CHAPTER 5

TRAFFIC SIGNAL DESIGN AND ILLUMINATION

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LIST OF EXHIBITS

5.0 TRAFFIC SIGNAL DESIGN AND ILLUMINATION

This chapter addresses traffic signal hardware and software—the infrastructure that controls the assignment of right-of-way for all intersection users, including vehicles, pedestrians, emergency vehicles, transit operators, trucks, and light-rail transit vehicles at locations where conflicts or hazardous conditions exist. The proper application and design of the traffic signal is a key component in improving the safety and efficiency of the intersection.

This chapter presents an overview of the fundamental principles of traffic signal design and illumination as they apply to signalized intersections. The topics discussed include:

- Traffic signal control types.
- Traffic signal phasing.
- Vehicle and pedestrian detection.
- Traffic signal pole layout.
- Traffic signal controllers.
- Basic signal timing parameters.
- Signing and pavement marking.
- Illumination.

5.1 TRAFFIC SIGNAL PHASING

The MUTCD defines a signal phase as the right-of-way, yellow change, and red clearance intervals in a cycle that are assigned to an independent traffic movement or combination of traffic movements.(1) Signal phasing is the sequence of individual signal phases or combinations of signal phases within a cycle that define the order in which various pedestrian and vehicular movements are assigned the right-of-way. The MUTCD provides rules for determining controller phasing, selecting allowable signal indication combinations for displays on an approach to a traffic control signal, and determining the order in which signal indications can be displayed.

Signal phasing at many intersections in the United States makes use of a standard National Electrical Manufacturers Association (NEMA) ring-and-barrier structure, shown in Exhibit 5-1. This structure organizes phases to prohibit conflicting movements (e.g., eastbound and southbound through movements) from timing concurrently, while allowing non-conflicting movements (e.g., northbound and southbound through movements) to time together. Most signal phasing patterns in use in the United States can be achieved through the selective assignment of phases to the standard NEMA ring-and-barrier structure.

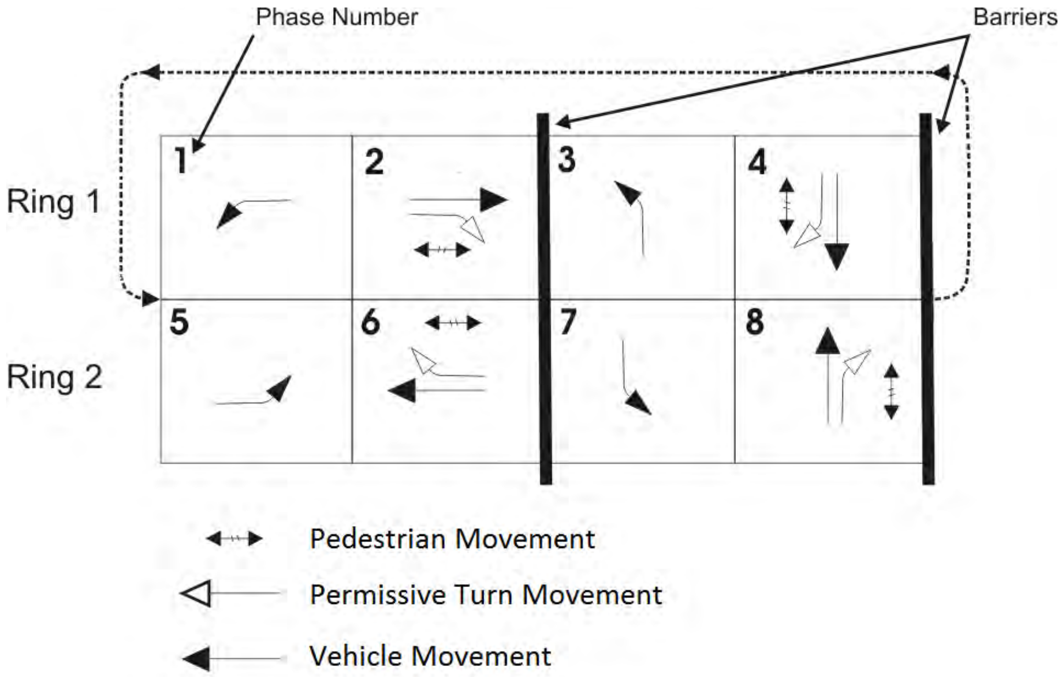


Exhibit 5-1. Standard NEMA ring-and-barrier structure.

Depending on the complexity of the intersection, two to eight phases are typically used, although most controllers provide far more phases to serve complex intersections or sets of intersections. Pedestrian movements are typically assigned to parallel vehicle movements.

Developing an appropriate phasing plan begins with determining the left-turn phase type at the intersection. The most basic form of control for a four-legged intersection is “permissive only” control, which allows drivers to make left turns after yielding to conflicting traffic and pedestrians and provides no special protected interval for left turns. As a general rule, practitioners should keep the number of phases to a minimum because each additional phase in the signal cycle reduces the time available to other phases, and each phase has its own startup delay time.

Provision of a separate left-turn lane, while not required, is recommended when providing a separate left-turn phase. Left-turn lanes increase operational efficiency by providing storage space where vehicles can await an adequate gap without blocking other traffic movements at the intersection. Left-turn lanes also increase the safety of an intersection by reducing rear-end and left-turn crashes. In most cases, the development of a signal phasing plan should involve an engineering analysis of the intersection. Several software packages are suitable for selecting an optimal phasing plan for a given set of geometric and traffic conditions for both individual intersections and for system optimization.

Practitioners must consider all intersection users during the development of a phasing plan, including pedestrians, bicyclists, transit vehicles, older drivers, and children. For example, on wide roadways pedestrian timing may require timing longer than what is required for vehicular traffic, which may have an effect on the operation analysis. The presence of older pedestrians or children may require a longer pedestrian clearance interval based on their slower walking speeds.

5.1.1 “Permissive-Only” Left-Turn Phasing

“Permissive-only” (also called “permitted-only”) phasing allows two opposing approaches to time concurrently, with left turns allowed after motorists yield to conflicting traffic and pedestrians. Exhibit 5-2 illustrates one possible implementation of this phasing pattern. Note that the two opposing movements could be run in concurrent phases using two rings; for example, the eastbound and westbound through movements shown in Exhibit 5-2 could be assigned as phase 2 and phase 6, respectively.

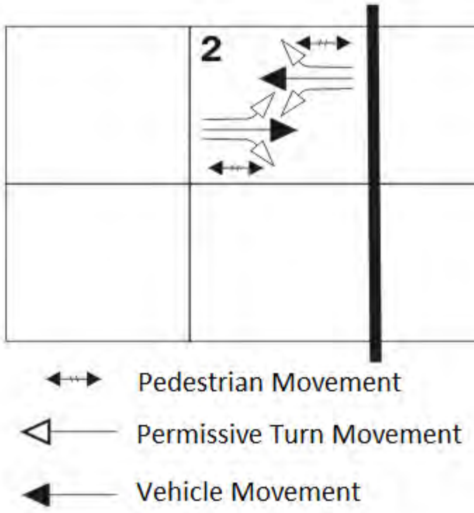


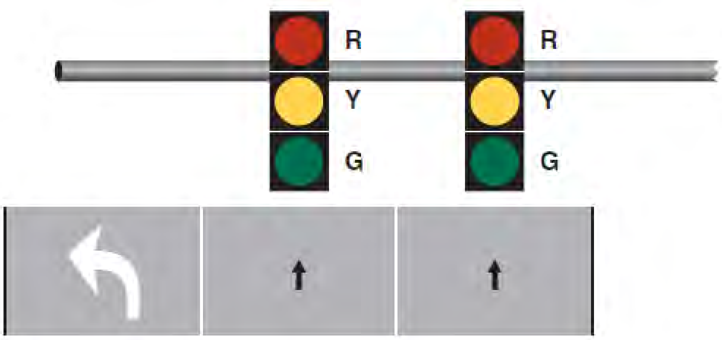
Exhibit 5-2. Typical phasing diagram for “permissive-only” left-turn phasing.

For most high-volume intersections, "permissive-only" left-turn phasing is generally not practical for major street movements because safety will be compromised in such situations, including left-turn safety. Minor side street movements, however, may function acceptably using “permissive-only” left-turn phasing, provided that traffic volumes are low enough to operate efficiently and safely without additional left-turn protection.

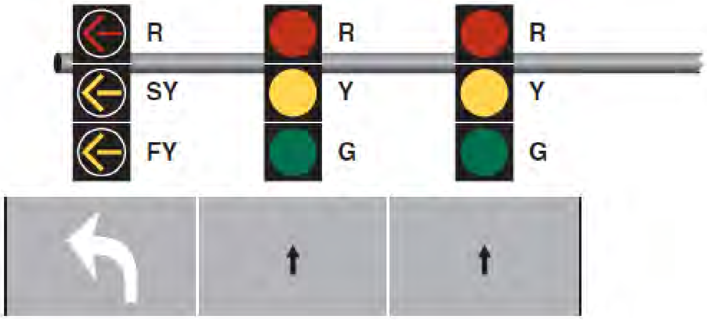
“Permissive-only” displays are signified most commonly in one of two ways. In the first case, if there is not an exclusive signal head assigned to a left-turn movement; instead, a three-section head with a circular green, circular yellow, and circular red is used. In this case, no regulatory sign is required.

In the second case, if there is a traffic signal head aligned with an exclusive left-turn lane, a three-section head with a flashing yellow arrow, steady yellow arrow, and steady red arrow is used.

As traffic volumes increase at the intersection, the number of adequate gaps to accommodate left-turning vehicles on the permissive indication may result in safety concerns at the intersection. Exhibit 5-3 shows common signal head arrangements that implement “permissive-only” phasing; refer to the MUTCD for other configurations.



(a) Permissive left-turn phasing using three-section signal heads over the through lanes only.



(b) Permissive left-turn phasing using three-section signal heads over the through lanes and a three-section signal head over the left turn lane.

Exhibit 5-3. Possible signal head arrangements for “permissive-only” left-turn phasing (Source: 2009 MUTCD)

5.1.1 “Protected-Only” Left-Turn Phasing

“Protected-only” phasing consists of providing a separate phase for left-turning traffic and allowing left turns to be made only on a green left arrow signal indication, with no pedestrian movement or vehicular traffic conflicting with the left turn. As a result, left-turn movements with “protected-only” phasing have a higher capacity than those with “permissive-only” phasing due to fewer conflicts. However, under lower volume conditions, this phasing scheme can cause an increase in delay for left-turning drivers. Exhibit 5-4 illustrates this phasing pattern. Typical signal head and associated signing arrangements that implement “protected-only” phasing are shown in Exhibit 5-5; refer to the MUTCD for other configurations. Chapter 11 of this document provides guidance on determining the need for protected left turns.

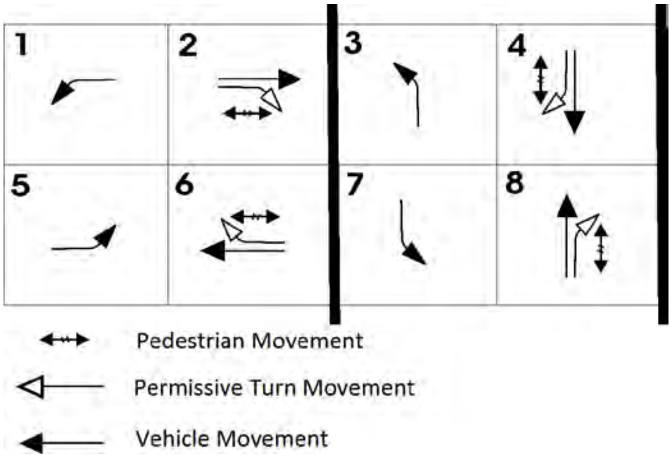


Exhibit 5-4. Typical phasing diagram for “protected-only” left-turn phasing.

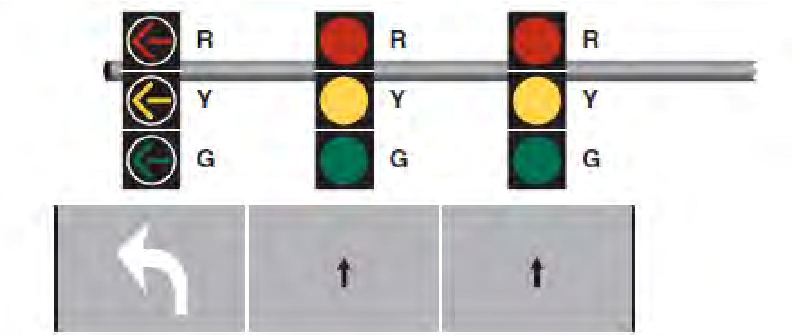


Exhibit 5-5. Possible signal head arrangement for “protected-only” left-turn phasing

(Source: 2009 MUTCD)

5.1.2 Protected-Permissive Left-Turn Phasing

A combination of protected and permissive left-turn phasing is referred to as protected-permissive left-turn (PPLT) operation. Exhibit 5-6 illustrates this phasing pattern. The 2009 MUTCD allows two different signal phasing techniques for this type of operation. The first is when the left-turn lane and the adjacent through lane share the same signal head. Exhibit 5-7(a) shows a typical signal head and associated signing arrangement that implements this type of protected-permissive phasing (refer to the MUTCD for other configurations).

The second phasing technique involves a separate signal head provided exclusively for a left-turn movement. In this case, the flashing yellow arrow is used for the permissive portion of the left-turn movement. Exhibit 5-7(b) shows a typical signal head and associated signing arrangement that implements this type of protected-permissive phasing (refer to the MUTCD for other configurations).

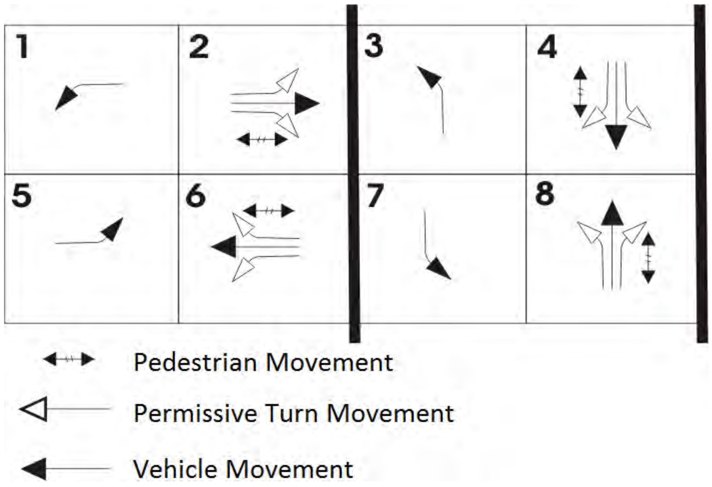
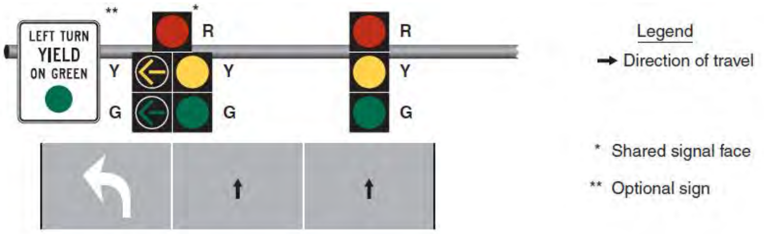
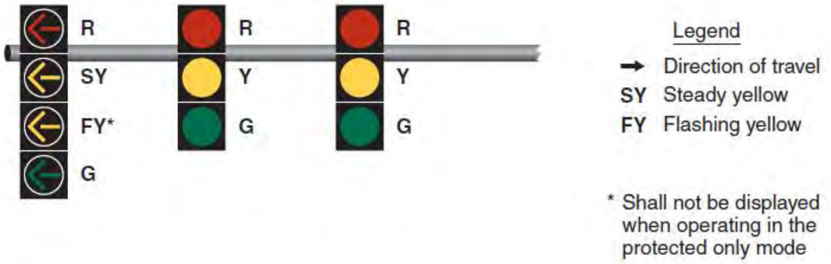


Exhibit 5-6. Typical phasing diagram for protected-permissive left-turn phasing.



(a) Protected-permissive left-turn phasing using a five-section head located directly above the lane line that separates the exclusive through and exclusive left-turn lane, along with an accompanying optional sign.



(b) Protected-permissive left-turn phasing using a five-section signal head located directly above the exclusive left-turn lane.

Exhibit 5-7. Possible signal head and signing arrangement for protected-permissive left-turn phasing.
Source: 2009 MUTCD

Observed improvements in signal progression and efficiency combined with driver acceptance have led to expanded usage of PPLT over the years. PPLT signals offer operational advantages when compared to “protected-only” operation. In protected-permissive phasing, consideration can be given to when in the cycle the protected left-turn movement is given. Where both protected left-turn movements on opposing approaches operate before the permissive phase, it is known as lead-lead operation. Conversely, where the permissive phases operate before the protected left-turn movements on opposing approaches, it is known as lag-lag operation. Lead-lag operation involves a protected left-turn movement on one approach, while the opposite left-turn movement experiences a permissive left-turn. They include the following (adapted with additions by the authors):(56)

- Average delay per left-turn vehicle is reduced.
- Protected green arrow time is reduced.
- There is potential to omit a protected left-turn phase.
- Arterial progression can be improved, particularly when special signal head treatments are used to allow lead-lag phasing.

The primary disadvantage of the permissive phase is an increased potential for vehicle-vehicle and vehicle-pedestrian conflicts. Younger and older drivers especially have difficulties interpreting the sufficient gap distance need to safety make permissive left turns. The use of permissive phasing also leaves pedestrians without a protected walk phase.

The controller phasing for protected-permissive mode is the most complicated phasing because of the safety implications created by the potential of a “yellow trap” occurring.

For ordinary lead-lead operations where both protected left-turn phases precede the permissive phases, the yellow trap does not occur, as both permissive phases end concurrently. However, this problem can occur when a permissive left turn is opposed by a lagging protected left turn. In this type of operation (known as lag-permissive), the yellow display seen by a left-turning driver is not indicative of the display seen by the opposing through driver. The opposing through display might remain green when the yellow signal indication is displayed to the permissive left-turn movement. A driver who turns left believing that the opposing driver has a yellow or red display when the opposing driver has a green display may be making an unsafe movement. Exhibit 5-8 illustrates this yellow trap.

Drivers who encounter this trap have entered the intersection on a permissive green waiting to make a left turn when sufficient gaps occur in opposing through traffic. If the absence of gaps in opposing through traffic requires them to make their turn during the yellow change or red clearance interval, they may be “stranded" in the intersection because of the absence of gaps and because the opposing through movement remains green. More importantly, they may incorrectly presume that the opposing through traffic is being terminated at the same time that the adjacent through movement is being terminated. Therefore, they may complete their turn believing that the opposing vehicles are slowing to a stop when in fact the opposing vehicles are proceeding into the intersection with a circular green signal indication.

There are options to eliminate the yellow trap situation. The first, and arguably best, option is the flashing yellow arrow operation for the permissive left-turn movement that became allowable with the 2009 MUTCD.

However, there may be circumstances in which that option is not feasible. If that is the case, the phase sequence at the intersection can be restricted to simultaneous leading (lead-lead) or lagging (lag-lag) left-turn phasing. However, it should be noted that under very light side street volumes, the leading left-turn phase can be activated such that it operates like a lagging left turn. This can be prevented using detector switching or a diode in the controller cabinet.

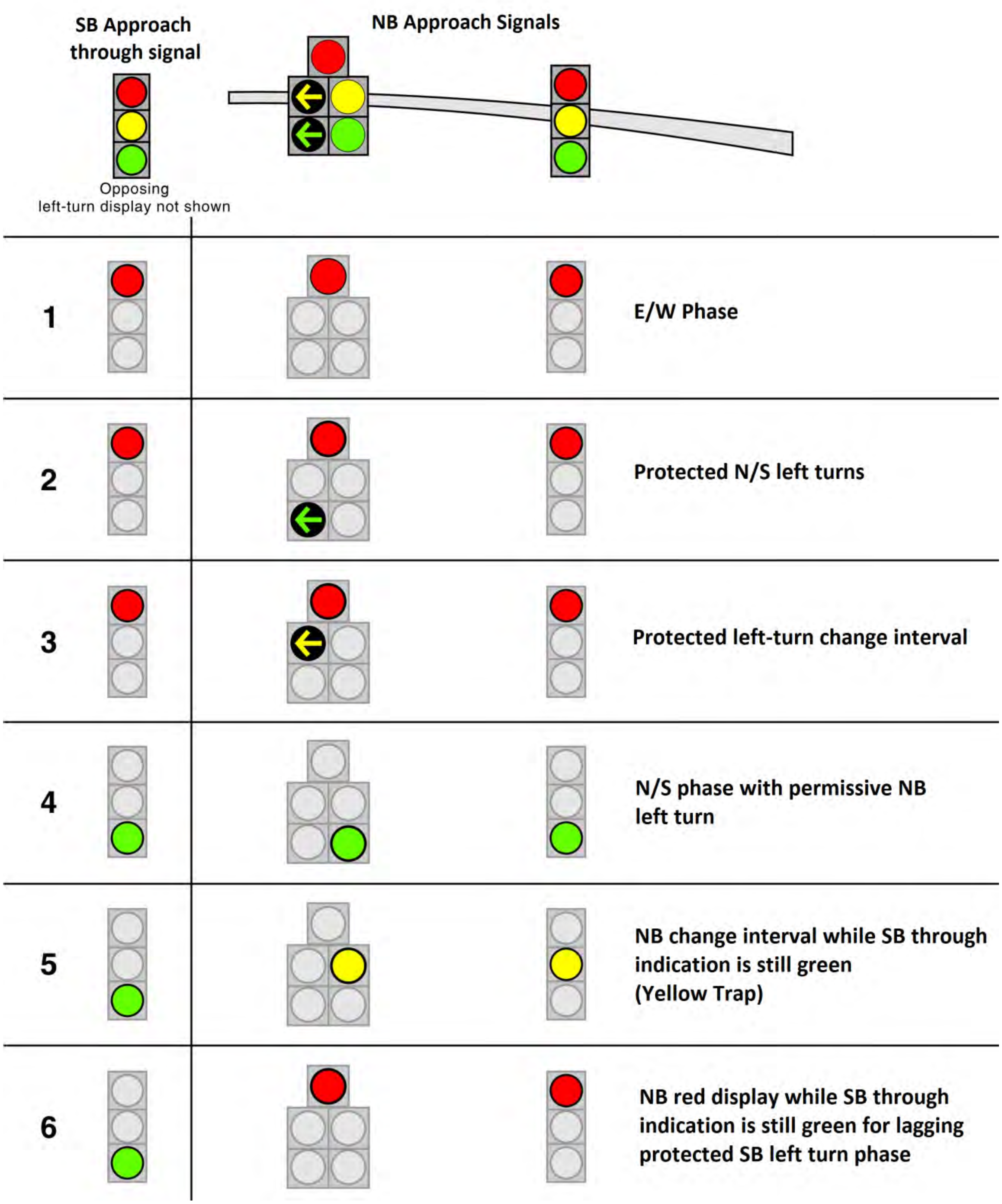


Exhibit 5-8. Illustration of the yellow trap.

5.1.3 Split Phasing

Split phasing consists of having two opposing approaches timed consecutively rather than concurrently (i.e., all movements originating from the west followed by all movements from the east). Split phasing can be implemented in a variety of ways, depending on signal controller capabilities and how pedestrian movements are treated.

Because of the inefficiency of a split phasing operation, it should only be considered after other operational methods or geometric solutions have been considered. In general, a new intersection should not be designed such that split phasing will be required. However, the following conditions could indicate that split phasing might be an appropriate design choice:

- **Multiple Turn Lanes.** There is a need to accommodate multiple turn lanes on an approach, but sufficient width is not available to provide separate lanes. Therefore, a shared through/left lane is required. Practitioners should perform an operational analysis to ensure this option is superior to a single turn lane option under various phasing scenarios.
- **Varied Traffic Volumes.** The left-turn lane volumes on two opposing approaches are approximately equal to the through traffic lane volumes, and the total approach volumes are significantly different on the two approaches. Under these somewhat unusual conditions, split phasing may prove more efficient than conventional phasing.
- **Offset Approach Issues.** A pair of opposing approaches is physically offset such that the opposing left turns could not proceed simultaneously or a permissive left turn could not be expected to yield to the opposing through movement.
- **Geometry.** The geometry of the intersection is such that the paths of opposing left turns would not be forgiving of errant behavior by turning motorists.
- **Crash History.** The safety experience indicates an unusual number of crashes (usually sideswipes or head-on collisions) involving opposing left turns. This may be a result of unusual geometric conditions that impede visibility of opposing traffic.
- **Lane Usage.** A pair of opposing approaches each has only a single lane available to accommodate all movements, and the left turns are heavy enough to require a protected phase.
- **Discrepant Demand.** One of the two opposing approaches has heavy demand and the other has minimal demand. Under this condition, the signal phase for the minimal approach would be skipped frequently and the heavy approach would function essentially as the stem of a T-intersection.

The MUTCD does not provide a standard method for indicating split phasing at an intersection. The methods vary considerably depending on what type of phasing sequence has been used. Exhibit 5-9 shows one way to implement split phasing that does not require the use of additional signs. It involves using a four-section head displaying both a circular green and a green left-turn arrow simultaneously.

However, additional measures are needed when the left-turn arrow would conflict with a concurrent pedestrian phase:(57)

- A special logic package can suppress the green arrow display when serving the pedestrian phase.
- A static sign indicating "LEFT TURN YIELD TO PEDS ON GREEN (symbolic circular green)" located next to the leftmost signal head for emphasis.
- A blankout sign indicating "LEFT TURN YIELD TO PEDS" activated when the conflicting vehicular and pedestrian phases run concurrently.

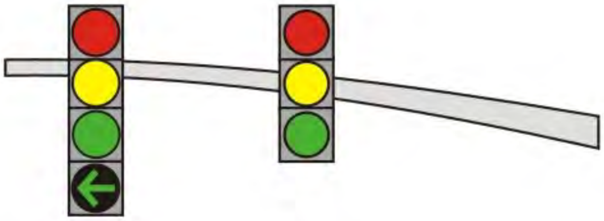


Exhibit 5-9. Common signal head arrangement for split phasing.

5.1.4 Prohibited Left-Turn Movements

Prohibiting left-turn movements at the intersection is an alternative to providing a left-turn phase. Under this scenario, left-turning drivers must divert to another facility or turn in advance of or beyond the intersection via a geometric treatment such as a jug handle or a downstream median U-turn. Left turns can be prohibited on a full- or part-time basis. The amount of traffic diverted, effects on transit routes, the adequacy of the routes likely to be used, and community impacts are all important issues to consider when investigating a turn prohibition. FHWA's Alternative Intersections and Interchanges Informational Report discusses a variety of treatments for redirecting left turns.(58)

5.1.5 Right-Turn Phasing

Practitioners may control right-turn phasing in a permissive or protected manner with different configurations depending on the presence of pedestrians and the lane configurations at the intersections.

Right turns can operate on overlap phases to increase efficiency for the traffic signal. An overlap is a set of outputs associated with two or more phase combinations. As described earlier, practitioners can assign various movements to a particular phase. In some instances, right-turn movements operating in exclusive lanes can be assigned to more than one phase that is not conflicting. In this instance, a right turn is operated at the same time as the left turn, as shown in Exhibit 5-10. The overlap forms a separate movement deriving its operation from its assigned phases (also called parent phases); for example, overlap A (OL A) is typically assigned to phase 2 (the adjacent through phase) and phase 3 (the non-conflicting left-turn phase from the cross street).

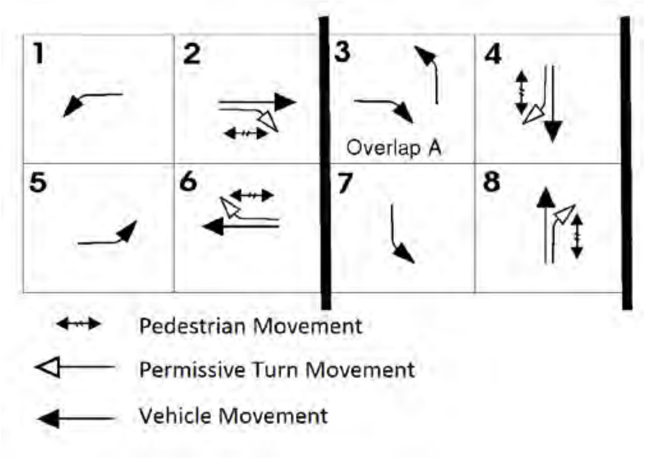


Exhibit 5-10. Typical phasing diagram illustrating a right-turn overlap.

A five-section head with a combination of circular and arrow indications is more commonly used. Note that the MUTCD requires the display of a yellow change interval between the display of a green right-turn arrow and a following circular green display that applies to the continuing right-turn movement on a permissive basis. This yellow change interval is necessary to convey the change in right-of-way from fully protected during the green arrow to requiring a yield to pedestrians and other vehicles during the circular green. This can be implemented by assigning the right-turn arrows to the same phase as the non-conflicting left-turn phase on the cross street and the circular indications to the same phase as the adjacent through movement. With the introduction of the flashing yellow arrow, there are numerous possibilities for signalizing a right-turn overlap phase. Refer to MUTCD Sections 4D.22 through 4D.24.(1)

This type of operation increases efficiency by providing more green time to this right-turn movement, but may compromise the intersection’s usability for visually impaired pedestrians. The transition from the protected right-turn movement on the green arrow to the permissive right-turn movement on the circular green masks the sound of the adjacent through vehicles. This makes it difficult for visually impaired pedestrians to hear when the adjacent through vehicles begin to move, which is used as an audible cue for crossing the street. Therefore, the use of accessible pedestrian signals to provide an audible indication of the start of the pedestrian phase may be needed to restore this cue.

Practitioners should note that a right-turn overlap may conflict with drivers making a legal U-turn on the concurrent (and protected) left-turn phase (in other words, both drivers are facing a green arrow for their movement). This conflict can be resolved by either prohibiting drivers from making a U-turn (R3-4, Sec. 2B.18) on that approach or by installing a U-TURN YIELD TO RIGHT TURN sign (R10-16, Sec. 2B.53) near the left-turn signal face.

5.2 VEHICLE AND PEDESTRIAN DISPLAYS

Signal displays can be generally categorized into those for vehicles and those for pedestrians. The following sections discuss each type.

5.2.1 Vehicle Displays

Practitioners should evaluate the location of signal heads based on visibility requirements and type of signal display. While MUTCD requirements govern signal head placement for signal displays (discussed in the previous section), local policies typically determine the specific signal head placement.

When designing signal head placement, practitioners should consider the following the in addition to the minimum requirements described in the MUTCD:

- Consistency with other intersections in the area.
- Geometric design issues that could confuse a driver.
- A high percentage of vehicles on one or more approaches that block lines of sight, including trucks and vans.
- The width of the intersection.
- The turning paths of the vehicles.

The 2009 MUTCD recommends that on high-speed approaches (85th percentile greater than 45 mph) or on approaches with three or more through lanes that the primary number of signal displays equal the number of through lanes. These signal displays should be installed over the center of each lane. With the advent of light emitting diode (LED) signal displays, the power requirements for additional signal displays is not significant.

At large signalized intersections, the use of additional signal heads may enhance the safety and operation of the intersection. Exhibit 5-11 shows a typical intersection design with five types of optional heads:

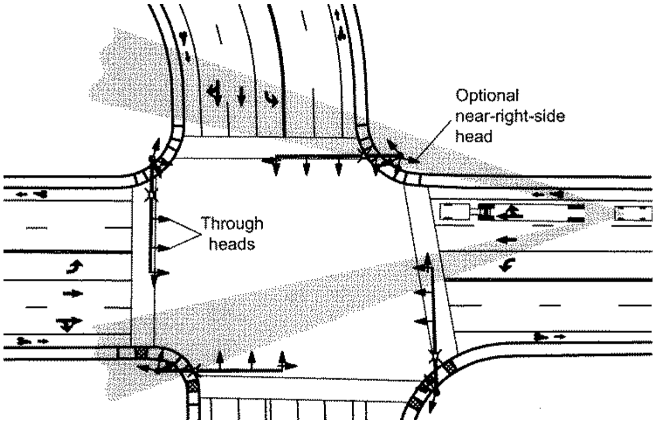
Optional Head #1: A near-right-side head that provides an advanced head at wide intersections as well as a supplemental head for road users unable to see the signal heads over the lanes due to their position behind large vehicles (trucks, etc.).

Optional Head #2: An extra through head that supplements the overhead signal heads. This head provides an indication for vehicles that might be behind large vehicles and may be more visible than the overhead signal head when the sun is near the horizon.

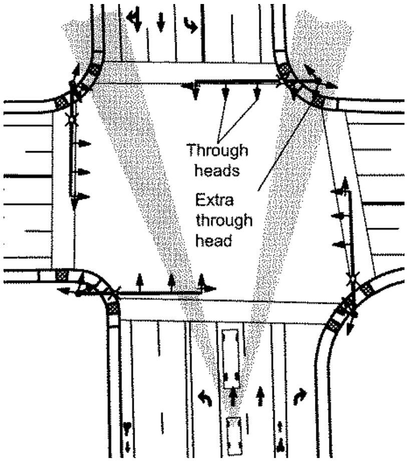
Optional Head #3: An extra left-turn head that guides left-turning vehicles across a wide intersection as they turn. It also improves visibility for vehicles behind large vehicles and for times of day when the sun nears the horizon.

Optional Head #4: A near-left-side head that provides an advance indication a curve in the road upstream of the intersection hampers visibility.

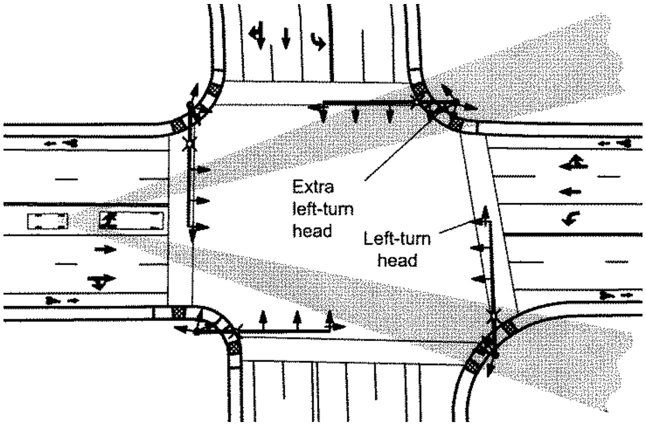
Optional Head #5: This head provides a display in direct view of a right-turn lane and provides a right-turn overlap phase in conjunction with the non-conflicting left-turn phase on the cross street. The head should contain either three circular indications or be a five-section head with three circular indications and two right-turn arrows due to the concurrent pedestrian crossing.



(a) Optional Head #1: Near-side head for through vehicles.

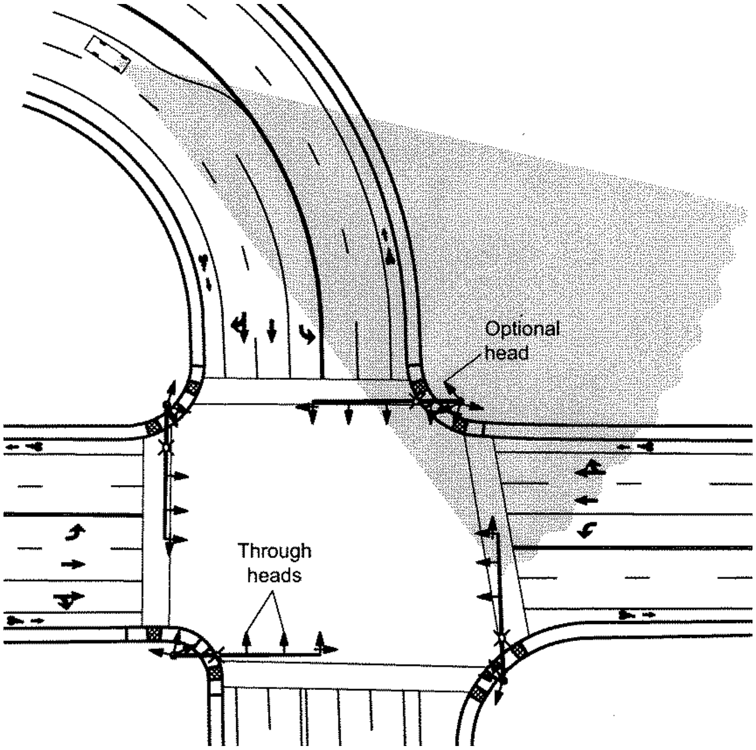


(b) Optional Head #2: Far-side supplemental head for through vehicles.

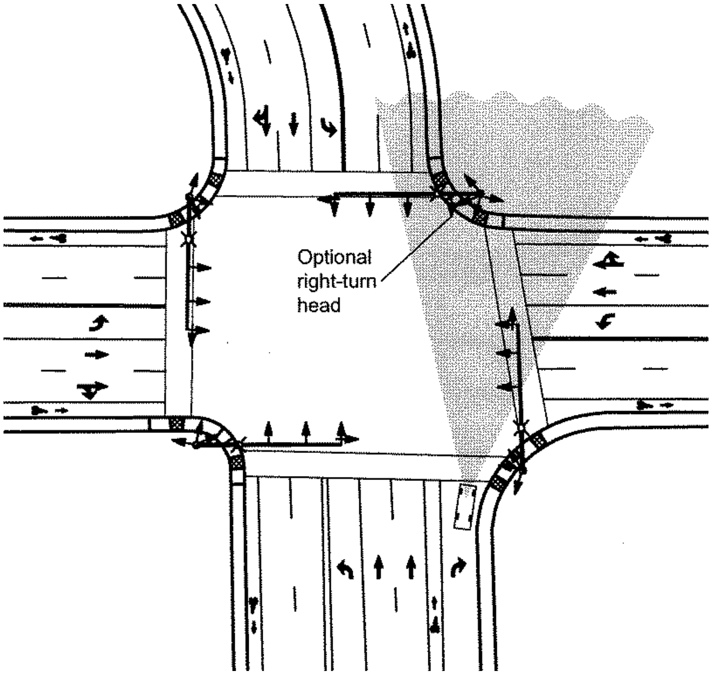


(c) Optional Head #3: Far-side supplemental head for left-turning vehicles.

Exhibit 5-11. Examples showing five optional signal head locations.



(d) Optional Head #4: Near-side head on curving approach.



(e) Optional Head #5: Far-side head for right-turning vehicles.

Exhibit 5-11 (cont’d). Examples showing five optional signal head locations.

5.2.2 Pedestrian Displays

According to section 4E.03 of the 2009 MUTCD, pedestrian signal heads shall be used in conjunction with vehicular traffic control signals under any of the following conditions:(1)

- If a traffic control signal is justified by an engineering study and meets Warrant 4, Pedestrian Volume, or Warrant 5, School Crossing (see MUTCD Chapter 4C).
- If an exclusive signal phase is provided or made available for pedestrian movements in one or more directions, with all conflicting vehicular movements being stopped.
- At an established school crossing at any signalized location.
- Where engineering judgment determines that multiphase signal indications (as with split-phase timing) would tend to confuse or cause conflicts with pedestrians using a crosswalk guided only by vehicular signal indications.

Pedestrian signals should be used under the following conditions:

- If it is necessary to assist pedestrians in making a reasonably safe crossing or if engineering judgment determines that pedestrian signal heads are justified to minimize vehicle-pedestrian conflicts.
- If pedestrians are permitted to cross a portion of a street – such as to or from a median of sufficient width for pedestrians to wait – during a particular interval but are not permitted to cross the remainder of the street during any part of the same interval.
- If no vehicular signal indications are visible to pedestrians, or if the vehicular signal indications that are visible to pedestrians starting or continuing a crossing provide insufficient guidance for them to decide when it is reasonably safe to cross, such as on one-way streets, at T-intersections, or at multiphase signal operations.

The MUTCD provides specific guidance on the type and size of pedestrian signal indications (Section 4E.04). As noted in the MUTCD, all new pedestrian signals shall use the UPRAISED HAND (symbolizing DON’T WALK) and WALKING PERSON (symbolizing WALK) indications, shown in Exhibit 5-12. The pedestrian displays shall be mounted so that the bottom of the pedestrian signal display housing (including mounting brackets) is no less than 7 ft and no more than 10 ft above sidewalk level.(1)

The 2009 MUTCD approves the use of pedestrian countdown displays. The countdown displays the number of seconds remaining in the pedestrian change interval. Section 4E.07 of the MUTCD requires them to be used on all crosswalks where the pedestrian change interval is more than 7 seconds.

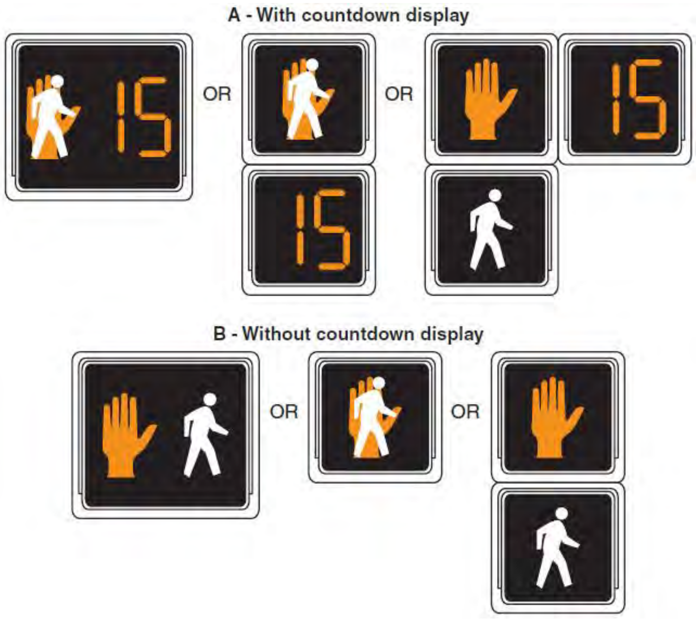


Exhibit 5-12. Pedestrian signal indications.
Source: 2009 MUTCD

Some signalized intersections have factors that may make them difficult for pedestrians who have visual disabilities to cross safely and effectively. As noted in the MUTCD (Section 4E.09), these factors include:(1)

- Increasingly quiet cars.
- Right-turn overlaps (which mask the sound of the beginning of the through phase).
- Continuous right-turn movements.
- Complex signal operations (e.g., protected-permissive phasing, lead-lag phasing, or atypical phasing sequences).
- Wide streets.
- Unusual intersection geometrics.

To address these challenges, accessible pedestrian signals have been developed to provide information to the pedestrian in a nonvisual format, such as audible tones, verbal messages, and/or vibrating surfaces. Details on these treatments can be found in the MUTCD(1) and in several references sponsored by the U.S. Access Board and the National Cooperative Highway Research Program (NCHRP).(59), (60), (61)

5.2.3 Pedestrian Hybrid Beacons

The 2009 edition of the MUTCD approved the optional use of pedestrian hybrid beacons (PHB) as a traffic control device. A pedestrian hybrid beacon is a special type of traffic control device used to warn and control traffic at an unsignalized location to assist pedestrians in crossing a street or highway at a marked crosswalk. Chapter 4F of the MUTCD describes the design and operation of these devices in more detail. The PHB in the MUTCD is based on a design previously known as a HAWK signal, developed in Tucson, Arizona.

Exhibit 5-13. Pedestrian hybrid beacon.
Source: FHWA Office of Safety

Although the PHB has been technically defined as a beacon and not a traffic signal, it may still require enabling legislation, which depends directly on a given State's laws concerning signals and what motorists are expected to do when approaching a "dark" signal. Many States require drivers to come to a full and complete stop at a dark signal. The presumption is that in this case, there has been a power outage at the intersection. However, in most States, a dark beacon does not require a motorist to stop, nor would a dark PHB.

The sequence of the PHB is illustrated in Exhibit 5-15.

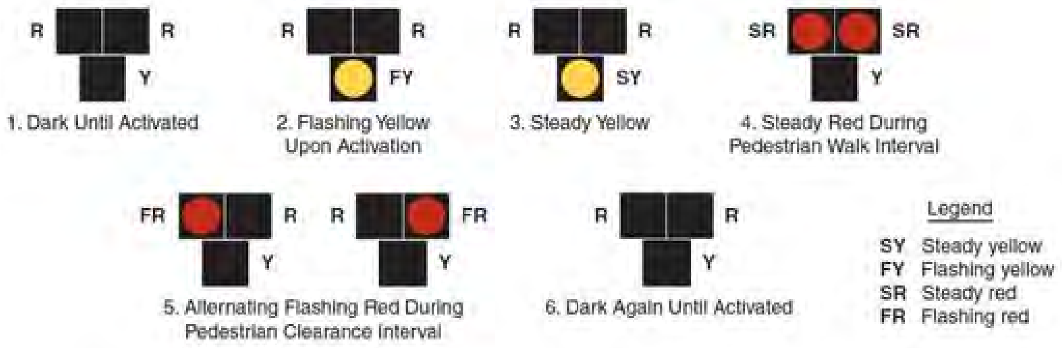


Exhibit 5-14. Sequence for a PHB.
Source: 2009 MUTCD

5.3 TRAFFIC SIGNAL POLE LAYOUT

Three primary types of signal configurations display vehicle signal indications:

- Mast arms.
- Span-wire configurations. Box span-wire design is preferred to diagonal design for new installation.
- Pedestal or post-mounted signal displays.

Exhibit 5-15 identifies the advantages and disadvantages of each configuration.

Advantages	Disadvantages
Mast arm vehicle signal	
• Provides more precise signal head placement • Lower maintenance costs • Many pole esthetic design options	• More costly than span wire • Mast arm lengths can limit use and be extremely costly for some large intersections
Span wire vehicle signal	
• Can accommodate large intersections • Flexibility in signal head placement • Lower initial cost than mast arms	• Higher maintenance costs • Wind and ice can cause problems • May be considered aesthetically unpleasing • Visibility not as good as a mast arm
Pedestal (post-mounted) vehicle signal	
• Low cost • Less impact on view corridors • Lower maintenance costs • Esthetics • Good for supplemental signals	• Difficult to meet MUTCD visibility requirements, particularly at large signalized intersections

Exhibit 5-15. Advantages and disadvantages of various configurations for displaying vehicle signal indications.

In addition to providing support for the optimal location of vehicle and pedestrian signal indications, signal poles need to be located carefully to address the following issues:

- Pedestrian walkway and ramp locations.
- Pedestrian pushbutton locations, unless separate pushbutton pedestals are provided.
- Clearance from the travel way.
- Available right-of-way and/or public easements.
- Overhead utility conflicts, as most power utilities require at least 10 ft clearance to power lines.
- Underground utilities, as most underground utilities are costly to relocate and therefore will impact the location of signal pole foundations.

The MUTCD,(1) the ADAAG,(36) and the AASHTO *Roadside Design Guide*(62) all contain guidance regarding the lateral placement of signal supports and cabinets. Generally, signal poles should be placed as far away from the curb as practically possible, not conflict with the pedestrian walking paths, and be located for easy access to the pushbuttons by all pedestrians. In some circumstances, it may be difficult or undesirable to locate a single pole that adequately serves both pedestrian ramps and provides adequate clearances. In these cases, one or more pedestals with the pedestrian signal heads and/or pushbuttons should be considered to ensure visibility of the pedestrian signal heads and accessibility to the pushbuttons.

5.4 TRAFFIC SIGNAL CONTROLLER AND CABINET

The traffic controller is the brain of the intersection. Most of the early electro-mechanical controllers have been replaced by solid state controllers across the country. Solid state controllers consist of the NEMA type controllers, Type 170 controllers, ATC Type 2070 controllers, and Advanced ATC controllers. Modern controllers can perform the basic functions needed at typical signalized intersections and have additional capabilities. These include the ability to communicate with other vendor software using standardized communication protocol called National Transportation Communication for ITS Protocol (NTCIP), ability to provide transit priority, control diamond interchanges, etc.

NEMA TS-1 is the first generation of NEMA controllers using discrete solid state electronics interface to the controller field-wiring back panel. TS-1 defines what the controller must do and defines the interface between the controller and the cabinet. Software is built into the controller and is not accessible by others. The newer version, TS-2, is similar to the TS-1 in the way the functionality is defined. However TS-2 specifies a cabinet bus interface unit (BIU) using RS-485 with Synchronous Data Link Control protocol (SDLC) to connect the controller, malfunction management unit (MMU), the detection system, and the back panel. The use of BIU interface reduces the complexity of signal controller cabinet. There are two types of TS-2 controllers. TS-2 Type 1 controller is a pure TS-2 controller whereas TS-2 Type 2 controller can be retrofitted into a TS-1 cabinet.

About the same time the TS-1 specifications were developed, the California Department of Transportation, City of Los Angeles, New York State Department of Transportation, and FHWA developed an open-architecture microcomputer for traffic control. This architecture facilitated the use of software developed by a third party, and the user has access to the software.

The California Department of Transportation led the development of the ATC Type 2070 architecture due to advancements in communications and processors. Model 2070 employs the open-architecture to facilitate the installation of aftermarket processors and other devices in the controllers. The 2070 controller can be placed either in a cabinet for a Type 170 controller or a NEMA controller with the right modules. Like Type 170 controller, software is provided by a third party.

Finally, the Advanced ATC type controller is the second generation of ATC controller with a single-board computer that provides a standard physical and electrical interface to all the other components in the controller.

5.4.1 Physical Location of Equipment

In locating the controller cabinet, consider the following:

- It should not interfere with sight lines for pedestrians or right-turning vehicles.
- It should be in a location less likely to be struck by an errant vehicle and not impeding pedestrian circulation, including wheelchairs and other devices that assist mobility.
- A technician at the cabinet should be able to see the signal indications for two approaches while standing at the cabinet.
- The cabinet should be located near the power source.
- The cabinet location should afford ready access by operations and maintenance personnel, including consideration for where personnel would park their vehicle.

5.5 DETECTION DEVICES

The detectors (or sensors) inform the signal controller of the presence, movement and/or occupancy of motor vehicles, pedestrians, or bicycles at a defined location: the upstream approach to, or downstream side of, an intersection. The signal controller can then use this information to perform its functions, such as allocate the amount of green time, select timing plans, and order signal phases.

5.5.1 Vehicle Detection

Vehicle detectors typically function as presence, pulse (advanced), or system (data). A detector may have more than one function. The detector location, relative to the intersection, often indicates its primary function: presence detectors are located in close proximity to the stop line; pulse detectors are located upstream, well in advance of the intersection; and system detectors are typically located midblock or just downstream of the intersection.

- *Presence* detectors alert the controller to waiting vehicles during the red interval and calls for additional green time (passage or extension) for moving vehicles during the green interval.
- *Pulse* detectors extend the green signal indication for approaching vehicles. Pulse detectors are often placed on high speed approaches to reduce the risk of motorists encountering a yellow signal indication within the dilemma zone. During the red interval, pulse detection of each vehicle can incrementally adjust green time above the ‘minimum green’ controller setting to ensure servicing of the developed queue.
- *System* detectors collect data such as speed, volume, occupancy, and/or queue information for the purpose of timing plan selection (when in traffic responsive operation), real-time adaptive control, and timing plan overrides. An example of override activation would be to order a special timing plan to prevent off-ramp, vehicle spillback onto an expressway when the off-ramp, queue detector is occupied.

Detectors are placed either in-roadway or over the roadway surface. The performance of in-roadway detectors such as inductive loops, magnetic, and magnetometer detectors depends upon the quality of the installation, proximity to the vehicle, and the condition of the pavement structure. These detectors are designed to be insensitive to inclement weather but are subject to disruption of service due to pavement milling, utility cuts, and pavement movement. The main disadvantage of in-roadway detection is the disturbance to the roadway surface and exposure of personnel to traffic during installation and maintenance. Over roadway detectors, such as video detection and digital matrix radar, are generally auto-programmable, multi-lane, and multi-functional. Digital matrix radar detectors are insensitive to weather, continuously track vehicles in the zone, and require little maintenance. Factors affecting the performance of video detection are often related to the camera lens and mounting: wind, fog, shadows, occlusion, etc. Newer types of detection feature remote monitoring and troubleshooting. Out of service or unreliable vehicle detection results in unused green time, diminished dilemma zone protection, omitted phases, poor optimization, and driver frustration. The FHWA *Traffic Detector Handbook* includes further discussion on detector technology.

The dilemma zone is that portion of the approach where a driver seeing a yellow indication must make a decision whether to stop safely or to proceed through the intersection. Hence, the minimum stopping distance usually dictates dilemma zone. The actual distances vary by jurisdictional policies. Practitioners should review these policies before designing the traffic signal and detector system. The typical location for advance detectors is based on stopping sight distance, as shown in Exhibit 5-16. The stopping distance can be computed for both the average stopping condition as well as the probability ranges for stopping. For higher speed approaches (45 mph or greater) and to account for the desired probability of stopping, pulse or advanced detection should be used. More detailed information on detector placement, including the results of several calculation methods, can be found in FHWA’s *Manual of Traffic Detector Design*.(58)

Exhibit 5-16. Location of advanced vehicle detectors.

Speed	Calculated Stopping Distance	Single Detector Setback	Multiple Detector Setback 10% Probability of Stopping	Multiple Detector Setback 90% Probability of Stopping
20 mph	72.2 ft	70 ft	—	—
25 mph	104.4 ft	105 ft	—	—
30 mph	140.8 ft	140 ft	—	—
35 mph	182.9 ft	185 ft	102 ft	254 ft
40 mph	231.0 ft	230 ft	122 ft	284 ft
45 mph	283.8 ft	*	152 ft	327 ft
50 mph	341.9 ft	*	172 ft	353 ft
55 mph	406.3 ft	*	234 ft	386 ft

* Use multiple detectors or volume-density modules.
Source: Reference 63 (table 4-3); Reference 64 (table 7-1);

Proper settings of the detector equipment can help fine tune operations and safety improvements at a signalized intersection. Both the detection equipment and the traffic signal controller are typically capable of adjusting the outputs from the detector and/or inputs to the controller. A few of the more common programmable features are lock, delay, extend, and switch.

- A **Lock** (Y or N) retains the call placed on the controller during the red signal indication for the phase even though a vehicle moves outside the detection zone. The lock feature is useful on left-turn lanes where a vehicle may creep forward while waiting on the protected left-turn green signal indication.
- A **Delay** (in seconds) can be set on turning lane detection where permissive turns are allowed in order to give vehicles time to select a safe gap to complete their turn, without placing the call to the controller for the protected left turn phase.
- An **Extend** (in seconds) holds the call upon the controller for a defined period of time after the vehicle leaves the zone of detection.
- A **Switch** dynamically changes the assignment of a vehicle detector to a different vehicle phase during a specific portion of the cycle length. For example, a heavy side street volume of left turners might benefit from unused green time from a lighter volume adjacent through movement. Switching moves the detector call from the left-turn phase (phase 7, protected lefts) to the adjacent through movement phase (phase 4, throughs & permissive lefts) during the through movement green time to accommodate more left turners. If switching were not used (as in this example), absent of a vehicle detection for phase 4 or 8 (side street throughs), then the side street protected left-turn phase would max out, cross the barrier, and return to the next phase to be served on the main street (see Exhibit 5-6).

When selecting the type of detection for new signalized intersections or as a replacement for detection at existing signalized intersections, the following considerations may be made:

- Is detection of multiple user groups required (i.e., motorists, pedestrians, motorcycles, etc.)?
- Is the detection proprietary or is it compatible with various/existing interfaces?
- Is the detection reliable and does it have a good reputation?
- What is the expected life of the detection?
- Will the detection require changes in existing infrastructure?

- Does the detection have the capability to be located where its repair will not require interrupting traffic? Are alternatives available that won't require the interruption of traffic flow?
- Will repairs need to be accomplished by contract or in-house?
- How do environmental conditions affect the detection (e.g., wind, ice, glare, occlusion, shadowing, and fog may limit the capabilities of some video and above-roadway detection)? Is there potential for accelerated wear and tear of equipment due to weather (freeze, thaw, heat) or pavement movement or failure?
- Does the detection have other capabilities aside from traffic detection (i.e., volume and classification counts, occupancy, etc.)? Compared with other methods of data collection, is this method reliable?
- What is the fail-safe condition for detected fault? Does the system have a diagnostic or alert system due to fault?
- If in-roadway detection is used, in what type of surface will the detection be installed (i.e., concrete, old asphalt, gravel, etc.)? Will future pavement surface maintenance affect its operation, temporarily (work zone during construction) or permanently?
- Will the detection require boring or trenching?
- What are the initial and lifecycle costs? Does the detection have ongoing regular maintenance costs?
- Do the detector equipment specifications match the stated operational and safety needs?

5.5.2 Pedestrian Detection

Pedestrian detection at actuated signals is typically accomplished through the use of pedestrian push buttons. Accessible pedestrian signal detectors, or devices to help pedestrians with visual or mobility impairments activate the pedestrian phase, may be pushbuttons or other passive detection devices. For pushbuttons to be accessible, they should be placed in accordance with the guidance in the MUTCD (Sections 4E.08, 4E.09).(1)

- Unobstructed and adjacent to a level all-weather surface to provide access by a wheelchair with a wheelchair-accessible route to the ramp.
- Within 5 ft of the crosswalk extended.
- If possible, between 1.5 and 6 ft from edge of curb. If physical constraints make this impractical, locate no more than 10 ft off the edge of the curb, shoulder, or pavement.
- Parallel to the crosswalk to be used.
- Separated from other pushbuttons by a distance of at least 10 ft.
- Mounted at a height of at least 3.5 ft and no more than 4.0 ft above the sidewalk.

Types of passive detection devices include, but are not limited to, video and infrared camera systems. Pedestrian detection can be helpful for assigning right-of-way when installed at locations with high demands of both pedestrian and vehicle volumes. As one form of transportation demand increases over another, the detection can instruct the signal controller to give precedence to the higher demand. Pedestrian detection may also allow for detection of users that will require extended walk times. Alternative methods of pedestrian detection, including infrared and microwave detectors, are emerging. Additional information on these devices can be found in FHWA's *Pedestrian Facilities User Guide—Providing Safety and Mobility.*(38)

5.6 TRAFFIC SIGNAL CONTROL TYPE

Traffic signals operate in pre-timed, semi-actuated, or actuated mode based on the presence and operations of detectors. Pre-timed signals operate with fixed cycle lengths and green splits, and in turn can operate either in isolation or coordination with adjacent traffic signals. Pre-timed coordinated signals can feature multiple timing plans with different cycle, split, and offset values for different periods of the day. Pre-timed control is ideally suited to closely spaced intersections where traffic volumes and patterns are relatively consistent on a daily or day-of-week basis.(66)

Actuated signals vary the amount of green time allocated to each phase based on traffic demand; these signals can operate either in a fully actuated or semi-actuated mode. Actuated control provides variable lengths of green timing for phases that are equipped with detectors. The time for each movement depends on the characteristics of the intersection and timing parameters which are based on demand at the intersection.

An intersection that is fully actuated does not have a fixed cycle length; the durations of all phases are dependent on either vehicle actuations on their approaches or on maximum green times. An intersection that is under semi-actuated control typically has detectors on the minor street and on the major street left turns, but not on the major street through movements. The signal controller dwells or rests in the major street through phases and services the minor movements (i.e., minor streets and major street left-turns) upon demand. The intersection does not have a fixed cycle length.

An actuated signal can also work in coordination with other nearby traffic signals. A coordinated signal with actuated phases (actuated-coordinated) operates similarly to an intersection under semi-actuated control. The major street through phases are usually not actuated, the minor movements (including major street left turns) are actuated, and the intersection operates with a fixed cycle length. By fixing the major street movements, the coordination creates a “green band” for traffic to move smoothly through multiple adjacent intersections. This green band can be increased if unused green time is available from the other movements; it can be given to the major street through movement to further improve coordination. This unused time can also be shared with other movements as desired by the practitioner.

Some agencies have implemented more advanced traffic control plans using additional detection or adaptive control plans. Traffic responsive systems typically include additional “system detectors” between signals to provide more information to the system. Volume thresholds for a set of sensors are pre-determined by the traffic engineer to invoke specific cycles, splits, and offset combinations. This information can be used to help the controller choose the most appropriate plans for the current situations. Adaptive control has been use to improve traffic congestion and reduce delay using conventional signal control systems. Adaptive signal control technology continuously adjusts the signal timing (including modifying cycle lengths) beyond what is done by fully actuated or actuated-coordinated control by responding to changing traffic patterns. Adaptive control can distribute green times equitably to all traffic movements, improve travel time reliability and prolong the effectiveness of a traffic signal timing plan.

5.7 BASIC SIGNAL TIMING PARAMETERS

Signal operation and timing have a significant impact on intersection performance. Controllers have a vast array of inputs that permit tailoring of controller operation to the specific intersection. This section provides guidance for determining basic timing parameters.

The development of a signal timing plan should address all user needs at a particular location, including pedestrians, bicyclists, transit vehicles, emergency vehicles, automobiles, and trucks. For the purposes of this section, signal timing is divided into two elements: pedestrian timing and vehicle timing.

5.7.1 Vehicle Timing—Green Interval

Ideally, the length of the green display should be sufficient to serve the demand present at the start of the green phase for each movement and should be able to move groups of vehicles, or platoons, in a coordinated system. At an actuated intersection, the length of the green interval varies based on inputs received from the detectors. Minimum and maximum green times for each phase are assigned to a controller to provide a range of allowable green times. Detectors are used to measure the amount of traffic and determine the required time for each movement within the allowable range.

In pre-timed operations, minimum green and maximum green are equal. The green interval should meet the driver expectancy requirements, pedestrian requirements, and the requirements to clear the expected queue at the stop line. When the detector is at the stop line, the minimum green time should meet driver expectancy requirements and pedestrian requirements.(1) The minimum green is generally set to approximately 5 to 15 seconds based on the type of street and the type of movement to meet driver expectancy.

When the detector is located upstream of the stop line, the minimum green must meet the additional requirement to clear the vehicles queued between the stop line and the detector nearest the stop line. Consider an intersection with the following properties: average vehicle spacing is 25 ft per vehicle, initial start-up time is 2 s, and vehicle headway is 2 s per vehicle. For an approach with a detector located 100 ft from the stop line, the minimum green time is 2 + (100 ft/25 ft x 2) = 10 s.

The maximum green time is the maximum limit to which the green time can be extended for a phase in the presence of a call from a conflicting phase. Exhibit 5-17 illustrates the functionality of maximum green timer. The maximum green timer begins when a call is placed on a conflicting phase. The phase is said to "max-out" if the maximum green time is reached even if actuations have been received that would typically extend the phase.

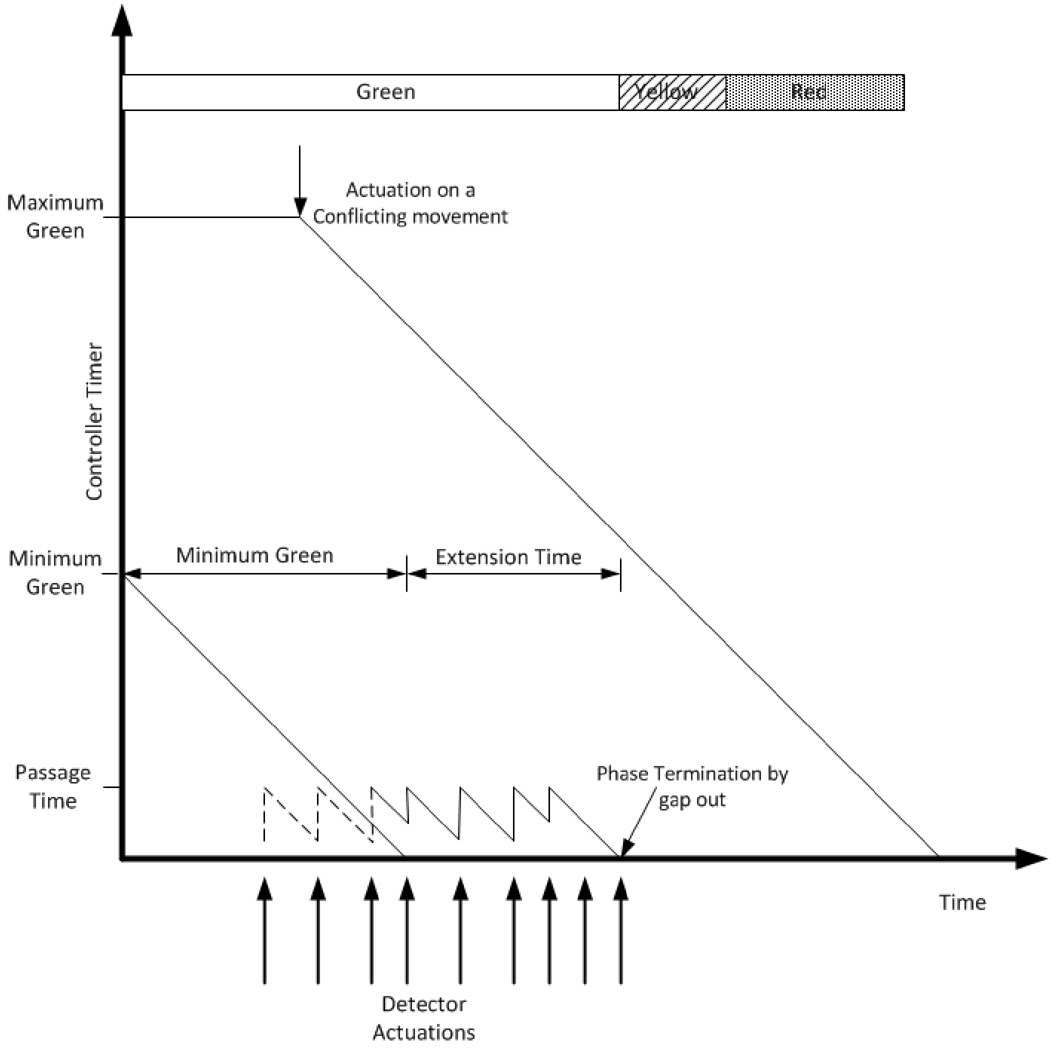


Exhibit 5-17. Illustration of maximum green functionality.

5.7.2 Vehicle Timing—Detector Inputs

One advantage of actuated control is its capacity to adjust timing parameters based on vehicle or pedestrian demand. The detectors and the timing parameters allow the signal to respond to varied flow throughout the day. For pedestrians, detectors are located for convenient access; for vehicles, detector spacing is a function of travel speed and the characteristics of the street. The operation of the signal is highly dependent on detector inputs. More information about detector features and settings for various detector configurations can be found in the FHWA *Traffic Detector Handbook.*(63)

Volume-density timing is used to improve the efficiency of intersection operation. A gap-reduction feature called *variable initial* is used to improve intersection efficiency on approaches where the detectors are not at the stop line (presence detection) but a distance upstream of the stop line (advance or pulse detection). Variable initial, as illustrated in Exhibit 5-18, alleviates the need to provide a large minimum green to clear all vehicles stored between the stop line and the detector and thus improves intersection efficiency during low volume conditions. Another volume density feature called gap reduction uses gap timers to reduce the allowable gap time the longer the signal is green. This type of timing makes the signal less likely to extend the green phase the longer the signal is green. A typical setting for a volume-density controller is to have the passage gap set to twice the calculated gap time to ensure the phase does not gap out too early. The minimum gap time might be set to less than the calculated gap time on multiple lane approaches, depending on the characteristics of the intersection.

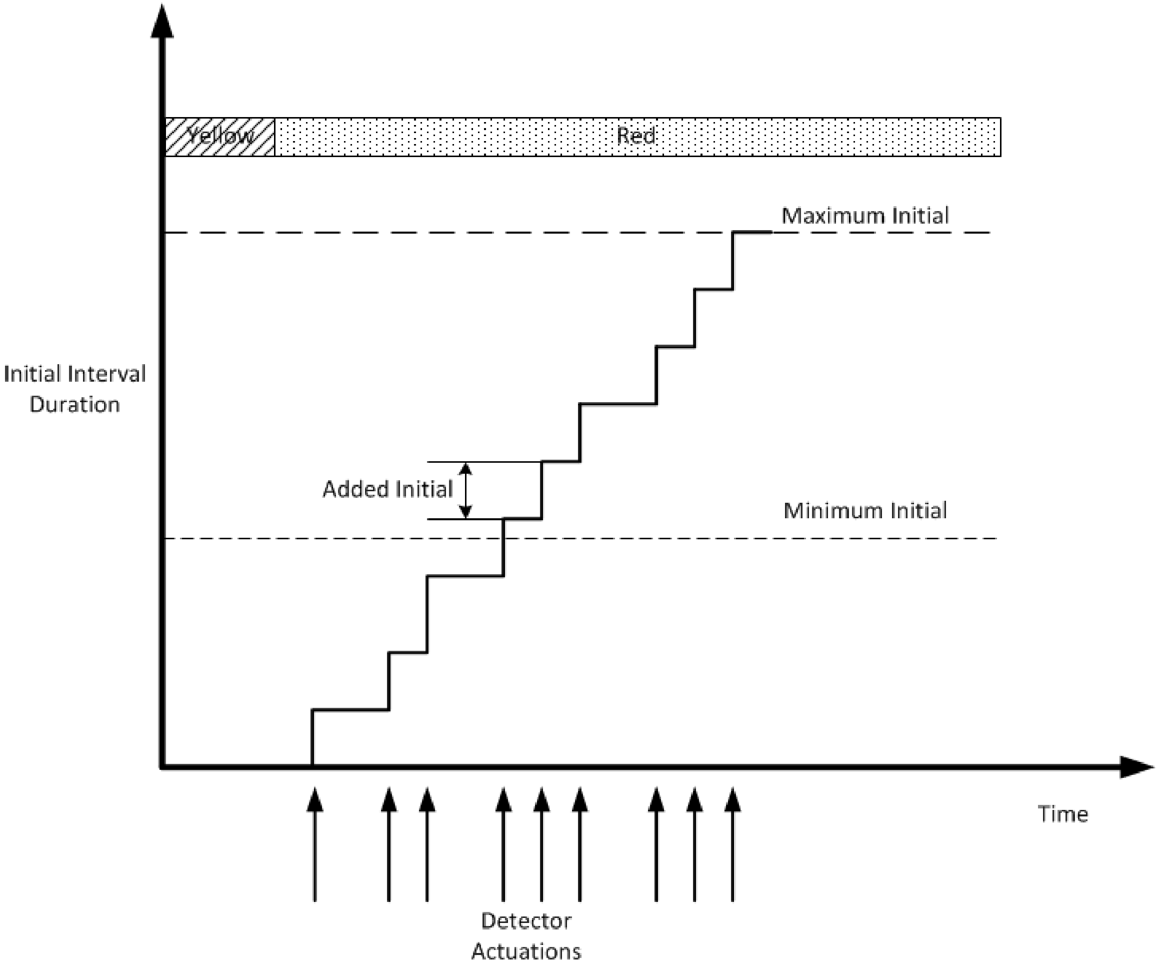


Exhibit 5-18. Illustration of variable initial feature.

Signal timing parameters may provide an opportunity to maximize the efficiency of the intersection. Signal timing parameters control how quickly the phase ends once traffic demand is no longer present. When coordination timings are used, the unused green time can be assigned to the coordinated phase or divided amongst the other phases, but should not exceed the split time.

5.7.3 Vehicle Timing—Vehicle Clearance

The vehicle clearance interval consists of the yellow change and red clearance intervals. The recommended practice for computing the vehicle clearance interval is the ITE formula (reference 56, equation 11-4), given in equation 2 (to use with metric inputs, use 1 m = 0.3048 ft):

$$CP = t + \frac{V}{2a + 64.4g} + \frac{W + L}{V} \quad \text{(U.S. Customary)}$$

where:
CP = change period (s)
t = perception-reaction time of the motorist (s); typically 1
V = speed of the approaching vehicle (ft/s)
a = comfortable deceleration rate of the vehicle (ft/s^2); typically 10 ft/s^2
W = width of the intersection, curb to curb (ft)
L = length of vehicle (ft); typically 20 ft
g = grade of the intersection approach (%); positive for upgrade, negative for downgrade

For change periods longer than 5 seconds, a red clearance interval is typically used. Some agencies use the value of the third term as a red clearance interval. The MUTCD does not require specific yellow or red intervals, but provides guidance that the yellow change interval should be approximately 3 to 6 seconds and that in most cases the red clearance interval should not exceed 6 seconds (Section 4D.26).(1) Note that because high-volume signalized intersections tend to be large and frequently on higher speed facilities, their clearance intervals are typically on the high end of the range. These longer clearance intervals increase loss time at the intersection and thus reduce capacity.

The topic of yellow and red clearance intervals has been much debated in the traffic engineering profession. At some locations, the yellow clearance interval is either too short or set improperly due to changes in posted speed limits or 85th percentile speeds. This is a common problem and frequently causes drivers to brake hard or to run through the intersection during the red phase. Because not all States follow the same law with regard to what is defined as "being in the intersection on the red phase," local practice for defining the yellow interval varies considerably.

Longer clearance intervals may cause drivers to enter the intersection later, breeding disrespect for the traffic signal. Wortman and Fox conducted a study that showed that the time of entry of vehicles into the intersection increased due to a longer yellow interval.(67) NCHRP 705 showed mixed results for the extension of the yellow change interval and the yellow/red change interval. It showed positive results on all crash types when the red change interval was extended.

5.7.4 Pedestrian Timing

Pedestrian timing requirements include a WALK interval and a pedestrian change (flashing upraised hand) interval. The WALK interval varies based upon local agency policy. The MUTCD recommends a minimum WALK time of 7 seconds, although WALK times as low as 4 seconds may be used if pedestrian volumes and characteristics do not require a 7-second interval (section 4E.06).(1) The WALK interval gives pedestrians adequate time to perceive the WALK indication and depart the curb before the pedestrian change (flashing upraised hand) interval begins.

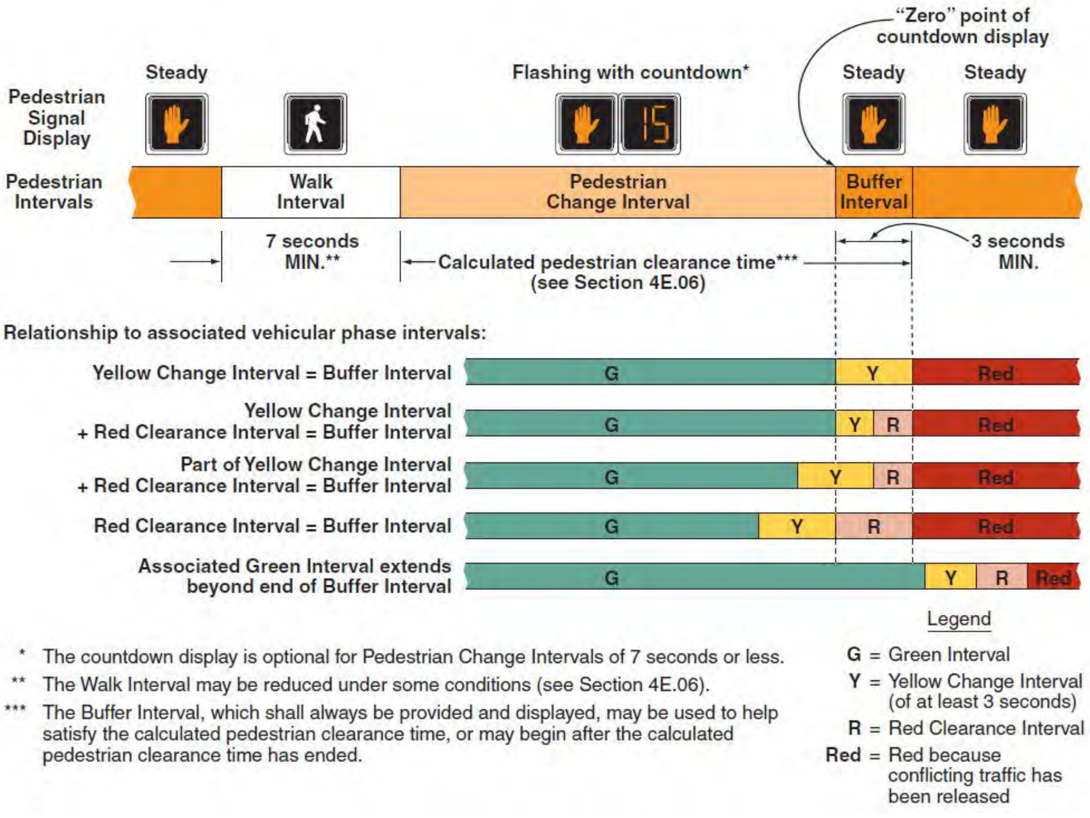
In downtown areas, longer WALK times are often appropriate to promote walking and serve pedestrian demand. School zones and areas with large numbers of elderly pedestrians also warrant consideration and the display of WALK times in excess of the minimum WALK time.

The MUTCD states that the pedestrian clearance time should allow a pedestrian crossing in the crosswalk to leave the curb and travel to at least the far side of the traveled way or to a median of sufficient width for pedestrians to wait. The MUTCD uses a walk speed of 3.5 ft/s for determining crossing times.(Error! Bookmark not defined.) However, FHWA pedestrian design guidance recommends a lower speed if needed to accommodate users who require additional time to cross the roadway, and in particular a lower speed in areas where there are concentrations of children and or elderly persons. Pedestrian clearance time is calculated using equation 1:

$$\text{Pedestrian Clearance Time} = \frac{\text{Crossing Distance}}{\text{Walking Speed}}$$

where: Pedestrian Clearance Time is in seconds
Crossing Distance is measured from the near curb to at least the far side of the traveled way or to a median; and
Walking Speed is 3.5 ft/s as indicated above.

Pedestrian clearance time is accommodated during either a combination of pedestrian change (upraised hand) interval time and yellow change and red clearance time or by pedestrian change (upraised hand) interval time alone. At high-volume locations, it may be necessary as a tradeoff for vehicular capacity to use the yellow change interval as part of satisfying the calculated pedestrian clearance time. According to the 2009 MUTCD,(1) a buffer interval illustrating a steady UPRAISED HAND symbolizing DON'T WALK shall be displayed following the pedestrian change interval for at least 3 seconds prior to the release of any conflicting vehicular movement. The pedestrian intervals are illustrated in Exhibit 5-19.



* The countdown display is optional for Pedestrian Change Intervals of 7 seconds or less.
** The Walk Interval may be reduced under some conditions (see Section 4E.06).
*** The Buffer Interval, which shall always be provided and displayed, may be used to help satisfy the calculated pedestrian clearance time, or may begin after the calculated pedestrian clearance time has ended.

Legend
G = Green Interval
Y = Yellow Change Interval (of at least 3 seconds)
R = Red Clearance Interval
Red = Red because conflicting traffic has been released

Exhibit 5-19. Pedestrian intervals.
Source: 2009 MUTCD

Practitioners should also consider the impact of longer pedestrian intervals on vehicular green time and overall cycle lengths. Consideration should be given to the volume of pedestrians, the pedestrian walk speed used to calculate the pedestrian interval, and the volume and turn movements of vehicular traffic.

5.7.5 Vehicle Timing—Cycle Length

For isolated, actuated intersections, cycle length varies from cycle to cycle based on traffic demand and signal timing parameters. For coordinated intersections, a background cycle length is used to achieve consistent operation between consecutive intersections. In general, shorter cycle lengths are preferable to longer ones because they result in less delay and shorter queues. However, the need to accommodate multiple pedestrian movements across wide roadways, coupled with complex signal phasing and minimum green requirements to accommodate signal progression in multiple directions, may sometimes require the use of even longer cycle lengths. Wherever possible, such use should be limited to peak traffic periods only.

In general, cycle lengths for conventional, four-legged intersections should not exceed 120 seconds, although larger intersections may require longer cycle lengths of 140 to 150 seconds. Some busy intersections even operate at 180-second cycle lengths. Longer cycle lengths generally result in increased delay and queues to all users, particularly minor movements.

5.8 SIGNING AND PAVEMENT MARKING DESIGN

Signs and pavement markings are important elements of signalized intersection design. Because of the complexity of driver decisions, particularly at large signalized intersections, special attention to signing and pavement markings can maximize the safety and efficiency of the intersection. At signalized intersections, these traffic control devices serve several key functions, including:

- Advance notice of the intersection.
- Directional route guidance.
- Lane use control, including indications of permissive or prohibited turning movements.
- Regulatory control of channelized right turn movements (e.g., through the use of YIELD signs).
- Delineation and warning of pedestrian crossing locations.
- Delineation and warning of bicycle lane locations.

The MUTCD is the primary reference for use in the design and placement of signs and pavement markings.(1) Additional resources include State supplements to the MUTCD and reference materials such as ITE's *Traffic Control Devices Handbook* (TCDH)(68) and *Traffic Signing Handbook.*(69)

Designing effective signing and pavement markings, particularly at high-volume signalized intersections, often requires thinking beyond standard drawings of typical sign and pavement marking layouts at intersections. High-volume signalized intersections typically have more lanes than most intersections. They may have redirected or restricted turning movements. They often join two or more designated routes (e.g., State highways) that require directional guidance to the user. They also are frequently located in urban areas where other intersections, driveways, and urban land use create visibility conflicts. The following questions, adapted from the ITE *Traffic Signing Handbook*,(69) represent a basic thought process recommended for engineers to follow when developing a sign layout at an intersection:

1. **From a given lateral and longitudinal position on the roadway, what information does the user need, both in advance and at the intersection?** At signalized intersections, is information on lane use provided at the intersection? Is advance street name information ("XX Street, Next Signal," etc.) and (if appropriate) route number directional signing provided in advance of the intersection? Exhibit 5-20 gives an example of an advance sign that provides street names for the next two signalized intersections.

Exhibit 5-20. Example of advance street name sign for two closely spaced intersections.

2. **Are there any on- or off-road conditions that would violate driver expectancy?** Lane drops and right-hand exits for left turns are both examples where driver expectancy is violated and should be addressed with signing. Exhibit 5-21 shows an example of signing used to advise motorists of a dropped lane at an upcoming intersection.

Exhibit 5-21. Example of signing for a left-hand lane drop.

3. **Is a specific action required by a road user?** If the road user needs to be in an appropriate lane in advance of an intersection to make a movement at the intersection, signing and corresponding pavement markings should convey this message to the user. Exhibit 5-22

provides an example of overhead signs and pavement markings used to assist drivers in selecting the proper lane on the approach to a signalized intersection.

Exhibit 5-22. Example of advance overhead signs and pavement markings indicating lane use for various destinations.

4. **Are signs located so that the road user will be able to see, comprehend, and attend to the intended message?** Signs must be simple enough to easily comprehend and attend to before the driver receives the next message. This requires adequate sign size, sign spacing, and attention to the number of elements on each sign. Additional signing enhancements, consistent with the principles of sign and message spreading (separating overlapping or numerous route signs onto two installations to improve comprehension and readability), may include the use of overhead signs in advance of large intersections and/or large retro-reflectorized or internally illuminated overhead signs (including street name signs) at the intersections.
5. **For what part of the driver population is the sign being designed?** Have the needs of older drivers or nonlocal drivers been accommodated? This may require the use of larger lettering or sign illumination.
6. **Does the sign "fit in" as part of the overall sign system?** Signing at an intersection needs to be consistent with the overall sign layout of the connecting road system. For example, the consistent use of guide signs is helpful to freeway users in identifying the appropriate exit. Similar consistency is needed on arterial streets with signalized intersections.

Pavement markings also convey important guidance, warnings, and regulatory lane-use information to users at signalized intersections. In addition to delineating lanes and lane use, pavement markings clearly identify pedestrian crossing areas, bike lanes, and other areas where driver attention is especially important. Where in-pavement detection is installed for bicycles and motorcycles, appropriate markings should be painted to guide these vehicles over the portion of the loop that will best detect them.

Several supplemental pavement markings are particularly useful at large signalized intersections. For example, the use of lane line extensions (dotted white lines) into the intersection can be a helpful tool where the intersection is so large that the alignment of through or turning lanes between entering the intersection and exiting the intersection could be confused. This can occur, for example, where multiple turn lanes are provided, where the through lane alignments make a curve through the intersection, or where the receiving lanes at an intersection are offset laterally from the approach lanes. In addition, pavement legends indicating route numbers and/or destinations in advance of the intersection (i.e., "horizontal signage") may be used to supplement signing for this purpose, as shown in Exhibit 5-23.

Exhibit 5-23. Example of pavement legends indicating destination route numbers ("horizontal signing").

5.9 ILLUMINATION DESIGN

As noted in the *American National Standard Practice for Roadway Lighting (RP-8-00)*, "[t]he principal purpose of roadway lighting is to produce quick, accurate, and comfortable visibility at night. These qualities of visibility may safeguard, facilitate, and encourage vehicular and pedestrian traffic… [T]he proper use of roadway lighting as an operative tool provides economic and social benefits to the public including:

(a) Reduction in night accidents, attendant human misery, and economic loss.

(b) Aid to police protection and enhanced sense of personal security.

(c) Facilitation of traffic flow.

(d) Promotion of business and the use of public facilities during the night hours.(70)

Specifically with respect to intersections, the document notes that "[s]everal studies have identified that the primary benefits produced by lighting of intersections along major streets is the reduction in night pedestrian, bicycle and fixed object accidents" (Section 3.6.2).(70) With respect to signalized intersections, roadway lighting can play an important role in enabling the intersection to operate at its best efficiency and safety. The highest traffic flows of the day (typically the evening peak period) may occur during dusk or night conditions where lighting is critically important, particularly in winter for North American cities in northern latitudes.

The document includes three different criteria for roadway lighting: illuminance, luminance, and small target visibility (STV). These are described as follows:

- Illuminance is the amount of light incident on the pavement surface from the lighting source.

- Luminance is the amount of light reflected from the pavement toward the driver's eyes. The luminance criterion requires more extensive evaluation. Because the reflectivity of the pavement surfaces constantly changes over time, it is difficult to accurately estimate this criterion.
- Small target visibility is the level of visibility of an array of targets on the roadway. The STV value is determined by the average of three components: the luminance of the targets and background, the adaptation level of adjacent surroundings, and the disability glare.

5.9.1 Illuminance

The two principal measures used in the illuminance method are light level and uniformity ratio. Light level represents the intensity of light output on the pavement surface and is reported in units of lux (metric) or footcandles (U.S. Customary). Uniformity represents the ratio of either the average-to-minimum light level (E_{avg}/E_{min}) or the maximum-to-minimum light level (E_{max}/E_{min}) on the pavement surface. The light level and uniformity requirements are dependent on the roadway classification and the level of pedestrian night activity.

The basic principle behind intersection lighting is that the amount of light on the intersection should be proportional to the classification of the intersecting streets and equal to the sum of the values used for each separate street. For example, if Street A is illuminated at a level of x and Street B is illuminated at a level of y, the intersection of the two streets should be illuminated at a level of $x+y$. RP-8-00 also specifies that if an intersecting roadway is illuminated above the recommended value, then the intersection illuminance value should be proportionately increased. If the intersection streets are not continuously lighted, a partial lighting system can be used. RP-8-00 and its annexes should be reviewed for more specific guidance on partial lighting, the specific calculation methods for determining illuminance, and guidance on the luminance and STV methods.(70)

Exhibit 5-24 presents the recommended illuminance for the intersections within the scope of this document located on continuously illuminated streets. Separate values have been provided for portland cement concrete road surfaces (RP-8-00 Road Surface Classification R1) and typical asphalt concrete road surfaces (RP-8-00 Road Surface Classification R2/R3).

Exhibit 5-25 presents the roadway and pedestrian area classifications used for determining the appropriate illuminance levels in exhibit 5-26. RP-8-00 clarifies that although the definitions given in exhibit 5-25 may be used and defined differently by other documents, zoning bylaws, and agencies, the area or roadway used for illumination calculations should best fit the descriptions contained in exhibit 5-25 (section 2.0, p. 3).(70)

5.9.2 Veiling Luminance

Stray light from light sources within the field of view produces veiled luminance. This stray light is superimposed in the eye on top of the retinal image of the object of interest, which alters the apparent brightness of that object and the background in which it is viewed. This glare, known as disability glare, reduces a person's visual performance and thus must be considered in the design of illumination on a roadway or intersection.(70) Exhibit 5-24 shows the maximum veiling luminance required for good intersection lighting design.

Exhibit 5-24. Recommended illuminance for the intersection of continuously lighted urban streets.

		Average Maintained Illuminance at Pavement			Uniformity Ratio (Eavg/Emin)[3]	Veiling Luminance Ratio (Lvmax/Lavg)[4]
		Pedestrian/Area Classification				
Pavement Classification[1]	**Roadway Classification**	**High (lux (fc)[2])**	**Medium (lux (fc)[2])**	**Low (lux (fc)[2])**		
R1	Major/Major	24.0 (2.4)	18.0 (1.8)	12.0 (1.2)	3.0	0.3
	Major/Collector	20.0 (2.0)	15.0 (1.5)	10.0 (1.0)	3.0	0.3
	Major/Local	18.0 (1.8)	14.0 (1.4)	9.0 (0.9)	3.0	0.3
	Collector/Collector	16.0 (1.6)	12.0 (1.2)	8.0 (0.8)	4.0	0.4
	Collector/Local	14.0 (1.4)	11.0 (1.1)	7.0 (0.7)	4.0	0.4
	Local/Local	12.0 (1.2)	10.0 (1.0)	6.0 (0.6)	6.0	0.4
R2/R3	Major/Major	34.0 (3.4)	26.0 (2.6)	18.0 (1.8)	3.0	0.3
	Major/Collector	29.0 (2.9)	22.0 (2.2)	15.0 (1.5)	3.0	0.3
	Major/Local	26.0 (2.6)	20.0 (2.0)	13.0 (1.3)	3.0	0.3
	Collector/Collector	24.0 (2.4)	18.0 (1.8)	12.0 (1.2)	4.0	0.4
	Collector/Local	21.0 (2.1)	16.0 (1.6)	10.0 (1.0)	4.0	0.4
	Local/Local	18.0 (1.8)	14.0 (1.4)	8.0 (0.8)	6.0	0.4

[1] R1 is typical for portland cement concrete surface; R2/R3 is typical for asphalt surface.

[2] fc = footcandles

[3] Eavg/Emin = Average illuminance divided by minimum illuminance

[4] Lvmax/Lavg = Maximum veiling luminance divided by average luminance.

Source: Reference 70, table 9 (for R2/R3 values); R1 values adapted from table 2.

Exhibit 5-25. RP-8-00 guidance for roadway and pedestrian/area classification for purposes of determining intersection illumination levels.

Roadway Classification	**Description**	**Average Daily Vehicular Traffic Volumes (ADT)**[1]
Major	That part of the roadway system that serves as the principal network for through-traffic flow. The routes connect areas of principal traffic generation and important rural roadways leaving the city. Also often known as "arterials," thoroughfares," or "preferentials."	More than 3,500
Collector	Roadways servicing traffic between major and local streets. These are streets used mainly for traffic movements within residential, commercial, and industrial areas. They do not handle long, through trips.	1,500 to 3,500
Local	Local streets are used primarily for direct access to residential, commercial, industrial, or other abutting property.	100 to 1,500

Pedestrian Conflict Area Classification	**Description**	**Possible Guidance on Pedestrian Traffic Volumes**[2]
High	Areas with significant numbers of pedestrians expected to be on the sidewalks or crossing the streets during darkness. Examples are downtown retail areas, near theaters, concert halls, stadiums, and transit terminals.	More than 100 pedestrians/hour
Medium	Areas where lesser numbers of pedestrians use the streets at night. Typical are downtown office areas, blocks with libraries, apartments, neighborhood shopping, industrial, older city areas, and streets with transit lines.	11 to 100 pedestrians/hour
Low	Areas with very low volumes of night pedestrian usage. These can occur in any of the cited roadway classifications but may be typified by suburban single family streets, very low density residential developments, and rural or semirural areas.	10 or fewer pedestrians/hour

Notes: [1] For purposes of intersection lighting levels only.

[2] Pedestrian volumes during the average annual first hour of darkness (typically 18:00-19:00), representing the total number of pedestrians walking on both sides of the street plus those crossing the street at non-intersection locations in a typical block or 656 ft section. RP-8-00 clearly specifies that the pedestrian volume thresholds presented here are a local option and should not be construed as a fixed warrant.

Source: Reference 70, sections 2.1, 2.2, and 3.6