CHAPTER 7

TRAFFIC CONTROL AND ANALYSIS AT SIGNALIZED INTERSECTIONS

The chapter begins by providing an overview of the physical elements of intersection configuration and traffic signal control. A basic understanding of these principles provides the foundation for designing intersection geometry and traffic movement sequence plans. This is followed by a presentation of concepts, definitions, and analytical techniques that are used in the design and analysis of signal timing plans at signalized intersections.

INTRODUCTION

- Unlike uninterrupted flow, in which vehicle movement is affected only by other vehicles and the roadway environment, **the introduction of a traffic control device such as a signal exerts a significant influence on the flow of vehicles.**

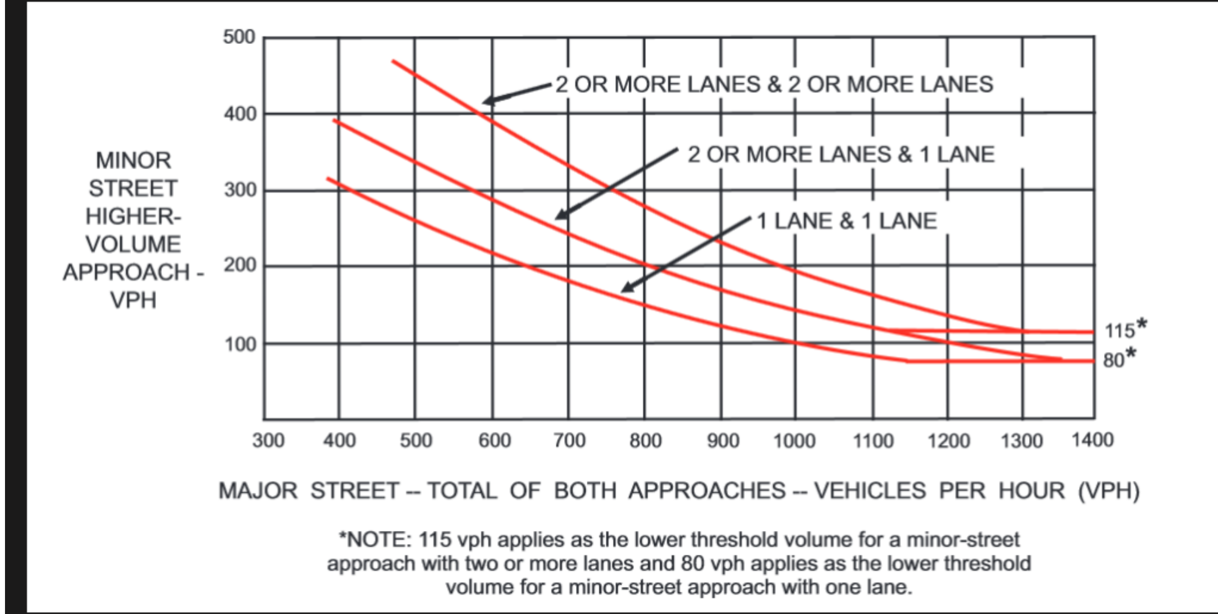
- An intersection is defined as an **at-grade** crossing of two or more roadways.

- **Most roadway intersections are not signalized** due to low traffic volumes and adequate sight distances. However, at some point, traffic volumes and accident frequency/severity (and other factors) reach a level that warrants the installation of a traffic signal

- There are a total of 9 **signal warrants**, which include consideration of vehicle volumes, pedestrian volumes, school crossings, signal coordination, and crash experience.

SIGNAL WARRANTS

- The MUTCD (Manual of Uniform Traffic Control Devices) is the engineer's guide for traffic control, so of course it is the basis for whether a signal is needed or not.
- A warrant is a condition that an intersection must meet to justify a signal installation.
- Traffic control signal needs studies
  - 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



Four Hour Vehicle Traffic Signal Warrants

Example

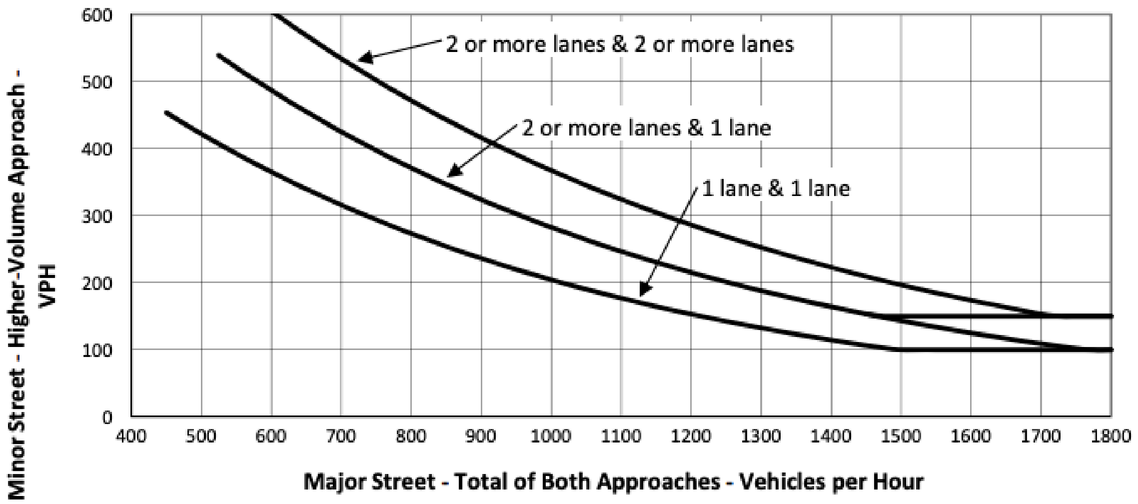
16. US-101 SOUTHBOUND OFF-RAMP / VAN NESS AVENUE & HAROLD WAY

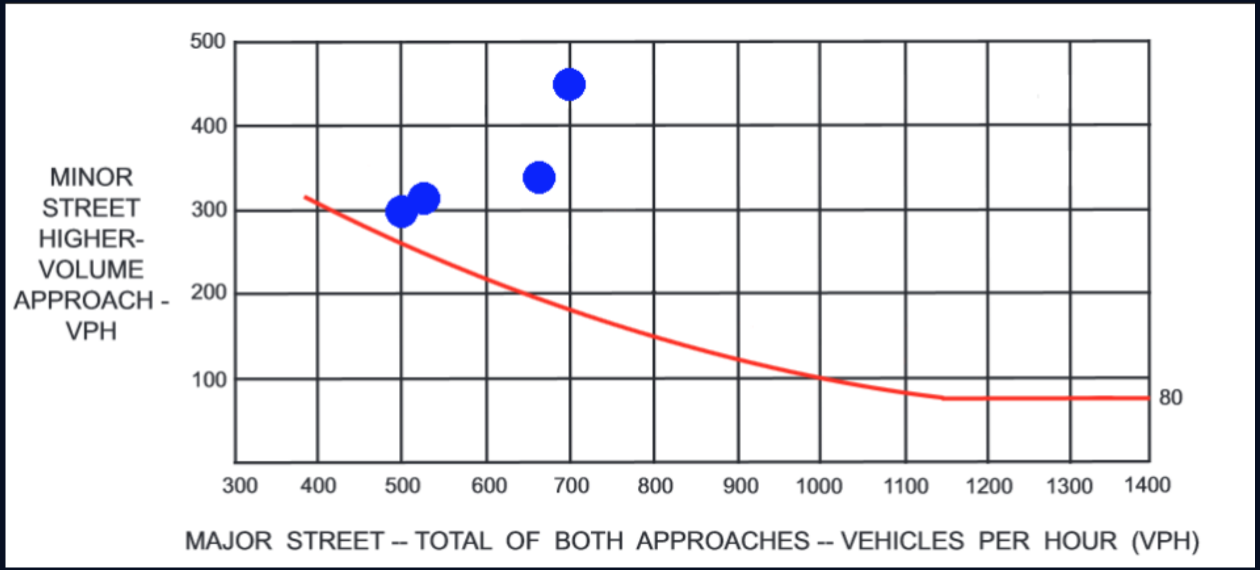
Major Street Name:	US-101 Southbound Off-ramp / Van Nes	Vehicles per Hour (Peak Hour)	
Minor Street Name:	Harold Way	Major Street (Approach 1):	1,015
		Major Street (Approach 2):	0
Major Street Lanes:	1	[a] Major Street Left-Turns:	0
Minor Street Lanes:	1	Minor Street (Higher Volume):	33
[b] Urban/Rural:	Urban		

Vehicles per Hour (Peak Hour)

Major Street (Approach 1):	1,015	Minimum Major Street Volume:	450
Major Street (Approach 2):	0	Satisfied?	YES
Total Major Street Volume:	1,015		
		Minimum Minor Street Volume:	200
Major Street Left Turns:	0	Satisfied?	NO
Minor Street (Higher Volume):	33		
Total Minor Street Volume:	33	Warrant 3 Satisfied?	**NO**

Figure 4C-3. Warrant 3, Peak Hour [c]





MINOR STREET HIGHER-VOLUME APPROACH - VPH
500
400
300
200
100
80
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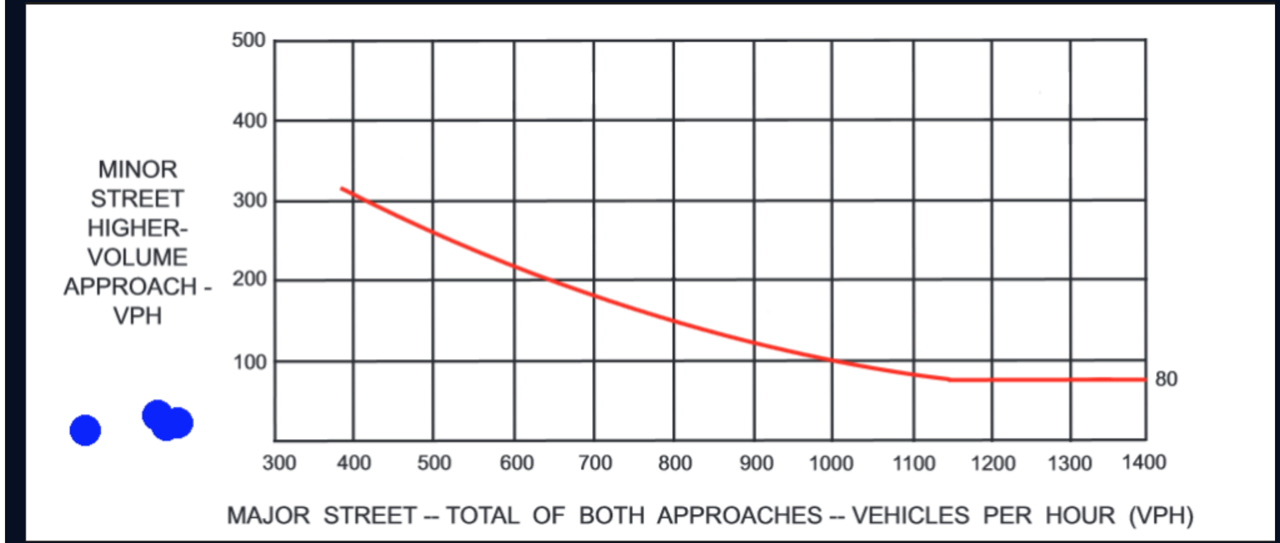
MAJOR STREET -- TOTAL OF BOTH APPROACHES -- VEHICLES PER HOUR (VPH)



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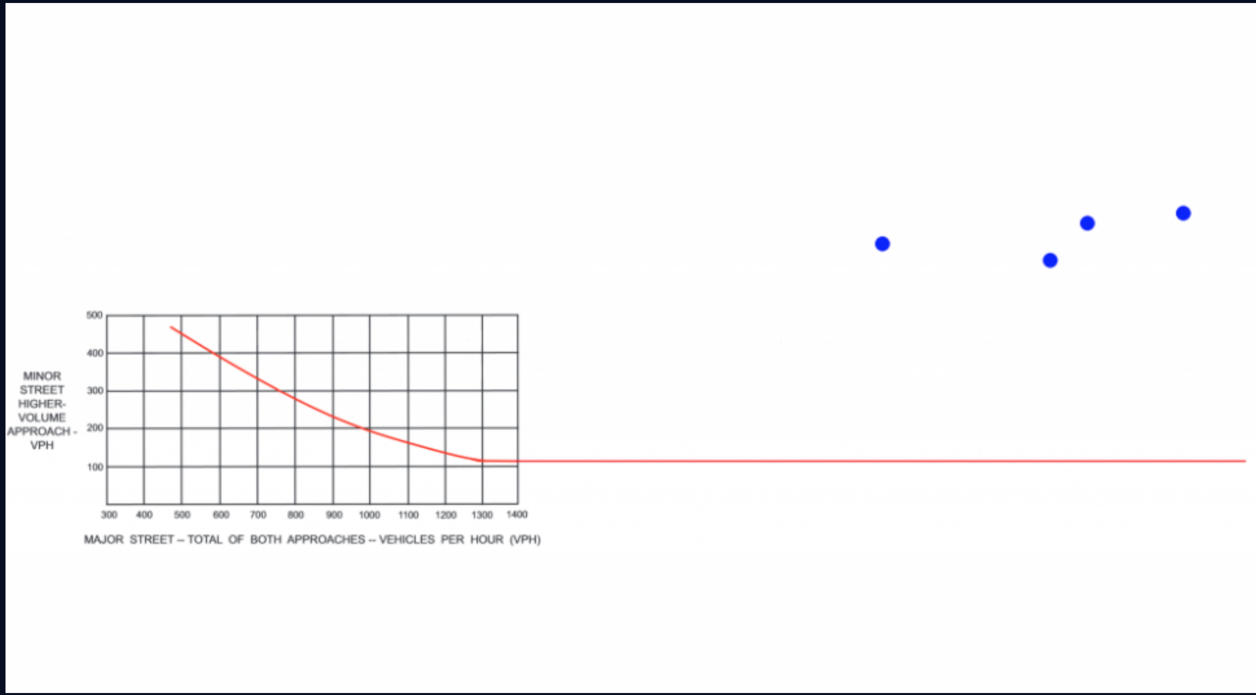

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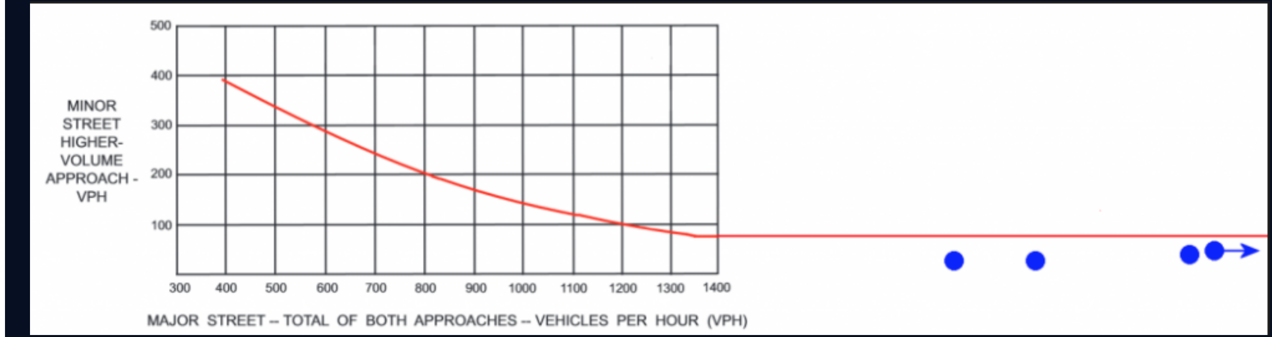

MINOR STREET HIGHER-VOLUME APPROACH - VPH
500
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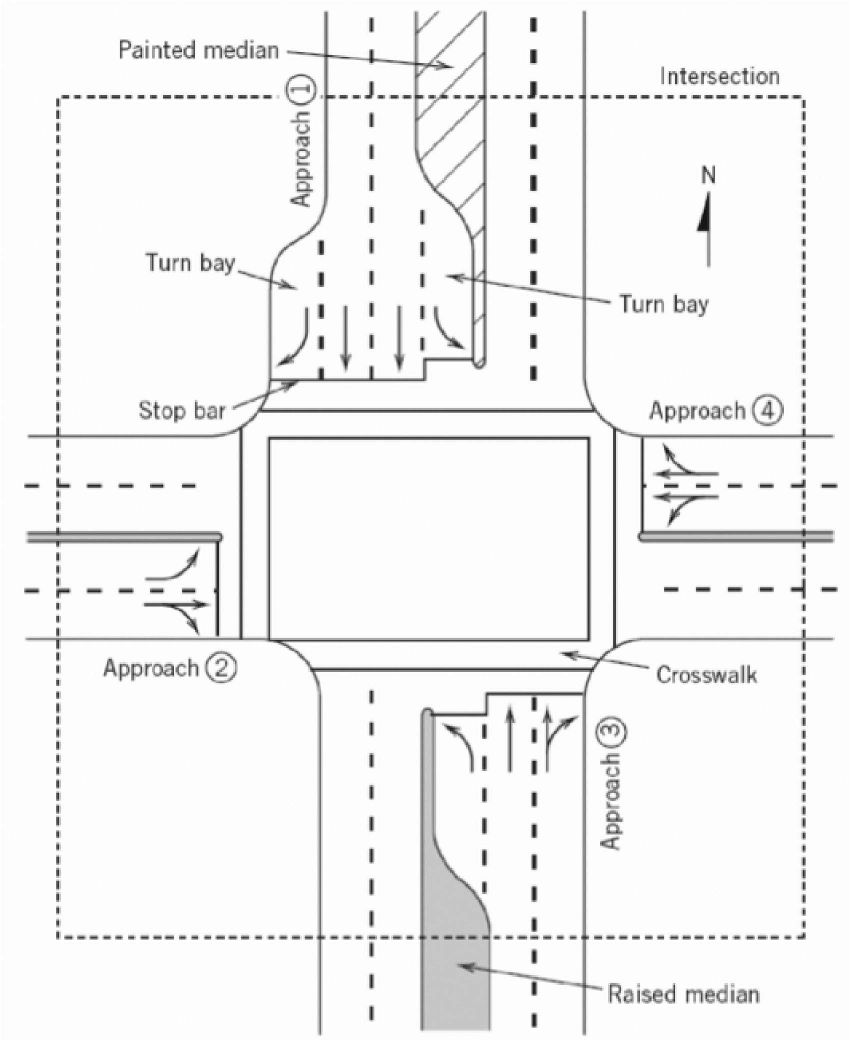
300
200
100
300 400 500 600 700 800 900 1000 1100 1200 1300 1400
MAJOR STREET -- TOTAL OF BOTH APPROACHES -- VEHICLES PER HOUR (VPH)

INTRODUCTION

- The **disadvantages** of installing and operating a traffic signal include
  - A poorly timed signal have a negative impact on the operation of the intersection by increasing vehicle delay
  - Increasing the rate of vehicle accidents (particularly rear-end accidents)
  - Causing a disruption in traffic progression
  - Encouraging the use of routes not intended for through traffic (such as routes through residential neighborhoods).
  - Costly to install
- The **advantages** of installing and operating a traffic signal include
  - a potential reduction in some types of crashes (particularly angle crashes),
  - provision for pedestrians to cross the street,
  - provision for side-street vehicles to enter the traffic stream,
  - provision for the progressive flow of traffic in a signal-system corridor,
  - possible improvements in capacity, and possible reductions in delays.

INTERSECTION AND SIGNAL CONTROL CHARACTERISTICS

- The roadways entering the intersection are segmented into **approaches**, which are defined by lane groups (groups of one or more lanes).
- These lane groups are usually based on the **allowed movements** (left, through, right) within each lane and the sequencing of allowed movements by the traffic signal.
- Because the lanes for the exclusive use of left and right turns are short, they are usually referred to as **bays** and are intended to hold a limited number of queued vehicles.
- **Queuing analysis** can be used to determine the length of bay necessary to prevent queued turning vehicles from
  - overflowing the bay and blocking the through lanes (known as **spillover**)
  - blocking the entrance of the turn bay (known as **spillback**)



TERMINOLOGY AND DEFINITIONS

- **Indication:** the illumination of one or more signal lenses (greens, yellows, reds) indicating an allowed or prohibited traffic movement.
- **Interval:** a period of time during which all signal indications (greens, yellows, reds)
- **Cycle:** one complete sequence (for all approaches) of signal indications (greens, yellows, reds).
- **Cycle length (C):** the total time for the signal to complete one cycle (usually expressed in seconds).
- **Green time (G):** the amount of time within a cycle for which a movement or combination of movements receives a green indication
- **Yellow time (Y):** the amount of time within a cycle for which a movement or combination of movements receives a yellow indication.
- **Red time (R):** the amount of time within a cycle for which a movement or combination of movements receives a red indication

TERMINOLOGY AND DEFINITIONS

- **All-red time (AR):** the time within a cycle in which all approaches have a red indication and it is referred to as <u>the clearance interval</u>
- **Phase:** the sum of the displayed green, yellow, and red times for a movement or combination of movements that receive the right of way simultaneously during the cycle. The sum of the phase lengths (in seconds) is the cycle length.
- **Protected movement:** a movement that has the right-of-way, which are always protected, and does not need to yield to conflicting movements
- **Permitted movement:** A movement that must yield to opposing traffic flow or a conflicting pedestrian movement. This movement is made during gaps (time headways) in opposing traffic and conflicting pedestrian movements.
- Traffic signal controllers are designed to operate in one or more of the following modes:
    - **pretimed:** a signal whose timing (cycle length, green time, etc.) is fixedand does not change
    - **semi-actuated:** a signal whose timing is affected when vehicles are detected (by video, pavement-embedded inductance loop detectors, etc.) on some, but not all, approaches.
    - **fully actuated:** a signal whose timing is completely influenced by the traffic volumes, when detected, on all of the approaches.

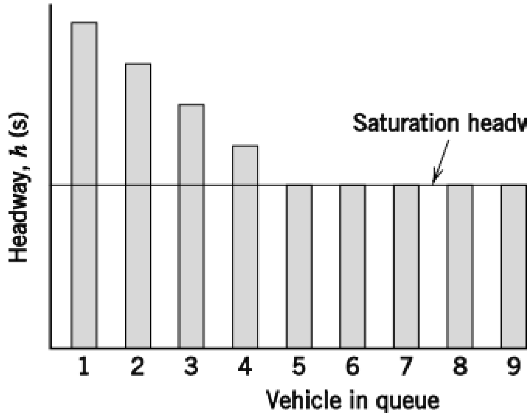
TRAFFIC FLOW FUNDAMENTALS FOR SIGNALIZED INTERSECTIONS

Saturation Flow rate

Saturation Flow rate: the max hourly volume that can pass through an intersection from given lane or group of lanes, if the lanes were provided with constant green throughout the hour.

- Research has shown that **max saturation flow rate of 1900 pc/h/ln** for signalized intersection which is based on headway of 1.9 sec.
- **The lane flow rate is affected by the following factors:**
    - Lane width
    - Grades
    - Curbside parking maneuvers
    - Bus stops and many other factors
    - The lanes allowing right or left turning have lower saturation rates.
- All these factors are applied by making adjustments to the saturation flow rates

  The end result is the flow rate of less than 1900 pc/h/ln which is also called adjusted flow rate



$$s = \frac{3600}{h}$$

s = saturation flow rate in veh/h,
h = saturation headway in s/veh, and
3600 = number of seconds per hour.

TRAFFIC FLOW FUNDAMENTALS FOR SIGNALIZED INTERSECTIONS

Loss Time

- **Start-up loss time:** The fraction of time lost during shifting from red to yellow or green which is not utilized due to reaction of drivers, usually 2 sec.
- **Clearance Lost Time:** Time between signal phases during which an intersection is not used by traffic. 2 seconds is typical.
- **Lost Time:** Time when an intersection is not effectively used by any approach. 4 seconds is typical.
- **Total Lost Time:** Total lost time per cycle during which the intersection is not used by any movement. The total lost time is the sum of start up and clearance time
- The stopping of traffic movement also results in lost time.
- When the signals turn from green to yellow, the part of time during yellow is also not utilized. This is called clearance time.
- For significant red lights running, the clearance lost time is negligible.
- For shorter cycles, the lost time percentage will be high.

$$t_L = t_{sl} + t_{cl}$$

t_L = total lost time for a movement during

t_{sl} = start-up lost time in seconds, and

t_{cl} = clearance lost time in seconds.

TRAFFIC FLOW FUNDAMENTALS FOR SIGNALIZED INTERSECTIONS

- **Effective Green:** is the time during which the traffic movement is effectively utilizing the intersection
- **Effective Red Times:** is the time during which a traffic movement is not utilizing the intersection.
- **Capacity:** The accounts for the hourly volume that can be accommodated on an intersection approach given that the approach will receive less than 100% green time.

$$c = s\left(\frac{g}{C}\right)$$

c: capacity (max hourly volume that can pass through an intersection

s = Saturation flow and

g/C: ratio of effective green to cycle time.

$$g = G + Y + AR - t_L$$

g = effective green time for a traffic movement in seconds,
G = displayed green time for a traffic movement in seconds,
Y = displayed yellow time for a traffic movement in seconds,
AR = displayed all-red time in seconds, and
t_L = total lost time for a movement during a cycle in seconds.

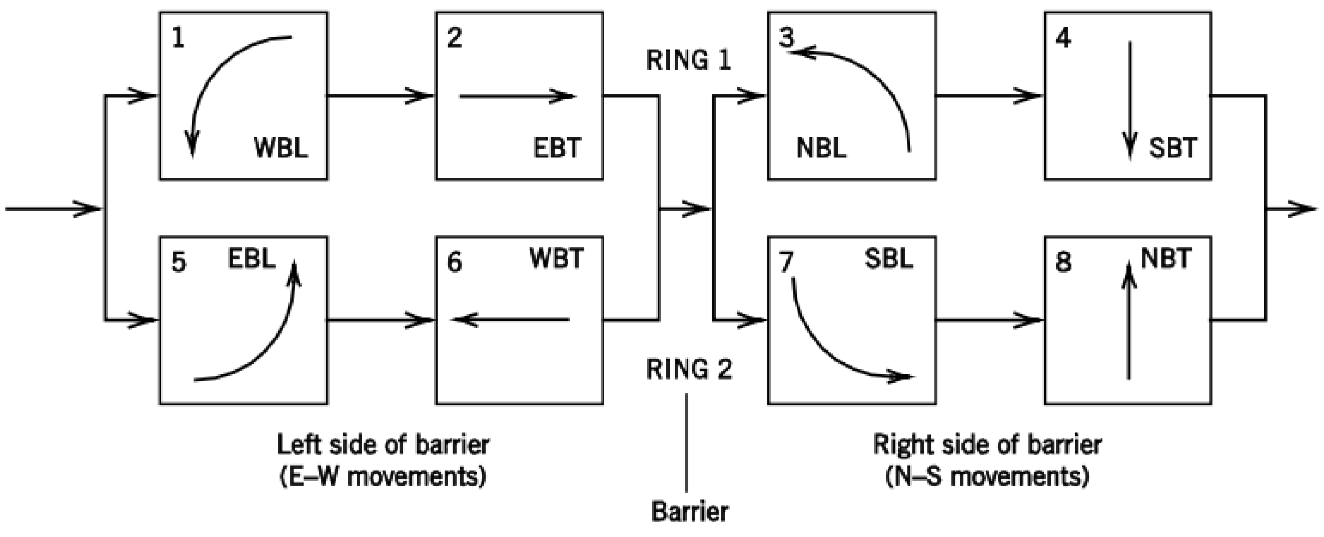
$$r = R + t_L = C - g$$

r = effective red time for a traffic movement in seconds,
R = displayed red time for a traffic movement in seconds, and
t_L = total lost time for a movement during a cycle in seconds.

C = cycle length in seconds, and
Other terms are as defined previously.

DEVELOPMENT OF A TRAFFIC SIGNAL PHASING AND TIMING PLAN

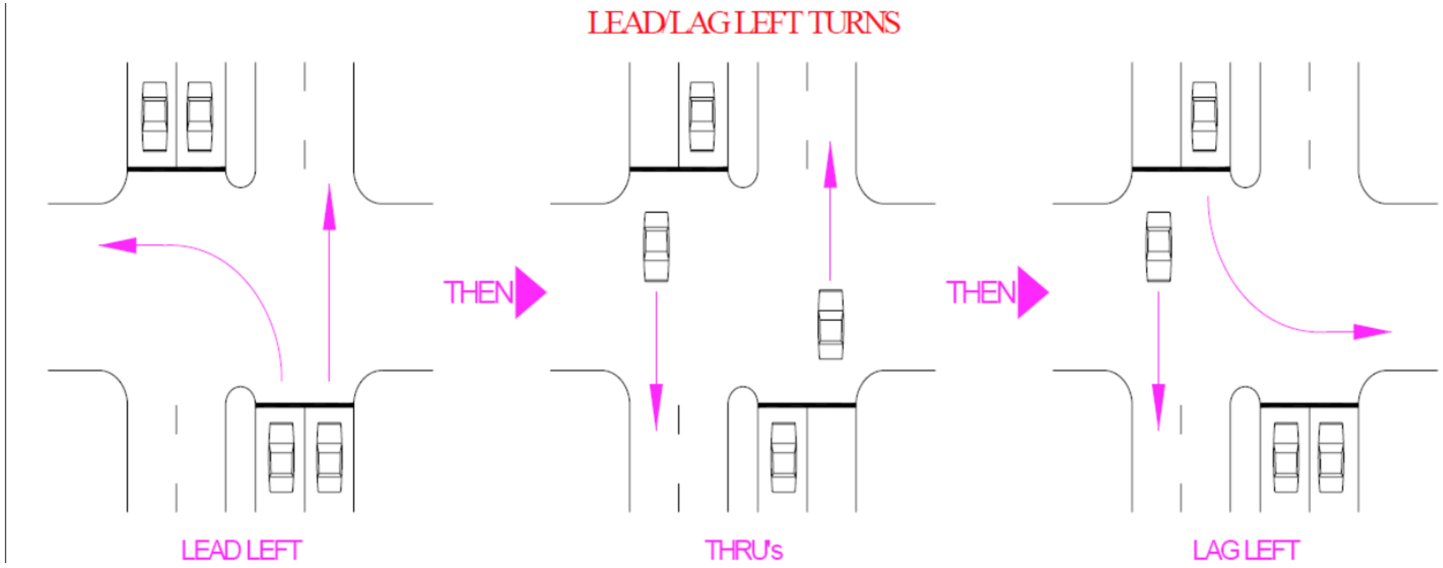
- Assuming the decision to install a traffic signal at an intersection has been made, an appropriate phasing and timing plan must be developed.
- The development of a traffic signal phasing and timing plan can be complex, particularly if the intersection has multiple-lane approaches and requires protected turning movements (a turn arrow). However, the timing plan analysis can be simplified by dealing with each approach separately.
- This section provides the basic process and fundamentals needed to develop a phasing and timing plan for an isolated, fixed-time (pretimed) traffic signal.

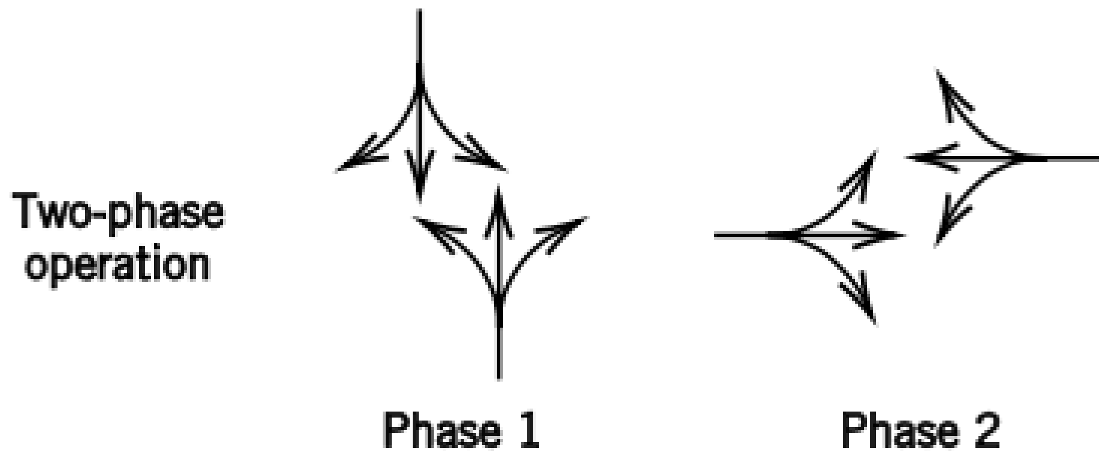


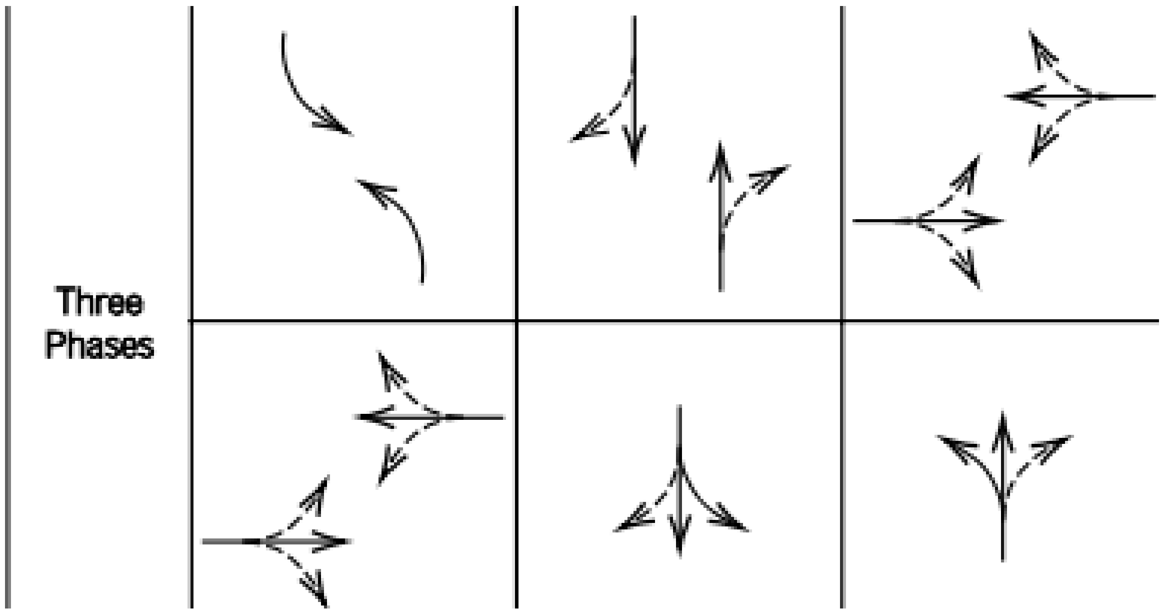
(a)

DEVELOPMENT OF A TRAFFIC SIGNAL PHASING AND TIMING PLAN

- Note: that the dashed lines represent permitted movements and the solid lines represent protected movements
- When the left turns precede the through and right-turn movements in the phasing sequence for an approach, they are referred to as **leading left turns.**
- When the left turns follow the through and right-turn movements, they are referred to as **lagging left turns.**
- It is also possible for a movement to be protected for a period of time and then permitted for a period of time, or vice versa.
- There is lost time (start-up and clearance) associated with each phase. Thus, with each phase added to a cycle, the lost time increases. Although the lost time may be only 3 to 5 seconds per phase, the accumulated lost time throughout the day can be significant.







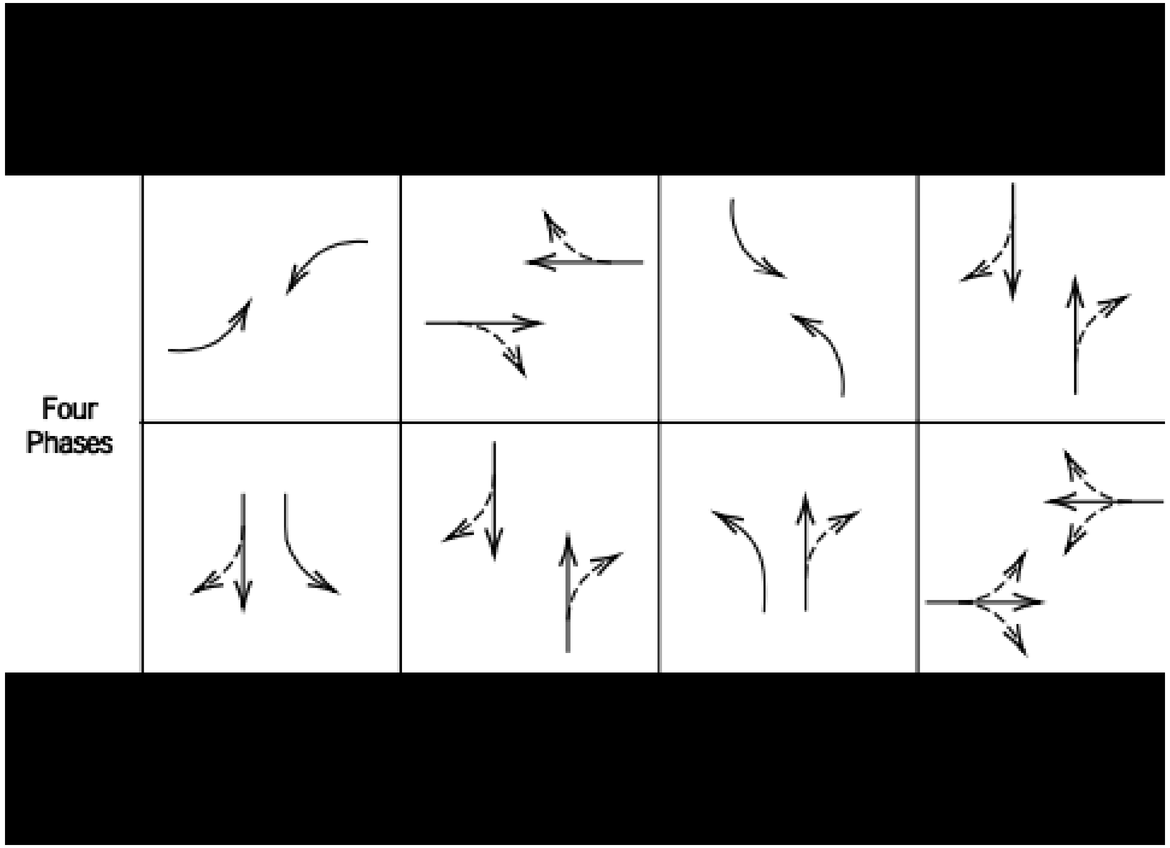
Two phases operation

Phase 1 accommodates the movement of the northbound and southbound vehicles, and phase 2 accommodates the movement of the eastbound and westbound vehicles.

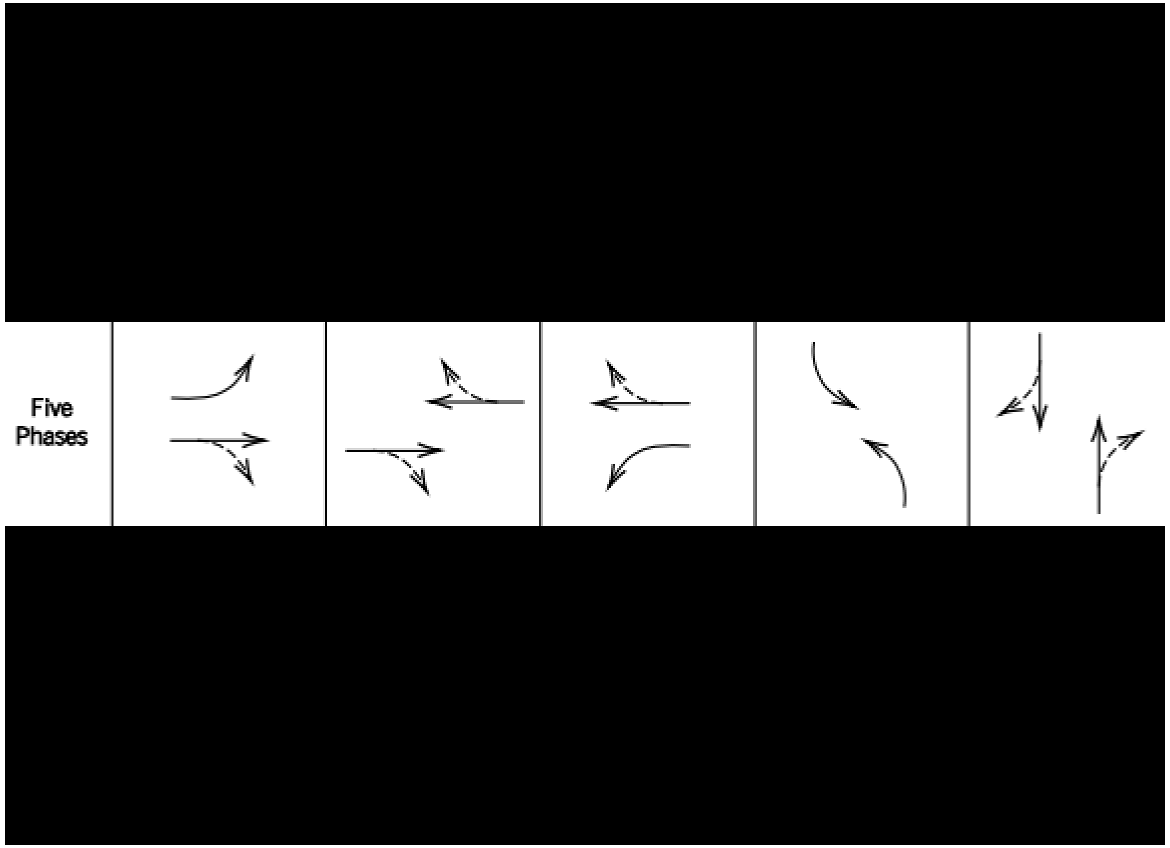
This phasing scheme, however, could prove to be very inefficient if one or more of the approaches includes a high left-turn volume.

Three-phase operation

If the high volume of left turns is present on both the northbound and southbound approaches, for example, each of these approaches could be given a separate phase. This would be more efficient because left-turning vehicles on these two approaches would not have to wait for gaps in the opposing traffic stream, thus greatly reducing delays for all vehicles.



Four phases operation



Five phase operation

Select Signal Phasing

PROTECTED LEFT TURN PHASE

- a primary concern in signal timing is to keep the **number of phases to a minimum**.
- Because protected-turn phases add to lost time, they should be **used only when warranted.**
- Because of opposing motor vehicle traffic, left-turn movements typically require a protected-turn phase much more often than right turns.
- In general, decisions on whether to provide a protected left-turn phase are based on one or more of the following factors:
    - Volume (just left turn or combination of left turn and opposing volume)
    - Delay Queuing (spillover)
    - Traffic progression
    - Opposing traffic speeds Geometry (number of left-turn lanes, crossing distance, sight distance)
    - Crash experience (which may also be related to any of the above factors)

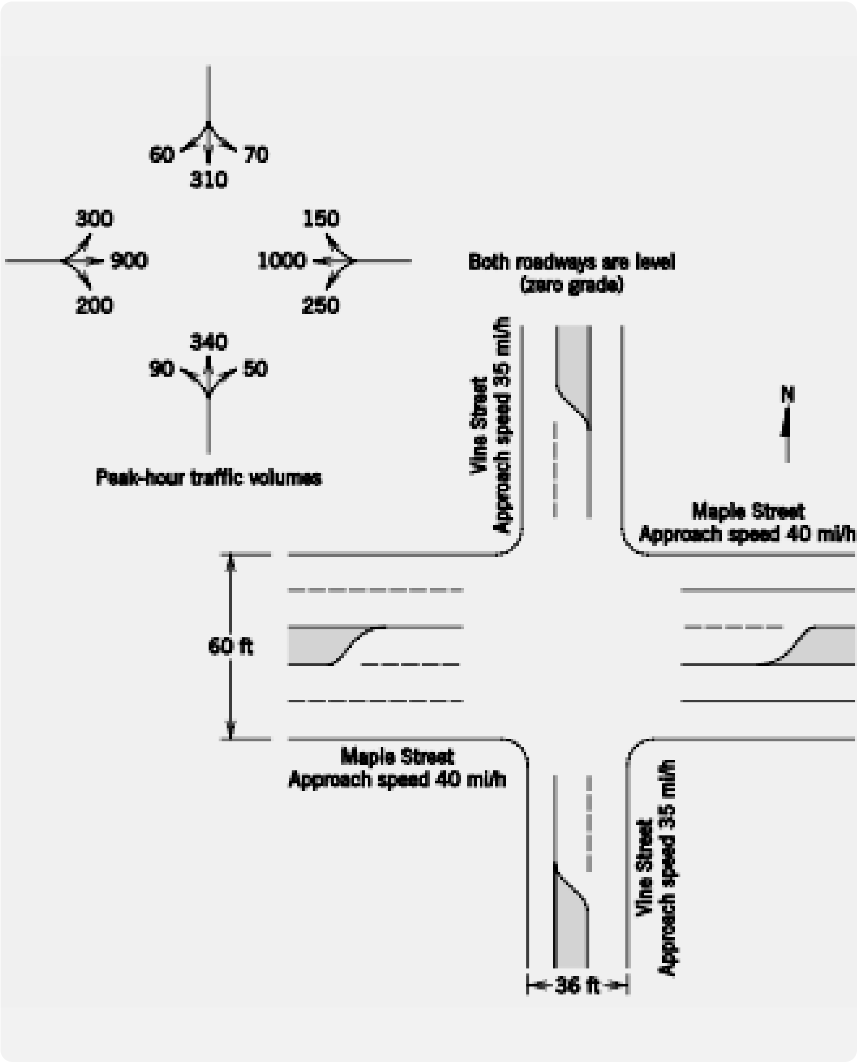
- The Highway Capacity Manual recommends that when the product of the left-turning vehicles and the opposing traffic exceeds **50,000 during peak hour for one opposing lane**, or **90,000 for two opposing lanes** or **110,000 for three opposing lanes**, then a protected left turn phase is required

EXAMPLE7.1

Refer to the intersection shown in Fig. 7.8. Use the cross-product guideline to determine if protected left-turn phases should be provided for any of the approaches.

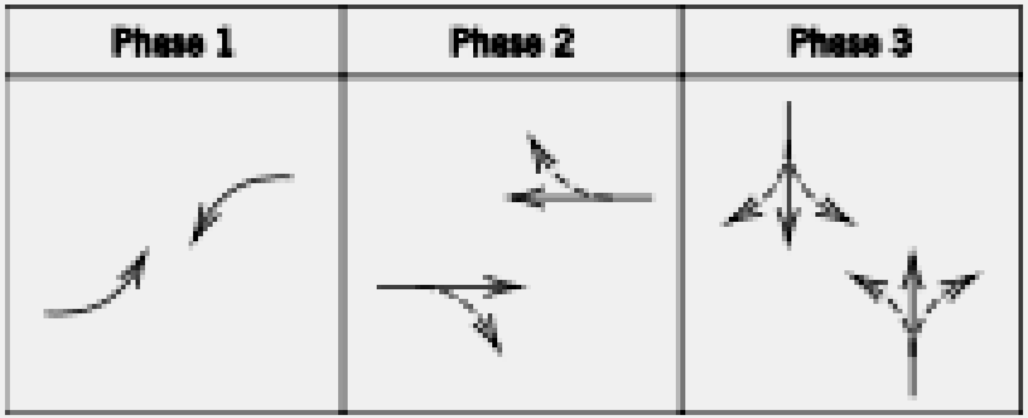
- There are 250 westbound vehicles that turn left during the peak hour.
- The product of the westbound left-turning vehicles and the opposing eastbound traffic (right-turn and straight- through vehicles) is **275,000 [250 × (900 + 200)].**
- There are 300 eastbound vehicles that turn left during the peak hour.
- The product of the eastbound left-turning vehicles and the opposing westbound traffic (right-turn and straight-through vehicles) is **345,000 [300 × (1000 + 150)].**
- Because the cross product for each of these approaches is greater than 90,000 (the requirement for two opposing lanes), a protected left-turn phase is suggested for the WB and EB left-turn movements.
- The NB and SB approaches do not require a protected left- turn phase using this criterion because the cross products for these approaches are less than 50,000 (for one opposing lane).

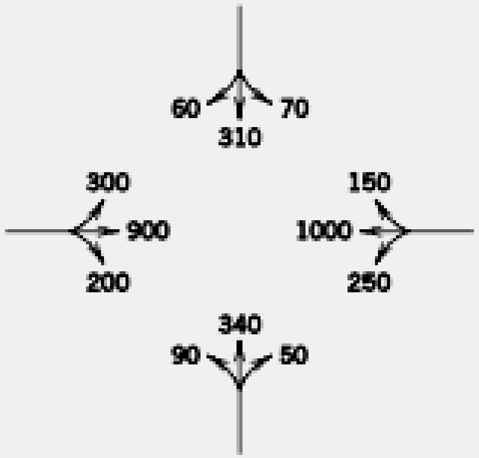
  Therefore, a three-phase traffic-signal plan is recommended



EXAMPLE7.1

Refer to the intersection shown in Fig. 7.8. Use the cross-product guideline to determine if protected left-turn phases should be provided for any of the approaches.

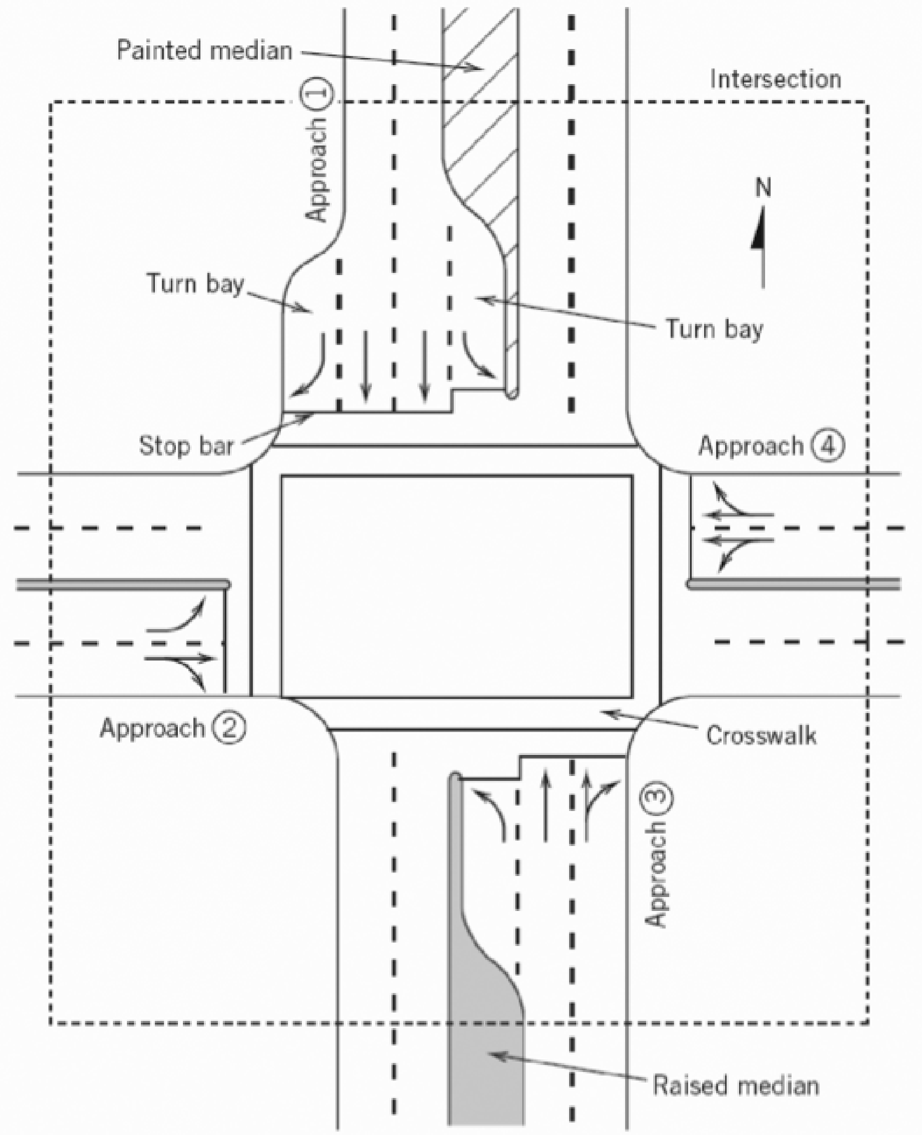




Peak-hour traffic volumes

STEPS TO SIGNAL DESIGN

- The process consists of:
  1. Development of a phase plan and sequence
  2. Determination of cycle length
  3. Allocating of effective green time or green splits
  4. Establishment of yellow and all red for each phase
  5. Checking pedestrian crossing requirements



ESTABLISH ANALYSIS LANE GROUPS

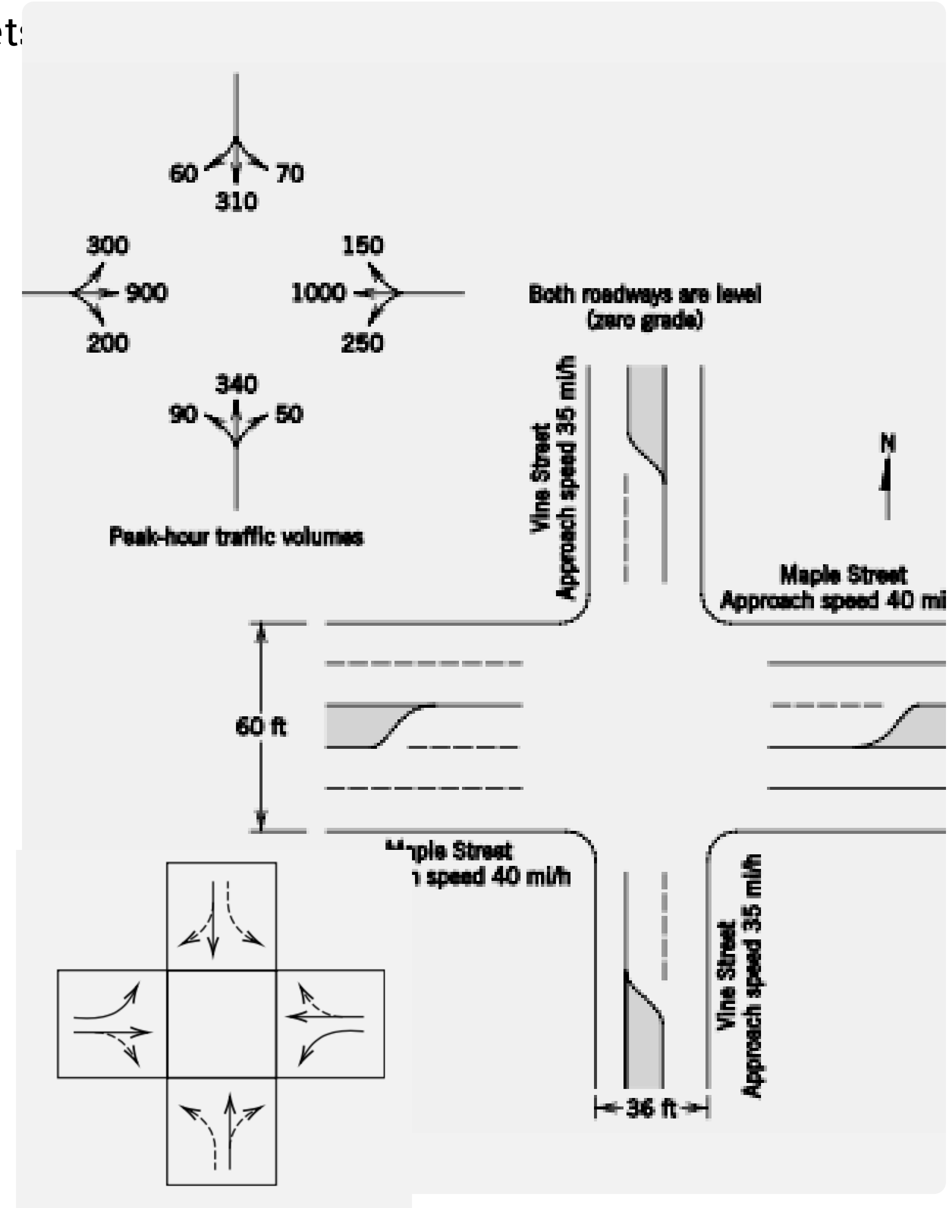
- Each intersection approach is initially treated separately, and the results are later aggregated. Thus, each approach must be subdivided into logical groupings of traffic movements for analysis purposes.
- The process consists of:
  - placing alike movements into movement groups (left-turn, right-turn, and through movements would be identified)
  - translating movement groups to lane groups based on the allowable movements from each lane.
  - The following general guidelines are offered for establishing lane groups [Transportation Research Board 2010]:
    - If an **exclusive turn lane** (or lanes) is present, it should be treated as a separate lane group.
    - If an approach includes an **exclusive left-turn and/or right-turn lan**e, the remaining lanes are usually considered as a single lane group.
    - Each **shared lane** on an approach should be treated as a separate lane group

Number of Approach Lanes	Movements by Lane and Corresponding Lane Groups
1	LT + TH + RT
2	EXC LT TH + RT
2	LT + TH TH + RT
3	EXC LT EXC TH TH + RT
3	EXC LT EXC TH EXC RT

EXAMPLE7.2

Determine the lane groups to use for analysis of the Maple and Vine Streets intersection

- The EB and WB left-turn movements will each be a lane group because they have a separate lane and move in a separate phase from the through/right-turn movements.
- The EB and WB through/right-turn movements proceed together in a separate phase and will therefore be separate lane groups.
- Although the right turns use only the outside lane, this movement's impact on the saturation flow rate for the two lanes combined will be determined.
- The NB and SB left turns will also each be a separate lane group.
- Because the through and right-turn movements use the same lane, they will be an individual lane group for both the NB and SB approaches.
- Even though they move during the same phase as the adjacent through and right-turn movements, these left turns are permitted and will have very different operating characteristics from the through and right-turn movements.



DETERMINE CRITICAL LANE GROUPS AND TOTAL CYCLE LOST TIME

- The lane group that controls the necessary green time for a phase is referred to as **the critical lane group.**
- The critical lane group for each phase is simply the lane group with the highest flow ratio of vehicle arrival rate to vehicle departure rate (λ/μ)
- The **flow ratio** is designated v/s (arrival flow rate divided by saturation flow rate)
- The sum of the flow ratios for the critical lane groups can be used to calculate a suitable cycle length
- The total lost time for the cycle will also be used in the calculation of cycle length.

$$Y_c = \sum_{i=1}^{n} \left(\frac{v}{s} \right)_{ci}$$

Y_c = sum of flow ratios for critical lane groups,
$(v/s)_{ci}$ = flow ratio for critical lane group i, and
n = number of critical lane groups.

$$L = \sum_{i=1}^{n} (t_L)_{ci}$$

L = total lost time for cycle in seconds,
$(t_L)_{ci}$ = total lost time for critical lane group i in seconds, and
n = number of critical lane groups.

EXAMPLE 7.3

Calculate the sum of the flow ratios for the critical lane groups for the three-phase timing plan determined in Example 7.1 given the saturation flow rates in Table 7.1.

Table 7.2 Flow Ratios and Critical Lane Groups for Three-Phase Design at Intersection of Maple Street and Vine Street

Phase 1	Phase 2	Phase 3
EB L: $\frac{300}{1750} = 0.171$ ✓	EB T/R: $\frac{1100}{3400} = 0.324$	SB L: $\frac{70}{450} = 0.156$
		NB L: $\frac{90}{475} = 0.189$
WB L: $\frac{250}{1750} = 0.143$	WB T/R: $\frac{1150}{3400} = 0.338$ ✓	SB T/R: $\frac{370}{1800} = 0.206$
		NB T/R: $\frac{390}{1800} = 0.217$ ✓

$$Y_c = \sum_{i=1}^{n} \left(\frac{v}{s}\right)_{ci}$$

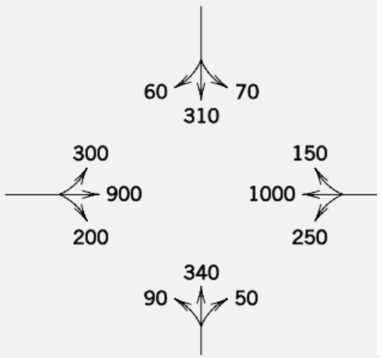
$$= 0.171 + 0.338 + 0.217 = \underline{\underline{0.726}}$$

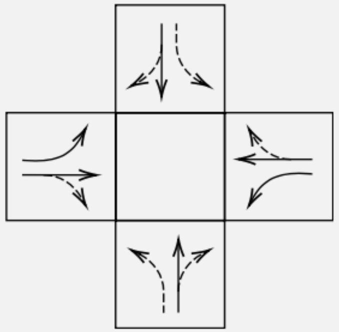
Assuming 2 seconds of start-up lost time and 2 seconds of clearance lost time (1 second of yellow time plus 1 second of all-red time)

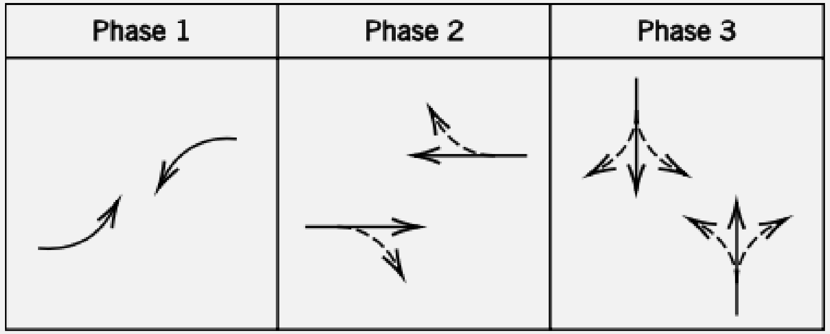
The total lost time for the cycle is then 12 seconds (3 phases × 4 s/phase).

Table 7.1 Saturation Flow Rates for Three-Phase Design at Intersection of Maple Street and Vine Street

Phase 1	Phase 2	Phase 3
EB L: 1750 veh/h	EB T/R: 3400 veh/h	SB L: 450 veh/h
		NB L: 475 veh/h
WB L: 1750 veh/h	WB T/R: 3400 veh/h	SB T/R: 1800 veh/h
		NB T/R: 1800 veh/h







EXAMPLE 7.4

Suppose it is necessary to run the NB and SB movements in a split-phase configuration (with phase 3 for SB movements and a new phase 4 for NB movements). Calculate the sum of the flow ratios for the critical lane groups and total cycle lost time for this situation, assuming the EB and WB movement phasing remains the same.

Table 7.3 Flow Ratios and Critical Lane Groups for Four-Phase Design (Split Phase for N-S Movements) at Intersection of Maple Street and Vine Street

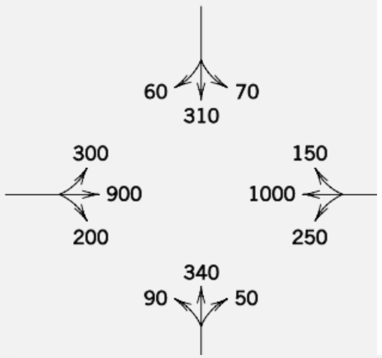
Phase 1	Phase 2	Phase 3	Phase 4
EB L: $\frac{300}{1750} = 0.171$ ✓	EB T/R: $\frac{1100}{3400} = 0.324$	SB L: $\frac{70}{1750} = 0.040$	NB L: $\frac{90}{1750} = 0.051$
WB L: $\frac{250}{1750} = 0.143$	WB T/R: $\frac{1150}{3400} = 0.338$ ✓	SB T/R: $\frac{370}{1800} = 0.206$ ✓	NB T/R: $\frac{390}{1800} = 0.217$ ✓

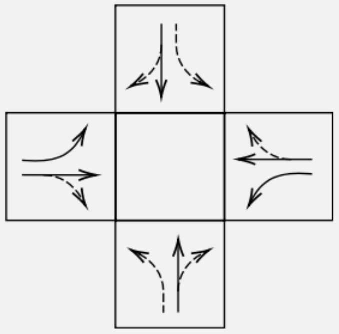
$$\sum_{i=1}^{n} \left(\frac{v}{s}\right)_{ci} = 0.171 + 0.338 + 0.206 + 0.217 = \underline{\underline{0.932}}$$

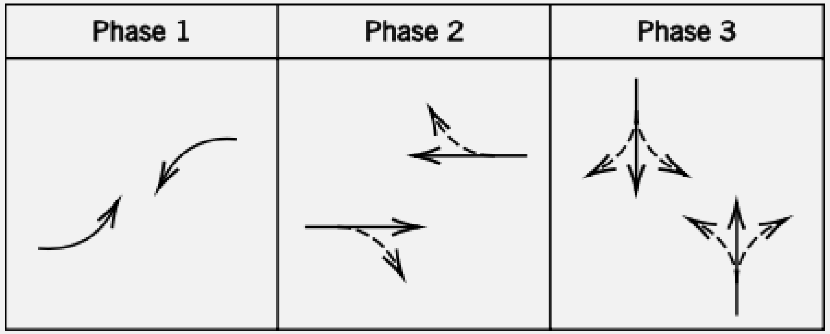
The total lost time for the cycle is 16 seconds (4 phases × 4 s/phase).

Table 7.1 Saturation Flow Rates for Three-Phase Design at Intersection of Maple Street and Vine Street

Phase 1	Phase 2	Phase 3
EB L: 1750 veh/h	EB T/R: 3400 veh/h	SB L: 450 veh/h NB L: 475 veh/h
WB L: 1750 veh/h	WB T/R: 3400 veh/h	SB T/R: 1800 veh/h NB T/R: 1800 veh/h







CALCULATE CYCLE LENGTH

- The cycle length is simply the summation of the individual phase lengths.
- Cycle lengths are generally kept as short as possible, typically between **60 and 75 seconds.** However, complex intersections with five or more phases can have cycle lengths of 120 seconds or more.
- Public acceptance or tolerance of large cycle lengths will vary by location (urban vs. rural), but as a rule, cycle lengths in excess of **3 minutes (180 seconds)** should be used only in exceptional circumstances.
- While the **total lost tim**e for the cycle and the **sum of the flow ratios** for the critical lane groups are predetermined, a critical intersection **volume/capacity ratio, X_c,** must be chosen for the desired degree of utilization.
  - if it is desired that the intersection operate at its full capacity, a value of **1.0** is used for X_c
  - to account for the randomness of vehicle arrivals X_c should be **less than one**
- The minimum cycle length equation gives the minimum cycle length necessary for the intersection to operate at a specified degree of capacity utilization and it **does not necessarily minimize the average vehicle delay** experienced by motorists at the intersection.

  A practical equation for the calculation of the cycle length that seeks to minimize vehicle delay was developed by Webster [1958].

$$C_{min} = \frac{L \times X_c}{X_c - \sum_{i=1}^{n} \left(\frac{v}{s}\right)_{ci}}$$

C_{min} = minimum necessary cycle length in seconds (typically rounded up to the nearest 5-second increment in practice),
L = total lost time for cycle in seconds,
X_c = critical v/c ratio for the intersection,
$(v/s)_{ci}$ = flow ratio for critical lane group i, and
n = number of critical lane groups.

$$C_{opt} = \frac{1.5 \times L + 5}{1.0 - \sum_{i=1}^{n} \left(\frac{v}{s}\right)_{ci}}$$

EXAMPLE 7.5

Calculate the minimum and optimal cycle lengths for the intersection of Maple and Vine Streets, using the information provided in the preceding examples, for both the three-phase and four-phase design.

- The sum of the flow ratios for the critical lane groups and the total cycle lost time were determined to be 0.726 and 12 seconds.
- A conservative value of 0.9 will be used for the critical intersection v/c ratio to minimize the potential of cycle failures due to occasionally high arrival volumes.

$$C_{min} = \frac{12 \times 0.9}{0.9 - 0.726} = 62.1 \rightarrow \underline{\underline{65\ \text{s}}} \text{ (rounding up to nearest 5 seconds)}$$

$$C_{opt} = \frac{1.5 \times 12 + 5}{1.0 - 0.726} = 83.9 \rightarrow \underline{\underline{85\ \text{s}}} \text{ (rounding up to nearest 5 seconds)}$$

- For the four-phase design, the sum of the critical flow ratios and the total cycle lost time were determined to be 0.932 and 16 seconds.
- The first issue with this design is that a higher Xc will need to be used because the sum of flow ratios for critical lane groups is higher than the 0.90 used for the three-phase design. To minimize the cycle length, the maximum value of 1.0 will be used for Xc

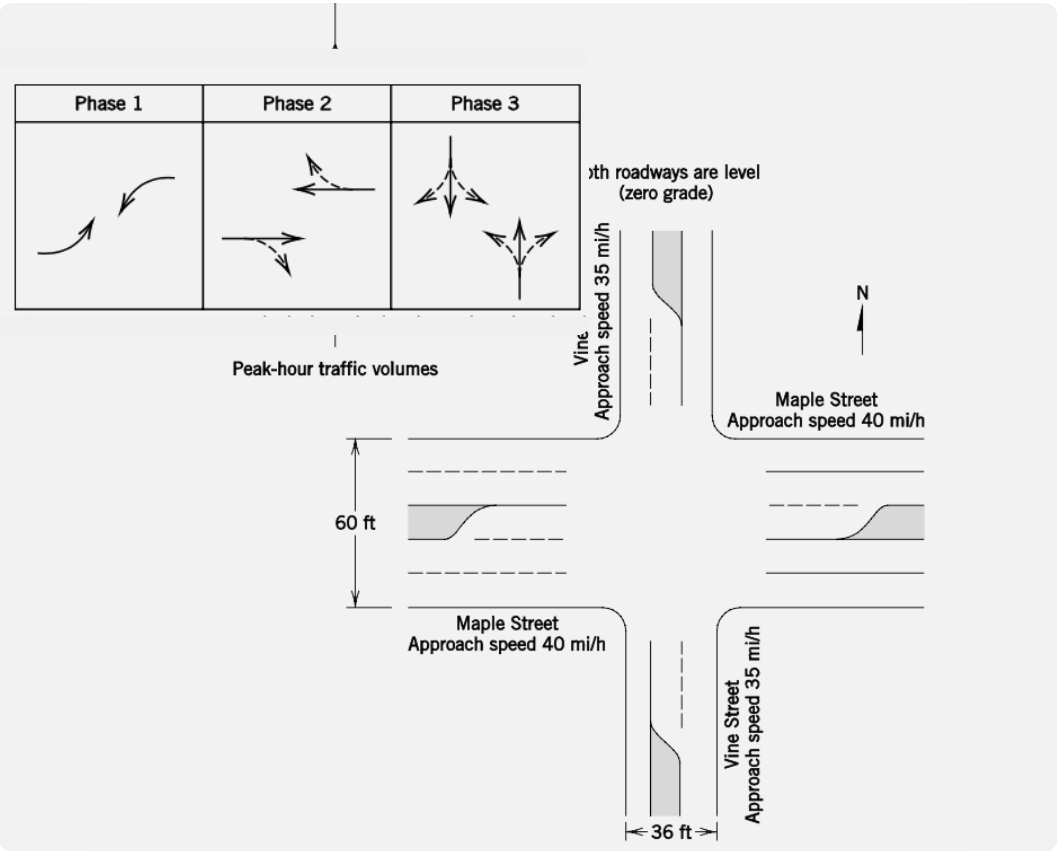
$$C_{min} = \frac{16 \times 1.0}{1.0 - 0.932} = \underline{\underline{235.3\ \text{s}}}$$

Despite the use of an Xc value of 1.0 (the intersection operating at capacity) to minimize the cycle length, an unreasonably high cycle length is still required for this design. Thus, this design is not nearly as desirable as the three-phase design.

EXAMPLE 7.5

Calculate the minimum and optimal cycle lengths for the intersection of Maple and Vine Streets, using the information provided in the preceding examples, for both the three-phase and four-phase design.

- Generally a split-phase design is recommended only under one or more of the following conditions:
  - The left turns are the dominant movement.
  - The left turns share a lane with the through movement.
  - There is a large difference in the total approach volumes.
  - There are unusual opposing approach geometrics.
  - It should also be noted that serving pedestrians in an efficient manner on split-phase approaches can be difficult.



ALLOCATION OF GREEN TIME

- The cycle length is the sum of all effective green times plus the total lost time.
- There are several strategies for allocating the green time to the various phases.
- One of the most popular and simplest is to distribute the green time so that the v/c ratios are equalized for the critical lane groups.

$$g_i = \left(\frac{v}{s}\right)_{ci} \left(\frac{C}{X_i}\right)$$

g_i = effective green time for phase i,

$(v/s)_{ci}$ = flow ratio for critical lane group i,

C = cycle length in seconds, and

X_i = v/c ratio for lane group i.

EXAMPLE 7.6

Determine the green-time allocations for the 65-second cycle length found in Example 7.5, using the method of v/c ratio equalization.

- Because the calculated cycle length was rounded up a few seconds, the critical intersection v/c ratio for this rounded cycle length will be calculated for use in the green-time allocation calculations

$$X_c = \frac{\sum_{i=1}^{n}\left(\frac{v}{s}\right)_i \times C}{C-L} \longrightarrow \begin{aligned} \Sigma(v/s)_{ci} &= 0.726 \text{ (Example 7.3)} \\ C &= 65 \text{ s (Example 7.5)} \\ L &= 12 \text{ s (Example 7.4)} \end{aligned} \longrightarrow X_c = \frac{0.726 \times 65}{65-12} = 0.890$$

- The cycle length of 65 seconds and Xc of 0.890 are used to calculate the effective green times for the three phases, as follows:

$$g_1 = \left(\frac{v}{s}\right)_{c1}\left(\frac{C}{X_1}\right) = 0.171 \times \frac{65}{0.890} = \underline{\underline{12.5\text{ s}}}$$ (EB and WB left-turn movements)

$$g_2 = \left(\frac{v}{s}\right)_{c2}\left(\frac{C}{X_2}\right) = 0.338 \times \frac{65}{0.890} = \underline{\underline{24.7\text{ s}}}$$ (EB and WB through and right-turn movements)

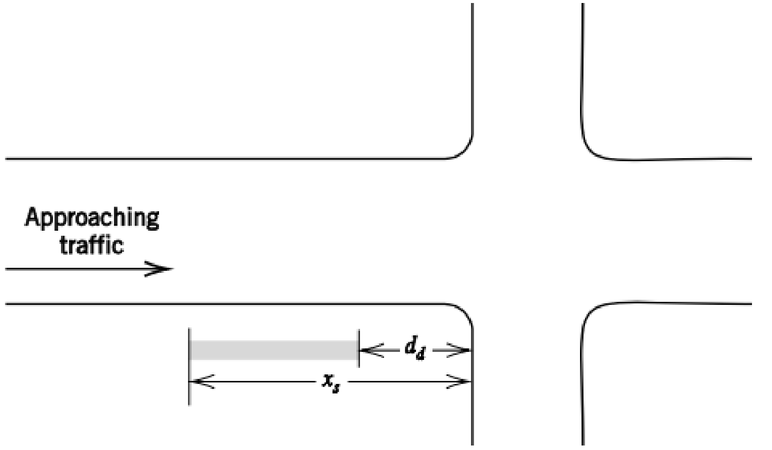
$$g_3 = \left(\frac{v}{s}\right)_{c3}\left(\frac{C}{X_3}\right) = 0.217 \times \frac{65}{0.890} = \underline{\underline{15.8\text{ s}}}$$ (NB and SB left-, through, and right-turn movements)

$$\begin{aligned} C &= g_1 + g_2 + g_3 + L \\ &= 12.5 + 24.7 + 15.8 + 12 = 65.0 \end{aligned}$$

CALCULATE CHANGE AND CLEARANCE INTERVALS

- **The change interval** alerts drivers that the green interval is about to end and that they should come to stop before entering the intersection, or continue through the intersection if they are too close to come to a safe stop.
- **The clearance interval** allows those vehicles that might have entered the intersection at the end of the yellow to clear the intersection before conflicting traffic movements are given a green signal indication.
- Typically, the yellow time is in the range of 3 to 5 seconds.
- Warning times that are shorter than 3 seconds and longer than 5 seconds are not practical because
    - long warning times encourage motorists to continue to enter the intersection

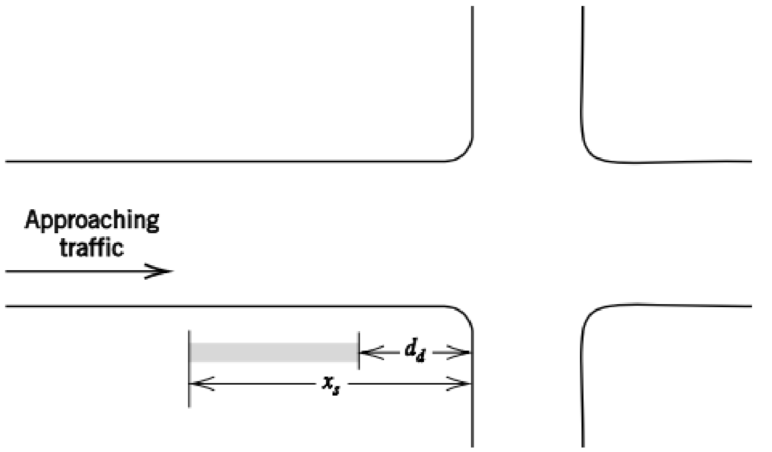
      short times can place the driver in a dilemma zone.



CALCULATE CHANGE AND CLEARANCE INTERVALS

Dilemma zone

- A dilemma zone is created for the driver if a safe stop before the intersection cannot be accomplished, and continuing through the intersection at a constant speed (without accelerating) will result in the vehicle entering the intersection during a red indication.
    1. Suppose a vehicle traveling at a constant speed requires distance x_s to stop.
    2. If the vehicle is closer to the intersection than distance d_d, then it can enter before the all-red indication.
    3. If the vehicle is in the shaded area (x_s – d_d from the intersection) when the yellow light is displayed, the driver is in the dilemma zone and can neither stop in time nor continue through the intersection at a constant speed without passing through a red indication.



CALCULATE CHANGE AND CLEARANCE INTERVALS

- Formulas and policies for calculating yellow (Y) and all-red (AR) times vary by agency, but one set of commonly accepted formulas is provided in the Traffic Engineering Handbook [ITE 1999]
- To avoid a dilemma zone and the possibility of a vehicle being in the intersection when a conflicting movement receives a green-signal indication, <u>the total of the change and clearance intervals (yellow plus all-red times) should always be equal to or greater than the sum of Eqs. 7.12 and 7.13</u>
- Note that separate calculations are usually required for exclusive left-turn phases, as vehicle approach speeds are often lower than for through vehicles and intersection crossing distances may be longer (due to the width of the opposing direction and the circular travel path).

$$Y = t_r + \frac{V}{2a + 2gG}$$

Y = yellow time (usually rounded up to the nearest 0.5 second),
t_r = driver perception/reaction time, usually taken as 1.0 second,
V = speed of approaching traffic in ft/s,
a = deceleration rate for the vehicle, usually taken as 10.0 ft/s^2,
g = acceleration due to gravity [32.2 ft/s^2], and
G = percent grade divided by 100.

$$AR = \frac{w + l}{V}$$

AR = all-red time (usually rounded up to the nearest 0.5 second),
w = width of the cross street in ft,
l = length of the vehicle, usually taken as 20 ft, and
V = speed of approaching traffic in ft/s.

EXAMPLE 7.7

Determine the yellow and all-red times for vehicles traveling on Vine and Maple Streets as shown in Fig 7.8.

For the Vine Street phasing (NB &SB)

$$Y = 1.0 + \frac{(35 \times 5280/3600)}{2(10)}$$

$$= 3.6 \rightarrow \underline{\underline{4.0\text{ s}}} \text{ (rounding to the nearest 0.5 s)}$$

$$AR = \frac{60 + 20}{35 \times 5280/3600}$$

$$= 1.6 \rightarrow \underline{\underline{2.0\text{ s}}} \text{ (rounding to the nearest 0.5 s)}$$

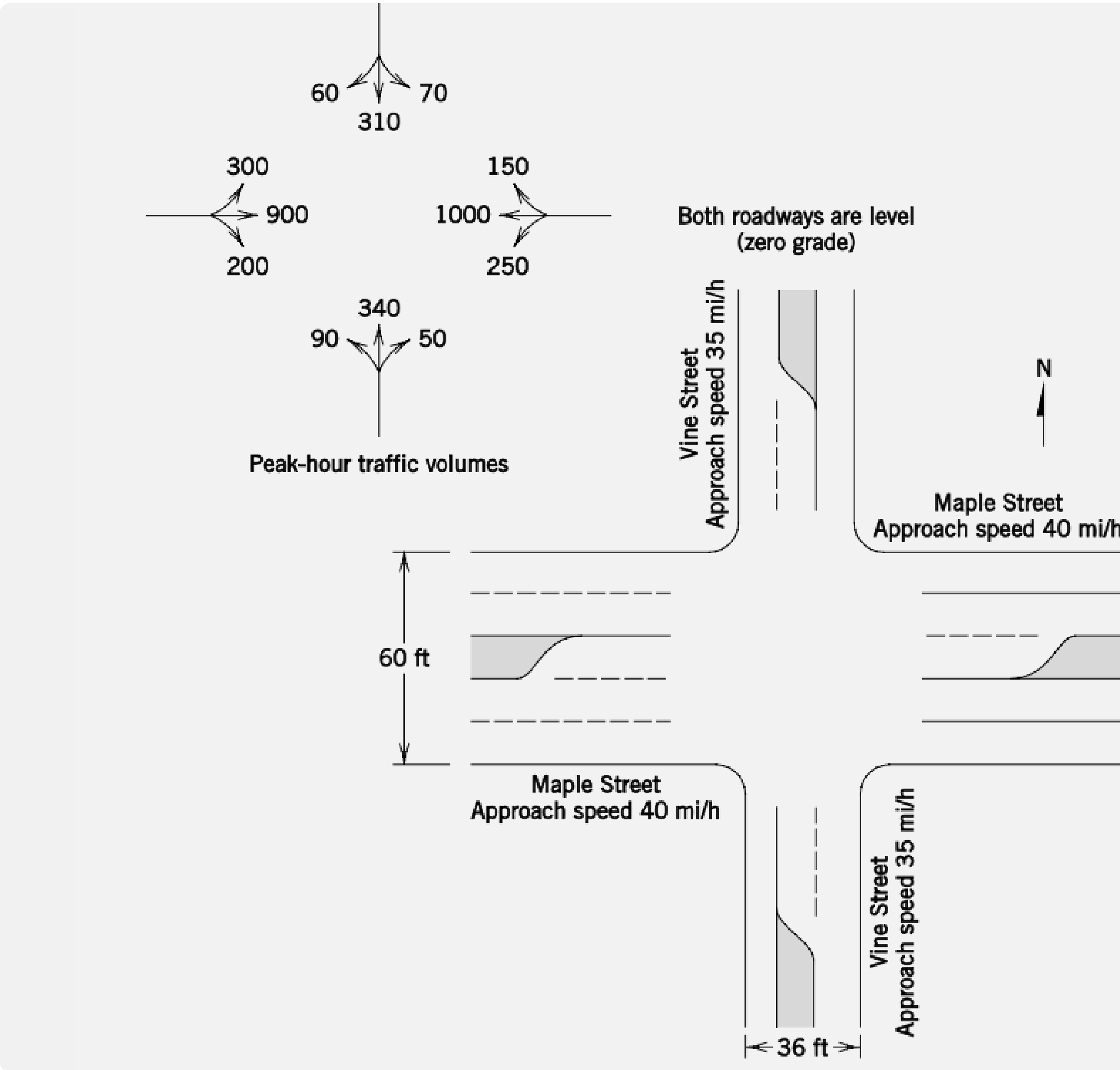
For the Maple Street phasing (EB &WB)

$$Y = 1.0 + \frac{(40 \times 5280/3600)}{2(10)}$$

$$= 3.9 \rightarrow \underline{\underline{4.0\text{ s}}} \text{ (rounding to the nearest 0.5 s)}$$

$$AR = \frac{36 + 20}{40 \times 5280/3600}$$

$$= \underline{\underline{1.0\text{ s}}}$$



CHECK PEDESTRIAN CROSSING TIME

- In urban areas and other locations where pedestrians are present, the signal-timing plan should be checked for its ability to provide adequate pedestrian crossing time.
- At locations where streets are wide and green times are short, it is possible that pedestrians can be caught in the middle of the intersection when the phase changes.
- If there is not enough green time for a pedestrian to safely cross the street, the apportioned green time should be increased to meet the pedestrian needs.
- The generally recommended **walking speed of 3.5 ft/s** [U.S. Federal Highway Administration 2009] represents a slower-than-average speed. However, at intersections where a significant number of slower pedestrians (elderly, vision impaired, etc.) are served, the use of a slower walking speed may be warranted.

$$G_p = 3.2 + \frac{L}{S_p} + \left(0.27 N_{ped}\right) \quad \text{for } W_E \leq 10 \text{ ft (3.05 m)}$$

$$G_p = 3.2 + \frac{L}{S_p} + \left(2.7 \frac{N_{ped}}{W_E}\right) \quad \text{for } W_E > 10 \text{ ft (3.05 m)}$$

G_p = minimum pedestrian green time in seconds,
3.2 = pedestrian start-up time in seconds,
L = crosswalk length in ft,
S_p = walking speed of pedestrians, usually taken as 3.5 ft/s,
N_{ped} = number of pedestrians crossing during an interval, and
W_E = effective crosswalk width in ft.

EXAMPLE 7.8

Determine the minimum amount of pedestrian green time required for the intersection of Vine and Maple Streets. Assume a maximum of 15 pedestrians crossing either street during any one phase and a crosswalk width of 8 ft.

For the Vine Street phasing (NB &SB)

$$G_p = 3.2 + \frac{60}{3.5} + (0.27 \times 15) = \underline{\underline{24.4 \text{ s}}}$$

- In Example 7.6, Vine Street was assigned 15.8 seconds of effective green time [13.8 seconds of displayed green time (from Eq. 7.3)]
- This amount of time is insufficient for pedestrians crossing Maple Street. Therefore, the green time for this phase will have to be increased to accommodate crossing pedestrians, and the overall signal timing plan adjusted accordingly

For the Maple Street phasing (EB &WB)

$$G_p = 3.2 + \frac{36}{3.5} + (0.27 \times 15) = \underline{\underline{17.5 \text{ s}}}$$

In Example 7.6, Maple Street was assigned 24.7 seconds of effective green time (23.7 seconds of displayed green time) for this phase, so this green time is adequate for pedestrians crossing Vine Street.