Traffic Signals and Signal Timing

1. Introduction

Traffic signals are the most commonly analyzed form of intersection control in many countries. They may not be the most common form of control overall, as so many low-volume unsignalized intersections exist in neighborhoods, subdivisions, and industrial parks. But signals are still the most common control form at intersections and along corridors that are likely to experience congestion due to high traffic demands. This may change in the future, as alternative forms of intersection control such as roundabouts are becoming increasingly popular (at the time of this writing, France has more than 20,000 roundabouts). But for now, one might say that traffic signals are still the "bread and butter" of most traffic operations engineers.

The following sections provide an introduction to signal warrants for deciding when to install a signal, the (hardware) components of a signal, a detailed walk through the signal timing process, and basic signal coordination concepts. Those interested in additional information on traffic signals are referred to the HCM for analysis procedures, and other resources for information about signal types, timing, and hardware, including the Signal Timing Manual4 (Urbanik et al., 2014) and the Traffic Detector Handbook (FHWA, 2006b; Klein et al., 2006).

Signal Warrants and MUTCD

The Manual on Uniform Traffic Control Devices (MUTCD) is a set of guidelines and standards published by the Federal Highway Administration (FHWA, 2009) for the installation and maintenance of traffic control devices. The MUTCD is divided into nine parts as follows:

- Part 1: General—Contains introduction and overview of MUTCD.
- Part 2: Signs—Contains guidance on a variety of signs in the categories of regulatory signs, warning signs, guide signs on surface streets and expressways, toll road signs, manage lane signs, and other specialized signs such as recreation and cultural interest areas.
- Part 3: Markings—Contains guidance for the use of pavement markings for all aspects of the roadway.
- Part 4: Highway Traffic Signals—Contains information on the installation and placement of traffic signals.
- Part 5: Traffic Control Devices for Low-Volume Roads.
- Part 6: Temporary Traffic Control—Contains guidance for signing and marking in work zones on surface streets and interstates.
- Part 7: Traffic Control Devices for School Areas
- Part 8: Traffic Control for Railroad and Light Rail Transit Grade Crossings

• Part 9: Traffic Control Devices for Bicycle Facilities In the language of the MUTCD, the manual commonly distinguishes between "shall" conditions (actual requirements to implement a traffic control device), "should" conditions (suggestion to implement a traffic control device, but not required), and "may" conditions (option or allowable to install a traffic control device).

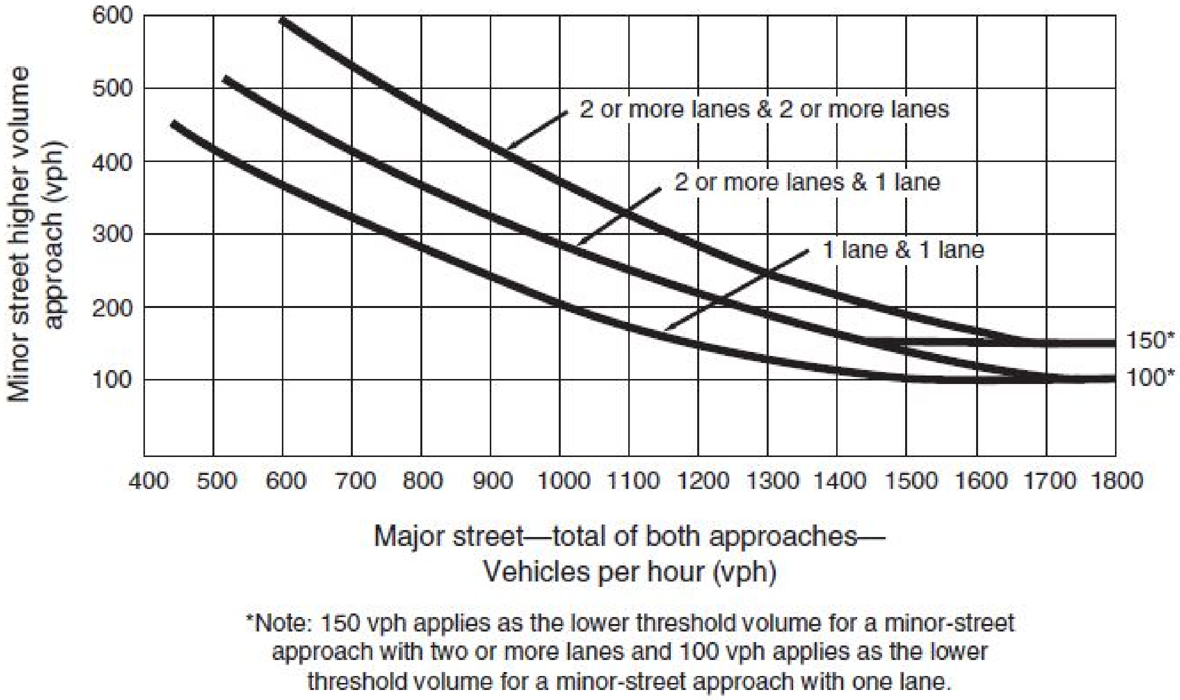
One of the more commonly used aspects of the MUTCD for traffic operational analysis are the signal warrants included in Part 4 of the manual.

<u>There are a total of nine signal warrants</u>:

• Warrant 1, eight-hour vehicular volume
• Warrant 2, four-hour vehicular volume
• Warrant 3, peak hour
• Warrant 4, pedestrian volume
• Warrant 5, school crossing
• Warrant 6, coordinated signal system
• Warrant 7, crash experience
• Warrant 8, roadway network
• Warrant 9, intersection near a grade crossing

Warrants are intended to be used as guidance to decide when it is appropriate to install a traffic signal. Warrants are not requirements, such that even if one or more warrants are met, a traffic signal does not necessarily have to be installed, but is further deemed as an appropriate treatment. If a location or a proposed location does not meet any of the nine warrants, a traffic signal is said to be "unwarranted" and is typically not an appropriate traffic control device for the location under study.

As an example, Figure below presents the peak-hour volume warrant for vehicular volumes at a signalized intersection. Based on the total major street volume (total of both approaches) and the higher minor street volume, a traffic signal is warranted if the combined volume lands above the lines drawn in the figure. Overall, three lines are shown for different roadway cross sections for major and minor street. This and other warrants can be reduced to 70% for small towns (less than 10,000 population), as well as for high-speed roadways (depending on warrant, greater than 35 or 40 mph). A second MUTCD example, Figure below, shows both the four-hour and peak-hour pedestrian signal warrant thresholds from Warrant 4. Similarly, a pedestrian signal is warranted when the combination of vehicular volumes (x-axis) and pedestrian volume (y-axis) exceeds the line drawn.



<u>Figure:</u> MUTCD peak-hour vehicular volume warrant.

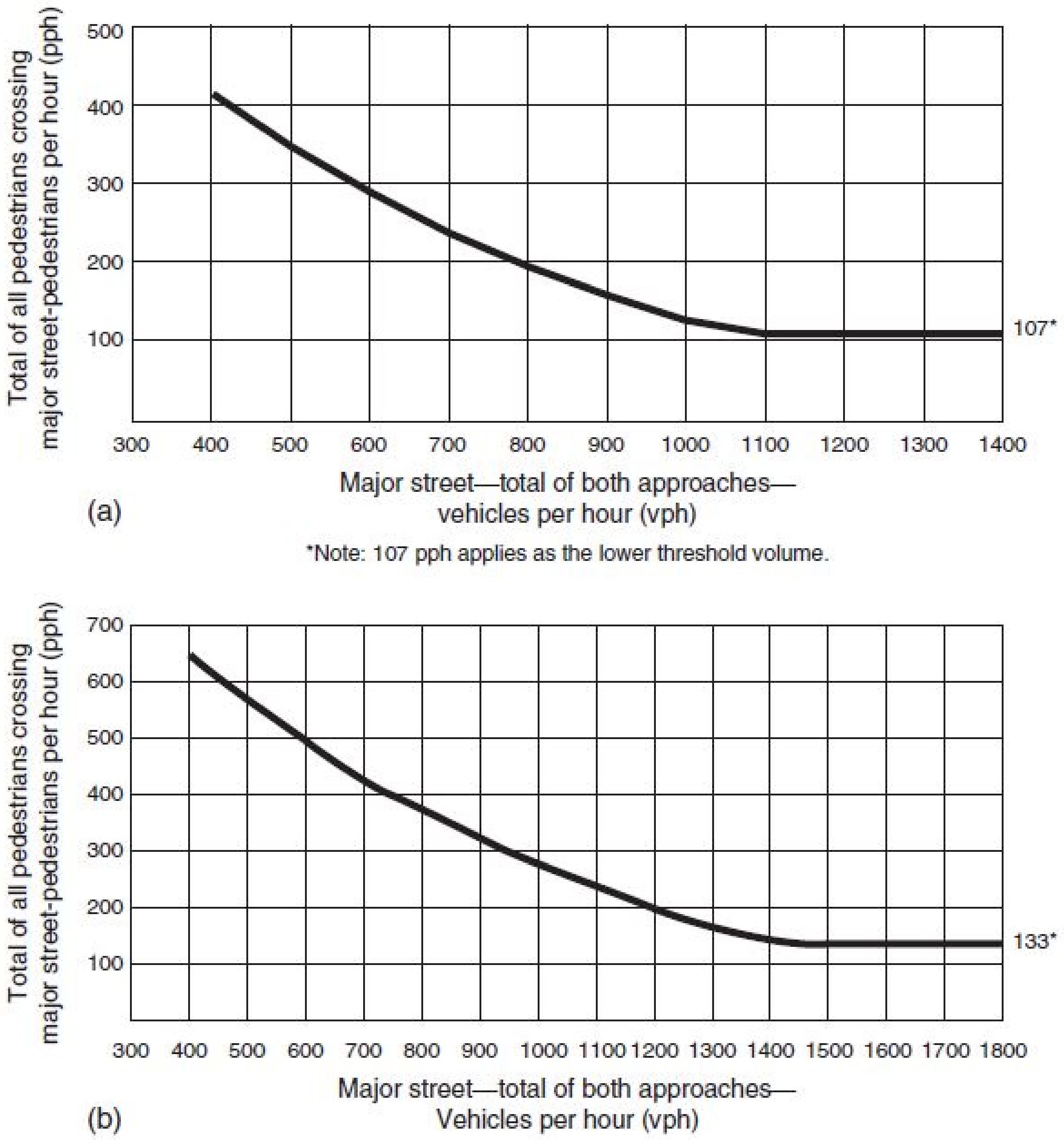


Figure: MUTCD pedestrian volume warrant. (a) Four-hour volume, and (b) peak hour volume. Source: http://mutcd.fhwa.dot.gov/pdfs/2009r1r2/pdf_index.htm.

Identify Left-Turn Treatments for All Intersection Approach Legs

The first question in signal timing is whether left-turn treatments for each approach are: permissive, protected, or a combination protected/ permissive mode.

In general, a protected left turn gives higher capacity for that left-turn movement, as left-turning vehicles don’t have to yield to the opposing through traffic as in the case of permissive phasing. However, a protected left turn takes time away from the (often heavier) through movements, and therefore should only be used if absolutely necessary.

As a general rule of thumb, left turns should be protected for high volume left-turning movements combined with high volumes of opposing through traffic. A useful calculation in this regard is to check the cross product of the two traffic streams. From this calculation, left turns should be protected if left-turn demand3opposing through is:

• 50,000 for 1 opposing lane
• 90,000 for 2 opposing lanes
• 110,000 for 3 opposing lanes

There are other reasons to protect left-turning movements, including:
• Sight distance is restricted for left turns to safely judge gaps in opposing traffic.
• Opposing vehicle speed is 45 mph or higher resulting in potentially high-severity collisions in the event of a crash.
• Presence of more than one left-turn lane, making gap selection difficult.
• Having a history of left-turn collisions under permissive control.
Protected/permissive control can be used to further increase the capacity of a protected left-control movement, or to shorten the duration of the protected phases, provided that none of the aforementioned safety considerations apply. For the purpose of the signal timing process, it is easiest to initially assume either protected or permissive control.

Identify Lane Groups for Each Approach

Lane groups are defined as one or more lanes on an approach that operate together under the same phase. Multiple through movements, for example, share the same lane group, as they are processed by the same phase. But having an exclusive left-turn lane allows that movement to be processed through its own phase, and it is therefore assigned its own lane group. The same holds for exclusive right-turn lanes. Any shared lanes (left/through, right/through, or left/through/right) are also assigned a separate lane group. The relationship between movements and lane groups is illustrated in Table below.

Table: Translating movements into lane groups

Number of lanes	Movements by lanes	Lane groups (LG)
1	Left, through, & right:	LG 1:
2	Exclusive left:	LG 1:
	Through & rights:	LG 2:
2	Left & Through:	LG 1:
	Through & right:	LG 2:
3	Exclusive left: Exclusive left:	LG 1:
	Through: Through:	LG 2:
	Through & right:	LG 3:

Determine Lane Group Traffic Data

Next, the analyst determines traffic data for each lane group, including adjusted volumes, saturation flow rates, and volume-to-saturation flow ratios (v/s). First, hourly volumes are adjusted to account for peak-hour factor and heavy vehicles.
From the volumes and saturation flow rates, the analyst computes the ratio of volume flow to saturation flow rate for each lane group. This is denoted as the v/s ratio. The maximum lane group v/s ratio for phase i is denoted as the critical v/s. The phase lane group with the highest v/s ratio is referred to as the phase's critical lane group.

Develop the Desired Phasing Plan for Intersection

Next, the analyst selects the phasing plan for the intersection, or tests different options for combining movements into phases, as well as sequencing different phases. This step requires an understanding of phasing options and practice. A useful approach to determine the optimum phase sequence is to try and minimize the sum of the critical v/s ratios.
Conceptually, each phase duration will be driven by one critical lane group, which is the one with the highest volume-to-saturation flow rate ratio. Summing these v/s ratios provides an estimate of the total congestion level of the intersection (before accounting for lost time).
Henceforth, any phasing scheme that can reduce this critical sum can reduce the congestion level and therefore improve performance. As a general rule, it is desirable to combine lane groups with similar v/s ratios in the same phase if at all possible, to make most efficient use of the allocated time (driven by the lane group with the highest v/s ratio).
To facilitate this step, it is helpful to think of phasing in relation to two rings with up to eight phases, as illustrated in the ring-barrier diagram shown in Figure below. In reality, a signal controller can have more than four rings and more than eight phases, but the following example represents the most common base configuration for traffic signals.

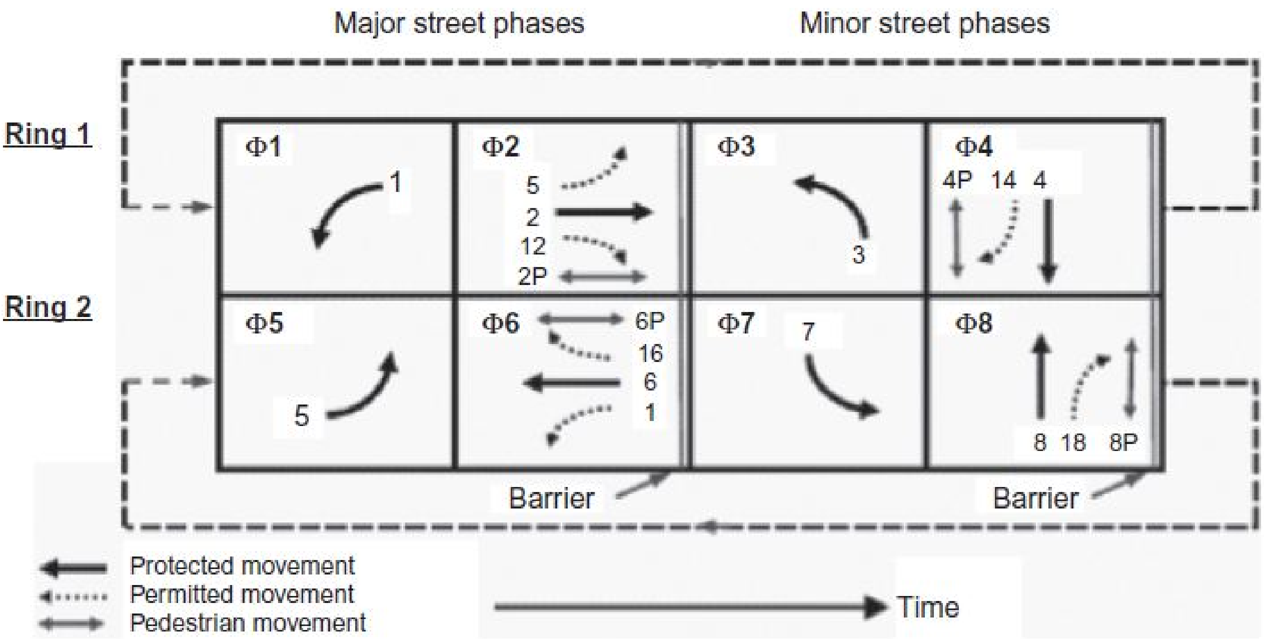


Figure: Dual-ring structure and sample movements. Source: TRB, 2015.

The dual-ring concept shows the movements within each phase and how they relate to all other movements. All movements on the major street (in this case east-west movements) must be completed before the movements on the minor street can start (north-south street in the example).

This is called crossing the barrier. Previous figure is an example of a standard 8-phase signal. The typical numbering convention for traffic signals is illustrated in Figure below. The major street through movements (east-west in example here, but could be north-south) are assigned numbers 2 and 6,with the major street left turns adjacent to them being numbered 5 and 7,respectively. The side-street through movements are numbered 4 and 8,with the adjacent left turns being assigned numbers 7 and 3, respectively. It emerges that all through movements are even numbered, while left turns are odd numbered. Similarly, adjacent through and left-turn numbers add up to 7 on the main line and 11 on the side street (sometimes referred to as the “7-11 rule”). Right turns are assigned movement numbers 12, 14, 16, and 18, adding 10 to the respective adjacent through movement. Finally, pedestrian movements are assigned numbers concurrent with the through movements they are associated with (e.g., pedestrian phase 4P runs concurrent with vehicle through movement 4).

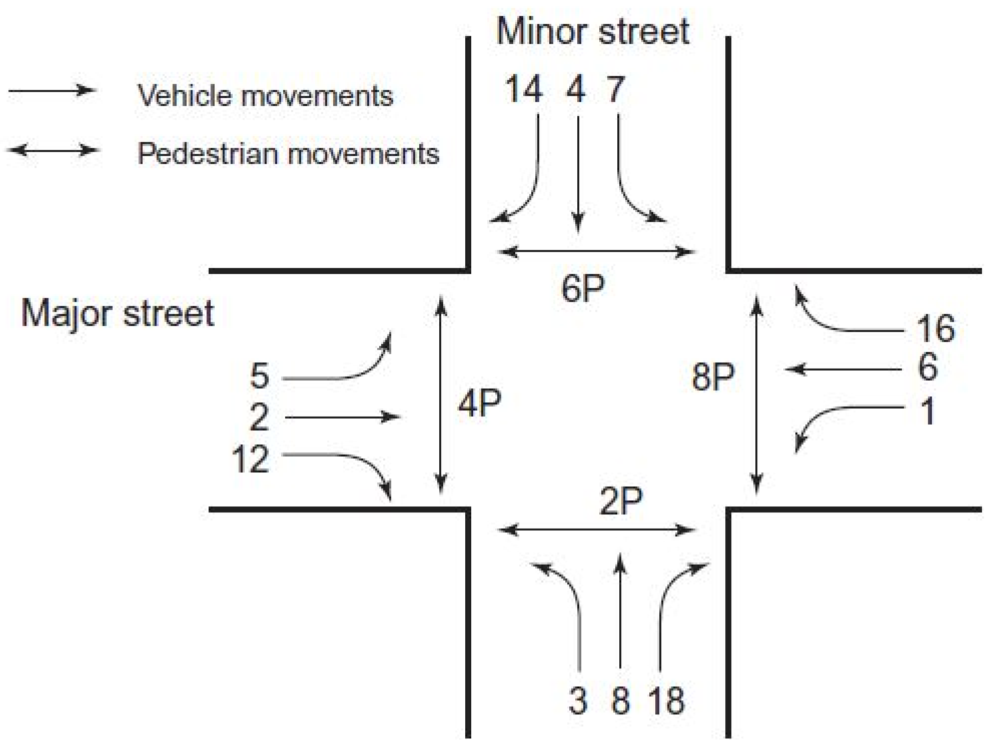


Figure: Movement numbering convention for traffic signals.

The ring-barrier diagram in previous figure is only one example of a traffic signal phase sequence with all left turns protected and leading the through movements. Many variations exist that result from lagging one or more left turns or running left turns in permissive mode. A specialized phase sequence referred to as split phasing runs the side-street movements sequentially with a phase for movements 3 and 8 being followed with a phase for movements 7 and 4. Split phasing is common when a heavy left turn exists on a minor approach, but the lane assignment is such that left turns cannot be protected (i.e., approach has a shared through/left lane). Regardless of the phase sequence, step 4 of the signal timing process sums the critical v/s ratios for each phase to determine the optimum phase sequence.
At this point in the timing process, the sum of critical v/s ratio should preferably be on the order of 0.8_0.9 or less, as lost time has not yet been accounted for. If the sum of critical v/s ratios approaches 1.0, it is highly unlikely that the timing plan will result in adequate performance, once lost times due to clearance and change intervals have been incorporated into the cycle.

Calculate Required Yellow and All-Red Times

When transitioning from a green indication of one movement to a green indication of a conflicting movement, a change and clearance interval is needed to assure that this transition happens in a safe manner. Generally, this transition includes a yellow time and an all-red time.
The yellow time (Y) is timed to provide dilemma zone protection to any approaching driver. The dilemma zone refers to a region in the approach to a traffic signal where the driver is too close and too fast to come to a stop before the signal (when seeing it transition from green to yellow).
The change interval is timed long enough to allow a driver to first react to the changing signal (perception-reaction time), and then to either safely come to a stop before the signal stop bar or to have sufficient time to proceed through the length of the intersection before transitioning to the phase for the next movement. Similarly, the all-red (AR) time is timed to allow a vehicle that didn't have time to break and that enters the intersection at the very moment the signal transitions from yellow to red.
Mathematically, the clearance interval (CI) is calculated as:

CI=Y+AR, or more precisely as shown in Eq. below:

$$CI = t_{PR} + \frac{S_0}{2 \times (a + Gg)} + \frac{W + L}{S_0}$$

where:
CI=change interval (s).
t_{PR} =perception-reaction time (s).
S_0=initial vehicle speed (ft/s).
a=vehicle deceleration rate (default is 11.2 ft/sec2).
G=approach grade (%).

g=gravitational acceleration (32.3 ft/sec2).
W=width of the intersection in direction of travel (ft).
L=length of vehicle (default is 20 ft).

The duration of the yellow interval should be greater than or equal to the sum of the first two terms in previous equ., with the all-red time greater than or equal to the third term.

Determine Lost Time Per Phase and Lost Time per Cycle

The lost time per phase (l) is typically 3-4 s as observed in the field. It is made up of start-up lost time (2.0 s) plus clearance lost time (1-2 s). A common lost time of 4 s per phase is a typical default used by many agencies. The lost-time concept and relationship to the green (G), yellow (Y), and red (R) indication for each phase split is illustrated in Figure below.

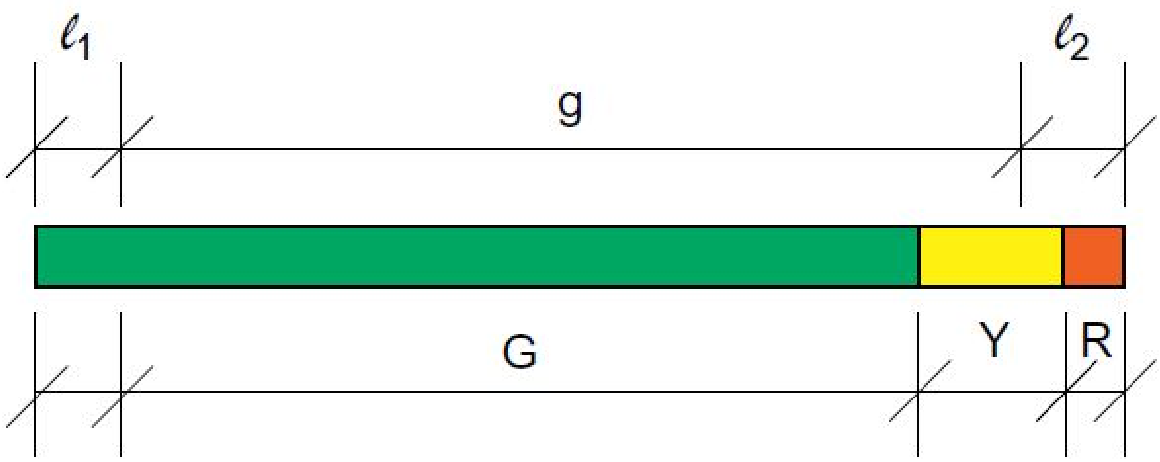


Figure: Illustration of lost time.

A phase split is made up of the sum of G1Y1R. As shown in the figure, after subtracting the start-up lost time (l_1) and end lost time (l_2), the remaining time is referred to as the effective green time, g. The effective green time is the time during which vehicles actually move for the given phase, and it is principally linked to the movement capacity. Notice also, that the effective green extends into the yellow indication, recognizing that some vehicles will be proceeding into the intersection during that time.
For the purpose of signal timing calculations, the total lost time per phase (l) is the sum of the individual lost times for each critical phase as follows:

$$\ell = \ell_1 + \ell_2$$

The total lost time per cycle (L) is the sum of the individual lost time for all critical phases. This sum should consider any overlaps, which are movements that are active in more than one phase. If a critical movement is shown in two successive phases, the lost time only applies once at the end of the (combined) phase indication.

Select a Target Volume-to-Capacity Ratio (Xc)

With lost times calculated, the analyst needs to select a target volume-to capacity ratio, X_c. Conceptually, an intersection designed to X_c=1.0 would be likely to have the perfect amount of time for each movement based on the predicted average traffic volume levels. However, as traffic volumes are not constant from cycle to cycle, the actual arrivals are expected to be lower and, more importantly, higher in some cycles. As such, it is good practice to not design a signal for operating at (average) capacity, but rather to incorporate a 10_15% safety margin. As such, a target X_c in the range of 0.85-0.90 is typically recommended for pretimed control, although values as high as 0.95 can work for some actuated intersections.

Estimate the Cycle Length

With the target X_c ratio and the sum of critical v/s ratios, the following equation can be used to estimate the cycle length for the intersection.
For this method, a desired intersection critical v/c ratio, X_c, must be specified, and entered into the Equation below to solve for cycle length, C. This becomes the trial cycle length because it will have to be checked against pedestrian requirements if they exist . The typical acceptable range for C is 40-180 s, with a general preference for shorter cycle lengths. The resulting cycle length should be rounded to the next highest 5 s for cycle lengths less than 80 s or to the next highest 10 s for cycle lengths greater than 80 s.

$$C = \frac{L(X_C)}{X_C - \sum \left(\frac{v}{s}\right)_i}$$

where:
C=cycle length (s).
L=total lost time per cycle (s).
PX_c=target v/c ratio.
$(v/s)_i$ =sum of critical v/s ratios.

Note that X_c is a great measure of the spare capacity at an intersection. An X_c of 0.80 means there is about 20% spare capacity with adjustments in signal timing and cycle length to accommodate additional traffic volumes. X_c is usually 0.80-0.90 for pretimed or semiactuated signals and 0.90-0.95 for actuated signals. If your choice of X_c results in an unacceptable cycle length, increase it and try again.

Alternatively, Webster’s optimum cycle length equation can be used as follows:

$$C_0 = \frac{1.5L + 5}{1 - \sum \left(\frac{v}{s}\right)_i}$$

where:
C_0=Webster’s optimum cycle length (s).
(all other variables are as defined previously)

Calculate Total Effective Green Time Available per Cycle

From the cycle length and total lost time, the total available effective green time per cycle can readily be estimated as C-L.
This is the total amount of time in each cycle that is available for traffic to move through the intersection. For example, if a signal has a cycle length of 120 s with four critical phases, each with a lost time of 4 s, the total available green time is
120-16=104 s. Expressed as a proportion of time, due to lost time the signal only provides 104/120=0.87, or 87% of the hour for vehicles to actually move through the intersection.

Accordingly, any sum of critical v/s ratios from step 4 that are greater than 0.87 in this case, would not be able to be processed through this signal under the selected timing plan and cycle length. This is a useful check before proceeding further with the computations.

Distribute Effective Green Time across All Phases

From the total green time, the analyst can now allocate the effective green time (g_i) to each phase based on its critical v/s. If the available movement time for all phases is C-L, the effective green time per phase is estimated as:

$$g_i = (C - L)\frac{\left(\frac{v}{s}\right)_i}{\sum \left(\frac{v}{s}\right)_i}$$

where:
g_i=effective green time for phase i (s).
(all other times are as defined previously)

Calculate Actual Green Time per Phase

Next, the actual green time per phase (G) is calculated. This is the actual duration of the green indication that is visible to the driver, and also programmed into the signal controller. It is calculated under consideration of the clearance interval (CI=Y+AR) and the start and end lost times ($l=l_1+l_2$). As illustrated in previous figure, the following relationship holds:

$$G + Y + AR = g + l_1 + l_2$$

This yields the following relationship for the actual green time G_i for phase i:

$$G_i = g_i - CI_i + l_i = g_i - (Y + AR) + (l_1 + l_2)$$

This equation is sometimes also expressed in terms of the extension of effective green time, e, which is defined as e=Y+AR- l_2. In this case, the actual green time is calculated as:

$$G_i = g_i + l_i - e$$

Note that it is common for major street movements to have a green time of at least 15 s, and minor street movements of at least 7 s. So while it is generally desirable to keep cycle lengths as low as possible, a slight increase in cycle length may be needed to assure that each G_i exceeds these minimum values.

Check Pedestrian Clearance Time Requirements

As the final step in signal timing, a check for pedestrian clearance times needs to be performed. Pedestrian movements are accommodated at many intersections, and are often needed to assure that pedestrians can get across the street safely and efficiently. Pedestrian phases consists of two intervals: First, the walk interval is intended to get pedestrians off the sidewalk and into the street. It typically has a minimum time of 5_7 s. Second, the flashing don’t walk interval is timed long-enough to assure that a pedestrian that steps into the roadway at the end of green can safely make it across the intersection.

The MUTCD requires that the flashing “don’t walk” phase be calculated as a function of the pedestrian walking speed and the crossing width. The default walking speed is set at 3.5 ft/s, which corresponds to the 15th percentile speed of pedestrians observed in a national study of pedestrian crossings (TRB, 2006). However, in cases where a significant portion of elderly or disabled pedestrians are expected to cross, that walking speed should be lowered to 3 ft/s or even less based on local data. As such, the minimum pedestrian phase duration is estimated as:

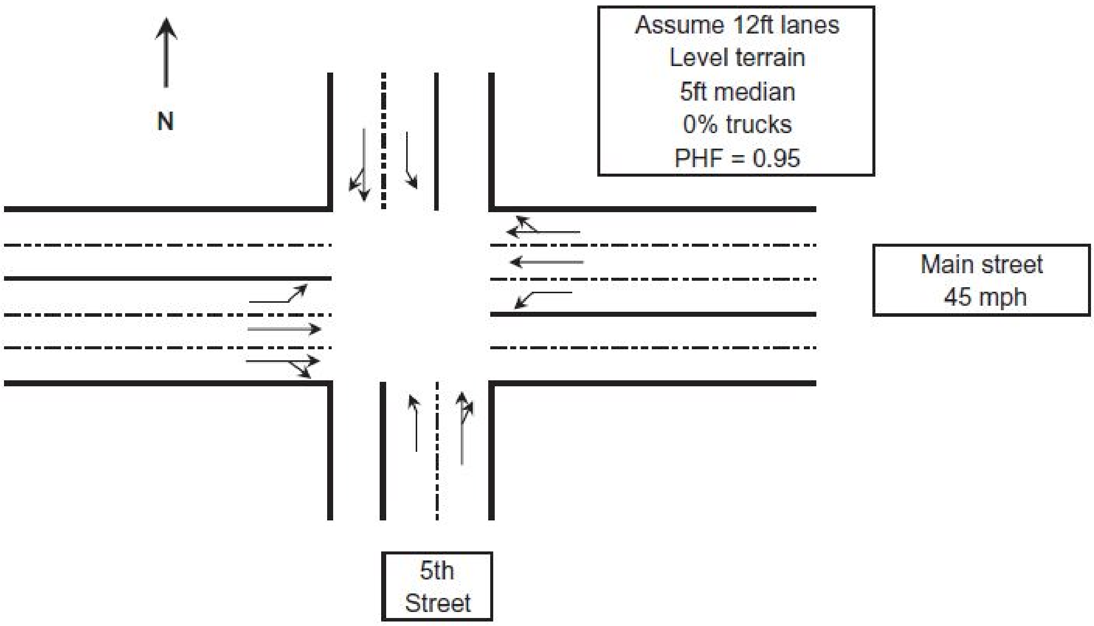
$$t_{ped,min} = t_W + t_{FDW} = t_W + \frac{W}{S_{ped}}$$

<u>where:</u>
$t_{ped,min}$ = minimum pedestrian phase duration (s).
t_W= duration of walk interval (default55-7 s).
t_{FDW} = duration of flashing "don't walk" indication (s).
W= crossing width (ft).
Sped= pedestrian walking speed (default53.5 ft/s).

If the total split for a vehicular phase (G+Y+AR) is less than the corresponding minimum pedestrian phase duration, the vehicle phase needs to be increased to allow for the minimum. As needed, cycle lengths may be increased to accommodate all phases. The need to make adjustments due to pedestrian clearance time requirements is most frequent for (low volume) side-street phases, which may otherwise only have a short split assigned to process vehicular volumes

Signal Timing Example

The following example illustrates the signal timing process in detail. Figure below shows a four-legged intersection of Main Street (running east-west) and 5th Street (running north-south). The figure shows lane assignment and basic assumption. Traffic volumes are given in Figure below.



<u>Figure</u>: Intersection geometry for signal timing example.

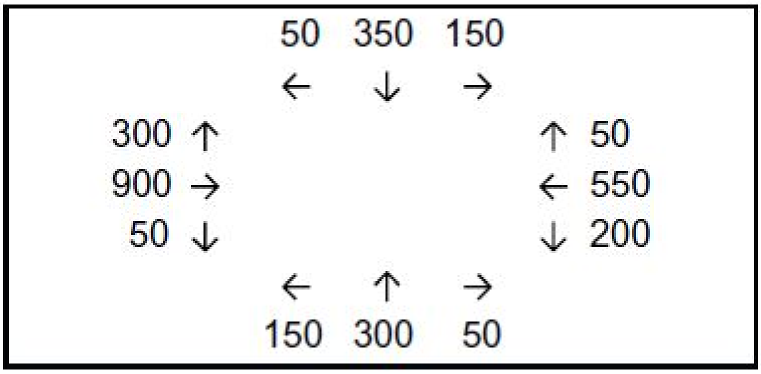


Figure: Traffic volumes for signal timing example.

Step 1: Identify Left-Turn Treatments

For this example, we will assume all protected left-turn phasing. In reality, some of the left turns may run as permissive (if volumes are low enough), or as protected-permissive, provided that adequate sight distances are provided and the permissive left turn can be completed safely. Permissive left turns would decrease the capacity of the left turn over a protected movement (at the same effective green time), while a protected permissive movement would add some capacity over the protected-only movement. So in some ways, the assumption of a protected-only movement is conservative, and additional capacity may be gained if permissive turns are eventually allowed at the intersection.

Step 2: Identify Lane Groups for Each Approach

Per HCM guidance presented that, each exclusive turn lane and each shared lane has to be assigned a separate lane group. As such, three lane groups emerge each for the east and west approaches, with two lane groups for the north and south approaches. This is illustrated in Figure below .

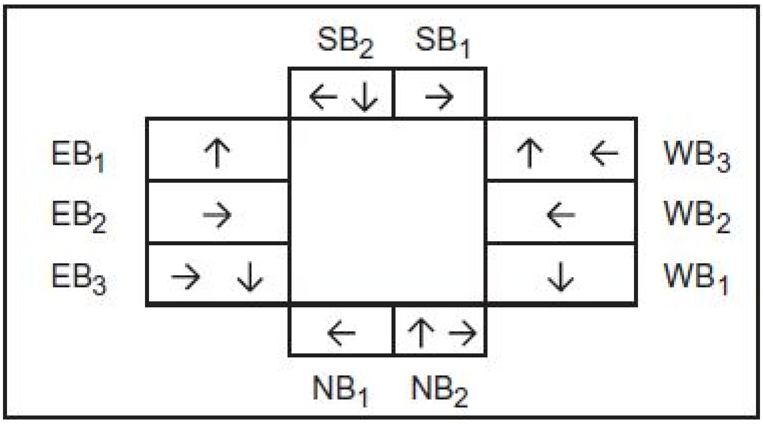


Figure: Lane groups for signal timing example.

Step 3: Determine Lane Group Traffic Data

The traffic volumes shown in previous Figure first need to converted into peak 15-min flow rates by dividing them by the peak hour factor (and typically a heavy vehicle adjustment factor and driver population adjustment factor, which do not apply in this example). These flow rates are then assigned to the different lane groups. For the through traffic on the eastbound and westbound approaches, it is assumed that 55% of through traffic chooses the exclusive lane, with 45% in the shared lane. In the absence of field data, this type of assumption has to be made by the analyst.
A good reasonableness check in this volume split is to assure similar v/s ratios for both lane groups, which does hold true in this example.

The lane group flow rates are then divided by the saturation flow rate of each lane group to give the v/s (volume to saturation flow) ratio for the lane group. Conceptually, the v/s ratio describes the fraction of an hour worth of green time needed to serve the demand of the particular lane group given its saturation flow rate (capacity). In this example, exclusive through lanes have an assumed saturation flow rate of 1900 passenger cars/h per lane; shared lanes a rate of 1800 passenger cars/h per lane; and exclusive left-turn lanes a rate of 1700 passenger cars/h per lane. The saturation flow rates can also be field measured or be calculated using the appropriate HCM equation. This entire process is illustrated in Tables below.

Table: Lane group traffic data for signal timing example-traffic volumes
Traffic volumes.

	NB			SB			EB			WB		
	L	T	R	L	T	R	L	T	R	L	T	R
Demand	150	300	50	150	350	50	300	900	50	200	550	50
Demand/PHF	158	316	53	158	389	53	310	947	53	211	579	53

Assume 55/45 split for through across exclusive/shared lanes

Table: Lane group traffic data for signal timing example-lane group volumes
Lane group volumes.

	NB_1	NB_2	SB_1	SB_2	EB_1	EB_2	EB_3	WB_1	WB_2	WB_3
Demand/PHF	158	369	158	442	316	521	479	211	318	314
SAT./Flow	1700	1900	1700	1,900	1700	1900	1800	1700	1900	1800
V/S	0.09	0.19	0.09	0.23	0.19	0.27	0.27	0.12	0.17	0.17

Step 4: Develop the Desired Phasing Plan

Figure below shows all v/s ratios applied to the lane group diagram. If one were to sum up all v/s ratios, the resulting sum equals 1.79. In other words, 179% of the cycle (or an hour) are needed to practice all these movements.

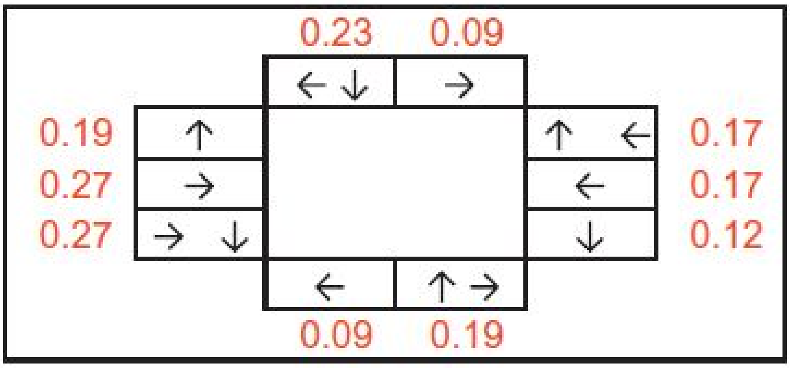


Figure : v/s ratios applied to movements.

Luckily, different lane groups and movements can be combined into the same phase. For example, northbound and southbound through movements can move together, thereby combining the 0.23 and 0.19 v/s ratio. The duration of this combined phase is governed by the phase with the higher v/s ratio, which is also referred to as the critical v/s ratio. Each phase accordingly will have one critical v/s ratio that determines the required phase duration, which can be summed for the intersection. The objective of step 4 is to come up with the best possible signal timing plan that minimizes the sum of critical v/s ratios for all phases.
Figure below illustrates three potential phasing schemes for this intersection drawn in a ring-barrier diagram representation. The signal timing process needs to find the sum of critical v/s ratios, which follows the critical path through the ring-barrier diagram. For each side of the barrier (east-west vs. north-south), one phase sequence is going to have the higher sum of critical v/s ratios.

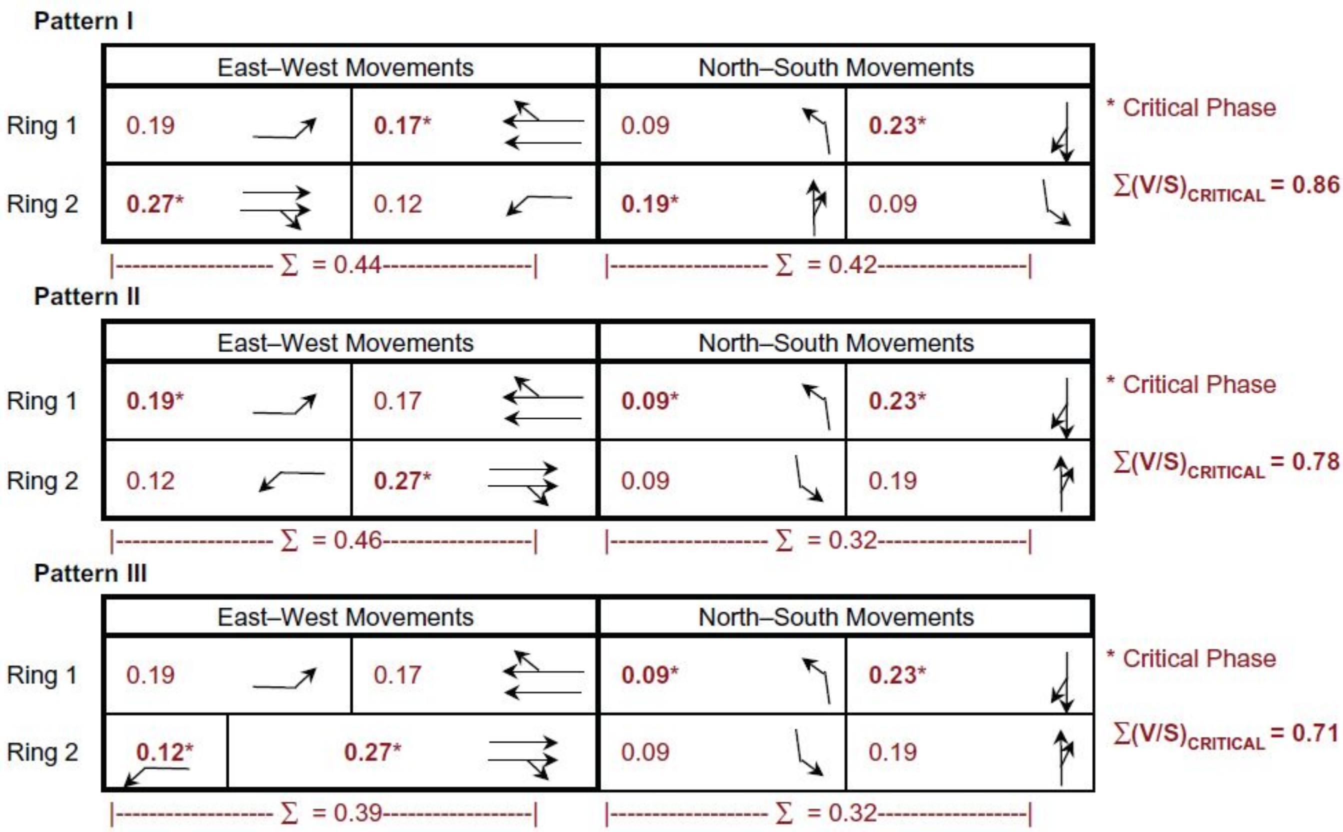


Figure: Illustration of three phasing patterns for signal timing example.

In the example, pattern I runs each approach sequentially: eastbound, westbound, northbound, and finally southbound. The resulting sum of critical v/s ratios is 0.86. The inefficiency in this scheme becomes apparent when scrutinizing the v/s ratios for left turns and through movements, where the latter tend to be higher.

Pattern II then combines left turns and through movements, as each pair has similar v/s ratios. The result is a more efficient overall phasing scheme and a sum of critical v/s ratios that is reduced to 0.78. Further improvements are possible when allowing one left turn to proceed longer than the other, if v/s ratios are uneven.

This is illustrated in pattern III, where the higher v/s ratio for the eastbound left turn (0.19) is given more time than the westbound left turn (0.12). This in turn allows the higher v/s eastbound through movement to start before the westbound through. The result is that both the heavy eastbound left and through phases are given more time than the lower-volume westbound movement. The resulting sum of critical v/s ratio is thereby reduced to 0.71, making this the preferred phasing scheme for the intersection.

Note that for the north-south phases, both left turns have identical v/s ratios, and no additional efficiency gains are therefore possible here.

<u>Step 5: Calculate Required Yellow and All-Red Times</u>

The clearance interval (yellow and all-red) is calculated from previous Eq. which explained earlier,

$$CI = t_{PR} + \frac{S_0}{2 \times (a + Gg)} + \frac{W + L}{S_0}$$

which is repeated as follows. First, the calculations are shown for the east-west street. The width of the intersection is calculated by summing 12-ft travel lanes and a 5-ft median.

I - East-west street

$$CI = \underbrace{t_{PR} + \frac{S_o}{2(a + G_8)}}_{\text{yellow}} + \underbrace{\frac{W + L}{S_o}}_{\text{red}}$$

$$W = 3(12\text{ ft}) + 5\text{ ft} = 41\text{ ft}$$

Lanes Median

$$S_o = 45\text{ mph} \times 1.47\text{ fps/mph} = 66.2\text{ fps}$$

$$CI = 1 + \frac{66.2}{2(11.2 + 0)} + \frac{41 + 20}{66.2}$$

$$CI = 1 + 2.96 + 0.92$$

Result: Use yellow > 4 s and AR > 1 s

I – North–south street

$$W = 5(12\text{ ft}) + 5\text{ ft} = 65\text{ ft}$$
$$S_o = 30\text{ mph} \times 1.47\text{ fps/mph} = 44.1\text{ fps}$$
$$CI = 1 + \frac{44.1}{2(11.2 + 0)} + \frac{65 + 20}{44.1}$$
$$CI = 1 + 1.96 + 1.93$$

Result: Use yellow > 3 s and AR > 2 s

Step 6: Determine Lost Time per Phase and Per Cycle

To calculate the lost time per phase, we can assume a start-up lost time of 2 s, as well as an end lost time of 2 s. As a result, the total lost time per (critical) phase is 4 s for both the north-south and the east-west movements.

The total lost time per cycle is then estimated by summing the lost times for all critical phases. Lost time applies every time a critical movement starts or stops along the critical path through the intersection phase sequence. In other words, Previous Figure that was used to calculate the sum of critical v/s ratios, can also be used to estimate the total lost time. In the figure, it is evident that each of the three phasing options features a sequence of four critical phases. As such, the total lost time for this eight movement, four-critical-phase intersection is:

$L = 4 \times 4\ s = 16\ s$ of total lost time, regardless of the phasing scheme applied.

Step 7: Select a Target Volume-to-Capacity Ratio

Next, we select a target volume-to-capacity ratio. In this example, we will select Xc=0.90, meaning that our intersection will be utilized at 90% of its theoretical capacity, thereby allowing a 10% safety margin for fluctuations in traffic volumes.

Step 8: Estimate the Cycle Length

With most inputs completed, we can now calculate the cycle length for the intersection. We show both options for doing so, starting with the minimum cycle length formula from Eq. below:

$$C = \frac{LX_C}{\left[X_C - \sum\left(\frac{V}{S}\right)_{Critical}\right]} = \frac{16(0.90)}{[0.9 - 0.71]} = 75.8\text{ s}$$

This value is typically rounded up to the nearest 5 s, so we will use a cycle length of 80 s. Second, we can calculate the optimum cycle length using Webster's equation from Eq. below:

$$C = \frac{1.5L + 5}{\left[1 - \sum\left(\frac{V}{S}\right)_{Critical}\right]} = \frac{1.5(16) + 5}{[1 - 0.71]} = 100 \text{ s}$$

Step 9: Total Effective Green Time Available per Cycle

The total effective green time is estimate by subtracting the 16-s total lost time from the cycle length, giving a time of 64 s and 84 s for cycle lengths of 80 and 100 s, respectively.

Step 10: Distribute Effective Green Times across All Phases

We can now distribute the effective green times across all phases using previous Equ. The resulting phase times for both cycle lengths are shown in Table below. The phases along the critical path for pattern from previous Figure are shown in bold and with " *" symbols. Note that the phases along the critical path by definition have to add up to the total available green time, which in this case is 64 and 84 s for the two cycle length options. The noncritical phases require less green time, and therefore do not add up to the total available effective green. It is common practice to extend the mainline movements for those noncritical movements, to use up any unallocated green time. For example, for the east-west movements, the effective green time for the critical movements (ring 2) in the 80 s cycle add up to:

$$10.8 + 24.3 = 35.2\ s.$$

But the noncritical movements in ring 1 add up to only

$$17.1 + 15.3 = 32.5\ s.$$

The difference of:

$35.2 - 32.5 = 2.7$ s is applied

to the westbound through movement, increasing its effective green time to

$$15.3 + 2.7 = 18\ s.$$

These modified effective green times are shown in parentheses in the table.

Table: Phase times for signal timing example.

Ring	Movement	v/s	C = 80 s	C = 100 s
1	EBL	0.19	17.1	22.5
	WBT	0.17	15.3 (18.0)	20.1 (23.7)
	NBL*	**0.09**	**8.1**	**10.6**
	SBT*	**0.23**	**20.7**	**27.2**
2	**WBL***	**0.12**	**10.8**	**14.2**
	EBT*	**0.27**	**24.3**	**31.9**
	SBL	0.09	8.1	10.6
	NBT	0.19	17.1 (20.7)	22.5 (27.2)

Step 11: Calculate Actual Green Time per Phase

The effective green times from Step 10 are not converted to actual green times programmed into the signal controller, and are seen by the drivers as a green indication. The actual green times are calculated as:

$$G_i = g_i - CI_i + l_i$$

In our example, all clearance intervals were 5 s (4+1 for east-west and 3+2 for north-south), and all lost times were assumed to be 4 s.
The resulting green times are shown in Table below.
These green times should be checked to assure that the minimum green time for all phases are provided, which are typically around 7 s for left turns and side-street phases and 15 s for through movements on the mainline. In this example, these minimum times are provided or both cycle lengths. Similarly, some signal controllers require green times to be rounded to the nearest full second, and rounding is good practice even for more flexible controllers. But before finalizing the phase times, there is one more check that needs to be performed.

Table: Actual green times for signal timing example.

Ring	Movement	C = 80 s	C = 100 s
1	EBL	16.1	21.5
	WBT	17.0	22.7
	NBL	7.1	9.6
	SBT	19.7	26.2
2	WBL	9.8	13.2
	EBT	23.3	30.9
	SBL	7.1	9.6
	NBT	19.7	26.2

Step 12: Check Pedestrian Clearance Time Requirements

The final step in the signal timing process is to check the pedestrian clearance times. Pedestrian movements are typically processed with the adjacent mainline through. Pedestrian clearance time requirements are calculated from Eq. below. We can assume a walk interval of 5 s for this intersection and a walking speed of 3.5 ft/s, per MUTCD.

$$t_{ped,min} = t_W + t_{FDW} = t_W + \frac{W}{S_{ped}}$$

Crossing minor street (east–west movements):

$$t_{ped,E-W} = 5 + \frac{41}{3.5} = 5 + 11.7 = 16.7 \text{ s minimum}$$

Crossing major street (north–south movements):

$$t_{ped,N-S} = 5 + \frac{65}{3.5} = 5 + 18.6 = 21.6 \text{ s minimum}$$

The currently assigned splits (green plus yellow plus all-red) for the east-west movements are shown in Table below. The comparison with the required pedestrian clearance times shows that the assigned splits for the through movement are long enough to accommodate pedestrians at a 5-s walk interval plus the required flashing “don’t walk” time. As a result, both an 80-s or a 100-s cycle would be feasible for this intersection. The decision of the final intersection timing depends on agency practices, as well as potential interaction with adjacent intersections, where a common cycle length is required if coordination is to be provided along a signalized intersection corridor.

Signal Coordination

Signal coordination means that vehicles traveling along the main road tend to progress or move through downstream signalized intersections without having to stop. There are several situations where signalized intersections adjacent to each other should be coordinated. Coordination is critical for signals at interchange ramp junctions because of queuing concerns between the closely spaced signals for both through traffic and left-turning traffic. Signal coordination along an arterial corridor will significantly reduce both overall travel time and delay for through vehicles using that corridor. Signal coordination along a one-way road allows for smooth progression of traffic, usually in a downtown area where one-way roads surround each block and there are often pairs of one-way roads on opposite sides of the blocks.

Time-Space Diagrams

A time-space diagram shows a platoon of vehicles moving along a street. Signal coordination is established when the platoon can arrive at a signalized intersection under a green interval and continue proceeding along the street without having to slow down or stop. Perfect progression using the entire green interval is rarely possible, especially if two-way progression is desired. The following two figures show a one-way progression pattern (Figures below) and a two-way progression pattern.

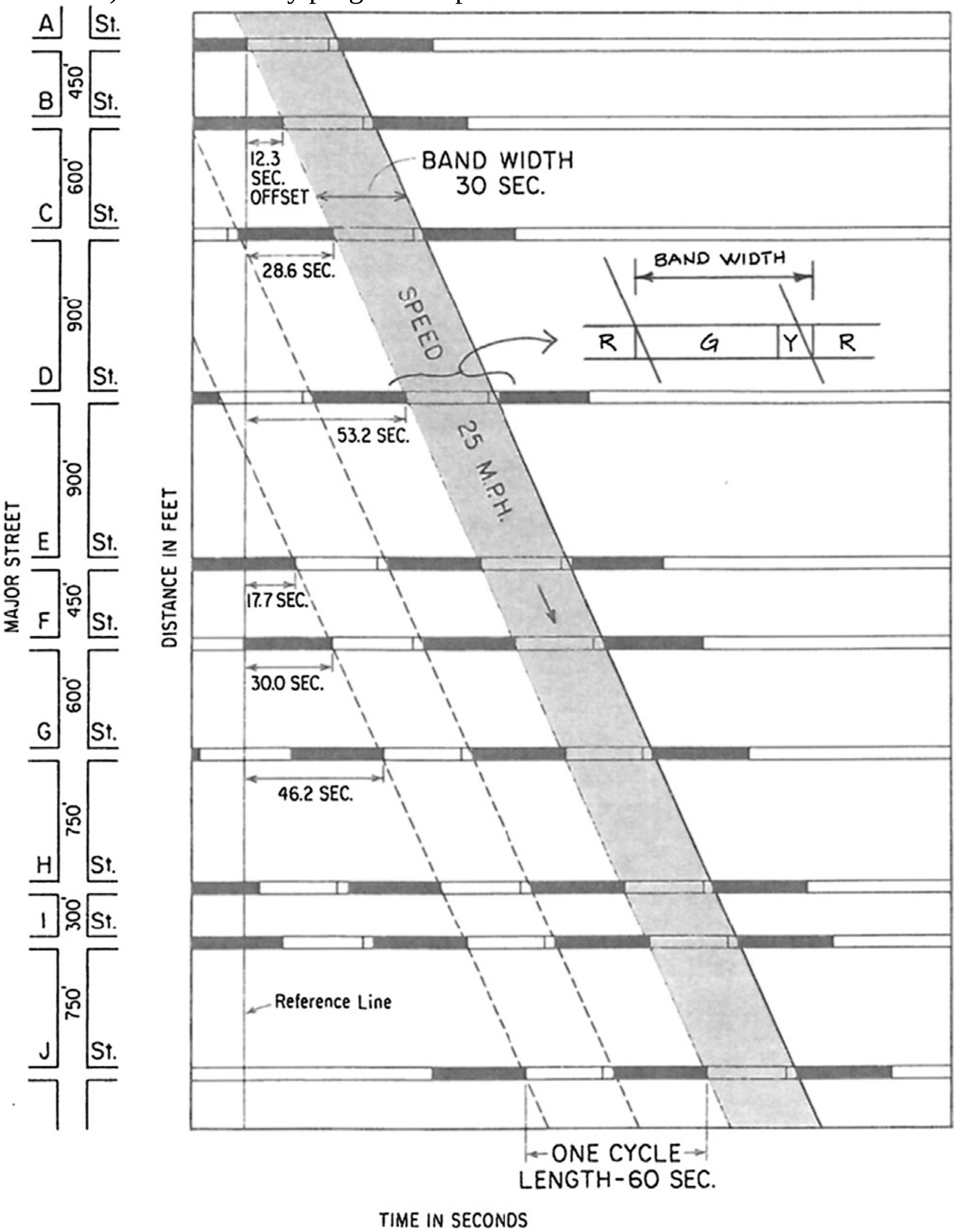


Figure: Time-space diagram for a one-way street.

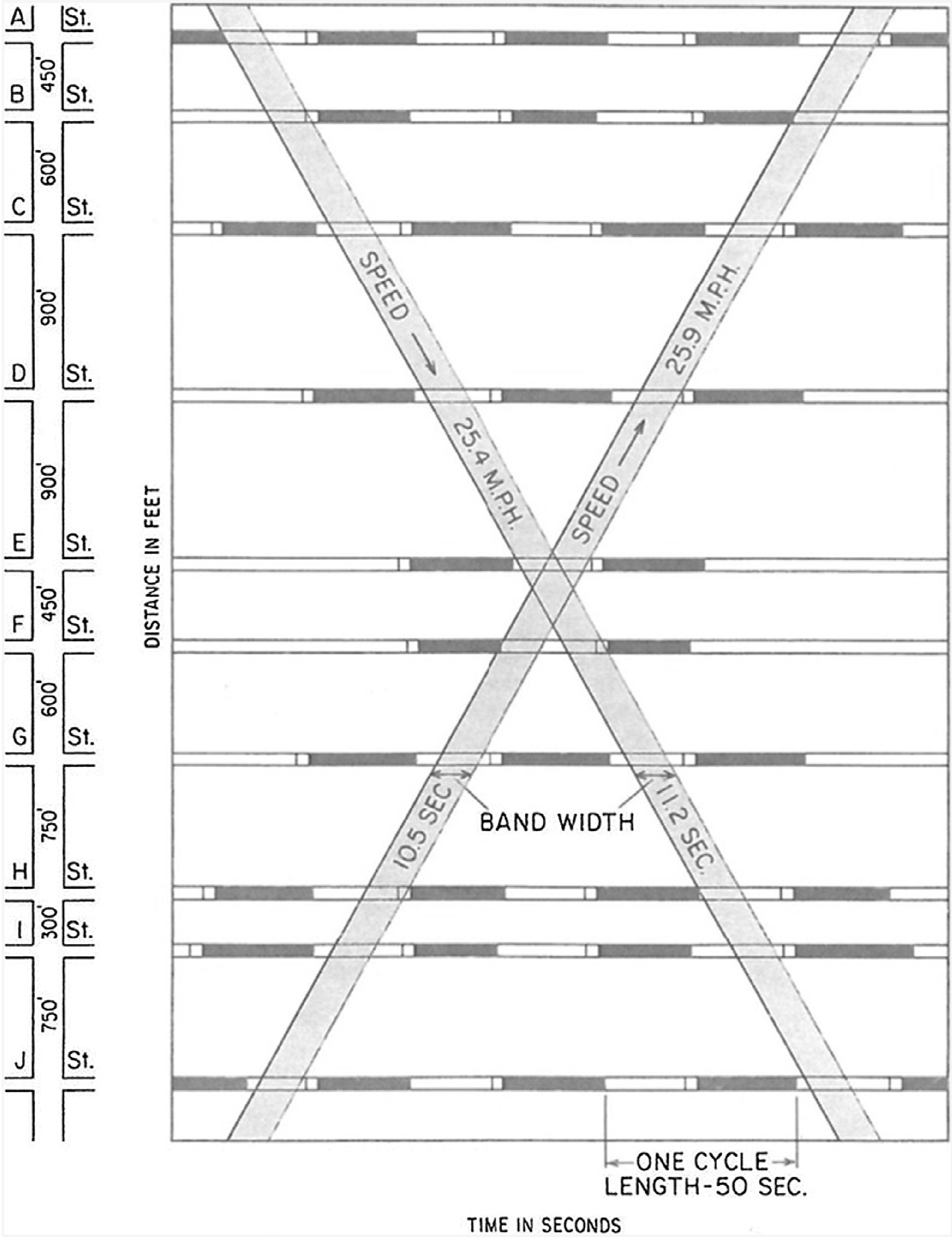


Figure: Time-space diagram for a two-way street.

Previous Figure depicts many new terms, which are defined as follows. These terms are critical in properly describing the progression aspects of the traffic stream.

- Reference line: This is a straight line drawn perpendicular to the time scale. The selection of its location is arbitrary, however, a convenient line would be the left edge of the figure. All offset times are measured away from the reference line in the direction of increasing time.
- Offset: The time in seconds from the reference line to the start of the green phase for the first full cycle at any intersection, thus, the offset must always be less than one cycle length. Offsets are calculated by taking the total distance (ft) traveled from the starting point to the intersection where the offset is needed and dividing by the travel speed (fps), remembering to subtract as many cycle lengths as necessary to get the offset time to be less than one cycle length.
- Bandwidth: Sometimes called progression bandwidth, it is the time between the two parallel progression speed lines. It represents the maximum time in seconds that a platoon of vehicles can progress through each intersection, and because the two lines are parallel, the bandwidth is the same for all intersections. The speed lines must pass through only the green (and/or yellow) interval at every intersection. The maximum bandwidth for an intersection occurs when the first speed line passes through the entering corner of the green interval and the second speed line passes through the exiting corner of the yellow interval resulting in a bandwidth that is slightly shorter than the green plus yellow intervals by the time to travel through the intersection, about 1.5 s. Note that the bandwidth time is measured along the time scale and is not the perpendicular measure between the two parallel lines.
- Cycle length: The time for one complete pass through critical phases in a timing plan. For a time-space diagram to repeat throughout the day, the cycle length must be the same at every intersection.
- Speed: The slope of the progression line, usually determined and plotted using fps and converted back and forth to mph as needed. Recall that 60 mph588 fps.

For all time-space diagrams, the vertical axis (usually distance) and the horizontal axis (usually time) must be drawn to scale. This includes the width of each intersection. A scaled diagram allows for determining the proper bandwidth and progression speed given a set of input criteria and the desired outcome. One can also calculate the efficiency of the bandwidth for a given direction. The formula is:

$$efficiency = \frac{band\ width}{cycle\ length} \times 100\%$$

An efficiency of 40% to 55% is considered good.

Drawing a Time-Space Diagram

In many cases, time-space diagrams are produced automatically through software. However, it is useful to understand the basic steps involved in drawing a time-space diagram, which are as follows:

1. Establish your distance and time scales to fit the layout on a page if possible.
2. Lay out your street intersections to scale, including the width of the side streets.
3. Select a reference line and draw it in.
4. If laying out offsets, calculate the offset at each intersection using distance (ft) divided by speed (ft/s) to yield seconds. This becomes the start of the green phase at that intersection.
5. Draw in all the green, yellow, and red intervals at each intersection using the offset as the measuring point (both forward and backward).
6. Draw in the speed lines (they must be parallel) to achieve maximum bandwidth and measure the width. If the speed lines are being fitted into an existing situation, calculate the speed by taking distance (ft) divided by travel time (s) giving fps and convert to mph.
7. Label the diagram.