Signal Timing and Phasing

Controller Unit Timing

A traffic signal controls traffic by assigning right-of-way to one traffic movement or several non-conflicting traffic movements at a time. Right-of-way is assigned by turning on a green signal for a certain length of time or an interval. Right-of-way is ended by a yellow change interval during which a yellow signal is displayed, followed by the display of a red signal. The device that times these intervals and switches the signal lamps is called a controller unit. This section will cover the operation of controller units and the various features and characteristics of the types currently available.

Control Concepts

Traffic control concepts for isolated intersections basically fall into two basic categories, pre-timed and traffic-actuated.

Pre-timed signal control

Under these conditions, the signal assigns right-of-way at an intersection according to a predetermined schedule. The sequence of right-of-way (phases), and the length of the time interval for each signal indication in the cycle is fixed. No recognition is given to the current traffic demand on the intersection approaches unless detectors are used. The major elements of pre-timed control are (1) fixed cycle length, (2) fixed phase length, and (3) number and sequence of phases.

Advantages to pre-timed control include:

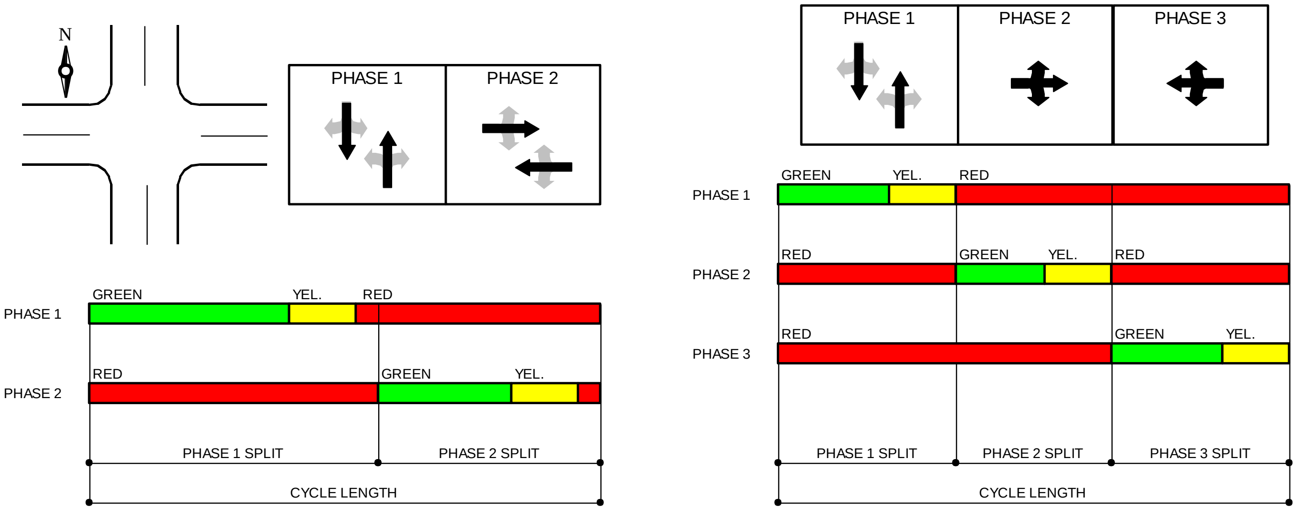
- ✓ Simplicity of equipment provides relatively easy servicing and maintenance.
- ✓ Can be coordinated to provide continuous flow of traffic at a given speed along a particular route, thus providing positive speed control.
- ✓ Timing is easily adjusted in the field.
- ✓ Under certain conditions can be programmed to handle peak conditions.

Disadvantages to pre-timed control include:

- ✓ Do not recognize or accommodate short-term fluctuations in traffic.
- ✓ Can cause excessive delay to vehicles and pedestrians during off-peak periods.

The left side of the following figure shows the timing operation for a basic two-phase or two-traffic movement pre-timed controller unit. The right side of the figure shows the timing operation for a three phase pre-timed controller unit. For the pre-timed controller, the length of time for each phase is fixed.

Exhibit 3-1 Basic Two-Phase Pre-timed Signal Operation



Traffic-actuated signal control

Traffic-actuated control attempts to adjust green time continuously, and, in some cases, the sequence of phasing. These adjustments occur in accordance with real-time measures of traffic demand obtained from vehicle detectors placed on one or more of the approaches to the intersection. The full range of actuated control capabilities depends on the type of equipment employed and the operational requirements.

Advantages to actuated signals include:

- ✓ Usually reduce delay (if properly timed).
- ✓ Adaptable to short-term fluctuations in traffic flow.
- ✓ Usually increase capacity (by continually reapportioning green time).
- ✓ Provide continuous operation under low volume conditions as an added safety feature, when pre-timed signals may be put on flashing operation to prevent excessive delay.
- ✓ Especially effective at multiple phase intersections.

Disadvantages to actuated control include:

- ✓ The cost of an actuated installation is higher than the cost of a pre-timed installation.
- ✓ Actuated controllers and detectors are much more complicated than pre-timed signal controllers, increasing maintenance and inspection skill requirements and costs.
- ✓ Detectors are costly to install and require careful inspection and maintenance to ensure proper operations.

Traffic actuated signal control can further be broken into the following categories:

Semi-Actuated Control. In semi-actuated control, the major movement receives green unless there is a conflicting call on a minor movement phase. The minor phases include any protected left-turn phases or side street through phases. Detectors are needed for each minor movement. Detectors may be used on the major movement if dilemma zone protection is desired.

In semi-actuated coordinated systems (referred to as Actuated Coordinated in Synchro), the major movement is the "sync" phase. Minor movement phases are served only after the sync phase yield point and are terminated on or before their respective force off points. These points occur at the same point in time during the background signal cycle and ensure that the major road phase will be coordinated with adjacent signal controllers.

In semi-actuated non-coordinated systems, the major movement phase is placed on minimum (or maximum) recall. The major movement rests in green until a conflicting call is placed. The conflicting phase is serviced as soon as a gap-out or max-out occurs on the major phase. Immediately after the yellow is presented to the major phase, a call is placed by the controller for the major phase, regardless of whether or not a major phase vehicle is present.

Full Actuated Control. In full actuated control, all signal phases are actuated and all signalized movements require detection. Generally used at isolated intersections; however, can also be used at high-demand intersections in coordinated systems.

Volume-density operation can be considered to be a more advanced form of full-actuated control. It has the ability to calculate the duration of minimum green based on actual demand (calls on red) and the ability to reduce the maximum allowable time between calls from passage time down to minimum gap. Reducing the allowable time between calls below the passage time will improve efficiency by being better able to detect the end of queued flow.

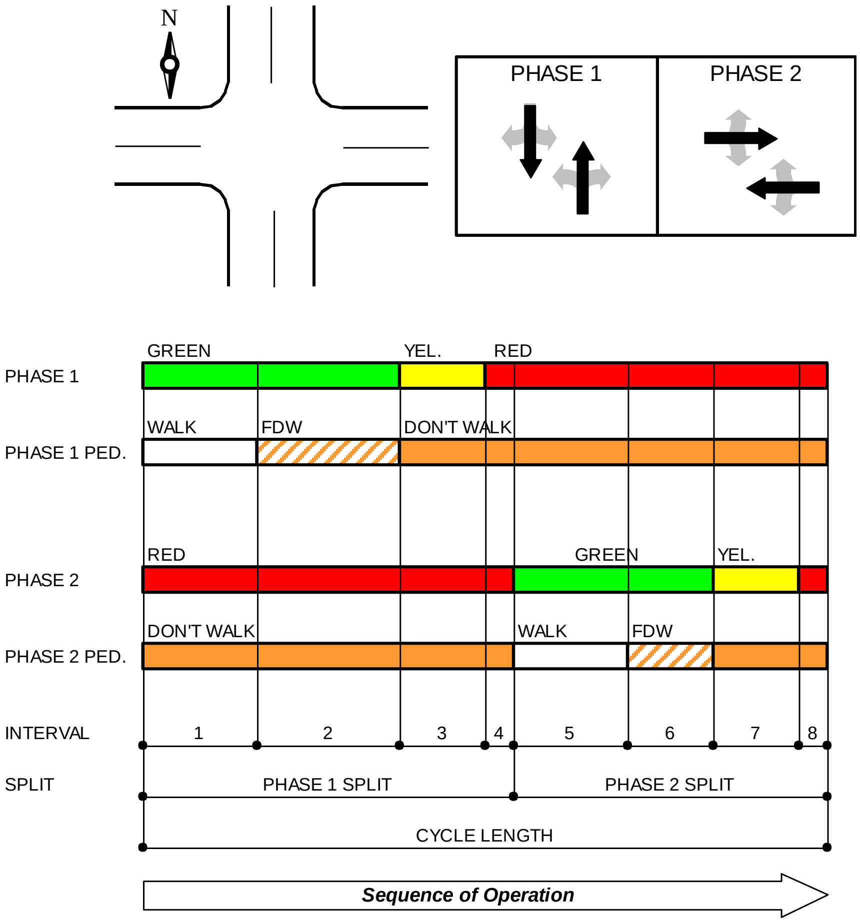
Traffic Signal Phasing

A traffic **signal phase**, or **split**, is the part of the cycle given to an individual movement, or combination of non-conflicting movements during one or more intervals. An **interval** is a portion of the cycle during which the signal indications do not change.

The predetermined order of phases is the sequence of operation. This order is fixed in a pre-timed controller, and under certain circumstances, may be variable with an actuated controller.

Consider the following figure for an example two-phase (single ring) signal with pedestrian timing.

Exhibit 3-2 Traffic Signal Phasing



In the figure, there are eight intervals where the signal indications do not change. Notice that intervals 4 and 8 are all red periods (interval 4 is the phase 1 all red and interval 8 is the phase 2 all red). The phase 1 split is made up of intervals 1 through 4 and the phase 2 split is made up of intervals 5 through 8. The sum of split 1 and 2 is the cycle length.

Ring and Barrier Structure

Ring

A ring is a term that is used to describe a series of conflicting phases that occur in an established order. A ring may be a single ring, dual ring, or multi-ring and is described in detail below. A good understanding of the ring structure is a good way to understand the operation of multiphase controllers.

Barrier

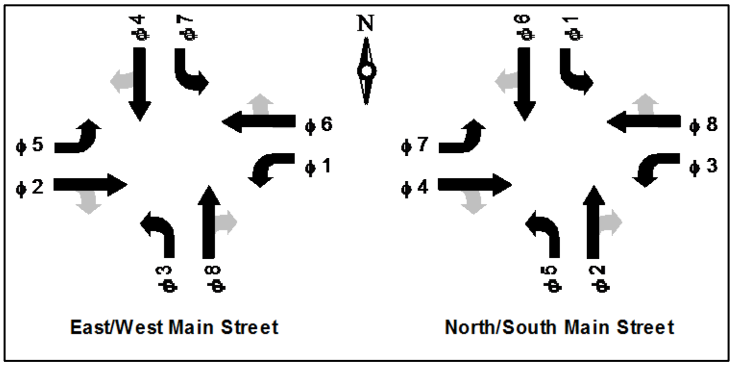
A barrier (compatibility line) is a reference point in the preferred sequence of a multi-ring controller unit at which all rings are interlocked. Barriers assure there will be no concurrent selection and timing of conflicting phases for traffic movements in different rings. All rings cross the barrier simultaneously to select and time phases on the other side.

Phase Numbers

Phase numbers are the labels assigned to the individual movements around the intersection. For an eight phase dual ring controller (see definition of dual ring), it is common to assign the main street through movements as phases 2 and 6. Also, it is common to use odd numbers for left turn signals and the even numbers for through signals. A rule of thumb is that the sum of the through movement and the adjacent left turn is equal to seven or eleven.

The figure below shows a typical phase numbering scheme for an east/west arterial and a north/south arterial.

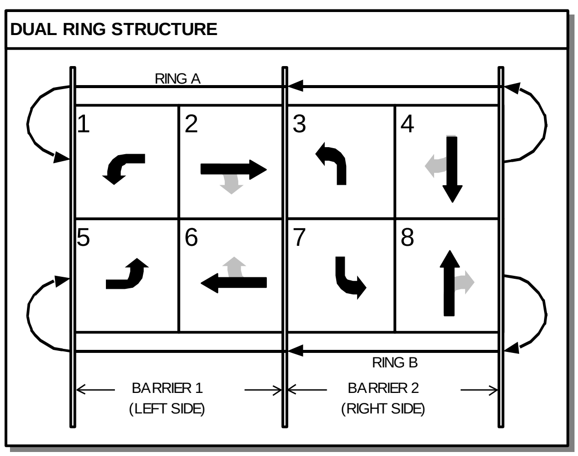
Exhibit 3-3 Common Phase Numbering Scheme



Dual Ring Control

By contrast to the pre-timed controller unit, the traffic actuated controller usually employs a "dual ring concurrent" timing process. The NEMA concept is illustrated in the figure below.

Exhibit 3-4 Dual Ring Control



The dual-ring controller uses a maximum of eight phase modules, each of which controls a single traffic signal face with red, yellow and green display. The eight phases are required to accommodate the eight movements (four through and four left turns) at the intersection. Phases 1 through 4 are included in ring 1, and phases 5 through 8 are included in ring 2. The two rings operate independently, except that their control must cross the "barrier" at the same time.

If the movements to be controlled by these eight phases are assigned properly, the controller will operate without giving the right-of-way simultaneously to conflicting movements. All of the movements from one street (usually the major street) must be assigned to the left side of the barrier. Similarly, all movements from the other street must be assigned to the right side.

On both sides of the barrier there are four movements (two through and two left). Each of the four may proceed without conflict with two of the other three. So if the left turn in any given direction is placed in ring 1 along with its opposing through movement, and the remaining two movements are placed in ring 2, it will be possible for either movement in ring 1 to be displayed simultaneously with either movement in ring 2 without conflict.

The dual-ring concurrent operation can be shown to maximize the operating efficiency at an intersection by eliminating the "slack" time on each cycle (i.e., control will follow one or the other of the two paths shown).

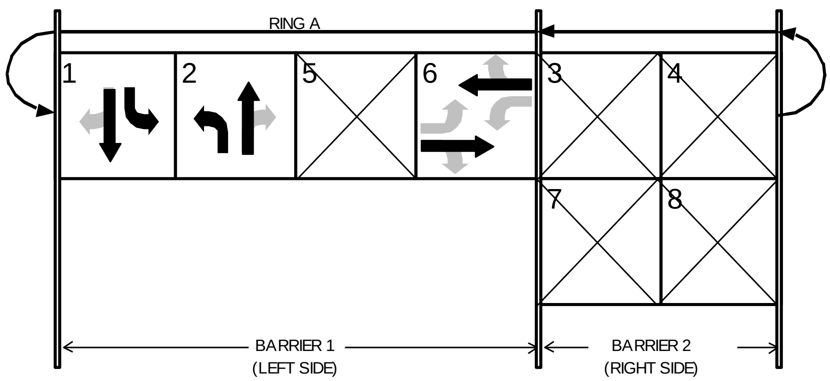
Modern controllers offer more flexibility in assigning traffic signal phases in order to control many complex or unique situations. TS2 controllers include four timing rings and up to sixteen vehicle phases and sixteen pedestrian phases. Each phase can be assigned to any ring. In addition, there are up to sixteen overlap assignments.

Single Ring (Sequential Phases)

Sometimes it is desirable to use a single ring and have the phases operate one at a time sequentially. Each phase is individually timed and can be skipped if there is no demand for it. This is called sequential or exclusive phasing. When using sequential phases on the left side of the barrier, phases 1-2-5-6 show in order. When using sequential phases on the right side of the barrier, phases 3-4-7-8 show in order.

The figure below is an example of a controller using Sequential phases. North and South traffic use split phasing, East and West share a phase.

Exhibit 3-5 Sequential Phasing



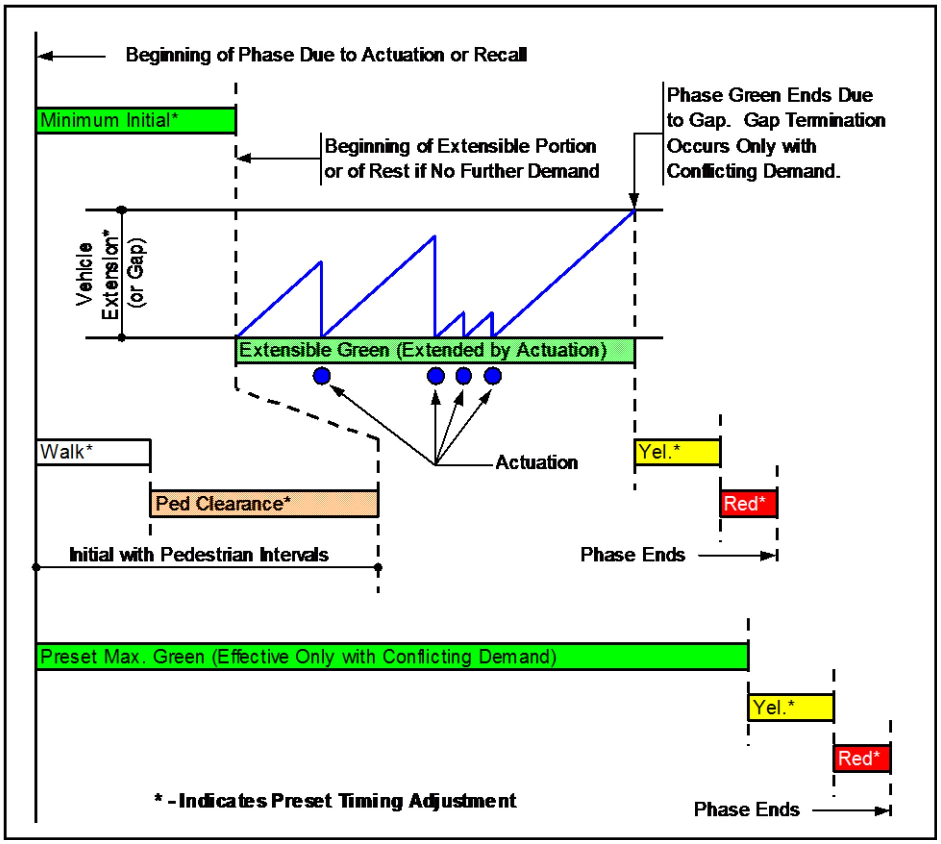
Phasing Parameters

Some of the basic principles of timing the green interval in a traffic actuated controller unit are as follows:

- ✓ There must be a **minimum green** time so that a stopped vehicle that receives a green signal has enough time to get started and partially across the intersection before the yellow signal appears. This time is termed the **initial portion** of the green interval.
- ✓ Each following vehicle requires green time. This is called **passage time**, **vehicle extension,** or **gap**. Gap refers to the distance between vehicles as well as the time between vehicles.
- ✓ There must be a **maximum time** that the green interval can be extended if opposing cars are waiting - this is called **extension limit** or **maximum**.
- ✓ A timing diagram for one traffic actuated phase is shown in the figure that follows. The other phase or phases operate in the same manner.

- ✓ The number of "presets" is the number of timing adjustments in the **extensible portion**. Each detector actuation starts the unit extension timing again. With no opposing calls the controller rests. Unit extensions continue being timed, but with no effect on the green interval.
- ✓ However, once an **actuation** is received from an opposing phase, unit extension is used to expedite servicing that phase as follows: if the time between actuations is greater than the preset unit extension or gap the extensible portion will be ended, the yellow change interval will appear and the next phase in sequence with demand will receive the right-of-way. This is called termination by gap or **gap-out**.
- ✓ An actuation from another phase received in any portion of the green interval also starts another timing circuit. This is called the extension limit or maximum green. Even if actuations are close enough in time to prevent gap termination, the maximum limit will terminate the green interval when the preset maximum expires. This is called termination by maximum green or **max-out**.

Exhibit 3-6 Traffic Actuated Phase Timing Diagram



Minimum Green

The Minimum Green Interval is the shortest green time of a phase. If a time setting control is designated as "minimum green," the green time shall be not less than that setting. For Mn/DOT practice on minimum green (minimum initial) times, refer to page 4-7.

Initial Intervals

There are three types of initial intervals as follows:

- ✓ Extensible initial

- ✓ Added initial
- ✓ Computed initial

Extensible initial is the method of calculating the variable initial period commonly used in field practice. This method adds the time specified as "seconds per actuation" to the minimum initial (green) for each vehicle actuation received by a phase during the yellow and/or red signal (depending on red and yellow lock) up to a maximum initial time. This method is common in both 170 and NEMA controllers.

Added initial is similar to extensible initial with the exception that the "seconds per actuation" calculation does not begin until a user specified number of vehicles actuations have occurred. The added initial option is generally used when long minimum green times are specified.

Computed initial calculates the amount of time given to each vehicle actuation (computed seconds per actuation) during the red signal display of the phase based on the following formula:

(Maximum initial interval time) ÷ (number of actuations that can be serviced during the minimum initial interval) x (number or recorded actuations). The total time allowed for the computed initial interval is limited by both the minimum green and maximum initial interval.

Passage Time

Passage Time (also referred to as vehicle extension or gap time) is the time that the phase will be extended for each actuation. Passage time is typically set as the time it takes to travel from the vehicle detector to the stop line at the travel speed of the roadway for pulse loops or the average acceptable headway between vehicles for presence loops located close to the stop line. Therefore, the vehicle extension is related to the minimum and maximum gap. For Mn/DOT practice on passage time refer to page 4-13.

Maximum Green

Depending on the type and manufacturer of the controller being simulated, there can be two methods for calculating the maximum amount of green time allowed per phase. Method 1 or maximum green, allows the user to input the maximum amount of green time a phase will be allowed to be active, (i.e. display green.) The max. timer in the controller begins its countdown at the receipt of a conflicting vehicle or pedestrian call, generally the beginning of phase green and includes any minimum green or variable initial period.

Method 2, maximum green extension, is the amount of time a phase will be allowed service after the minimum green and variable initial have timed out. While some controller manufacturers still allow maximum green extension, it is more commonly found in older isolated NEMA and Type 170 controllers. Assuming that vehicle headways remain less than the vehicle extension time during the green signal display of the phase, Method 1 will always produce the same timing value. However, in Method 2 the total green time is not only dependent on vehicle headways during the phase green but also on the number of vehicles that arrive during the red display for the calculation of variable initial. Therefore, total green time for Method 2 can vary from cycle to cycle irrelevant of vehicle headways.

If the controller is operating within a coordinated system the maximum green time specified in the controller may not be appropriate for the cycle/split combination selected by the master controller. In this case the phase can max-out early without ever reaching the force-off point (the end of the assigned phase split) for the phase.

Note: In certain manufacturers' controllers, there will be a timing function called "MAX EXT." This is not the same as maximum extension green but the number of seconds used to extend the maximum green value when "MAX 3" is active.

For Mn/DOT practice on maximum green times, refer to page 4-15.

Pedestrian Phasing

Because pedestrians move at a slower speed than vehicles, they require different treatment of the green interval. A pedestrian actuation, therefore, results in more green time than would be allowed for a vehicle: a "Walk" interval followed by a flashing "Don't Walk" pedestrian clearance. In the absences of opposing calls, succeeding pedestrian actuations will recycle the pedestrian indications.

- ✓ Pedestrian intervals result in a green interval for the parallel vehicle phase or phases. The figure on the page 3-11 shows the timing diagram for pedestrian operation.
- ✓ It is also possible to have an exclusive pedestrian phase. That is, no vehicle green intervals will occur. All pedestrian signals at an intersection could be controlled by this phase.

Red Vehicle Clearance

Red clearances (ALL RED) is the safety clearance interval at the end of a phase that displays red for all traffic movements. For Mn/DOT practice on red clearance intervals see page 4-18.

Recall

Normally a controller unit will, in the absence of actuation, rest on the last phase serviced. By means of a recall switch the controller unit can be forced to return to a particular phase's green interval, even with no demand.

Every phase has the capability of operation with the following types of recall:

- ✓ *Minimum Recall*. When active and in the absence of a vehicle call on the phase, a temporary call to service the minimum initial time will be placed on the phase. If a vehicle call is received prior to the phase being serviced the temporary call will be removed. Once the phase is serviced it can be extended based on normal vehicle demand.
- ✓ *Maximum Recall.* With the maximum vehicle recall active a constant vehicle call will be placed on the phase. This constant call will force the controller to time the maximum green. Maximum recall is generally used to call a phase when local detection is not present or inoperative.
- ✓ *Pedestrian Recall.* This feature provides vehicle green and pedestrian walk and clearance intervals. After that, normal green timing is in effect except that pedestrian calls will not recycle pedestrian intervals until opposing phases are serviced.
- ✓ In addition, a phase has a vehicle call placed on it if it is terminated with some passage time remaining. This can happen with termination by maximum.
- ✓ If all of the active phases of a controller unit are placed on recall the controller unit will operate in a pre-timed mode. It should be added that unless the detectors are disconnected from a phase, that phase's green interval could be extended beyond the preset minimum if the recall is to minimum.

Volume Density Control

Even more sophisticated operation is possible with the volume density traffic actuated controller unit. In addition to the features discussed above, volume density provides two means of modifying the basic timing intervals. These are:

- ✓ *Variable initial* is a means of extending the initial portion of the green interval. This is done on the basis of the number of actuations above a preset number while the phase is displaying yellow or red. This extended initial provides additional green time for a queue of vehicles waiting, when the

Left Turn Phasing

A critical element to the operation of a traffic signal is the determination of the appropriate phasing scheme. At signalized intersections where traffic volumes are heavy or speeds are high, vehicles attempting to turn left across opposing traffic may constitute significant safety and capacity problems. Based on this, there are additional considerations for determining the left turn phasing alternative. These include:

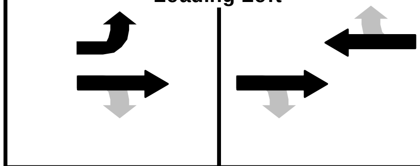
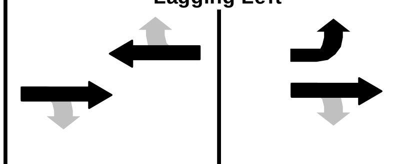
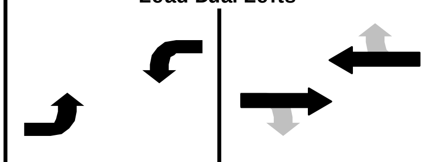
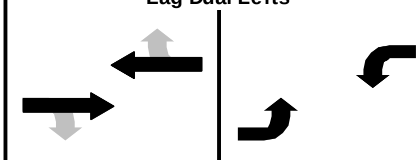
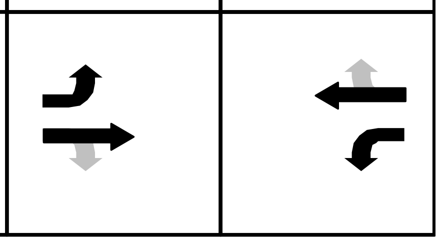
- ✓ *Heaviest Left Turn Protected* - This is a leading left phase scheme in which the left-turning vehicles from only one approach are protected and move on an arrow indication proceeding the opposing through movement; or a lagging left when the protected left turn follows the through movement phase.
- ✓ *Both Left Turns Protected (Without Overlap)* - When the opposing left turns move simultaneously followed by the through movements, it is called a “lead dual left”. If the left turns follow the through movement, it is called a “lag dual left”.
- ✓ *Both Left Turns Protected (With Overlap)* - In this operation, opposing left turns start simultaneously. When one terminates, the through movement in the same direction as the extending left movement is started. When the extended left is terminated, the remaining through movement is started. When this type of phasing is used on both streets, it is termed “quad left phasing”.
- ✓ *Lead Lag* - This phasing is combined with a leading protected left in one direction, followed by the through movements, followed by a lag left in the opposing direction. It is sometimes used in systems to provide a wider two-way through band.
- ✓ *Directional Separation (Split)* - First, one approach moves with all opposing traffic stopped, then the other approach moves with the first approach stopped.

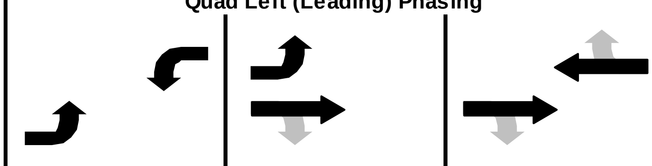
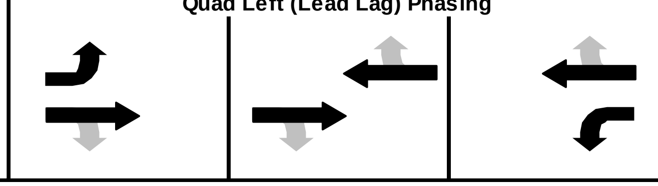
The figure on the following page shows the above basic left turn phasing schemes.

Whether or not separate left turn phasing should be provided is a decision that must be based on engineering analysis. This analysis may involve serious trade-offs between safety, capacity, and delay considerations.

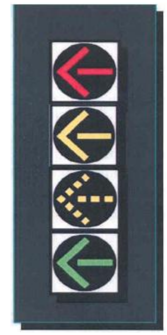
- ✓ Separation of left turns and opposing traffic may reduce accidents that result from conflicts between these movements, and may increase left turn capacity. However, through traffic capacity may be reduced.
- ✓ Left turn phasing may reduce peak period delay for left turners, but may increase overall intersection delay. Off-peak left turn delay may also increase.

Exhibit 3-10 Left Turn Phasing

Heaviest Left Turn Protected This is a leading left phase scheme in which the left-turning vehicles from only one approach are protected and move on an arrow indication proceeding the opposing through movement; or a lagging left when the protected left turn follows the through movement phase.	**Leading Left**  **- OR -** **Lagging Left** 
Both Left Turns Protected (Without Overlap) When the opposing left turns move simultaneously followed by the through movements, it is called a "lead dual left". If the left turns follow the through movement, it is called a "lag dual left".	**Lead Dual Lefts**  **- OR -** **Lag Dual Lefts** 
Directional Seperation (Split) First, one approach moves with all opposing traffic stopped, then the other approach moves with the first approach stopped.	

Both Turns Protected (with Overlap) In this operation, opposing left turns start simultaneously. When one terminates, the through movement in the same direction as the extending left movement is started. When the extended left is terminated, the remaining through movement is started. When this type of phasing is used on both streets, it is termed "quad left phasing". ***Lead Lag*** phasing is combined with a leading protected left in one direction, followed by the through movements, followed by a lag left in the opposing direction. It is sometimes used in systems to provide a wider two-way through band. .	**Quad Left (Leading) Phasing**  **- OR -** **Quad Left (Lead Lag) Phasing** 

Flashing Yellow Arrow Display



The Flashing Yellow Arrow (FYA) head is a signal that uses a flashing yellow arrow indication for permissive left turns instead of using a green ball. A 7-year national study determined that the 4-section FYA signal head with a red arrow on top, followed by a steady yellow arrow, a flashing yellow arrow, and then a green arrow on the bottom was the best and safest type of left-turn signal head based on driver confirmation and field implementation studies.

The FYA head is now the recommended left turn head in the Federal 2009 Manual of Uniform Traffic Control Devices (MUTCD). This version of the MUTCD includes language on the use of the flashing yellow arrow for permitted left turns that states:

> "Vehicular traffic, on an approach to an intersection, facing a flashing YELLOW ARROW signal indication, displayed alone or in combination with another signal indication, is permitted to cautiously enter the intersection only to make the movement indicated by such arrow, or other such movement as is permitted by other signal indications displayed at the same time.
>
> Such vehicular traffic, including vehicles turning right or left or making a U-turn, shall yield the right-of-way to:
>
> a) Pedestrians lawfully within an associated crosswalk, and
> b) Other vehicles lawfully within the intersection.
>
> In addition, vehicular traffic turning left or making a U-turn to the left shall yield the right-of-way to other vehicles approaching from the opposite direction so closely as to constitute an immediate hazard during the time when such turning vehicle is moving across or within the intersection."

At the time of publication of this Manual, Mn/DOT is updating the Minnesota MUTCD. It is anticipated that the above language from the Federal MUTCD will be found in the MN MUTCD.

Mn/DOT does encourage the use of FYA whenever appropriate. Additional details on the FYA can be found by visiting:

http://www.dot.state.mn.us/trafficeng/signals/flashingyellowarrow.html

http://mutcd.fhwa.dot.gov/resources/interim_approval/ia_10_flashyellarrow.htm

http://www.fhwa.dot.gov/publications/research/safety/09036/index.cfm

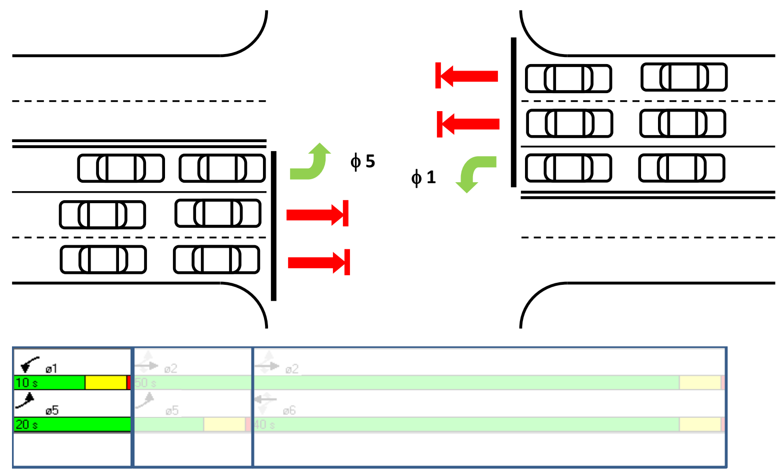
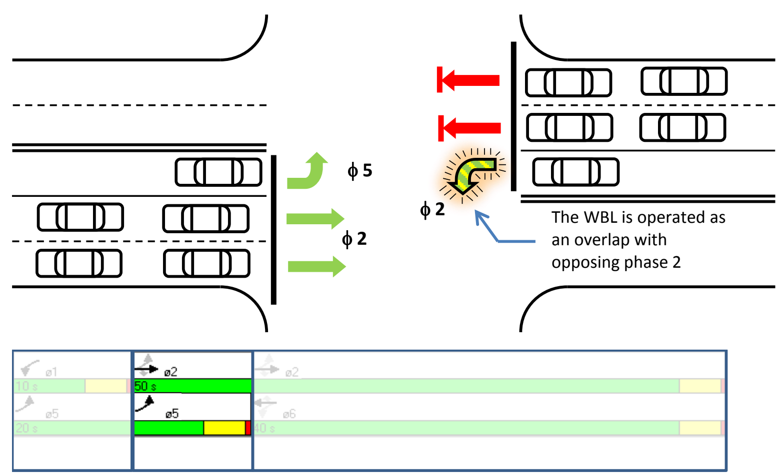
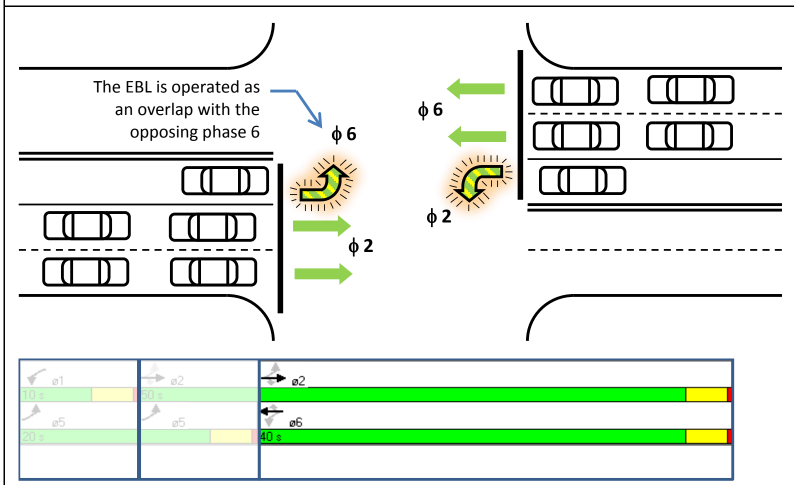
Flashing Yellow Arrow and the Left Turn Trap

Exhibit 3-11 illustrated a left turn trap with traditional lead/lag phasing (i.e., a green ball indication is used for the permitted left turns). Using a FYA indication can eliminate the trap condition illustrated in this Exhibit.

Once again, consider the EBL vehicle in this Exhibit. During interval 1, the EBL receives a green arrow and proceeds under the protected movement. During interval 2, the EBL shows the flashing yellow arrow indication and the movement operates as a permissive movement. In interval 3, the EBL remains a flashing yellow arrow indication instead of turning red. The EBL FYA actually operates as an overlap to phase 6. Therefore, the EBL and opposing WBT terminate at the same time as expected by the driver.

Exhibit 3-12 illustrates the signal operation of the FYA even under the "soft-trap" condition and how this can be eliminated.

Exhibit 3-12 FYA to Eliminate Left Turn Trap

	**Interval 1**: During this interval, normal leading protected and opposing left turn phases operate. This is the typical operation even with a traditional 5-section signal indication. At the end of this interval, phase 1 clears the intersection with a solid yellow arrow.
	**Interval 2**: During this interval phase 2 begins green as phase 5 continues green in normal operation. The opposing left turn is operated as a FYA. In a traditional 5-section operation, the opposing left turn would be red.
	**Interval 3**: In this interval, phase 2 and 6 throughs receive a green ball indication. The opposing lefts are operated as an FYA overlap with the opposing through. This will ensure that the left turn clears (turns yellow) and then red with the opposing through, thus eliminating the left turn trap.

Minnesota Flashing Yellow Arrow

The section on "**Flashing Yellow Arrow Display**" starting on page 3-24 discusses the FYA from a national and Federal MUTCD perspective. The following sections discuss the use of the FYA within Minnesota.

The discussions in this section "Minnesota Flashing Yellow Arrow" are current at the time of printing this publication. However, the items mentioned are anticipated to be continually changing. Please be sure to constently check the Mn/DOT website for updates (See Mn/DOT Website and Contacts on page 3-34).

Variable vs. Fixed Phasing Operation Signal Heads

Traditionally, the operation of the left turn signal was considered Fixed. That is, if a protected left turn head was installed, then this signal would operate in protected operation for the entire day. It may be that a protected left is desirable for a specific time of day (i.e., heavy opposing flow is the reason for the protected operation), but this may "penalize" the other twenty-three hours of the day that do not require protected-only operation. One advantage to the FYA signal indication is that it can change the mode of operation on a time of day (TOD) basis. In summary:

- ✓ The FYA head is a "variable phasing operation" head that can operate with either protected, protected/permissive, or permissive phasing operation by time-of-day settings.
- ✓ Standard 3-section protected and 3-section permissive heads are "fixed phasing operation" heads that can only operate in one phasing operation 24 hours a day.
- ✓ Given that the FYA head can operate protected 24 hours a day, if desired, the standard 3-section protected head will soon become obsolete as there is no reason to install a 3-section protected head and not have the ability to change the phasing operation in the future.
- ✓ Standard 5-section heads are "flexible phasing operation" heads, but only with either protected/permissive or permissive operation by time-of-day settings.

Use of the Flashing Yellow Arrow Signal Head

New Signal Design

All agencies should consider using a FYA in their design of new signals with exclusive left turn lanes. However, it's still acceptable to use a 3-section protected or 5-section protected/permissive head for new signal installations. Designs should conform to the Federal and MN MUTCDs. The 2009 Federal MUTCD no longer allows a green circular permitted signal indication centered over an exclusive left turn lane (see the Federal MUTCD Section 4D.13).

Even if a left turn movement may <u>never</u> have a high enough left-turn volume to run protected/permissive, consider using a FYA head for exclusive left turn lanes as it gives flexibility in case volumes increase in the future, and it also gives a clearer message to left turning vehicles that they must yield to opposing traffic when turning left.

The incremental increase in cost of a 4-section FYA signal head is insignificant in the overall cost of the new signal. In fact, the 4-section signal head may be less expensive than the 5-section protected/permissive signal head.

Retrofit Signal Design

An existing signal with exclusive left turn lanes may be retrofitted with FYA operation. Consideration should take into account the type of cabinet, controller, loop detection, and mast arm locations when retrofitting a signal for FYA. This issue is currently under development by Mn/DOT and more information is forthcoming.

When Not to Operate a FYA Head

Under certain situations, the FYA indication should not be used as noted below, even if the 4-section FYA head is in place.

A. Opposing Left Turn Paths Conflict

- ✓ Road design will be responsible for noting on signal design plan that opposing left turns conflict by running AutoTurn and cannot be allowed to turn at the same time.

B. Very Limited Sight Distance

- ✓ Sight distance is so limited that a left turn cannot be made safely even under very low volume conditions

C. Shared Left/Through Lane(s)

- ✓ The concept of using a Flashing Yellow Arrow head on approaches with shared left-turn/through lanes is under development, but is currently only recommended for experimental use and more information is forthcoming (see the section "Mn/DOT Website and Contacts" on page 3-34 if considering this type of operation).

In addition, see the sections below regarding FYA use with pre-emption (emergency vehicle and railroad).

Yellow and All-Red Times

Yellow time for clearing the green arrow for leading or lagging left turns will be the same as the current agency standard for left-turn operation (see page 4-17).

Yellow time for clearing the FYA will be the opposing through yellow time (3.5 to 6.0 sec) as the FYA will be driven by an overlap with the opposing through phase.

When transitioning from a protected left turn to a permissive left turn in protected/permissive operations, the all-red time will be 2 seconds with the red arrow being shown.

Permissive Operation When Adjacent through Head is Red

The FYA display will allow for a permissive operation when the adjacent through head is red (see Exhibit 3-12). This was not possible with the 5-section protected/permissive head. This situation could occur if one left turn movement runs longer than the opposing left turn movement and the shorter left turn will get the permissive flashing yellow arrow while the opposing left turn is causing the adjacent through head to still be red.

Adjacent through heads may also be red when lagging lefts are used with protected/permissive operation. This is also something that wasn't possible with the 5-section protected/permissive head as it would cause a "left-turn trap" (See the discussion on "Left Turn Trapping" on page 3-22). The FYA head doesn't cause a left-turn trap because it is an exclusive head for left turning vehicles (see the topic "Flashing Yellow Arrow and the Left Turn Trap" on page 3-24). However, it is a new operation for motorists in that they will be looking for gaps while yielding on the flashing yellow arrow while the adjacent through head goes yellow due to the opposing protected/permissive lagging left. The flashing yellow arrow will continue to operate even though the adjacent head goes red and motorists will need to continue to yield to oncoming traffic.

- ✓ steady DON'T WALK indication, means that a pedestrian shall not enter the roadway in the direction of the indication.

Walk

The MN MUTCD states, "Under normal conditions, the WALK interval should be at least 4 to 7 seconds in length so that pedestrians will have adequate opportunity to leave the curb before the clearance interval is shown." Research indicates that queues (more than 24 people) requiring more than 7 seconds to discharge occur very rarely and will usually be found only in certain sections of large metropolitan areas. The minimum WALK interval under low volume (less than 10 pedestrians per cycle) conditions could possibly be lowered to 4 - 5 seconds but the importance of the inattentiveness factor should be also weighted in this decision.

Flashing Don't Walk

NOTE: The information in this section is currently being updated in the Minnesota MUTCD. See the section Pedestrian Timing (2009 Federal MUTCD) on page 4-7. It is anticipated that the MN MUTCD will adopt the Federal MUTCD requirements for pedestrian timing.

The duration of the pedestrian clearance time should be sufficient to allow a pedestrian crossing in the crosswalk who left the curb or shoulder at the end of the WALKING PERSON (symbolizing WALK) signal indication to travel at a walking speed of 3.5 feet per second to at least the far side of the traveled way or to a median of sufficient width for pedestrians to wait.

The *flashing* DON'T WALK interval is determined by the following formula:

flashing DON'T WALK = D/R

D = Distance from the near curb or shoulder to at least the far side of the traveled way or to a median of greater than 6 feet.

R = Walking rate of 3.5 feet per second assumed walking rate unless special conditions (school kids, elderly or handicapped) require a slower walking rate.

When determining the distance, consideration should be given to the pedestrian's normal walking path. Pedestrian timing should consider the pedestrian walking to the nearest pedestrian and/or vehicle indication following a marked or unmarked crosswalk.

On median divided roadways, consideration should be given to providing sufficient time to the pedestrians to cross both roadways. A pedestrian's goal is to cross the total roadway and does not expect to stop at the dividing median and wait till the next cycle. If the median is less than 6 feet wide the pedestrian should be provided sufficient time to cross both roadways as a median less than 6 feet wide is not considered a safe refuge island.

Normal walking speed is assumed to be 3.5 feet per second. This is as cited in the 2009 Federal MUTCD and will be the walking speed used in the pending update to the MN MUTCD. In selecting a walking rate, consideration must be given to the type of pedestrians, volume of pedestrians, intersection location and geometrics and overall signal operation.

Signal controllers used by Mn/DOT do not time the yellow vehicle indication concurrent with the flashing DON'T WALK. This is assuming minimum vehicle green time. The steady DON'T WALK is displayed at the onset of yellow to encourage any pedestrians still in the street to complete the crossing without delay. Because of this and a MN MUTCD Ruling No. IV-35, Pedestrian Clearance Interval Calculation, the yellow interval may be included in the pedestrian clearance time (i.e., the pedestrian clearance time is equal to flashing DON'T WALK interval plus the yellow interval). The *flashing* DON'T WALK interval could then be determined by the following formula:

flashing DON'T WALK = (D/R) - Yellow

However, the ruling also states, "Discretion should be used in utilizing the latitude afforded by Section 4E". Therefore, as a general practice, this should not be followed unless it is necessary to minimize the pedestrian timing. By subtracting the yellow interval, pedestrians may receive the steady DON'T WALK before they reach the far side of the farthest traveled lane. Engineering studies and judgment should be exercised in determining walking rates, distances and utilizing the yellow interval as part of the pedestrian clearance interval.

Pedestrian Timing Recommended Practice

At the time of the publication of this manual, the MN MUTCD was being updated. It is anticipated that the MN MUTCD will follow closely the language as found in the 2009 Federal MUTCD. Pertinent sections of the Federal MUTCD can be found on page 4-7.

For single roadways, and divided roadway with median island less than 6 feet wide and pedestrian indications on each side, the pedestrian will be provided time to cross from the near side curb or shoulder to the far side of the traveled way.

WALK = 7 seconds

(this may be reduced to 4 seconds if it is necessary to minimize pedestrian timing considering the other factors)

flashing DON'T WALK = (D/R)

(time should not be less than WALK time and the time may be reduced by the yellow interval if it is necessary to minimize pedestrian timing considering other factors)

D = Distance from the near curb or shoulder to at least the far side of the traveled way.

R = Walking rate of 3.5 feet per second is the assumed walking rate unless special conditions (school kids, elderly or handicapped) require a slower walking rate.

Divided Roadways

A divided road is one with a median island over 6 feet wide **and includes a pedestrian pushbutton in the median**. If a pushbutton is not in the median, the recommended practice above must be used (i.e., the pedestrian clearance interval must cross them completely from near side curb to far side curb).

Option 1 - Cross to Median Only

(Pedestrian indications present)

The WALK and *flashing* DON'T WALK should be determined as above. The crossing distance should be determined by using the longest distance from the curb or shoulder to the median. The pedestrian will be provided time to cross to the median on one cycle and time to cross the other side on the next cycle when the pedestrian push button is activated.

Option 2 - Cross Completely

In order for the pedestrian to cross the total roadway, the WALK indication must take the pedestrian past the median island before the flashing DON'T WALK is displayed. If the flashing DON'T WALK is displayed before the pedestrian reaches the median island, the pedestrian should stop at the median island and wait till the next WALK indication. The following special timing should allow the pedestrian to cross both roadways.

This timing also provides for a pedestrian that may start to cross the first roadway at the end of WALK. This pedestrian is provided enough flashing DON'T WALK to reach the median island and finish the crossing on the next WALK indication.

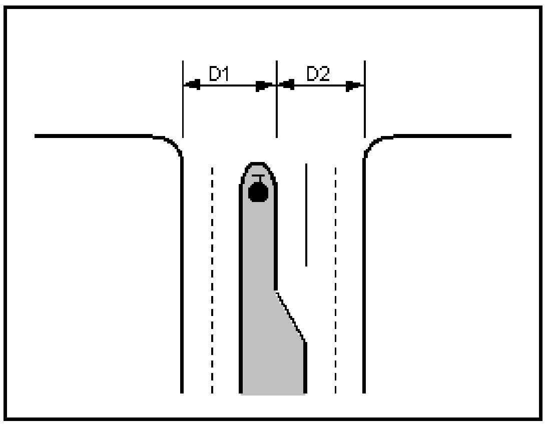
WALK = D1/R

flashing DON'T WALK = (D2/R)

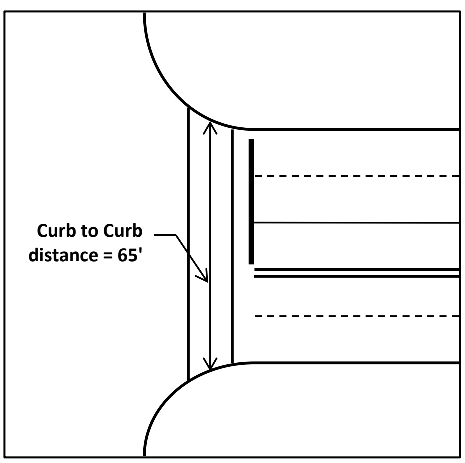
(this time may be less than the WALK time and the time may be reduced by the yellow time if it is necessary to minimize the pedestrian timing considering other factors)

Refer to Exhibit 4-2 for D1 and D2 determination.

Exhibit 4-2 Pedestrian Crossing Distances



***Example**:* Consider the intersection shown below.



Assume a walking speed of 3.5 feet per second with no special pedestrian requirements.

The pedestrian clearance would then be, FDW = 65 feet / 3.5 feet per second = **19 seconds**

Pedestrian Timing (2009 Federal MUTCD)

The following information is from the 2009 Federal 2009 MUTCD. The latest information can be found by visiting http://mutcd.fhwa.dot.gov/.

SUM OF CRITICAL VOLUME	2 PHASE	5 PHASE	8 PHASE
700	45	60	90
800	60	75	105
900	60	75	105
1000	75	90	105
1100	75	90	105
1200	90	105	120
1300	105	120	135
1400	120	135	150
1500	135	150	165
1600	150	165	180
1700	165	180	180
1800	180	180	180

Phase Change Interval

The MN MUTCD states that the exclusive function of the steady yellow interval shall be to warn traffic of an impending change of right-of-way assignment. The yellow vehicle change interval should have a range of approximately 3 to 6 seconds. Generally the longer intervals are appropriate to higher approach speeds. The yellow vehicle change interval should be followed by a short all-way red clearance interval, of sufficient duration to permit the intersection to clear before cross traffic is released.

Minnesota Traffic Laws state that vehicular traffic facing a yellow indication is warned that the related green movement is being terminated or that the red indication will be exhibited immediately thereafter when vehicular traffic shall not enter the intersection. Therefore, the yellow and all-red intervals advise that the green interval is about to end and either;

- ✓ permits the vehicle to come to a safe stop at the stop line, or
- ✓ allows vehicles that are to near the intersection to stop or safely clear the intersection.

Yellow Timing

The following formulas may be used to determine the yellow time. This is based on the Institute of Transportation Engineers equation for yellow clearance interval.

$$Y = t + \frac{1.467\,v}{2(a + 32.2g)}$$

English

Y = Yellow Interval in seconds

t = perception-reaction time, assumed to be 1 second

v = posted speed, miles per hour

a = deceleration rate, assumed to be 10 feet/sec^2

g = + or - grade of approach in percent/100

Exhibit 4-4 Yellow Timing Values

Posted Speed	Percent Grade							Mn/DOT
	+3	+2	+1	Level	-1	-2	-3	
25	2.7	2.7	2.8	2.8	2.9	3.0	3.0	**3.0**
30	3.0	3.1	3.1	3.2	3.3	3.4	3.4	**3.5**
35	3.3	3.4	3.5	3.6	3.7	3.7	3.8	**4.0**
40	3.7	3.8	3.8	3.9	4.0	4.1	4.3	**4.0**
45	4.0	4.1	4.2	4.3	4.4	4.5	4.7	**4.5**
50	4.4	4.5	4.6	4.7	4.8	4.9	5.1	**5.0**
55	4.7	4.8	4.8	5.0	5.2	5.3	5.5	**5.5**
60	5.0	5.1	5.1	5.4	5.6	5.7	5.9	**6.0**
65	5.4	5.5	5.5	5.8	5.9	6.1	6.3	**6.0**

Yellow Interval for Left Turns

Mn/DOT will often use 25 mph (or a value of 3.0 seconds) for left turns. If timing a single point urban interchange (SPUI) or an intersection with a wide, sweeping radius, assume a speed of 35 mph.

All Red

The following formulas may be used to determine the red time. This is based on the Institute of Transportation Engineers (ITE) equation for red clearance interval.

$$R = \frac{w + L}{1.467v}$$

English

R = All red clearance interval in seconds

w = width of intersection, stop line to ~~center~~ the end of the farthest conflicting lane

l = length of vehicle, assumed to be 20 feet

v = posted speed in mile per hour

Exhibit 4-5 All Red Times

Posted Speed	Width of Intersection								
	30	40	50	60	70	80	90	100	110
25	1.4	1.6	1.9	2.2	2.5	2.7	3.0	3.3	3.5
30	1.1	1.4	1.6	1.8	2.0	2.3	2.5	2.7	3.0
35	1.0	1.2	1.4	1.6	1.8	1.9	2.1	2.3	2.5
40	0.9	1.0	1.2	1.4	1.5	1.7	1.9	2.0	2.2
45	0.8	0.9	1.1	1.2	1.4	1.5	1.7	1.8	2.0
50	0.7	0.8	1.0	1.1	1.2	1.4	1.5	1.6	1.8
55	0.6	0.7	0.9	1.0	1.1	1.2	1.4	1.5	1.6
60	0.6	0.7	0.8	0.9	1.0	1.1	1.3	1.4	1.5

These formulas are general and should only be used as a guide. Other factors at an intersection (such as approach grades, visibility, truck traffic and local traffic characteristics) should be considered. It is important that approach grades and truck traffic are considered in determining the yellow and red intervals. The yellow interval must not be too short (causing quick stops and/or red violations) nor too long (causing regular “driving of the yellow”).

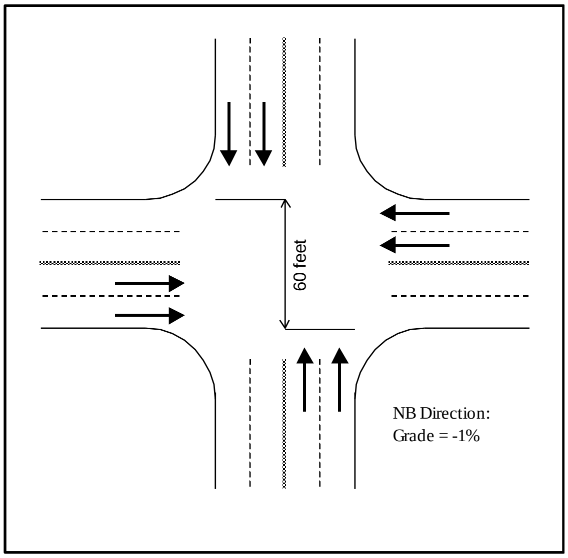
The all-red should be in the range of 1 to 5 seconds.

All Red for Left Turns

Mn/DOT will often use 25 mph for left turns. If timing a single point urban interchange (SPUI) or an intersection with a wide, sweeping radius, assume a speed of 35 mph.

The width of the intersection, w, for a left turn is commonly determined from a scaled intersection drawing. This distance (w) is measured along the path of the left turn vehicle from the stop to the end of the farthest conflicting lane.

Example*:* Consider the intersection shown in the figure below.



Assume the following:

t = 1.0 seconds

v = 45 mph

a = 10 feet per second

l = 20 feet

g = -1 percent

$$Y + R = 1.0 + \frac{1.467\,(45)}{2\{10 + 32.2(-0.01)\}} + \frac{60 + 20}{1.467\,(45)}$$

Y + AR = 1.0 + 3.41 + 1.21 = 5.62 seconds

Use,

Yellow = 4.4 seconds and All Red = 1.2 seconds

5. COORDINATION CONCEPTS

Cycle Length

The cycle length is the total time to complete one sequence of signalization around an intersection. In an actuated controller unit, a complete cycle is dependent on the presence of calls on all phases. In a pre-timed controller unit (see page 3-5) it is a complete sequence of signal indications.

The equation presented on page 3-1 is for isolated pre-timed signal locations only. A detailed network analysis should be performed using a software package such as Synchro or TRANSYT for cycle length determination in a coordinated system. The use of computer models allows for multiple iterations of varying cycle combinations to determine the optimum signal timing parameters.

Signal Timing Intervals and Splits

The sum of the green, yellow, and all red intervals typically defines an individual phase **split**. A split is then the segment of the cycle length allocated to each phase that may occur (expressed in percent or seconds).

The primary considerations that must be given to vehicle split times are as follows:

- ✓ The phase duration must be no shorter than some absolute **minimum time**, such as five to seven seconds of green plus the required clearance interval. If pedestrians may be crossing with this phase, their crossing time must also be considered and included in the minimum phase length.
- ✓ A phase must be long enough to avoid over saturating any approach associated with it. Too short a time will cause frequent **cycle failures** where some traffic fails to clear during its phase.
- ✓ A phase length must not be so long that green time is wasted and vehicles on other approaches are delayed needlessly.
- ✓ Phase lengths should be properly designed to efficiently balance the cycle time available among the several phases, not just "equitably" between, say, north-south and east-west.

Offset

The **offset** is the time relationship, expressed in seconds or percent of cycle length, determined by the difference between a fixed point in the cycle length and a system reference point.

Proper determination and application of intersection offsets provide for the efficient movement of platoons through multiple intersections during the green indication. Properly timed offsets can significantly reduce delay and improve driver satisfaction with the system timing.

Progression Measures

All of the coordinated system analysis models have some MOEs associated with the green bands in the Time-Space Diagram (TSD). In fact some of the models utilize progression MOEs as a component of the optimization objective function. The more common of these MOEs are introduced below.

Bandwidth Efficiency

PASSER II uses this measure as its objective function. This is simply the proportion of the cycle that is included in through green bands, extending the entire length of the system. A simple TSD showing perfect time-space progression illustrates the concept. Mathematically, efficiency is calculated as:

$$E = \frac{B_f + B_r}{2C}$$

Comparisons between "before" and "after" data should be performed for:

- ✓ System-wide measures-of-effectiveness output from the simulation models, and
- ✓ Field-collected measures such as travel time.

Also, refer to Chapter 4 for Mn/DOT's procedure to time a traffic control signal.

Traffic Signal Control Systems

System Concept

A system may be defined as an arrangement or combination of interacting or interdependent parts which form a unified whole serving a common purpose. The system concept as related to traffic signal control includes the methods, equipment, and techniques required to coordinate traffic flow along an arterial or throughout an area.

System Objective

The major objective of a traffic control system is to permit continuous movement and/or minimize delay along an arterial or throughout a network of major streets. This involves the selection, implementation, and monitoring of the most appropriate operational plan. Basically, a traffic signal system provides the appropriate and necessary timing plans for each intersection in terms of individual needs as well as the combined needs of a series of intersections.

Relationship of Timing Plans to Traffic Control

In the system concept a timing plan is defined by a combination of control parameters for one or more intersections based upon an analysis of demand. Timing plans can be provided as a function of equipment at the local intersection, the central control point, or both. Timing plans consist of:

1. *A system Cycle*. A specific cycle length is imposed throughout the system covered by the timing plan.
2. *Split*. All intersections in the system have defined splits which are the apportionment of the cycle to the various phases present at that intersection.
3. *Offset*. Each intersection has a unique offset. The offset is the relationship of the beginning of the main street green at this intersection to a master system base time. Offsets are generally expressed in seconds. Properly established offsets along a street can potentially provide for smooth traffic flow without stopping.

Basis of Selecting Timing Plans

The selection parameters which define timing plans include:

1. *Historic Data* Time of Day information compiled from traffic counts to reflect traffic volumes for specified time of day (morning peak, midday, afternoon peak, etc.) and day of week.
2. *Current Data* Real time on-street volumes from traffic detection equipment.
3. *Special Data* Special events, emergency route assignment, special right-of-way preemption (fire equipment, ambulances, buses, etc.)

Types of Traffic Signal Control Systems

Many combinations of methods, equipment, and techniques can comprise a traffic signal control system. Generally, these systems fall into the following basic types.

Time Based Coordinated (TBC) System

This form of coordination utilizes non-interconnected controllers with auxiliary devices called time based coordinators. These devices use the power company supplied frequency to keep time very accurately. Various timing plans can be established with time of day and day of week plan changes. Since all intersections use the same power source, the time-based coordinators provide coordination without physical interconnection.

Global Positioning System (GPS) receivers have been used for several years to provide a clock sync to ensure TBC is maintained.

Interconnected Pre-timed System

This type of system was originally developed for electromechanical controllers, but can also be used with some of the newer controllers. Local intersections are physically interconnected (usually by a 7-wire cable) to ensure coordinated operation. The system provides automatic re-synchronization should a signal go “out of step”. The number of timing plans is a function of the number of dials and the number of offsets and splits per dial; the most common system consists of a three-dial, three-offset, one-split combination. Timing plans are normally selected by a time clock or time dependent programming device. The local controller for one intersection may act as master controller for the system.

Traffic Responsive System

Basically, this is an interconnected system utilizing a master controller for pattern (Cycle/offset/splits) selection. Traffic detectors are used to sample directional volumes and detector occupancy. Volume and occupancy metrics determine which of the available patterns is selected (i.e., inbound, outbound, or average) based on predetermined thresholds. The master controller may be an analog or a digital computer.

Interconnected Actuated Systems

Generally a small system with a master-slave relationship (i.e., two or more fully-or semi-actuated local controllers with one acting as system master and controlling cycle length for the other controllers). Offset capability is limited. A variation of this system uses a system master, coordinating units, and local actuated controllers. The master may be traffic responsive or combination of time clocks.

Traffic Adaptive System

Traffic adaptive systems perform “real-time” adjustments to the cycle length, splits and offsets in response to traffic demand. Traffic adaptive systems require extensive detection inputs. Complete and accurate traffic flow data must be gathered, processed and communicated to the central computer.

Advanced Traffic Management Systems (ATMS)

ATMS are capable of monitoring and controlling thousands of intersection controllers using state of the art architecture like TCP/IP and NTCIP. ATMS offer complete traffic and data management including real time field reporting for multiple users over distributed local and wide area networks and remote access.

ATMS offer scalable software solutions that support a range of users including:

- ✓ School zone flashers
- ✓ Freeway management
- ✓ CMS, VMS, DMS
- ✓ CCTV surveillance

- ✓ HOV lane control
- ✓ Reversible lane control signals
- ✓ Real-time split monitoring and time space reporting
- ✓ Incident detection
- ✓ Light rail control systems
- ✓ Transit priority systems
- ✓ 1.5 generation timing plan development using Synchro or PASSER
- ✓ 2.0 Generation control (Traffic Responsive and Traffic Adaptive)
- ✓ Integrated video detection
- ✓ Real time preemption log retrieval

Time-Space Diagrams

These are prepared to determine the offsets on individual intersections.

A time-space diagram is a chart on which distance is plotted against time. The location of each signalized intersection is plotted along one axis. At each such point the signal color sequence and split are plotted in such a manner that through bands are available for each direction of traffic flow. The slope of the through band (distance divided by time) is the speed of progression, and width indicates the time available for a platoon traveling through systems.

For two-way streets, the diagram is usually prepared to give equal consideration to each direction of travel. Where appropriate types of program controllers are available, separate peak-hour diagrams are prepared for streets carrying heavy directional peak volumes; these will favor travel in the peak direction. The cycle length may be changed (for the entire system) and the offsets are changed through the use of time clocks in the master controller. Sample time-space diagrams for off-peak and evening peak periods are shown in the figures below.

When a coordinated system is established for a certain speed during all periods of the day, supplemental signs may be erected which inform the driver of that speed.