestrian movements (where applicable). The objective of this research was to determine whether drivers presented with an FYA permissive indication comprehended their yield requirements to pedestrians crossing legally, parallel to the through traffic. The methodology included a driving simulator study and a follow-up static computer-based evaluation administered to drivers and pedestrians.

Thirty-six participants drove through five permissive scenarios in the driving simulator, as shown in Figure 30. The third and fifth scenarios were three-legged, T-intersections; the remaining scenarios were standard four-leg intersections. Each scenario was presented to the driver twice, once with a pedestrian attempting to cross and once without a pedestrian. Driver responses when pedestrians were attempting to cross were categorized into the following groups (Knodler et al. 2006a):

- Correct—The driver waited for the pedestrian to cross before beginning the left-turn.
- Fail-safe—The driver started the left-turn but stopped in the opposing through lanes to wait for the pedestrian to finish crossing (when no through traffic was present).
- Fail-critical —The driver did not yield to the pedestrian and either sped up to cut in front of the pedestrian, swerved to avoid the pedestrian, or slammed on the brakes—otherwise, the driver would have struck the pedestrian.

The results of the simulator study showed no statistically significant differences in responses among the five scenarios for any display type; however, the percentage of correct responses was significantly lower than the percentage of fail-safe responses, as shown in Figure 30. This result indicates low driver comprehension for the requirement to yield to pedestrians.

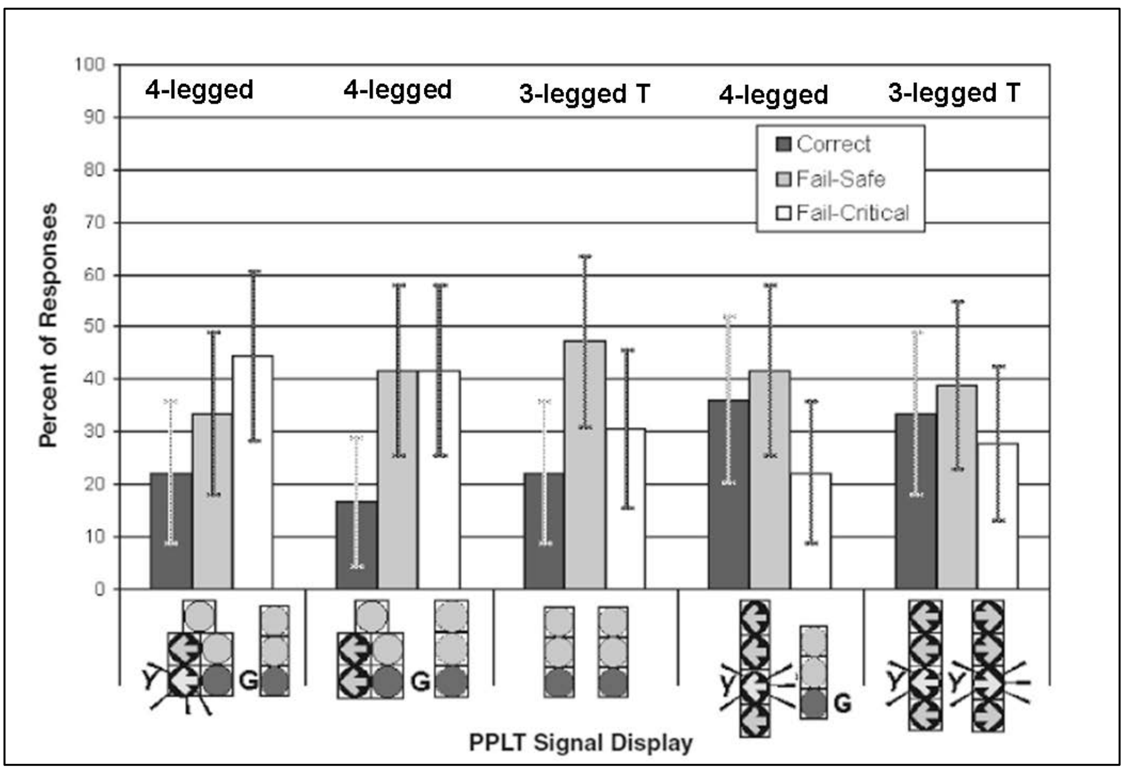


Figure 30. Breakdown of responses from the driving simulator study (Source: Knodler et al. 2006a).

The same 36 drivers also completed a follow-up static survey in which the same five scenarios from the driving simulation were presented in the computer evaluation. There were no statistically significant differences in the percentage of correct responses between scenarios at the standard four-leg intersections. However, statistically significant differences were found between the two T-intersection scenarios; the FYA permissive display had significantly more “yield” as well as “stop and wait” responses, while the CG permissive display had significantly more “go” responses (Knodler et al. 2006a).

To provide more observations, an additional 103 drivers participated in the independent static evaluation. A total of 25 scenarios were created that involved nine permissive left-turn displays, depicted on the x-axis of Figure 31.

An additional variable was introduced in the independent static evaluation. Each of the 25 scenarios was evaluated with no pedestrians, with a pedestrian waiting to cross, and with a visually impaired pedestrian with a guide dog waiting to cross. The researchers wanted to study whether the type of pedestrian would have an effect on driver responses. The new total of 75 scenarios would take too long for each participant to complete, so 25 of the total 75 were selected at random for each participant. The question and responses presented to the participants were similar to those in previous studies; however, if the driver selected the “yield” option, he/she was then asked a follow-up question: “If you want to turn left, and see the traffic signals shown, to whom are you required to yield?” The participant could select one or more of the following choices (Knodler et al. 2006a):

- Opposing vehicles
- Pedestrians
- Cross-street vehicles
- None of the above

There were no statistical differences in the percentage of “yield” (correct) responses with respect to the additional variable tested (pedestrian type), and thus the results were combined as shown in Figure 31.

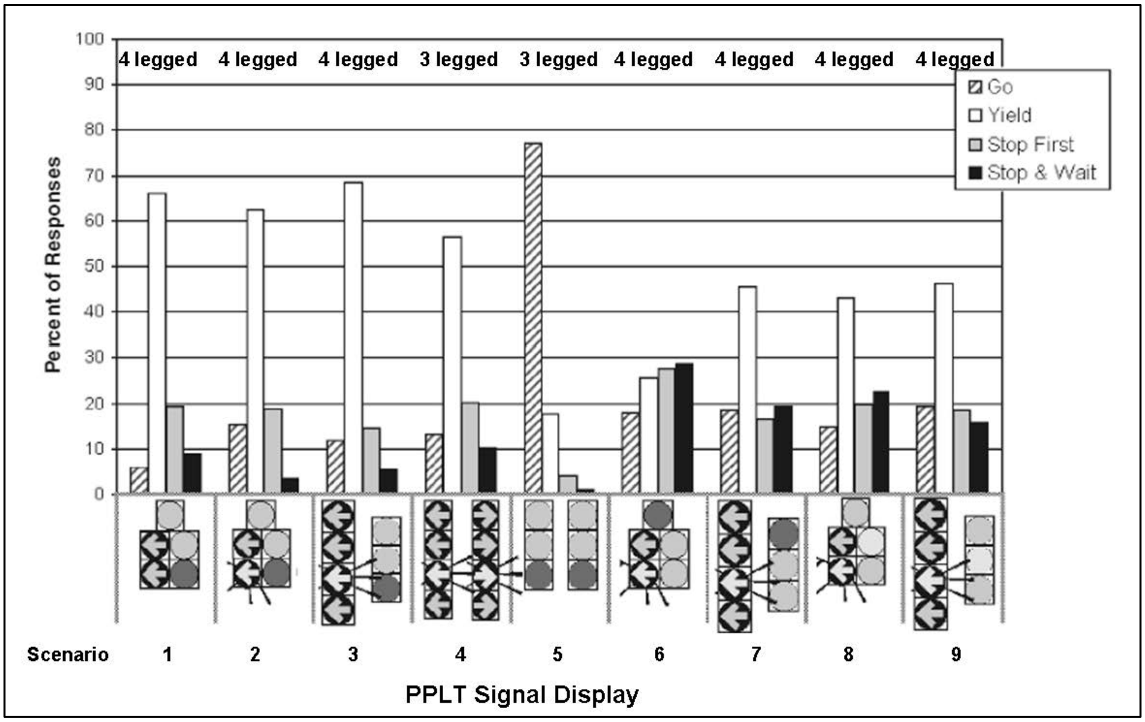


Figure 31. Driver responses from the independent static evaluation (Source: Knodler et al. 2006a).

The following conclusions were drawn concerning the four-leg intersections (all scenarios except four and five) (Knodler et al. 2006a):

- Scenario six (FYA/CR cluster) had a significantly lower percentage of "yield" responses than all other scenarios except scenario eight; however, the difference between scenarios were not significant.
- Scenarios one and three (both had CG through indications) had significantly higher percentages of correct responses than the four scenarios that contained all combinations of FYA permissive indications with CY or CR through indications (scenarios six through nine).
- There were no statistically significant differences in the percentage of "go" responses.
- Seventy-three percent of drivers who responded that they would "yield" indicated some level of requirement to yield to pedestrians in the follow-up question.

Additional conclusions were drawn regarding the 3-legged intersections (scenarios four and five) (Knodler et al. 2006a):

- The percentage of "yield," "stop first," and "stop and wait" responses were all statistically higher for scenario four (using FYA) than scenario five (using CG permissive indication).
- The percentage of "go" responses was statistically higher for scenario five than scenario four.

One hundred test subjects participated in a pedestrian static evaluation survey, in which the respondents were pedestrians. The following question was asked: “You are standing on the curb waiting to cross. Given the traffic signals shown, are you permitted to walk?” Participants selected one of the following choices: yes, no, or not sure. The seven permissive displays that were evaluated are shown at the bottom of Figure 32. Some of the scenarios included pedestrian signal heads and some did not. The correct response when a pedestrian signal head was present and the “Flashing Don’t Walk” sign was displayed was “no.” The correct response when pedestrian signal heads were absent was “yes,” as a pedestrian would be allowed to proceed in that situation (Knodler et al. 2006a). A breakdown of the correct responses is presented in Figure 32.

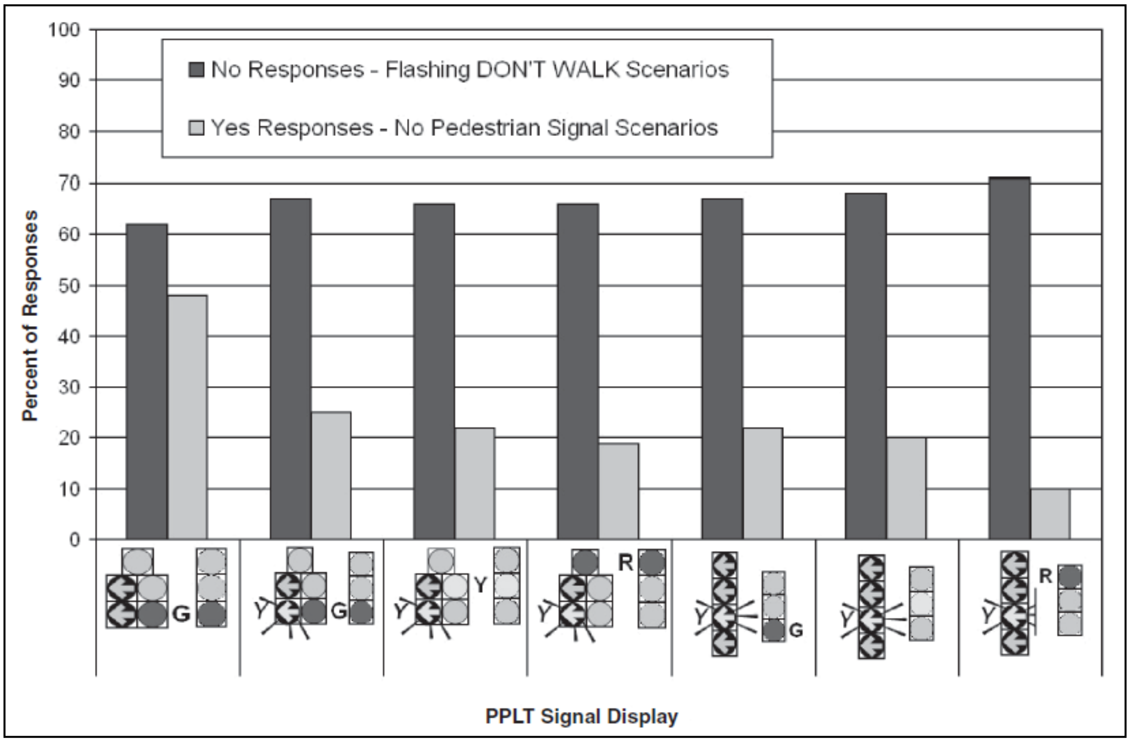


Figure 32. Breakdown of correct responses for pedestrian static evaluation (Source: Knodler et al. 2006a).

It was observed that when pedestrian signals were absent, the CG permissive indication was associated with higher pedestrian understanding that they could cross, compared with the other displays. The authors suggested that this could have resulted from pedestrian’s previous exposure to the CG permissive indication. It is likely that the participants have crossed a street while facing a CG permissive indication but have probably never seen an FYA. However, more than half of the pedestrians did not understand the correct crossing procedures in the absence of pedestrian signals when the FYA was displayed. Another result found from the pedestrian static evaluation was that one in four pedestrians responded that they would walk on the “Flashing Don’t Walk” signal (which is an incorrect response) regardless of what permissive indication was shown in that particular question (Knodler et al. 2006a).

The authors concluded that driver recognition of their yield requirements to pedestrians was not negatively affected by the application of FYA. Comprehension by drivers and pedestrians was not ideal, but the FYA did not degrade it further. The authors recommended that FYA permissive indications could be effectively used at intersections where pedestrians are prevalent (Knodler et al. 2006a).

2.2.2.4 Comprehension of the FYA at Separated Left-Turn Lanes

Research was conducted in 2006 as a continuation of NCHRP Report 493 to quantify driver comprehension of the FYA permissive indication, compared with that of the FRA permissive indication used at exclusive left-turn lanes at wide intersections. At these locations, the left-turn lane and signal are separated from the through and right-turn lanes. The through indications are not visible from the viewpoint of the left-turning vehicle. The research consisted of tasks similar to previously conducted research: a driving simulator study, a follow-up static evaluation, and an independent static evaluation. The experiments were administered in Massachusetts and Wisconsin. Participants in these experiments had not previously encountered the FYA permissive indication (Knodler et al. 2006b).

In the driving simulator study, four permissive displays involving the FYA and FRA (as shown in the bottom of Figure 33) were tested. It was noted that several agencies used the FRA as the permissive signal indication at sites with a separated left-turn lane design. The researchers wanted to compare driver comprehension of the FYA in this situation as compared with the commonly used FRA (Knodler et al. 2006b).

The responses in the simulator study were categorized in such a way that the data were comparable to the static evaluation results. The methodology used in the NCHRP 493 research, explained previously, was adopted for this study. The same PPLT displays from the simulation were tested in the static evaluation. Each driver observed 29 scenarios in a random order during the static evaluation (Knodler et al. 2006b). There were a total of 54 participants in the simulator experiment and follow-up static evaluation.

The following results from the driving simulator study were observed, based on statistical analyses using the chi-square test (Knodler et al. 2006b), as shown in Figure 33:

- The FYA scenarios showed a significantly higher “yield” response rate than the FRA scenarios.
- Scenario two, when compared with scenario four, both with FYA displays, showed no significant difference in the percentage of “yield” responses.
- Scenario one, when compared with scenario three, both with FRA displays, showed no statistically significant difference in percentages of “stop first” or “yield” responses.
- The scenarios involving the FYA permissive indications (two and four) showed a significantly higher percentage of fail-critical (“go”) responses than the FRA scenarios (in which zero fail-critical responses were observed); however, it was noted that apart from one of the “go” responses, they all took place in the initial FYA scenario observed by that specific driver. According to the authors, these “go” responses may be linked to the driving simulator environment, the interpretation of gaps in through traffic, and the first introduction to the display.
- In some instances, participants observing the FRA indication stopped and waited, as if waiting for the correct signal, and had to be instructed to proceed. The scenarios with the FYA indications had no such responses associated with them.

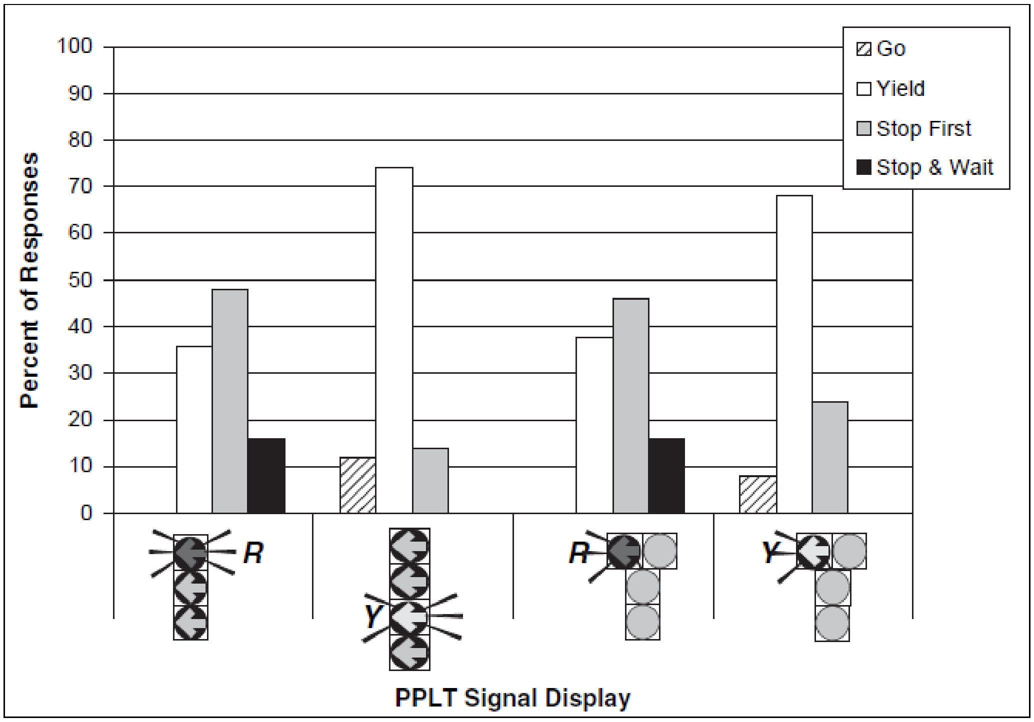


Figure 33. Responses from the driving simulator results (Source: Knodler et al. 2006b).

After the completion of the simulator experiment, the participants also completed a follow-up static evaluation. The correct response for the FYA scenarios was “yield,” and the correct response for the FRA scenarios was “stop first.” The results of the follow-up static evaluation were consistent with the simulator results (Figure 34) and are as follows (Knodler et al. 2006b):

- The “yield” response rate was higher for the FYA scenarios than the FRA scenarios. In contrast, the “stop first” response rate was higher for the FRA scenarios than the FYA scenarios.
- The FYA scenarios (two and four) showed no significant difference in “yield” responses, and the two FRA scenarios showed no significant difference in “stop first” responses. All scenarios showed similar percentages of correct responses (“yield” for FYA and “stop first” for FYA).
- Out of a total of seven “go” responses, six of them resulted from the FYA scenarios, and one of them occurred in the FRA scenario (with three-section vertical configuration).

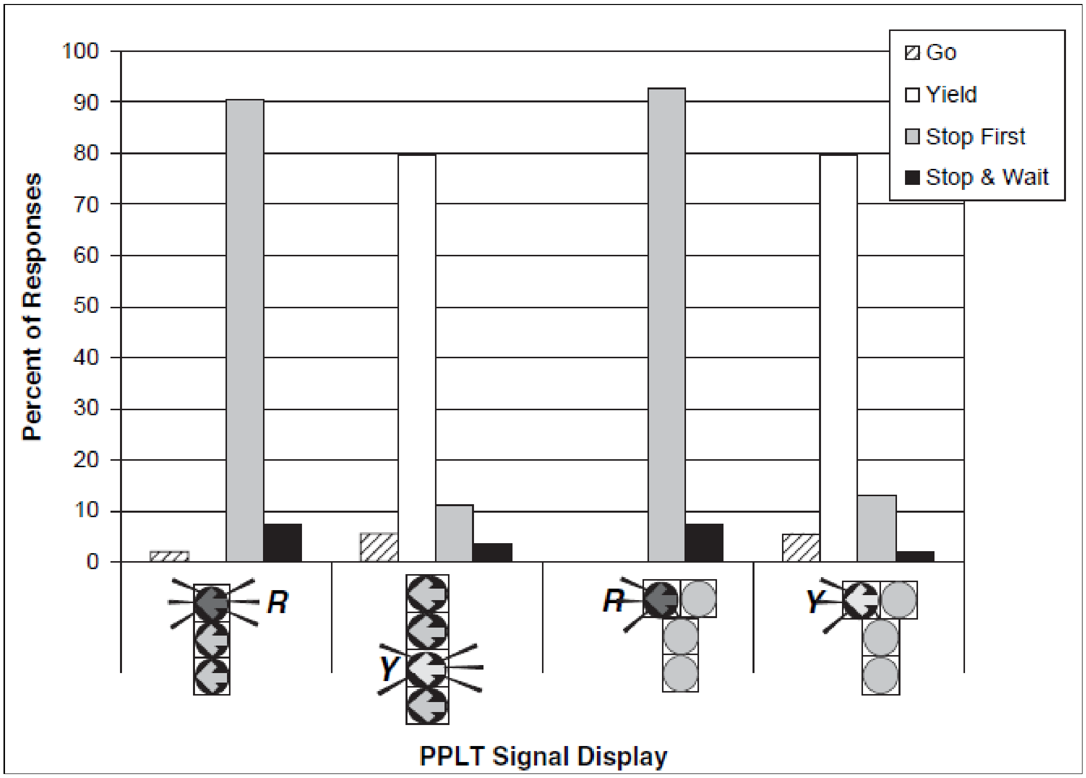


Figure 34. Responses to the follow-up static evaluation (Source: Knodler et al. 2006b).

All “go” (fail-critical) responses from the simulator study were matched with the corresponding driver to the same scenario in the follow-up static evaluation. Out of the six drivers who had “go” responses from the simulation involving the FYA scenario in a four-section vertical configuration, four of them responded correctly in the follow-up static evaluation, and one responded in a more cautious manner by selecting “stop first.” Just one of the drivers responded “go” in both the simulator experiment and the follow-up evaluation. Out of the four drivers who had “go” responses involving the FYA scenario in a four-section cluster configuration, three of them responded correctly in the follow-up static evaluation, and one of them gave the same fail-critical response (Knodler et al. 2006b).

The independent static evaluation was completed by more than 100 participants in Madison, Wisconsin, and Amherst, Massachusetts. The responses to the scenarios in the independent static evaluation were classified the same way as in the follow-up static evaluation. The responses from Massachusetts and Wisconsin were aggregated for analysis because no statistical differences were found between the respondents in Madison and Amherst. The findings for the independent static evaluation were consistent with simulator and follow-up evaluation results. The following findings were drawn from the independent static evaluation and are shown in Figure 35 (Knodler et al. 2006b):

- The “yield” response rates associated with the FYA scenarios were equivalent to the “stop first” response rates observed for the FRA scenarios.
- The FYA scenarios had a statistically greater percentage of fail-critical (“go”) responses than the FRA scenarios. By contrast, the FRA scenarios showed a statistically higher percentage of fail-safe (“stop and wait”) responses than the FYA scenarios.

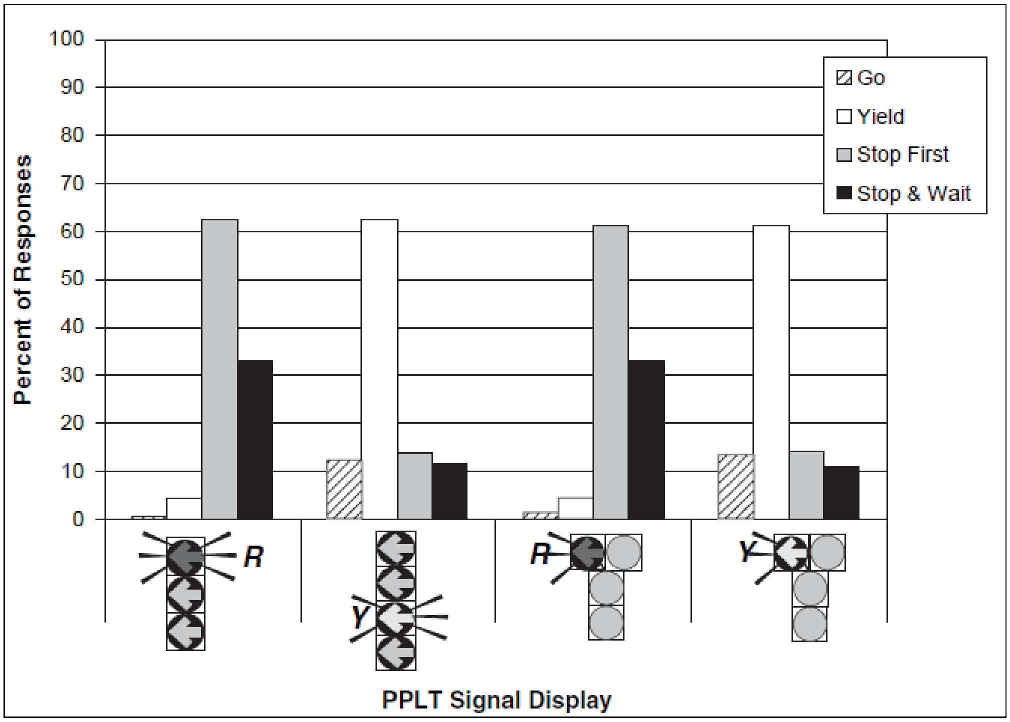


Figure 35. Responses from the independent static evaluation—FYA/FRA at separated left-turn lanes (Source: Knodler et al. 2006b).

Consistent with the results of NCHRP Report 493 (Brehmer et al. 2003), the FYA permissive indication scenarios examined in this study had a high percentage of driver comprehension when first encountered; however, the FYA indication showed a high percentage of initial fail-critical responses. The authors indicate that supplemental signage and training may be required at locations with wide medians and separated left-turn lanes. The FRA indication was incorrectly comprehended by many drivers, as shown by the large number of drivers who interpreted the FRA as a yield movement instead of an indication that requires drivers to stop first during the driving simulator study. The authors believe the meaning of the FRA could become diluted if used too often, and drivers may simply yield when a stop is critical. The authors suggest that FYA indications for permissive movements could be used for wide-median intersections if a permissive indication is desired but only after they have been more widely implemented (Knodler et al. 2006b).

2.2.2.5 Comprehension of the CG After Installation and Comprehension of the FYA

A 2007 study presented the results of research conducted by Knodler et al. to evaluate the potential impact on driver understanding of the CG permissive indication as the FYA permissive indications are gradually implemented and installed. The authors questioned whether, once drivers were aware of the meaning of the FYA, would they incorrectly interpret the CG permissive indication as “go” instead of “yield.”

Three primary tools were used to evaluate driver comprehension: a driving simulator experiment, a follow-up static evaluation for participants that completed the simulator study, and an independent static evaluation. To assess the impact on driver comprehension, the results from the simulation, follow-up static evaluation, and the independent static evaluation were compared with results from similar research studies also conducted by the authors. In the previous research, drivers evaluating a CG permissive indication had not been exposed to or learned the meaning of the FYA. In this study, drivers were trained on the meaning of the FYA so that the impact of the FYA on drivers' perceived meaning of the CG permissive indication could be quantified (Knodler et al. 2007a).

The static evaluation was administered to the 25 driver simulator participants, as well as 100 independent participants. The participants were assumed to be representative of the driving population. FYA training was provided in the beginning of the static evaluation and consisted of information displayed on the computer screen, as shown in Figure 36, explaining what the FYA does and does not imply:

- FYA requires drivers to yield to oncoming traffic and select an appropriate gap in the opposing traffic.
- FYA does not give drivers the right-of-way.
- FYA does not require drivers to stop and wait for an appropriate signal indication.

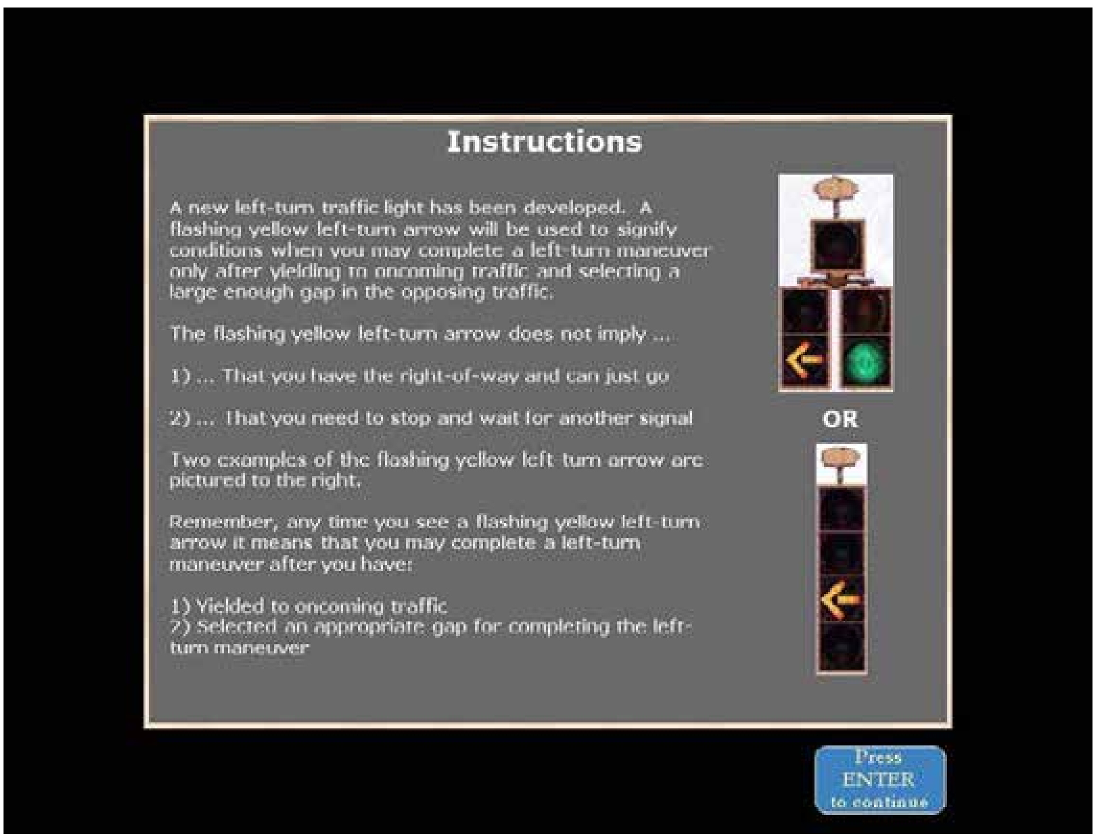


Figure 36. Computer screen showing FYA training received by survey participants(Source: Knodler et al. 2007a).

Drivers observed seven scenarios displaying either the FYA or green arrow left-turn indications. In the final scenario, drivers observed a CG permissive indication and were asked what they would do. The question and possible responses presented to drivers in this study were similar to those presented in previous studies (Knodler et al. 2007a).

The driving simulator experiment followed a similar format to the static evaluations. The 25 simulator participants were trained about the FYA before being seated in the simulator. The drivers' responses were recorded and categorized as correct, fail-safe, and fail-critical. Following the seventh intersection, drivers traversed a long rural segment that was intended to represent a transition from one municipality to a nearby jurisdiction. The drivers then encountered the CG scenario (Knodler et al. 2007a).

The researchers compared the correct responses from this simulator study with those of a previous study that did not include FYA training but followed a similar methodology. The authors did not find statistically significant differences in the drivers' responses to the CG permissive signal, after encountering the FYA signal (Figure 37).

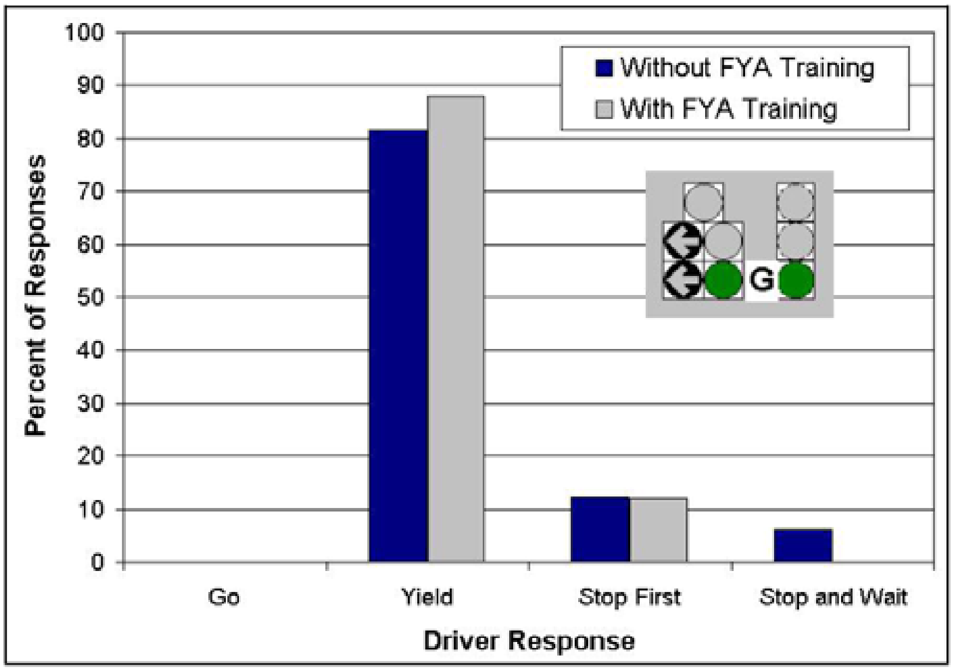


Figure 37. Driver responses from the CG scenario for the simulator studies with and without FYA training (Source: Knodler et al. 2007a).

The follow-up static evaluation results for the CG scenario showed a statistically significant difference in the number of "yield" responses, with more drivers responding correctly after FYA training; however, when "yield" and "stop first" responses were both considered to be correct, the difference in the percentage correct with and without FYA training was not statistically significant. The results are summarized in Figure 38.

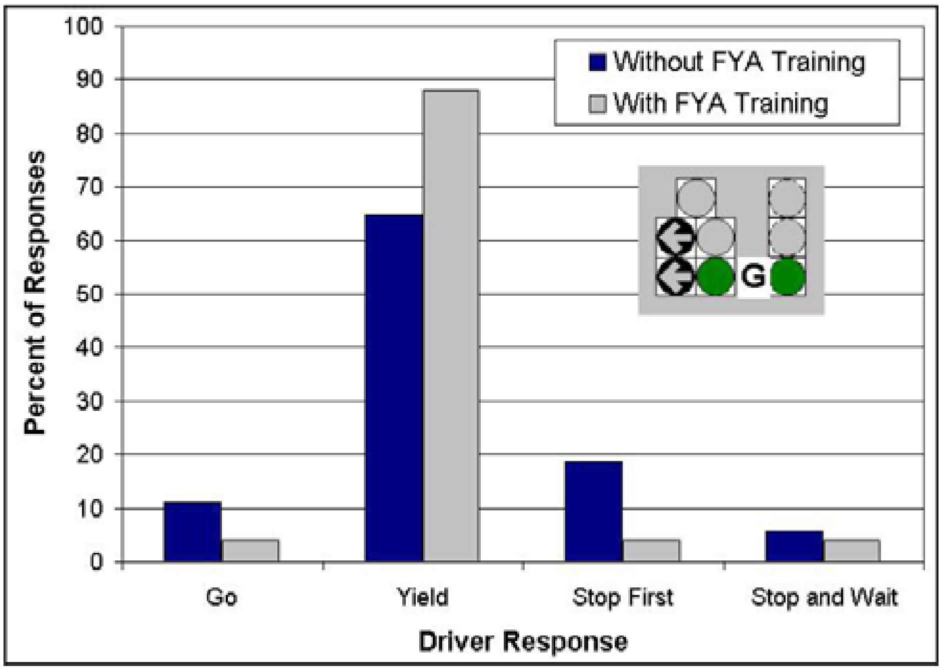


Figure 38. Driver responses for the CG scenario in the follow-up static evaluations with and without FYA training (Source: Knodler et al. 2007a).

One hundred drivers participated in the independent static evaluation. When the responses to the CG scenario from the current study were compared with the previous study, no statistically significant differences in the responses were found. An additional comparison between the responses to the FYA scenarios before and after training was conducted. Four scenarios were compared, including an FYA/CG cluster, an FYA with adjacent CG through indication, an FYA/CR cluster, and an FYA with adjacent CR through indication. The percentage of "yield" responses increased significantly for both the FYA/CG cluster and the FYA with adjacent CG through indication. The difference in "yield" responses at scenarios with CR through indications before and after FYA training was not statistically significant, and the authors mentioned that more "stop" responses could be expected at these scenarios because the CR implies "stop."

The authors concluded that there is little evidence to suggest that the FYA permissive indication will impact driver comprehension of the CG permissive indication; however, there is evidence to suggest that driver training on yield requirements in general may prove beneficial because more drivers in the study responded correctly after learning the definition of the FYA. Also, initial evidence regarding the impact of future FYA training efforts was discovered. The two scenarios pictured as examples in the FYA training were associated with higher percentages of correct responses after FYA training than all other FYA scenarios not pictured in the training. The authors recommend that more research needs to be conducted to investigate the impact of exposure times. The drivers in this study were exposed to the FYA for only the length of the time that the study took to complete. Results could vary if a driver had been exposed to FYAs for a longer period of time.

2.2.2.6 Comprehension of the Solid Yellow Arrow After Introduction of the FYA

Another follow-up study to the research conducted as a part of NCHRP 493 was conducted to assess whether the introduction of the FYA as a permissive left-turn indication altered driver understanding of the solid yellow arrow (SYA) as used in the left-turn change interval (Knodler et al. 2007b).

Driver comprehension was evaluated using a computer-based static evaluation taken by 212 drivers in Wisconsin and Massachusetts. The survey involved six stages. In the first stage, the driver was shown an image of an SYA and asked, “What does this traffic signal mean?” The following choices were available:

- You have the right-of-way and can go.
- You are required to yield.
- You must stop and wait for the appropriate traffic signal.
- The preceding movement is ending.
- The red light is coming next.

Stage two involved two SYA scenarios, one with a SYA in a five-section cluster with a simultaneous CR and the other with a SYA in a four-section vertical arrangement. For these two scenarios, the driver was asked a similar question and was presented with similar response options as previous static driver understanding evaluations. Stage three involved an FYA training session. The training screen was identical to one used in a previously mentioned study, as shown in Figure 36. In stage four, after having received FYA training, the participants were shown nine scenarios, showing either an FYA or a green arrow, and were asked to indicate what they would do if they wanted to turn left. Stage five was the same as stage two; drivers repeated the same two scenarios involving the SYA. The last stage asked the drivers to repeat stage one and identify the meaning of the SYA. The researchers were not necessarily interested in seeing whether participants indicated the correct answer but whether their comprehension of the SYA had changed after FYA training (Knodler et al. 2007b).

A total of 212 drivers participated in the static evaluation. Only 34% of the drivers had identical responses to stages one and six (both involving identifying the meaning of the SYA), i.e., before and after FYA training; however, the number of “go” responses decreased significantly. The percentage of “yield” responses from drivers in Massachusetts and Wisconsin both increased but was only statistically significant in Massachusetts. When the SYA scenarios were evaluated, no statistically significant differences were found between the before and after FYA training periods for any particular response for the SYA scenarios (Knodler et al. 2007b).

As a result of the drivers’ responses in this study, the authors concluded the following (Knodler et al. 2007b):

- There was no evidence to suggest that the FYA permissive indication would negatively affect driver understanding of the SYA indication.
- When responding to the SYA indication, only 34% of the drivers responded the same before and after exposure to the FYA; however, the changes in responses were cautious in nature.
- The distributions of driver responses before and after exposure to the FYA were statistically equivalent between the driving simulator study and the static evaluation.

2.2.2.7 Evaluating Safety Effectiveness of the FYA from Crash Data

Crash-based analyses were conducted to evaluate the safety effectiveness of intersections where FYA had been installed by 2007, as part of the research presented in NCHRP Web-Only Document 123 (Noyce, Bergh, and Chapman 2007b). There was a need to evaluate the safety of the intersections quantitatively using the FYA and to document the experiences of each implementation agency quantitatively. Crash experience was used as the main safety measure. Other parameters such as signal phasing, vehicular flow rates, speed limits, and intersection geometry were also considered in the evaluation.

The researchers aimed to evaluate every FYA site in existence at the time of this study. However, for the following reasons, this was not possible. The FYA received interim approval in March 2006. After that date, it was not possible to track all installations of FYAs because of the increased frequency of installation and lack of specific location information for each site. Also, most agencies were not collecting data for new sites implemented after March 2006. For those agencies that did collect data, it was realized that the length of the after period was insufficient. Therefore, the data in this study mostly included sites that were implemented prior to the *MUTCD*'s approval of FYAs and had at least one year of crash data available for the after period at the time the study was conducted (Noyce, Bergh, and Chapman 2007b).

There were 53 sites across the country that had enough information and data available to be studied. Twenty-seven of these sites were originally protected-only phasing and were changed to PPLT phasing with the FYA, 21 sites were operating with PPLT phasing before the installation of the FYA, and five sites were operating with permissive-only phasing before being changed to PPLT phasing when the FYA was installed. The sites were categorized into the following groups (Noyce, Bergh, and Chapman 2007b):

- Group A—operated with PPLT control before FYA installation (21 sites)
- Group B—operated with protected-only phasing before FYA installation (27 sites)
- Group C—operated with permissive-only phasing before FYA installation (5 sites)

A sign test was conducted to associate an increase or decrease in crash frequencies on an individual intersection basis. Only 35 sites had enough data to be evaluated using the sign test, and they were evaluated for total crash frequencies, left-turn crash frequencies, and FYA left-turn crash frequencies. A left-turn crash included all crashes that involved a left-turning vehicle. A target crash group, FYA left-turn crashes, was created to isolate the effect of the FYA on the crash frequency. This group included crashes involving a vehicle making a left-turn from an approach where an FYA display was installed. In the before period, a left-turn crash was considered an FYA left-turn crash if it occurred on an approach that was later implemented with the FYA.

The results of the sign test showed that all sites in group A had a reduction in crash frequency or stayed the same for left-turn crashes and FYA left-turn crashes from the before to the after period. Twelve of the 13 sites in group A also had statistically significant reductions in total crashes. A summary of these results is presented in Figure 39 (FYA left-turn crashes are not depicted).

Group B showed an increase in total crashes at 12 of the 18 sites, an increase in left-turn crashes at 14 of the 18 sites, and an increase of FYA left-turn crashes at 13 of the 18 sites. Group B sites did not have statistically significant increases in total crashes, but the increase in left-turn crashes was statistically significant. The authors were not surprised because a permissive phase was added at the intersections in group B, which had operated before then with protected-only left-turn phasing. The results for total and left-turn crashes in group B are shown in Figure 40 (FYA left-turn crashes are not depicted).

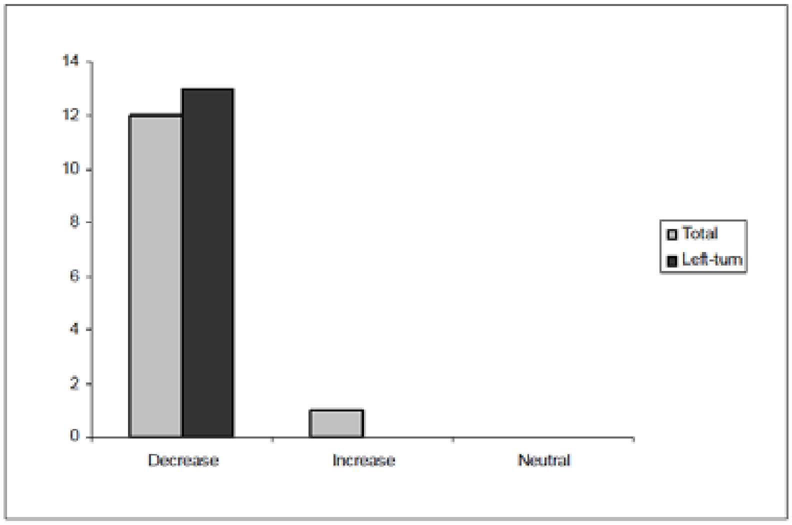


Figure 39. Group A sign test results for total crashes and left-turn crashes (Source: Noyce, Bergh, and Chapman 2007b).

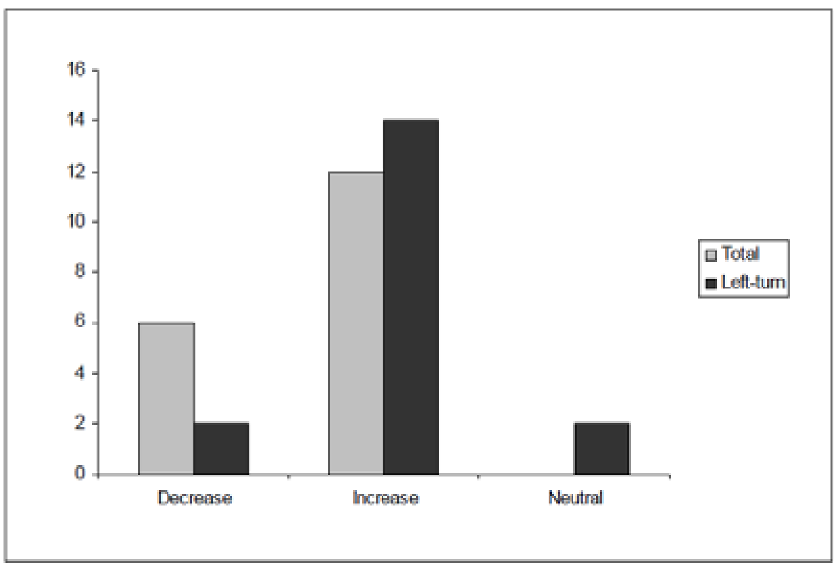


Figure 40. Group B sign test results for total crashes and left-turn crashes (Source: Noyce, Bergh, and Chapman 2007b).

No formal analysis could be conducted on the four sites in group C because of a lack of data and small sample size.

The authors then sought to develop a prediction model for FYA crashes using a linear trend analysis. This model would be used to predict the expected after-crashes had the FYA not been implemented. The authors then used the model to forecast crashes at the test sites and compared the forecasted value with the observed annual crash frequency. This analysis showed similar results to the sign test. All 13 sites in group A showed a decrease or no change in left-turn crash frequency, and sites in group B showed an increase or no change in left-turn crash frequency at 11 of 18 locations.

An empirical Bayes (EB) analysis was also completed. The researchers identified 19 intersections that had sufficient data to be used in this analysis. These intersections had all operated with PPLT control before the installation of the FYA. Fifteen of the 19 intersections showed a reduction in crashes, but this was not a statistically significant finding. Two of the 19 intersections showed an increase in crashes.

Finally, a regression analysis was completed to investigate the effect on crash frequencies by several potential independent variables, including average daily traffic (ADT) before, ADT after, volume ratio (after/before), total crashes before, left-turn crashes before, target (number of FYA left-turn) crashes before, number of approaches implemented with the FYA, average number of through traffic lanes opposing the FYA left-turn lane, posted speed limit, and months of crash data (time) after implementation. It was found that for group A total crashes, the average crash frequency increased as the number of opposing through lanes increased, as the posted speed limit decreased (which is not intuitive), and as the frequency of crashes in the before period increased. It was found that for group B total crashes, the average crash frequency increased as the volume ratio increased and as the number of months decreased (crashes decreased with time). For group B left-turn crashes, the average crash frequency increased as the number of approaches implemented with the FYA increased and as the number of months decreased.

The authors concluded the following from their research:

- Intersections (in group A) that operated with PPLT phasing before and after the FYA indication was installed showed an improvement in safety. All 13 of the sites analyzed had a reduction in left-turn crashes. The use of the FYA at such intersections resulted in this reduction.
- Safety was not improved at intersections (in group B) that functioned with protected-only phasing before the protected/permissive FYA implementation. There was an increase in left-turn crashes for 14 of the 18 study sites. For these intersections, the authors concluded that the change in the left-turn signal phasing from protected-only to protected/permissive had a greater impact on safety than the indication change.
- There was a very limited amount of data for intersections (in group C) that operated with a permissive-only phasing before the FYA indication was implemented. Therefore, no conclusions could be made about the change from permissive-only to FYA PPLT control.

2.4 DRIVER COMPREHENSION SURVEYS

A study was conducted in April 2008 in Creve Coeur, Missouri, in an area where FYA indications had been implemented. The primary objective of this study was to determine how well area drivers understood the meaning of the FYA left-turn indication. FYAs were compared with the CG indication in terms of driver understandability through the use of a computer-based static survey administered at several locations in Creve Coeur (Henery and Geyer 2008).

The questionnaire was similar to the one used in NCHRP Report 493. The participant was presented with images of intersections and asked, “If you want to turn left and you see the signals shown, you would …”

- Go (you have right-of-way).
- Yield (wait for gap).
- Stop.

Six scenarios were evaluated by each participant. Two scenarios involved the FYA permissive indication without a supplemental sign, one scenario involved the CG permissive indication with a supplemental sign, and three scenarios involved protected left turns or a CR indication for left-turn vehicles, as shown at the bottom of Figure 41. Questions one, four, five, and six had adjacent CG through indications while questions two and three had adjacent CR through indications displayed (Henery and Geyer 2008).

Age was the only restriction imposed on participants because they had to be 15 or older. The survey was presented to respondents via a laptop computer set up in predetermined public locations. The only exception was that one of the locations was a high school driver education class. All of the students in the class were asked to participate in the survey, and all age groups were well represented except for the 65+ age group (only 2% of respondents) (Henery and Geyer 2008).

Overall, there were 204 respondents. Question two involving the FYA permissive indication with a CR through indication received a 65.2% correct response rate, and 18.7% of the responses were incorrect with a “go” answer. Question 5 involving the FYA permissive indication with a CG through indication received 79.5% correct responses. The scenario involving the CG permissive indication with the supplemental sign had a 94% response rate. Of the 204 total respondents, 53.8% indicated they had seen the FYA signal while driving (Henery and Geyer 2008).

When correct responses were filtered by age, the under-24 age group had the lowest percent correct of all age groups for all questions except for questions 2 and 6; the 65+ age group had a lower percentage of correct responses for these two questions. Question 2 displaying the FYA had the lowest percentages of correct responses for each age group, while question 4 displaying a solid CR had the highest (Henery and Geyer 2008). The breakdown of correct response by age group is shown in Figure 41.

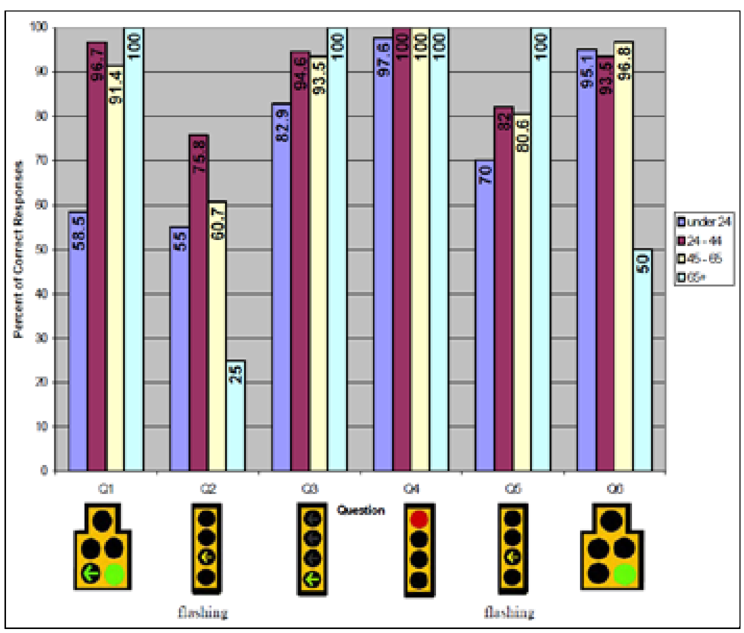


Figure 41. Correct responses by age group (Source: Henery and Geyer 2008).

When the results were filtered by exposure to the FYA, those drivers who indicated they had encountered the FYA while driving had a higher percentage of correct responses for both scenarios that involved the FYA permissive indication (Q2 and Q5).

The authors concluded that drivers had a better understanding for the CG with the “left-turn yield on green” sign when compared with the FYA indication. Drivers that had previously encountered the FYA indication had a consistently higher correct response rate although even this subgroup within the population had a better understanding for the CG permissive indication with the “left-turn yield on green” sign. The authors recommended that FYAs should be installed with caution at more locations around the state and that a public information campaign should be started (Henery and Geyer 2008). The authors’ conclusions were not supported by statistical testing.

As a part of a 2011 study by Qi, Yuan et al., two web-based surveys were conducted. One survey was distributed to traffic engineers in department of transportation agencies to collect information from the nationwide professional community regarding the FYA signal display. The second survey was distributed to general motorists to gather information about the drivers’ understanding of the FYA permissive left-turn indications (Qi, Yuan, et al. 2011).

For the traffic engineer survey, the authors received 37 responses. The respondents noted three safety issues with the implementation of FYA with PPLT operation. They expressed concern in using FYA in a three-section signal head. The *MUTCD* allows use of the FYA in a three-section signal head when clearance, wind loads, or other reasons will not allow the use of the four-section signal head. A dual-arrow section is used to display both the green and flashing yellow arrows (Qi, Yuan, et al. 2011). Figure 42 shows this type of signal head.

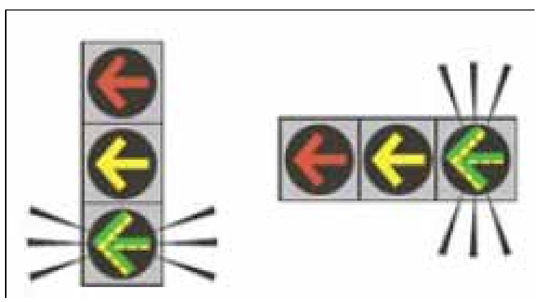


Figure 42. Three-section FYA signal head for PPLT operation (Source: Qi, Yuan, et al. 2011).

The concern with this type of signal head was that drivers who are color blind may experience difficulty distinguishing between the green and flashing yellow arrows that occupy the same space on the signal head. The authors noted that although problems using the three-section signal head in practice have not come up, traffic engineers are still concerned about using it.

The second issue that arose from the traffic engineer survey was that drivers may mistake the FYA for a steady yellow arrow. If a driver were to very quickly glance at the signal when the FYA was in flashing mode, he/she may misinterpret the message as a steady yellow arrow and assume that the turn may be completed.

The third issue pertained to driver confusion; some of the survey respondents indicated that drivers may be confused with two allowable left-turn permissive indications

(FYA and CG). Engineers also noted that drivers may be confused with the steady yellow arrow indication in FYA PPLT control. The steady yellow arrow is displayed twice in the same cycle and has two meanings. The steady yellow arrow follows the green arrow and the end of a protected left-turn phase, and the left-turn driver still has the right-of-way in this case over the opposing through traffic. The steady yellow arrow also follows the FYA at the end of the permissive left-turn phase; and in this situation, the left-turn driver must continue to yield to opposing through traffic. The two meanings for the steady yellow arrow may confuse drivers and cause conflicts (Qi, Yuan, et al. 2011). Figure 43 shows the two meanings associated with the steady yellow arrow.

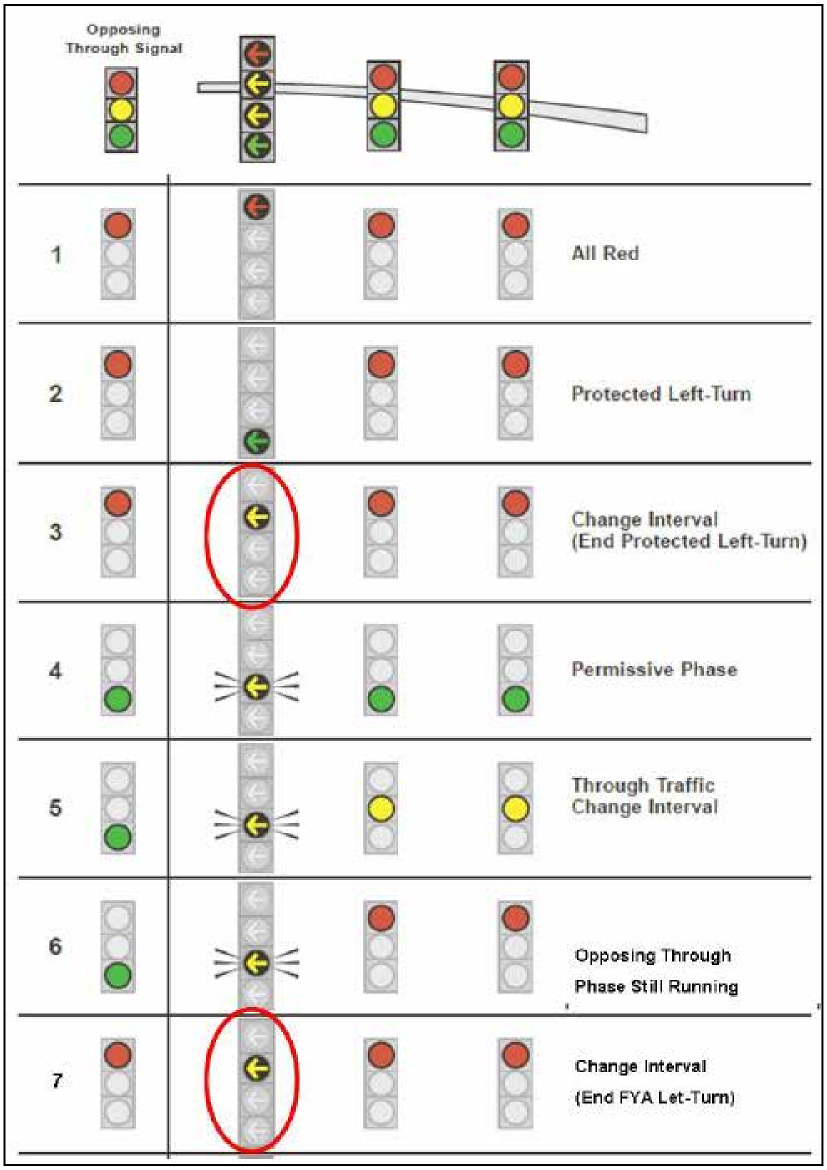


Figure 43. Two meanings associated with the steady yellow arrow in FYA PPLT control (Source: Qi, Yuan, et al. 2011).

The authors also distributed a survey to general motorists to assess driver understanding of the FYA, and 126 responses were received. The respondents had a wide age range and varying levels of driving experience. The major findings from this survey are as follows and are shown in Figure 44 (Qi, Yuan, et al. 2011):

- The FYA indication was well understood by drivers, with a correct response rate of up to 92%.
- Only about 3% of drivers had fail-critical responses.
- The adjacent through traffic signal may have an impact on drivers' understanding of the FYA.

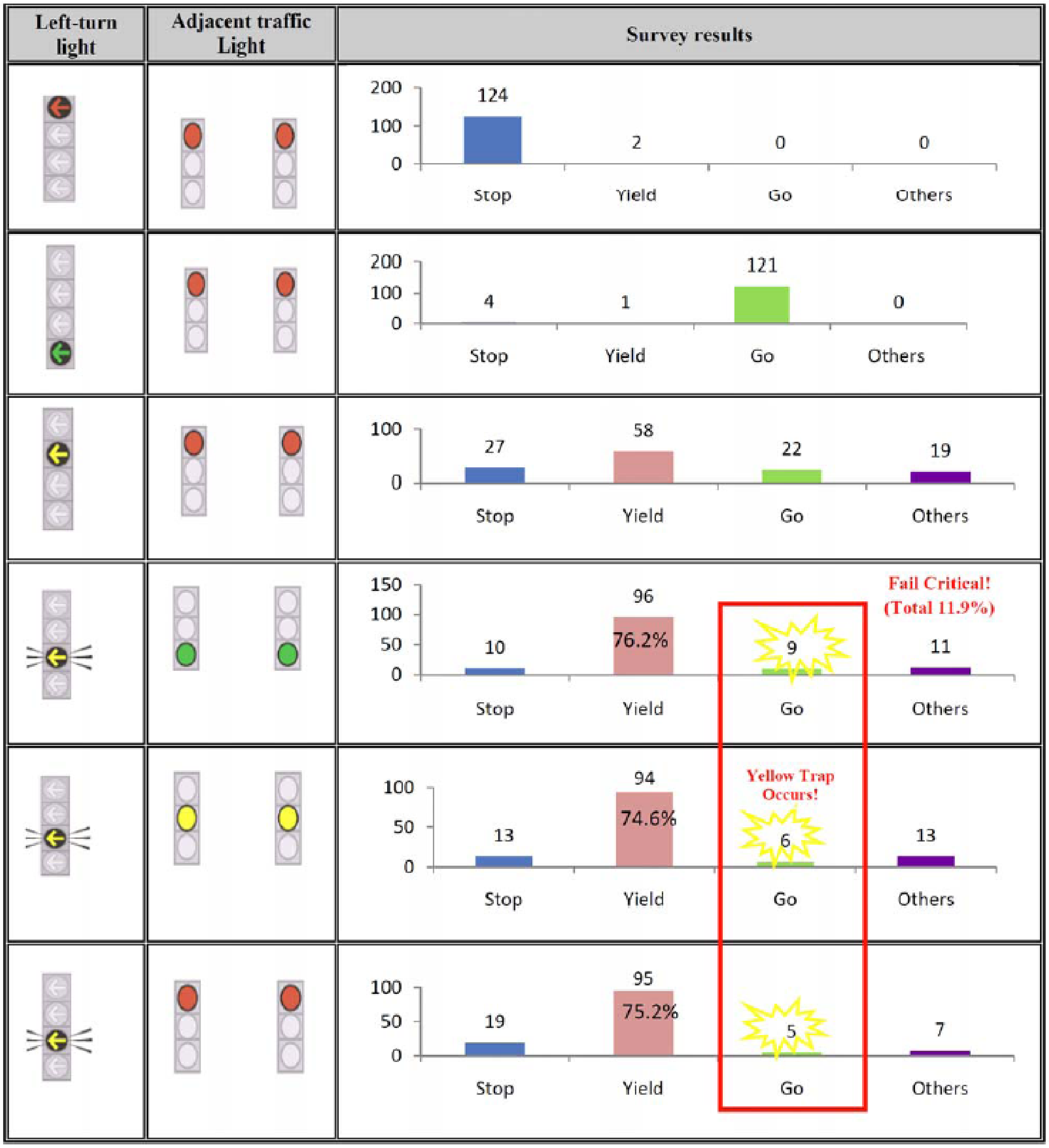


Figure 44. Driver responses to left-turn signal displays in general motorist survey (Source: Qi, Yuan, et al. 2011).

The authors suggested that because the adjacent through traffic signal may have a negative impact on driver understanding of the FYA, louvered signal heads may be considered for the through lights. They also suggested that the three-section signal head with the dual-arrow section be used with great caution (Qi, Yuan, et al. 2011).

2.5 TRAFFIC CRASH-BASED STUDIES

A before and after crash analysis was conducted by the city of Federal Way, Washington, in 2010 to evaluate the safety of FYAs (Perez 2010). At the time this report was written, eight out of the city's 76 signalized intersections had been equipped with FYA displays for PPLT movements. The integration of FYAs in the city of Federal Way also included changes in left-turn operations. The evaluation study included seven intersections, which are as follows:

- At three intersections, the left-turn phasing was changed from protected-only in the before period to PPLT phasing with FYA in the after period.
- At two intersections, the only change in the PPLT operation was the addition of the FYA indication.
- At one intersection, the left-turn phasing was modified from permissive-only to PPLT phasing with FYA.
- At one intersection, the left-turn phasing for one road was originally permissive-only but then upgraded to PPLT phasing with FYA, while the other road was changed from protected-only to PPLT phasing with FYA.

Some of the improvement projects also included the installation of far left auxiliary left-turn signals and the inclusion of a right-turn overlap phase. It should be noted that because other improvements besides the FYA were installed and a variety of left-turn phasing changes were made, the safety impacts of the FYA for PPLT operation cannot be isolated. Thus, the results of this study should be viewed with caution.

The city of Federal Way launched a public awareness campaign to educate drivers on the meaning of FYA indications through the use of a web page and several press releases. The public comments regarding the FYA indication were mostly positive, with some drivers even requesting FYAs to be installed at more locations; however, some drivers complained that the state law and driver's manual did not contain explicit language to address the use of FYAs for PPLT movements. In December 2008, an instructional sign, shown in Figure 45, was installed at locations functioning with an FYA indication. Negative feedback from the public decreased since the initial installations of this PPLT indication (Perez 2010).

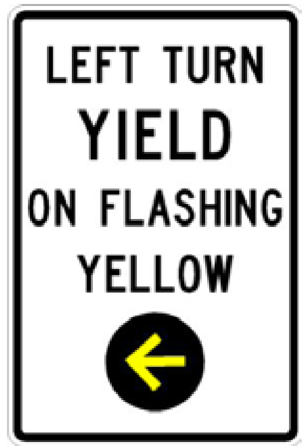


Figure 45. Supplemental signage installed at locations using the FYA indication (Source: Perez 2010).

The crash analysis was based on three years of before crash data and three years of after crash data, or as much data as was available. For intersections where crash data were not available for the entire year, the crash frequencies were annualized.

The before and after crash data were classified by crash type, severity, and type of phasing conversion. Crash rates and severity rates were calculated on a per-million-entering-vehicle basis.

Among the seven intersections analyzed overall, it was found that there was a 9% reduction in crash rates, with an 8% reduction in severity rates; however, there was variability among the intersections. The overall analysis showed that after the installation of FYAs, crashes were reduced for the following crash types: rear-end, right-angle, backing, and head-on collisions. Fixed-object, pedestrian, and turning crashes were found to have increased after the installation of the FYA indication (Perez 2010).

More meaningful results were obtained when the data were arranged by the type of phasing conversion. The evaluation of the intersections converting from protected-only phasing to PPLT phasing with FYA showed a 15% increase in crash rates, with a 41% increase in severity rates. The majority of the changes in crash and severity rates were attributed to the addition of the permissive phase. Another possible cause could be a learning curve issue. When the first year of after crash data was removed from the analysis, the results showed a positive change in crash and severity rates. The results obtained from the analysis of locations converting from PPLT control to PPLT phasing with FYA were more promising. A 39% reduction in crash rates and a 64% reduction in severity rates were observed. Specifically, there was an increase in fixed-object and rear-end crashes but a decrease in turning, right-angle, pedestrian, and head-on crashes.

The author concluded that although limitations existed in sample size, safety benefits were observed for intersections that were converted from PPLT phasing to PPLT phasing with FYA. For the conversion from protected-only to PPLT with FYA, an increase in collisions was observed (Perez 2010).

Another crash-based study aimed at evaluating safety benefits of FYAs was conducted by researchers from the University of North Carolina at Charlotte (Pulugurtha, Agurla, and Khader 2011). The before and after crash data were collected and analyzed at six selected intersections in the city of Charlotte. The FYA installations occurred in 2007 and

2008. The before and after analysis periods varied based on data availability and date of installation and activation. A three-year before period and a one-year after period were used. The researchers used a projected average annual daily traffic (AADT) for the after period, using a 3% growth rate (Pulugurtha, Agurla, and Khader 2011).

The EB analysis method was chosen by the researchers for the analysis of the crash data. This method was used because it minimizes the regression-to-mean bias and can be applied when sample sizes are small or when unequal before and after periods exist. The EB method compares the actual number of crashes after installation of the FYA with an estimated expected number of crashes in the after period had the FYA not been installed.

Table 2 summarizes the results of the EB analyses. A ratio of actual after-crashes over expected after-crashes of less than one shows an improvement in safety. For five out of the six selected study intersections, the observed number of crashes was lower than the expected number of crashes. This finding implies that there was a safety improvement at five out of the six intersections after the FYA signals were installed (Pulugurtha, Agurla, and Khader 2011).

The authors commented that although the results were positive, it cannot be concluded that FYAs had been very effective in reducing crashes at all locations. They suggested that a larger sample size and only left-turn crashes be considered in future investigations (Pulugurtha, Agurla, and Khader 2011).

Table 2. Number of Crashes and Ratios for Actual and Expected Results
(Source: Pulugurtha, Agurla, and Khader 2011)

Study Intersection (i)	After - Estimated # Crashes per year ($C_{E,i}$)	After - Actual # Crashes per Year ($C_{A,i}$)	Ratio = ($C_{A,i}/C_{E,i}$)
East 5th St / 7th St	8.8	8	0.9
I-77 SB Ramp / Sunset Rd	28.4	22	0.8
I-85 SB Ramp / Mallard Creek Ch Rd	33.5	37	1.1
Erwin Rd / Tryon St	15.6	9	0.6
Ballantyne Commons / Durant Blvd	18.9	10	0.5
Charlotte Town Ave / S Kings Dr	18.1	11	0.6

A 2011 crash-based study was conducted under NCHRP Report 705: *Evaluation of Safety Strategies at Signalized Intersections*. As a part of this study, crash modification factors (CMFs) were developed from before and after evaluations of three types of FYA treatments in North Carolina, Washington, and Oregon. Intersections with protected-only control, permissive-only control, and PPLT control were changed to PPLT control with the FYA signal indication (Srinivasan, Lyon, et al. 2011; Srinivasan, Gross, et al. 2011).

The characteristics of the study intersections by location are as follows:

- Five intersections located in Kennewick, Washington—Four used PPLT phasing in the before period and one used permissive-only phasing in the before period.
- Thirty-four intersections located in Beaverton, Gresham, Oregon City, and Portland, Oregon—Twenty-four sites operated with protected-only phasing in the

before period, three operated with permissive-only phasing, three operated with PPLT phasing, and four sites prohibited left turns.

- Sixteen intersections located in urban areas of North Carolina—Five intersections used protected-only phasing in the before period, five sites used a “doghouse” arrangement with PPLT phasing in the before period at one leg and permissive-only phasing in the before period at another leg, and six sites used a “doghouse” arrangement with PPLT phasing in the before period at two legs.

Fifty-one of the intersections were used in the crash analysis, and their aggregated characteristics are as follows:

- A total of nine intersections with 36 legs, 20 of which were treated with PPLT phasing using the FYA indication, operated with permissive-only or PPLT phasing with at least one permissive approach in the before period.
- A total of 13 intersections with 51 legs, 27 of which were treated with PPLT phasing using the FYA indication, operated with PPLT phasing in the before period.
- A total of 29 intersections with 111 legs, 56 of which were treated with PPLT phasing using the FYA indication, operated with protected-only phasing in the before period (Srinivasan, Gross, et al. 2011).

The EB analysis method was used for the 16 study sites in North Carolina. Forty-nine reference sites were found to help create the safety performance function (SPF). The full EB method could not be used for the five study sites in Washington and for the 30 study sites in Oregon because of limited data for the reference sites. The researchers used some aspects of the EB method and a before and after with control comparison to evaluate crashes at these locations. It should also be noted that four of the five study locations in Washington had other changes that were installed at the same time as the FYA and thus were excluded from further analysis (Srinivasan, Lyon, et al. 2011).

The crash effectiveness results varied depending on the “before” left-turn phasing type. The “after” condition for all the study sites had PPLT control with the FYA installed. The study sites that were protected-only in the before period experienced statistically significant increases in total intersection crashes and total intersection left-turn crashes. Sites that had at least one leg with permissive-only control and the remaining legs with PPLT control in the before period experienced statistically significant reductions in total and left-turn crashes. Study sites with all legs operating in PPLT control in the before period experienced a small reduction in crashes that was not statistically significant (Srinivasan, Lyon, et al. 2011). CMF results by phasing change and for both total intersection crashes and total intersection left-turn crashes are shown in Table 3.

Table 3. CMFs and Standard Errors for FYA Installation (Source: Srinivasan, Gross, et al. 2011)

Left-Turn Phasing Before (sites) (legs treated)	Crash Type	CMF (S.E.)
Permissive or combination of permissive and protected-permissive (at least 1 converted leg was permissive in the before period) (9 sites) (20 legs treated)	Total Intersection Crashes	0.753 (0.094) #
	Total Intersection Left-Turn Crashes	0.635 (0.126) #
Protected-Permissive (all converted legs had protected-permissive in the before period) (13 sites) (27 legs treated)	Total Intersection Crashes	0.922 (0.104)
	Total Intersection Left-Turn Crashes	0.806 (0.146)
Protected (all converted legs had protected in the before period) (29 sites) (56 legs treated)	Total Intersection Crashes	1.338 (0.097) #
	Total Intersection Left-Turn Crashes	2.242 (0.276) #

Note: # Statistically significant at the 0.05 level

The authors concluded that the change in signal phasing may have had more of an impact on safety than the FYA signal indication. The largest benefit occurred when at least one leg operated under permissive-only control before being changed to PPLT control with the FYA in the after period. The authors suggested that further research be done to study the relationship between the number of legs treated with the FYA and the impact on crashes. They also suggested that the effect of left-turn volume and opposing through volume on safety be studied (Srinivasan, Lyon, et al. 2011).

A crash-based study published in 2011 evaluated the safety performance of 17 intersections that had FYAs installed in Tyler, Texas, and in Kennewick, Washington. All of the study intersections operated with PPLT control both before and after the installation of the FYA. Four to six years of before crash data and one to two years of after crash data were collected and analyzed (Qi, Zhang, et al. 2011).

The authors used the EB method to evaluate the safety effectiveness of the FYA. The four to six years of before crash data from the study intersections was used to calculate a model. However, it should be noted that the authors used the same data set to develop the model and to evaluate the safety effectiveness, which is not an appropriate procedure. The authors determined that a negative binomial regression was a better fit than a Poisson regression model and used it to predict crashes had the FYA not been installed. The ratios of the observed crash rate after FYA installation over the predicted after crash rate from the EB model were determined. A ratio less than one indicated that the FYA signal improved safety.

The computed ratios were found to be less than or equal to one at 14 out of the 17 study intersections. The three intersections with a ratio greater than one were studied further using police crash reports, signal timing, geometric design, and other information. The authors stated that the increased crash rate at one of the three sites with a ratio greater than one was not related to the FYA. They also found two specific crash problems that occurred at the other two intersections involving “red trap” and “yellow sneakers” (Qi, Zhang, et al. 2011).

The first issue pertained to a red trap problem. One intersection was converted from a lead PPLT operation to a lead-lag PPLT control. At this location, some left-turn vehicles arrived at the intersection during the steady yellow interval at the end of their direction's lead protected phase. The driver may have been confused with this indication and stopped in the intersection to wait for a gap. When the left-turn arrow went to red, a driver may have assumed the next movement would have been a cross-street movement instead of an opposing through movement and rushed to complete his/her turn, causing a crash with opposing through traffic. The authors stated three reasons for this problem (Qi, Zhang, et al. 2011):

- Confusion over steady yellow arrow—Some drivers may choose to stop in the intersection and yield to opposing traffic because they mistake the steady yellow arrow for an FYA or they are confused about its meaning. In FYA PPLT operation, the steady yellow arrow is displayed twice in the same cycle and has two meanings (refer to Figure 43).
- Heavy left-turn volume—There is a higher chance of a left-turn vehicle arriving on the steady yellow interval.
- Split phasing—The leading protected left-turn interval could end at the same time as the adjacent through, causing drivers to possibly think the next movement will be a cross-street movement.

The authors suggested that a relatively long red arrow of three to four seconds be used between the steady yellow arrow and the FYA, which would allow time for confused drivers to clear the intersection.

The second crash problem pertained to the conflicting yellow sneakers problem. This crash type occurred at a T-intersection with a relatively high speed limit (40 mph). This type of crash occurs when both the left-turn and opposing through vehicles see a steady yellow and both vehicles speed up to go through the intersection as a yellow sneaker and collide. The FYA PPLT control allows the permissive left-turn in the leading direction to be extended into the opposing protected lag phase, which causes the permissive left-turn phase and opposing through phase to end at the same time. In CG PPLT control, the leading permissive left-turn phase ends well before the lagging through phase and this problem does not occur. The authors mentioned that higher left-turn and through volumes along with relatively high speeds increased the chances of drivers from both directions acting as yellow sneakers. The authors recommended a delay to the start of the FYA yellow clearance interval and suggested that the yellow interval for the opposing through start earlier and end before the yellow interval for the FYA begin (Qi, Zhang, et al. 2011).

Both the red trap and conflicting yellow sneakers problems were related to intersections with heavy traffic volumes and the use of lead-lag left-turn phases. The authors suggested that if installation of the FYA is required then the lead-lag signal phasing sequence is not recommended. They also noted that the use of the FYA allows for different phasing at different times of the day (Qi, Zhang, et al. 2011).

2.6 TRAFFIC OPERATIONS-BASED STUDIES

A study conducted by Lin, Thiagarajan, and Atie sought to develop an approach to observe drivers' reactions at intersections using the FYA. To do this, the authors created a flow chart that would assist in analyzing whether or not a driver was choosing a correct response to the signal, as displayed in Figure 46. Driver behavior categories in response to four signal intervals were observed (solid red arrow, SRA; SYA; solid green arrow, SGA; and FYA). The FYA interval involved more categories because it was the interval of most interest (Lin, Thiagarajan, and Atie 2008).

In Figure 46, the authors categorized responses at FYAs accordingly (Lin, Thiagarajan, and Atie 2008):

- Correct response—(f), (j), (l), (m)
- Incorrect but safe response— (h), (i), (k)
- Incorrect and unsafe response—(g), (n)

The authors also decided to use a more precise safe-gap measurement between the left-turn vehicle and the opposing through vehicles. This measurement involved the position of the two vehicles and their speeds.

An intersection in St. Louis, Missouri, was used in the case study. This intersection was selected to capture reaction samples under FYA because it had the FYA installed and used FYA phasing all day except for the peak period. The researchers categorized driver responses based on their own judgment, using the flowchart presented in Figure 46. These results showed that 93.4% of the observations fell into a category of correct response, 5.5% were incorrect but safe, and 1% was categorized as incorrect and unsafe (Lin, Thiagarajan, and Atie 2008).

The video recording was then reviewed a second time but with the calculated safe-gap distance projected into the intersection. The results from this study showed that about 95% of drivers responded to the FYA indication correctly and safely; however, approximately 5% of these drivers did not turn when there were appropriate gaps in the traffic stream. This condition is not a safety problem but could increase delay if a queue forms behind the waiting vehicle.

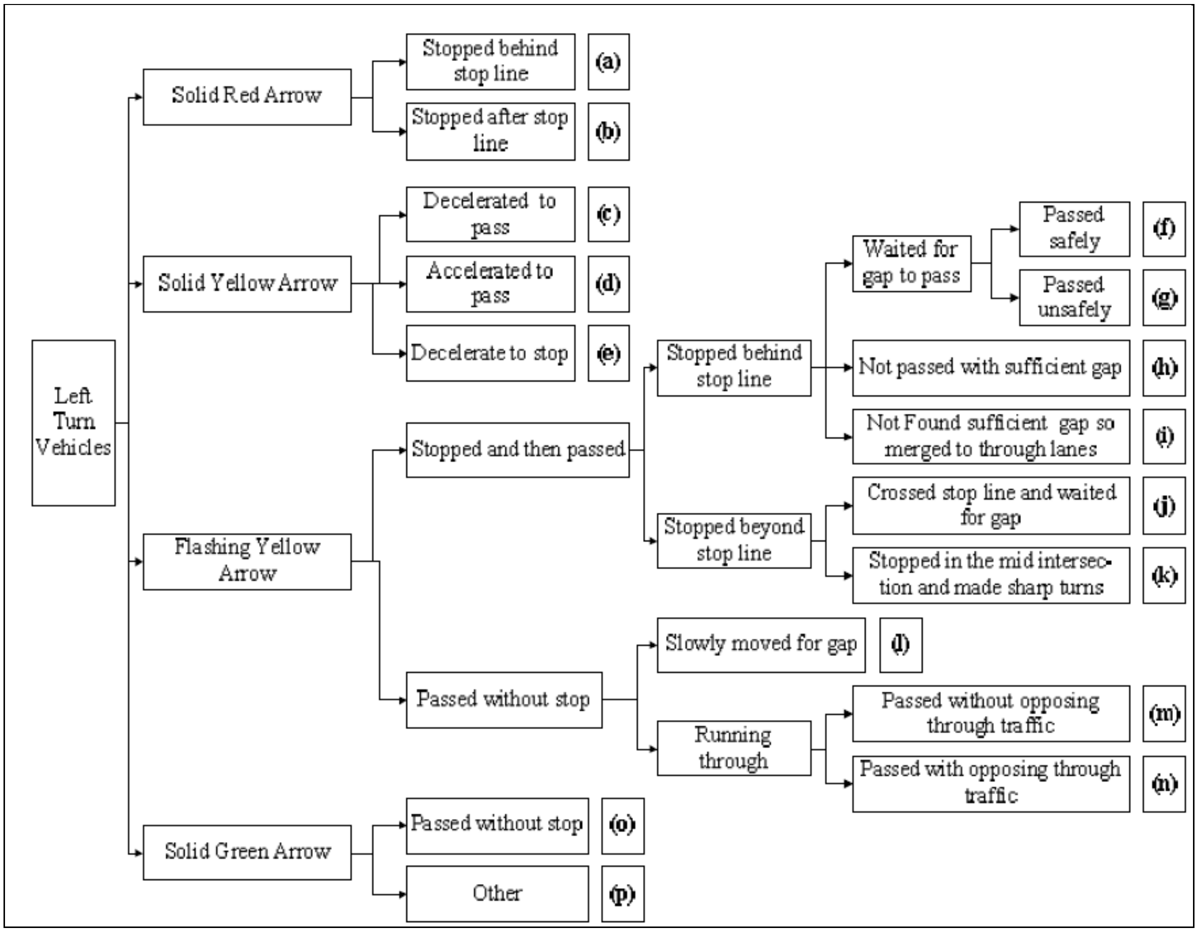


Figure 46. Flowchart developed by research team to categorize driver responses (Source: Lin, Thiagarajan, and Atie 2008).

From this study, the authors concluded the following (Lin, Thiagarajan, and Atie 2008):

- The video observation methodology is a better approach than a questionnaire survey and simulation survey when analyzing driver understanding because it reflects drivers' responses in reality.
- The research methodology provided a precise gap definition to distinguish safe and unsafe left turns.
- During the analysis, approximately 95% of the vehicles observed turning left during the FYA permissive phase did so safely.

The authors recommended that more analyses be done to compare drivers' reactions to FYA permissive indications with those to traditional CG permissive indications. They also recommended a systematic video observation method be developed that provides a more measured technique, such as acceleration/deceleration measurements, to support the sufficient gap measurement (Lin, Thiagarajan, and Atie 2008).

As a part of a study published in 2011 by Qi, Yuan, et al., a traffic conflict analysis was completed. A total of 301 hours of traffic conflict data was collected at five locations in

Austin and Bellmead, Texas, before and after the implementation of the FYA (163 hours before and 138 hours after the installation of FYA).

All locations were converted from PPLT display with CG indication to PPLT display with FYA indication. The sites had various phasing sequences, relatively high left-turn–related crash rates, and a variety of geometric and traffic conditions. Seven types of traffic conflicts and four types of traffic events were collected and analyzed for both the before and after periods (Qi, Yuan, et al. 2011). The statistically significant results, based on an independent non-parametric statistical test, are summarized below.

A Type 1 traffic conflict was a conflict that occurred between the subject left- or U-turn vehicle and opposing through traffic. This type of conflict was reduced at four out of the five study locations. The one location that experienced an increase had significantly higher volumes and limited gaps, creating a more stressful driving situation. Although the implementation of the FYA was found to impact the Type 1 conflict between left-turn and opposing through vehicles, it had little impact on conflicts involving U-turns (Qi, Yuan, et al. 2011). Type 2 traffic events occurred when the subject left-turn driver hesitated on the permissive left-turn indication. This type of event decreased at all five locations. Type 3 traffic events occurred when the subject left-turn driver ran the red light. Type 4 traffic events occurred when the left-turn driver backed up behind the stop bar. The authors explained that these two types of events are related because both are situations in which the left-turn driver becomes “trapped” in the intersection at the end of the permissive phase and must decide whether to go or to back up. Both Type 3 and Type 4 events increased at two study locations. These study locations had high traffic volumes and lead-lead phasing (Qi, Yuan, et al. 2011).

The authors recommended that the FYA not be used at very busy intersections with high volumes that use lead left-turn phasing. They also stated that the FYA signals at one of the study intersections (the one with negative traffic conflict results) were removed after one month because of complaints from drivers. This study location is the only one that experienced this problem (Qi, Yuan, et al. 2011).

CHAPTER 3 SUMMARY AND CONCLUSIONS

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 interval. 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 following sections provide a summary of the authors' results and findings.

3.1 NCHRP REPORT 493 AND FOLLOW-UP STUDIES

The authors of the NCHRP 493 report, Brehmer, Kacir, Noyce, and Manser, as well as others, Knodler, Bergh, Chapman, et al., published several papers in transportation journals documenting their analysis and results from the NCHRP Report 493, as well as follow-up studies on the impacts of FYAs.

The following conclusions were drawn regarding the FYA permissive indication in NCHRP Report 493 (Brehmer et al. 2003; Knodler et al. 2001; 2005b; Noyce, Fambro, and Kacir 2003):

- In the photographic driver survey, out of the CG, FCY, FCR, FYA, and FRA, the CG permissive indication had the lowest percent correct out of all indications (50%) and the FCY and FCR had the highest percent correct responses.
- In the field traffic operations study, follow-up headway was higher for the flashing red displays than the other displays, probably a result of legal requirements in the vehicle code that state a vehicle must first stop.
- 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 driver understanding and significantly lower fail-critical rates than the scenarios involving the CG display.
- 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. The implementing agencies, the public, and law enforcement had a mostly positive reaction to the FYA.

The authors also made the following recommendations (Brehmer et al. 2003; Kacir, Brehmer, and Noyce 2003a; 2003b):

- 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.
- Flashing red indications (circular and arrow) should be limited to certain situations in which a complete stop is recommended for left-turning traffic during the permissive state.
- If there is a widespread use of the flashing red indications for PPLT control, the meaning and effectiveness of the indication may be undermined.

Several follow-up studies from the authors of NCHRP Report 493 were presented in this report. The following conclusions are drawn from these studies:

- Concerning five-section signal arrangements, the FYA and 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).
- Drivers' 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, Noyce, and Fisher 2007).
- There is no evidence to suggest that the FYA permissive indication would negatively affect the understanding of the SYA used in change intervals (Knodler and Fisher 2009; Knodler et al. 2007).

3.2 DRIVER SURVEYS AND CRASH-BASED AND OPERATIONAL STUDIES

Additional crash-based, operations-based, and driver understanding survey studies were reviewed and presented in this synthesis. A summary of the various authors' conclusions from these studies are as follows:

- 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 switch 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, Bergh, and Chapman 2007b; Perez 2010; Pulugurtha, Agurla, and Khader 2011; Srinivasan, Lyon, et al. 2011; Srinivasan, Gross, et al. 2011).
- 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). However, these findings

were not supported by statistical analysis and were based on a sample size of 204 drivers.

- An operations-based study determined that 95% of vehicles observed turning left during the FYA permissive indication did so safely (Lin, Thiagarajan, and Atie 2008).
- A study conducted in Texas found that some high-volume intersections operating with the FYA and lead-lag left-turn phasing showed an increase in certain types of traffic conflicts (Qi, Yuan, et al. 2011). They suggested that louvered signal heads be used to prevent the left-turn drivers from seeing the adjacent through signals, especially when lead-lag left-turn phasing is operated (Qi, Yuan, et al. 2011). They concluded that the FYA indication was well understood by drivers, based on driver survey results.
- 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 (Qi, Zhang, et al. 2011).

REFERENCES

American Traffic Safety Services Association/Institute of Transportation Engineers/American Association of State Highway and Transportation Officials/Federal Highway Administration. 2001. *Uniform Traffic Control Devices*, Washington, D.C.

Antonucci, N.D., K.K. Hardy, K.L. Slack, R.P. Pfefer, and T.R. Neuman. 2004. *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan.* Volume 12. Transportation Research Board, Washington, D.C.

Brehmer, C.L., K.C. Kacir, D.A. Noyce, and M.P. Manser. 2003. *NCHRP Report 493: Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control.* Transportation Research Board of the National Academies, Washington, D.C.

California Center for Innovative Transportation, August 2004.

Federal Highway Administration (FHWA). 2009. *Manual on Uniform Traffic Control Devices for Streets and Highways*. U.S Department of Transportation.

Henery, S., and R. Geyer. 2008 (June). *Assessment of Driver Recognition of Flashing Yellow Left-Turn Arrows in Missouri*. Missouri Department of Transportation.

Kacir, K.C., C.L. Brehmer, and D.A. Noyce. 2003a. Improved Left-Turn Signal Operation: How the Flashing Yellow Arrow Left-Turn Display Can Enhance Intersection Operations. In *Proceedings of the Institute of Transportation Engineers 2003 Annual Meeting*. Seattle, WA, August 24–27, 2003.

Kacir, K., C.L. Brehmer, and D. Noyce. 2003b. A Recommended Permissive Display for Protective/Permissive Left-Turn Control. *Institute of Transportation Engineers Journal* 73(12):32, 37–40.

Knodler, M.A., and D.L. Fisher. 2009 (Nov.). *An Evaluation of Driver Comprehension Related to Solid Yellow Change Indications and the Potential Impact of the Flashing Yellow Arrow Permissive Indication*. New England University Transportation Center.

Knodler, M.A., D.A. Noyce, and D.L. Fisher. 2007. Evaluating the Impact of Two Allowable Permissive Left-Turn Indications. *Transportation Research Record: Journal of the Transportation Research Board No. 2018*, TRB, National Research Council, Washington, D.C.

Knodler, M.A., D.A. Noyce, K.C. Kacir, and C.L. Brehmer. 2001. *Driver Understanding of the Green Ball and Flashing Yellow Arrow Permitted Indications: A Driving Simulator Experiment*. Wisconsin Traffic Operations and Safety Laboratory. University of Wisconsin-Madison, Department of Civil and Environmental Engineering.

Knodler, M.A., D.A. Noyce, K.C. Kacir, and C.L. Brehmer. 2005a. Evaluation of Flashing Yellow Arrow in Traffic Signal Displays with Simultaneous Permissive Indications. *Transportation Research Record: Journal of the Transportation Research Board No. 1918*, TRB, National Research Council, Washington, D.C.

Knodler, M.A., D.A. Noyce, K.C. Kacir and C.L. Brehmer. 2005b. Evaluation of Traffic Signal Displays for Protected-Permissive Left-Turn Control Using Driving Simulator Technology. *Journal of Transportation Engineering* 131(4):270–278).

Knodler, M.A., D.A. Noyce, K.C. Kacir and C.L. Brehmer. 2006a. Analysis of Driver and Pedestrian Comprehension of Requirements for Permissive Left-Turn Applications. *Transportation Research Record: Journal of the Transportation Research Board No.*

1982, TRB, National Research Council, Washington, D.C.

Knodler, M.A., D.A. Noyce, K.C. Kacir and C.L. Brehmer. 2006b. Potential Application of Flashing Yellow Arrow Permissive Indication in Separated Left-Turn Lanes. *Transportation Research Record: Journal of the Transportation Research Board No. 1973*, TRB, National Research Council, Washington, D.C.

Knodler, M.A., D.A. Noyce, K.C. Kacir and C.L. Brehmer. 2007. An Evaluation of Driver Comprehension of Solid Yellow Indications Resulting from Implementation of the Flashing Yellow Arrow. *Transportation Research Board 2007 Annual Meeting CD-ROM Paper #07-2293*, TRB, Washington, D.C.

Lin, P.W., G. Thiagarajan, and D. Atie. 2008. Analysis of Drivers' Reaction to the Flashing Yellow Arrow Signal Design from Field Observation. In *Proceedings (CD-ROM) of the 15th World Congress on Intelligent Transport Systems and ITS America's 2008 Annual Meeting.* New York, NY, November 16–20, 2008.

National Highway Traffic Safety Administration (NHTSA). 1999. *Traffic Safety Facts 1998: A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System*. U.S Department of Transportation.

Noyce, D.A. 2003 (Aug.). Improving Left-Turn Safety Using Flashing Yellow Arrow Permissive Indications. In *Proceedings of the 2003 Mid-Continent Transportation Research Symposium*. Iowa State University, Institute for Transportation, Center for Transportation Research and Education. Ames, IA, August 21–23, 2003.

Noyce, D.A., C.R. Bergh, and J.R. Chapman. 2007a (Dec.). *Evaluation of the Flashing Yellow Arrow Permissive Left-Turn Indication Field Implementation.* Transportation Research Board of the National Academies, Washington, D.C.

Noyce, D.A., C.R. Bergh, and J.R. Chapman. 2007b. NCHRP Web-Only Document 123: *Evaluation of the Flashing Yellow Arrow Permissive-Only Left-Turn Indication Field Implementation*. Transportation Research Board of the National Academies, Washington, D.C.

Noyce, D.A., D.B. Fambro, and K.C. Kacir. 2003. Traffic Characteristics of Protected/Permissive Left-Turn Signal Displays. *Transportation Research Record: Journal of the Transportation Research Board No. 1708*, TRB, National Research Council, Washington, D.C.

Noyce, D.A., and C.R. Smith. 2003. Driving Simulators Evaluation of Novel Traffic-Control Devices: Protected-Permissive Left-Turn Signal Display Analysis. *Transportation Research Record: Journal of the Transportation Research Board No. 1844*, TRB, National Research Council, Washington, D.C.

Paniati, J.F. Interim Approval for Optional Use of Flashing Yellow Arrow for Permissive Left-turns (IA-10). FHWA Policy Memorandums. FHWA, Washington, D.C. March 20, 2006. http://mutcd.fhwa.dot.gov/resources/interim_approval/pdf/ia-10_flashyellarrow.pdf. Accessed June 6, 2011.

Perez, R.A. 2010 (Sep.). *Safety Implications of Conversions to Flashing Yellow Arrow Indications*. City of Federal Way, WA.

Pulugurtha, S.S., M. Agurla, and K.S.C. Khader. 2011 (Mar.). How Effective Are "Flashing Yellow Arrow" Signals in Enhancing Safety? In *Proceedings of Transportation and Development Institute Congress 2011*. Chicago, IL, March 13–16, 2011.

Qi, Y., P. Yuan, X. Chen, and M. Zhang. 2011. Safety of Flashing Yellow Arrow Indication with Protected-Permissive Left-Turn (PPLT) Operation. In *Proceedings of the Transportation Research Board 91st Annual Meeting*, TRB, National Research Council. Washington, D.C., January 22–26, 2012.

Qi, Y., M. Zhang, Y. Wang, and X. Chen. 2011. Safety Performance of Flashing Yellow Arrow Signal Indication. In *Proceedings of the Transportation Research Board 91st Annual Meeting,* TRB, National Research Council. Washington, D.C., January 22–26, 2012.

Rietgraf, A., 2013. *Evaluation of Alternative Left-turn Permissive Indications at Intersections with Protected / Permissive Left-turn Control in Peoria and Bloomington, Illinois.* M.S. Thesis, Bradley University, Peoria, IL.

Smith, D.L., and Najm, W.G. 2001. Analysis of Crossing Path Crashes for Intelligent Vehicle Applications. Paper No. ITS00533. In *Proceedings of the Eighth World Congress on Intelligent Transport Systems*. Sydney, Australia, October 2001.

Srinivasan, R., C. Lyon, B. Persaud, J. Baek, F. Gross, S. Smith, and C. Sundstrom. 2011. Crash Modification Factors for Changing Left-turn Phasing. *In Proceedings of the Transportation Research Board 91st Annual Meeting,* TRB, National Research Council. Washington, D.C., January 22–26, 2012.

Srinivasan, R., F. Gross, C. Lyon, B. Persaud, K. Eccles, A. Hamidi, J. Baek, S. Smith, N. Lefler, C. Sundstrom, and D. Carter. 2011. *NCHRP Report 705: Evaluation of Safety Strategies at Signalized Intersections*, Transportation Research Board of the National Academies, Washington, D.C.

Illinois Department of Transportation

ILLINOIS
UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN