NCHRP

REPORT 493

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Evaluation of Traffic Signal Displays for Protected/ Permissive Left-Turn Control

TRANSPORTATION RESEARCH BOARD
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Evaluation of Traffic Signal Displays for Protected/ Permissive Left-Turn Control

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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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Kittelson & Associates, Inc. (KAI) performed the research project reported herein under NCHRP Project 3-54 in association with Siemens Gardner Transportation Systems, the University of Massachusetts at Amherst (UMass), and the Texas Transportation Institute (TTI). The project was directed by Kent C. Kacir, formerly of KAI, now of Siemens Gardner Transportation Systems, as the Principal Investigator. Bill Kloos, also formally of KAI, now with the City of Portland, Oregon, also provided project direction as the Co-Principal Investigator. The other authors of this report are David A. Noyce, former Assistant Professor of Civil Engineering at the University of Massachusetts at Amherst, now Assistant Professor of Civil Engineering at University of Wisconsin-Madison, and Christopher L. Brehmer of KAI.

The work performed at Kittelson & Associates, Inc., was conducted under the direction of Kent Kacir. Wayne Kittelson, Senior Principal at KAI, served as the Project Principal. Chris Brehmer of KAI served as the Senior Engineer on the project. The work performed at UMass was conducted under the supervision of Dr. Noyce with the assistance of Michael A. Knodler Jr., Graduate Research Assistant. The work performed at TTI was conducted under the supervision of Roger J. Koppa, Associate Professor, with the assistance of Michael P. Manser, Associate Research Scientist, and Jacqueline Jenkins, Graduate Assistant Research. The authors wish to recognize the invaluable contributions of the late Daniel B. Fambro, Professor, TTI, who directed much of the study plan development of this research project. His insights and commitment to the project were significant to its success.

The project was guided by the panel members listed above, as well as the following technical advisors:

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FOREWORD

By B. Ray Derr
Staff Officer
Transportation Research Board

This report recommends traffic signal displays for protected/permissive left-turn control. The recommendations are based on a comprehensive evaluation of the safety and effectiveness of alternative traffic signal displays and phasing through laboratory and field studies. These studies are summarized in the report and detailed information on them is available on the enclosed CD-ROM, *CRP-CD-35*. Traffic signal designers and operators will find the report informative, as will those interested in human factors research. A key audience for the report will be those responsible for the *Manual on Uniform Traffic Control Devices* (MUTCD) because it is intended that the recommendations be considered for the next edition.

Protected/permissive left-turn (PPLT) traffic controls increase the left-turn capacity and reduce delay at intersections by providing an exclusive turn phase for left turns as well as a phase during which left turns can be made as opposing traffic will allow. The protected left turn can either lead (or precede) or lag (or follow) the opposing through signal phase. PPLT controls have been implemented in a variety of ways, because the MUTCD provides limited guidance. At least six displays to indicate the permissive phase are known to exist in the United States (i.e., straight five-section head with circular green, five-section cluster head with circular green, flashing circular red, flashing circular yellow, flashing red arrow, and flashing yellow arrow). Variations also exist in the phasing, signal displays, arrangement, signal placement, and use of supplemental signs. There have been concerns that some of these variations may confuse motorists, and validation of their relative operational and safety advantages was needed.

A key concern with PPLT control is the "yellow trap," which occurs during the change from permitted left turns in both directions to a lagging protected left turn in one direction. The MUTCD requires that all circular signal indications on an approach to an intersection display the same color. The left-turning driver whose permitted interval is ending may try to sneak through the intersection on the yellow indication, not realizing that the opposing through traffic still has a green indication. To avoid the yellow trap, most agencies do not use leading/lagging PPLT. An innovation known as "Dallas Display" allows this operation without the yellow trap by operating the permissive left turns simultaneously with the opposing through movement. Previous research has shown that this operation reduces delay and improves safety, but is not easily implemented in all situations.

Under NCHRP Projects 3-54 and 3-54(2), Kittelson & Associates and their subcontractors reviewed the literature and surveyed state and local transportation agencies to determine what displays are used for PPLT and the prevalance of each. They then assessed the safety and operational characteristics of each display qualitatively and analyzed crash data for a more quantitative assessment. Of particular interest was how the different displays handled the yellow trap. Surveys of drivers using both static photographs and video were conducted to better understand how well the various displays are comprehended. Following a meeting with the oversight panel to select the best displays for further study, driving simulator testing was used to gain a better understanding of driver comprehension in a dynamic environment. Because the research conducted pointed to the flashing yellow arrow as a promising display, pilot installations were made in several cities to determine how well it operates in real-life conditions and to identify implementation issues.

In the interest of brevity, this report presents only the highlights of a very comprehensive project. Working papers from the individual studies mentioned above are included on the enclosed CD-ROM, *CRP-CD-35*.

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EVALUATION OF TRAFFIC SIGNAL DISPLAYS FOR PROTECTED/ PERMISSIVE LEFT-TURN CONTROL

SUMMARY

The NCHRP 3-54 Project is the culmination of extensive research efforts to identify the "best" traffic signal display for protected/permissive left-turn (PPLT) control. The research efforts respond to decades of practice wherein practitioners have experimented with various displays and signal phasing schemes that either avoided—by design—safety problems (e.g., yellow trap) or attempted to convey a clearer message to the driver on the correct right-of-way (i.e., permissive movement).

Conducted over a 7-year period, the NCHRP 3-54 project is the most comprehensive study of the PPLT display to date. The research team members surveyed current practice, studied driver understanding of known permissive displays in the United States, analyzed crash data, analyzed operational data, studied the implementation of an experimental permissive display, and conducted a confirmation study using a full-scale driving simulator to study driver understanding of the most promising permissive displays.

Unlike previous research, the NCHRP 3-54 study focused heavily on human factors and the techniques used to observe human reactions. Previous studies typically relied on crash data to indicate how well drivers understood one display compared with other displays or traffic control devices. However, crash data generally are unreliable for assessing driver reaction to different displays because the level of detail of individual crash reports typically does not identify the traffic signal control indications illuminated at the time of the crash.

The NCHRP 3-54 study used modern techniques to present visual images or interactive situations whereby human reaction could be evaluated independently. Each of the 14 individual study tasks was successful in gathering pertinent data. The study task results and findings led the research team to develop a concise set of recommendations. Additionally, many findings from this study will lead to safer implementations of PPLT control. For example, this study identified how well drivers understand multiple indications illuminated at the same time within the same display arrangement. How adjacent signal display indication (e.g., through movement) affects drivers' interpretations of the left-turn display indications was also identified. Further, differences in drivers' reactions to flashing indications versus steady indications were explored and documented.

RESEARCH PROBLEM STATEMENT

The increase in traffic volume on urban roadways has led engineers to develop innovative means to control traffic. With an increase in traffic volume, a driver has fewer available gaps in the opposing through traffic to execute a left-turn maneuver safely. To alleviate this situation, signal phasing was designed to provide a protected left-turn phase for part of the signal cycle. The resulting increase in safety came at the expense of operational efficiency.

To regain some of the lost efficiency, traffic signals were designed to protect the left-turn movement during a portion of the signal cycle and to allow a permissive movement during the remainder of the signal cycle, resulting in left-turn control that is commonly known as protected-permissive left-turn control, or simply PPLT control (or phasing). If a protected movement is warranted, PPLT control has been shown to increase left-turn capacity and reduce delay at intersections (as compared with protected-only control) by providing an exclusive turn phase for left turns as well as a permissive phase during which left turns can be made if gaps in opposing through traffic will allow, all within the same cycle. The left-turn phase (interval) can precede (lead) or follow (lag) the through phase.

PPLT Displays

Over the years, PPLT control has been implemented in various ways. Variability occurs in signal display arrangement, placement, and permissive indications. The variance in implementation has been consistent with the *Manual on Uniform Traffic Control Devices* (MUTCD) because, historically, the manual provided limited guidance. The Federal Highway Administration (FHWA) recommends a five-section signal display. Consistent with the FHWA's recommendation, many states have adopted the five-section cluster or "doghouse" signal display arrangement as their standard. The five-section cluster is located in a shared overhead position, between the through and turning lanes, providing a green arrow indication for the protected phase and a circular green indication for the permissive phase. The circular green indication is shared with the through movement.

Several transportation agencies within the United States have designed and implemented unique PPLT phasing displays with the intent to convey a clearer message of drivers' left-turn control. Several unique displays have been implemented as experimental traffic control devices with approval by FHWA. To date, at least five variations of the permissive indications are in use in the United States: the MUTCD standard circular green indication; the flashing circular red indication, the flashing circular yellow indication, the flashing red arrow indication, and the flashing yellow arrow indication.

Lead-Lag Phasing with PPLT Control

The left-turn phase can lead or lag the opposing through movement. Traffic engineers often would like to increase operational efficiency on roadways by using lead-lag signal phasing, but cannot safely do so if PPLT control is used. The MUTCD does not preclude the use of lead-lag left turns with PPLT control; however, doing so will create what is known as the "yellow trap." The yellow trap condition essentially leads the left-turning driver into the intersection when it is unsafe to do so, even though the signal displays are correct. During the signal change from permissive movements in both directions to a lagging protected movement in one direction, a yellow trap is presented to the left-turning driver whose permissive left-turn phase is terminating. The yellow trap occurs when a signal changes from the permissive left-turn intervals in both directions to a lagging protected movement in only one direction. A driver attempting to make a left turn on the permissive circular green indication becomes trapped in the intersection when the circular green indication turns yellow for the change interval (for the through traffic). The left-turn driver who is attempting to clear the intersection sees the adjacent through lanes receive the circular yellow indication for their change interval. The left-turner mistakenly believes that the opposing traffic also has the yellow change interval and so makes the left turn, in effect becoming a "sneaker." The yellow trap occurs because the opposing traffic does not, in fact, receive a yellow change interval, but instead has a circular green indication in the through lanes and a protected left-turn arrow indication. The potential for serious conflict occurs between the sneaker vehicle and the opposing, non-stopping, through traffic.

To avoid the hazardous yellow trap situation, traffic engineers use either simultaneous leading (lead-lead) or lagging (lag-lag) left-turn phasing. With lead-lead (protected-permissive) left-turn phasing, both left-turn phase indications are initially illuminated together. With most modern signal controllers, if the left-turn demand diminishes on one side, the opposing through-lane traffic can proceed concurrently with the remaining left-turn phase movement traffic. Conversely, for lag-lag (permissive-protected) left-turn phasing, both left-turn phase indications may not be illuminated together; however both left-turn phases must also terminate together. The lag-lag left-turn phasing results in a potential decrease in capacity and increase in delay. For both the protected-permissive (lead-lead) and permissive-protected (lag-lag) signal phasing operation, the permissive left-turn circular green indication can be illuminated for the through movement and the left-turn movement. The driver making the left-turn movement may proceed if there is an acceptable gap in the opposing traffic stream. The lead-lead and lag-lag signal phasing operation has been in use for many years.

Since approximately the mid-1980s, some traffic engineers have implemented an innovative signal phasing operation known as the "Dallas Display." The Dallas Display permits phase overlaps and was designed to eliminate the potentially unsafe yellow trap situation by allowing a continued permissive left-turn during the opposite approach leading and lagging protected left-turn phase. The Dallas Display advances traffic engineers' ability to maximize signal coordination by allowing protected-permissive and lead-lag operation within the same signal cycle.

NEED FOR RESEARCH

Traffic engineers have long cited the advantages of implementing PPLT control (e.g., improved operational efficiency and traffic progression, reduced vehicle delay, reduced fuel consumption, and reduced air pollution). The disadvantage, some argue, is that PPLT control can be deployed in such a way that the yellow trap is created, and there is potential for driver confusion. Nevertheless, many practicing agencies have found the advantages to outweigh the potential disadvantages. Additionally, several agencies in the United States have deployed various types of signal phasing techniques to avoid the yellow trap and/or resolve the potential driver confusion problem. Over the past two decades (in some limited cases, three decades), some agencies have been granted approval from FHWA to implement unique displays, or display arrangements, on an experimental basis. The premise for these implementations was the potential for a safer or more efficient traffic control device. Examples of these unique displays are the flashing red and flashing yellow circular and arrow indications.

The National Committee on Uniform Traffic Control Devices (NCUTCD), which provides guidance to the FHWA on the MUTCD, has expressed concern that the variety of PPLT controls currently in use may confuse drivers traveling throughout the United States and has long proposed a comprehensive national study that would validate the operational advantages and safety aspects of the various PPLT control devices and signal arrangements.

NCHRP 3-54 RESEARCH OBJECTIVE

The objective of the NCHRP 3-54 project was to evaluate the safety and effectiveness of different signal displays and phasing for PPLT control through laboratory and field studies. Study activities were designed to gather, analyze, and interpret data that would serve as the basis for recommending a uniform display for PPLT control. The study considered all current applications of PPLT control in the United States, including arrangement, indications, placement, phasing sequence, and safety considerations (e.g., the yellow trap).

NCHRP Project 3-54 did not develop any guidelines, warrants, or recommendations for the use of PPLT control. The underlying assumption was that the traffic engineer had decided that PPLT control is an appropriate left-turn treatment. The goal of this research project was to identify the “best” or most appropriate signal display, including arrangement and indications.

RESEARCH PLAN

NCHRP Project 3-54 consisted of individual study tasks as identified in Figure S-1. In October of 1999, the research team and project panel met to review the study PPLT displays and to determine which displays showed the most potential. As part of the meeting, several decisions were made, including the decision to reduce the number of displays to those with the most potential for further study. Additionally, the project panel directed the research team to conduct a thorough evaluation of one particular display through field implementation. Brief descriptions of the key study activities follow. (Chapter 3 provides detailed information on each study task.)

Identify Technical Advisors

Before beginning the formal study effort, potential members of a Technical Advisory Group were sought. The Technical Advisory Group was to consist of at least five knowledgeable professionals who would provide the project panel with first-hand experience and expertise in the evaluation of PPLT signal displays. Members of the advisory group were to be well-respected and experienced traffic engineers knowledgeable about the PPLT issue. The research team also sought regular interaction with the Signals Technical Committee of the NCUTCD to provide a regular flow of information to the full committee.

Agency Survey

To assess the current state of the practice, the research team conducted an extensive literature review to investigate the state of the art in PPLT display. Both published and unpublished literature was evaluated, including literature from international sources.

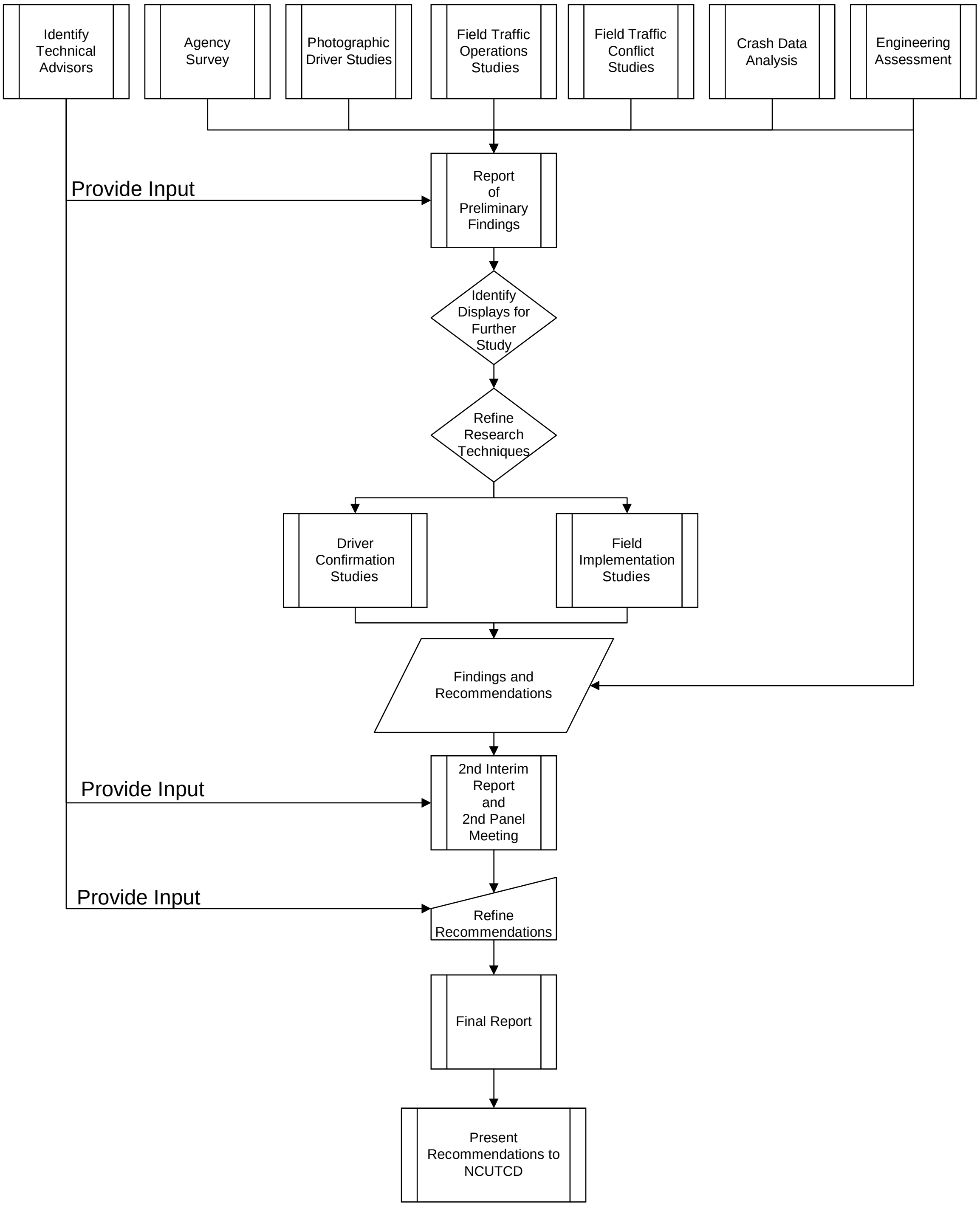


Figure S-1. Final work plan.

This task also included the administration of a survey of transportation agencies to solicit information regarding the number and type of left-turn traffic control devices in use across the United States. The objective of the agency survey was to identify and quantify the different types of PPLT displays in use. The survey was administered to transportation professionals at the state and city levels who were directly involved with PPLT design and installations. Data on PPLT installations in all 50 states and parts of Canada were obtained.

The significant findings of the agency survey are as follows:

- Nearly 110,000 traffic signals in the United States (29% of all signals in the United States) have at least one approach with PPLT operation.
- In 34 of the 50 states, the five-section cluster PPLT display is used most, with 41% of the states reporting the use of only one PPLT as the state standard. Specifically, 63% of all PPLT displays are the five-section cluster display.
- A total of 40% of the responding agencies always use the PPLT display for one of the two required through movement displays, and another 37% sometimes do.
- A total of 50% of the reporting agencies use supplemental displays (e.g., additional pole-mounted display on the far left side of the intersection); therefore the left-turn display can be visible to the through motorist.
- The circular green PPLT indication was used in 165 of the 168 reporting agencies. Other indications used were flashing circular red, flashing red arrow, flashing circular yellow, and the flashing yellow arrow.

Photographic Driver Studies

Photographic driver studies evaluated driver understanding of the circular green, flashing yellow arrow, flashing circular yellow, flashing red arrow, and flashing circular red permissive displays in association with different arrangements, placements, and traffic/lane configurations. Computer-generated PPLT signal displays on static background photographs were used to represent the dynamic aspects of the PPLT displays. More than 300 drivers participated in each of eight geographic locations around the United States. All study participants were licensed drivers.

The following findings were key to refining the research plan and developing recommendations:

- Simultaneous illumination of two display indications significantly reduced driver understanding.
- The circular green indication had the lowest level of driver comprehension (nearly 50%) of all PPLT displays studied.
- The through indication had little effect on driver comprehension of the left-turn PPLT indication.
- Age had a significant effect on driver comprehension. In at least one PPLT scenario, drivers over the age of 65 only responded correctly 20% of the time. Older drivers responded more correctly to the flashing circular red and yellow indications.
- Flashing indications were understood better than steady indications, as evidenced by overall time to respond to the indication in question.
- The circular indication was better understood when compared with arrow indications.
- The red indications were understood better than the other displays studied.

Field Traffic Operations Studies

The operations studies consisted of quantifying the capacity and delay associated with various PPLT displays by analyzing saturation flow rates, lost times, response times, and follow-up headways. The traffic studies were completed in the same eight geographic locations in which the photographic driver studies were conducted to provide additional insights into driver behavior related to alternative PPLT displays. As part of this effort, the research team worked with local traffic engineers to identify representative sites with PPLT displays and to then gather crash, traffic, geometry, and other relevant data for each site. More than 8 hr of conflict data per intersection were collected at three intersections within each geographic study area.

This work activity identified that study location was a significant factor, but that PPLT signal display arrangement and phasing was not a significant factor affecting the saturation flow rate. Additionally, this work activity showed that signal phasing significantly influenced the start-up lost time, but that PPLT signal display arrangement or study location did not.

Field Traffic Conflict Studies

The traffic conflict studies focused solely on the left-turn movement. Conflict studies were completed in the same eight geographic locations as the photographic driver and field traffic operations studies. The purpose of these studies was to quantify left-turn conflict rates and event rates for different PPLT signal displays and indications. The conflict studies involved the collection and analysis of 8 hr of conflict data on a typical weekday at 24 study intersections. At each intersection, traffic conflicts were observed and classified into one of six types.

The conflict analysis study task showed that, overall, traffic conflicts were low for all PPLT displays evaluated, and few left-turn conflicts were associated with the PPLT display.

Crash Data Analysis

The research team conducted a review of crash data to determine and compare left-turn crash rates associated with various PPLT displays. In addition, selected components of a crash database created in 1988 as part of an FHWA study were examined.

The crash analysis showed that, based on (1) the average crash rate per year and (2) average crashes per 100 left-turning vehicles, the four-section flashing circular yellow indication used in Seattle, Washington, experienced the fewest number of crashes per year. The analysis of the average crash rate by intersection indicated that the flashing red arrow used in Cupertino, California, had the lowest average crash rate. The circular green indication had the highest average statistic in three of the four evaluations studied and reported above.

Ultimately, the crash data analysis did not identify any safety problems among the PPLT displays studied. The data showed that the flashing circular yellow indication typically had the lowest (best) statistic and the circular green indication (MUTCD standard) had the highest (worst) statistic.

Engineering Assessment

The engineering assessment sought to identify the objective and subjective information needed to evaluate the proposed displays. To assist the assessment, an evaluation matrix was developed. The evaluation matrix included considerations addressing the key issues of safety, operations, implementation, human factors, and versatility and was updated as each study activity was completed.

The engineering assessment was conducted continuously over the course of the study. At the conclusion of the research tasks discussed above, the research team made the following assessments:

- The flashing yellow arrow and the circular green indication can be used in both exclusive and shared PPLT signal displays, whereas the flashing yellow circular indication and flashing red arrow indications can only be used in an exclusive PPLT display.

- The flashing yellow arrow indication and circular green indication present the best displays for further study.

Report of Preliminary Findings

Using the data collected to date, the research team prepared a comprehensive analysis of the results obtained from the agency evaluation, photographic driver studies, conflict studies, and crash studies. This information was presented to the members of the project panel, who in turn reviewed the findings and ultimately reduced the number of PPLT displays for future consideration. In addition to selecting a subset of promising PPLT displays to be studied further, the project panel provided direction to complete the confirmation study and to conduct a field implementation study.

Driver Confirmation Studies

Before the research team could make a firm recommendation on a “best” display to be used as a national standard, the research team conducted a confirmation study whereby human subjects (drivers) were tested in a full-scale simulator. The confirmation study evaluated 12 PPLT signal display scenarios, each with a different permissive indication, display face, location, and through movement indication. Each of the PPLT signal displays included only the circular green indication and/or flashing yellow permissive indications. Two separate confirmation studies were conducted—one at the University of Massachusetts and one at the Texas A&M University. The two confirmation studies were created to be near identical, within the practical budget limits of the study.

The driver confirmation study demonstrated the following:

- There was a high level of comprehension with no variation between the different PPLT displays tested.
- The data showed no statistical difference in driver comprehension when the data were cross-analyzed by permissive indication, display arrangement, through indication, and/or location of the display.
- Males and females had statistically equivalent levels of comprehension.
- Drivers over the age of 45 had significantly fewer fail-critical responses than those 45 and younger.
- Drivers who drive between 10,000 and 20,000 miles per year had significantly more responses that were correct and significantly fewer fail-critical responses than those who drove fewer than 10,000 miles per year.
- The level of education that the drivers possessed did not have a significant effect on comprehension.
- PPLT displays with the four-section vertical display face resulted in a significantly greater number of correct responses compared with the five-section vertical and five-section cluster display arrangements.
- The location of the PPLT signal display did not result in statistically significant differences.

Field Implementation Studies

An experimental flashing yellow arrow display was field tested because it had shown promise from both safety and driver comprehension perspectives in previous task activities and had ranked high in the Engineering Assessment. Volunteer agencies were sought from across the United States to install and operate the experimental flashing yellow arrow display. In conjunction with the use of the experimental display (which required permission from FHWA to operate), "before" and "after" studies were completed at each intersection where the flashing yellow arrow display was installed and at nearby control sites. These "before" and "after" studies allowed the research team to quantify the impact of the changeover from the MUCTD circular green indication to the flashing yellow arrow indication.

The flashing yellow arrow indication was implemented in the following six U.S. jurisdictions:

- Montgomery County, Maryland;
- Tucson, Arizona;
- Woodburn, Oregon;
- Jackson County, Oregon;
- Beaverton, Oregon; and
- Broward County, Florida.

With the exception of the PPLT display implemented in Tucson, Arizona, all PPLT displays were implemented with few problems and remain operational as of the date of this report. As explained in greater detail in Chapter 3, the PPLT display implemented in Tucson, Arizona, was removed from operation because of safety concerns expressed by city management. For each of the 15 intersections under study, only the PPLT display was changed from the MUTCD standard circular green indication to the flashing yellow arrow display.

Findings of the field implementation study include the following:

- Review of before and after field conflict data showed no differences attributable to the change in the PPLT display.
- Before and after observations of follow-up headway and flow rate data for the study and control intersections demonstrated that the change in PPLT display had negligible impact.
- The implementation study demonstrated that the flashing yellow arrow display can be field implemented (albeit with minor issues) using existing traffic control hardware and software. Technical implementation issues identified during the field implementation process could be dealt with appropriately in any future developments of hardware and/or software, should the flashing yellow arrow display become a standard.
- Traffic engineers who participated in the implementation study (and those who declined participation) generally expressed their approval of the flashing yellow arrow display because of the following:
  - It provides an exclusive signal display for the left-turn control.
  - The indication was flashing, which attracted more attention.
  - The indication provided enhanced operation control.
- Public comments from citizens who experienced the flashing yellow arrow display in the field were generally positive. Several implementing agencies reported

receiving e-mails or written letters from the motoring public with most, if not all, in support of the flashing yellow arrow display.

Engineering Assessment (Update)

At the completion of the driver confirmation studies and the field implementation studies, the research team reviewed the engineering assessment findings to reflect current data. The final findings are reported below:

- The flashing yellow arrow display was shown to offer the highest level of safety.
- The circular green indication using the Dallas Display and the flashing yellow arrow display was shown to rank "best" in the category of operations.
- The circular green indication was shown to rank "best" as being implementable.
- The flashing yellow arrow display was shown to be the "best" in the category of human factors.
- The flashing yellow arrow display was shown to have the most versatile characteristics and the circular green indication was the least versatile.

RECOMMENDATIONS

Based on the results and findings of the various research activities, the research team and the project panel identified the following three recommendations:

<u>Recommendation 1:</u> **The flashing yellow arrow display should be included in the MUTCD as an allowable alternative display to the circular green indication when used in PPLT control/operation.**

Displays. The four-section, all-arrow display face should be the only display allowed.

The only display that justifies an exception to this recommendation is the three-section display face with bi-modal lens. The three-section display face with bi-modal lens should also be allowed given that it operates the same as does the four-section display face. Only one indication shall be illuminated at any time.

Location. The flashing yellow arrow operation shall only be used in an exclusive signal arrangement. It is recommended, but not required, that the left-turn signal face be placed over the left turn lane.

Supplemental Signs. Supplemental signing is not warranted with flashing yellow arrow display. Use of supplemental signing is optional.

Phasing. When used for left-turn treatments, the flashing yellow arrow display shall be tied to the opposing through green indication/display.

<u>Recommendation 2:</u> **Conduct Follow-Up Study**

It is recommended that a follow-up study to this project be conducted. The follow-up study should be conducted after there has been ample time for an implementation trial period by agencies currently participating in the field implementation as well as other potential additional agencies that may choose to implement based on the findings of this research effort. Sufficient time should also be allowed such that before and after crash data can be acquired at the study intersections and corresponding control sites.

The follow-up study should

- Analyze all available crash data for the experimental flashing yellow arrow displays implemented as part of this study;
- Identify whether the flashing yellow arrow display should become the only display allowed in the MUTCD for PPLT operation;
- Identify whether, if the flashing yellow arrow is selected to become the only display allowed for PPLT, the MUTCD should also be changed to add the following prohibition: "For Permissive Only Mode operation, a signal face displaying a circular green indication shall not be located directly over or in line with a left-turn lane"; and
- Identify an implementation plan.

Recommendation 3: Restrict Use of Flashing Red Indications

The use of the flashing red indication should only be implemented at locations where an engineering study has identified that all drivers must come to a complete stop before proceeding on the permissive interval.

PROJECT FINDINGS SUMMARY

Figure S-2 illustrates the flow of work activities and the relevant findings that lead to the study recommendations.

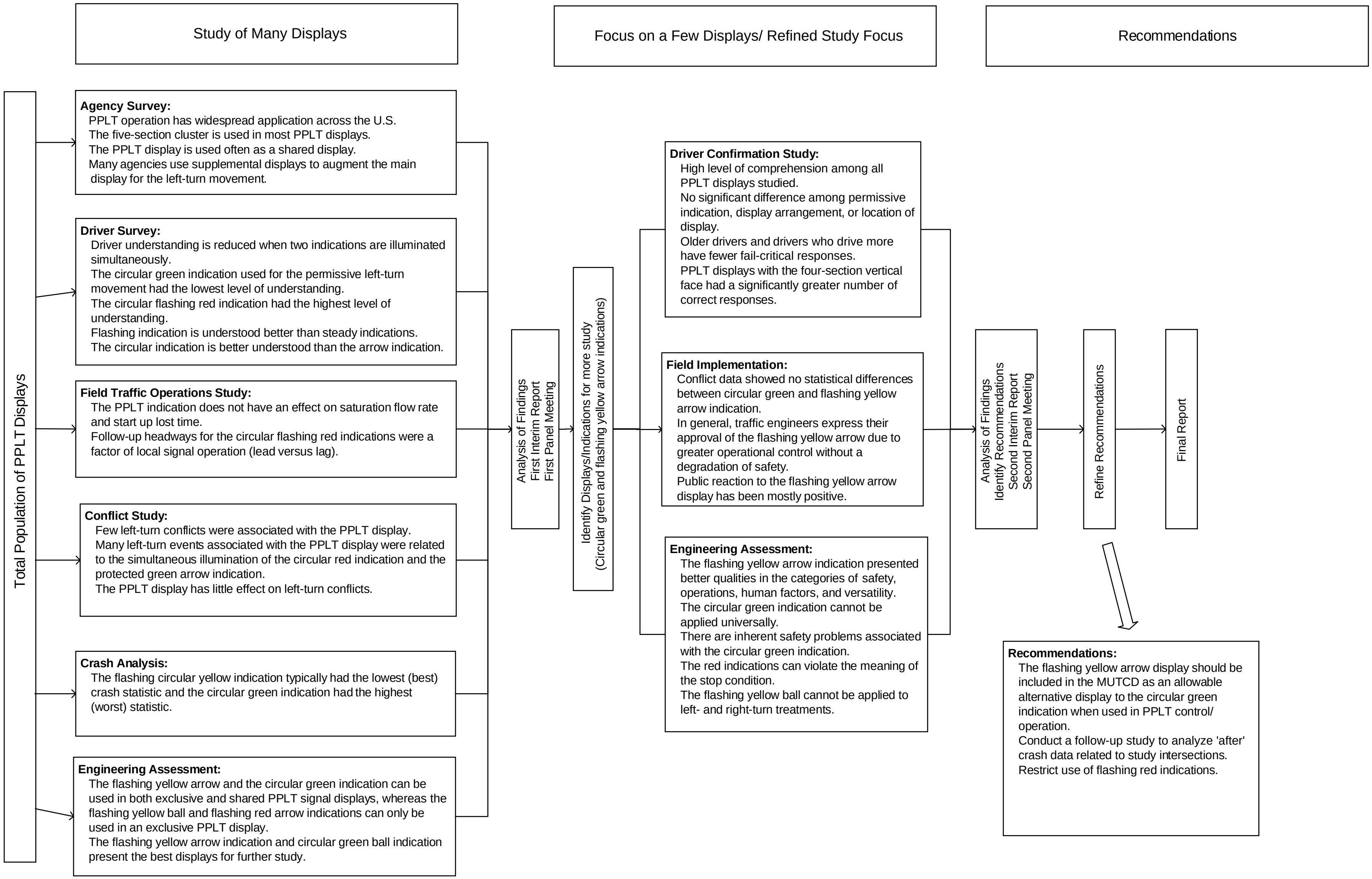


Figure S-2. Work flow of activities and findings that led to the development of recommendations.

DEFINITIONS

The following list of definitions is intended to clarify the manner in which they are used in this report. Some of the terms listed may not appear in this document. The research team has attempted to use terminology consistently throughout this final report and in the various working papers documenting the detailed progression of the project; however, there has been a change in direction within the industry and, in particular, within the National Committee on Uniform Traffic Control Devices regarding terminology.

Change Interval: The yellow change interval follows the green interval to warn traffic of an impending change in the right-of-way assignment. The yellow change interval may be followed by a red clearance interval.

Cluster Arrangement: Cluster arrangement refers to a particular arrangement of signal indications where four of them are clustered in the form of a square, and the fifth signal indication (circular red) is mounted directly on the top, either centered or off to one side.

Cycle Length: See signal cycle.

Dallas Display: Also called Dallas Phasing. Also call Permissive Lead-Lag. A unique signal operation designed to eliminate the “yellow trap” situation by allowing a continued permissive left-turn during the opposite approach lagging protected left-turn phase. In order to accomplish this, a left-turn circular green indication is displayed, in an exclusive display, during the adjacent through movement green and yellow indications and continues to be displayed during the lagging protected left-turn green arrow and through circular green (or straight green arrow) indications for the opposite approach. The continuing circular green left-turn indication is terminated by a circular yellow indication that is simultaneously displayed with the opposing through movement yellow clearance. This type of operation requires the use of visibility-limited (e.g., louvered) signal faces to shield the circular green and yellow indications intended for the left-turn lane traffic from the adjacent through traffic.

Display: The signal face as a unit (assembly) that conveys the message to the driver. The display consists of the individual section, regardless of configuration. Historically, this term has been used in reference to the signal head.

Display Face: The part of a signal head provided for controlling traffic in a single direction. Same as “signal face” and “display.”

Doghouse: See cluster arrangement.

Exclusive Display: A display on a single approach for controlling only the left-turn movement.

FHWA: Federal Highway Administration

Horizontal Arrangement: A particular arrangement of signal indications in a horizontal position. This term is the same as the horizontal display face in the MUTCD.

Interval: A discrete portion of the signal cycle during which the signal indications remain unchanged.

Lagging Left Turn: A phase sequence in which a protected left-turn phase follows the opposing through-movement phase.

Lead Left Turn: A phase sequence in which a protected left-turn phase precedes the opposing through-movement phase.

Lead-Lead Left Turn: Also called dual leading left turns. Indicates a phase sequence in which two left-turn movements from opposite directions of a roadway are both served by leading protected phases. When both streets at the intersection are serviced in this manner, the operation is referred to as quad left-turn phasing.

Lead-Lag Left Turn: A phase sequence in which one left-turn movement is served by a leading protected phase and the other left-turn movement (from the opposite direction of the same street) is served by a lagging protected phase.

Lag-Lag Left Turn: A phase sequence in which two left-turn movements from opposite directions of a street are both served by lagging protected phases.

MUTCD: *Manual on Uniform Traffic Control Devices*

NCUTCD: National Committee on Uniform Traffic Control Devices

Permissive Mode: A mode of traffic control signal operation in which left or right turns may be made on a circular green signal indication after yielding to oncoming traffic and pedestrians.

Phase: A part of the traffic signal time cycle allocated to any combination of traffic movements receiving right-of-way simultaneously during one or more intervals.

Phase Sequence: The order in which a controller cycles through all phases.

Preemption: The term used when the normal signal sequence at an intersection is interrupted or altered in deference to a special situation such as the passage of a train, a bridge opening, or the granting of the right-of-way to an emergency vehicle.

Protected Mode: A mode of traffic control signal operation in which left or right turns may be made when a left or right green arrow signal indication is displayed.

Protected/Permissive Mode: A mode of traffic signal operation in which the left-turn movement is presented during both the protected mode and the permissive mode on an approach during the same signal cycle.

In this report, the term protected/permissive does not necessarily imply a particular phasing order (i.e., protected/permissive or permissive/protected). In practice, the phase sequence is important.

Protected Permissive Left-Turn Display: Also referenced as PPLT display. This term is used to reference specifically or generically the indication or display used in conjunction with protected permissive left-turn control.

Protected Permissive Left-Turn Control: Also referenced as PPLT control or PPLT operation. This term is used to identify the signal operation that uses protected permissive signal phasing.

Shared Display: A signal display is considered to be a shared display when it constitutes one of the two required displays for the through movement and provides the left-turn movement indication.

Signal Cycle: The total time required to complete either one sequence of signal phases at a signalized intersection with pretimed operation or a sequence of those phases with traffic demand at a signalized intersection with traffic-actuated operation.

Signal Display Arrangement: The signal arrangement as a unit (assembly) that conveys the message to the driver. The display arrangement consists of the individual sections, regardless of configuration. Historically, this term has been used in reference to the signal head.

Signal Face: The part of a signal head provided for controlling traffic in a single direction. This is the same as a display face.

Signal Head: Historically, this term has referred to an assembly containing one or more signal faces that may be designated as one-way, two-way, and so forth. See also signal display or signal display arrangement.

Signal Indications: The illumination of a signal lens, such as the circular green indication.

Signal Lens: The part of a signal section through which light from the light source or reflectors passes. In doing so, light is directed into a prescribed pattern, is filtered to a prescribed color, and, where necessary, is provided with a prescribed symbol or message.

Signal Section: The assembly of a housing, lens, and light source with necessary components and supporting hardware providing one signal indication.

Signal System: Two or more traffic control signals operating in coordination.

Vertical Arrangement: A particular arrangement of signal indications in a vertical position. This term is the same as the vertical display face in the MUTCD.

Yellow Trap: A situation where the driver sees a yellow indication for a change interval in the left-turn signal face and the adjacent through signal face and assumes that the opposing traffic also receives the yellow change interval.

CHAPTER 1

INTRODUCTION

This report is the culmination of extensive research efforts to identify the "best" traffic signal display for protected/permissive left-turn (PPLT) control. The research efforts respond to decades of practice whereby practitioners have experimented with various displays and signal phasing schemes that either avoided—by design—safety problems (e.g., yellow trap) or attempted to convey a clearer message to the driver on the correct right-of-way (i.e., permissive movement).

Conducted over a 7-year period, the NCHRP 3-54 study is the most comprehensive study of the PPLT display to date. In the course of the study, the research team has surveyed current practice, studied driver understanding of known permissive displays in the United States, analyzed crash data, analyzed operational data, studied the implementation of an experimental permissive display, and conducted a confirmation study using a full-scale driving simulator to study driver understanding of the most promising permissive displays.

Unlike previous research, the NCHRP 3-54 study focused on human factors and the techniques used to observe human reactions. Previous studies typically relied on crash data to indicate how well drivers understood one display compared with other displays or traffic control devices. However, crash data are generally unreliable for assessing driver reaction to different displays because the level of detail of individual crash reports typically does not identify the traffic signal control indications illuminated at the time of the crash.

The NCHRP 3-54 study used modern techniques to present visual images and interactive situations whereby human reaction could be independently evaluated. As detailed in Chapter 3 of this report, 14 individual study tasks were completed, and each produced useful data. Through analysis and review of the study task results and findings, the research team was able to develop a concise set of recommendations. Additionally, many findings that have come from this study will lead to safer implementations of PPLT control. For example, this study has identified how well drivers understand multiple indications illuminated at the same time within the same display arrangement. The effects of adjacent signal display indication (e.g., through movement) as they relate to driver interpretation of the left-turn display indications were also identified. Further, differences in driver reactions to flashing indications versus steady indications were explored and documented.

As previously mentioned, this report is a culmination of many tasks conducted over several years. Each major study task was documented by a working paper. The reader is encouraged to review the various working papers contained as appendixes to this report and provided on the accompanying CD-ROM for the task design, results, and findings.

The remainder of this chapter discusses the research problem statement, the need for more research, the objective of the research project, the development of the research plan, and an overview of study tasks completed in conjunction with the overall study.

RESEARCH PROBLEM STATEMENT

The increase in traffic volume on urban roadways has led engineers to develop innovative means to control traffic. With an increase in traffic volume, a driver has fewer available gaps in the opposing through traffic to execute a left-turn maneuver safely. To alleviate this situation, signal phasing was designed to provide a protected left-turn phase for a portion of the signal cycle. The resulting increase in safety came at the expense of operational efficiency.

To regain some of the lost efficiency, traffic signals were designed to protect the left-turn movement during a portion of the signal cycle and allow a permissive movement during the remainder of the signal cycle, thereby resulting in left-turn control that is commonly known as protected-permissive left-turn control, or simply PPLT control (or phasing). If a protected movement is warranted, PPLT control has been shown to increase left-turn capacity and reduce delay at intersections (as compared with protected-only control) by providing an exclusive turn phase for left turns as well as a permissive phase during which left turns can be made if gaps in opposing through traffic will allow, all within the same cycle. The left-turn phase (interval) can precede (lead) or follow (lag) the through phase.

PPLT Displays

Over the years, PPLT control has been implemented in various ways. Variability occurs in signal display arrangement, placement, and permissive indications. The variance in implementation has been consistent with the *Manual on Uniform Traffic Control Devices* (MUTCD) because the manual historically provided limited guidance (*1*). The FHWA recommends a five-section signal display (*2*). Consistent with the FHWA's recommendation, many states have adopted the five-section cluster or "doghouse" signal display arrangement as their standard. The five-section cluster is located in a shared overhead position typically between the through and turning lanes, providing a green arrow indication for the protected phase and a circular green indication for the permissive phase. The circular green indication is shared with the through movement.

Several transportation agencies in theUnited States have designed and implemented unique PPLT phasing displays so as to convey more clearly drivers' left-turn control. Several unique displays have been implemented as experimental traffic control devices with approval by FHWA. To date, at least five variations of the permissive indications are in use in the United States: the MUTCD standard circular green indication; the flashing circular red indication, the flashing circular yellow indication, the flashing red arrow indication, and the flashing yellow arrow indication. Figure 1-1 illustrates the various permissive display indication and display arrangements that have been or are in use in the United States. Chapter 3 of this report provides a detailed discussion of the PPLT displays shown in Figure 1-1.

Lead-Lag Phasing with PPLT Control

The left-turn phase can lead or lag the opposing through movement. Traffic engineers often want to increase operational efficiency on roadways by using lead-lag signal phasing but cannot safely do so if PPLT control is used. The MUTCD does not preclude the use of lead-lag left turns with PPLT control; however, doing so will create what is known as the "yellow trap." The yellow trap condition essentially leads the left-turning driver into the intersection when it may not be safe to do so, even though the signal displays are correct. During the signal change from permissive movements in both directions to a lagging protected movement in one direction, a yellow trap is presented to the left-turning driver whose permissive left-turn phase is terminating. Figure 1-2 illustrates how the yellow trap occurs.

As shown in Figure 1-2, the yellow trap occurs when a signal changes from the permissive left-turn intervals in both directions to a lagging protected movement in only one direction. A driver attempting to make a left turn on the permissive circular green indication becomes trapped in the intersection when the circular green indication turns yellow for the change interval (for the through traffic). The left-turn driver who is attempting to clear the intersection sees the adjacent through lanes receive the circular yellow indication for their change interval. The left-turning driver mistakenly believes that the opposing traffic also has the yellow change interval and so makes the left turn, in effect becoming a sneaker. The yellow trap occurs because the opposing traffic does not, in fact, receive a yellow change interval but instead has a circular green indication in the through lanes and a protected left-turn arrow indication. The potential for serious conflict occurs between the sneaker and the opposing, non-stopping, through traffic.

To avoid the hazardous yellow trap situation, traffic engineers use either simultaneous leading (lead-lead) or lagging (lag-lag) left-turn phasing. With lead-lead (protected-permissive) left-turn phasing, both left-turn phase indications are initially illuminated together. With most modern signal controllers, if the left-turn demand diminishes on one side, the opposing through-lane traffic can proceed concurrently with the remaining left-turn phase movement traffic. With lag-lag (permissive-protected) left-turn phasing, both left-turn phase indications may not be illuminated simultaneously; however both left-turn phases must always terminate simultaneously. The lag-lag left-turn phasing results in a potential decrease in capacity and increase in delay. For both the protected-permissive (lead-lead) and permissive-protected (lag-lag) signal phasing operation, the permissive left-turn circular green indication can be illuminated for the through movement and the left-turn movement. The driver making the left-turn movement may proceed if there is an acceptable gap in the opposing traffic stream. The lead-lead and lag-lag signal phasing operation has been in use for many years.

Since approximately the mid-1980s, some traffic engineers have implemented an innovative signal phasing operation known as the "Dallas Display." The Dallas Display permits phase overlaps and was designed to eliminate the potentially unsafe yellow trap situation by allowing a continued permissive left-turn during the opposite approach leading and lagging protected left-turn phase. The Dallas Display advances traffic engineers' ability to maximize signal coordination by allowing protected-permissive and lead-lag operation within the same signal cycle. Research has shown that the Dallas Display is operationally efficient and minimizes delay while maintaining safety (*3*).

Traffic engineers have long cited the advantages of implementing PPLT control, such as improved operational efficiency and traffic progression, reduced vehicle delay, reduced fuel consumption, and reduced air pollution. The disadvantage, some argue, is that PPLT control can be deployed in such a way that the yellow trap is created, thereby causing potential driver confusion. Nevertheless, many practicing agencies have found the advantages to outweigh the disadvantages. Additionally, several agencies in the United States have deployed various types of signal phasing techniques to avoid the yellow trap, resolve the potential driver confusion problem, or both. Over the past two decades (in some limited cases, three decades), some agencies have been granted approval from FHWA to implement unique displays or display arrangements

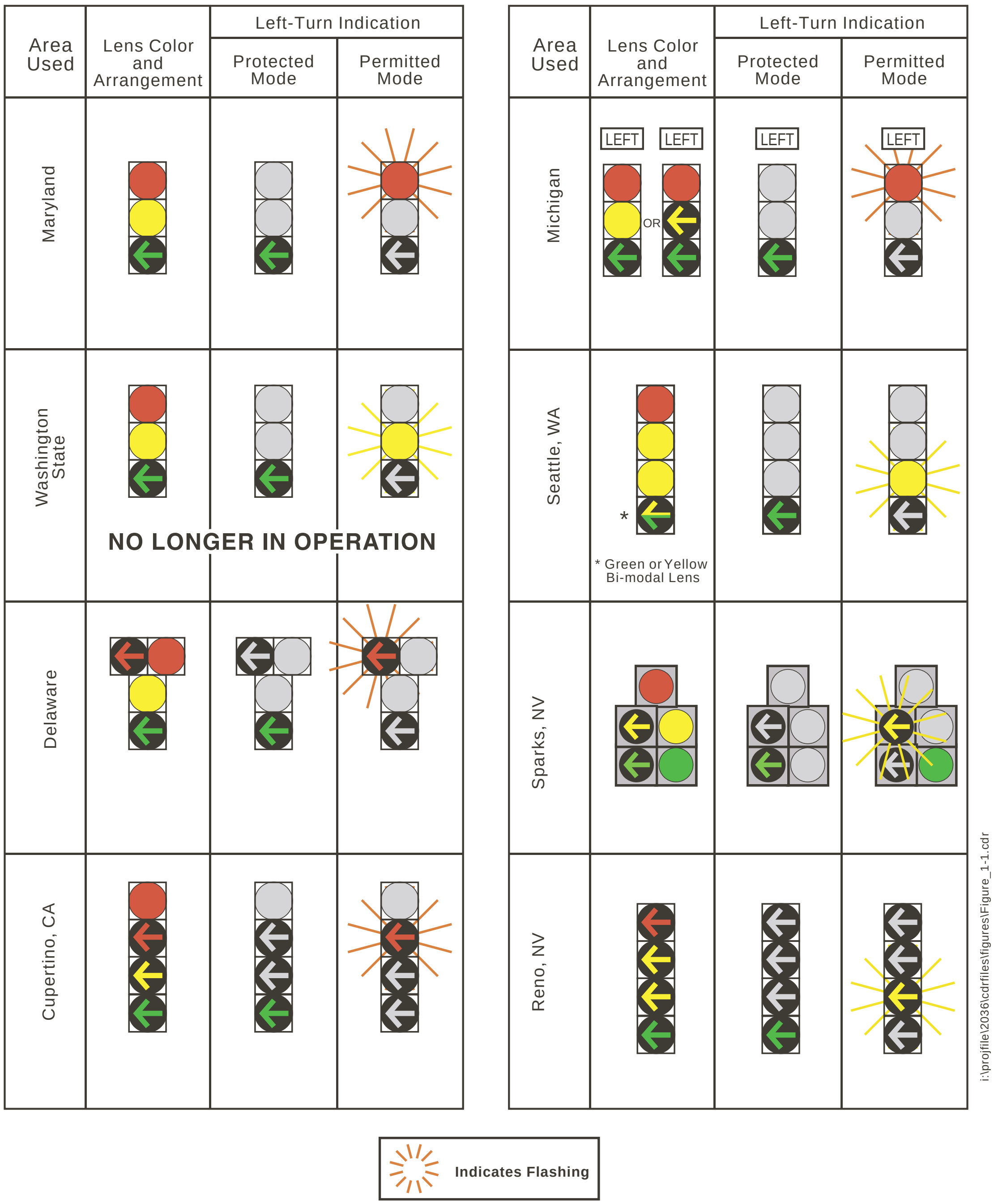


Figure 1-1. Variations in PPLT displays.

on an experimental basis. The premise for these implementations has been the potential for a safer or more efficient traffic control device.

The National Committee on Uniform Traffic Control Devices (NCUTCD), which provides guidance to FHWA on the MUTCD, has expressed concern that the variety of PPLT controls in use may confuse drivers traveling throughout the United States and has long proposed a comprehensive national study that would validate the operational advantages and safety aspects of the various PPLT control devices and signal arrangements.

NCHRP 3-54 RESEARCH OBJECTIVE

The objective of NCHRP Project 3-54 was to evaluate the safety and effectiveness of different signal displays and phasing for PPLT control through laboratory and field stud-

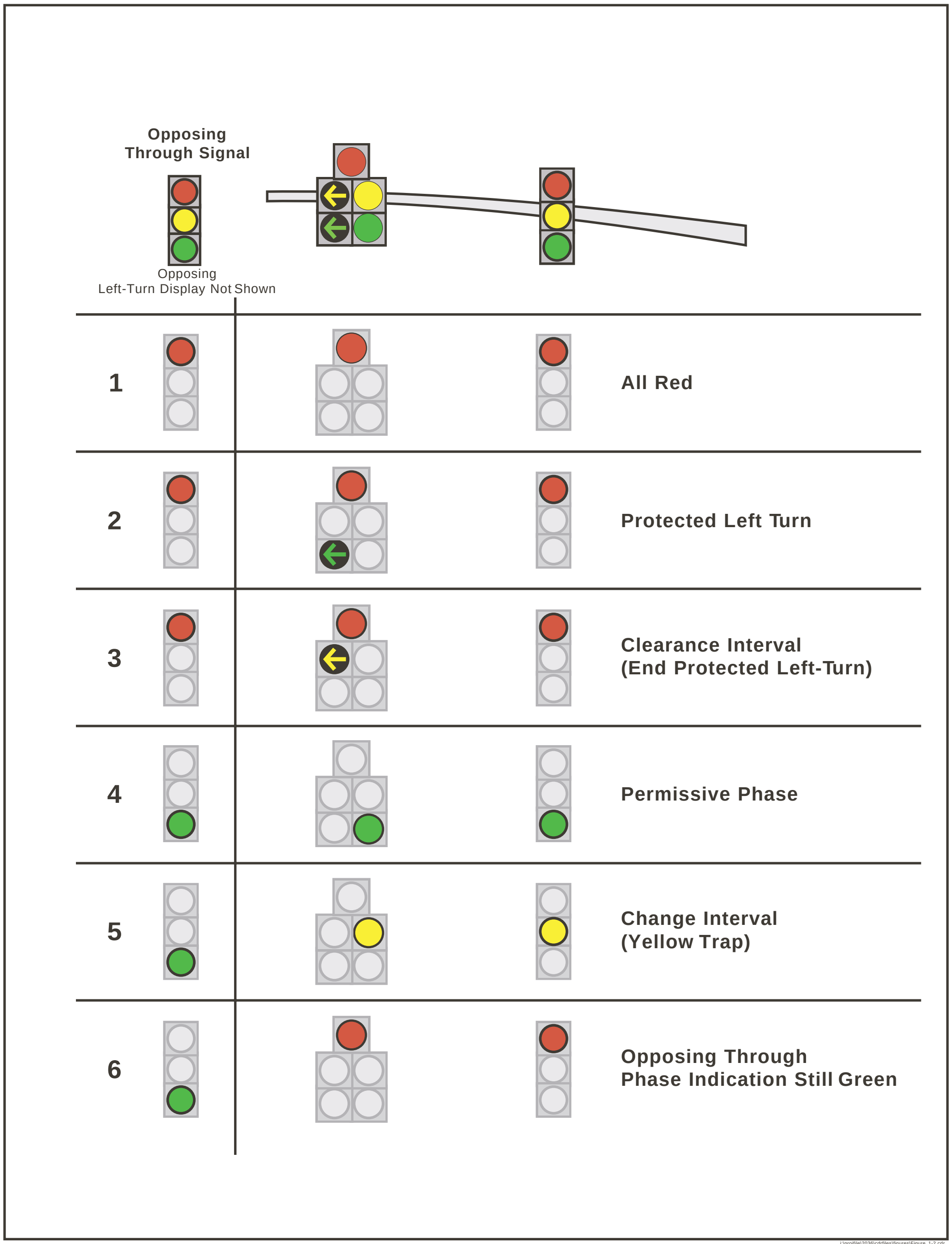


Figure 1-2. Yellow trap with MUTCD 5-section PPLT display.

ies. Study activities were designed to gather, analyze, and interpret data that would serve as the basis for recommending a uniform display for PPLT control. The study considered all current applications of PPLT control in the United States, including arrangement, indications, placement, phasing sequence, and safety considerations (e.g., the yellow trap).

NCHRP Project 3-54 did not develop any guidelines, warrants, or recommendations for the use of PPLT control. The underlying assumption was that the traffic engineer had decided that PPLT control is an appropriate left-turn treatment. The goal of this research project was to identify the "best" or most appropriate signal display, including arrangement and indications.

DEVELOPMENT OF RESEARCH PLAN

The NCHRP 3-54 study was conducted in two distinct phases. Phase 1 was exploratory in nature and focused on the development of the study plan to be carried out in Phase 2. Phase 1 study activities included the following:

- Review relevant literature,
- Define appropriate study factors,
- Identify and recommend study approach, and
- Document results.

The research team developed the Phase 2 work plan using the systems engineering approach. The work plan started with a study of all known PPLT displays and would methodically reduce the number PPLT displays being studied to a select few that would receive more concentrated study. The basic elements of the proposed work plan were (1) a survey of current PPLT use across the United States and at several international locations, (2) a study of driver understanding of known PPLT displays, (3) the use of computer simulation on a select number of PPLT displays, and (4) field studies. Figure 1-3 depicts how the work plan in Phase 2 would systematically narrow the number of displays being studied to a point where the "best" display would be identified.

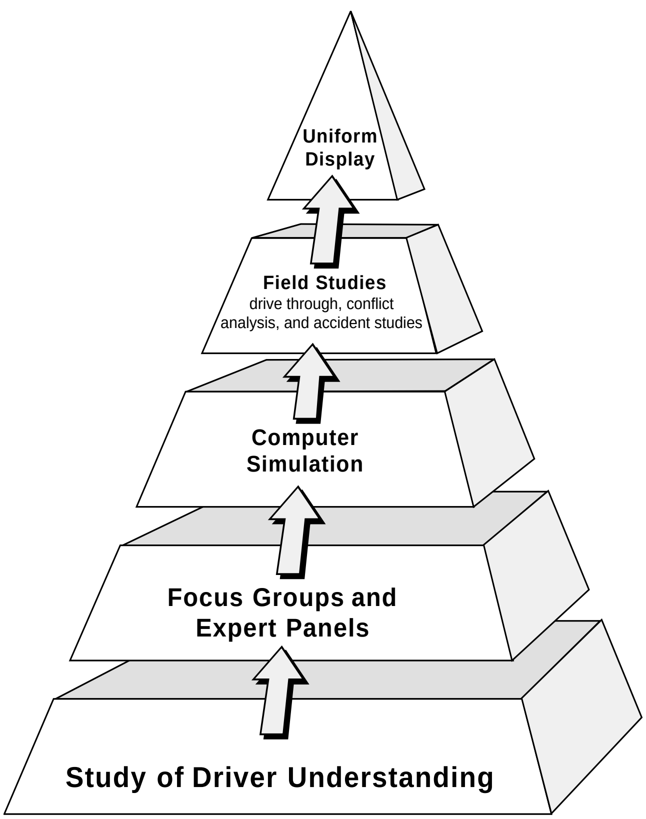


Figure 1-3. Conceptual work flow of the original Phase 2 work plan.

Building on the systems engineering approach, a revised Phase 2 work plan was developed as shown in Figure 1-4. The project's initial study activities were designed to help refine the number of displays studied in the following study tasks. Subsequent activities focused on a select number of displays that were studied with laboratory and field techniques that confirmed earlier findings and answered questions that would ultimately lead to recommendations.

Throughout the study, the research team solicited advice and comments from a team of technical advisors. These advisors were selected from the traffic engineering community because of their hands-on experience with various applications of PPLT control and unique permissive displays.

Because many questions of a practical application could not be answered with a laboratory test, the research team designed an Engineering Assessment study task. This Engineering Assessment task augmented the findings of other study tasks, including many field implementation issues. The Engineering Assessment task started in the initial stages of the project and continued through to the final stages of the project. In its final form, the NCHRP 3-54 study consisted of individual study tasks as identified in Figure 1-5. In October of 1999, the research team and project panel met to review the study PPLT displays and to determine which displays showed the most potential. As part of the meeting, several decisions were made, including the decision to reduce the number of displays to those with the most potential for further study. Additionally, the project panel directed the research team to conduct a thorough evaluation of one particular display through field implementation.

REVIEW OF KEY WORK PLAN ACTIVITIES

As previously stated, the NCHRP 3-54 study was structured into individual study tasks that consisted of data collection activities, reporting, and meetings with the project panel. Key individual study activities are discussed in Chapter 3 of this report. The greatest amount of detail related to each of the key study activities is found in the project working papers, which are appendixes to this report and are provided on the accompanying CD-ROM. Below are brief descriptions of nine key study activities; the other five tasks were panel meetings and documentation.

Identify Technical Advisors

Before beginning the formal study effort, potential members of a Technical Advisory Group were sought. The Technical Advisory Group was to consist of at least five knowledgeable professionals who would provide the project panel with first-hand experience and expertise in the evaluation of PPLT signal displays. Members of the advisory group were to be well-respected, experienced, traffic engineers knowledgeable about the PPLT issue. The research team also had

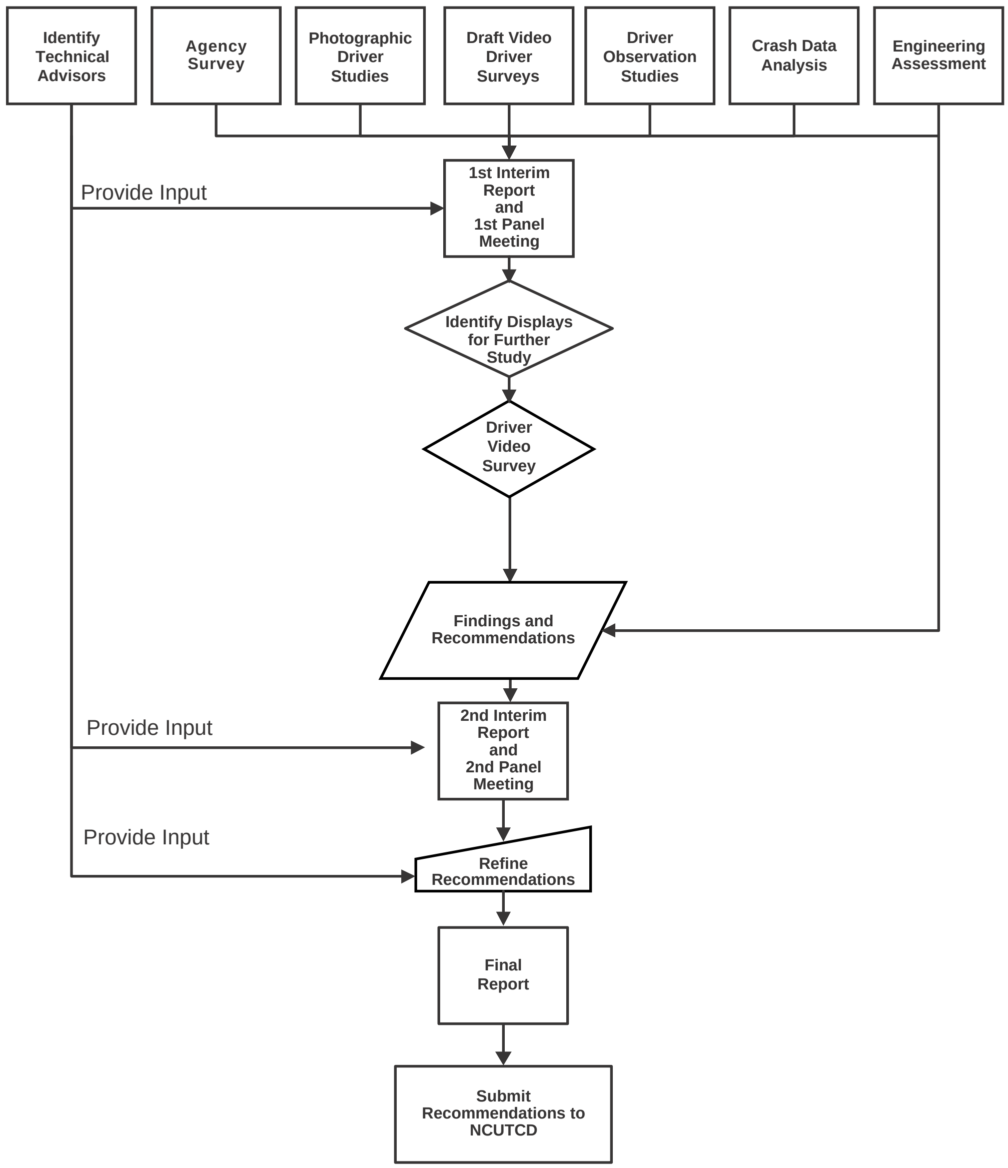


Figure 1-4. Proposed Phase 2 work plan.

regular interaction with the Signals Technical Committee of the NCUTCD in order to provide a regular flow of information to the full committee.

Agency Survey

To assess the current state of the practice, the research team conducted an extensive literature review and administered a survey of transportation agencies. The literature review identified the current state of the art in PPLT displays and included published and unpublished literature (including material from international sources).

The agency survey solicited information on the number and type of left-turn traffic control devices in use across the United States. The objective of the agency survey was to identify and quantify the different types of PPLT displays in use. The survey was administered to transportation professionals at the state and city levels who were directly involved with PPLT design and installations. Data on PPLT installations in all 50 states and parts of Canada were obtained.

Photographic Driver Studies

Photographic driver studies evaluated drivers' understanding of the circular green, flashing yellow arrow, flashing circular yellow, flashing red arrow, and flashing circular red permissive displays in association with different arrangements, placements, and traffic/lane configurations. Computer-generated PPLT signal displays on static background photographs were used to represent the dynamic aspects of the

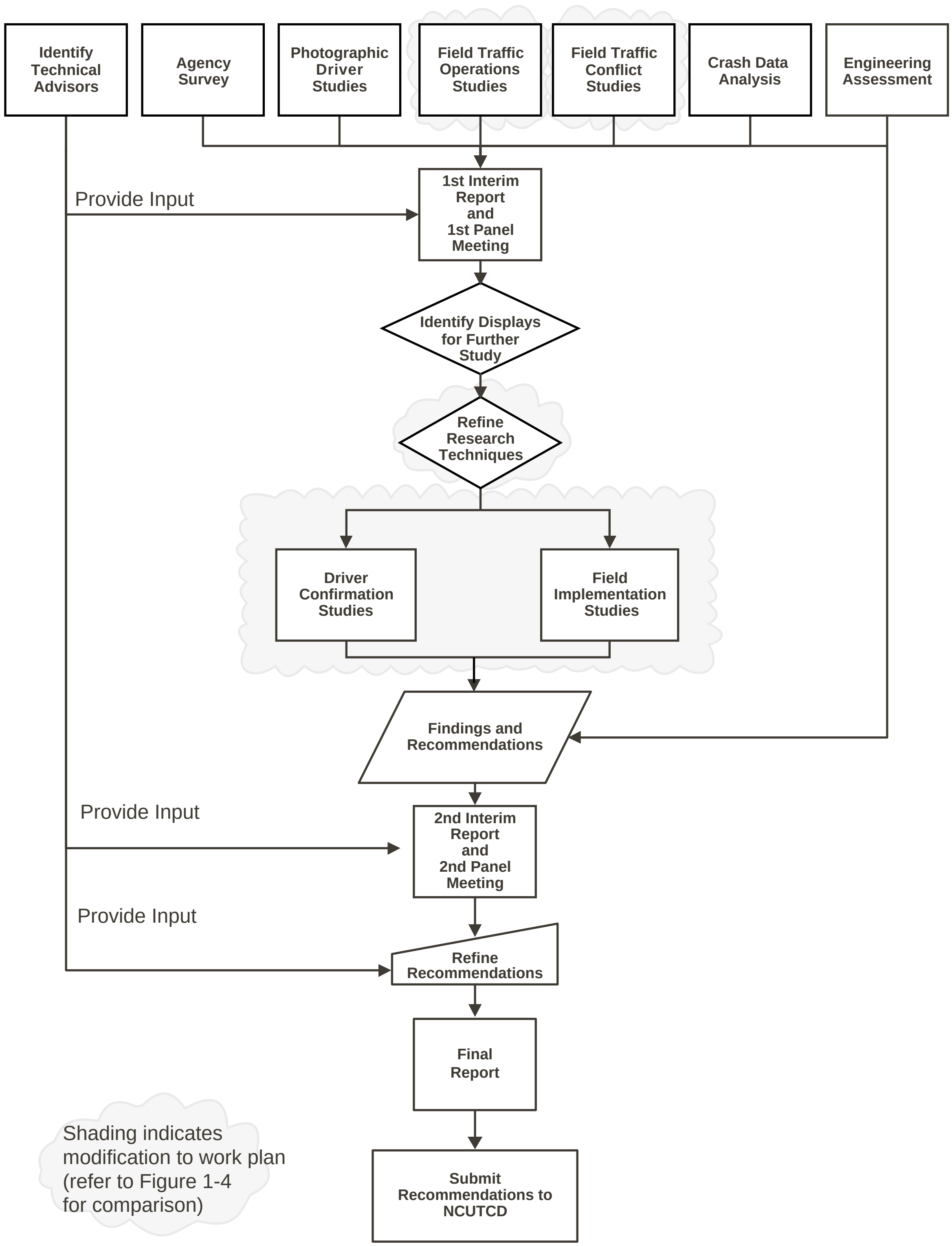


Figure 1-5. Final Phase 2 work plan.

PPLT displays. Over 300 drivers participated in each of eight geographic locations around the United States for a total of more than 2,400 drivers. All study participants were licensed drivers.

Field Traffic Operations Studies

Another major focus involved completion of (1) several traffic operations studies to determine the effects of the PPLT signal display types and (2) a traffic conflict study to determine the safety effects of each of the PPLT displays. The observation studies included quantifying the capacity and delay associated with various PPLT displays by analyzing saturation flow rates, lost times, response times, and follow-up headways. Field traffic conflict studies focused solely on the left-turn movement.

The traffic observation studies were conducted in the same eight geographic locations as the photographic driver studies in order to provide additional insights into driver behavior related to alternative PPLT displays. As part of this effort, the research team worked with local traffic engineers to identify representative sites with PPLT displays and to then gather crash, traffic, geometry, and other relevant data for each site. More than 8 hours of conflict data per intersection were collected at three intersections within each geographic study area for a total of 192 hours.

Crash Data Analysis

The research team conducted a review of crash data to determine and compare left-turn crash rates associated with various PPLT displays. In addition, selected components of a crash database created in 1988 as part of a FHWA study were examined.

Engineering Assessment

The Engineering Assessment sought to identify the objective and subjective information needed to evaluate the proposed displays. To assist in the assessment, an evaluation matrix was developed. The evaluation matrix included considerations addressing safety, operations, implementation, human factors, and versatility and was updated as each study activity was completed.

Data Analysis and Report of Preliminary Findings

Using the data collected from the agency evaluation, photographic driver studies, conflict studies, and crash studies, the research team prepared a comprehensive analysis of the results obtained to that point in the research project. This information was presented to the project panel, which in turn reviewed the findings and ultimately reduced the number of PPLT displays for future consideration. In addition to selecting a subset of promising PPLT displays to be further studied, the panel provided direction to complete the confirmation study and to conduct a field implementation study.

Driver Confirmation Studies

Using full-scale dynamic driving simulators located at the University of Massachusetts (UMass) and the Texas Transportation Institute (TTI), the research team developed a virtual driving environment to further test driver understanding of select PPLT displays and associated behavior. Study participants were required to navigate a virtual world containing various signal displays, different arrangements and locations, and opposing traffic, with the intent of evaluating driver performance at pre-selected intersections controlled by PPLT displays in an actual driving environment. The researchers at UMass and TTI were tasked with each testing 200 drivers of various demographic backgrounds for a total of 400 drivers.

Field Implementation Studies

Field implementation of an experimental flashing yellow arrow display was conducted to field test a display that had shown promise in safety and driver comprehension in previous task activities and had ranked high in the Engineering Assessment. Volunteer agencies were sought from across the United States to install and operate the experimental flashing yellow arrow display. In conjunction with use of the experimental display (which required permission from FHWA to operate), "before" and "after" studies were completed at each intersection where the flashing yellow arrow display was installed and at nearby control sites. These "before" and "after" studies allowed the research team to quantify the impact of the changeover from the MUCTD circular green indication to the flashing yellow arrow indication.

REPORT ORGANIZATION

Chapter 2 of this report provides background material and sets the stage for discussion of the study methodology, findings, and recommendations as presented throughout the remainder of the report. Chapter 2 presents a detailed description of PPLT control, key issues related to this type of signal phasing, and a description of current practices to mitigate some of the known disadvantages of using PPLT.

Chapter 3 summarizes the results of the individual project work elements, including the findings derived from each of the major project activities and the implications those findings had on the direction of the project. Chapter 4 provides a more in-depth discussion of findings surrounding one of the experimental PPLT displays, the flashing yellow arrow. Chapter 5 presents the final recommendations derived from the research project.

CHAPTER 2

BACKGROUND

This chapter provides a general overview of left-turn control, advantages and disadvantages of PPLT signal phasing, current standards for PPLT control, and some of the previously documented variations in PPLT displays used around the world. Much of the material presented herein was gathered through a review of published literature and current industry practice.

For decades, traffic engineers have relied on the MUTCD (*1*) to provide guidance regarding the installation and operation of all types of traffic control devices, including left-turn signal display and phasing. To be effective, the MUTCD must be specific enough to ensure uniformity, while allowing latitude to adapt the traffic control device to specific needs. For left-turn control, the MUTCD addresses the design and application of traffic control signs, pavement markings, traffic signal installations, and traffic islands. The MUTCD identifies several possible combinations of left-turn and through-movement signal lens arrangements (or displays) and provides some general guidelines for locating signal heads and advisory signing. The choice of left-turn control depends on several factors that must be evaluated by the traffic engineer using design guidelines and engineering judgment.

MODES OF LEFT-TURN CONTROL

The MUTCD defines four modes of left-turn control: permissive, protected, protected/permissive, and variable left-turn mode as described below.

Permissive left-turn control typically is used at locations without left-turn signals. Under permissive operation, the MUTCD does not require an exclusive signal indication or signal face for left turns. Consequently, one signal display can be used for all traffic movements on a single approach and the circular green indication permits left turns to be made after drivers yield to oncoming traffic and pedestrians.

Protected left-turn control is used where there is an exclusive display for left-turn movements. With this type of traffic control, left turns may be made only when a green arrow indication is displayed.

Under PPLT control, left-turning traffic is protected from oncoming traffic during the protected interval, during which the green arrow indication is displayed. In another part of the cycle, during which the circular green indication is typically displayed, left-turn movements may be made after drivers yield to oncoming traffic and pedestrians.

Variable left-turn mode describes a situation in which the operating mode changes among the protected-only mode, the permissive-only mode, and/or the protected/permissive mode during different periods of the day.

Combinations of signal arrangements used with the various left-turn controls cited above (as defined in the MUTCD) are illustrated in Figure 2-1. The application of these displays depends on the availability of an exclusive left-turn lane, the traffic signal phasing, and the mode of signal operation.

CURRENT STANDARDS FOR PROTECTED/PERMISSIVE CONTROL

The MUTCD is the mandated source for determining traffic control devices for left-turn maneuvers (*1*). It is not a legal requirement to install any device identified in the MUTCD; however, if a traffic control device is installed, it must comply with the provisions of the MUTCD subject to mandatory, advisory, or permissive requirements.

The PPLT mode of operation, as currently defined in the MUTCD, has a protected, left-turn interval indicated by a green arrow during part of the signal cycle and a permissive left-turn interval indicated by a circular green indication during another part of the cycle where the left turn must yield to opposing traffic.

To ensure that these basic requirements are met, the MUTCD identifies five considerations for the employment of traffic signal displays and other traffic control devices: placement, operation, design, maintenance, and uniformity. These considerations are discussed below.

Signal Display Placement

To understand the placement needs of a PPLT display, it is first important to understand how general traffic signal placement is governed and how left-turn signal displays are located for permissive mode only and protected mode only.

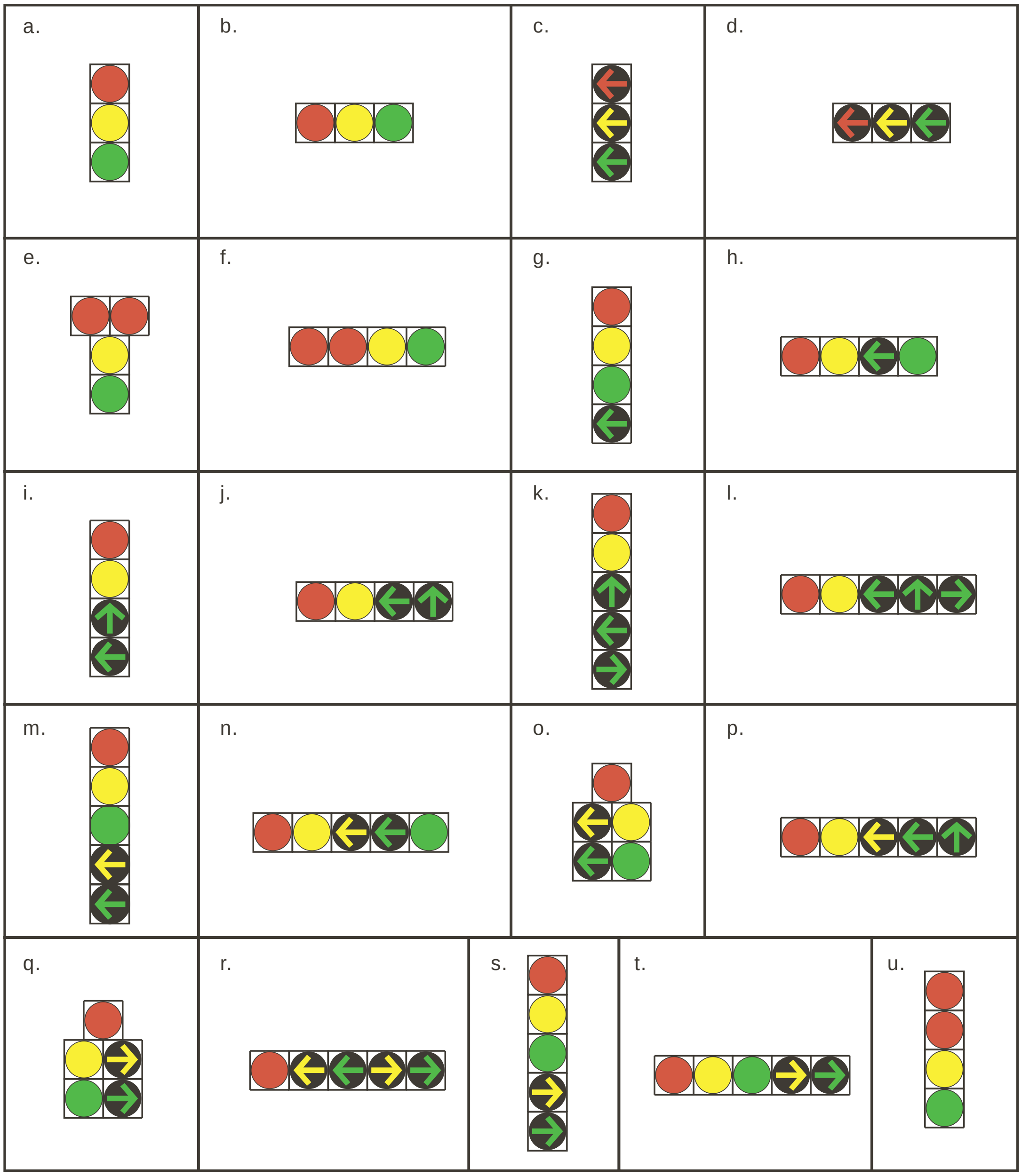


Figure 2-1. MUTCD arrangements of traffic signal displays.

General Traffic Signal Display Placement Criteria

A traffic signal display should be placed to ensure that it is within the driver's cone of vision so that it will unmistakably command attention. The display should also be positioned in relation to the point, object, or situation to which it applies to help convey the proper meaning. In addition to being suitably legible, the display must be located so that a driver traveling at normal speed has adequate time to observe the display, comprehend its meaning, and make the proper response.

As illustrated in Figure 2-2, the MUTCD indicates that the traffic signal display should be located not less than 40 ft nor more than 150 ft beyond the stop line. The signal "shall be located between two lines intersecting with the center of the approach lanes at the stop line, one making an angle of approximately 20 degrees to the right of the approach extended and the other making an angle of approximately 20 degrees to the left of the center of the approach extended" (*1*). Previous research has suggested that this 20-deg "cone of vision" be reduced to 10 deg to improve conspicuity (*4*).

Beyond the basic horizontal signal face location requirements shown in Figure 2-2, specific placement criteria are identified in the MUTCD; these criteria depend on the type of left-turn control. These requirements are described below.

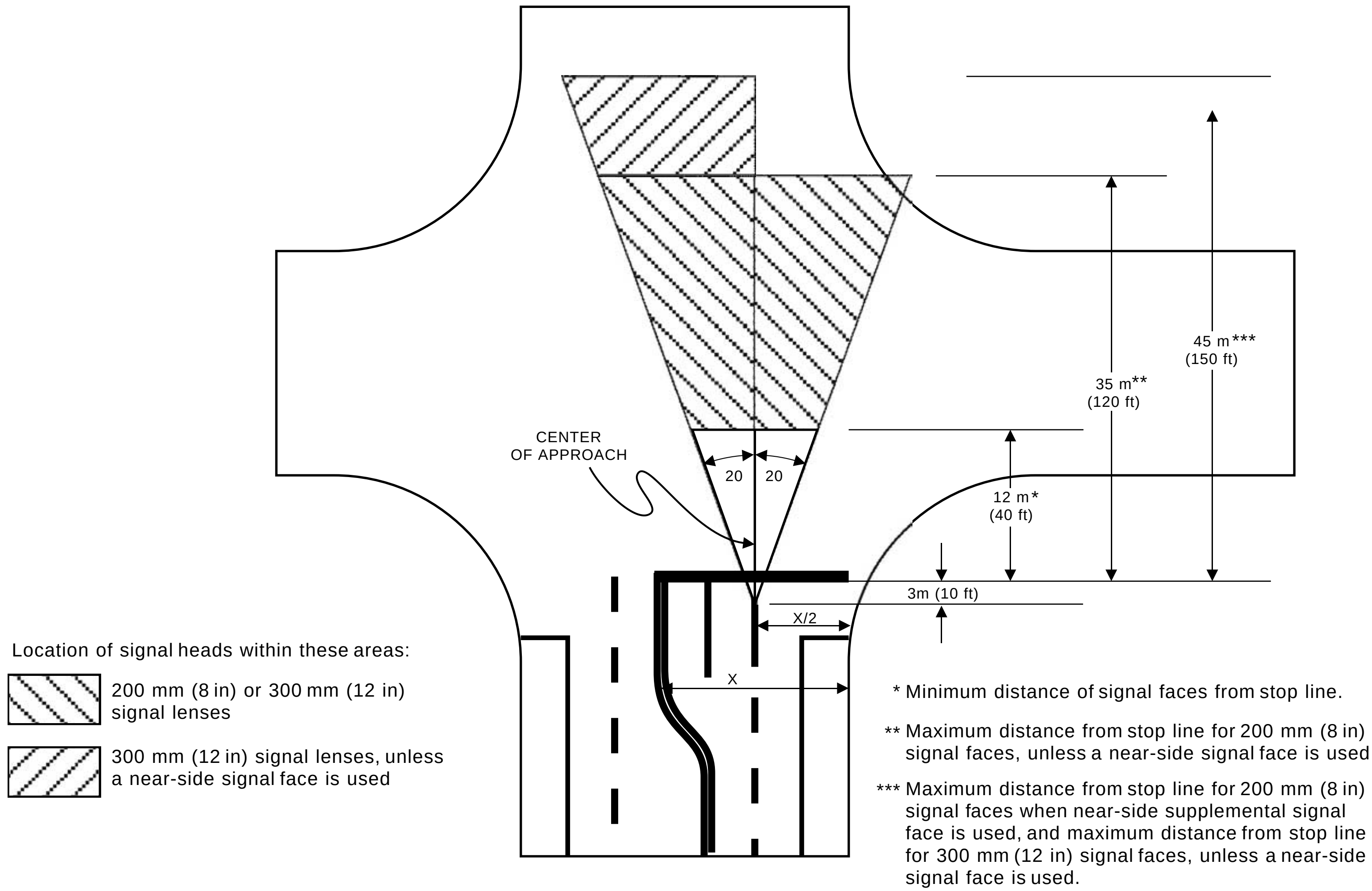


Figure 2-2. MUTCD criteria for horizontal location of signal faces.

Left-Turn Signal Display Placement Criteria for Permissive Mode Only

The MUTCD does not require an exclusive signal display for the left-turn movement if the left turn is going to be made in the permissive mode only. In this mode, the left-turning vehicle is directed by the through-traffic signal indication (a circular green) that is terminated with a circular yellow followed by a circular red.

Left-Turn Signal Display Placement Criteria for Protected Mode Only

The protected-only left-turn signal phase requires an exclusive signal face to control the left-turn movement. This signal face is normally located in line with the center of the left-turn lane, either overhead on the far side of the intersection or ground mounted in the median. The MUTCD does not require dual signal indications and 8 ft of horizontal separation between signal faces for protected-only left-turn signal indications and the adjacent signal indications; however, the MUTCD does require that a signal face mounted on a span wire or mast arm be located as near as practical to the driver's normal view line (*1*).

Left-Turn Signal Display Placement Criteria for PPLT Mode

Because a PPLT display controls both the permissive left-turn movement and the protected left-turn movement, there is flexibility in the location of the display. Figure 2-3 illustrates two potential overhead signal display placement alternatives allowed by the MUTCD for PPLT control. In addition to the alternatives shown in Figure 2-3, post-mounted median and farside display placements are also used. The placement of a given PPLT display ultimately depends on the type of display used. In some instances, PPLT control is implemented without the benefit of having an exclusive left-turn lane.

Operation

The traffic signal display should be operated in conjunction with the appropriate traffic control devices and equipment to meet traffic requirements at a given location (*1*). Further, "the display must be placed and operated in a uniform and consistent manner to ensure that drivers can respond properly to the display, given their previous exposure to similar traffic control situations." (*1*)

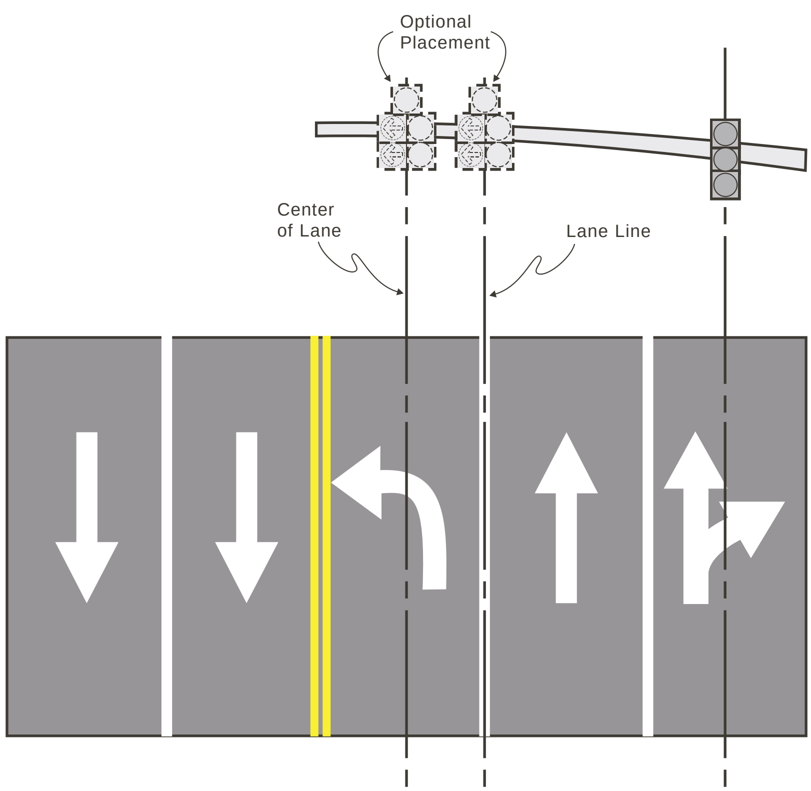


Figure 2-3. Overhead PPLT display placement options.

Design

Features such as size, contrast, colors, shape, composition, and lighting or reflectorization should be combined to draw attention to the display (*4*). The shape, size, and colors of the display should produce a clear meaning. Legibility and size should be combined with placement to permit adequate response time. The display's uniformity, size, legibility, and comprehensibility should command respect from drivers when the display is encountered.

The PPLT signal display must provide for both protected left turns and permissive left turns during the signal cycle. The most commonly used signal displays are the five-section cluster, vertical, or horizontal, shown in Figures 2-1 -o, -m, and -n, respectively. As shown in Figures 1-1 and 2-4, the signal indications for PPLT mode left turns are provided by either a shared signal face or an exclusive signal face used only by left-turn traffic.

Shared PPLT Display Arrangement

In a shared application, the signal face indicating a protected left-turn movement is one of the two required signal faces for the approach and is usually not directly over the left-turn lane. It displays a left-turn green arrow signal indication and the adjacent through movement indication (circular red or circular green) simultaneously. The MUTCD further requires that the signal faces for the through traffic on the opposing approach simultaneously display circular red signal indications. During the permissive left-turn movement, all signal faces on the approach display circular green signal indications. At any point in the signal cycle, all signal faces on the approach are required to simultaneously display the same color of circular indications to both through and left-turn road users (variations are allowed when louvered signals are used as explained later in this chapter) (*1*).

Exclusive PPLT Display Arrangement

In applications using an exclusive signal display arrangement for the left-turn movement, a separate signal face, usually located directly over the left-turn lane, is provided in addition to the minimum two required signal faces for the through movements. The separate face is required to simultaneously display a left-turn green arrow signal indication and a circular red signal indication for the protected phase of the signal cycle. A circular green indication is displayed for the permissive interval. The MUTCD further requires that the signal faces for the through traffic on the opposing approach simultaneously display circular red signal indications. During the permissive left-turn movement, the left-turn signal face displays a circular green signal indication (*1*).

Maintenance

Traffic signal displays should be well maintained to ensure that legibility is retained and the display is visible. The display should be removed if it is no longer needed (*1*). Clean, legible, and properly mounted displays, in good working condition, command the respect of every travel mode at the intersection. In addition to regular maintenance, traffic displays should be adjusted regularly to address current conditions. The fact that a display is in good working order should not be a basis for deferring needed replacement or change. Conversely, poor maintenance can destroy the value of a group of traffic signal displays by minimizing the respect commanded by individual displays.

Uniformity

Uniformity means treating similar traffic situations in the same way. Uniform traffic signal displays aid the road user by simplifying recognition and understanding (*1*). Uniform displays also help road users, police and enforcement personnel, and traffic courts interpret appropriate driver behavior. Uniform traffic control displays are also economical because consistent manufacturing, installation, maintenance, and administration processes can be used.

Signal Phasing

Various signal phase sequences can be used for the PPLT mode such as leading or lagging protected turn intervals, with adjacent through traffic either moving concurrently with the left turn or stopped. The MUTCD requires that all same-color circular indications in all signal faces on an approach be simultaneously illuminated when PPLT operation is used with one exception: when using an exclusive left-turn signal face with circular green and circular yellow signal indications that are visibility limited from the adjacent through movement, the left-turn signal is not required to simultaneously display the same color of circular indication as the faces for the adjacent through movement. Further, in this visibility limited arrangement, a circular green signal indication for the permissive left-turn movement can be displayed while the signal faces for the adjacent through movement display a circular red indication and the opposing left-turn displays a left-turn green arrow indication for a protected left-turn movement (*1*). This arrangement, commonly referred to as the Dallas Display (or Dallas Phasing), is used to eliminate the previously acknowledged yellow trap. Figure 2-5 illustrates a typical Dallas Display.

In situations where an exclusive left-turn signal face is provided and the left-turn signal face does not simultaneously display the same color circular indication as the adjacent through movement, the MUTCD requires that a combination of a LEFT TURN SIGNAL sign (R10-11) and a LEFT

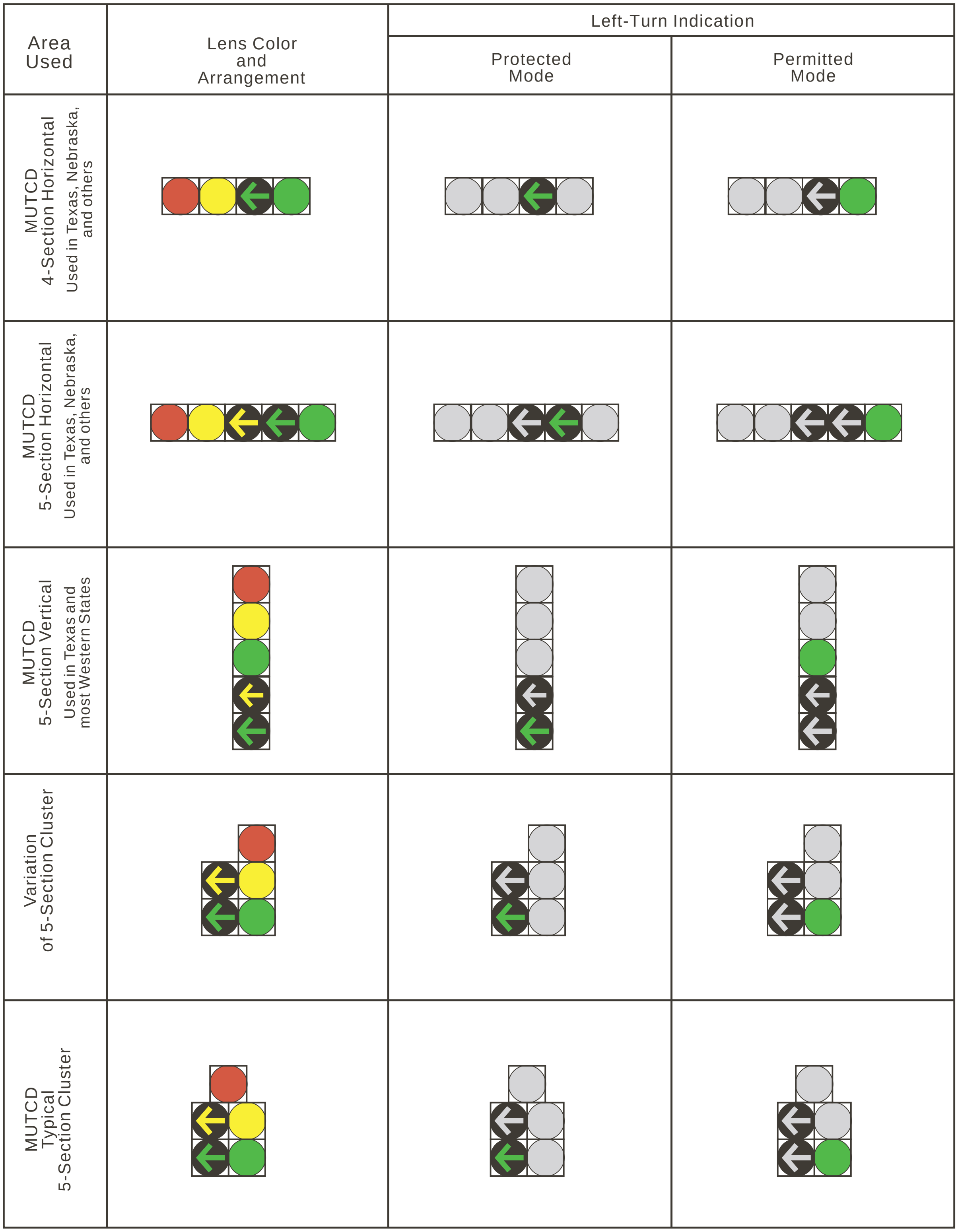


Figure 2-4. Variations in PPLT displays.

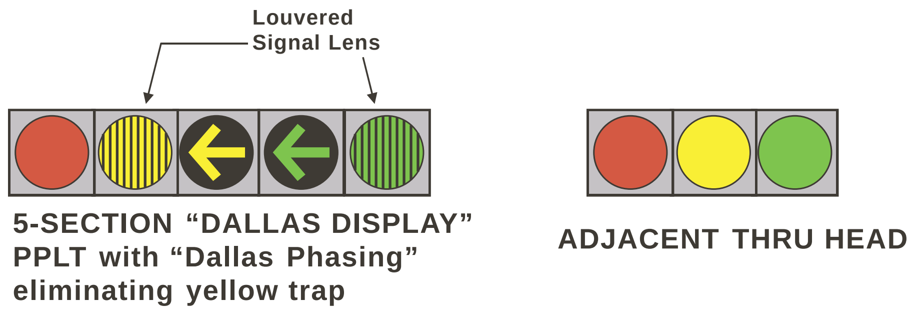


Figure 2-5. Illustration of Dallas display.

TURN YIELD ON GREEN (symbolic circular green indication) sign (R10-12) be used (*1*).

In some applications, use of protected, permissive, or PPLT operations at a given location may be changed by time of day to reflect changes in the traffic conditions. In these instances, in addition to meeting the previously documented criteria, the MUTCD stipulates that (1) the circular green and circular yellow signal indications shall not be displayed when operating in protected-only mode and (2) the left-turn green arrow and left-turn yellow arrow signal indications shall not be displayed when operating in the permissive-only mode. Although no specific signing for a time of day application is identified, the MUTCD notes that "additional appropriate signal indications or changeable message signs may be used to meet the requirements for the variable left-turn mode" (*1*).

ALTERNATIVE DISPLAYS USED IN THE UNITED STATES

Several innovative displays and phasing arrangements have been created within the past 20 years. Five variations of the display indicating the permissive phase are known to exist, only one of which includes the use of the MUTCD standard circular green indication. These include use of the flashing circular red, the flashing red arrow, the flashing circular yellow, and the flashing yellow arrow indications. Figures 1-1 and 2-4 illustrate the various PPLT displays used throughout the United States. There have also been some innovative advances in signal phase sequence, such as the "Dallas Display," which alleviate the yellow trap. The manner of use and frequency of occurrence for each type of display are discussed in the following subsections and reflect data collected in 1998.

Flashing Red Display

Flashing red displays are used in Maryland (flashing circular red indication), Michigan (flashing circular red indication), Delaware (flashing red arrow indication), and California (flashing red arrow indication). The flashing circular red indication as currently used in Maryland is primarily applied at two-phase "T" intersections (approximately 13 locations). This display consists of a three-section display with a flashing circular red indication, a circular yellow or yellow arrow indication, and a green arrow indication for left-turn movements from the top of the "T" to the stem of the "T." Because many of these intersections are freeway on-ramps, the leg on the top of the "T" in the same direction as the left turn may not have signal indications. The signal rests in flashing red for the left-turn driver with green for opposing traffic. After the left-turning vehicle occupies the left-turn bay for a set period, the driver receives a protected phase. Michigan uses PPLT phasing with flashing circular red indications. The left-turn lane has an exclusive three-section display consisting of a circular red indication, a circular yellow indication, and a green arrow indication for left-turn movements. In some cases, a yellow arrow is used in place of the circular yellow indication. The left-turn movements are operated in a PPLT (dual lagging) mode. The circular red indication is flashed during the permissive interval. A protected left-turn green arrow indication is provided only if left-turn demand exists at the end of the permissive phase.

The flashing permissive circular red operation has been used in Michigan since about 1975. One of the earliest installations of the flashing red is believed to have been in Ann Arbor, Michigan. The Michigan Department of Transportation (MDOT) estimated that the State of Michigan operates the flashing circular red indication at 100 locations, mostly in urban areas. Another 200 installations are operated locally by Wayne and Oakland Counties. In the greater Grand Rapids area, 72 additional locations use this PPLT indication.

Delaware uses the flashing red arrow indication in a four-section, left-turn display. The display consists of a red arrow indication next to a circular red indication, with a yellow arrow indication and a green arrow indication centered under the red indications. The permissive interval is indicated by a flashing red arrow.

The Delaware DOT estimated that approximately 100 locations in Delaware have the flashing red arrow permissive phase, with the first installations dating to the early 1980s. Most locations operate with a leading protected phase. After the red arrow flashing permissive interval, a solid circular red indication is displayed to the left-turning vehicle, rather than again displaying a yellow arrow indication (a change interval is not provided). Delaware has also developed controller logic to omit the left-turn phase call until the opposing queue is dissipated.

The City of Cupertino, California, has installed a flashing red arrow permissive indication in at least three locations. The City uses a vertical, four-section display with a circular red indication, a flashing red arrow indication, a yellow arrow indication, and a green arrow indication. Typically, one left-turn display is median mounted with a second left-turn display post mounted on the far left side of the intersection.

Flashing Yellow Display

The City of Seattle, Washington, uses the flashing circular yellow indication to communicate the permissive left-turn interval at approximately 20 installations, with additional intersections still being added periodically. Seattle is using a four-section vertical display that has a circular red indication, a circular yellow indication, a flashing circular yellow indication, and a dual indication yellow arrow/green arrow section. Typically, these locations are low volume and operate in a PPLT mode throughout the day. The flashing circular yellow indication has been in use in the City of Seattle since about 1966 and has also been installed in a few other locations in the Seattle metro area. The staff at the City of Seattle promotes the use of the flashing circular yellow indication because this indication provides high contrast during the nighttime hours of operation. It is during the nighttime hours that the City has identified a reduction in crash rates over the use of the circular green display (*5*). The implementation of the flashing circular yellow indication was before light-emitting diode (LED) lens technology met acceptable standards for widespread deployment.

The City of Reno, Nevada, installed a flashing yellow arrow permissive display at five locations around the City. The typical implementation design used a four-section vertical display with a red arrow indication, a yellow arrow indication, a yellow flashing arrow indication, and a green arrow indication. The display was mounted on a mast arm over the left-turn lane, with a second left-turn display post-mounted on the far left side of the intersection. Because of a change in the City of Reno's Traffic Engineering staff, the City elected to remove the flashing yellow arrow displays so that all permissive displays were uniform within the city.

In April 1998, the nearby City of Sparks, Nevada, installed a flashing yellow arrow permissive display at six locations with approval from FHWA. The City has continued to install the flashing yellow arrow display at more locations. The experimental design uses an exclusive five-section cluster display arrangement, with the flashing yellow arrow in the standard yellow arrow location. The circular green indication is illuminated simultaneously with the flashing yellow arrow indication during the permissive left-turn interval. By design, the flashing yellow arrow is a supplemental indication to the circular green indication; therefore, two indications essentially convey the same information. To accomplish the flashing yellow output, the city installed specially designed logic control units in the controller cabinet. The display is accompanied with the supplemental sign R10-1 LEFT TURN YIELD ON GREEN (circular green indication symbol). The supplemental sign is consistent with standard practices and consistent with the MUTCD.

Lead-Lag Displays

A traffic control technique designed to avoid the yellow trap is known as "Dallas Display" operation. The Dallas Display, developed in the mid 1980s (1986-1987) by a group of traffic engineers in Dallas County, Texas, requires the standard three-section signal display for the through movement and an exclusive, five-section left-turn signal display. First implemented in the cities of Dallas and Richardson, Texas, the five-section signal display is typically centered over the left-turn lane in a vertical, cluster, or, most often, horizontal configuration. The circular green indication and circular yellow indication in the left-turn display are overlapped with both through movements and are shielded so that they can be seen only by the left-turning traffic.

An alternative to the Dallas Display was developed in Arlington, Texas, and is sometimes called the "Arlington Display." The Arlington Display uses the same Dallas Display concept, except that the lagging protected left-turn direction does not receive a permissive interval during the leading direction protected interval. This permissive interval is excluded for two reasons. First, the permissive direction is usually facing an opposing through queue that is just starting to dissipate, making it unlikely that the permissive left-turn maneuver can be made safely. Second, some practitioners believe that the display of the permissive interval without the same-direction through traffic receiving a circular green indication is confusing to drivers.

The Dallas or Arlington PPLT displays are used at more than 600 locations in Texas. The Dallas Display operation has recently been installed at several locations in Las Vegas and Carson City, Nevada. Las Vegas has programmed several other locations for conversion to PPLT phasing in the near future. Most recently, the cities of Los Angeles and Upland, California, have installed the Dallas Display at several intersections. As noted within the previous discussion of display applications, the 2000 MUTCD allows for the use of visibility-limited, left-turn signal faces that implement the Dallas Display.

PRACTICES OUTSIDE THE UNITED STATES

The United States is not the only country trying to increase drivers' understanding of the permissive left-turn display. Practices from other countries that were identified for this report are discussed below.

Canada

Within Canada, there has been a concerted effort among many of the provinces to gain uniformity in the displays used for the protected, permissive, and PPLT control. Many areas of Canada use a flashing indication, but for different reasons than the United States. For example, the provinces of British Columbia, Alberta, and Saskatchewan use the flashing green left-turn arrow indication for the protected left-turn phase, whether it is protected only or protected/permissive. Ontario communicates a protected left-turn movement using the flashing circular green indication at some intersections and a solid green arrow indication (same as the United States) at other locations.

In 1997, the Transportation Association of Canada adopted new traffic signal standards aimed at increasing driver safety and signal operating efficiency. The most significant changes involve the introduction of one arrow display (flashing green arrow indication) for all protected left- and right-turn signal displays, removal of the nonstandard flashing circular green indication for protected turn indications, introduction of the steady amber arrow change interval, provision of a minimum of two traffic signal heads for through and left-turn movements, and provision of a flashing DON'T WALK change interval for pedestrian displays. The steady circular green indication is used to display the permissive interval.

Based on telephone interviews conducted by the research team in 1995 and a 2002 follow-up conversation, support for the flashing display centered on the following issues: (1) the flashing indication provides a more visible message to the driver; (2) the flashing indication assists drivers with color vision problems (color anomalous/color deficient); and (3) the indication has been associated with increased saturation flow rates for the left-turn movement. Proponents of the flashing display also acknowledge that there are disadvantages, including the following: (1) the display is not consistent with the steady green arrow indication currently used in many areas throughout Canada and the United States and (2) there is no uniform meaning for a flashing indication.

To support the hypothesis that the flashing display increases saturation flow, there were limited studies of the left-turn saturation flow for the flashing display versus the non-flashing display (*6*). In a 1991 study, the saturation flow for the two displays was studied in Edmonton, Alberta, and Victoria, British Columbia. The data confirmed the hypothesis that the flashing display increases the saturation flow. It is believed that the flashing indications demand more attention from drivers. It should be noted that the NCHRP 3-54 study also studied saturation flow rate for different signal displays and indications and did not reach similar findings.

In many provinces, left-turn indications are being displayed through a variable (fiber-optic or LED) lens. The green arrow indication will terminate to the yellow change interval using the same lens. In response to concern that drivers with color vision problems would have difficulty in distinguishing between the two indications, the flashing indication was proposed. The Canadian Association of Optometrists supports use of a flashing indication (*7*). It was believed that a flashing green display would allow all drivers, regardless of their vision conditions, to better discriminate between the different displays. There is some resistance in Canada to the use of the flashing protected left-turn indication. For example, Ontario already uses a steady green for simultaneous leading PPLT phasing. Ontario has thousands of signalized left turns and the cost to convert has been estimated to be high.

Standard specifications were approved by the Council for Traffic Control Signals in 1997. Part B of the Manual of Uniform Traffic Control Devices for Canada was subsequently completed and adoption has been underway across the country. The British Columbia Ministry of Transportation standard for protected only left-turn movements was a display consisting of a three-section head (steady green arrow, steady yellow arrow, and a solid circular red indication). The Ministry's standard for PPLT displays incorporated a flashing green arrow and then a steady yellow arrow, resulting in a four-section signal. The administrative staff of Highway Safety at the British Columbia Ministry of Transportation estimates implementation of the new standards should be completed within 10 years. It has been estimated that the cost of implementation is \$35 million (1992 Canadian dollars) (*8*).

Europe

Several European countries are experimenting with the use of the flashing yellow indication for the permissive left turn. In Heidelberg, Germany, the flashing yellow arrow indication is used on the Neckarstaden at the Congress House and Stadhalle for the permissive interval of PPLT phasing. The flashing yellow arrow indication is also used for the permissive interval in Bern, Switzerland. In Strasbourg, France, the flashing yellow indication is used for right-turning traffic to indicate "yield to pedestrian traffic." In Spain, there is some use of the flashing yellow arrow indication for the permissive left-turn interval.

There has been a concerted effort by practicing European traffic engineers to develop a European standard for the use of the flashing yellow arrow indication, though efforts to implement nationwide across Switzerland were unsuccessful because of concerns expressed by the Swiss federal police department.

A European research study concluded that (1) turning vehicles cause accidents, because they periodically misinterpret the prevailing signals' "full green" and "green" indication with flashing light (In Switzerland, the Ordinance for Road Signals stipulates that a flashing warning signal be positioned beside the green signal to caution drivers about on-coming vehicles.) as a "go ahead"; and (2) the "flashing yellow arrow" proves to be a simpler and more uniform signal—drivers of turning vehicles understand it better and at least some accidents are prevented (*9, 10*).

A more in-depth study of the flashing yellow arrow indication in 1990 compared the accident statistics at 35 signal installations with flashing yellow arrows in Zurich, Switzerland, and St. Gallen, Germany, with a control study of 22 intersections without flashing yellow arrows in Zurich, Switzerland, and Winterthur, Germany (*11*). Accident data were analyzed for a 2.5-year period before the flashing yellow arrow indication was installed and for a 1.5-year period afterwards. According to this study, the traffic signals with the flashing yellow arrows led to a significant accident reduction at the 35 survey installations.

Australia

Researchers at the University of Adelaide, Australia, conducted a three-part study of six traffic signal displays, including a flashing yellow arrow indication. Their efforts focused on analysis of crash data at intersections with the study displays, a driver survey, and a reaction time experiment comparing speed and accuracy of responses to computer-based animation of the traffic light displays. Overall, the study determined that there were no conclusive findings demonstrating superiority of the flashing indication as compared with other traditional display applications. The research report conclusion section identifies that the flashing yellow arrow indication shows promise and offers a recommendation that the use of a flashing yellow arrow display be further investigated, potentially through dialog with researchers from the NCHRP 3-54 project being conducted in the United States (*12*).

THE LEFT-TURN PROBLEM

As evidenced by the multiple phasing and display options identified in the previous sections, accommodating left-turning vehicles at signalized intersections has been an ongoing concern for transportation engineers as they seek a balance between intersection capacity and safety through signal phasing techniques. After deciding that a left-turn phase is required, one of the major decisions faced in timing traffic signals is to appropriately assign time for left-turn movements. As the number of left-turning vehicles increases, average delay and accident potential for both through and left-turning vehicles also increases. Exclusive left-turn lanes and protected left-turn phases are commonly used to minimize the impact of left-turning vehicles. When a protected left-turn phase is used, however, the time to provide that phase must be taken from the through phases, or the cycle length must be extended. Other decisions the engineer must make concern the type of left-turn phasing that best satisfies the left-turn demand and the left-turn phase sequence that maximizes progression, particularly if the intersection is located on an arterial street.

ADVANTAGES OF PROTECTED/PERMISSIVE LEFT-TURN PHASING

Transportation professionals have chosen PPLT phasing for many reasons, including minimizing delay, improving progression, and reducing fuel consumption and air pollution. From an operational standpoint, an agency might consider using PPLT phasing to increase the operational efficiency of an intersection. PPLT phasing can reduce delay for left-turning vehicles under low-to-moderate traffic volume conditions. PPLT phasing is especially effective in reducing left-turn vehicle delay when it is operated with a coordinated signal system.

Many jurisdictions use the lead-lag left-turn phase sequence at intersections within a signal system to improve progression. The benefits of the lead-lag left-turn phasing are further enhanced with protected/permissive lead-lag phasing. By allowing vehicles to turn left during the permissive interval, required left-turn green phase time can be reduced, allowing more green time for the coordinated movements. This technique is especially effective for coordinated arterial signals where the progressed platoons in each direction do not pass through the signal at exactly the same time. Several studies (*3, 13, 14*) on lead-lag PPLT operation have found intersection delay and crashes are reduced over traditional PPLT operation. A comprehensive evaluation of the impacts of PPLT phasing associated with coordinated signal timing was completed in western San Bernardino County, California (*15*). The City of Upland, California, where much of this study was completed, was using the Dallas Display. The researcher documented a 30 to 50% reduction in vehicle delay when comparing protected-only to PPLT phasing (*15*). PPLT phasing can also improve the air quality. The California study showed that increasing average speed, reducing overall travel time, and reducing the number of stops resulted in a significant reduction in mobile source emissions. The study documented a reduction in reactive organic compounds (ROC), carbon monoxide (CO), and nitrogen oxide (NO_x) emissions by 9 to 12% per day when comparing protected (lead-lag) with protected/permissive (lead-lag) left-turn phasing (Dallas Display).

DISADVANTAGES OF THE MUTCD CIRCULAR GREEN DISPLAY

Although there are many reasons to use PPLT control, some disadvantages have not been resolved. First, many traffic and safety engineers question whether drivers fully understand the meaning of the permissive indication. Their observations suggest that drivers may be confused about how to make the left turn safely, particularly when PPLT phasing is used. They have also observed that some left-turning traffic at intersections with PPLT control does not use the permissive phase (even when adequate gaps in the opposing traffic are available) and instead turn left only when given the protected left-turn arrow indication. In other locations, left-turn drivers may interpret the circular green as a protected display.

A second disadvantage of PPLT lead-lag phasing is the "yellow trap." The yellow trap can occur in a number of other situations, such as during signal preemption for emergency vehicles, during signal preemption for railroad grade crossings, during re-service of lead left-turn phases, or during an overlapping green extension for "slot" (or inside) clearance at an offset intersection.

SUMMARY

Through a review of published literature and industry practice, this chapter has provided an overview of the current use of left-turn control, specifically focusing on PPLT control. Basic advantages and disadvantages of PPLT signal phasing and some of the previously documented variations in PPLT displays used around the world were identified. Chapter 3 builds on this basic information as detailed elements of the NCHRP 3-54 project are presented.

CHAPTER 3

RESEARCH ACTIVITIES AND FINDINGS

The research project encompassed 14 individual tasks; 8 study tasks and 6 meeting/report tasks. The eight study tasks are discussed below:

- Agency Survey,
- Photographic Driver Study,
- Field Traffic Operations Study,
- Field Traffic Conflict Study,
- Crash Data Analysis,
- Driver Confirmation Study,
- Field Implementation Study, and
- Engineering Assessment.

Each of these work activities is discussed in general detail below. The work activity objective, methodology, results, and findings are identified. A complete description and findings for each of these work activities can be found in the working papers included in the accompanying CD-ROM.

AGENCY SURVEY

The discussion in Chapter 2 demonstrated that there is a wide variation in the use and application of the PPLT control throughout the United States and abroad. To identify and quantify the different types of PPLT control displays adequately, the research team administered an agency survey. The survey was mailed to all 50 state traffic engineers for DOTs and to traffic engineers in 275 of the largest city and county transportation agencies in the United States and Canada.

Objective

The objective of the agency evaluation effort was to identify and quantify the different PPLT displays, design, and phase sequencing used in the United States.

Methodology

A survey was developed to collect information about the use of PPLT signal displays in the United States. The survey consisted of three sections having a total of 15 questions.

The first section of the survey, General Information, included two questions to determine how many signalized intersections were located in the jurisdiction and to what extent the PPLT signal display was used.

The second section of the survey included nine questions about the use of the PPLT signal display, including inquiries about the display arrangement, mounting type and location, use of secondary PPLT signal displays, and the type of signal indication used for the permissive phase of the PPLT.

The third section of the survey included questions about how the agency uses PPLT signal displays for different geometric roadway conditions, if the agency uses any special technique(s) to avoid the yellow trap, and if there are any local laws or ordinances governing the use of PPLT signal displays.

The survey responses were summarized and analyzed to determine to what extent PPLT signal displays are being used in the United States.

Results

One hundred and eighty (55%) of the surveys were returned, including six from Canada and six from agencies not using PPLT signal displays. Excluding the Canadian surveys (Canadian use of PPLT signal displays is discussed in Chapter 2 of this report) and the jurisdictions not using PPLT displays, the remaining 168 returned surveys were used to develop the findings summarized below.

Findings

- Collectively, the 168 agencies identified 107,219 signalized intersections. Of those, 30,870, or 29%, used PPLT signal phasing.
- The five-section cluster display was the predominant arrangement used in 34 states and represented 63% of all reported PPLT signal displays. The next most commonly used PPLT signal display arrangement was the five-section vertical, which accounted for approximately 19% of all reported PPLT signal displays.
- The five-section horizontal display was used predominantly in two states and accounted for approximately 9% of the reported PPLT signal displays. Use of the

four-section and three-section PPLT signal displays were less common. They were found to be in use in a few states and accounted for less than 10% of all reported PPLT signal displays.

- A total of 41% of the agencies reported use of a single (consistent) PPLT signal display arrangement throughout their jurisdictions. Most agencies used a combination of post-mounted five-section vertical displays in median applications and five-section vertical or five-section cluster displays for mast arm or span wire mounting.
- Thirty-three agencies identified a total of 1,650 PPLT signal displays with bimodal arrow indications. These agencies explained that the bimodal indications reduced the space requirement of the signal display (by eliminating one signal section/lens), resulting in energy savings. The remaining 135 agencies did not use bimodal indications.
- Mast arm and span wire mounting was used predominantly in combination with the cluster PPLT signal display. Use of pole mountings was primarily reported with vertical PPLT signal displays for median applications.
- A total of 52% of the responding agencies mounted the overhead PPLT signal display on the lane line between the left-turn lane and the adjacent through lane, while 40% mounted the PPLT signal display over the center of the left-turn lane.
- The use of secondary or additional PPLT signal displays was nearly evenly split—49% of the agencies responding to the survey used a secondary PPLT signal display (which was usually pole mounted on the far side of the intersection), while 51% did not.
- Of the responding agencies, 40% always used the PPLT signal display as one of the two MUTCD-required through movement displays, while 37% sometimes did and 23% never did.
- The circular green permissive indication was used by 165 of the 168 agencies for left turns. Other permissive indications in use included the flashing circular yellow indication, flashing yellow arrow indication, flashing circular red indication, and flashing red arrow indication.
- PPLT signal displays were generally used with exclusive left-turn lanes—89% of left-turn lanes were exclusive, 8% were shared, and 3% were a combination of exclusive and shared lanes.
- There was little consistency in the use of supplemental signs among the responding agencies—49% of the agencies always use signs, 34% use signs only in certain conditions, and 17% do not use signs. When signs are used, more than 75% of the signs are the MUTCD R10-12 sign.
- A total of 83% of the signalized intersections using PPLT signal phasing employed a leading sequence, while 11% used a lagging sequence and 6% used a lead/lag sequence.
- A total of 53% of the responding agencies indicated that they did not use any special phasing or techniques to avoid the yellow trap, while 5% of the agencies indicated that they use Dallas or Arlington Display, 18% use exclusive left lead with PPLT lag, and 25% indicated that they used some other method.
- All off the responding agencies referred to state statutes or local ordinances that require either specific display types, display indications, or compliance with state manuals; however, only 7% of the agencies indicated that there was a law or ordinance that required certain practices in the use of PPLT phasing.

PHOTOGRAPHIC DRIVER STUDY

This section of the report summarizes a photographic driver survey that was undertaken as part of the research study. Several human perceptions affect drivers' understanding of the traffic control signal. The visual search processes, perception and reaction, and recognition and comprehension that drivers exhibit can be investigated and used to evaluate PPLT signal displays. Drivers' expectation and the complexity of the traffic control signal also influence drivers' understanding and can be incorporated into the evaluation.

Objective

The objective of the photographic driver study was to evaluate the different PPLT signal displays used in the United States (as identified through the literature review and agency survey). The evaluation explored driver understanding of the signal indication under various conditions. The conditions varied through the use of protected left-turn indications, permissive left-turn indications, through-movement indications, and PPLT signal display arrangements.

Methodology

A computer-based study tool using both dynamic and static elements was developed and used to collect data about drivers' understanding of the different PPLT signal indications and displays. To create a reasonable simulation of the driver's view, photographs of existing signalized intersections were incorporated into the computer software. These photographs acted as the background scenes for different PPLT signal displays. Over 100 photographs were categorized into three groups based on the mounting type, location of the PPLT signal display, and intersection geometry. Six photographs (two from each group) were selected to be used in the study and were incorporated into the software. Five of the six selected photos contained a vehicle in the opposing through lane(s). Because of the static nature of the photo, it was impossible to determine if the opposing vehicle was stationary or proceeding through the intersection. The remaining photo, without a vehicle in the opposing through lanes, was used as a control photo providing a means of analyzing the effect that the presence of a vehicle in the opposing through lane had on survey responses. Figures 3-1 through 3-6 illustrate each of the six background photos used in the evaluation.

Two hundred unique scenarios were produced using the six selected photographs and combinations of protected left-turn indications, permissive left-turn indications, through-movement indications, and PPLT signal display arrangements. An all-red scenario was also created for each of the PPLT signal display arrangements. A randomizer function was added to

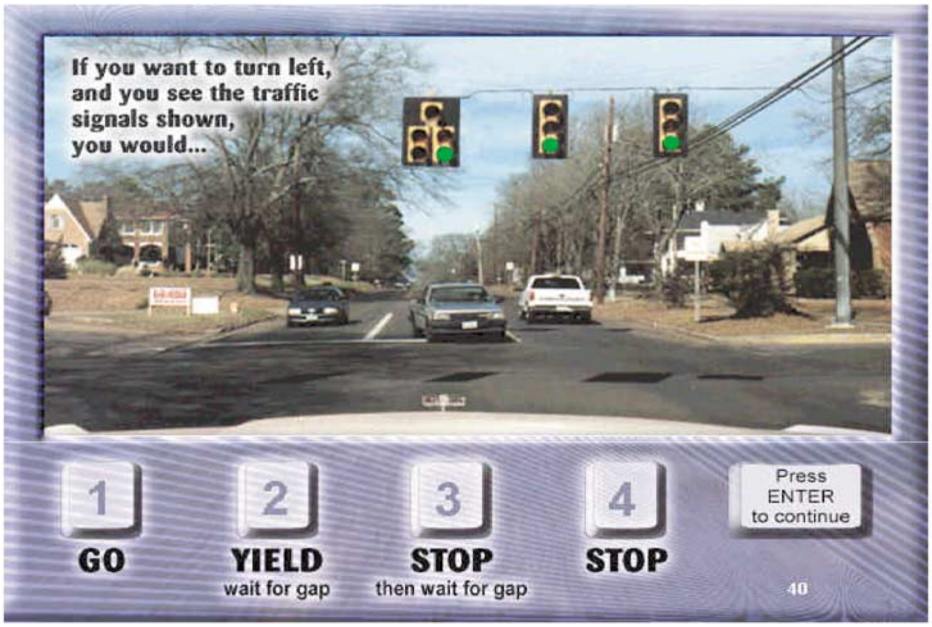


Figure 3-1. Photographic driver survey—background picture 1.

Figure 3-2. Photographic driver survey—background picture 2.

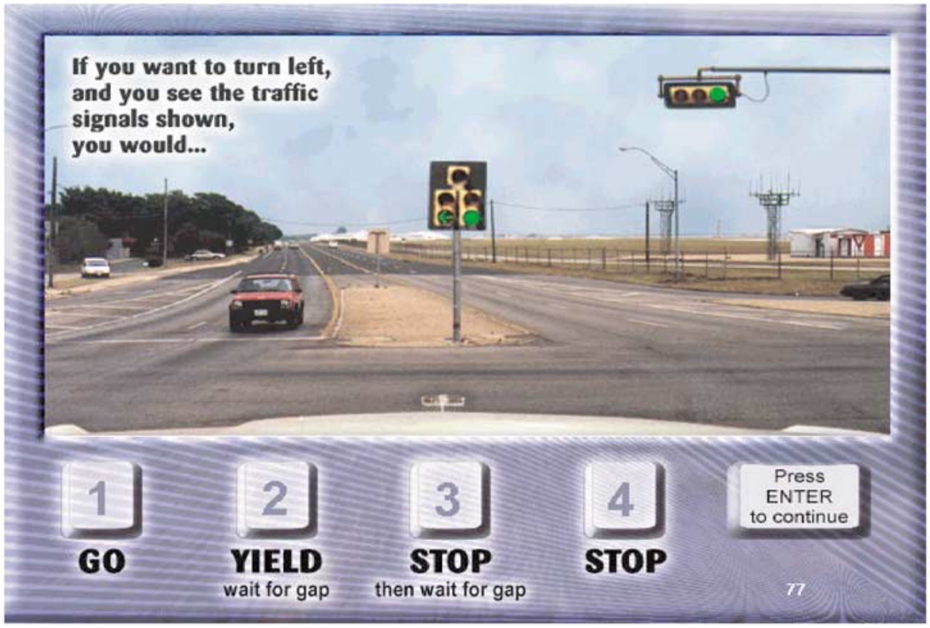


Figure 3-3. Photographic driver survey—background picture 3.

the software, which allowed a subset of 30 of the 200 scenarios to be randomly presented to each driver participating in the study.

Survey Tool

One of the objectives in the development of the photographic driver survey was to make it as self-explanatory and self-administering as possible, requiring little input from the survey administrator as each driver completed the survey. To meet this objective, all survey instructions were included as a sound track within the survey software. Along with the general survey instructions, the computer operations necessary to complete the survey were demonstrated through an example survey question.

The use of laptop computers in the photographic driver study provided the opportunity to include three additional fea-

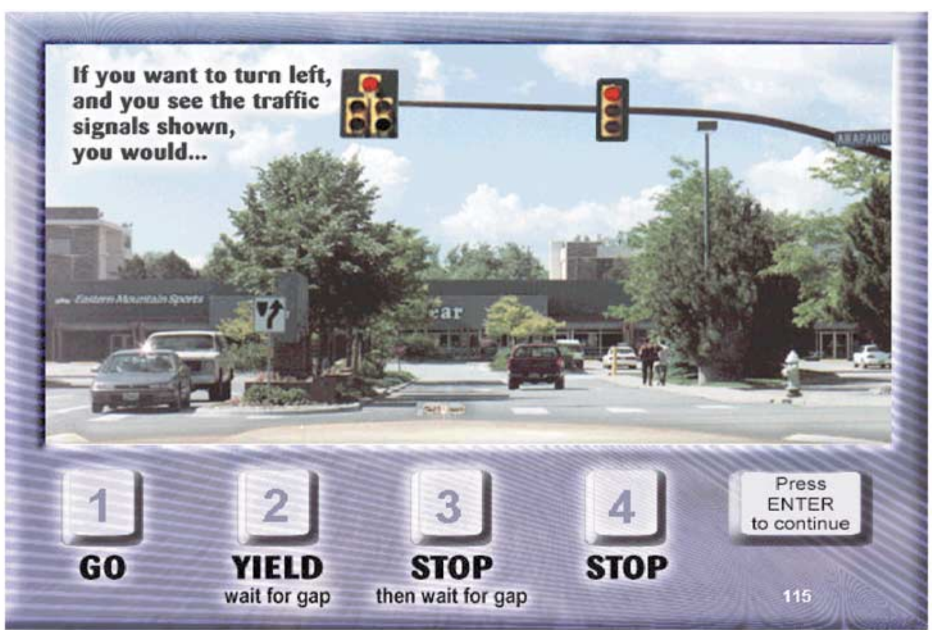


Figure 3-4. Photographic driver survey—background picture 4.

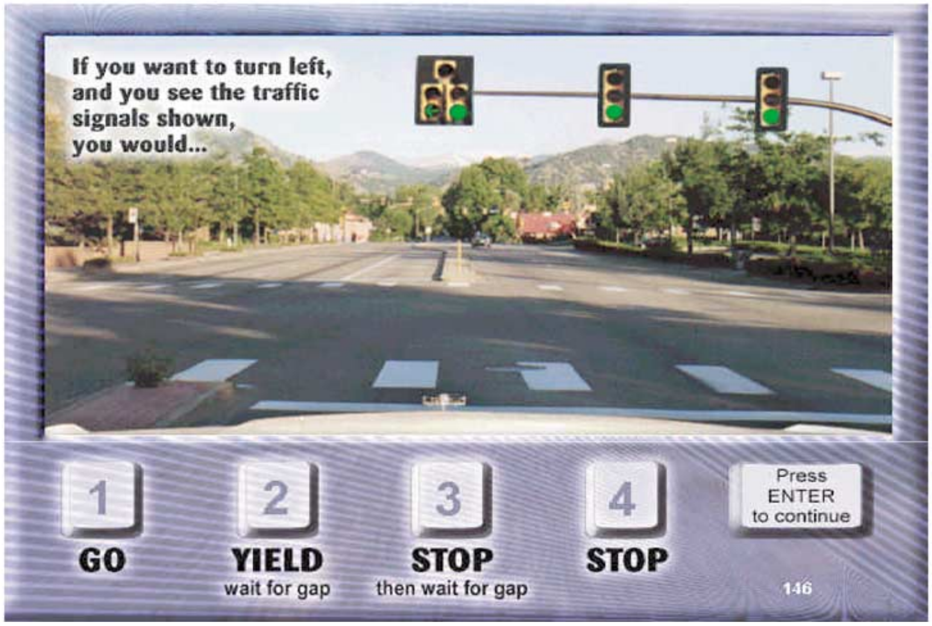


Figure 3-5. Photographic driver survey—background picture 5.

tures in the software design. First, the computer clock time was recorded for each survey response, measured from the time the scenario was presented on the computer screen to the time a response was selected. Response time data were used as a surrogate measure of driver understanding; longer response times were correlated to lower levels of driver understanding. Averaging the response times for each scenario minimized bias related to distractions, guessing, and other time variances not related to understanding.

The second feature added to the software was an initial screen that allowed the survey administrator to enter the computer number, the location of the survey, and the number of scenarios to be randomly selected and presented to each driver. This screen was only active when the software was initially loaded at the start of each survey session. The final feature added to the software was a file writing procedure for processing the survey data. As each survey response was recorded, the location, date, computer number, demographic

Figure 3-6. Photographic driver survey—background picture 6.

data, scenario number, response time, and response were written as a single row of data in a text file.

With respect to the actual operation of the survey instrument, the driver was asked “If you want to turn left, and you see the traffic signals shown, you would . . .” as each study scenario was presented. The driver used the computer keyboard to select what he or she believed to be the appropriate response. Options were as follows:

- Go.
- Yield. Wait for gap.
- Stop, then wait for gap.
- Stop.

The driver also could choose not to respond.

In addition, drivers were asked additional demographic questions, including their sexes, ages, and educational levels; whether they live in a city, suburb, or rural area; and how many miles they drove the previous year.

Survey Locations

The study was administered to respondents in Dallas, Texas; Dover, Delaware; Oakland County, Michigan; College Station, Texas; Seattle, Washington; Portland, Oregon; Cupertino, California; and Orlando, Florida. Through the study methodology, a sample size of 2,400 participants was sought. The study was conducted primarily at local drivers licensing facilities. Photographs of the driver study being administered at various locations are provided in Figures 3-7 and 3-8. Data were compiled into a single spreadsheet database and were then analyzed to determine the drivers’ understanding of the different PPLT signal displays and indications, using both descriptive and statistical procedures.

Results

A total of 2,465 drivers participated in the study, exceeding the target of 2,400 participants. At least 300 drivers completed the study at all but one of the eight locations. Because each study respondent was presented with 30 scenarios, a total of 73,950 responses were recorded.

Of the 2,465 drivers, 58% were male, 41% were female, and the balance (1%) did not respond to the gender question. A total of 27% were less than 24 years of age, 44% were between 25 and 44, 21% were between 45 and 65, and 7% were over 65. The remaining respondents (1%) did not provide their ages. In total, 58% of the participating drivers lived in a city, 30% in a suburban location, 11% in a rural location, and 1% did not respond. In total, 5% of the respondents indicated that they did not drive at all last year; 31% drove fewer than 10,000 miles; 44% drove between 10,000 and 20,000 miles; 19% drove more than 20,000 miles; and 1% did not respond. Education levels among the participants were relatively uniform—29% of the drivers had a high school or equivalent education, 35% had some college education, and 35% had a college degree, with 1% not responding.

Figure 3-7. Example of driver evaluation study workstation at Department of Motor Vehicles.

Figure 3-8. Example of driver evaluation study workstations at shopping center.

Findings

Analyses were performed to evaluate the drivers' understanding of three signal indications: all-red, protected, and permissive. (For further information on these analyses, consult Working Paper No. 3, which is included in the appendixes on the accompanying CD-ROM.) Understanding was measured by the percentage of correct responses to the study scenarios. The results of statistical analyses presented in the following sections were all conducted using analysis of variance (ANOVA) procedures at a 95% level of confidence.

An overall analysis of the demographic characteristics of the drivers in relation to the total number of survey scenarios evaluated and percentage of correct responses is presented in Table 3-1. Note that these results contain responses to all display types.

All-Red Indication Findings

- Figure 3-9 summarizes the percentage of correct responses to all-red indications. Statistical analysis of

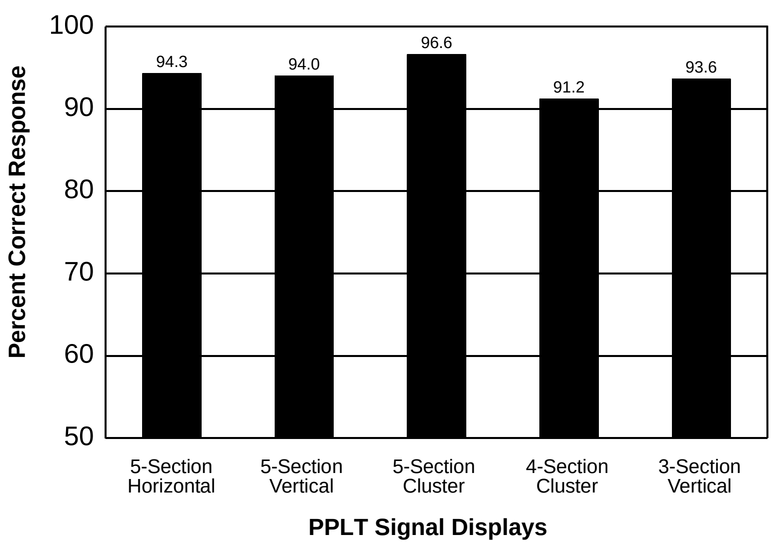


Figure 3-9. Driver understanding of all-red indications in PPLT signal displays.

TABLE 3-1 Summary of survey scenario demographics (as a function of total number of surveys evaluated for all display types)

Demographic	Level	Number of Responses	Percentage of Correct Responses
Location	Dallas	9,299	68.5
	Dover	9,722	75.6
	Oakland County	9,722	70.7
	College Station	9,034	74.6
	Seattle	9,658	78.5
	Portland	8,869	71.5
	Cupertino	8,923	69.7
	Orlando	8,226	66.7
Gender	Male	42,189	72.7
	Female	30,125	71.3
	Not Provided	456	68.9
Age	< 24	19,942	72.2
	24 – 44	32,191	73.1
	45 – 65	15,171	71.1
	> 65	4,958	67.3
	Not Provided	508	74.2
Residence	City	42,063	71.8
	Suburb	21,880	72.8
	Rural	8,528	71.8
	Not Provided	299	67.9
Miles Driven	None	3,344	62.7
	< 10,000	22,523	70.2
	10,000 to 20,000	32,746	74.1
	> 20,000	13,916	72.4
	Not Provided	241	77.2
Color Vision (Have trouble seeing red or green?)	No	69,217	72.3
	Yes	3,372	66.1
	Not Provided	181	80.7
Education	High School	20,738	67.4
	Some College	25,849	73.3
	College Degree	25,891	74.6
	Not Provided	292	66.8

the data determined that PPLT signal display type did not affect driver understanding with all-red indications.

- There was a significant difference in response times among gender and age groups. Female drivers (93.5%) had a slightly higher correct response rate than male drivers (92.8%). Drivers over the age of 65 had a 90.0% correct response rate compared with a 93.8% correct response rate for the under-24 age group.

Protected Indication Findings

- Figure 3-10 summarizes the percentage of correct responses to protected indications in the PPLT displays.
- As suggested by Figure 3-10, a statistically significant difference was found between display arrangements when considering protected indications, particularly when simultaneous displays were used in the same display arrangement. Simultaneous indications were not presented with the three and four-section displays.
- Driver understanding was significantly lower when a green arrow and a circular red indication were presented simultaneously within all five-section PPLT signal displays.
- When the green arrow and circular red indications were shown simultaneously in a five-section signal display, driver understanding was lowest with the horizontal display. Locating the green arrow to the right of the circular red indication in a five-section horizontal display arrangement as required by the MUTCD appeared to increase confusion.
- When the green arrow and circular green indications are shown simultaneously, the five-section horizontal display has the lowest level of driver understanding.
- When only a green arrow indication is provided in a left-turn signal display, driver understanding of the protected indications was not affected by the through movement indication.
- Age was found to be statistically significant because drivers over the age of 65 had an 82.5% correct response rate compared with an 88.6% correct response rate for drivers aged 24 to 44. In general, the percentage of correct responses decreased as driver age increased.

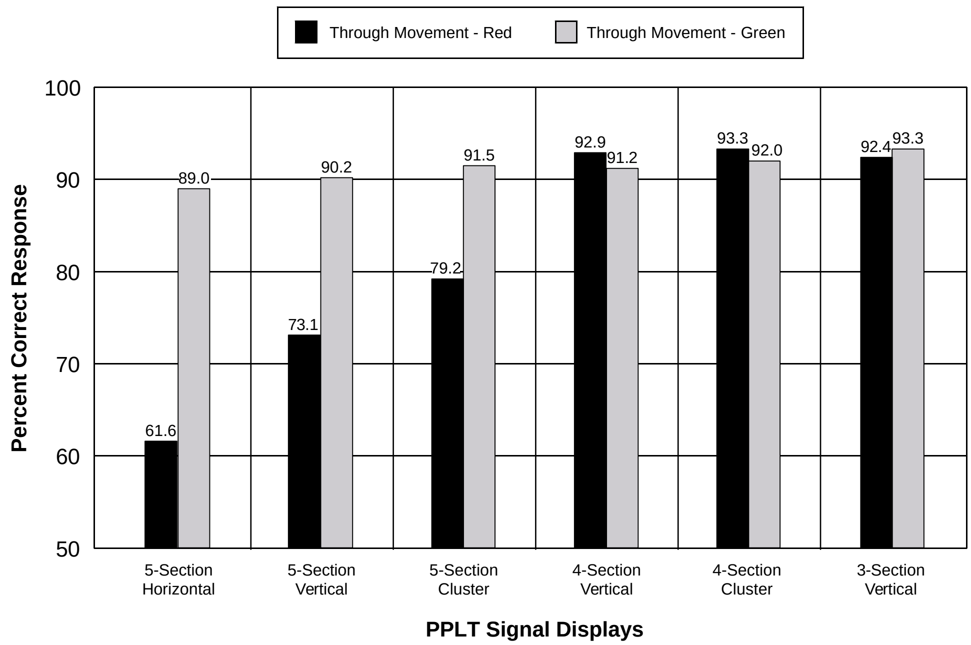


Figure 3-10. Driver understanding of protected indications in PPLT signal displays.

- The average response time associated with the five-section PPLT signal display arrangement was greatest and was longer than the average of all response times for all PPLT signal display arrangements. The longest response time was associated with the five-section horizontal PPLT signal display. This higher average response time correlates with the lower correct response rate attributed to the simultaneous illumination of the green arrow and the solid circular red indication.
- When the protected left-turn indication was exclusive (from the through-movement indication), the through-movement indication did not significantly affect drivers' understanding of the left-turn indication. The highest correct response rates were associated with the four-section and three-section PPLT signal display arrangements. These results support the use of an exclusive head.

Permissive Indication Findings

- Figures 3-11 and 3-12 summarize the percentage of correct responses to permissive indications in the PPLT displays. As shown in Figure 3-11, the circular green

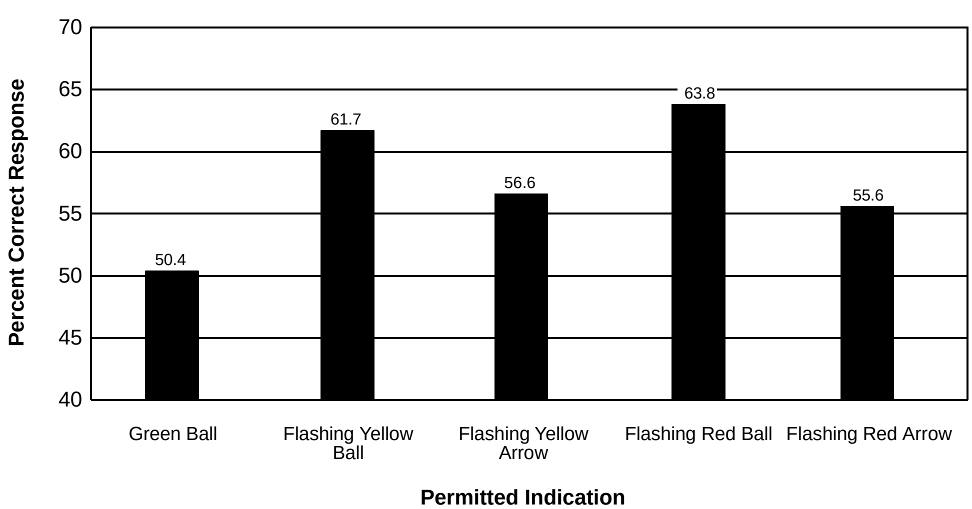


Figure 3-11. Percentage of correct responses for the permitted indications in PPLT signal displays.

indication had the lowest level of driver comprehension, at 50%.

- Figure 3-12 provides more detailed information on the percentage of correct responses to permissive indications in PPLT signal displays by display type. The differences among the arrangements were determined to be directly related to the permissive indications used within each signal display.
- The correct response rate for male drivers was 57.7% as compared with a 54.8% correct response rate for female drivers. This difference was statistically significant. Age was found to be statistically significant because drivers over the age of 65 had a 51.4% correct response rate compared with a 57.5% correct response rate for drivers aged 24 to 44.
- Drivers over the age of 65 had extremely low correct response rates with the permissive circular green indications. When the permissive circular green indication and the circular red through-movement indication were shown, less than 29% of older drivers correctly responded.
- Drivers over the age of 65 had a higher correct response rate with the flashing circular red indication and flashing yellow permissive indications than all other age groups. A total of 70% of drivers over the age of 65 correctly understood the flashing circular red indication.
- Average response time was generally lower for the flashing permissive indications. A trend in average response time by age was very evident as drivers over the age of 65 took between 2 and 4 sec of additional time to respond when compared with drivers under the age of 24.
- The analysis of the permissive left-turn indication reveals that a flashing indication is better understood than a solid indication, and a circular indication is better understood than an arrow indication.

General Findings

- Drivers' understanding of the PPLT signal displays was evaluated by combining the results from the all-red, protected left-turn, and permissive left-turn scenarios. The cluster arrangement was associated with the largest number of correct responses and the fewest fail critical responses of the five-section PPLT signal display arrangements. (For further information on these analyses, consult Working Paper No. 3, which is included in the appendixes on the accompanying CD-ROM.) The overall highest correct response rate was associated with the three-section vertical PPLT arrangement that uses a flashing circular red indication as the left-turn permissive indication.
- There was no evidence to suggest that the placement of the PPLT signal display influenced drivers' understanding of the PPLT signal display.
- The influence of the intersection geometry could not be measured because the study simulated only exclusive left-turn lane configurations.

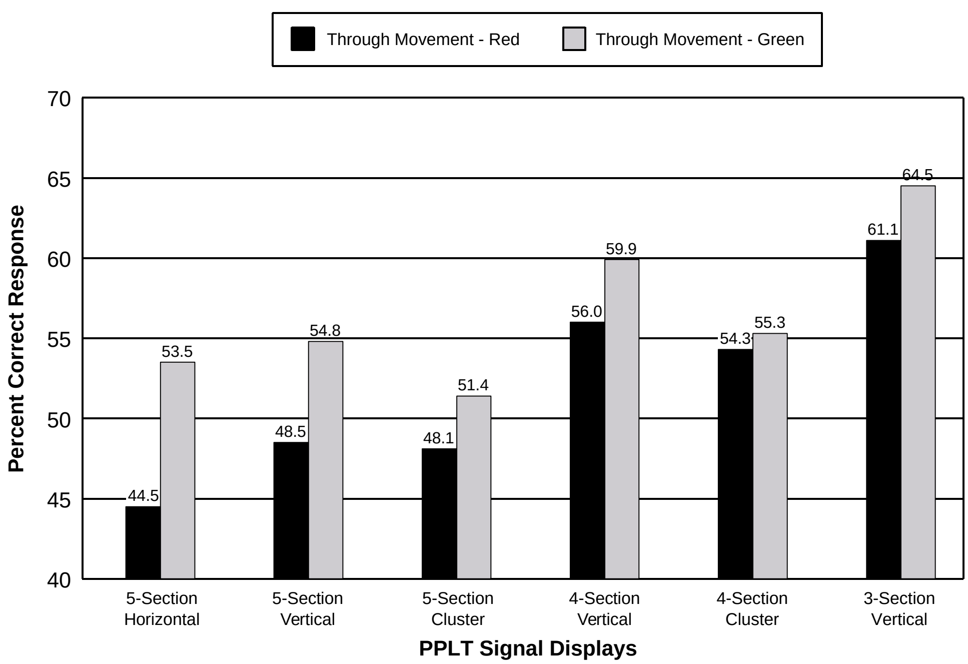


Figure 3-12. Percentage of correct responses to permissive indications by PPLT display type.

FIELD TRAFFIC OPERATIONS STUDY

Capacity and delay are two common measures of effectiveness in evaluating signalized intersection operations (*16*). *Capacity* is defined as the maximum rate of flow at which vehicles can be reasonably expected to traverse a point, a uniform segment of a lane, or a roadway during a specific period under prevailing roadway, traffic, and control conditions. *Delay* is the additional travel time experienced by a driver beyond what would reasonably be desired for a given trip.

Left-turn capacity at a signalized intersection is calculated using the saturation flow rate. *Saturation flow rate* is defined as the maximum rate of flow that can pass through a given lane group under prevailing traffic and roadway conditions, assuming that the lane group has 100% of green time available (*16*). Saturation flow is usually reached after the fourth vehicle in a queue has entered the intersection.

At the beginning of each protected left-turn movement, the first several vehicles in the queue experience start-up time losses that result in their movement at less than the saturation flow rate (*16*). This time loss is referred to as the *start-up lost time*, which is made up of the perception and reaction time (response time) to the change in signal indication along with the vehicle acceleration time to free-flow speed. Start-up lost time is important in evaluating left-turn lane capacity and driver reaction to the traffic signal indication. Reaction time was considered to include the perception time in addition to the reaction time to the onset of the green arrow indication.

Gap acceptance and follow-up headway also affect left-turn capacity and delay. *Gap acceptance* refers to the time headway in the opposing traffic stream that left-turn drivers are willing to turn through during the permissive left-turn phase. The median time headway between two successive vehicles in opposing traffic streams accepted by left-turn drivers during the permissive left-turn phase is referred to as the *critical gap*. Follow-up headway is the time between the departure of a permissive left-turn vehicle and the departure of the next vehicle using the same gap under a condition of continuous queuing. Left-turn delay can be evaluated by quantifying each of the operational variables and applying the procedures included in Chapter 16 of the *Highway Capacity Manual* (*16*).

Objective

The objective of the traffic operations study was to quantify the capacity and delay effects of PPLT signal displays and indications currently used in the United States. This objective was achieved through analysis of saturation flow rates, lost times, response times, and follow-up headways. This analysis was used to describe the driver understanding associated with the PPLT signal displays and indications.

Methodology

Field traffic operations data were collected at eight study locations: Dallas, Texas; Dover, Delaware; Oakland County, Michigan; College Station, Texas; Seattle, Washington; Portland, Oregon; Cupertino, California; and Orlando, Florida. These locations provided a range of PPLT signal displays and left-turn permissive indications and were the same sites as the photographic driver study.

With the assistance of local transportation officials, a total of 26 study intersections were identified. Intersection selections were based on left-turn lane geometry, PPLT display arrangement, and left-turn phasing. At each intersection, a video camera was installed to record the left-turn traffic flow. In addition to video taping the left-turn traffic, a researcher at the intersection simultaneously operated a portable computer and the software program HEADWAY to collect data. The data collected using the HEADWAY program were then used to compute left-turn saturation flow rate, start-up lost time, response time, and follow-up headway.

Results

Saturation flow rate, lost time, response time, and follow-up headway data were collected for 26 intersections located throughout the eight study locations. Two additional site locations were studied in Texas to evaluate the green indication used in the Dallas Display in a lead-lead and lag-lag phase sequence. The PPLT signal indications investigated included the circular green, flashing circular yellow, flashing red arrow, and flashing circular red indications. At the time the field observation studies were prepared, no flashing yellow arrow display was available for study (the field studies were completed before implementation of the Sparks display in April of 1998).

Findings

The detailed findings of the field traffic operations studies are documented in Working Paper #4. General findings include the following:

- As shown in Table 3-2, analysis of the observed saturation flow rate data determined that the geographic location was a significant contributor to the variance in the average saturation flow rates. The PPLT signal display arrangement and phasing were not statistically significant.
- Analysis of the start-up lost time data showed that the differences in average start-up lost time were significantly influenced by the PPLT signal phasing and were not significantly influenced by the PPLT signal display arrangement or study location.

TABLE 3-2 Saturation flow rate data

City	ID[1]	PPLT Display[2]	PI[3]	Left-Turn Phasing	Saturation Flow Rate (vphgpl)		Rank Order
					Average	SD[4]	
Dallas, TX	1	5-Vert.	GB	Lead	2,201	36.55	6
	2	5-Horz.	GB	Dallas-Lead	2,211	36.09	5
	3	5-Horz.	GB	Dallas-Lag	2,320	97.50	3
	4	5-Horz.	GB	Dallas-Lead	2,091	98.38	8
	5	5-Horz.	GB	Dallas-Lag	2,063	58.97	12
Dover, DE	6	4-Cluster	FRA	Lead	2,214	151.91	4
	7	4-Cluster	FRA	Lead	1,977	19.75	16.5
	8	4-Cluster	FRA	Lead	1,999	118.21	15
Oakland County, MI	9	3-Vert.	FRB	Lag	2,168	111.09	7
	10	3-Vert.	FRB	Lag	2,399	86.51	2
	11	3-Vert.	FRB	Lag	2,402	52.54	1
College Station, TX	12	5-Horz.	GB	Lead	1,973	60.65	18
	13	5-Horz.	GB	Lead	2,025	78.42	14
	14	5-Cluster	GB	Lag	2,045	57.13	13
Seattle, WA	15	4-Vert.	FYB	Lead	1,773	3.00	22
	16	4-Vert.	FYB	Lead	---	---	24.5
	17	4-Vert.	FYB	Lead	---	---	24.5
Portland, OR	18	5-Cluster	GB	Lead	---	---	24.5
	19	5-Cluster	GB	Lead	1,871	40.13	21
	20	5-Cluster	GB	Lead	1,977	7.00	16.5
Cupertino, CA	21	4-Vert.	FRA	Lead	2,065	48.26	11
	22	4-Vert.	FRA	Lead	1,944	146.93	20
	23	4-Vert.	FRA	Lead	---	---	24.5
Orlando, FL	24	5-Cluster	GB	Lead	2,067	42.58	10
	25	5-Cluster	GB	Lead	2,072	61.87	9
	26	5-Cluster	GB	Lead	1,963	102.93	19

1. Intersection Identification Number

2. Number of signal display sections (3, 4, or 5) - arrangement (Horizontal, Vertical, or Cluster)

3. Permitted Indication - G = Green; Y = Yellow; R = Red; B = Ball (circular indication); A = Arrow; F = Flashing

4. Standard Deviation

- Analysis of the response time data indicated differences in average response time to be significantly influenced by the PPLT signal arrangement and phasing and by the study location, although most of the variability was explained by the effect of the PPLT signal phasing.
- Analysis of the follow-up headway data considered the effect of the PPLT signal display and the left-turn permissive indication. The results of this analysis are shown in Table 3-3.

As shown in Table 3-3, the follow-up headway associated with the flashing red PPLT indication used in Dover was longer than all other observed follow-up headways. The follow-up headway associated with the flashing red PPLT indication used in Michigan was comparable to the follow-up headway associated with the circular green, flashing circular yellow, and flashing red arrow indications.

FIELD TRAFFIC CONFLICT STUDY

Traffic conflicts involve the interaction of two or more drivers where one or more drivers take evasive action to avoid a collision (*17, 18, 19*). Traffic conflict studies provide one of the most effective ways to supplement crash studies in estimating the crash potential of various PPLT signal displays. In addition, traffic conflict studies can be used to estimate traffic safety when crash rates are not available. Collecting traffic conflict data can also be valuable in identifying whether unsafe vehicle maneuvers are prevalent at an intersection. Conflict studies also provide an effective way to study specific geometric applications at PPLT intersections.

Conflicts can be considered vehicle interactions that may lead to crashes. For a conflict to occur, the road users must be on a collision course (*17, 18, 19*). The primary requirement of a traffic conflict is that the action of one user places another user on a collision path unless evasive action is taken. Collisions and near-miss situations that occur without evasive maneuvers, or when the evasive action is inappropriate or inadequate for conditions, are also recorded as conflicts.

TABLE 3-3 Rank order of PPLT signal display by average follow-up headway

PPLT Signal Display	Location	Permissive Indication	Rank Order
5-Section Vertical	Dallas, TX	Circular Green	3
4-Section Vertical	Seattle, WA	Flashing Circular Yellow	4
4-Section Vertical	Cupertino, CA	Flashing Red Arrow	6
3-Section Vertical	Oakland County, MI	Flashing Circular Red	5
5-Section Horizontal	College Station, TX	Circular Green	2
5-Section Cluster	Portland, OR	Circular Green	1
4-Section Cluster	Dover, DE	Flashing Red Arrow	7

Conflict studies are used to evaluate safety, as well as to select signal phasing. An Institute of Transportation Engineers (ITE) study found that 33% of reporting agencies used a left-turn conflict rate of four conflicts per 100 left-turning vehicles as a warrant for implementing PPLT signal phasing (*20*).

Objective

The objective of the traffic conflict study was to quantify left-turn conflict rates and event rates for different PPLT signal displays and indications. Traffic events are unusual, dangerous, or illegal non-conflict maneuvers such as red indication violations, backing, hesitation on signal change, and slowing considerably in a traffic lane.

Methodology

Conflict studies were conducted in Dallas, Texas; Dover, Delaware; Oakland County, Michigan; College Station, Texas; Seattle, Washington; Portland, Oregon; Cupertino, California; and Orlando, Florida. These locations provided a range of PPLT signal displays and left-turn permissive indications and were the same locations where the photographic driver study and operations studies were conducted.

With the assistance of local transportation officials, a total of 26 study intersections were identified. Specific intersections were selected based on the left-turn lane geometry, PPLT display arrangement, and left-turn phasing.

At each intersection, conflict data were recorded on a data collection form. Each intersection was observed for 8 hr on a weekday between 7:00 a.m. and 6:00 p.m. To back up real-time observations, a video camera was also installed at each intersection. The videotape was reviewed to clarify any discrepancy in the manually recorded field data.

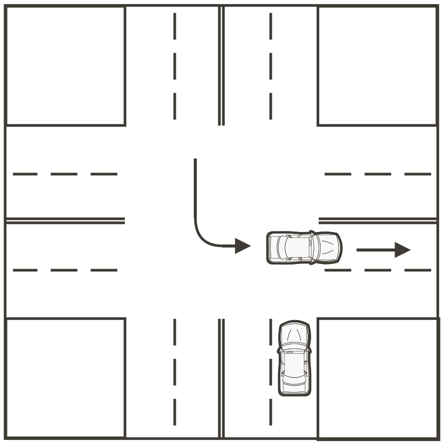
Observed conflicts were categorized as follows:

- Type 1—opposing left-turn conflicts;
- Type 2—left-turn/same direction conflicts;
- Type 3—left-turn/lane change conflicts; and
- Type 4—secondary conflicts, such as those involving a pedestrian or bicyclist or resulting from a lane overflow.

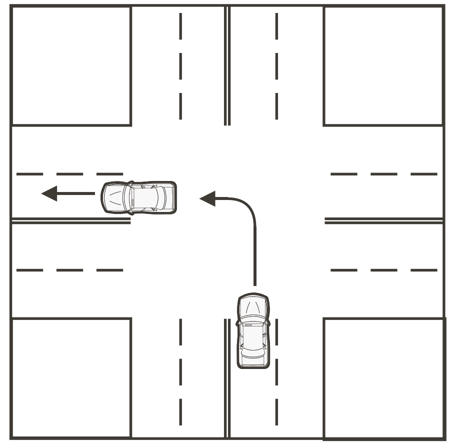
Figure 3-13 illustrates the conflict types.

The observed traffic events were also categorized by type as follows:

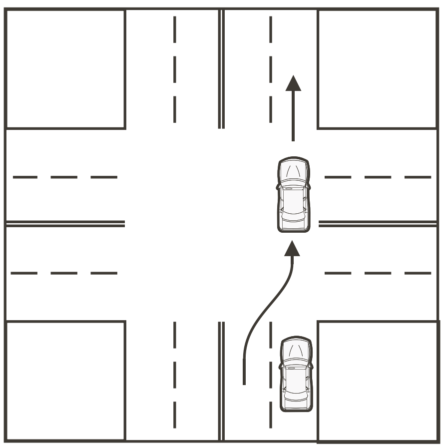
- Type 1—driver hesitating on the left-turn protected indication
- Type 2—driver hesitating on the left-turn permissive indication
- Type 3—driver going through the circular red indication
- Type 4—driver backing a vehicle out of the intersection, back into the left-turn lane



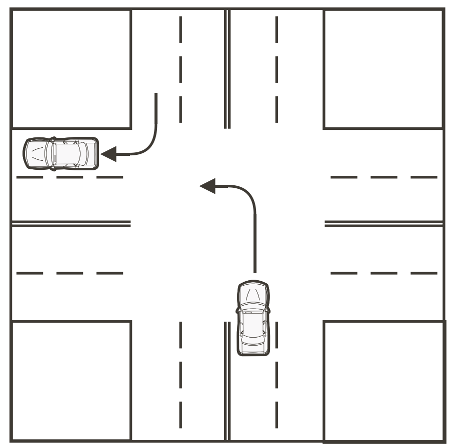
Type 1: Opposing left-turn conflict



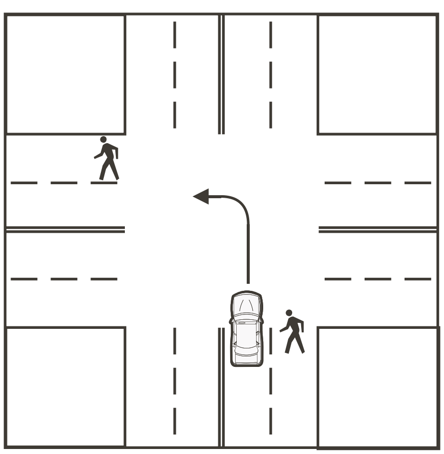
Type 2: Left-turn, same direction conflict



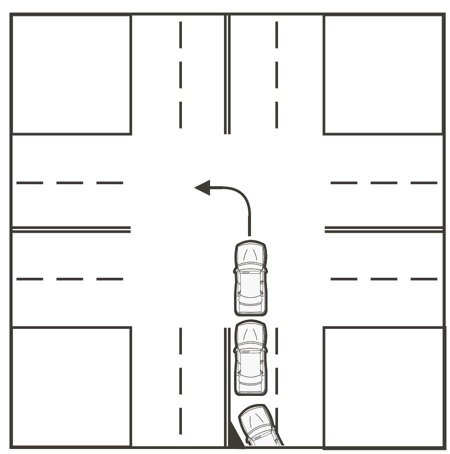
Type 3: Lane-change conflict



Type 4: Opposing right-turn-on-red conflict



Type 4: Left-turn ped/bicycle far/near side conflict



Type 4: Left-turn lane overflow

Figure 3-13. Illustration of conflict types.

Results

A total of 11 hr of data were collected at each of the 24 study intersections for a total of 264 hr of observation time. During the observation period, the research team observed approximately 22,000 vehicles; of which 5,000 were left-turn vehicles; and 17,000 were through vehicles.

A total of 166 left-turn conflicts were observed: 155 Type 1, 9 Type 2, and 2 Type 3 conflicts. No Type 4 conflicts were observed.

Of a total of 242 traffic events observed, 147 were Type 1, 53 were Type 2, 5 were Type 3, and 37 were Type 4.

Findings

- Overall, the left-turn conflict rates were low for all PPLT displays evaluated.
- Few left-turn conflicts were associated with the PPLT display.
- Most left-turn events were related to hesitation at the onset of the green indication.
- Aggressive driving appeared to be the cause of 146 of the 155 Type 1 conflicts. Drivers continued to make left-turn maneuvers during the yellow and all-red phase following the protected left-turn phase and were in conflict with the opposing through traffic.
- Eight Type 1 conflicts appeared to be the result of the driver's assuming the right-of-way when the left-turn permissive circular green indication was illuminated. Two of these conflicts occurred at intersections with the five-section horizontal PPLT arrangement and the remainder occurred at intersections with the five-section cluster PPLT arrangement.
- One Type 1 conflict appeared to be the result of the driver's assuming the right-of-way when the left-turn permissive flashing red arrow indication was illuminated on a four-section cluster arrangement.
- The nine Type 2 conflicts were primarily the result of a driver's hesitating to turn left on the left-turn permissive indication. The sudden hesitation would cause a conflict with the following vehicles. There appeared to be a relationship between the driver's understanding of the permissive circular green indication and the observed Type 2 conflicts.
- The two Type 3 conflicts were a result of driver error and not the lack of understanding of the PPLT signal display.
- The largest occurrence of Type 1 traffic events involved the five-section horizontal PPLT signal display arrangement. The simultaneous illumination of the green arrow and the circular red indications appeared to increase the workload of the driver, resulting in an increase in driver uncertainty.
- Type 2 traffic events were observed at each of the study intersections. The occurrence did not appear to be related to the PPLT signal arrangement or phasing or indication.
- Numerous drivers were observed proceeding through the all-red indication (i.e., red light runners). Therefore, Type 3 events were recorded only when the action was clearly a function of driver misunderstanding. For this reason, only five Type 3 events were recorded, and the occurrences showed no pattern to suggest an influence of the PPLT signal display, indication, or phasing.
- Of the 37 observed Type 4 events, 33 were associated with a flashing permissive indication. The driver would enter the intersection during the permissive phase and not have the opportunity to make the left-turn maneuver. The driver would then choose to back up.

CRASH DATA ANALYSIS

Given the the extensive use of crash data in many past studies in the evaluation of left-turn control, the research team conducted a limited study of crash history related to the unique displays used in PPLT control. The project panel and research team recognized that current crash reporting techniques do not adequately document causes of a crash as they relate to traffic signal operation, much less the particular signal display. To overcome this short coming, the research team identified a work plan that would compare the various PPLT control displays against one another and make judgments as to whether a particular display was more or less prone to increased crash occurrence.

Objective

The objective of the crash analysis was to determine and compare left-turn crash rates associated with various PPLT signal displays. The details of the crash data analysis are described in the following sections.

Methodology

To accomplish the objective of the crash data analysis, three tasks were conducted. Those tasks are listed below:

- Perform a literature review to obtain background information on crash data analysis procedures and to review the results of previous studies;
- Obtain traffic volumes, geometric design, signal display information, and 3 years' of crash data for the study intersections (the same intersections studied in the operational study and the conflict study were evaluated in the crash analysis). In addition, crash data were sought from agencies around the United States;
- Reduce the data and analyze the results.

Results

Since the mid-1970s, more than 40 reports have been published on the use and operational impacts of the PPLT signal control treatment. Several of these reports were spurred by the increase in the use of PPLT phasing. In general, many of these reports identified trends in vehicle delay, vehicle conflicts, and vehicle crashes. Further, these studies related the effects of PPLT phasing to geometric and physical conditions, such as traffic volume, number of opposing lanes, signal displays, and the use of supplemental signing. Over 30% of the reports are focused on warrants or guidelines related to the use of PPLT phasing.

The purpose of the literature review was to identify how crash data were evaluated and what crash statistic should be used for this study. The literature review was selective in that not all reports related to PPLT phasing were studied. Certainly, many good reports are available as a resource. The literature review identified reports that were key to this study because of the significance related to their findings and/or the strict focus related to PPLT phasing. Specifically some reports focused on the PPLT indications, display arrangement, and/or display location—all of which are study factors for this NCHRP study.

The select literature review identified several key findings related to PPLT phasing:

- Hummer determined that the crash frequency is higher for PPLT intersections with leading left-turns compared with lagging left-turns (*21*). However, Upchurch determined that this was true for intersections with three opposing lanes of traffic (*22*). Upchurch determined that the lagging PPLT had the worst crash record when there were two opposing lanes of traffic.
- Almost all literature shows that the leading protected left-turn phasing has the lowest crash rate (*22, 23*).
- Upchurch (*22*) and Hauer et al. (*24*) both determined that crash frequency relationship to traffic demand is nonlinear.
- Bonneson and McCoy determined there was no statistical difference in crash frequency among the most common PPLT display arrangements (*25*).
- The Washington Section of ITE determined the flashing circular yellow display was safer than the circular green permissive display (*26*).
- Agent (*27, 28, 29*) determined that the use of PPLT phasing can reduce left-turn delay by 50% and total delay by 24%, compared with protected-only phasing.

Although not all reports agree with one another, the general findings related to the use in PPLT phasing, in aggregate, suggest the following:

- Vehicle delay decreases,
- Fuel usage decreases,
- Vehicle progression is improved, and
- Vehicle crashes increase.

The use in PPLT phasing should be applied on a case-by-case basis, because not all intersection approaches are candidates for PPLT phasing.

Data Analysis

For the purpose of this study, the research team identified three sources of crash data for analysis. First, crash data were obtained from the same 24 study intersections examined in the operational and conflict studies. Specifically, crash data were obtained for each of the following eight geographic regions of the United States (three intersections per geographic location): College Station and Dallas, Texas; Portland, Oregon; Seattle, Washington; Detroit, Michigan; Cupertino, California; Dover, Delaware; and Orlando, Florida. The crash data were requested for the most recent 3 years.

The second source of crash data was from the network of volunteers identified through the Agency Survey. Without exception, these data represented the circular green permissive display (as allowed in the MUTCD).

For the third source of crash data, the research team evaluated the database created in 1988 as part of a previous FHWA study of PPLT displays (*23*). This third source of data was identified as a potential source of historical data, in that some of those intersections were thought to still be in operation as they were in 1988. The research team intended to use the information in the database as additional analysis locations and thus as new data points or for comparative analysis. It was later determined that none of the intersections in the database were using the same PPLT display and the same intersection geometry and, as a result, no further analysis of the database was prepared.

Findings

Crash Analysis of the 24 Study Intersections

The research team calculated several different crash statistics as follows: (1) average number of crashes per year per intersection, (2) the average number of crashes per year per 100 left-turning vehicles, (3) the average number of crashes per year per 100,000 left-turning times opposing through vehicles, and (4) the average rate for the intersection based only on left-turn crashes. The findings of these analyses are presented below.

- The analysis of the average crash rate per year indicated that the four-section (dual indication) flashing circular yellow indication used in Seattle experienced the fewest number of crashes (per year) at 0.75. The highest average crash rate per year occurred in Oakland County, Michigan. Ranking by city is summarized in Table 3-4.

- An analysis of average crashes per 100 left-turning vehicles indicated again that the flashing circular yellow indication used in Seattle was the lowest. The highest average statistic was 2.29 in College Station, Texas, which had a circular green indication. Ranking by city is summarized in Table 3-5.
- An analysis of the average crashes per [100,000 left-turning vehicles multiplied by opposing through vehicles] indicated yet again that the flashing circular yellow indication used in Seattle had the lowest statistic and that the circular green indication in College Station had the highest statistic. Ranking by city is summarized in Table 3-6.
- An analysis of the average left-turn crash rate by intersection indicated that Cupertino, California, had the lowest average at 0.28. The highest average crash rate by intersection was College Station, Texas, at 0.70. Ranking by city is summarized in Table 3-7.

In the aggregate, the crash analysis findings show that the PPLT displays studied did not perform consistently within a selection of four crash statistics. The ranking of one crash statistic did not match that of another crash statistic. Two particular displays, the flashing circular yellow indication used in Seattle and the circular green indication used in College Station, did rank similarly among most of the crash statistics. Further, there was no correlation between the crash rate analysis and the conflict study results in rank ordering.

Crash Analysis of the Intersections Identified Through Volunteer Agencies

Six volunteer agencies responded to a request to supply crash data: the City of Modesto, California; the Mississippi DOT; the North Carolina DOT; the Texas DOT; the Washington DOT; and the Wisconsin DOT. A total of 135 intersections of crash data were received, of which 120 intersections were used in the analysis. These crash data represented a total of 284 intersection approaches using PPLT control. All of these intersections used the five-section cluster or five-section vertical display arrangement. The crash analysis consisted of computing the average crash rate for the intersection and resulted in a rate that represents the overall average accident rate for the PPLT design type, calculated as the average of the intersection accident rates.

In general, most of the intersections yielded results similar to those found in Portland, Orlando, Dallas, and College Station (locations that also use the circular green indication). Several intersections yielded average crash rates of 1.5 and higher (which may indicate a safety problem). No meaningful trends were identified.

TABLE 3-4 Ranking of PPLT performance based on crashes per year

City	PPLT Indication	Crash Rate
Seattle	Circular Flashing Yellow	0.75
Cupertino	Flashing Red Arrow	0.83
Dover	Flashing Red Arrow	0.85
Portland	Circular Green	1.04
Orlando	Circular Green	1.48
Dallas	Circular Green	2.06
College Station	Circular Green	2.53
Oakland County	Flashing Circular Red	2.92

TABLE 3-5 Ranking of PPLT performance based on crashes per 100 left-turning vehicles

City	PPLT Indication	Crash Rate
Seattle	Circular Flashing Yellow	0.47
Portland	Circular Green	0.71
Orlando	Circular Green	0.73
Cupertino	Flashing Red Arrow	0.87
Dover	Flashing Red Arrow	0.96
Dallas	Circular Green	1.10
Oakland County	Flashing Circular Red	1.23
College Station	Circular Green	2.29

DRIVER CONFIRMATION STUDY

The driver confirmation study was conducted using fully-interactive dynamic full-scale driving simulators located in the Human Performance Laboratory on the University of Massachusetts—Amherst (UMass) campus and at the Texas Transportation Institute (TTI) at Texas A&M University. An evaluation of the same PPLT signal displays in a static environment was also completed at both locations to provide

TABLE 3-6 Ranking of PPLT performance based on crashes per [100,000 left turn × opposing through vehicles]

City	PPLT Indication	Crash Rate
Seattle	Circular Flashing Yellow	0.87
Cupertino	Flashing Red Arrow	0.91
Orlando	Circular Green	0.92
Oakland County	Flashing Circular Red	1.18
Dover	Flashing Red Arrow	1.85
Portland	Circular Green	2.27
Dallas	Circular Green	4.56
College Station	Circular Green	6.75

TABLE 3-7 Ranking of PPLT performance based on average left-turn crash rate

City	PPLT Indication	Crash Rate
Cupertino	Flashing Red Arrow	0.28
Dover	Flashing Red Arrow	0.29
Dallas	Circular Green	0.34
Seattle	Circular Flashing Yellow	0.34
Oakland County	Flashing Circular Red	0.44
Orlando	Circular Green	0.49
Portland	Circular Green	0.52
College Station	Circular Green	0.70

comparison data to the simulator experiment as well as to the photographic driver study.

Objective

The objective of the driver confirmation study was to evaluate drivers' comprehension of the most promising types of PPLT signal displays using full-scale driving simulators. The following sections summarize the development and administration of the driving simulation experiment and the follow-up static evaluation completed at both universities.

Signal Displays Studied

The previous research activities were used collectively to identify the displays studied in this research task. Following lengthy and detailed discussions of study results, the research team and project panel identified 12 PPLT signal displays for further evaluation. The selected displays differed in permissive indication, display face, location, and through movement indication. Each of the PPLT signal displays included only the circular green indication and/or flashing yellow arrow permissive indications.

The flashing red permissive indications and the circular yellow permissive indication were not evaluated in this effort. The flashing red arrow and circular red indications were eliminated by the project panel from future consideration after much discussion with the research team because of the message that these indications presented (i.e.,"stop, then proceed if a gap is available" rather than the more typical PPLT "proceed if a gap is available" message). Additionally, the flashing permissive red indications may dilute the meaning of other red stop indications. The circular yellow indication was eliminated because the flashing yellow arrow display had nearly the same level of driver comprehension and the flashing yellow arrow could be applied to either left- or right-turn treatments.

The circular green permissive indication represented the current state of the practice, and the flashing yellow arrow permissive indication represented the most promising alternative, based on study findings to date and panel recommendations. Figure 3-14 illustrates the PPLT displays evaluated in the driving simulation experiment.

As shown in Figure 3-14, the research team included a unique PPLT display that was currently in operation in Sparks, Nevada. This "Sparks Display" uses an exclusive left-turn signal display (five-section cluster) and simultaneously illuminates the circular green indication and the flashing yellow arrow indication during the permissive left-turn interval. In this application, the flashing yellow arrow indication is supplemental information to the circular green indication.

Simulator Environment

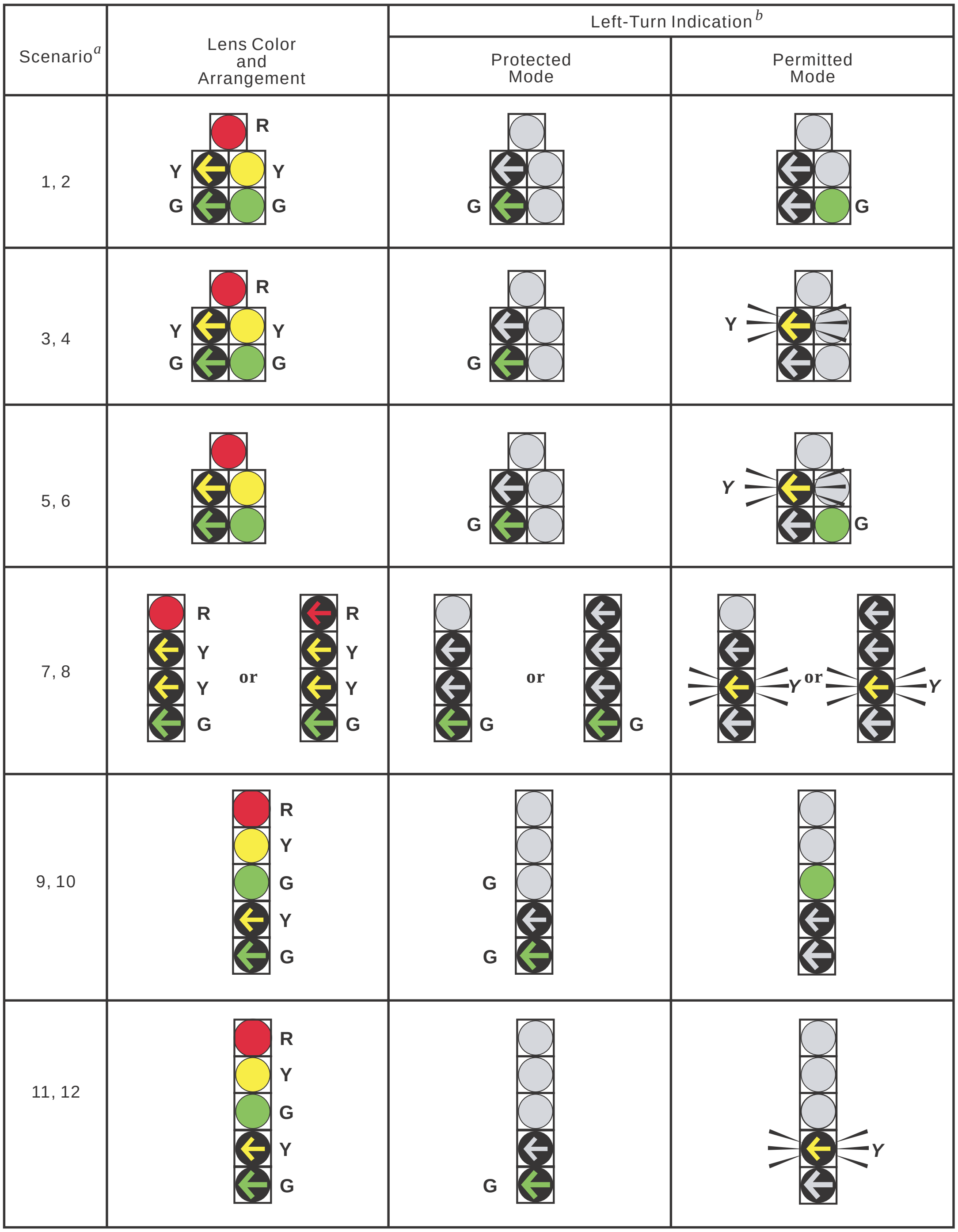
Similar driving simulators at UMass and TTI were used to complete the experiment. The two simulators are briefly described below.

A fixed-base, fully interactive dynamic driving simulator, housed in the Human Performance Laboratory on the UMass campus, was used to complete the driving simulation experiment. The vehicle base of the driving simulator is a 1995, four-door Saturn sedan. Drivers can control the steering, braking, and accelerating similar to the actual driving process; the visual roadway adjusts according to the driver's actions. Three separate images were projected to create the "visual world" on a large semi-circular projection screen creating a field-of-view that subtends approximately 150 deg. The simulator also featured a surround audio system, a 60-Hz refresh rate, and a resolution of 1024 x 768 dots per inch. The UMass driving simulator is pictured in Figure 3-15.

At TTI, the apparatus used for the experiment was a driving environment simulator (DESi). Almost identical to the UMass simulator, DESi consisted of three white screens 2.28 m (90 in) in height and width, a 1995 Saturn SC2 complete vehicle, three image-generation personal computers, one data collection personal computer, and three liquid crystal display Proxima 6810 projectors. The three separate images projected onto the screens were aligned so they appeared to the driver as one single image covering a 150-deg field of view horizontally and a 50-deg field of view vertically. Consistent with the UMass simulator, participants sat in the center of the DESi in the driver's seat of the Saturn, from which they could control the steering, braking, and accelerating similar to the actual driving process. The TTI driving simulator is pictured in Figure 3-16. Figure 3-17 depicts a typical PPLT intersection in the UMass driving simulator experiment.

Simulator Study Methodology

Each driver was presented with a practice course before the execution of the actual experimental modules. The practice course was provided to familiarize the driver with the simulator environment. Oral communication between the



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

[a] 1, 3, 5, 7, 9, 11 -GB through indication; 2, 4, 6, 8, 10, 12 - RB through indication

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

Figure 3-14. PPLT displays evaluated in driver simulator experiment.

Figure 3-15. UMass Human Performance Laboratory driving simulator.

research team and the driver was avoided. Therefore, drivers navigated through the modules by using guide signs provided on each intersection approach. In addition, drivers were asked to observe speed limit signs (30 mph), providing a higher level of realism and speed control during the experiment. The driving portion of the experiment, including the practice module, required between 15 and 20 min to complete.

Drivers' response to each PPLT signal display scenario presented was recorded manually as correct or incorrect by two members of the research team. Incorrect responses were further classified as being fail-safe or fail-critical. A fail-safe response was one in which the driver did not correctly respond to PPLT signal display but did not infringe on the right-of-way of the opposing traffic. A fail-critical response was an incorrect response in which the driver incorrectly responded to PPLT signal display and impeded the right-of-way of opposing traffic, creating the potential for a crash.

Throughout the study, drivers were asked to express their thoughts out loud about anything they observed. Research team members were present to record the results of the simulation, including responses at each intersection and other driving-related factors such as indecision, unnecessary braking, or pertinent verbal comments. Each experiment was recorded on videotape allowing the researchers to verify and review the manually collected data.

Opposing Traffic

Each of the PPLT signal displays was evaluated with opposing traffic at the intersection. The introduction of opposing traffic required drivers to evaluate simultaneously the PPLT signal display, traffic movement, and opposing gaps to complete a safe permissive left-turn maneuver. This methodology was used to replicate the decision process required during actual operation of a motorized vehicle within the roadway system.

All gaps in opposing traffic were consistently applied at intersections where drivers were required to make a permitted left-turn maneuver. Six opposing vehicles were used. Two vehicles were always positioned at the stop bar in the two through lanes opposing the left-turn driver. The remaining four were positioned further upstream in a specified gap sequence. Gaps were set at 3 and 7 sec in a series of 7-3-7-7; therefore, opposing vehicles crossed the intersection 7, 10, 17, and 24 sec behind the two initially queued opposing vehi-

Figure 3-16. TTI driving environment simulator (DESi).

cles. The critical gap concept was used to select the gap sizes. The Highway Capacity Manual indicates that a critical gap value of approximately 5.5 sec for permitted left-turn maneuvers in the design of a four-lane roadway is acceptable (*16*). Therefore, a 3-sec gap was selected because it was small enough that most drivers will not accept it, and a 7-sec gap was selected because it was generally acceptable to most drivers. Providing a consistent sequence of 3- and 7-sec gaps prevented gap selection from being a significant variable in the PPLT analysis.

The only difference in the driving simulator experiments at UMass and TTI was the initial method of introducing the opposing traffic. For simplification, the methods will be referred to as the Release Method of Opposing Traffic (RMOT) and the Continuous Method of Opposing Traffic (CMOT).

The RMOT is the methodology described above. A trigger in the simulator model, similar to that used to change the signal indications, was placed near the left-turn stop bar at each PPLT intersection to release the opposing traffic. By placing the opposing traffic release trigger approximately 5 ft from the stop bar, left-turn drivers were required to make a decision as to the meaning of the PPLT signal indication and desired action before knowing the actions of the opposing traffic.

At TTI, the research team explored the effects of a slightly different opposing vehicle method. A total of 116 drivers completed the experiment, which used the CMOT traffic. The CMOT method of opposing traffic had the opposing traffic moving as the driver approached the intersection. All gaps in opposing traffic were consistent with the RMOT method and applied at each intersection where drivers were required to make a permitted left-turn maneuver.

The opposing traffic consisted of three vehicles. As the driver approached the intersection, a trigger in the simulation located approximately 400 ft upstream of the left-turn stop bar released the opposing traffic. At this time, the first opposing vehicle was located approximately 950 ft downstream of the driver. The opposing vehicle was set to match the speed of the driver. In this setup, the first opposing vehicle approached the intersection, almost mirroring the driver so that they reached the intersection at approximately the same time. The next two vehicles followed the initial opposing vehicle 3 and 10 sec after the first vehicle; therefore, the driver observed a 3- and a 7-sec gap after the initial opposing vehicle had passed.

Using two methods of opposing traffic allowed for an evaluation of opposing traffic impacts on driver comprehension of PPLT signal displays. To determine the geographical

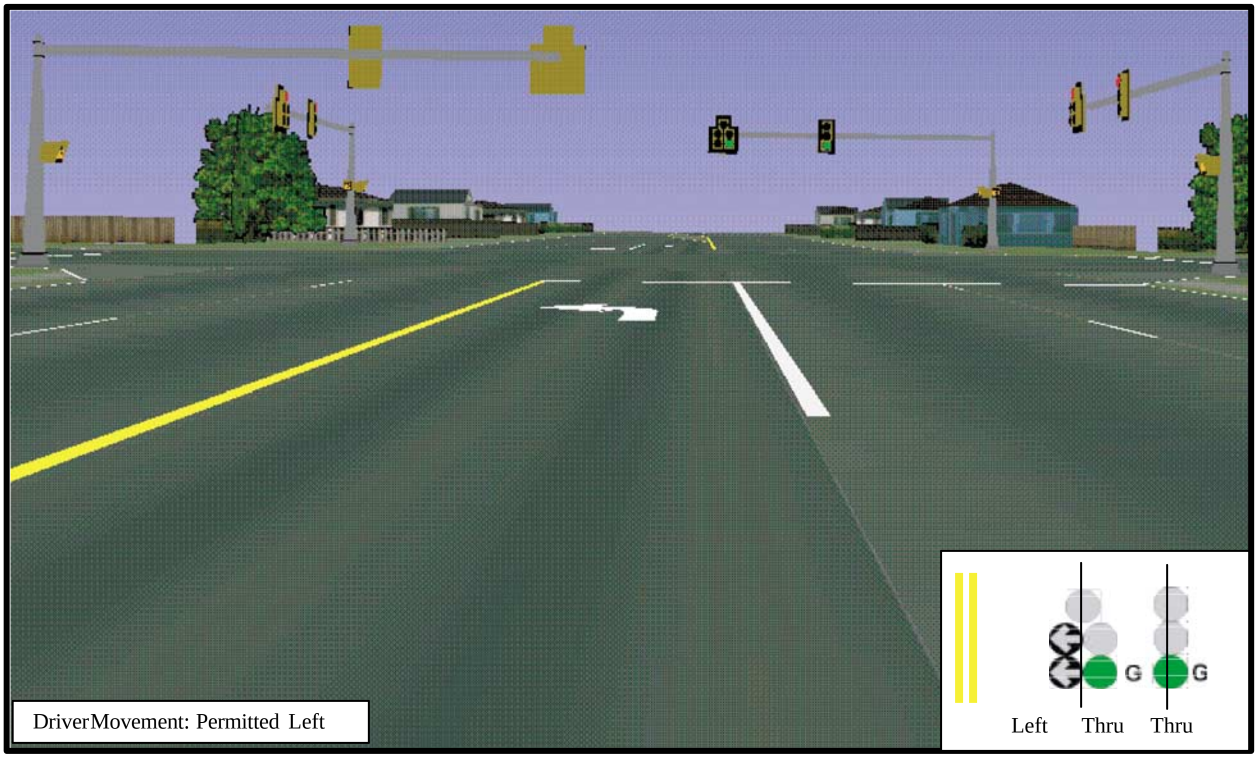


Figure 3-17. Screen capture of typical intersection in simulator at UMass.

effects of drivers in the simulated environment, the last 93 drivers at TTI completed the experiment observing the RMOT opposing traffic. Therefore, experimental methodology and the information observed by drivers in the simulation were identical.

Video-Based Static Evaluation

After completing the driving portion of the study, drivers were asked to participate in a static evaluation of PPLT signal displays. The static evaluation was administered using videocassette recordings of the screen captures for the 12 PPLT displays. The driver was shown each display for 30 sec and asked to choose one of four responses to the traffic signal displays. Similar to the earlier Photographic Driver Study research effort, the four potential responses were as follows:

- 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.

Once drivers responded with one of the four possible choices, they were asked to indicate their confidence in the answer. Additionally, any comments made by the drivers regarding the displays were manually recorded.

Confirmation Study Sample Size

The approved research plan stipulated that 400 drivers complete the driving simulator experiment, of which 200 subjects would be tested at UMass and 200 subjects would be tested at TTI. To represent the general driving population, four age groups of drivers were identified. In addition, an attempt was made to include an equal number of male and female drivers and a range of educational and ethnic backgrounds. A total of 464 drivers participated in the study, of which 432 completed all experimental elements, yielding 4,613 individual evaluated PPLT scenarios (5,230 PPLT scenarios with the static evaluation).

Of the 432 participants who completed the study, the data for 316 became the focus of the report findings. The 316 drivers were a combination of the UMass drivers along with the TTI drivers who completed the experiment using the previously described RMOT method.

Confirmation Study Findings

Driver comprehension was determined from the distribution of correct and incorrect responses for each of the selected PPLT signal displays. Several categories of incorrect responses were used to further evaluate these data. Analysis of variance (ANOVA) statistical techniques were used to analyze all collected data to evaluate drivers' comprehension related to the 12 selected PPLT signal displays.

Driving Simulator Findings

Based on analysis of the 316 (223 at UMass and 93 at TTI) driver evaluations (3,402 displays) that were obtained in a procedurally equivalent manner, several key findings were made. These findings are presented below as they relate to geographical effects comparing drivers from Massachusetts and Texas, effects of display type, driver demographics, first-time reactions, and learned behavior.

Statistical comparisons were made to evaluate whether there were detectable geographic effects between drivers in Texas and Massachusetts. When considering the 12 experimental PPLT signal displays in each geographic location, there were no statistically significant differences between locations. Because no statistically significant differences were found between drivers from Texas and Massachusetts, the two databases were combined for further analysis.

With respect to display type, the following findings were then made:

- In the aggregate, the data showed a high level of comprehension with no variation between the different PPLT displays tested. Drivers responded correctly 91% of the time with no statistical difference between the 12 PPLT displays
- The percentage of correct responses showed no statistical difference in driver comprehension when the data were cross-analyzed by permissive indication, display arrangement, through indication, and location of the display.
- There was no statistical difference in the percentage of correct responses between permissive indication (circular green indication, flashing yellow arrow, circular green indication/flashing yellow arrow), signal display arrangement (five-section cluster, four-section vertical, or five-section vertical), PPLT display location (shared or exclusive), or adjacent through indication (circular green indication or circular red indication). Additionally, there were no significant differences by the various PPLT display components in terms of the percentage of fail critical responses.

Demographic factors such as sex, age, driver experience, and education were all expected to influence driver understanding of the PPLT displays. When evaluated on the basis of demographic effects, the following findings were made:

- The data showed that the overall level of correct responses to each permissive indication was not significant when analyzed by sex, age, number of miles driven annually, or education.
- Combined analysis of the data showed an interaction effect between sex and age. In this analysis, there was a statistically significant difference between the three age groups (ages under 24, ages 24–45, ages over 45) within the female drivers and the percentage of correct responses.
- There were no statistically significant differences in the percentage of correct or fail critical responses for the sex demographic across the 12 PPLT signal displays evaluated. Males and females had statistically equivalent levels of comprehension.
- Considering failure responses, the age demographic resulted in statistically significant differences. Drivers over the age of 45 had significantly fewer fail critical responses. Overall, older drivers were more cautious in the driving simulator experiment, often opting to wait for all opposing vehicles to pass before completing the permissive left-turn maneuver.
- Drivers who had driven between 10,000 and 20,000 miles in the previous year had significantly more correct responses and significantly fewer fail critical responses than those who drove fewer than 10,000 miles in the previous year.
- Education level of the drivers was not statistically significant in determining comprehension levels in terms of the percentage of correct responses. However, PPLT Scenario 3 (five-section cluster in a shared location with a flashing yellow arrow permissive indication and circular green through indication) was comprehended significantly more by drivers with only a high school diploma than drivers with a higher education level.

Another area of interest in evaluating drivers' responses to the PPLT displays presented in the simulator environment was the manner in which drivers responded the first time they were presented a given PPLT display. Such an evaluation was expected to provide insight as to the intuitive nature of the PPLT display(s). In addition, comparison of results for the same driver reacting to each permissive indication were reviewed to assess whether any detectable learning occurred as they proceeded through the virtual world. Each of the PPLT signal displays was equally likely to be the first PPLT display evaluated because of the balanced design of the experiment. Consequently, each of the 316 drivers in this dataset had an equally likely chance of observing any of the 12 PPLT signal displays first. Findings of the evaluation include the following:

- Analysis of the first observed PPLT display encountered by each of the 316 drivers determined that the number of correct responses was not significantly different across the 12 PPLT signal displays.
- When reviewing driver responses to the first observed PPLT signal display, there were significantly more fail critical responses when using the five-section cluster in a shared location with a flashing yellow arrow permissive indication and circular green through indication than when using a five-section cluster in a shared loca-

tion with a circular green permissive indication and circular green through indication.

- It was noted that the five-section cluster with circular green permissive indication and circular green through indication has been commonly used in both Massachusetts and Texas, and it was deemed reasonable to assume that drivers had encountered this display prior to participating in the experiment.

Static Evaluation Findings

Based on analysis of 436 driver evaluations (5,230 displays), the findings of the video-based static evaluation experiment included the following:

- Overall driver comprehension was high—83% of 5,230 scenarios were evaluated correctly.
- The permissive indication resulted in statistically significant differences of correct and fail critical responses. In contrast to the previously described driver simulator findings, displays with the flashing yellow arrow permissive indication and the circular green/flashing yellow arrow simultaneous permissive indication had significantly more correct responses than displays with the circular green permissive indication. Displays with the circular green permissive indication were associated with significantly more fail critical responses than displays with either the flashing yellow arrow or circular green/flashing yellow arrow permissive indications.
- PPLT displays with the four-section vertical display face had a significantly greater number of correct responses compared with the five-section vertical and five-section cluster displays. However, only the flashing yellow arrow permissive indication was evaluated in this display face, and it is likely this combination that accounts for the increased percentage of correct responses.
- Scenarios that contained circular red indications in the through movement signal heads resulted in a significantly lower percentage of correct responses to the PPLT displays than when the circular green through indications were presented. PPLT displays associated with the circular red through indication also resulted in significantly more fail critical responses. The research team considered the lower correct response rate to result from unfamiliarity. It is not common to use a permissive green indication for the left-turn lane and a red indication for the through movement. This demonstrated again that simultaneously displaying conflicting indications causes confusion.
- The location of the PPLT signal display (whether it was a shared or an exclusive display) did not result in statistically significant differences in correct responses.
- In contrast to the previously described driver simulator findings, statistically significant differences were observed within age, education, and driving experience demographics. Drivers over the age of 45 had a significantly lower comprehension of the PPLT signal displays. Drivers with only a high school diploma had a significantly lower comprehension than drivers with a higher education level. Interestingly, those who drove between 10,000 and 20,000 miles in the previous year had significantly more correct responses than those who drove fewer than 10,000 miles and those who drove over 20,000 miles the previous year.

Driving Simulator and Static Evaluation Comparison Findings

The results of both the driving simulator and static evaluation were compared for each driver and for all drivers combined. This analysis was completed to see how basic driver comprehension (as demonstrated by the static evaluation) compared with driver actions when presented the same signal display scenario, but with the addition of all of the dynamic elements associated with driving. Combining the results of both the driving simulator experiment and video-based static evaluation led to the following conclusions:

- Driver comprehension in the simulator experiment was significantly higher than the static evaluation. The results validate two important beliefs:
  – Driver decision making during a left-turn maneuver incorporates much more than comprehension of the PPLT display. In fact, drivers often based their decision on opposing vehicle movements rather than the PPLT display. Drivers who do not completely comprehend the meaning of the PPLT display use other available information to make their decision.
  – What drivers say they will do (based on comprehension of the PPLT display alone) and what they actually do in the driving environment are not always consistent.
- The biggest inconsistencies occurred for displays with the circular green permissive indication. In the simulator experiment, the four scenarios with the circular green permissive indication resulted in fail critical responses 6% of the time. By contrast, the same four scenarios in the static evaluation resulted in fail critical responses 19% of the time. Drivers are confused by the circular green indication and often assume it provides right-of-way during the permissive left-turn interval. This lack of comprehension is not directly reflected in left-turn crash statistics, because drivers compensate for comprehension deficiencies by considering other information, such as following the lead vehicle, gauging opposing traffic, and choosing acceptable gaps.
- In the simulator experiment, the through indication had little effect on driver comprehension, while in the static

evaluation, the circular red through indication resulted in lower comprehension levels. Based on driver comments throughout the entire experiment, drivers often did not observe the through indication in the simulator but noticed the through indication in the static evaluation. This behavioral pattern was explainable, because, in a pure evaluation of comprehension, drivers search for all available information. The only information in the static evaluation was the left-turn and through indication. Therefore, if the driver was unsure about the meaning of the left-turn indication, he or she used the through movement and prior experiences in order to decide how to act. Many times, this practice still led to an incorrect response.

- Comparing all types of responses in both of the experiments, it can be said that many drivers base their left-turn decision on surrounding traffic, specifically the opposing traffic, instead of the signal indication. This was shown to result primarily from a lack of driver understanding of the indication. Under experimental conditions, several drivers made left-turn decisions without any consideration of the PPLT display.

Implications of Driver Comprehension Study Findings

Collectively, the study data showed a high level of comprehension with no variation between the different PPLT displays tested. There was no statistical difference in driver comprehension when the data were cross-analyzed by permissive indication, arrangement, through indication, and location of the display. The lack of significant differences documented in this study is in itself a significant finding. Given that the confirmation studies found no difference in display types, there is evidence to suggest that the PPLT indication is only one of many elements that the driver takes into account when making left-turn decisions. This result also explains why low level of comprehension related to the circular green permissive indication is not consistent with left-turn crash frequencies.

FIELD IMPLEMENTATION STUDY

To address the lack of real-world applications of the flashing yellow arrow PPLT display, the project panel approved the study of the flashing yellow arrow display in the field as part of the NCHRP 3-54 (02) amended study. The project panel thought that this task was needed before such a display, if deemed “best understood,” could be recommended to the NCUTCD.

Objective

The objective of the field implementation study was to document the implementation of the flashing yellow arrow display, associated technical and non-technical issues, and safety and cost implications associated with implementing this display. The following sections summarize the development and administration of the implementation study, the field data collected, and the results.

Methodology

The field implementation study was initiated, at the request of the project panel, to collect actual field data on the flashing yellow arrow display. The implementation study collected before and after data relevant to the implementation of a flashing yellow arrow PPLT display (e.g., conflict data) to record the safety performance associated with the flashing yellow arrow display. The implementation study also collected field operational data, such as start-up lost time and saturation flow rate data, to quantify the operational impacts. The implementation study monitored field installation by the operating agency and documented techniques as well as the issues resolved (e.g., control logic) for successful implementation to be achieved. In addition, agency assistance was sought to help quantify other implementation issues, such as field personnel reaction, as well as labor, hardware, and software costs. The following sections discuss background information on how the study locations were identified and what was required of the volunteering agencies and the research team.

Implementation Plan

The research team sought the participation of volunteer agencies on a national basis. In August 2000, the research team issued a Request for Proposal for an Implementation Plan for submittal to volunteer agencies, identifying the project goals and objectives, project requirements, and responsibilities of both the volunteer agencies and the research team. A copy of the Implementation Plan is included in Working Paper No. 8 on the accompanying CD-ROM.

The research team was very specific about the characteristics of the study and control intersections, as well as the display that would be used in the implementation study.

Each volunteer agency implementing the flashing yellow arrow display was required to first request (and receive) approval for experimentation of a traffic control device though FHWA.

Characteristics of Study Intersections

The intersections selected for evaluation currently operated PPLT signal phasing and were considered typical intersections containing no unique geometric or operational features. Specific features sought in study intersections included the following:

- Right angle intersections with four approaches,
- Exclusive left-turn lane(s) on the study approach,
- Current use of the green arrow indication for the protected left-turn movement, and the circular green indication for the permissive left-turn indication
- Relatively flat approach grades,
- Lane widths of 12 ft,
- No on-street parking, and
- No other variables that directly affect the left-turn movement being evaluated.

Each agency that volunteered to participate in the study was asked to identify at least three intersections for improvement (i.e., installation of the new flashing yellow arrow PPLT signal display). An additional three intersections were identified within each study region that did not receive any improvements during the study period. These intersections served as control sites. Therefore, at least six study sites were requested at each study region (study regions sometimes involved multiple agencies).

Proposed Flashing Yellow Arrow Display Face

The research team, in partnership with project panel and Technical Advisory Group members, identified several display faces that research demonstrated as having good driver understanding. Four possible PPLT signal displays were recommended for installation of the flashing yellow arrow display at locations where there was an exclusive left-turn lane, and the left-turn display was an exclusive display (not used by the adjacent through movements). Those alternative displays are shown in Figure 3-18 below. As shown in Figure 3-18, the display could be implemented in four different configurations, using three or four sections and horizontal or vertical alignments. The three-section display options involve shared use of a bi-modal section by the green and flashing yellow arrows. The three-section display face may be desired for clearance purposes or for ease of implementation, if an existing three-section display face is available. The signal display face could be mounted either vertically or horizontally.

In the exclusive display application, one, and only one, of the four arrows was illuminated at any time. The flashing yellow arrow was illuminated during the permissive phase when traffic could turn after yielding to opposing through traffic and/or pedestrians. The other three arrows were used for the normal three-color exclusive left turn display. The red arrow indication was displayed when a left-turn movement was prohibited. The green arrow indication was displayed when the left-turn movement could be made with no conflicting simultaneous vehicle or pedestrian movement (protected operation). The steady yellow arrow indication was illuminated for a few seconds as a clearance indication following both the green arrow indication and the flashing yellow arrow indication.

Implementation Study Findings

Participating Agencies

Beginning in August 2000, the research team contacted over 35 agencies from across the United States. Of those 35 agencies, 9 submitted a request to FHWA for experimentation of the flashing yellow arrow display. Two of those nine study implementation locations withdrew from participation because of controller logic issues or implementation procedures not consistent with the project objectives.

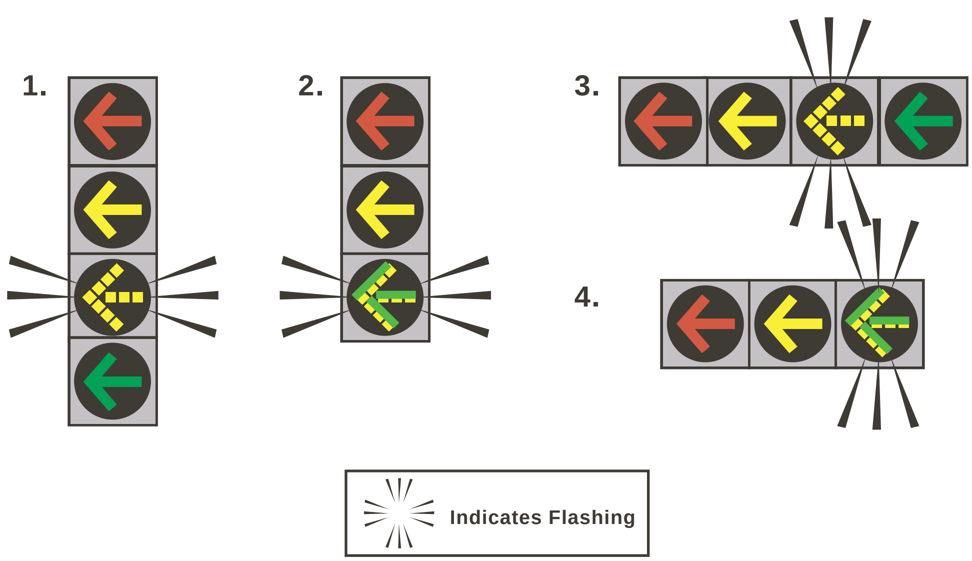


Figure 3-18. Exclusive flashing yellow arrow display faces.

The first agency to respond to the volunteer solicitation was Montgomery County, Maryland. In September 2000, Montgomery County implemented the flashing yellow arrow display at three intersections. Maryland's participation in the implementation study was subsequently followed by other agencies as summarized in Table 3-8.

Other Agency Participation

In addition to the agencies listed in Table 3-8 that have implemented the experimental flashing yellow arrow display, three other agencies requested and received FHWA approval to participate in the study. Two of the agencies were ultimately unable to participate and one agency was not able to implement within the time frame allotted to the research project; further details are as follows:

- The City of Kennewick, Washington, received FHWA approval to implement and planned to do so by October 2001, but later withdrew from the study because of signal controller complications that could not be resolved to the city traffic engineer's satisfaction.
- The City of Carson City, Nevada, submitted its request for implementation to FHWA; however, the proposed implementation included a supplemental sign explaining the meaning of the flashing yellow arrow display. After discussions with the research team, it was decided that FHWA would approve the installation if the supplemental sign was dropped from the implementation. As the completion of the research project approached, Carson City had not responded to FHWA and it remained unclear how or if the City would proceed with implementation.
- Snohomish County, Washington, received FHWA approval for implementation and planed to implement at one intersection; however, implementation was delayed by traffic signal controller software issues that were not resolved by the software manufacturer prior to completion of the research project.

Summary of Field Implementation Locations

Montgomery County, Maryland. Montgomery County implemented the flashing yellow arrow display in September 2000 at three intersections. A four-section vertical all-arrows display was used. The flashing yellow arrow indication was tied to the opposing through green indication. The County used Econolite NEMA controllers for local intersection management, and implementation required special external logic. The County did not issue a media press release prior to implementation but did use variable message signs in advance of the intersections for a period of 48 hr. The County has had minimal citizen feedback during the more than 2 years of deployment.

Tucson, Arizona. The City of Tucson, Arizona, was the only agency to implement and then discontinue use of the flashing yellow arrow display. The City implemented flashing yellow arrow on May 30, 2001, at two intersections, replacing PPLT displays with a five-section vertical display face. The City of Tucson used the flashing yellow arrow for their right-turn overlaps for more than 10 years without any problems. The City's local intersection management software was used with Econolite ASC/2 controllers. The City used an external flashing circuit tied to the flashing yellow arrow indication, which did not conflict with the controller's conflict monitor.

Within 1 week of implementation of the flashing yellow arrow, there was a crash at one of the study intersections. The city manager directed the city traffic engineer to rescind par-

TABLE 3-8 Summary of implementation study sites

Agency	Implementation Date	Number of Implementation Sites
Montgomery County, Maryland	September 2000	3
City of Tucson, Arizona	May 2001	3
Jackson County, Oregon	May 2001	1*
Oregon Department of Transportation	June 2001	2
City of Beaverton, Oregon	April 2002	3
Broward County, Florida	June 2002	3**

*One site in Jackson County met the NCHRP 3-54 study requirements. The County implemented non-conforming displays at five other locations in the County with FHWA approval.
**In September 2002, Broward County received approval from FHWA to implement the flashing yellow arrow display at two additional intersections bringing the total number of flashing yellow arrow implementation sites to five.

ticipation in the implementation study. The flashing yellow arrow was not reported to be directly linked to the cause of the crash. Based on feedback from the operations engineer, the intersection operations performed well during the time that the flashing yellow arrow display was in effect. The flashing yellow arrow display continues to be used for the right-turn overlap movements, as it has for more than 10 years.

Jackson County, Oregon. Jackson County, Oregon, pursued a different path with its implementation of the flashing yellow arrow display. The county traffic engineer for Jackson County approached the research team to implement the flashing yellow arrow display in the county. The County had only one intersection that could be converted from existing PPLT to the flashing yellow arrow display that met the research project's requirements. The County submitted the FHWA request for experimentation and it was approved by FHWA. The single intersection began operating with a flashing yellow arrow display using a four-section all-arrow vertical display face.

Since initial implementation in 2001, Jackson County converted five existing exclusive (protected only) left-turn operations to PPLT control with a flashing yellow arrow display. However, in these installations, the County used a three-section vertical display face—the center indication was used for the yellow arrow clearance (following the circular green indication) and the flashing yellow arrow (permissive period) indication. The County pursued this approach to eliminate the costs of a new display face (four-section) and running additional wire cable and to address vertical clearance issues. The County submitted a request to FHWA for approval to implement the three-section arrangement of the flashing yellow arrow display. The request was originally denied by FHWA but later approved by FHWA after FHWA staff reviewed video of the intersection showing the operation. The video showed the adjacent through signals going to yellow at the same time as the flashing yellow arrow changed to a steady yellow arrow in the same section. The ability of left-turn drivers to see the through signals changing to yellow made it less necessary for the change from the flashing yellow arrow to the steady yellow arrow to be positional. Accordingly, FHWA issued a letter authorizing the County to implement the three-section PPLT flashing yellow arrow display. Figures 3-19 and 3-20 illustrate Jackson County's retrofit of a three-section display and the corresponding operation of the signal.

The County received very positive feedback from the local police department and citizens. The County's local intersection management was a Type 170 controller with Wapiti W4IKS firmware. Special command box logic was required to implement the flashing yellow arrow indication.

Woodburn, Oregon. The Oregon Department of Transportation (ODOT) implemented the flashing yellow arrow display in June 2001 at two intersections in Woodburn, Oregon. A four-section vertical all-arrows display was used. The local intersection management was a Type 170 controller with Wapiti W4IKS firmware. Special command box logic was required to implement the flashing yellow arrow indication. ODOT and the local City government (City of Woodburn) staff reported receiving minimal public feedback regarding the flashing yellow arrow displays.

Beaverton, Oregon. The City of Beaverton, Oregon, implemented the flashing yellow arrow display at three study locations in April 2002 after having been granted authority to implement the flashing yellow arrow display from the City Traffic Commission and the Mayor's office. A four-section all-arrows display was used. The local intersection management was controlled by a Type 170 controller with Wapiti W4IKS firmware. Special command box logic was required to implement the flashing yellow arrow indication. The City was able to use the same basic logic developed by ODOT for the Woodburn site in their implementation. At the time this report was prepared, no problems had been experienced at the intersections.

Broward County, Florida. Broward County was first approached by the contractor to implement the flashing yellow arrow display in May 2000. It was not until May 2002 that the County implemented the experimental display. This 2-year relationship between the contractor and implementing agency is an example of the many challenges that agencies faced in participating in this study as well as making future changes. Implementation in Broward County was delayed by many factors, most of which could be attributed to limited County staff resources (time) and the desire to implement a

Figure 3-19. Jackson County, Oregon—3-section retrofit to flashing yellow arrow PPLT display.

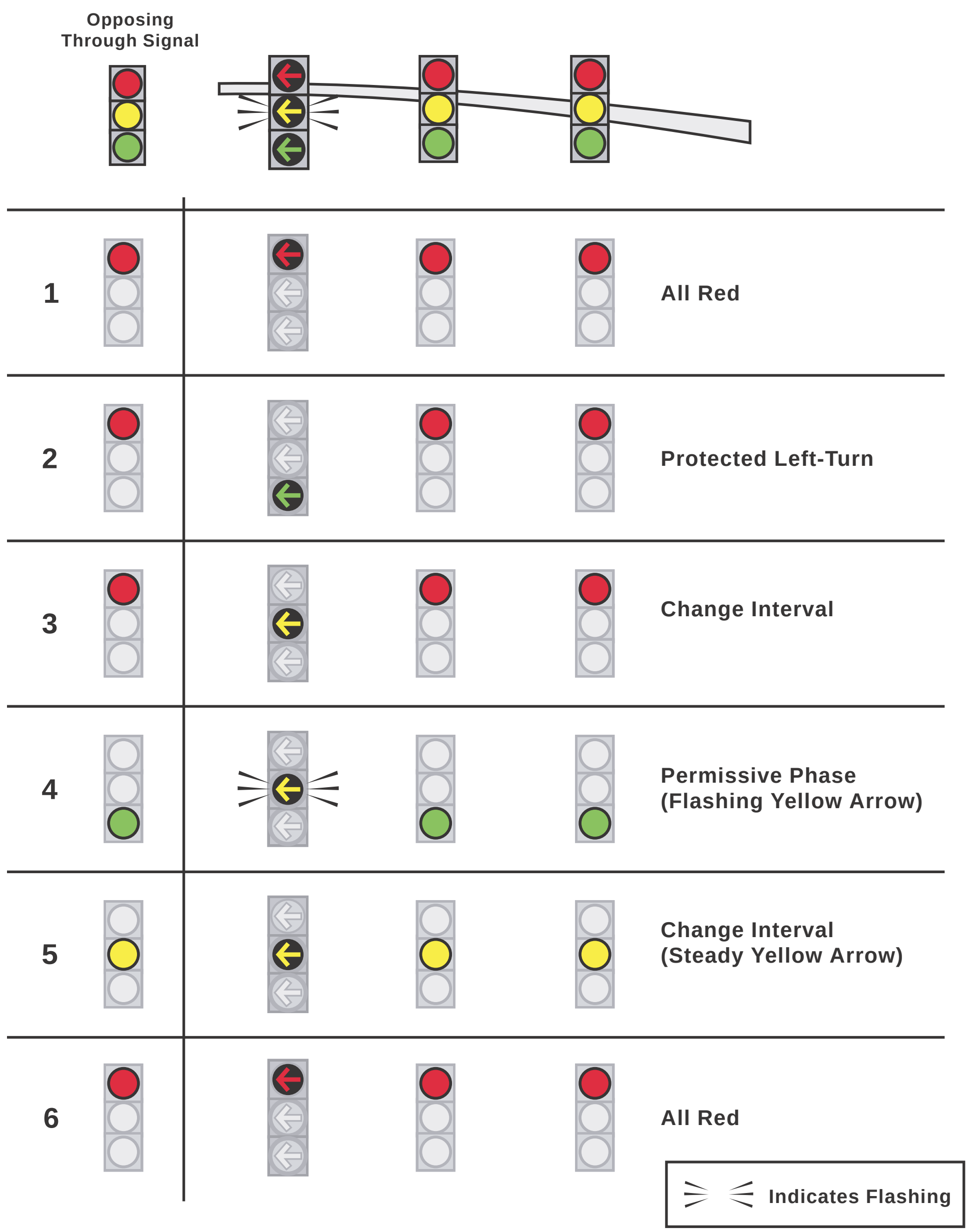


Figure 3-20. Operation of Jackson County, Oregon's 3-section flashing yellow arrow PPLT display.

different display from that requested by the research project (which required an additional FHWA approval process).

Ultimately, the County implemented a five-section vertical display, with the top two indications being a circular red indication and a circular yellow indication. The bottom three indications were all arrows with the flashing yellow arrow contained in the middle section as shown in Figure 3-21. It was the County's desire to clear the approach with all circular yellow indications, rather than clearing the left-turn movement with a yellow arrow indication, as the research team proposed.

In October 2002, the County received approval from FHWA to implement the flashing yellow arrow display at two additional intersections, bringing the total number of intersections with the flashing yellow display to five.

Conflict Analysis Findings

As part of the field implementation study effort, before and after studies were conducted at each of the flashing yellow arrow implementation study sites. The local jurisdiction and/or research team members videotaped 16 hr of before/after data. The research team reviewed the videotapes to conduct a conflict rate analysis.

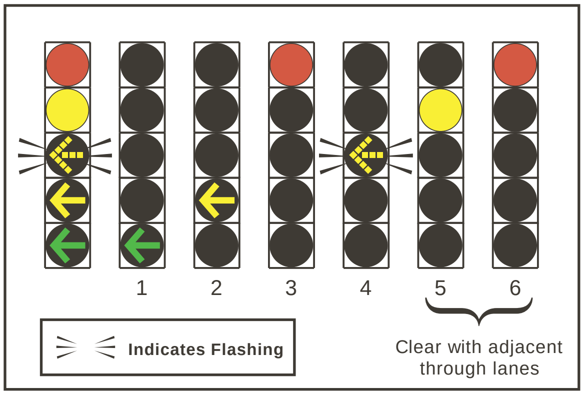


Figure 3-21. Broward County flashing yellow arrow display arrangement.

The before and after conflict analysis focused on conflicts and events specifically related to the left-turn signal display. This typically included driver hesitation on a permissive indication (circular green indication or flashing yellow arrow) or driver hesitation on a protected indication (green arrow). Driver hesitation in either instance provided an indication about drivers' comprehension of the presented indication. Left-turn conflicts, such as a driver failing to yield the right of way to opposing traffic on a permissive indication, were also observed because such conflicts provided the research team with additional information about drivers' comprehension of the particular left-turn indication. Although many conflicts were observed, this analysis focused on only those related to the left-turn signal display. The results of the conflict analysis are shown in Tables 3-9 and 3-10 for the before and after analysis periods, respectively.

As shown by the two tables, there was little notable difference in the before and after conflict rate and no difference that could be attributed to the change in PPLT display.

Follow-up headway information and corresponding flow rate were also evaluated for the permissive left-turn movements. The headways between queued permissive left-turn vehicles selecting the same gap in opposing traffic were determined from the field videos. Tables 3-9 and 3-10 also show the follow-up headway findings. At many intersections, few instances with two permissive left-turns being made in the same gap were observed, and the corresponding headway and flow rate information is based on only a small sample size. Based on the data available, the change in PPLT display to the flashing yellow arrow had a negligible impact on follow-up headway. A site-by-site summary of the analysis findings is documented in Working Paper 8.

Field Observations During Flashing Yellow Arrow Activation

In addition to the before and after data collection and analysis, members of the research team were present as the flashing yellow arrow permissive indication was activated at six of the site locations. The premise for these visits was to observe whether there was any evidence of initial driver confusion that might not be apparent from observation of the after videos, particularly if drivers had learned the meaning of the experimental display before the video data were collected. Researchers present at the three Beaverton, Oregon, flashing yellow arrow installation sites observed no unusual or significant findings at the time the display was activated. Similar results were observed at the three Broward County, Florida, experimental sites as the flashing yellow arrow indication was activated. The observations made at the time the flashing yellow arrow display was switched on are consistent with both the before and after video data at these intersections, indicating no significant difference when changing from a circular green to a flashing yellow arrow permissive indication. The research team conducted on-site observations of flashing yellow arrow operation used in Montgomery County, Maryland, and Woodburn, Oregon. Conditions similar to those in Beaverton, Oregon, and Broward County, Florida, were observed.

Post-Implementation Survey of Volunteer Agencies

A post-implementation survey was administered to the agencies that participated in the implementation study. The survey sought to identify issues that had to be dealt with to implement the flashing yellow arrow display, the cost to the agency to implement the flashing yellow arrow display, and whether there was support within the agency and outside the agency for the flashing yellow arrow display.

Overall, each of the participating volunteer agencies experienced favorable results with the flashing yellow arrow display implementation. The most commonly reported problem was overcoming the current design of controllers and conflict monitors. In all cases, the participating agencies had to use either internal logic (e.g., command box in the Wapiti firmware for the Type 170 controller) or some type of external logic or relay device to implement the flashing yellow arrow display. These changes were necessary because the permissive flashing yellow arrow and circular green through movement indications could not illuminate simultaneously (prior to conversion, the circular green indication was used to communicate both the through and permissive movements). It is assumed that new controller software and any significant upgrade of existing controller software will include this functionality so that, over time, external logic will no longer be needed. The special logic described above can be implemented using a "logic box" external to the signal controller, or with software enhancements in the signal controller.

The cost to implement the flashing yellow arrow display was relatively low (approximately $750 for new signal heads and about 200 staff-hours total). All agencies received sig-

TABLE 3-9 Study intersection conflict data before flashing yellow arrow implementation—Page 1 of 2

State	Observation Period	Location	Intersection	Site Type	PPLT Display	Data Source	Hours of Video Reviewed	Observational Safety Analysis (Display Based)			Follow-Up Headway (veh/hr) / Sample Size
								Conflicts	Event		
									Hesitation on GB	Hesitation on GA	
OR	May 2001	Woodburn	Hwy 99 @ Hardcastle St.	Study	5-Section Cluster	ODOT	16	0	0	0	NA
		Woodburn	Hwy 99 @ Lincoln St.	Study	5-Section Cluster	ODOT	17	0	1	0	1,321 (12)
		Woodburn	Hwy 99 @ Young St.	Control	5-Section Cluster	ODOT	26	0	3	1	1,440 (10)
		McMinnville	Hwy 99 @ Baker Creek Rd.	Control	5-Section Cluster	ODOT	22	0	2	0	1,460 (9)
OR	April 2002	Beaverton	SW Allen Blvd. @ Wilson Ave.	Study	5-Section Cluster	UMass	23	0	2	3	1,545 (40)
		Beaverton	SW Allen Blvd. @ Menlo Dr.	Study	5-Section Cluster	UMass	23	0	0	4	1,410 (32)
		Beaverton	SW 125th St. @ Longhorn Ln.	Study	5-Section Cluster	UMass	21	0	0	3	1,470 (18)
		Beaverton	SW 72nd St. @ Bonita St.	Control	5-Section Cluster	UMass	24	1	10	12	1,790 (35)
		Beaverton	SW Oleson St. @ Vermont St.	Control	5-Section Cluster	UMass	20	0	1	0	1,750 (25)
		Beaverton	NW Murray Rd. @ Science Park Rd.	Control	5-Section Cluster	UMass	16	1	1	0	1,661 (25)
AZ	May 2001	Tucson	Ajo Way @ Park Ave.	Study	5-Section Vertical	Tucson	24	0	0	0	1,408 (15)

GB=Circular Green Indication
GA=Green Arrow Indication

TABLE 3-9 Study intersection conflict data before flashing yellow arrow implementation—Page 2 of 2

State	Observation Period	Location	Intersection	Site Type	PPLT Display	Data Source	Hours of Video Reviewed	Observational Safety Analysis (Display Based)			Follow-Up Headway (veh/hr) / Sample Size
									Event		
								Conflicts	Hesitation on GB	Hesitation on GA	
MD	August 2000	Mont. Cty	Cecil St. @ E. Gude Dr.	Study	5-Section Cluster	County	16	0	1	0	1,925 (64)
		Mont. Cty	E. Randolph Rd @ Fairland Rd.	Study	5-Section Cluster	County	16	0	0	0	1,809 (83)
		Mont. Cty	Montrose Rd. @ Tower Oaks Blvd	Study	5-Section Cluster	County	16	1	1	0	1,800 (28)
FL	January 2002	Broward Cty	Broward Blvd. @ SW 69th Ave.	Study	5-Section Cluster	UMass	8	1	3	2	1,470 (77)
		Broward Cty	Coral Springs Dr. @ Wiles Rd.	Study	5-Section Cluster	UMass	8	1	0	13	1,598 (13)
		Broward Cty	Sample Rd. @ Riverside Dr.	Study	5-Section Cluster	UMass	8	1	6	4	1,933 (17)
		Broward Cty	Broward Blvd. @ SW 70th Ave.	Control	5-Section Cluster	UMass	8	3	0	9	1,735 (37)
		Broward Cty	University Dr. @ Wiles Rd.	Control	5-Section Cluster	UMass	8	0	7	1	1,711 (20)
		Broward Cty	Sample Rd. @ Rock Island Rd.	Control	5-Section Cluster	UMass	8	0	2	1	1,931 (21)

GB=Circular Green Indication
GA=Green Arrow Indication

TABLE 3-10 Study intersection conflict data after flashing yellow arrow implementation—Page 1 of 3

State	Observation Period	Location	Intersection	Site Type	PPLT Display	Data Source	Hours of Video Reviewed	Observational Safety Analysis (Display Based)			Follow-Up Headway (veh/hr) / Sample Size
									Events		
								Conflicts	Hesitation on FYA	Hesitation on GA	
OR	December 2001	Woodburn	Hwy 99 @ Hardcastle St.	Study	4-Section Vertical	ODOT	12	0	3	0	1,375 (15)
		Woodburn	Hwy 99 @ Lincoln St.	Study	4-Section Vertical	ODOT	12	0	1	0	1,465 (19)
		Woodburn	Hwy 99 @ Young St.	Control	5-Section Cluster	ODOT	12	0	1 (GB)	0	1,535 (45)
		McMinnville	Hwy 99 @ Baker Creek Rd.	Control	5-Section Cluster	ODOT	12	0	1 (GB)	0	1,962 (10)
OR	June 2002	Beaverton	SW Allen Blvd. @ Wilson Ave.	Study	4-Section Vertical	UMass	16	0	4	0	1,650 (47)
		Beaverton	SW Allen Blvd. @ Menlo Dr.	Study	4-Section Vertical	UMass	16	0	1	0	1,415 (9)
		Beaverton	SW 125th St. @ Longhorn Ln.	Study	4-Section Vertical	UMass	15	0	1	0	NA
		Beaverton	SW 72nd St. @ Bonita St.	Control	5-Section Cluster	UMass	20	0	6 (GB)	9	1,728 (35)
		Beaverton	SW Oleson St. @ Vermont St.	Control	5-Section Cluster	UMass	18	0	0	0	1,760 (24)
		Beaverton	SW Murray Rd. @ Science Park Rd.	Control	5-Section Cluster	UMass	18	1	0	1	1,603 (22)

FYA=Flashing Yellow Arrow Indication
GA=Green Arrow Indication

TABLE 3-10 Study intersection conflict data after flashing yellow arrow implementation—Page 2 of 3

State	Observation Period	Location	Intersection	Site Type	PPLT Display	Data Source	Hours of Video Reviewed	Observational Safety Analysis (Display Based)			Follow-Up Headway (veh/hr) / Sample Size
								Conflicts	Events		
									Hesitation on FYA	Hesitation on GA	
OR	June 2002	Jackson Cty	Hamrick Rd. @ E. Pine St.	Study	4-Section Vertical	UMass	20	0	6	3	1,550 (61)
		Jackson Cty	E. Pine St. @ Peninger St.	Study	3-Section Vertical	UMass	17	1	0	8	1,440 (35)
		Jackson Cty	Table Rock Rd. @ Vilas Rd.	Study	3-Section Vertical	UMass	19	0	1	1	1,584 (15)
		Jackson Cty	Stewart St. @ Columbus St.	Control	5-Section Cluster	UMass	16	0	0	6	NA
AZ	June 2001	Tucson	Ajo Way @ Park Ave.	Study	5-Section Vertical	Tucson	12	0	0	0	1,735 (14)
MD	October 2000	Mont. Cty	Cecil St. @ E. Gude Dr.	Study	4-Section Vertical	County	16	0	0	0	1,818 (38)
		Mont. Cty	E. Randolph Rd @ Fairland Rd.	Study	4-Section Vertical	County	16	0	0	0	1,827 (70)
		Mont. Cty	Montrose Rd. @ Tower Oaks Blvd	Study	4-Section Vertical	County	16	1	1	0	1,800 (42)

FYA=Flashing Yellow Arrow Indication
GA= Green Arrow Indication

TABLE 3-10 Study intersection conflict data after flashing yellow arrow implementation—Page 3 of 3

State	Observation Period	Location	Intersection	Site Type	PPLT Display	Data Source	Hours of Video Reviewed	Observational Safety Analysis (Display Based)			Follow-Up Headway (veh/hr) / Sample Size
								Conflicts	Events		
									Hesitation on FYA	Hesitation on GA	
FL	July 2002	Broward Cty	Broward Blvd. @ SW 69th Ave.	Study	4-Section Vertical	UMass	17	1	2	5	1,644 (31)
		Broward Cty	Coral Springs Dr. @ Wiles Rd.	Study	4-Section Vertical	UMass	23	0	2	4	1,492 (12)
		Broward Cty	Sample Rd. @ Riverside Dr.	Study	4-Section Vertical	UMass	19	0	5	1	1,933 (35)
		Broward Cty	Broward Blvd. @ SW 70th Ave.	Control	5-Section Cluster	UMass	16	0	2 (GB)	2	1,593 (33)
		Broward Cty	University Dr. @ Wiles Rd.	Control	5-Section Cluster	UMass	20	0	2 (GB)	10	1,803 (24)
		Broward Cty	Sample Rd. @ Rock Island Rd.	Control	5-Section Cluster	UMass	18	1	0	1	2,016 (20)

GA=Green Arrow Indication
FYA=Flashing Yellow Arrow Indication

nificantly more positive than negative comment from the public and from their own staffs.

Agency Feedback

In addition to the formal written survey response comments, there was considerable anecdotal evidence that provided preliminary insight into the agencies' perspectives on use of the flashing yellow arrow display. The overall response to the flashing yellow arrow display from traffic engineers around the county was positive. In general, traffic engineers expressed their approval of the flashing yellow arrow display because of the following:

- The configuration provided an exclusive signal display for the left-turn control.
- The indication was flashing, which attracted more attention.
- The traffic engineers had more operational control.

In general, local law enforcement agencies were supportive of the flashing yellow arrow display; however, there was some hesitation from city councils and county commissioners because of concern about trying something new that was not formally part of the MUTCD.

Public Reaction

Public comments from citizens who experienced the flashing yellow arrow display in the field were generally positive. Several volunteer agencies reported receiving e-mails or written letters from the motoring public with most, if not all, in support of the flashing yellow arrow display.

As part of the ongoing study activities, the research team observed driver reaction to the flashing yellow arrow display immediately upon implementation in the field. The drivers' responses to the new displays suggest there was very little confusion, with most drivers driving through the intersection as if nothing were changed. Interestingly, at least one agency that has implemented the flashing yellow arrow display reported that drivers waiting to make a permissive left turn now stop behind the stop bar and wait for a gap in opposing traffic (rather than entering the intersection before stopping).

Agencies Declining Participation

A significant challenge encountered by the research team was the recruitment of volunteer agencies to participate in the field implementation study. The research team solicited involvement from 35 individual operating agencies, of which 26 declined for various reasons. Through the course of verbal discussions with agency representatives and responses to a follow-up survey that the research team conducted, the primary reason cited by agencies for not participating was their lack of resources. Other explanations for not participating in the implementation study included controller capabilities, changes in management staff, and/or lack of technical and/or managerial staff.

ENGINEERING ASSESSMENT

In the initial stages of the research, the research team developed an engineering assessment intended to explore the many subjective elements affecting the use of traffic signal displays that were not measured through scientific experiment. To perform the Engineering Assessment, the research team considered practical issues related to how an agency would actually implement a particular signal display or indication. The discussion below presents the final engineering assessment that was developed after completion of the Driver Confirmation and Field Implementation studies.

Objective

The Engineering Assessment considered scientific and nonscientific implementation issues in the following areas: safety, operations, implementability, human factors, and versatility. The updated engineering assessment identified objective and subjective information needed in order to evaluate the signal displays/indications. The assessment provided a thorough evaluation based upon sound engineering practice and the findings of the various elements composing the research project.

Methodology

The research team identified and answered questions related to safety, operations, implementability, human factors, and versatility. Experiences of practicing traffic engineers and basic engineering judgment were applied when appropriate.

Two significant tables were developed in the engineering assessment. The first table, Table 3-11, lists each of the major categories (e.g., safety and operations) and each question within each category. Each answer to each question was rated from highest to lowest. By design, quantitative scores were not associated with any display and/or indication (individual questions were not weighted equally). Therefore, judgment was used to assess which displays and/or indications performed better than others. Many of the questions in Table 3-11 require further explanation or clarification of intent and/or meaning. Each question in Table 3-11 is explored in more detail in the full technical report documented in Working Paper No.1, Engineering Assessment, included in the appendixes on the accompanying CD-ROM.

The second table, Table 3-12, identified allowable combinations of placement, display faces, and left-turn phasing. This

TABLE 3-11 Engineering assessment evaluation matrix—Page 1 of 4

#	Questions to be answered	Solid Circular Green Indication: Traditional Five-Section	Solid Circular Green Indication: Circular Green + Flashing Arrow	Solid Circular Green Indication: Dallas Display	Flashing Yellow Arrow	Comments
SAFETY						
S-1	Does it fail safe? Is a misunderstanding of the indication likely to result in a safe action?	○	○	○	◑	The driver simulation/confirmation study has shown safer operation for the flashing yellow arrow
S-2	Can the indication eliminate the yellow trap under all operational and field conditions?	○	○	◕	●	
S-3	Can a red clearance be displayed after leading left?	○	○	●	●	
S-4	Can the start of permissive indication be delayed?	○	○	●	●	
S-5	Does it avoid dilution of the safety or meaning of other indications?	◕	◕	◕	◕	
S-6	Are traffic violations minimized?					
S-7	Are accident costs reduced?					
S-8	Are conflicts reduced?	○	○	○	◔	
OPERATIONS						
O-1	Does the indication increase total delay to the driver due to indecision, increased start-up lost times, reduced travel speeds, and/or lower saturation flow rates?	◕	◕	◕	●	
O-2	Does the indication impact pedestrian movements?	◑	◑	◑	◑	All indications mean yield to left-turn driver
O-3	Can the indication be used with lead/lag operation?	○	◑	●	●	
O-4	Does the indication impact opposing left-turning traffic?	◔	◔	●	●	
O-5	Does the indication allow the skipping of all side-street phases?	○	○	●	●	
O-6	Is the indication consistent with flashing indications?	●	●	●	●	
O-7	Does operating the intersection in flashing mode provide negative consequences?	●	●	●	●	
O-8	Does the indication lead to false starts or related driver errors?	◔	◕	◑	◕	

Ranking scale: ● = highest/best; ○ = lowest/worst

TABLE 3-11 Engineering assessment evaluation matrix—Page 2 of 4

#	Questions to be answered	Solid Circular Green			Flashing Yellow Arrow	Comments
		Traditional Five-Section	Circular Green + Flashing Arrow	Dallas Display		
	IMPLEMENTABILITY					
I-1	Are there significant issues with installation? Can the indication be placed to meet with the current MUTCD requirements?	●	◑	●	◑	Circular Green + Flashing Arrow and flashing yellow arrow will require amendment of MUTCD
I-2	Are there issues with conversion of existing indications? -Convert a signal currently using traditional five-section indication? -Convert a signal currently using permissive-only? -Convert a signal currently using protected-only?	● ◑ ◑	◕ ◑ ◑	◑ ◑ ◔	◔ ◑ ◕	
I-3	Are there legal issues to consider including the Uniform Vehicle Code and state and local laws?	●	◕	◕	◕	
I-4	Does the signal indication permit maximum number of signal phasing strategies?	○	○	◑	●	
	HUMAN FACTORS					
H-1	Is the indication universally understood? Does the indication meet both a priori and ad hoc driver expectancies?	◑	◕	◑	◕	
H-2	Do drivers respond correctly to the information presented?	◑	◑	◑	◑	
H-3	Do drivers accept the indication? Does the indication increase driver workload, reduce conspicuity, or increase driver error?	◑	◑	◑	◑	
H-4	Are supplemental signs required for understanding?	○	○	○	●	
H-5	Do drivers exposed to the "new" indication easily learn the meaning?	◑	◑	◔	◕	
H-6	Does the signal indication fail safe? What are the consequences of a driver misinterpreting the signal indication message?	○	○	○	◑	

Ranking scale: ● = highest/best; ○ = lowest/worst

TABLE 3-11 Engineering assessment evaluation matrix—Page 3 of 4

#	Questions to be answered	Solid Circular Green: Traditional Five-Section	Solid Circular Green: Circular Green +Flashing Arrow	Solid Circular Green: Dallas Display	Flashing Yellow Arrow	Comments
	VERSATILITY					
V-1	Does it allow permissive-only operation?	●	●	●	●	
V-2	Does it allow protected-only operation?	○	○	●	●	
V-3	Does it allow change between mode of operation by time of day?	○	○	●	●	
V-4	Can it be used on curved approaches?	●	●	○	●	
V-5	Does it allow two far-side LT heads in customary locations?	●	●	○	●	
V-6	Does it allow use of any phase sequence?	○	○	●	●	
V-7	Is it applicable to right turns as well as left?	◑	◕	◑	●	
V-8	Can it be used with span wire-mounted signals?	●	●	◑	●	
V-9	Can heads be in same location as permanent protected-only heads for easy conversion?	◑	◑	◔	●	
V-10	Can heads be in same location as permanent permissive-only heads for easy conversion?	●	●	○	◕	
V-11	Does it allow use of all of the opposing through green time for permissive turns?	◔	◔	●	●	
V-12	Can it be used when the left-turn lane is shared with through traffic?	●	●	○	●	
V-13	Can permissive, turning traffic proceed legally without stopping?	●	●	●	●	
V-14	Could it replace all current standard and non-standard PPLT indications?	◔	◔	○	●	
V-15	Can it be used where there is no adjacent through movement?	◑	◑	◑	●	
V-16	Can it be used where the adjacent through movement is unsignalized?	○	○	●	●	

Ranking scale: ● = highest/best; ○ = lowest/worst

TABLE 3-11 Engineering assessment evaluation matrix—Page 4 of 4

#	Questions to be answered	Solid Circular Green			Flashing Yellow Arrow	Comments
		Traditional Five-Section	Circular Green + Flashing Arrow	Dallas Display		
	VERSATILITY (continued)					
V-17	Can it be used when the left-turn slot is physically separated or on different alignment than through lane (wide median, etc.)?	○	○	◑	●	
V-18	Can the signal indication be placed horizontally or vertically in the same arrangement?	◑	◑	◑	●	
V-19	Does it work under all preemption scenarios?	○	◔	●	●	
V-20	Does it avoid the yellow trap situation under all circumstances?	○	○	◑	●	
V-21	Can the permissive indication be easily applied to other than PPLT situations?	○	○	○	●	
V-22	Will practitioners likely use the indication if made the standard, <u>or allowed alternate</u>?	●	◑	◑	●	

Ranking scale: ● = highest/best; ○ = lowest/worst

TABLE 3-12 Allowable combinations of placement, display face, and phasing for potential display type

Placement	Indication Arrangement	Phasing	DISPLAY TYPE: Traditional Five-Section Circular Green	DISPLAY TYPE: Solid Circular Green – Dallas Display	DISPLAY TYPE: Flashing Yellow Arrow
Shared Indication with Through	Five-section Cluster	Lead-Lead Lefts	Y	N	Y[1]
		Lag-Lag Lefts	Y[2]	N	Y[1]
		Lead-Lag Lefts	N	N	Y[1]
	Five-section Vertical	Lead-Lead Lefts	Y	N	Y[1]
		Lag-Lag Lefts	Y[2]	N	Y[1]
		Lead-Lag Lefts	N	N	Y[1]
	Five-section Horizontal	Lead-Lead Lefts	Y	N	Y[1]
		Lag-Lag Lefts	Y[2]	N	Y[1]
		Lead-Lag Lefts	N	N	Y[1]
Exclusive Indication	Five-section Cluster	Lead-Lead Lefts	Y	Y	Y
		Lag-Lag Lefts	Y[2]	Y	Y
		Lead-Lag Lefts	N	Y	Y
	Five-section Vertical	Lead-Lead Lefts	Y	Y	Y
		Lag-Lag Lefts	Y[2]	Y	Y
		Lead-Lag Lefts	N	Y	Y
	Five-section Horizontal	Lead-Lead Lefts	Y	Y	Y
		Lag-Lag Lefts	Y[2]	Y	Y
		Lead-Lag Lefts	N	Y	Y

Footnotes: 1. Assumes that the yellow arrow indication serves to both clear the green arrow indication and flash for the permissive interval. Use the bi-modal in the bottom and use the yellow for the clearance.
2. Works only if serve both lagging lefts at the same time, otherwise a yellow trap may be created.

table identified the practical considerations regarding display or indication, based on (1) whether the display/indication could be used in a shared display face or an exclusive display and (2) whether the display/indication could be used in a lead-lead, lag-lag, or lead-lag left-turn signal operation.

Findings

The Engineering Assessment material presented in Table 3-11 focused on key issues surrounding safety, operations, implementability, human factors, and versatility. The findings of this assessment are highlighted below:

- Within the category of *safety*, the assessment findings suggest that the flashing yellow arrow display offered the highest level of safety, followed by the circular green indication using the Dallas Display.
- Within the category of *operations*, the circular green indication display using the Dallas Display performed similarly to the flashing indications, with the remaining circular green indication displays performing at lesser levels.
- Within the category of *implementability*, the circular green indication was identified as being easiest to implement. This finding reflects the status of the circular green indication as being the current standard for most agencies. By comparison, the flashing yellow arrow display was found to be easier to implement than a standard circular green indication in an exclusive left-turn display and, overall, nearly equal to the implementability of a circular green indication display using the Dallas Display.
- Within the category of *human factors*, the flashing yellow arrow display was found to rank the best.
- Within the category of *versatility*, the flashing yellow arrow display was clearly shown to offer the most versatility while the standard circular green display shared with a through lane offered the least.

Table 3-12 identified allowable combinations of placement, display face, and left-turn phasing and highlights the fact that only the circular green indication and the flashing yellow arrow can be used in both the shared display and in the exclusive left-turn display. The circular green indication has some limitations in the shared display placement (e.g., it cannot be used for lead-lag phasing, must serve both lagging lefts at the same time, and has yellow trap potential). Consequently, the comparison provided in Table 3-12 points out that the flashing yellow arrow appears to be the most widely applicable option.

CHAPTER 4
DISCUSSION

The NCHRP 3-54 (02) research project looked at all possible PPLT displays and shortened the list of PPLT displays to a select few. The research team collected sufficient data to narrow the list of potential PPLT displays after extensive discussions with the project panel members.

The final study tasks of the project were focused on an evaluation of the flashing yellow arrow display in comparison with the circular green indication, the MUTCD standard. The application of a driver simulator provided an in-depth analysis of driver understanding of the displays studied. When compared with PPLT displays with a circular green permissive indication, the flashing yellow arrow indication was shown to exhibit superior qualities in some analyses and equal qualities in others. In only a few cases did the flashing yellow arrow indication not yield a higher level of understanding as compared with the circular green indication, such as when the display was "first observed." The laboratory-based research techniques did not universally demonstrate that the flashing yellow arrow indication represents a far superior indication to the circular green indication. The findings of the laboratory-based research support the position that the flashing yellow arrow indication represents the best alternative to the circular green indication.

Complementing the laboratory-based research techniques was the in-the-field-based implementation study in which the flashing yellow arrow indication was deployed in the real world and thoroughly studied. The Implementation Study results demonstrated that the flashing yellow arrow indication was well understood in almost all deployment cases. Analysis of the conflict data suggests that the flashing yellow arrow indication is at least as safe as the current MUTCD standard (circular green indication). Where deployed, the flashing yellow arrow indication was preferred by almost all of the traffic engineers, field technicians, and citizens when compared with the circular green PPLT indication. The Implementation Study identified hardware and software issues related to implementing the flashing yellow arrow display that would need to be addressed before any widespread deployment could be conducted. Through the Engineering Assessment, the flashing yellow arrow display was identified in three of the five categories as "best" and near equal to the circular green indication in the remaining two categories.

All PPLT displays and/or indications have been researched thoroughly. The flashing yellow arrow indication/display was found to result in a high level of understanding and a lower fail critical rate as compared with the circular green indication. The flashing yellow arrow display offers more versatile field application features (e.g., the display can be (1) operated in various operational modes by time of day and (2) implemented on any signal mount and intersection configuration) as compared with the circular green indication. To that end, the recommendations presented in Chapter 5 focus on the flashing yellow arrow display as preferrable to the circular green indication.

The various research activities completed throughout the course of the project consistently supported the use of the flashing yellow arrow indication as an alternative to the MUTCD circular green permissive indication. The Engineering Assessment summarized many of the aspects by which the flashing yellow arrow display was found to be equal to or superior to existing PPLT displays. Similarly, the Confirmation Study and the Field Implementation Plan demonstrated the viability of the flashing yellow arrow display, as well as its performance and acceptance upon introduction to the motoring public. The remainder of this chapter outlines the research team's basis for the recommendations documented in Chapter 5.

FINDINGS OF THE CONFIRMATION STUDY

The results of the Confirmation Study showed the following:

- The flashing yellow arrow display was as well understood (measured in terms of correct responses to questions presented) as the circular green indication.
- There was no significant difference in the motoring public's correctly interpreting the meaning of the flashing yellow arrow indication as compared with the circular green indication. The data demonstrated that drivers' understanding of the flashing yellow arrow display increased with exposure.
- The flashing yellow arrow display showed a higher fail-safe response as compared with the circular green indication.
- The conflict studies demonstrated that drivers interpret the flashing yellow arrow display correctly.

FINDINGS OF THE FIELD IMPLEMENTATION STUDY

The results of the Field Implementation Study demonstrated the following:

- The flashing yellow arrow display was successfully implemented in the field with relatively little or no technical or political issues. Post-implementation public testimony almost unanimously supported use of the experimental display. For example, the Jackson County, Oregon, traffic engineer received the following voice message referring to the new flashing yellow arrow PPLT display: "I'm [name removed for privacy] calling to comment about your flashing yellow arrow on a turn lane. I think it's the best thing since sliced bread. It is easy to understand, makes traffic flow much more smoothly, makes a lot better sense, you don't sit there waiting to make a left turn when nobody's coming. The one in downtown Medford confused me, the green light and the green arrow [referring to the standard MUTCD five-section cluster PPLT display]. I'm confused with that; but with the flashing yellow light—I think it's wonderful. Don't change a thing." Letters and additional testimony are presented later in this chapter.
- Most practicing traffic engineers contacted during the study endorse the flashing yellow arrow display.
- The field data support high understanding of the flashing yellow arrow display.

In addition to the many technical results of the research elements supporting the flashing yellow arrow display, it is also appropriate to reflect on the practical elements of why the flashing yellow arrow display provides equal or superior performance as compared with the circular green PPLT indication.

OPERATIONAL ADVANTAGES

There are many reasons some modes of left-turn operation (e.g., permissive only, protected only, protected permissive, lead/lag, and so forth) are chosen or the mode is changed during the day. In most cases, however, it is for operational efficiency, such as to increase the left-turn capacity, improve traffic progression through coordinated signals, or reduce the duration required for the protected phase, including full suppression of the protected phase. Each of the various control modes of left-turn operation has certain advantages and disadvantages. It has also been demonstrated that the current MUTCD standard circular green indication display presents safety problems.

As a result, traffic engineers have had to balance efficiency and safety when designing and operating intersections. Innovative traffic engineers have searched for ways to maintain intersection safety and improve intersection operations, as demonstrated by the multiple non-standard PPLT displays currently in use within the United States. Given this discussion as a preamble, the flashing yellow arrow display, in an all-arrow display face, supports the following modes of left-turn operations.

Protected-Only Operation

The flashing yellow arrow display can be operated in a protected-only mode. In the protected-only mode, the flashing yellow arrow permissive indication is not used.

Protected-Permissive Operation

The flashing yellow arrow display is "logically tied" to the green output of the opposing through movement to avoid the yellow left-turn trap. Logically tying a phase means that the traffic signal control software outputs the flashing yellow arrow indication (permissive turn) only during the green interval of the opposing through phase. This ensures that when the permissive display terminates, the opposing through phase will terminate simultaneously.

The original research problem statement addressed the yellow trap issue as a major concern and it was, in fact, fundamental to initiation of this research project. As shown in Figure 4-1, logically tying the flashing yellow arrow indication to the opposing through green indication completely eliminates the yellow trap, even when lead/lag phasing is used or when side street phases are skipped and the leading left-turn phase now follows the through phase.

Permissive-Protected Operation

Historically, most traffic engineers with lagging protected operations serve both left-turn phases for the same duration so as to not create the yellow trap. Because the flashing yellow arrow display is tied to the opposing through movement, thereby eliminating the yellow trap, this operation becomes much more efficient. This operation is especially useful for skipping the protected-only sequence when there is inadequate vehicular demand.

Permissive-Only Operation

The permissive left-turn operation allows the drivers to execute left turns when gaps occur within the opposing through movement. The flashing yellow arrow display allows the signal operation to change modes during the day in any way, or for longer periods of time, if desired. A key advantage to this flexibility is that the signal operation could, for example, change from an eight-phase protected-only operation during peak hours, to an eight-phase protected/permissive operation during the day, to a simple two-phase permissive-only signal

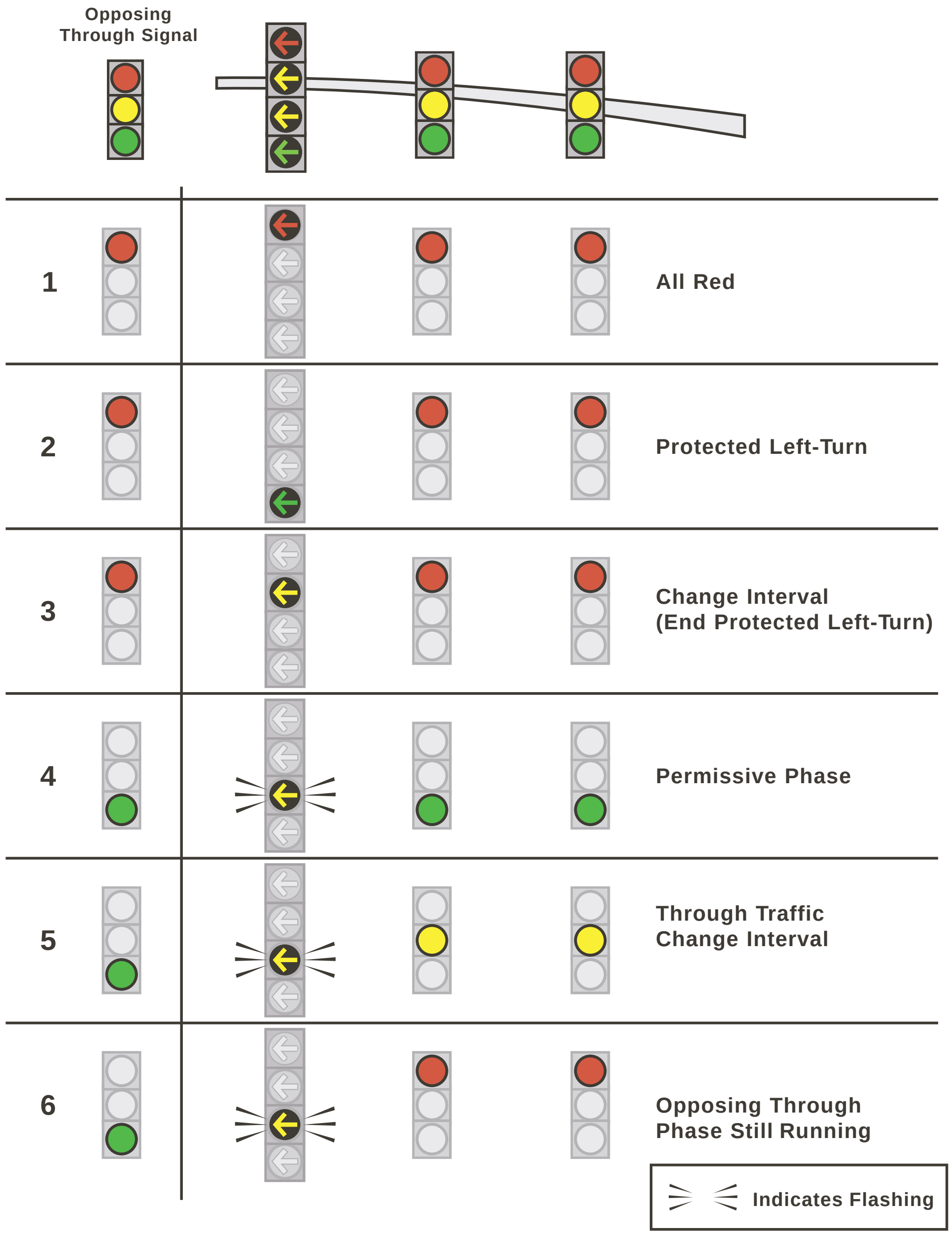


Figure 4-1. Flashing yellow arrow logical link.

operation during low volume conditions. It is also feasible for one direction to operate protected-permissive while the opposite approach uses a different mode. All combinations are feasible and can be selected to optimize the operational efficiency as conditions change.

OTHER CONSIDERATIONS

Supplemental Display Arrangements

The flashing yellow arrow display supports all of the modes of left-turn operation as identified above and can be implemented in states that require supplemental signal faces. States such as California use supplemental signal faces that are normally located on the far left side of the intersection. This type of operation is not possible with the Dallas display because of its need for optical shielding.

Right-Turn Overlap Display

The flashing yellow arrow display would solve the problem of having to prohibit the conflicting U-turn when operating a right turn overlap during a side street left-turn phase. Similarly, the flashing yellow arrow display could be used for drivers who might have to yield to pedestrians while turning right from approaches with no through movement and in cases where a circular green indication cannot be displayed (e.g., because of a one-way opposite approach).

UNIVERSAL APPLICATION

The flashing yellow arrow is the only display that provides a universal solution. It can be used at every intersection, no matter how unusual. Other PPLT displays cannot be used in some situations, such as when the signal arrangements are mounted on span wires, when dual far-side signal arrangements are needed (e.g., in California), when there is no adjacent through movement, when the approach is curved, or when the turn must be held (not even permissive) during railroad preempt although both through movements can proceed.

RECEIVED JAN 2002 JACKSON COUNTY ROADS & PARKS

January 9, 2002

Dear Mr. Niemeyer,

I wanted to write you in response to Dace Cochran's *Cop Corner* article in today's Medford Mail Tribune. He mentioned that flashing yellow arrows are being introduced in Jackson County as a way to study their effect versus the signals that utilize both a green arrow and solid circle.

From my personal experience, I like the flashing yellow arrows much better than the "combo" signals. I witnessed an accident at the intersection of Murphy Road and Barnett Road, here in Medford. One comment I heard from the man at fault was that he had seen a solid green circle (he was turning left onto Murphy), so he thought he had the right-of-way. The man driving the car that hit the first man was heading West on Barnett, and t-boned the first man's vehicle. Of course, the man driving the second car also saw a solid green circle. My opinion is that if the intersection had flashing yellow arrows at the turn-lane, this accident may have been avoided. Again speaking from my own experiences, I have noticed my reaction to each type of signal. When I see a green light, my first reaction is "go", so I sometimes find myself responding to that trained response rather than the one that says "don't go when another car is coming". Alternately, when I see a flashing yellow arrow, there is no question that I need to watch what I'm doing, look for approaching vehicles, and turn when it's safe.

I hope this feedback is helpful to you and your study. I would like to see more of these signals installed around the valley, and look forward to reading more about this project in the near future.

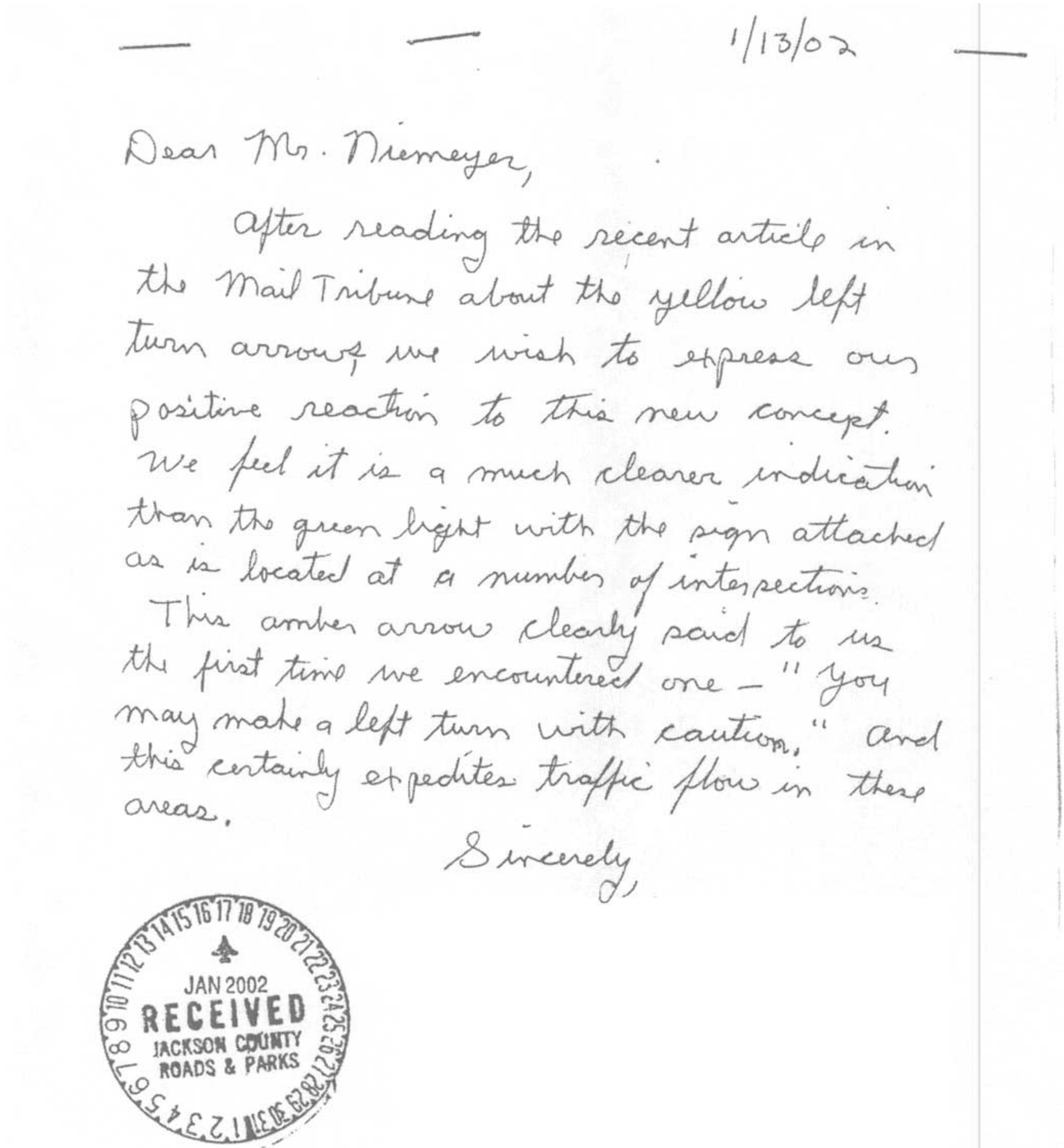
Thank you,

Figure 4-2a. Letter in support.

A NEED FOR CHANGE

There was much discussion within traffic engineering forums that left-turning drivers need to know that there is a change in right-of-way permissions. It has been proposed that a new display was needed that would change in color, mode, position, and shape. That way, when in operation, drivers would be alerted to new information on the signal face so they could align their movements with the correct right-of-way permissions.

The flashing yellow arrow display, in a four-section display face, provides a change in color (green to yellow), a change in mode (steady to flashing), a change in position (a lateral change in display placement and a vertical change in the display arrangement), and a change in shape (circular green to a yellow arrow).



1/13/02

Dear Mr. Niemeyer,

After reading the recent article in the Mail Tribune about the yellow left turn arrow, we wish to express our positive reaction to this new concept. We feel it is a much clearer indication than the green light with the sign attached as is located at a number of intersections.

This amber arrow clearly said to us the first time we encountered one – "You may make a left turn with caution." and this certainly expedites traffic flow in these areas.

Sincerely,

JAN 2002
RECEIVED
JACKSON COUNTY
ROADS & PARKS

Figure 4-2b. Letter in support.

PUBLIC SUPPORT FOR THE DISPLAY

The reaction from the public toward the flashing yellow arrow has been positive. The Field Implementation Study identified all seven implementing agencies as receiving mostly positive feedback from local citizens. For example, as found in Jackson County, Oregon, most of those in favor of the flashing yellow arrow display wanted the displays retrofitted to other intersections where protected-only left turn phasing was in operation. Figures 4-2a and 4-2b contain letters submitted by local citizens supporting use of the flashing yellow arrow displays.

Even outside the auspices of the NCHRP 3-54 project, public reaction has been overwhelmingly favorable. For example: the City of Reno, Nevada, received tremendous public response immediately upon converting several intersections to using the flashing yellow arrow display. A total of 66% of the callers favored the new display, 27% were neutral (asked for information), and 7% were negative (they did not see a reason for the change). Although there were some negative feelings about changing to the flashing yellow arrow display, such a response can be expected anytime there is change in operation.

IMPLICATIONS FOR NONCONFORMING PPLT DISPLAYS

This research project was initiated at the request of the Signals Technical Committee of the National Committee on Uniform Traffic Control Devices. A goal of the study was to identify the "best" PPLT display that would lead to the determination of a national standard, whether that display was the circular green indication or some other indication. This study has shown that the flashing yellow arrow indication is better understood than the circular green indication when used for PPLT operation. The recommendations identified in Chapter 5 identify the flashing yellow arrow display as the preferred alternative to the circular green indication. The future status of other displays/indications currently in use around the United States that do not conform to either the circular green indication or the new proposed alternative indication will need to be determined by FHWA.

CHAPTER 5

RECOMMENDATIONS

Through the course of this study, the individual study tasks such as the Agency Evaluation, Photographic Driver Study, Traffic Operations Study, Traffic Conflict Study, Crash Analysis, Driver Simulation Study, Field Implementation Study, and Engineering Assessment have provided the research team with a tremendous amount of data. Chapters 2, 3, and 4 of this report have presented these data and captured key findings derived from the study task activities. This chapter provides the research team's recommendations based on the collective project findings.

Based on the findings of this project, the research team makes the three recommendations identified below.

RECOMMENDATION #1: INCORPORATE FLASHING YELLOW ARROW DISPLAY INTO THE MUTCD

It is recommended that the flashing yellow arrow display be included in the MUTCD as an allowable alternative display to the circular green indication when used in PPLT control/operation.

RECOMMENDATION #1A: DISPLAYS

The four-section, all-arrow display face should be the only display allowed. The only display that justifies an exception to this recommendation is the three-section display face with bi-modal lens. The three-section display face with bi-modal lens should also be allowed because it operates in the same way as does the four-section display face. Only one indication shall be illuminated at any time. Allowed variations could be as follows:

- The agency may use a circular red indication in lieu of the red arrow.
- A three-section all-arrow display using the center section as a change interval and the permissive interval is allowed, provided that all yellow change intervals for the approach are initiated simultaneously.
- A five-section display may be used.

Figure 5-1 illustrates two potential options for retrofitting a five-section display to incorporate the flashing yellow arrow. The five-section heads shown in Figure 5-1 would serve only as the left-turn signal and would have to be shielded from the adjacent through movement lanes. The adjacent through movement indication would have to be provided on an exclusive display. Furthermore, only one indication in the five-section display would be illuminated at any time.

As shown in Figure 5-1, the five-section display could incorporate an all-arrow arrangement or a yellow circular indication and a red circular indication. If the red circular indication is used, a yellow circular indication or yellow arrow indication could be used for the permissive phase change interval. However, if a red arrow indication is used, the yellow arrow indication must be provided for the change interval. In either case, the protected left-turn elements of the display would remain in their current location and the flashing yellow arrow would replace the current green circular permissive indication in the bottom right corner of the display.

RECOMMENDATION #1B: LOCATION

The flashing yellow arrow operation shall only be used in an exclusive signal arrangement. The left-turn signal face should be placed over the left turn lane.

RECOMMENDATION #1C: SUPPLEMENTAL SIGNS

Supplemental signing is not warranted with a flashing yellow arrow display. Use of supplemental signing is optional. If a supplemental sign is deemed necessary, the following sign should be used: YIELD ON FLASHING YELLOW ARROW or YIELD ON FLASHING YELLOW [Symbolic Arrow].

RECOMMENDATION #1D: PHASING

When used for left-turn treatments, the flashing yellow arrow shall be tied to the opposing through-green indication/display. There may be a delay in the illumination of the flashing yellow arrow display.

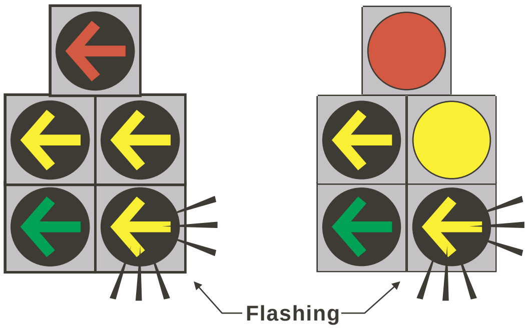


Figure 5-1. Potential flashing yellow arrow retrofit to five-section cluster display (exclusive left-turn display).

RECOMMENDATION 2: CONDUCT FOLLOW-UP STUDY

It is recommended that a follow-up study be conducted for this project. The follow-up study should be conducted after there has been sufficient time for an implementation trial period for agencies currently participating in the field implementation as well as for any additional agencies that may choose to implement based on the findings of this research effort. Sufficient time should also be allowed to acquire before and after crash data at the study intersections and corresponding control sites. Given the difficulties encountered in obtaining useful crash data for this research project, it is strongly encouraged that any participating agencies carefully compile and maintain crash data records for the study intersections. Once initiated, the follow-up study should

- Analyze all available crash data for the experimental flashing yellow arrow displays implemented as part of this study;
- Identify whether the flashing yellow arrow display should become the only display allowed in the MUTCD for a protected-permissive left-turn operation;
- Identify whether, if the flashing yellow arrow is selected to become the only display allowed for PPLT, the MUTCD should also be changed to add the following prohibition: "For Permissive Only Mode operation, a signal face displaying a circular green indication shall not be located directly over or in line with a left-turn lane"; and
- Identify an implementation plan.

RECOMMENDATION 3: RESTRICT USE OF FLASHING RED INDICATIONS

The use of the flashing red indication should only be implemented where an engineering study has identified that all drivers must come to a complete stop before proceeding on the permissive interval.

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Abbreviations used without definitions in TRB publications:

AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
FAA	Federal Aviation Administration
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ITE	Institute of Transportation Engineers
NCHRP	National Cooperative Highway Research Program
NCTRP	National Cooperative Transit Research and Development Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
SAE	Society of Automotive Engineers
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
U.S.DOT	United States Department of Transportation