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.

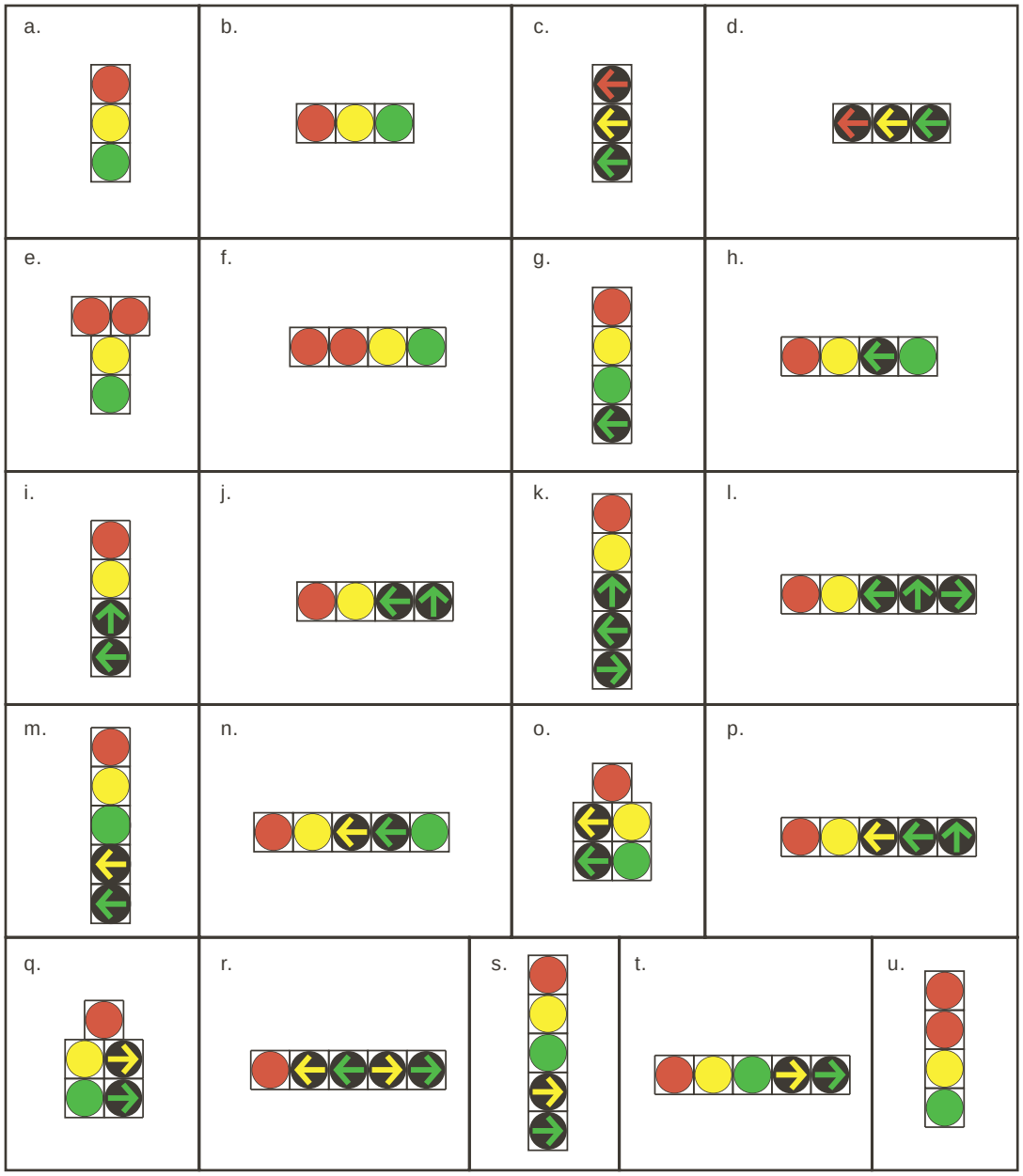

Figure 2-1. MUTCD arrangements of traffic signal displays.

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.

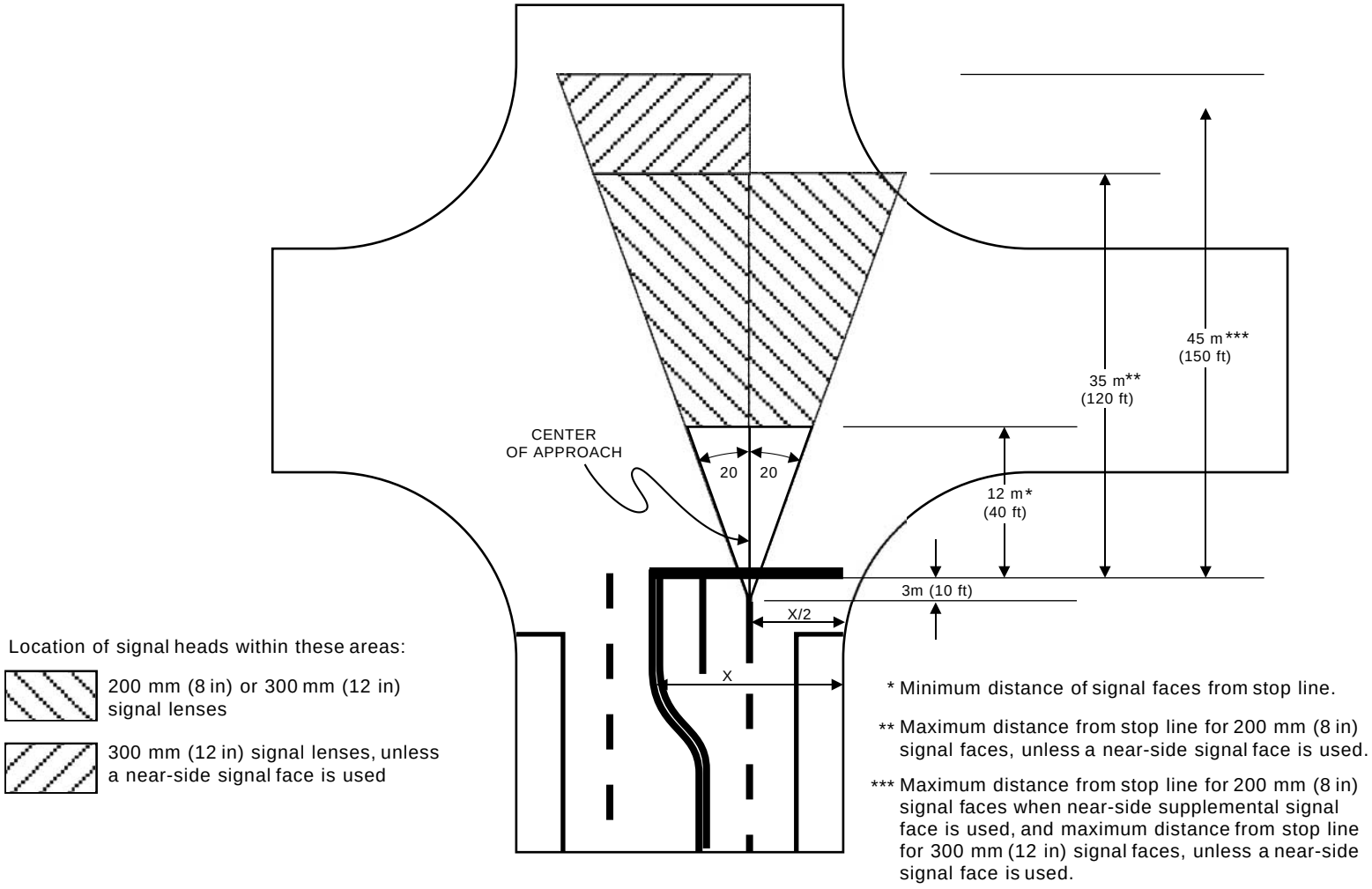

Figure 2-2. MUTCD criteria for horizontal location of signal faces.

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*)

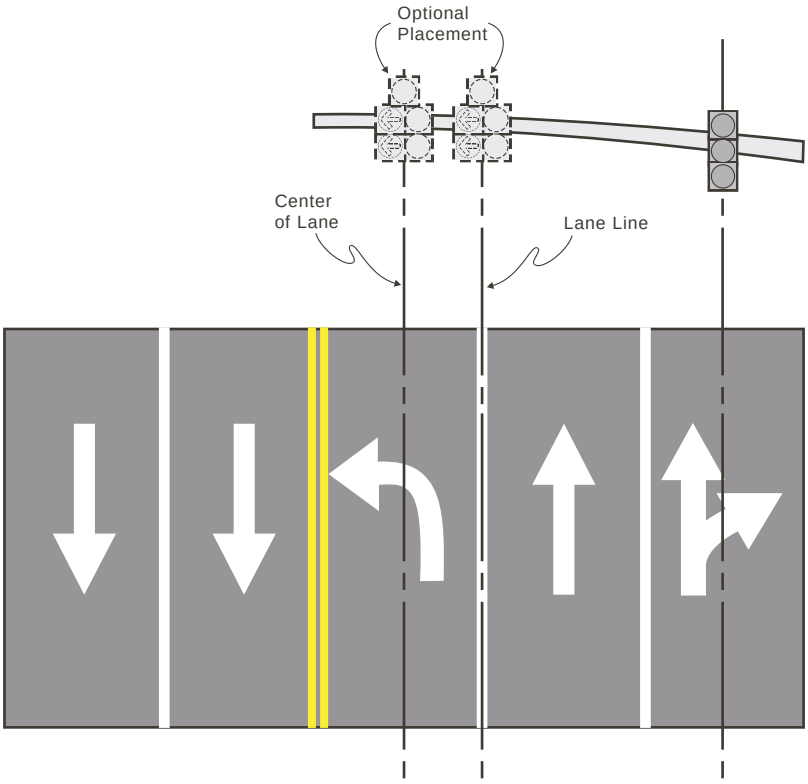

Figure 2-3. Overhead PPLT display placement options.

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

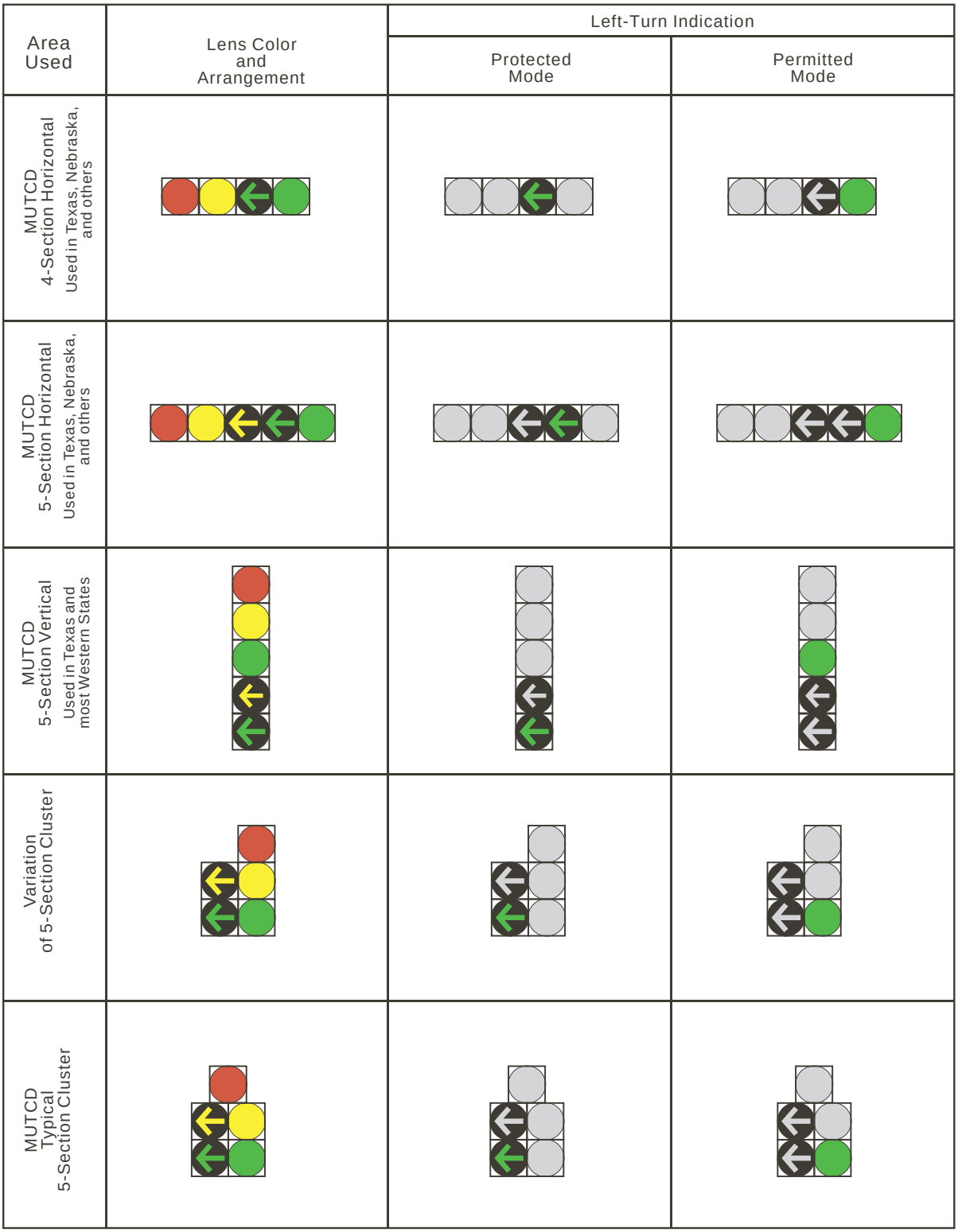

Figure 2-4. Variations in PPLT displays.

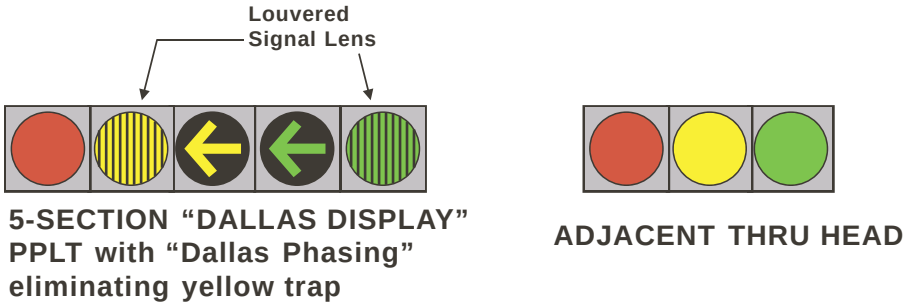

Figure 2-5. Illustration of Dallas display.

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.