MEMORANDUM

Date: June 4, 2003

Project #: 2036.13

To: Ray Derr
   National Academy of Sciences
   Transportation Research Board
   500 5th Street NW, Room 455
   Washington, D.C. 20001

From: Kent Kacir, P.E., Principal Investigator
      Chris Brehmer, P.E.
      David Noyce, P.E., Ph.D.
      Bill Kloos, P.E.
      Warren Tighe, P.E.

Project: NCHRP 3-54: Evaluation of Traffic Signal Displays for Protected/Permissive Left-Turn Control

Subject: Response to NCUTCD Signals Technical Committee Questions

The NCHRP 3-54 Research Team presented the results of the research project to the National Committee on Uniform Traffic Control Devices (NCUTCD) Signals Technical Committee in January 2003. The results of the study were unofficially accepted by the Committee; however, the Committee presented five key questions to the Research Team for a follow up assignment.

This memorandum provides a formal written response to those five questions. The response by the Research Team to each of the five questions was based on information that was readily available to the Research Team and/or could be derived from literature contained in the project files. For ease of review, each question is identified in italics text and is followed by a brief summary of the Research Team’s response, which is followed by a detailed discussion and documentation.

The Research Team will present these findings at the June 11, 2003 mid-year meeting.
1. **QUESTION 1: USE OF A SHARED DISPLAY**

What is the (left-turner) driver’s comprehension of the FYA when used in a five-section display, which is a shared display with the adjacent through lane? More specifically, what is driver’s comprehension with the FYA in a five-section head when it is used as one of the two required heads, thus requiring the through movement indication to be displayed simultaneously? Considering the location of the FYA permissive indication as a bi-modal section, (which is also used for the protected green arrow indication) what is the drivers’ understanding of levels in the cluster, i.e., top is stop, middle is clearance, and bottom is yield/go?

1.1. **Research Team Response:**

1.1.1. **Response Summary**

The Research Team recommends that the flashing yellow arrow display be contained in an exclusive signal display arrangement. In this arrangement, the exclusive signal display provides the left-turn driver with specific information pertaining to their unique movement. The Research Team further recommends that only one signal indication be illuminated at any given time. There is clear evidence that driver’s understanding decreases and driver error increases when simultaneous signal indications are illuminated in a single display.

The research performed during the NCHRP 3-54 study focused on comparing the performance, (for left-turn drivers) of the existing five-section shared display with alternative displays, including the separate left-turn-only flashing yellow arrow display. No study was conducted of the shared display containing both the flashing yellow arrow and circular red or yellow indications illuminated simultaneously as that is not a logical display to use in new installations. The Research Team has conducted research on a signal display that shows a flashing yellow arrow and a circular green indication illuminated simultaneously; and the research data supports a high level of understanding. This display is currently being used in Sparks, Nevada with reportably good driver understanding and reduced crash frequency. However, at this time, the Research Team does not support the use of this hybrid head because of its limitations in application (e.g., does not prevent the yellow trap with lead-lag operation) and the whole intent of this project is to identify a signal display for universal application (for uniformity). Such a hybrid head could be used as a temporary display during a period of time for conversion, but it should be recognized as having many limitations in application (lead-lead left-turn operation). Therefore, the Research Team has no information as to driver behavior when faced with a hybrid head. To that regard, should the NCUTCD desire the use of this ‘hybrid’ display, the Research Team recommends further study to identify driver understanding and expectations related to the flashing yellow arrow in such a display (see Figure 3, which illustrates potential combinations of indications that provide seemingly conflicting but correct information).

1.1.2. **Literature Review**

The Research Team conducted a review of the literature contained in the NCHRP 3-54 research project files to provide insight towards driver comprehension associated with shared displays. The Research Team identified two key studies relevant to the response to this question.
University of Texas at Arlington

A 1993 research effort conducted in Texas documented that motorists better understood a protected left-turn movement when shown a green arrow alone as compared to the simultaneous use of a green arrow indication and a circular green indication when no auxiliary sign was provided (Reference 1). The same study further recommended that a circular red indication and a green arrow indication not be shown simultaneously on a five-section head (five-section horizontal, used for dual-left turn operation) unless there is only one other signal head for the through traffic. The reason cited for not using a circular red indication and a green arrow indication simultaneously was that the circular red indication “indicates a strong prohibition” while the green arrow indication indicates an allowable movement, leading to the potential for drivers to misinterpret the indication.

University of Nebraska

A subsequent study prepared by the University of Nebraska – Lincoln identified similar findings related to the use of simultaneous indications in the same signal display (Reference 2). Like the Texas study, the Nebraska study found that drivers were better able to understand a protected indication in a five-section horizontal display when only the green arrow indication was shown (as opposed to simultaneously illuminating the green arrow indication and the circular red indication).

Additional Studies

Additional documentation of past studies involving various combinations of traffic signal displays for protected and protected/permissive use are presented in Working Paper 3 of the NCHRP 3-54(2) Research Project.

1.1.3. NCHRP 3-54(2) Research Evidence

Several elements of the NCHRP 3-54 research project provide insight into driver’s understanding of PPLT displays that can be related to the use of the flashing yellow arrow in a five-section display. The following paragraphs highlight relevant portions of the research effort, including the agency survey, engineering assessment, field conflict and operations data, and findings related to the use of simultaneous indications.

Agency Survey

As part of the NCHRP 3-54(2) project, the Research Team administered an agency survey that was mailed to all 50 state traffic engineers for Departments of Transportation and to traffic engineers in 275 of the largest city and county transportation agencies in the United States and Canada. The survey consisted of three sections with a total of fifteen questions, one of which asked the agency if they used bi-modal left-turn indications.

One hundred and eighty, or fifty-five percent, of the surveys were returned, including six from Canada and six from agencies not using PPLT signal displays. Excluding the Canadian surveys and the jurisdictions that responded but did not use PPLT displays, the remaining 168 returned surveys were reviewed to assess the placement of PPLT displays. Of the 168 surveys, 33 of the agencies indicated that they currently used bi-modal yellow/green left-turn arrows. Of the 33 agencies, nearly 1,650 PPLT signal displays contained the bi-modal arrow.
The primary reason cited by agencies for using the bi-modal arrows was the reduction in signal display size. Energy savings associated with the bi-modal indications were also cited in those instances where light emitting diode (LED) technology was used. Bi-modal indications were primarily reported to be in use in the northeast and New England states of New Hampshire, New York, New Jersey, Connecticut, Rhode Island, and Massachusetts. Illinois, Hawaii, Arizona, Kansas, Montana, Missouri, and Washington State also reported the use of a limited number of bi-modal arrow indications. The continued use of these displays provides at least anecdotal evidence of their acceptance by the traveling public.

**Engineering Assessment**

Also as part of the NCHRP 3-54(2) project, the Research Team prepared an Engineering Assessment that, among other things, reviewed allowable combinations of placement, display face, and left-turn phasing in protected/permissive left-turn (PPLT) displays. The results of this assessment, shown in Table 1, highlight 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 can’t be used for lead-lag phasing; must serve both lagging lefts at the same time; has yellow trap potential). Consequently, the comparison provided in Table 1 points out that the flashing yellow arrow appears to be the most universal option from an engineering perspective.

<table>
<thead>
<tr>
<th>Display Type</th>
<th>Place</th>
<th>Arrival Arrangement</th>
<th>Phasing</th>
<th>Traditional Five-Section Circular Green</th>
<th>Solid Circular Green – Dallas Display</th>
<th>Flashing Yellow Arrow</th>
</tr>
</thead>
<tbody>
<tr>
<td>Shared Indication with Through</td>
<td>Five-section Cluster</td>
<td>Lead-lead Lefts</td>
<td><strong>Y</strong></td>
<td>N/A</td>
<td>N/A</td>
<td><strong>Y</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lag-Lag Lefts</td>
<td><strong>Y</strong></td>
<td>N/A</td>
<td>N/A</td>
<td><strong>Y</strong></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Lead-Lag Lefts</td>
<td><strong>N</strong></td>
<td>N/A</td>
<td>N/A</td>
<td><strong>Y</strong></td>
</tr>
<tr>
<td>Five-section Vertical</td>
<td>Lead-Lead Lefts</td>
<td><strong>Y</strong></td>
<td>N/A</td>
<td>N/A</td>
<td><strong>Y</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lag-Lag Lefts</td>
<td><strong>Y</strong></td>
<td>N/A</td>
<td>N/A</td>
<td><strong>Y</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lead-Lag Lefts</td>
<td><strong>N</strong></td>
<td>N/A</td>
<td>N/A</td>
<td><strong>Y</strong></td>
<td></td>
</tr>
<tr>
<td>Five-section Horizontal</td>
<td>Lead-Lead Lefts</td>
<td><strong>Y</strong></td>
<td>N/A</td>
<td>N/A</td>
<td><strong>Y</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lag-Lag Lefts</td>
<td><strong>Y</strong></td>
<td>N/A</td>
<td>N/A</td>
<td><strong>Y</strong></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Lead-Lag Lefts</td>
<td><strong>N</strong></td>
<td>N/A</td>
<td>N/A</td>
<td><strong>Y</strong></td>
<td></td>
</tr>
</tbody>
</table>

*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.
Field Conflict and Operations Data

Using the field conflict and operations data collected in the initial efforts of NCHRP 3-54, it was documented that the simultaneous illumination of signal faces with conflicting messages could be confusing to drivers and potentially lead to safety problems.

When reviewing the field conflict studies (which were conducted at 24 intersections in eight cities across the United States), Noyce found little difference in traffic conflicts due to the variance in PPLT signal displays. In contrast, traffic events involving left-turn vehicles hesitating or not turning left during the protected left-turn green arrow accounted for 60 percent of all events observed. Most of these traffic events where found at intersections containing a five-section horizontal signal display, located over the lane line, using a leading (dual) left-turn signal phasing sequence. With a dual leading left-turn sequence, the green arrow indication was illuminated after the conclusion of the side street phase, while the adjacent through movements continued to receive a circular red indication indication. Subsequently, the green arrow and circular red indications were simultaneously illuminated in the five-section horizontal PPLT signal display. With the green arrow indication located to the right of the circular red indication in the five-section horizontal display, drivers appeared to either miss the initial illumination of the green arrow indication, be confused by its meaning, or hesitate for several seconds to be assured that making the left-turn maneuver was safe (Reference 3).

In a related study, Noyce quantified saturation flow rate, start-up lost time, response time, and follow-up headway associated with selected PPLT signal displays (Reference 4). Using the same 24 intersections reviewed in the conflict study, Noyce found that start-up lost time and response time were larger when the green arrow and circular red indication were shown simultaneously than when the green arrow was shown with a circular green indication or separately. Start-up lost times averaged approximately 2.1 seconds and response times approximately 3.0 seconds. These results suggest that left-turn vehicle delay is increased when the green arrow and a circular red indication are simultaneously displayed, likely due to driver confusion associated with the conflicting meaning of these indications.

Subsequent Research

Noyce and Kacir further reviewed the issue of simultaneous illumination of signals building on the database collected through the NCHRP 3-54 project (Reference 5). The additional research was prepared using the database developed through the Photographic Driver Study component of the research project. The Photographic Driver Study consisted of a series of static photographs of various PPLT displays (some of the displays such as the flashing yellow arrow, flashing red arrow, etc. were animated) shown on one of six backgrounds. For each photograph, drivers were asked the following question:

“If you want to turn left, and you see the traffic signals shown, you would...”
Four responses to the question were developed, one that applied to each of the protected, permitted, and all-red left-turn indication. The four responses were:

- GO
- YIELD - wait for gap
- STOP - then wait for gap
- STOP

Focusing on the protected left-turn indications in the driver study, approximately 1,500 total responses were received to the five-section horizontal display and 2,200 responses were received for all other signal displays. This subset of data was derived from a total survey sample of 2,465 drivers and the 73,950 PPLT signal display scenarios the drivers collectively provided.

Using the database, it was documented that the majority of incorrect responses to five-section PPLT displays with the green arrow and circular red indication (as shown in Figure 1) were stop, then wait for gap, demonstrating some confusion with the simultaneously illuminated indications. Similar confusion was not found when the green arrow and circular green indications were shown simultaneously or when the green arrow indication was shown individually (refer to Figure 1).

![Figure 1: Application of the Flashing Yellow Arrow Indication Using a Five-Section Cluster Display](image)

The correct response rate with the simultaneous green arrow and circular red indications were much different. Average correct response rate was only 71 percent; ranging from 62 percent for drivers over the age of 65 to nearly 75 percent for drivers less than 24 years of age.

Focusing on drivers over the age of 65, correct response rate for the simultaneous green arrow and circular red indications was 62 percent compared to the 86 percent for the green arrow and circular green combination and 89 percent for the green arrow indication only. This result was found to be statistically significant (p = 0.0001) using analysis of variance (ANOVA) procedures. When considering only the five-section horizontal display with simultaneous green arrow and circular red indications, only 49 percent of the older drivers responded correctly.

The results of this research indicated that the simultaneous illumination of the green arrow and circular red indications in a five-section PPLT signal display during a protected left-turn phase significantly reduced driver understanding, added response time to the driving decision, and
increased driver error. This finding was especially true for drivers over the age of 65. The reason for the decrease in comprehension was likely due to the increased perceptual processing required and the associated increase in driver workload.

When the green arrow and circular red indications were shown simultaneously in a five-section signal display, driver understanding was lowest with the horizontal arrangement. Locating the green arrow to the right of the circular red indication in a five-section horizontal display arrangement appeared to provide additional confusion. When the green arrow and circular green indications were shown simultaneously, the five-section horizontal display also has the lowest level of driver understanding; however, nearly 89 percent of drivers correctly understood the meaning.

1.1.4. Implementation

The previously described research efforts have direct implications on the five-section cluster and five-section horizontal PPLT displays, both of which use simultaneous illumination of potentially conflicting indications. Use of a traditional five-section cluster display modified to accommodate a flashing yellow arrow indication for the permissive phase (as conceptually illustrated in Figure 2 below) would also be subject to the same condition of potentially conflicting indications as shown below.

![Figure 2: Application of the Flashing Yellow Arrow Indication Using a Five-Section Cluster Display](image-url)

<table>
<thead>
<tr>
<th>Lens Color and Arrangement</th>
<th>Permissive Mode</th>
<th>Protected Mode</th>
</tr>
</thead>
<tbody>
<tr>
<td>R</td>
<td>Y</td>
<td>G</td>
</tr>
</tbody>
</table>

R = Red  Y = Yellow  G = Green  Y = Flashing Yellow

*The indication illuminated for the given mode is identified by the color letter*

As illustrated in Figure 2, a bi-modal indication would be used to incorporate the shared five-section cluster arrangement while still adhering to Manual on Uniform Traffic Control Devices (MUTCD) requirements for accommodating simultaneous through and left-turn requirements. In the PPLT signal display presented in Figure 2, the permissive indication would display a flashing yellow arrow permissive indication presented simultaneously with a circular green indication. Both the protected green arrow and permissive flashing yellow arrow indications would be cleared with a solid yellow arrow indication in the signal section directly above the bi-modal section. This display configuration is a recommended alternative because it uses a change of indication and location to alert drivers of the change in right-of-way.
Figure 3 illustrates the operation of the five-section cluster display with the flashing yellow arrow permissive indication in lead-lag operation. The figure clearly identifies all possible combinations of indications that would be presented to the left-turn driver, including those involving simultaneous illumination of conflicting indications (circular red indication and green arrow indication).

Beyond the overall concern associated with presenting simultaneous indications, the Research Team is particularly interested in drivers’ understanding of two phase sequences associated with the use of a five-section cluster flashing yellow arrow PPLT display. Specifically, there is concern as to drivers’ understanding of the indications illuminated during a lagging left-turn movement. As shown in Figure 3, during the change interval for an opposing lagging left-turn, drivers will be exposed to a brief period when the through traffics’ circular yellow indication and the flashing yellow arrow indication will be illuminated simultaneously, followed by a period when the through traffics’ circular red indication and the flashing yellow arrow indication will be illuminated simultaneously. Given the literature cited illustrating drivers’ lack of understanding when shown a green arrow and a circular red indication in the same display, it is questionable how well the change interval will be understood. If the change interval is not understood, it could lead to the creation of a yellow trap, nullifying one of the benefits of the flashing yellow arrow.

1.1.5. Discussion

Historically, shared heads such as the five-section protected/permissive head (which is often located close to the line separating the left-turn lane from the adjacent through lane) have been installed because they are the only MUTCD display that enables protected/permissive left turn operation. If the recommended flashing yellow arrow display were included in the MUTCD, it is assumed that during traffic signal design, all users desiring PPLT operation would install a separate, left-turn-only, all-arrows, flashing yellow arrow head for the left-turn movement, separate from all through movement heads.

It seems the issue of a shared head involving a flashing yellow arrow arises only in the context of retrofits to signals that currently have a traditional five-section shared head, and where the cost of separating the left-turn and through-movement display into two separate heads is prohibitive. Depending on the configuration, such a retrofit may involve, in addition to replacement of the shared head with separate left and through heads, a new longer or stronger mast arm, and installation of new wiring from the left-turn head to the cabinet – hence the potential interest in a hybrid head.

In the retrofit context, the question arises as to whether adding a flashing yellow arrow indication to an existing five-section head (that combination is here called a “hybrid display” or “hybrid head”) is an improvement over the traditional five-section head and should be considered as a worthwhile interim upgrade, or whether the existing head should remain as is until such time as a separate left-turn-only flashing yellow arrow head can be installed. Although no research has been conducted into motorist’s behavior relative to the hybrid display, we can consider some of the other characteristics of such a display.

First it is necessary to consider alternative operational modes for a hybrid display. Two potential options are presented below.
Figure 3: Phasing in a 5-Section Cluster
PPLT Display With a Flashing Yellow Arrow

<table>
<thead>
<tr>
<th>Phasing</th>
<th>Left-Main Phase</th>
<th>Left Side Street</th>
<th>Opposite Main Phase</th>
<th>Opposite Side Street</th>
</tr>
</thead>
<tbody>
<tr>
<td>All Red</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
</tr>
<tr>
<td>Lagging Protected Left-Turn</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
</tr>
<tr>
<td>Yellow Change Interval</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
</tr>
<tr>
<td>Red Clearance</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
</tr>
<tr>
<td>Permissive Phase</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
</tr>
<tr>
<td>Yellow Change Interval</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
</tr>
<tr>
<td>Red Clearance</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
</tr>
<tr>
<td>Lagging Protected Left-Turn</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
</tr>
<tr>
<td>Yellow Change Interval</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
</tr>
<tr>
<td>Red Clearance</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
<td>☺</td>
</tr>
</tbody>
</table>

Opposing traffic signal heads viewed as if transparent.

Bi-Modal Arrow

Side Street Green

Indicates Flashing

i:\projfile\2036\cdrfiles\june_2003\figures\figure_3.cdr
Option 1

Option 1 uses the existing five lenses and wiring unchanged, and flashes the yellow arrow whenever the circular green indication is on and neither the green arrow nor the steady yellow arrow indications are on. In this option, flashing the yellow arrow is simply a means of emphasizing that left turns can be made permissively while the circular green indication is displayed alone. A similar display is in use in the City of Sparks, Nevada. Option 1 may or may not help avoid misinterpretation of the circular green indication as a protected left-turn indication. Both this and the subsequently-discussed option fail to flash the yellow arrow consistently when ever the circular green indication is displayed, which is of some concern.

Regardless of its impact on drive understanding, it does nothing to overcome the yellow trap and lost-time shortcomings of the traditional shared head. The lost-time problem refers to the fact that a permissive left turn cannot be made when the both the through and protected left turn phases in the opposite direction are green, even though it is perfectly safe to do so.

Option 1 avoids the need for any change to the signal head or wiring, but requires special logic be added in the controller or intermediate hardware to flash the yellow arrow appropriately (e.g., suppress flashing the yellow arrow when the left turn phase is active), and may require modification of the conflict monitor or malfunction management unit (MMU).

Option 2

Option 2 requires the installation of a bi-modal green and yellow arrow indication in place of the existing green arrow indication, and then operates the arrows portion of the head the same as recommended for the separate left-turn-only, all-arrows, flashing yellow arrow head. In this case, the flashing yellow arrow indication is tied to the opposing through movement green, rather than the same-direction through green. Similar to Option 1, this option displays the flashing yellow arrow simultaneously with the circular green indication at some times, and not at others. As discussed below, it can also result in the circular green indication being shown alone with no arrows illuminated during the red clearance interval of the left-turn phase.

Option 2 overcomes the left-turn trap and lost-time problems associated with the traditional five-section head and Option 1. It would allow the use of lead-lag and unconstrained lag-lag phasing at PPLT signals that currently may be limited to lead-lead phase sequencing only because of yellow trap considerations.

Option 2 requires installation of the bimodal lens, installation of new wiring from the hybrid head to the cabinet, modified logic in the controller or intermediate hardware to provide the flashing yellow arrow logic, and probably a change in the conflict monitor or MMU.

Is the Hybrid Display Worthwhile?

Adding a flashing yellow arrow indication to a shared head will add to the complexity and number of different permutations of indications-on combinations seen by motorists, including the first instance of mixing flashing and steady indications in the same head.

Not only does the number of different combinations of indications-on increase (from 9 to 12 in the case of Option 2), but so does the number of different combination transition sequences. For
example, if the protected left-turn phase has a red clearance interval, the hybrid display Option 2 can change from circular green with yellow arrow, to circular green only (for the duration of the red clearance interval), to circular green with flashing yellow arrow. Adding to the complexity of shared heads seems counter to the goal of the project.

Both hybrid options still involve the simultaneous display of a circular red and a green arrow. This combination has been shown in research studies to be a frequent source of confusion for drivers. Some motorists will stop and then proceed when they approach this display.

The Option 1 hybrid seems to have limited usefulness. Option 1 does not address the yellow trap, lost-time, and circular-red-with-green-arrow confusion problems associated with the traditional five-section head, yet still involves some significant cost for additional control logic in a retrofit situation. It is questionable whether there would be much demand for use of this type of display. It is recommended that any further discussion of a hybrid display focus on Option 2.

The Option 2 hybrid does address the yellow trap and lost-time problems, but retains the circular-red-with-green-arrow confusion problem. Also, the cost of modifying a traditional PPLT signal to use the Option 2 hybrid head is not trivial. It involves new lenses (bi-modal) new wiring, and new control logic. There may also be limited demand for this option.

It should be clear that the Research Team advocates that all new installations of the PPLT operation should use only the four section all-arrow display, or allow variations as identified in the project recommendations. The retrofit of existing PPLT operations currently using the MUTCD shared display should be carefully evaluated for the reasons identified in the above discussion. The Research Team recommendation is for an exclusive left-turn display and not a shared display.

With respect to the last part of the question posed by the NCUTCD, no documentation was identified related to drivers’ understanding of levels in the cluster, i.e., top is stop, middle is clearance, and bottom is yield/go. While the Research Team believes that the spatial location of the indication (top, middle, bottom) does in fact have an intuitive meaning to drivers and fundamentally makes sense, there is no known evidence to support that hypothesis and at least a small study would be needed to validate it.

Beyond the illustrations and documentation provided above, the current research findings do not offer any additional insight into driver’s comprehension of the use of a flashing yellow arrow permissive indication in a five-section cluster PPLT display. This is an area that additional research would be required to evaluate if further analysis is deemed appropriate.

1.1.6. **Recommended Next Steps**

Should the NCUTCD traffic signals committee desire additional documentation and research regarding the use of a flashing yellow arrow indication in a five-section cluster display, a driver behavior/driver comprehension study should be conducted.
2. **QUESTION 2**

What is (left-turner) driver’s comprehension of the solid yellow arrow (as used in the clearance) when the flashing yellow arrow permitted indication is used?

2.1. **Research Team Response:**

2.1.1. **Response Summary**

This question focuses on the effectiveness of clearing a flashing yellow arrow with a steady yellow arrow. From the outset of the project, some commentators have expressed concern that a driver could emerge from behind a truck or otherwise first see the steady yellow arrow without having seen that it follows a flashing yellow arrow, and assume it is the termination of a protected turn phase. Research and real-world results suggest this concern is unfounded. We can only speculate as to the psychology involved. Motorists who cannot see the signal display because of some obscuration are unlikely to be approaching at high speed as they will want to see the display before entering the intersection. A solid yellow means “stop if you can do so safely” and they are likely to be able do just that. Anyone deliberately “sneaking” through on the yellow will tend to be very alert.

More concretely, previous research efforts have documented evidence that the majority of drivers correctly interpret the meaning of the solid yellow arrow display. The evidence points to this indication as being a safe and effective means of terminating the flashing yellow arrow. Note that the recommended flashing yellow arrow display involves a change in position between the flashing yellow and steady yellow lenses. The change in position is intended to contribute to the effectiveness of the display, although it may not be necessary, as experienced in Jackson County, Oregon. Thus, the anecdotal observation data from real-world installations in this country and in Europe suggest that the display is safe. The Research Team recommends the use of the steady yellow arrow for clearing flashing yellow arrow permissive display, and no further study is warranted at this time.

2.1.2. **Literature Review**

Reviewing the NCHRP 3-54 research project files, the Research Team identified three key studies relevant to the response to this question.

*ITE Committee 4D-61 (4)*

In 1961, the Technical Council of the Institute of Traffic Engineers assigned Committee 4D-61 (4) the responsibility to investigate the various applications of red and yellow arrow signal indications and to initiate an evaluation of the uses that would be both comprehensive and objective (Reference 7). The committee recommended that the use of red and yellow arrow signal indications should continue to accumulate experience that would be valuable in the final decision for or against standardization. The committee also made the following recommended definitions:
Steady Yellow Arrow – Traffic continuing to move in the direction of the arrow is cautioned that its movement is about to be terminated and should stop if it can do so safely.

Steady Red Arrow – Traffic continuing to move in the direction of the arrow must stop until directed to proceed by a circular green or green arrow.

Flashing Yellow Arrow – Traffic intending to move in the direction of the arrow is directed to make its movement with more than usual caution and to yield to pedestrians or vehicles legally within the intersection.

Flashing Red Arrow – Traffic intending to move in the direction of the arrow shall stop before entering the intersection and then make its movement, yielding to pedestrians or vehicles legally within the intersection.

Federal Highway Administration

In 1978, the Federal Highway Administration (FHWA), developed and administered a brief survey to test driver understanding of left-turn signalization concepts (Reference 8). The survey was administered in four urban cities (Costa Mesa, and Berkeley, CA, Evanston, IL, and Glastonbury, CT). The paper survey was supplemented with an actual signal display controlled by the survey administrator.

The survey posed the question: “What does the yellow arrow mean when it comes on between the green arrow and the green ball [circular green]?” The driver was then instructed to choose one of three potential responses listed below:

- Opposing through traffic will be starting up and you must wait for safe gaps in oncoming traffic before making your left turn
- You may make left turns without worrying about oncoming traffic
- After the arrow, you will be able to make a left turn while oncoming traffic stops and yields to you.

Table 2 below summarizes the survey response results.
As indicated in Table 2, over 87 percent of the survey participants concluded a yellow arrow shown between a green arrow and a circular green indication meant that opposing traffic would be given the right-of-way and they (the driver) would need to wait for a safe gap in oncoming traffic before completing their left-turn. Ultimately, the 1978 study concluded that driver education was needed. It should be pointed out that, as of the time the 1978 study was prepared, only seven states had laws pertaining to the meaning of yellow and red arrows (none of which the survey was administered in).

The FHWA study also administered a state-of-the-art agency survey. The agency survey was sent to 360 transportation agencies in the United States, including 133 cities with populations less than 100,000; 103 cities with a population greater than 100,000; and 72 counties. One question in the survey was directed at the type of clearance interval used between the green arrow indication and the circular green indication. Forty-five percent of the responding agencies indicated that they used the yellow arrow, while nineteen percent used a blank clearance, and thirty-six percent used some ‘other’ type of clearance (Reference 8).

**Texas Transportation Institute**

In 1991, a driver survey of 1,745 drivers across the state of Texas was prepared as part of a comprehensive study of multiple traffic control devices (Reference 9). The survey, conducted by the Texas Transportation Institute, included a question regarding the yellow arrow signal indication. The survey question was: “What does it mean when the yellow arrow is on?” The purpose of this question (as identified in the report) was to query if the drivers recognized that it is legal to enter the intersection during a steady yellow indication. The driver was instructed to choose one of four possible responses. The four potential responses were:

- You should not enter the intersection
- Your time to turn is about to begin
- Your time to turn is about to end
- Not sure

Table 3 below summarizes the survey response results.

---

**Table 2  Summary of FHWA Driver Survey Responses**

(When asked: “What does the yellow arrow mean when it comes on between the green arrow and the green ball [indication]?”)

<table>
<thead>
<tr>
<th>Response</th>
<th>Percent of Drivers Selecting Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>Opposing through traffic will be starting up and you must wait for safe</td>
<td>87.2</td>
</tr>
<tr>
<td>gaps in oncoming traffic before making your left turn.</td>
<td></td>
</tr>
<tr>
<td>You may make left turns without worrying about oncoming traffic.</td>
<td>3.5</td>
</tr>
<tr>
<td>After the arrow, you will be able to make a left-turn while oncoming</td>
<td>9.2</td>
</tr>
<tr>
<td>traffic stops and yields to you.</td>
<td></td>
</tr>
</tbody>
</table>

---
Table 3
Summary of Driver Survey Responses
(When asked: “What does it mean when the yellow arrow is on?”)

<table>
<thead>
<tr>
<th>Response</th>
<th>Percent of Drivers Selecting Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>You should not enter the intersection</td>
<td>6.1</td>
</tr>
<tr>
<td>Your time to turn is about to begin</td>
<td>7.1</td>
</tr>
<tr>
<td>Your time to turn is about to end.</td>
<td>80.4</td>
</tr>
<tr>
<td>Not sure.</td>
<td>6.4</td>
</tr>
</tbody>
</table>

As indicated in Table 3, the responses to the survey question indicate that 80 percent of the sampled driving population understood that the meaning of the steady yellow arrow meant that their movement was ending.

2.1.3. **NCHRP 3-54(2) Research Evidence**

The NCHRP 3-54 research project focused on the understanding of the permissive display and did not query subjects on their understanding of the clearance interval display. Visual inspection of operations at intersections that were converted to the flashing yellow arrow PPLT display did not identify any concerns with driver understanding of the clearance interval upon introduction of the flashing yellow arrow. It is worth noting that the flashing yellow arrow implementation in Broward County, Florida was deployed with the circular yellow indication based on local jurisdictions concerns associated with leading a motorist into the intersection with the steady yellow arrow (which historically has followed the green arrow and preceded the circular green indication).

It is hypothesized that the change in mode (flashing to solid) and the simultaneous change in position within the signal display provide sufficient information to drivers that the clearance interval has begun and that the permissive phase is ending. Figures 4 through 6 illustrate how the four-section vertical PPLT display operates, including the clearance interval displays.

2.1.4. **Recommended Next Steps**

The Research Team believes that the meaning of a solid yellow arrow is understood by drivers and does not propose any additional studies at this time; however, a study could be developed to provide further investigation of the Research Team’s hypothesis if it is deemed necessary.
Figure 4: Lead - Lead Phasing in a 4-Section Vertical PPLT Display

Opposing traffic signal heads viewed as if transparent.
Figure 5: Lead-Lag Phasing in a 4-Section Vertical PPLT Display

Opposing traffic signal heads viewed as if transparent.

- All Red
- Leading Protected Left-Turn
- Yellow Change Interval
- Left-Turn Red Interval
- Permissive Phase
- Yellow Change Interval
- Approach Red
- Lagging Left
- Yellow Change Interval
- Red Clearance

Side Street Green

Indicates Flashing
<table>
<thead>
<tr>
<th>Phase</th>
<th>Traffic Signals</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>All Red</strong></td>
<td>![Traffic Lights]</td>
</tr>
<tr>
<td><strong>Permissive Phase</strong></td>
<td>![Traffic Lights]</td>
</tr>
<tr>
<td><strong>Yellow Change Interval</strong></td>
<td>![Traffic Lights]</td>
</tr>
<tr>
<td><strong>All Red</strong></td>
<td>![Traffic Lights]</td>
</tr>
<tr>
<td><strong>Lagging Protected Left-Turn</strong></td>
<td>![Traffic Lights]</td>
</tr>
<tr>
<td><strong>Yellow Change Interval</strong></td>
<td>![Traffic Lights]</td>
</tr>
<tr>
<td><strong>Red Clearance</strong></td>
<td>![Traffic Lights]</td>
</tr>
</tbody>
</table>

- **Side Street Green**: Indicates Flashing.
3. QUESTION 3

If one jurisdiction deploys the FYA in many/most PPLT applications, and the driver becomes accustomed to the FYA operation; then what does that same driver believe to be the meaning of the circular green indication in other jurisdictions (perhaps neighboring) where only the circular green indication is still used for PPLT operation? In other words, if the FYA is gradually implemented at a number of intersections, and drivers comprehend the FYA indication, will this have an impact on the driver comprehension of the circular green permissive indication that will remain in operation at other intersections? If drivers learn to understand that the FYA means permissive/yield, will they more frequently assume that the permissive green indicates a right-of-way condition?

3.1. Research Team Response:

3.1.1. Response Summary

The Research Team has conducted a limited survey of practicing traffic engineers on this subject and finds no evidence to support the concern raised for the following reasons: A) there is anecdotal evidence from the City of Seattle related to the implementation of the flashing circular yellow display along Aurora Boulevard in the mid-1960’s that shows that even along one corridor, multiple agencies implemented either the circular green indication or the flashing circular yellow indication for the permissive left-turn display and motorists understanding was not seen as problematic1; B) the implementation of the flashing yellow arrow will not likely be quick, therefore drivers will interface to both types of displays and react correctly to each display (the steady yellow arrow was implemented over time, for example, before it became more common practice); C) typical drivers do not stay within one community such that they are not aware of other jurisdictional practices; and D) drivers will continue to turn left permissively on a circular green indication at signals with no left-turn phasing, thus preserving familiarity with circular-green-means-yield.

3.1.2. Literature Review

A literature review of materials identified through the course of the NCHRP 3-54(2) research project provides some limited insight to the issue. During the initial stages of the NCHRP 3-54(2) research project, it was documented that a flashing circular yellow indication is used in the State of Washington for the permissive phase of PPLT control. In Washington, the change to a flashing circular yellow permitted indication was started in 1966 (Reference 10). Additional application of the flashing circular yellow indication resulted from a permitted indication safety study conducted by the Washington section of ITE between 1978 and 1985 (Reference 10 and Reference 11). The ITE committee evaluated a number of factors, including conflict rates, crash rates, drivers’ opinions, vehicle delay, and compliance at 30 locations. The findings of that study supported continued use of the flashing yellow arrow and noted no degradation in drivers’ understanding of the circular green indication as a result of the use of the flashing circular yellow indication (though this topic was not explicitly explored by the study).

---

1 Telephone conversation between Kent Kacir and Barry Fairfax, May 2003. Mr. Fairfax was the practicing Traffic Engineer for the City of Seattle at that time.
3.1.3. **NCHRP 3-54(2) Research Evidence**

Experimental PPLT displays using the flashing yellow arrow permissive indication were implemented by six agencies in the United States as part of the NCHRP 3-54 research project. Montgomery County, Maryland was the first agency to implement, followed by Tucson, Arizona; Jackson County, Oregon; the Oregon Department of Transportation (ODOT); Beaverton, Oregon; and Broward County, Florida. Each of the agencies implementing the experimental flashing yellow arrow PPLT display also continued to use PPLT displays operating a permissive circular green indication at other nearby locations. In some instances (such as along Highway 99E in Woodburn, Oregon where ODOT implemented the flashing yellow arrow), traditional five-section cluster PPLT displays are located at adjacent upstream and downstream intersections. To date, there have been few problems reported by agencies implementing the flashing yellow arrow indication related to misinterpretation of the flashing yellow arrow permissive indication.

3.1.4. **Recommended Next Steps**

There is no evidence to support that driver’s will become accustomed to the flashing yellow arrow such that they expect it to be the only display for permissive left-turn movements. The Research Team does support conducting a limited study to quantify the potential impact implementation of the flashing yellow arrow indication has on driver comprehension of the various forms of the circular green permissive indication.

Should the NCUTCD traffic signals committee desire additional documentation and research investigating the impact of the flashing yellow arrow indication on driver understanding of the circular green permissive indication, some combination of a static and dynamic driver study could be developed to further evaluate the issue. Similar to previous NCHRP 3-54(2) research efforts, a driver simulator could be used to train drivers in learning the meaning of the flashing yellow arrow permissive indication by repeated exposure throughout a visual simulation. Those same drivers could then be shown intersections with a circular green permissive indication to determine their comprehension of the circular green. A computer-based static evaluation could then be used to further evaluate the difference in driver comprehension of the circular green permissive indication after repeated exposure to the flashing yellow arrow indication.
4. QUESTION 4

How can the FYA be applied to intersections that use the 5-section display located both in the median and on the far left, and the 5-section display contains one of the two required circular green indications for the through movement? What is the best method of applying the FYA permissive indication in states that require a different number of signal heads other than those required by the MUTCD?

4.1. Research Team Response:

4.1.1. Response Summary

A significant advantage of the flashing yellow arrow display is the flexibility it offers in placement. The flashing yellow arrow display can be used in all applications, even for those states that require supplemental left-turn displays. The Research Team does recognize that some states, such as Wisconsin, require additional supplemental displays on the near-side of the intersection and other locations. Observing Wisconsin state design standards, it is apparent that their design essentially implements redundant displays that are affectively shared displays. Therefore, in the case for Wisconsin, the manner in which they proceed lies first in their acceptance in the answer to Question #1.

The Research Team has identified an optimum signal display for communicating traffic control information to the driver attempting the permissive left-turn maneuver (PPLT operation). It is possible that, for states that require display arrangements or specific locations of displays, the recommended four-section all arrow display may not be directly implementable without changes to state or local government design standards. The Research Team recognizes that making changes to standards is not trivial; however, the Research Team does know of at least one state that already developed proposed changes to state standards essentially adopting the recommended display in anticipation for future language in the MUTCD allowing such a display.

4.1.2. Literature Review

The Research Team has reviewed several state and local agency standards for relevant standard designs. While there are design standards for many governmental agencies (state and local) and consortium forums, the Research Team has identified a few for discussion below.

Orange County

The Orange County Traffic Engineering Council, a consortium of southern California communities, evaluated and selected a five-section cluster display for the overhead PPLT signal display and a five-section vertical display for a far left pole-mount display (Reference 12). The purpose of selecting a single set of displays was to implement traffic display uniformity in the region to eliminate or at least minimize the problem with driver confusion.

Florida

A similar evaluation of left-turn traffic signal displays was completed in the state of Florida because of the unique composition of tourist and retiree traffic on Florida’s roadways (Reference
Florida concluded that the five-section cluster display should be used for all PPLT applications. The policy statement states that a five-section cluster display increases safety by reducing driver misunderstanding related to the permissive left-turn movement.

Wisconsin

A review of the Wisconsin traffic signal design manual (Reference 14) identifies several geometric layouts and location of signal displays. In general, the standard shows the through movement signal displays located on the near-right, the far right, near-side median, and the far side median. In some geometric scenarios there are as many as six displays facing a single approach. Again, in general, most signal displays are located on the right side and the median, with the uniqueness being the supplemental displays located on the near-side of the intersection.

4.1.3. NCHRP 3-54(2) Research Evidence

As documented in the Research Team response to Question #1, part of the NCHRP 3-54(2) project involved the administration of an agency survey. Through the agency survey, the question of mounting locations for secondary PPLT displays was explored. Of the 168 agencies responding with PPLT displays, 83 indicated that they use a secondary PPLT signal display, while 85 indicated that they did not.

Of the agencies that use a secondary or additional PPLT signal display, the majority place the additional display on a farside pole mount. Sixty-seven agencies indicated that they place the secondary PPLT signal display at the farside. Twenty-two agencies indicated that they place the secondary PPLT signal displaying a median pole-mount location, and eight agencies use a nearside pole mount location. The 11 agencies that indicated “other” in the survey response generally used a second overhead PPLT signal display, either mast-arm or span-wire mounted.

Further questioning through the survey inquired as to whether agencies did anything different or “unique” at wide median and/or narrow right-of-way intersections with no median as compared to their standard PPLT treatment. The findings of the survey documented that 39 agencies developed “unique” treatments at wide median intersections. At wide median intersections, the most commonly reported difference was the addition of another PPLT signal display, either median or farside pole mounted. The addition of another PPLT signal display may also require the repositioning of the other signal displays at the intersection. The only other commonly cited difference at wide median intersections was the elimination of PPLT signal phasing. Fifteen agencies indicated that they would not use PPLT signal phasing at wide median intersections.

In addition to the unique circumstances identified through the agency survey, it has been noted that a number of states, including Illinois and Wisconsin, require from four or six total signal heads per approach. Wisconsin requires that a minimum of four heads be provided: one near side on the right, one on the far side over the through traffic, one on the far side over the left-turn lane, and one on the far side left. The final report for the NCHRP 3-54(2) project recommended a location/placement for PPLT signal displays based on MUTCD requirements; however, no recommendation was made regarding applications where additional signal heads would be required under specific state guidelines (Reference 6).
4.1.4. **Recommended Next Steps**

It is not the position of the Research Team to instruct governing bodies to change their standards to accommodate the proposed four-section all arrow display. The Research Team has identified several displays that provide optimum information to the permissive left-turning driver. The Research Team acknowledges that many standards authored by a variety of agencies and forums do not directly accommodate the Team’s recommended display. There is a willingness on the part of the Research Team to work with agencies in defining ways to implement the flashing yellow arrow in such a way that is consistent with the findings and recommendations of the NCHRP 3-54 Research Project, while keeping focused on creating a standardized display for uniform use by all agencies.

The Research Team recommends that the individual agencies consider how to adopt the recommended four-section all-arrow display for all PPLT installations. The agencies should consider how drivers receive the intended information.

5. **QUESTION 5**

*Is driver comprehension of the circular green indication greater/different if the signal display/indication is located over the lane line, or centered over the left-turn lane?*

5.1. **Research Team Response:**

5.1.1. **Response Summary**

The NCHRP 3-54 research project (as studied) did not identify any significant differences in driver understanding of the circular green indication and display placement. No additional research data was identified that contradicts this finding. The Research Team does not believe further study of the circular green indication and horizontal display placement is warranted.

5.1.2. **Literature Review**

Figure 7 illustrates two potential overhead signal display placement alternatives allowed by the MUTCD for PPLT control. In addition to the alternatives shown in the figure, post-mounted median and farside display placements are also used.
A literature review of materials identified through the course of the NCHRP 3-54 research project determined that the issue of lane placement has been investigated in the past. Sobhi, analyzing data obtained by Ketron & Associates as part of a 1988 JHK study on left-turn signal displays, found no significant difference in drivers’ comprehension when considering arrangement (Reference 15). The highest correct response rate was associated with separately located left-turn signal displays, including a median-mounted five-section vertical display and a mast arm-mounted five-section cluster display. Both of these displays were found to be superior to four-section vertical displays (Reference 16).

Agent evaluated the placement of PPLT signal displays related to traffic crashes at 58 intersections in Kentucky (Reference 17 and Reference 18). The dominant PPLT signal display in Agent’s study was the five-section cluster display. Agent found that signal displays placed between the left-turn lane and adjacent through lane led to a lower left-turn crash rate than signal displays placed in the middle of the left-turn lane.

In 1994, researchers at the University of Nebraska – Lincoln compared driver understanding of PPLT displays center over the left-turn lane with those shared on the lane line (Reference 2). A statistically significant difference was documented indicating that drivers better understood or at
least preferred the PPLT display when the display was center over the left-turn lane, though the researchers noted that the difference was in the range of four to five percent of the drivers.

Additional documentation of past studies and their findings with respect to use of the circular green indication for the permissive are documented in Working Paper 3 of the NCHRP 3-54 research project.

5.1.3. NCHRP 3-54(2) Research Evidence

As previously documented in the Research Team response to Question #1, part of the NCHRP 3-54(2) project involved an agency survey. The survey consisted of three sections with a total of fifteen questions, one of which asked the agency to indicate the percentage of shared, exclusive, and combination left-turn lanes in their jurisdiction.

Of the 168 surveys used in the analysis, 52 percent indicated that they mount overhead PPLT displays on the lane line between the left-turn lane and the adjacent through lane. Forty percent of the agencies reported centering the PPLT signal display over the left-turn lane. The remaining seven percent fell in an “other” category, generally placing the PPLT signal display somewhere between the centerline of the left-turn lane and the lane line between the left-turn lane and adjacent through lane. Several agencies reported centering the PPLT displays over the leftmost through lane. In addition, agencies that used mast arms indicated that the exact placement of the PPLT display was often determined by the available length of the mast arm.

Display placement was reviewed as a potential issue in virtually every analysis prepared for the NCHRP 3-54 project. In each case, the Research Team found that it was not a significant variable in driver comprehension; however, the team also added a caveat to this finding. For example, in the Photographic Driver Survey, it was noted that the resolution/size of the computer screen and simulator environment may have made it difficult to clearly distinguish location and therefore not a strong test. Nevertheless, horizontal placement was specifically investigated as a variable throughout and no significant difference was found.

5.1.4. Recommended Next Steps

Previous research has evaluated driver comprehension of the circular green permissive indication relative to placement and found no significance. Given that the proposed PPLT display is an all arrow display, the Research Team does not see the need to pursue this issue further.
References:


2) Bonneson and McCoy. *Driver Understanding of PPLT Signal Displays*, University of Nebraska, 1994.


