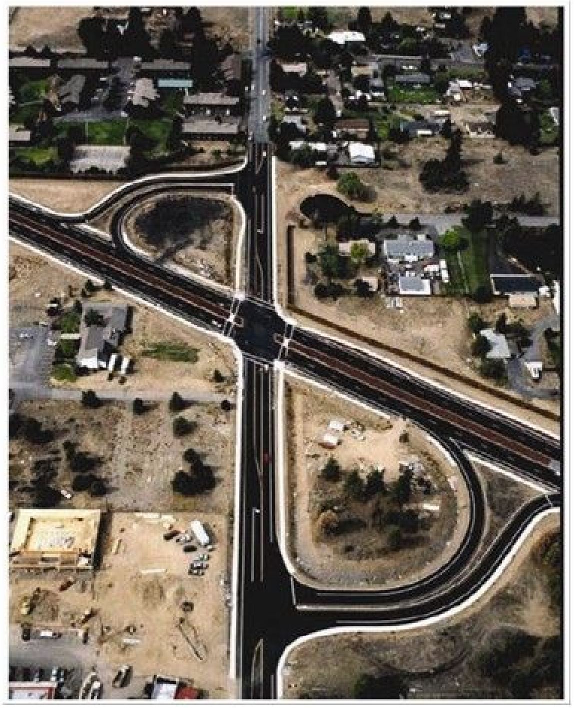
Intersections

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



(a) (b)

Figure 7.1 Examples of at-grade intersections a) on highways and b) in urban areas

Types of intersections

- Some may classify intersections as 3-way, 4-way, 5-way, 6-way, etc. depending on the number of road segments (arms) that come together at the intersection.
  - 3-way intersection - A junction between three road segments (arms) is a T-junction (two arms form one road) or a Y-junction.
  - 4-way intersections are the most common, because they usually involve a crossing over of two streets or roads.

(a) (b) (c)

Figure 7.2 Examples of a) a three-way, b) a four-way, and c) a five-way intersection

Types of intersections

- Another way of classifying intersections is by traffic control:
  - Uncontrolled intersections, without signs or signals (or sometimes with a warning sign).

Figure 7.3a An example of uncontrolled intersection

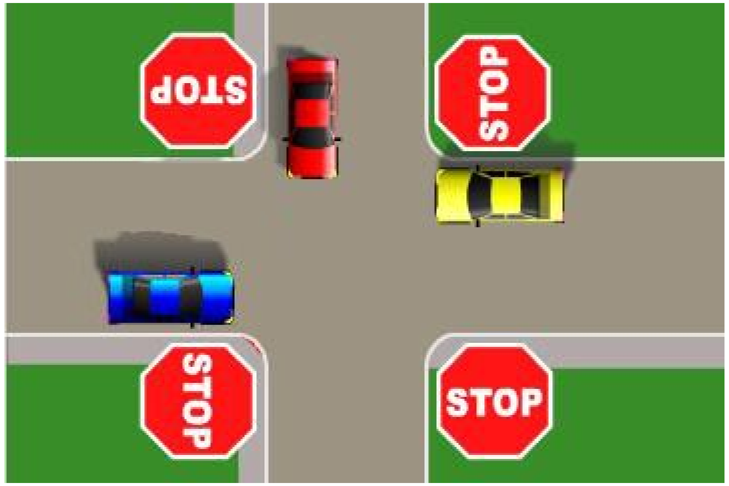
Types of intersections

- Priority rules may vary by country: on a 4-way intersection traffic from the right often has priority; on a 3-way intersection either traffic from the right has priority again, or traffic on the continuing road.
- Yield-controlled intersections may or may not have specific "YIELD" signs (known as "GIVE WAY" signs in some countries).

Figure 7.3b Yield-controlled intersections may or may not have specific "YIELD" signs (known as "GIVE WAY" signs in some countries

Types of intersections

- Stop-controlled intersections have one or more "STOP" signs.
- Two-way stops are common, while some countries also employ four-way stops.



(a) (b)

Figure 7.3c Intersections can be designed to have a) a four-way or b) a two-way stop control

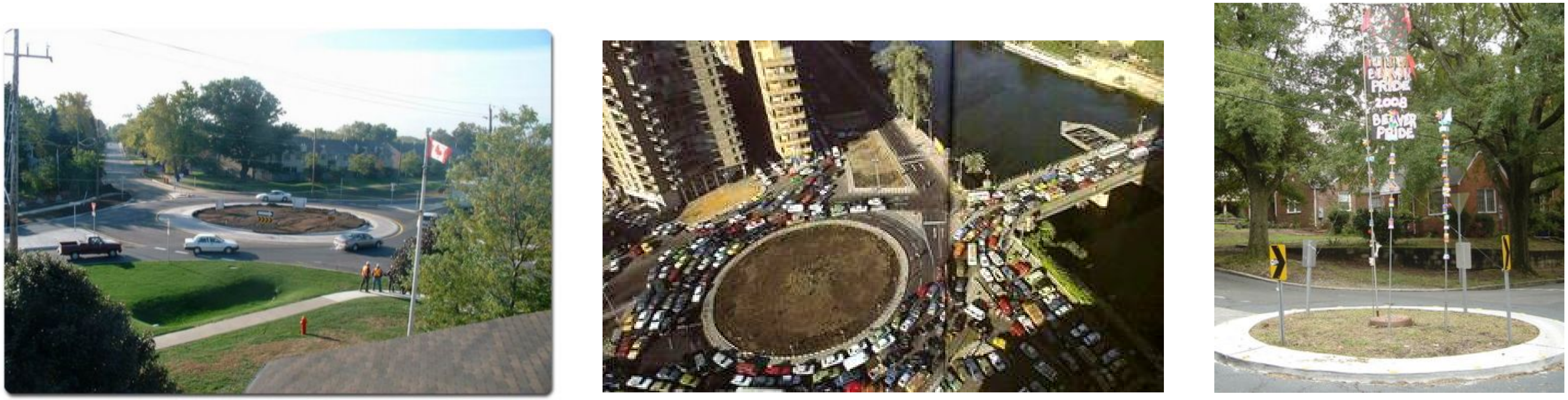
Types of intersections

- Signal-controlled intersections depend on traffic signals which indicate which traffic is allowed to proceed at any particular time.

Figure 7.3d   An example of signalized intersection

Types of intersections

- A traffic circle is a type of intersection at which traffic streams are directed around a circle. Types of traffic circles include roundabouts, 'mini-roundabouts', 'rotaries', "STOP"-controlled circles, and signal-controlled circles.



(a) (b) (c)

Figure 7.3e Use of traffic circles as a) and b)roundabouts, and c) a traffic calming circle

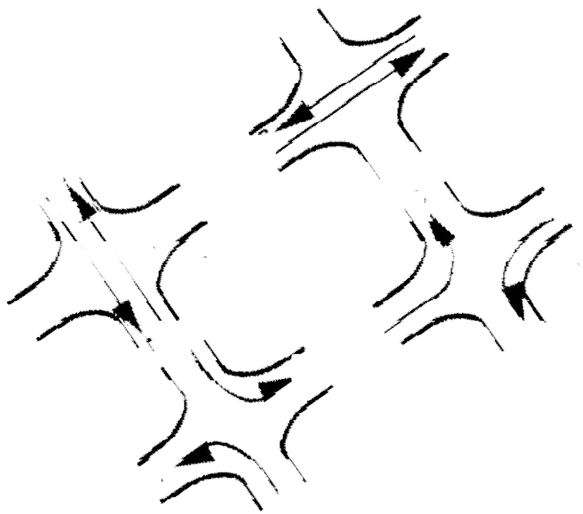
Traffic Control & Analysis at Signalized Intersections

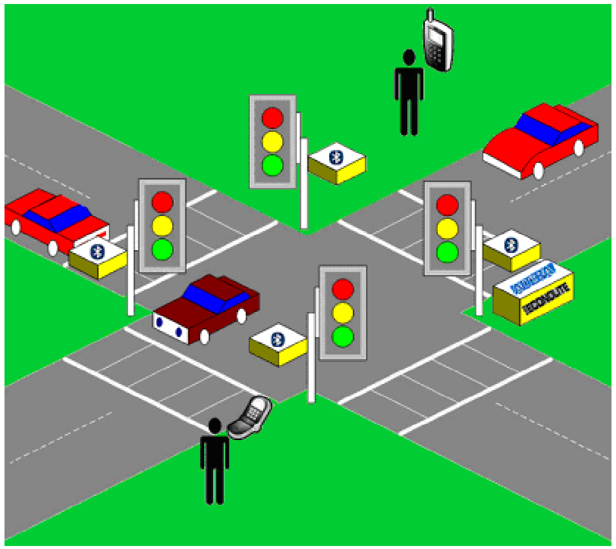
Motivation:

- Due to conflicting traffic movements, roadway intersections are a source of great concern to traffic engineers.
- Intersections can be a major source of crashes and vehicle delays (as vehicles yield to avoid conflicts with other vehicles).
- 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.

Intersections

- For analysis, 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.





Traffic Signalization -Definitions

The following terminology is commonly used in the design of traffic signal controls.

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) remain the same for all approaches.

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.

Cycle length: The total time for the signal to complete one cycle (given the symbol C and usually expressed in seconds).

Traffic Signalization -Definitions

Green time (G): The amount of time within a cycle for which a movement or combination of movements receives a green indication (the illumination of a signal lens).

Yellow time (Y): The amount of time within a cycle for which a movement or combination of movements receives a yellow indication. This time is referred to as the change interval, as it alerts drivers that the signal indication is about to change from green to red.

Red time (R): The amount of time within a cycle for which a movement or combination of movements receives a red indication. This is expressed in seconds and given the symbol R.

Traffic Signalization -Definitions

All-red time (AR)

- The time within a cycle in which all approaches have a red indication.
- This time is referred to as the clearance interval, because it allows vehicles that might have entered at the end of the yellow interval to clear the intersection before the green phase starts for the next conflicting movement(s).
- This type of interval is becoming increasingly common for safety reasons because the rate of vehicles entering at the end of the yellow and beginning of the red indication has steadily increased in recent years.

The term "**movement**" is used frequently in the preceding definitions. In addition to a directional descriptor, such as left, through, or right, a distinction is made by categorizing movements as either **protected** or **permitted**.

Traffic Signalization -Definitions

Protected movement:

- A movement that has the right-of-way and does not need to yield to conflicting movements, such as opposing vehicle traffic or pedestrians.
- Through movements, which are always protected, are given a green full circle indication (or in some geometric configurations, a green arrow pointing up).
- Left- or right-turn movements that are protected are given a green arrow indication (pointing either left or right).

Traffic Signalization -Definitions

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.
- Left- or right-turn movements with a green full circle indication are permitted movements.
- Left-turning vehicles in this situation must wait for gaps in the opposing through and right-turning traffic before making their turns.
- Right- turning vehicles must yield to pedestrians in the adjacent crosswalk before making their turns.

Traffic Signalization -Definitions

Pre-timed:

- A signal whose timing (cycle length, green time, etc.) is fixed over specified time periods and does not change in response to changes in traffic flow at the intersection.
- No vehicle detection is necessary with this mode of operation.

Semi-actuated:

- A signal whose timing (cycle length, green time, etc.) is affected when vehicles are detected (by video, pavement-embedded inductance loop detectors, etc.) on some, but not all, approaches.
- This mode of operation is usually found where a low-volume road intersects a high- volume road, often referred to as the minor and major streets, respectively. In such cases, green time is allocated to the major street until vehicles are detected on the minor street; then the green indication is briefly allocated to the minor street and then returned to the major street.

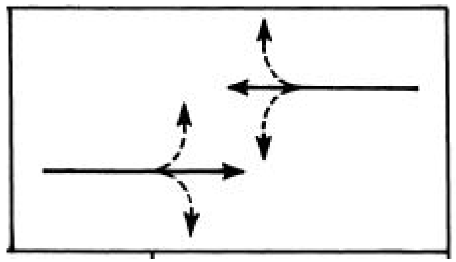
Traffic Signalization -Definitions

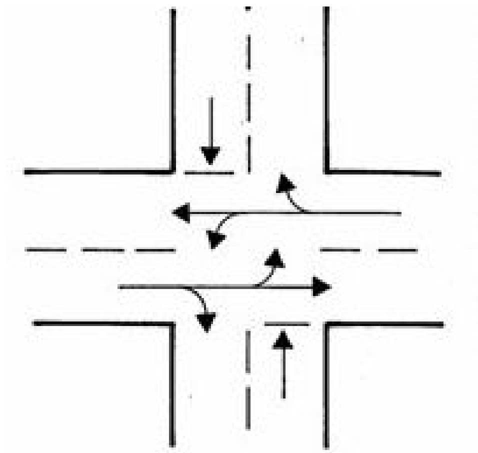
Fully-actuated:

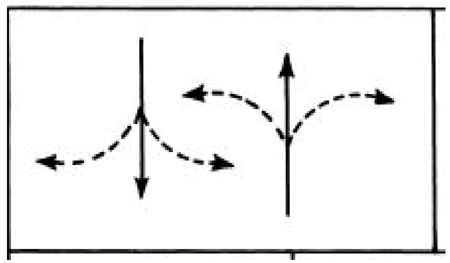
- A signal whose timing (cycle length, green time, etc.) is completely influenced by the traffic volumes, when detected, on all of the approaches.
- Fully actuated signals are most commonly used at intersections of two major streets and where substantial variations exist in all approach traffic volumes over the course of a day.

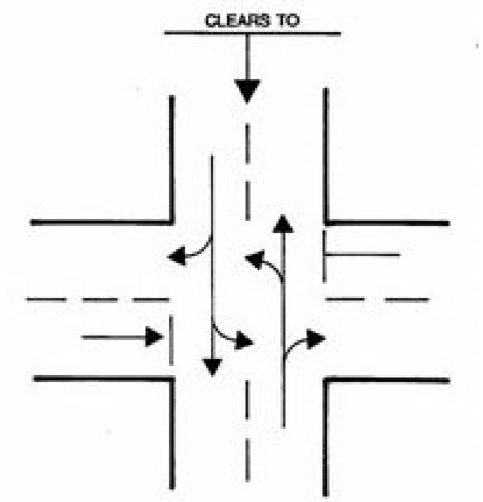
Phase Diagrams

a) Two-phase diagrams



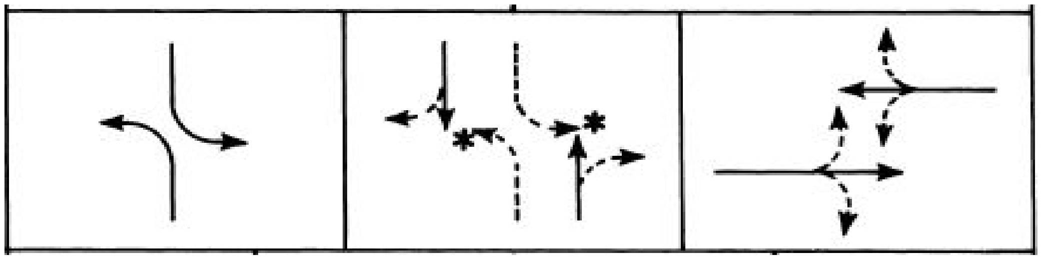


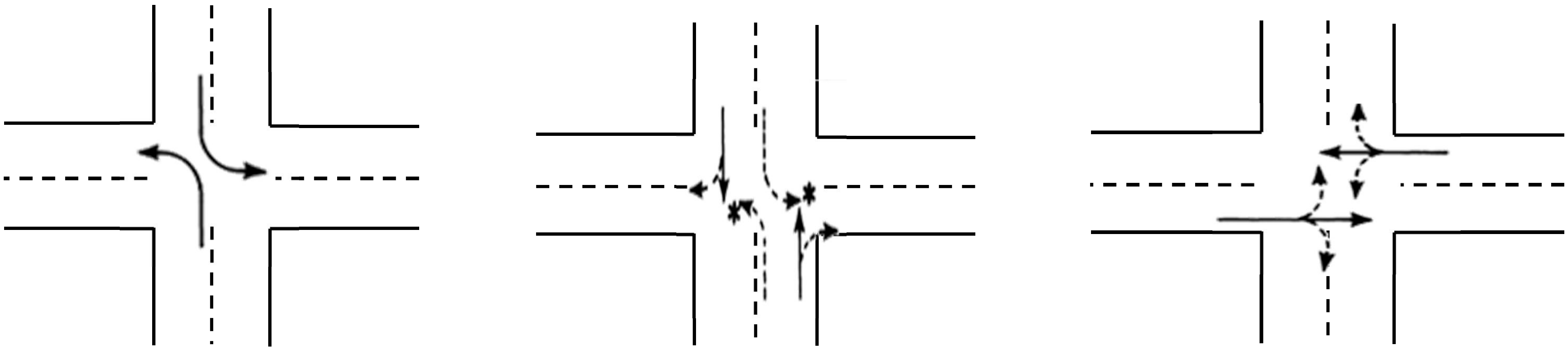




Phase Diagrams

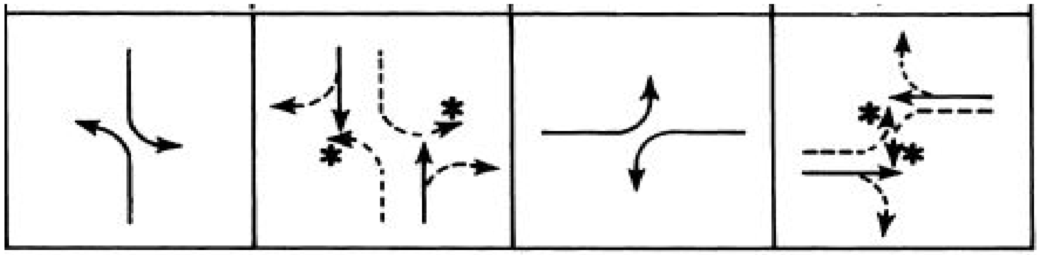
b) Three-phase diagrams (with an exclusive left-turn phase)

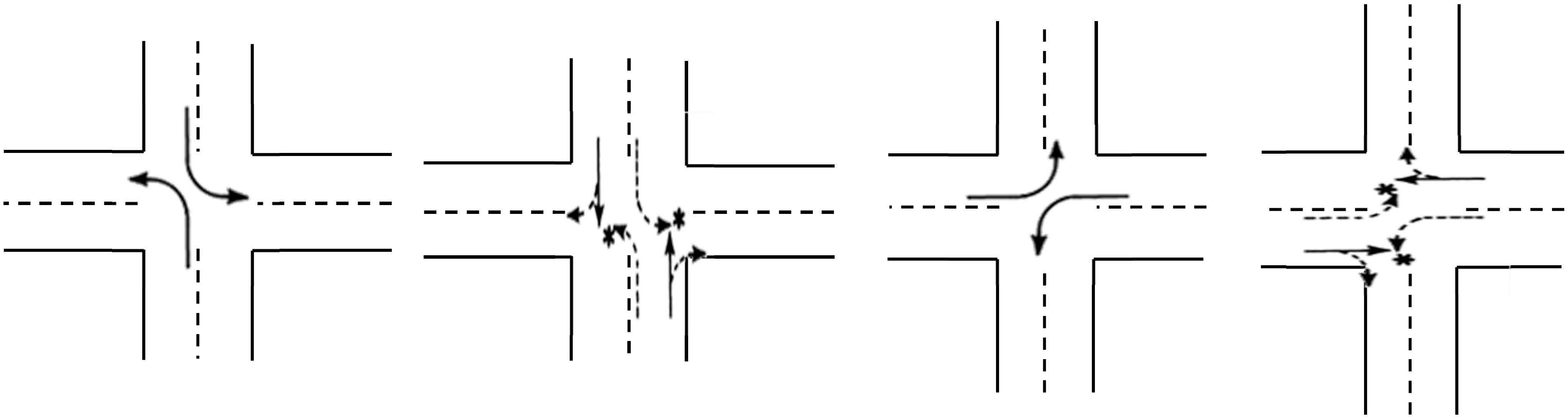




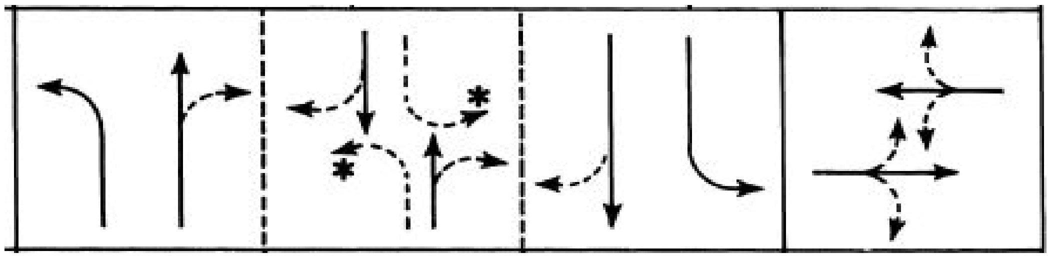
Phase Diagrams

c) Four-phase diagrams (with two exclusive left-turn phases)





d) Four-phase diagrams (with leading/lagging green overlapping phases)



Analysis of Traffic at Signalized Intersections

Saturation Flow Rate:

- The saturation flow rate is the maximum hourly volume that can pass through an intersection, from a given lane or group of lanes, if that lane (or lanes) were allocated constant green over the course of an hour.
- Saturation flow rate is given by

$$S = \frac{3600}{h} \tag{7.1}$$

where

S = saturation flow rate in veh/h,

h = saturation headway in s/veh.

Analysis of Traffic at Signalized Intersections

Lost Time

- Due to the traffic signal's function of continuously alternating the right-of-way between conflicting movements, traffic streams are continuously started and stopped.
- Every time this happens, a portion of the cycle length is not being completely utilized, which translates to lost time (time that is not effectively serving any movement of traffic).
- Total lost time for a phase is a combination of start-up and clearance lost times.
- Start-up lost time takes place at the beginning of “green (G)”indication, while the clearance lost time takes place during the “yellow (Y)” and at the beginning of “red(R)” indications.

Analysis of Traffic at Signalized Intersections

- Start-up lost times occur because when a signal indication turns from red to green, drivers in the queue do not instantly start moving at the saturation flow rate; there is an initial lag due to drivers reacting to the change of signal indication (**the first lost time period t_1 in the Green indication in Figure 7.4)**
- This start-up lost time has a typical value of around 2 seconds.

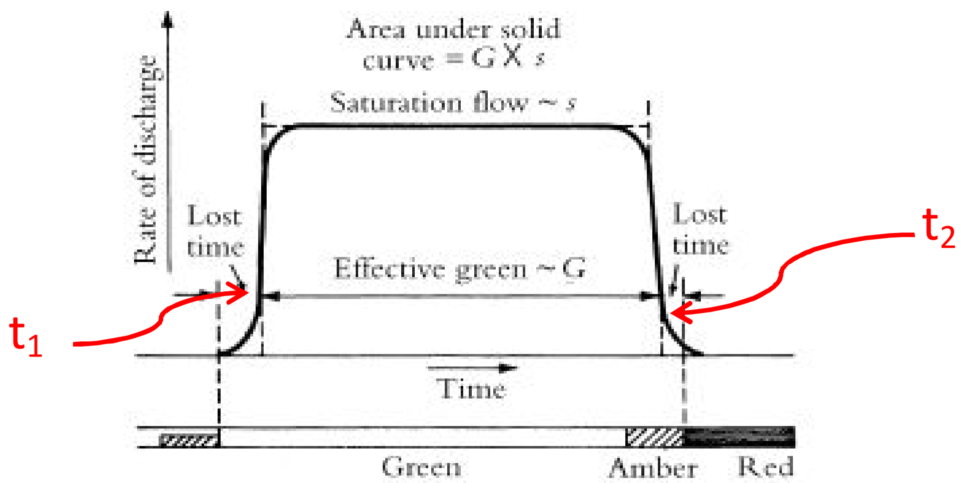


Figure 7.4 Discharge of vehicles at various times and lost times during a Green period

Analysis of Traffic at Signalized Intersections

- Stopping of traffic results in lost time, referred as “clearance lost time”
- When the signal indication turns “green (G)” to “yellow(Y)”, the last portion of Y is generally not utilized, (the second lost time period t2 in the Green indication in Figure 7.4)
- Additionally, if there is an “all-red (AR)” interval, this period is not utilized by the traffic, too)
- The **total lost time (t_L)** can be written as the summation of the **start-up lost time (t_{sl})** and **clearance lost time (t_{cl})**, and given as

$$t_L = t_{sl} + t_{cl} = t_1 + t_2 + AR \qquad (7.2)$$

- t_1, t_2 are as shown in figure 7.4. and AR is shown in Figure 7.5.
- Hence $t_{sl} = t_1$ and $t_{cl} = t_2 + AR$

Analysis of Traffic at Signalized Intersections

Light sequence diagram

The diagram that shows the timing of signal indications for all phases simultaneously during a cycle of a signal control system. A light sequence diagram for a three-phase system is shown below.

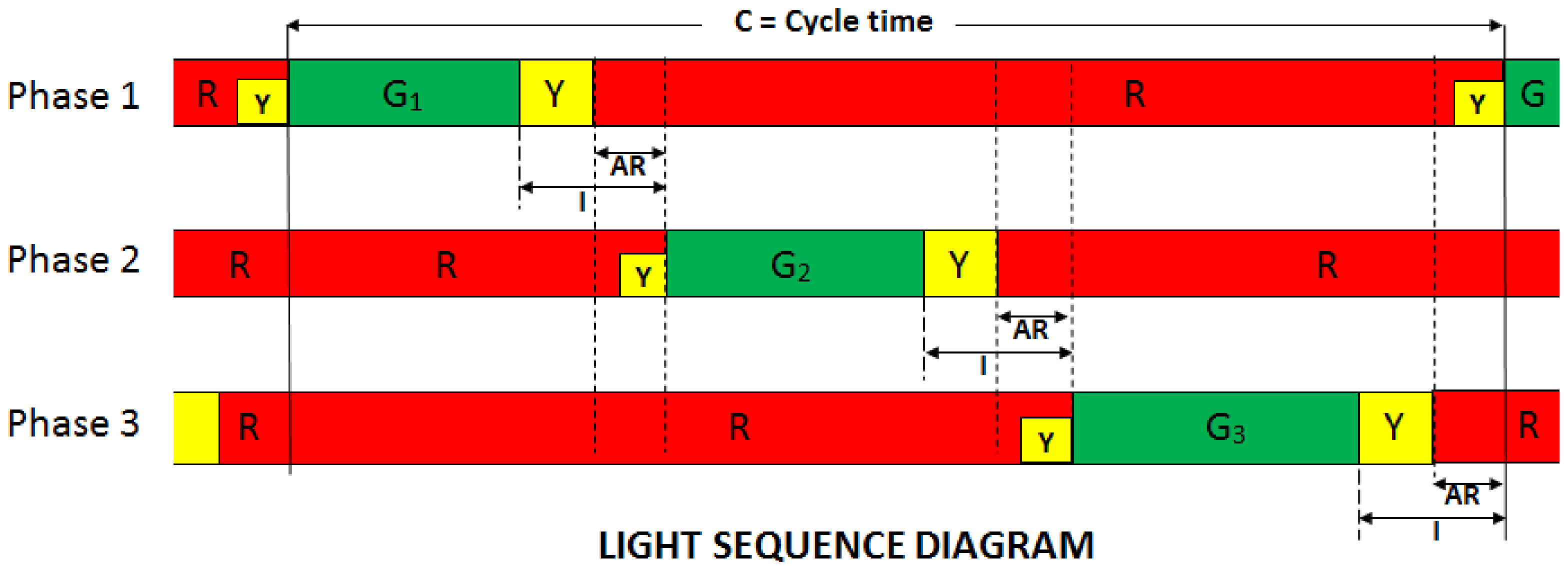


Figure 7.5 Light sequence diagram

Analysis of Traffic at Signalized Intersections

- In order to draw light sequence diagram, G_i (actual green times), Y (Yellow or Amber time), all red time (AR) or I (Intergreen period) should be known.
- **All red time (AR):** the lost time due to signal indications showing red for all phases during one cycle.
- **Intergreen period (I)**: Time interval between end of the green period of the phase losing the right of way and the beginning of the green period of the phase gaining the right of way.
- For a given signal system the following relations hold:

$$I = Y + AR \tag{7.3}$$

$$C = \sum_1^n G_i + nI = \sum_1^n G_i + n(Y + AR) \tag{7.4}$$

Where, ***n*** = the number of phase

G_i **=** Actual green time for phase i

Analysis of Traffic at Signalized Intersections

Effective Green and Red Times

- Time during a cycle that is effectively (or not effectively) utilized by traffic must be used rather than the time for which green, yellow, and red signal indications are actually displayed, because they are most likely different.
- This result in two measures of interest: **the effective green time** and **the effective red time**.
- The effective green time is the time during which a traffic movement is effectively utilizing the intersection.

Analysis of Traffic at Signalized Intersections

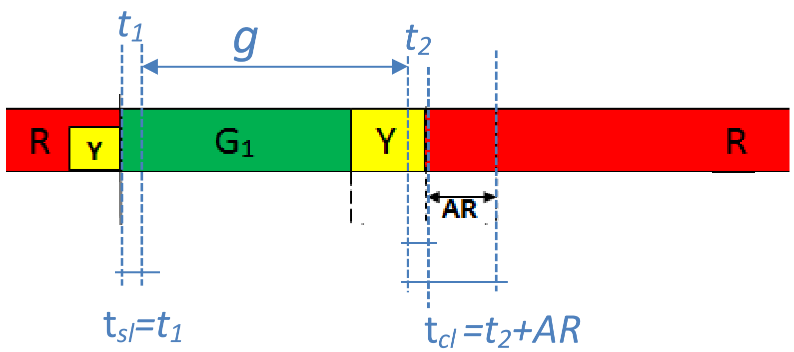
- The effective green time for a given movement or phase is calculated as:

$$g = G + Y + AR - t_L \tag{7.5}$$

where

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

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



Analysis of Traffic at Signalized Intersections

- The effective red time is the time during which a traffic movement is not effectively utilizing the intersection.
- The effective red time for a given movement or phase is calculated as

$$r = R + t_L - AR \qquad (7.6)$$

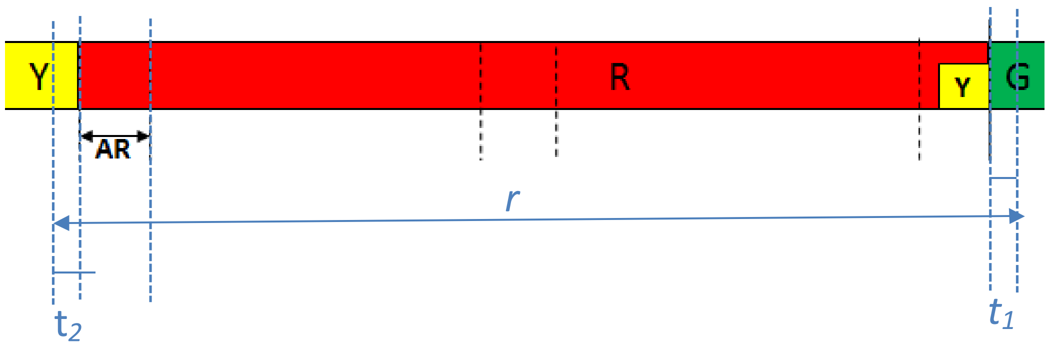
Replacing $t_L = t_1 + t_2 + AR$, we get $r = R + t_1 + t_2$

where

r = effective red time for a traffic movement in seconds,

R = displayed red time for a traffic movement in seconds, and

$\boldsymbol{t_L}$ = total lost time for a movement during a cycle in seconds.



Analysis of Traffic at Signalized Intersections

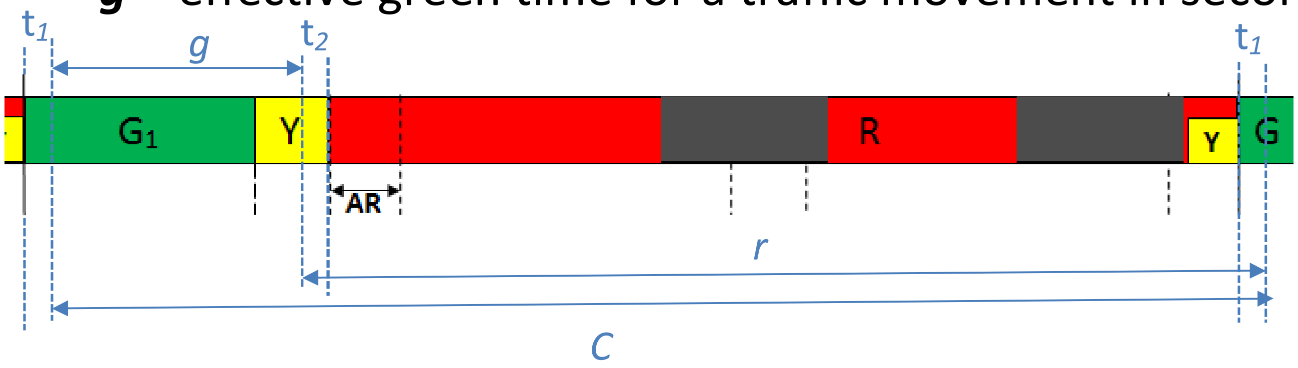
Alternatively, the effective red time can be calculated as follows, assuming the cycle length and effective green time have already been determined:

$$r = C - g \tag{7.7}$$

where

C = cycle length in seconds, and

g = effective green time for a traffic movement in seconds.



Analysis of Traffic at Signalized Intersections

- As movements on an intersection approach do not receive a constant green indication, another measure must be defined that accounts for the hourly volume that can be accommodated on an intersection approach given that the approach will receive less than 100% green time.
- This measure is capacity and is given by

$$cap_i = S_i \frac{g_i}{C} \tag{7.8}$$

where

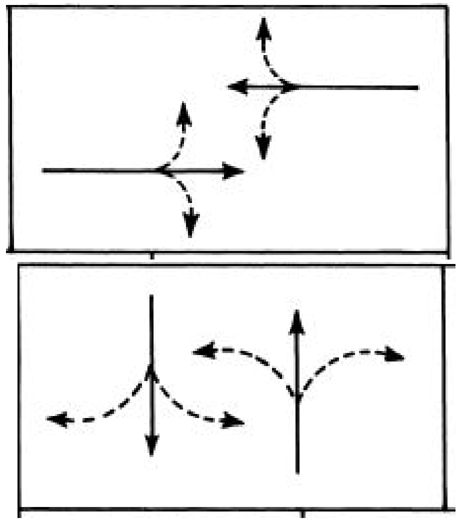
cap = capacity (the maximum hourly volume that can pass through an intersection) in veh/h,

S = saturation flow rate in veh/h, and

g/C = ratio of effective green time to cycle length.

Traffic Signal Phasing and Timing Plan

Select Signal Phasing

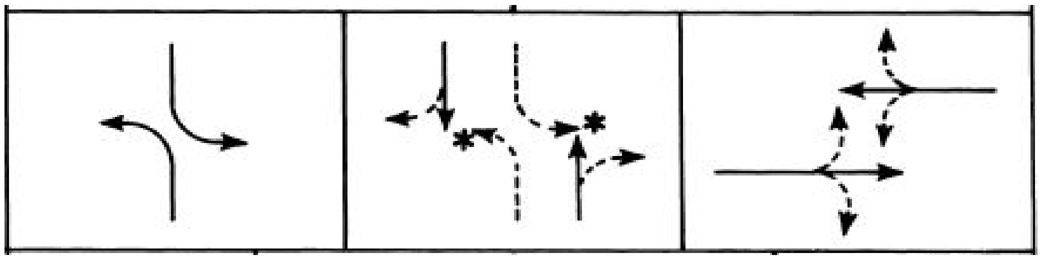


- The most basic traffic signal cycle is made up of two phases.
  - In this case, Phase 1 accommodates the movement of the northbound and southbound vehicles, and Phase 2 accommodates the movement of the eastbound and westbound vehicles.
- These phases will alternate during the continuous operation of the signal.
- This phasing scheme, however, could prove to be very inefficient if one or more of the approaches includes a **high left-turn volume**.

Traffic Signal Phasing and Timing Plan

Select Signal Phasing

- If the high volume of left turns is present on one or both the northbound and southbound approaches **(i.e. more than 60 veh/hr)**, each of these approaches would be given a separate phase.
- This would result in a **three-phase** operation.



Traffic Signal Phasing and Timing Plan

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.
- Based on the lane and traffic movement distribution on an approach, lane groups can be readily determined. Typical lane groupings are shown in Fig 7.6.

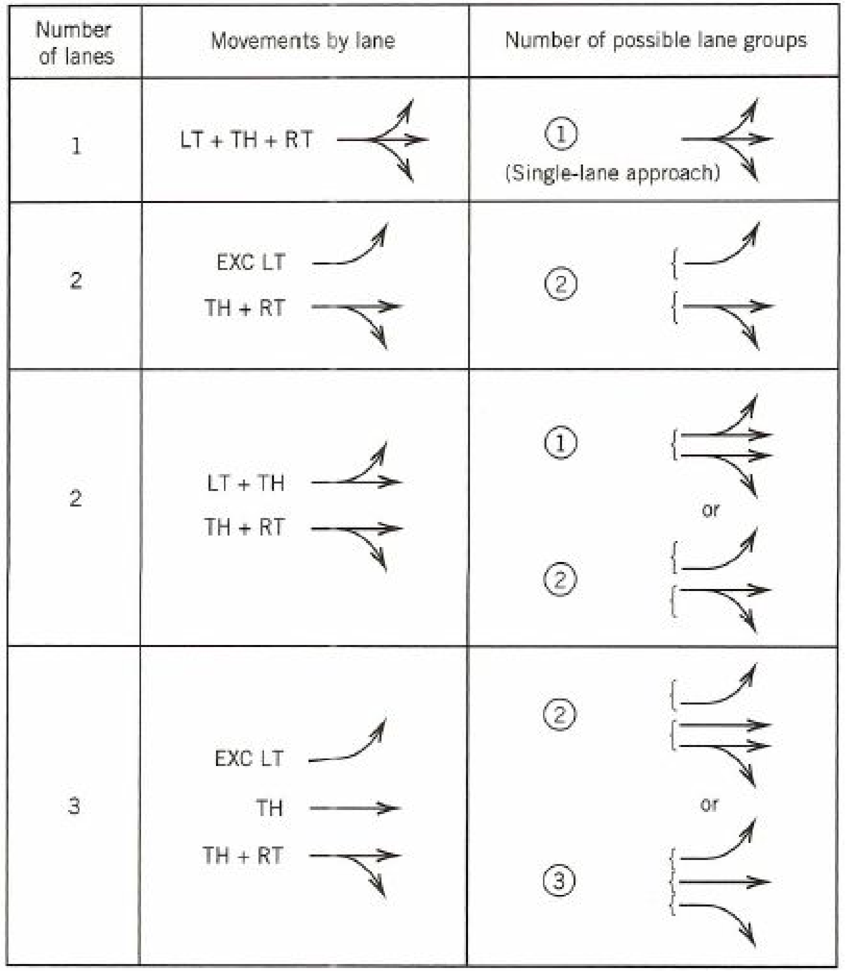


Figure 7.6 Typical lane groupings for analysis (LT= Left turn, TH= through, RT = right turn, EXC = exclusive)

Traffic Signal Phasing and Timing Plan

Determine Critical Lane Groups and Total Cycle Lost Time

- For any combination of lane group movements during a particular phase, one of these lane groups will control the necessary green time for that phase.
- This lane group is referred to as the critical lane group.
- The sum of the flow ratios for the critical lane groups can be used to calculate a suitable cycle length. This is given by

$$Y_C = \sum_{i=1}^{n} \left(\frac{v}{s}\right)_{ci} \tag{7.9}$$

where

Yc = sum of flow ratios for critical lane groups,

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

n = number of critical lane groups.

Traffic Signal Phasing and Timing Plan

- The total lost time for the cycle will also be used in the calculation of cycle length.
- In determining the total lost time for the cycle, the general rule is to apply the lost time for a critical lane group when its movements are initiated.

The total cycle lost time is given as

$$L = \sum_{1}^{n} (t_L)_{ci} \tag{7.10}$$

where

L = total lost time for cycle in seconds,

$(\boldsymbol{t_L})_{\boldsymbol{ci}}$ = total lost time for critical lane group i in seconds, and

n = number of critical lane groups.

Traffic Signal Phasing and Timing Plan

- A practical equation for the calculation of the cycle length that seeks to minimize vehicle delay was developed by Webster [1958]. **Webster's optimum cycle length formula is;**

$$C_{opt} = \frac{1.5L+5}{1-Y_c} \tag{7.11}$$

where

C_{opt}= cycle length to minimize delay in seconds, and

Other terms are as defined previously.

Traffic Signal Phasing and Timing Plan

- The cycle length determined from this calculation is only approximate. Webster noted that values between 0.75 C_{opt} and 1.5 C_{opt} will likely give similar values of delay.
- Calculating an accurate optimal cycle length (and phase length) can be a very computationally intensive exercise for all but the simplest signalized intersections, especially if coordination among multiple signals is involved.
- It should be noted that regardless of the optimal cycle length calculated, practical maximum cycle lengths must generally be observed.
- 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.**

Traffic Signal Phasing and Timing Plan

Allocate Green Time

After a cycle length has been calculated, it is necessary to determine how much green time should be allocated to each phase.

- The cycle length is the sum of all effective green times plus the total lost time. Thus, after subtracting the total lost time from the cycle length, the remaining time can be distributed as green time among the phases of the cycle.
- There are several strategies for allocating the green time to the various phases. One of the most popular and simplest way to allocate green time is to distribute the green time such that the v/c ratios are equalized for the critical lane groups, as by the following equation:

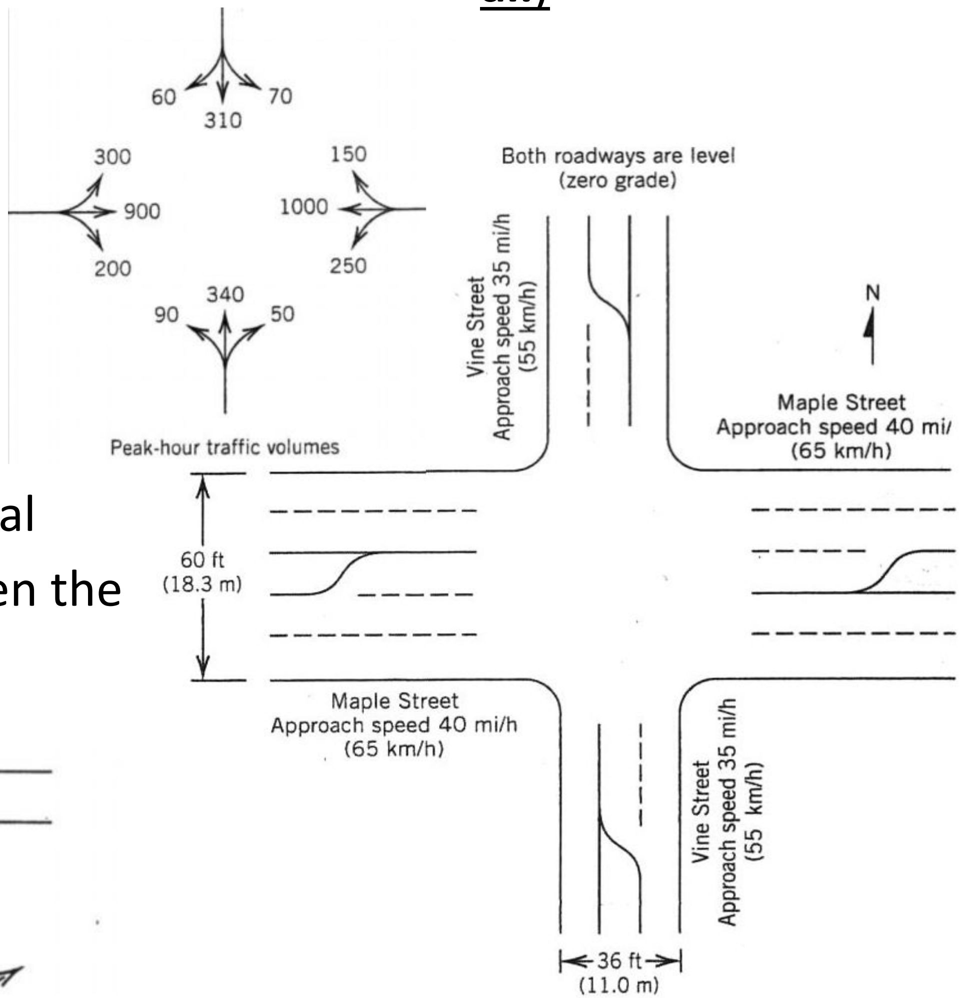
$$g_i = \left(\frac{v}{s}\right)_{ci} \left(\frac{C-L}{Y_C}\right) \qquad (7.12)$$

where **g_i** = effective green time for phase i,
$(v/s)_{ci}$ = flow ratio for critical lane group i,
C = cycle length in seconds

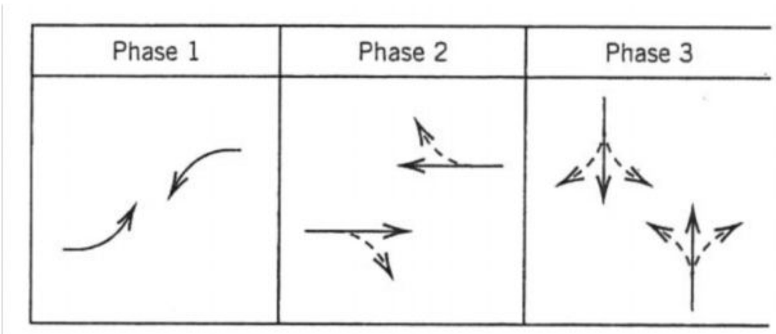
Traffic Signal Phasing and Timing Plan

<u>Example 1 (Example 7.8 from Mannering et al.)</u>

For the given intersection of Maple St and Vine St, a 3-phase timing plan is selected with a protected left-turn phase for E-W flow (on Maple St).



Calculate the sum of the flow ratios for the critical lane groups for the three-phase timing plan (given the saturation flow rates in Table 1)



Example 1 (given data)

Table 1 Saturation Flow Rates for Maple St-Vine St Intersection (in veh/h)

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

Table 2 Peak Hour Flow Rates for Maple St-Vine St Intersection (in veh/h)

Phase 1	Phase 2	Phase 3
EB L: 300	EB T/R: 1100	SB L: 70
		NB L: 90
WB L: 250	WB T/R: 1150	SB T/R: 370
		NB T/R: 390

Example 1 (solution)

The flow ratios (observed flow / saturation flow) will now be calculated, with the critical lane group for each phase indicated with a mark in Table 3 (which are the EB left turn, the WB through and right turn, and the NB through and right turn, for group for phases 1, 2, and 3, respectively, are

Table 3 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: (300/1750)=0.171♦	EB T/R: (1110/3400)=0.324	SB L: (70/450)=0.156
		NB L: (90/475)=0.189
WB L: (250/1750=0.143	**WB T/R: (1150/3400)=0.338 ♦**	SB T/R: (370/1800)=0.206
		NB T/R: (390/1800)=0.217♦

Example 1 (Solution continued)

- The sum of the flow ratios for the critical lane groups for this phasing plan will be needed for the next section.
- Since this phasing plan does not include any overlapping phases, this value is simply the sum of the highest lane group (v/s) ratios for the three phases, as follows:

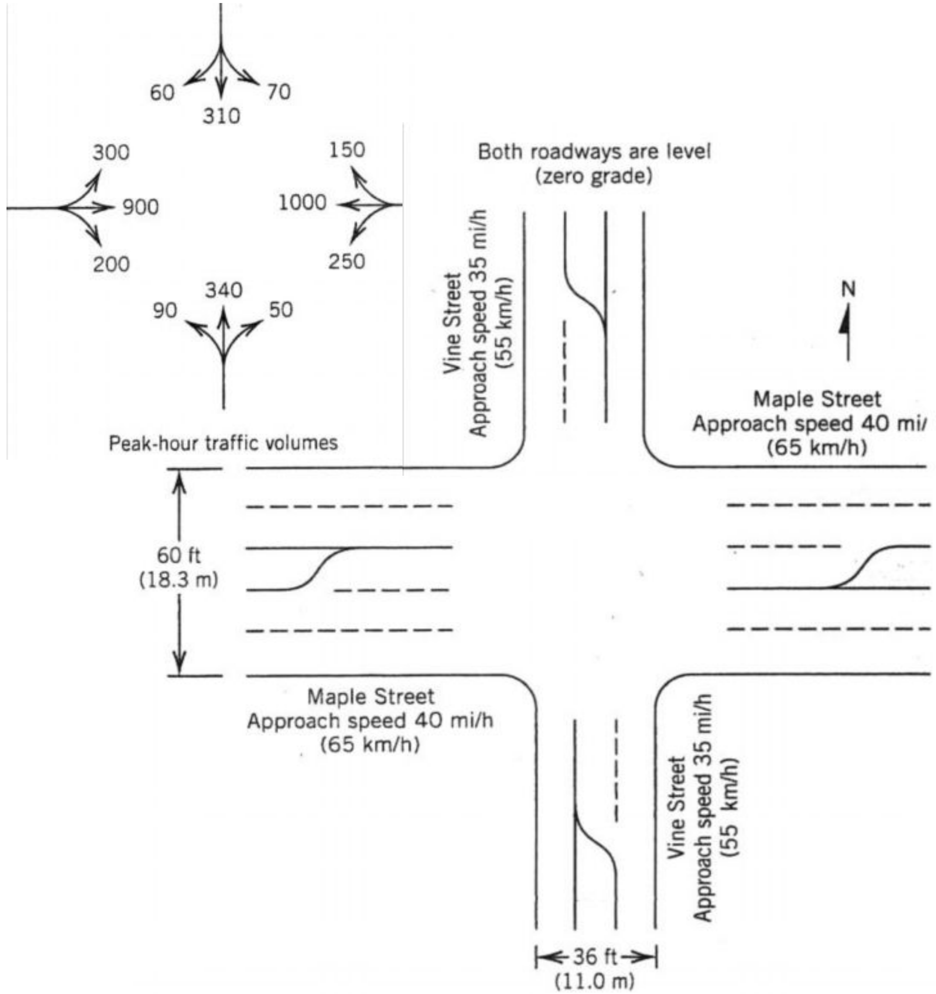
$$Y_C = \sum \left(\frac{v}{s}\right)_{ci} = 0.171 + 0.338 + 0.217 = 0.726$$

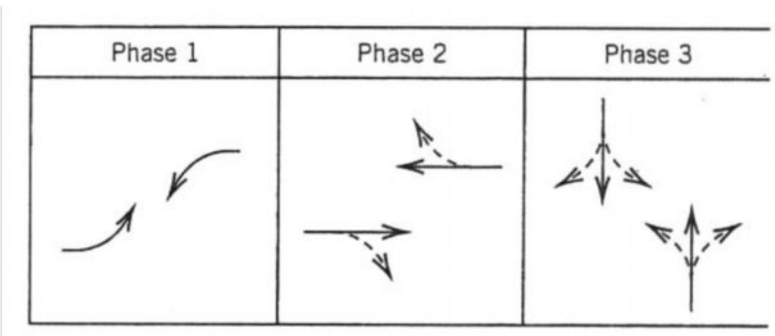
- **Assuming 2 seconds of start-up lost time and 2 seconds of clearance lost time** (1 second lost time for yellow plus 1 second of all-red time), for each critical lane group, gives a lost time of 4 s/phase.
- The total lost time for the cycle is then 12 seconds (3 phases x 4 s/phase).

Traffic Signal Phasing and Timing Plan

Example 2

Calculate the optimal cycle lengths for the intersection of Maple and Vine Streets, using the information provided in the preceding examples, for the three-phase design. Assume 2 seconds of start-up lost time and 2 seconds of clearance lost-time (1 second for yellow time and 1 second of all-red time)





Example 2 (Solution):

For the three-phase design (Example 1), the sum of the flow ratios for the critical lane groups is determined to be 0.726.

For two seconds of start-up lost time and 2 seconds of clearance lost time (1 second lost time for yellow plus 1 second of all-red time), the lost time for phase is calculated as from Eq. 7.2:

$$t_L = t_{sl} + t_{cl} = t_1 + t_2 + AR$$

tL = 2 + 2 = 2 + 1 + 1 = 4 s.

Total lost time (L) from equation 7.10:

L =4 + 4 + 4 = 12 s

$$C_{opt} = \frac{1.5x12+5}{1.0-0.726} = 83.9 \rightarrow 85s$$ (rounding up to nearest 5 seconds)

Traffic Signal Phasing and Timing Plan

Example 3

Determine the green-time allocations for the 85-second cycle length found in Example 2, using the method of v/c ratio equalization.

Solution:

Using $\sum(\frac{v}{s})_{ci} = Y_c = 0.726$ (Example 1) ; C=85 s (Example 2) ;   L = 12 s (Example 1)

- The effective green time for (EB and WB left-turn movements)

$$g_1 = \left(\frac{v}{s}\right)_{c1}\left(\frac{c-L}{Y_C}\right) = 0.171 * \frac{85-12}{0.726} = 17.2s$$

- The effective green time for (EB and WB through and right-turn movements)

$$g_2 = \left(\frac{v}{s}\right)_{c1}\left(\frac{c-L}{Y_C}\right) = 0.338 * \frac{85-12}{0.726} = 34.0\ s$$

- The effective green time for (NB and SB left-through, and right-turn movements)

$$g_3 = \left(\frac{v}{s}\right)_{c3}\left(\frac{c-L}{Y_C}\right) = 0.217 * \frac{85-12}{0.726} = 21.8$$

Example 3 (solution continued)

- The cycle length is checked by summing these effective green times and the lost time, giving

  $C = g_1 + g_2 + g_3 + L = 17.2 + 34.0 + 21.8 + 12 = 85.0\ s$

  Since C was selected as 85 sec, the calculations are correct.

- In order to calculate actual green times, Yellow time should be known. Assuming 2.0 s of yellow time for each phase, actual green times will be calculated from Eq. 7.5. By rewriting Eq. 7.5 :

  $G = g - Y - AR + t_L$ *Or* $G = Y + t_1 + t_2$

  G_1 = 17.2 - 2.0 -1.0 + 4.0 = 17.2 - 2.0 + 2.0 + 1.0 = 18.2 s.
  G_2 = 34.2 - 2.0 -1.0 + 4.0 = 34.2 - 2.0 + 2.0 + 1.0 = 33.0 s.
  G_3 = 21.8 - 2.0 -1.0 + 4.0 = 21.8 - 2.0 + 2.0 + 1.0 = 30.8 s.
  $\sum G_i$ =82 s.

$C = \sum_1^n G_i + nI = \sum_1^n G_i + n(Y + AR)$ = 82 + (2.0 + 1.0) = 85.0 s (solution verified)

Example 4

For a four-way intersection, a four-phase signal control system (with two exclusive left turn phases for E-W and N-S flows), is designed for the given information below.

a) Verify if the designed 4-phase system is appropriate
b) Draw the phase diagrams.
c) Calculate actual green times and the cycle time
d) Draw Light Sequence diagrams.

Given data for the intersection	
Direction S-N	**Direction W-E**
Saturation Flow Rates	
S_{SN} = 2445 vph S_{SN_L} =1010 vph	S_{EW} = 2773 vph S_{EW_L} =1300 vph
Demand volume	
760 vph	1000 vph
20% left turning 15% right turning	18% left turning 20% right turning
Signalization	
g_{NS} =34 seconds g_{NS_L}= 21 seconds g_{EW}= 41 seconds g_{EW_L}= 19 seconds t_L= 2.5 seconds/phase Y: 4 seconds; I(intergreen)= 5.5 seconds	

Example 4 (solution):

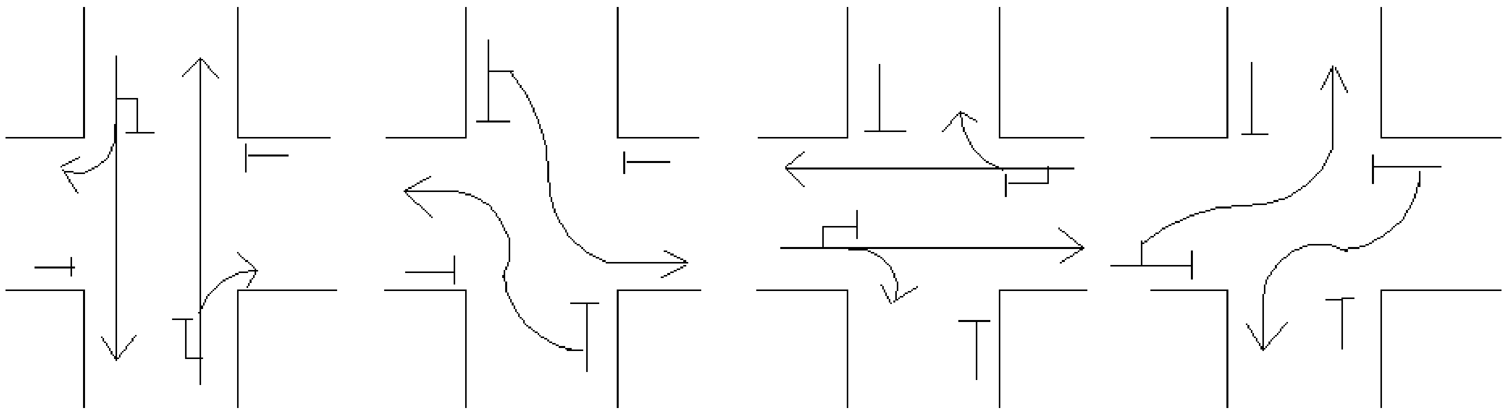
a) To find the number of phases (n), calculate the left turning volumes as

S-N Left $= v_{(\mathrm{S-N})\mathrm{L}}$ = 760 * 0.20 = 152 vph > 60 vph

E-W Left $= v_{(\mathrm{E-W})\mathrm{L}}$ =1000 * 0.18 = 180 vph > 60 vph ;

Therefore, n = 4 phases

b) Phase diagrams:



Example 4 (Solution continued):

c) Cycle time calculation

$g_{NS} = 34\ seconds$ $\qquad$ $g_{NS\_L} = 21\ seconds$

$g_{EW} = 41\ seconds$ $\qquad$ $g_{EW\_L} = 19\ seconds$

$AR = I - Y = 5.5 - 4 = 1.5\ seconds$ (Eq.7.3, p.26)

Calculate actual green times (G_i) using $G_i = g_i - Y + t_L - AR$ (Eq.7.5, p.28)

$$G_{NS} = g_{NS} - Y + t_L - AR = 34 - 4 + 2.5 - 1.5 = 31\ seconds$$

$$G_{NS\_L} = g_{NS\_L} - Y + t_L - AR = 21 - 4 + 2.5 - 1.5 = 18\ seconds$$

$$G_{EW} = g_{EW} - Y + t_L - AR = 41 - 4 + 2.5 - 1.5 = 38\ seconds$$

$$G_{EW\_L} = g_{EW\_L} - Y + t_L - AR = 19 - 4 + 2.5 - 1.5 = 16\ seconds$$

Cycle time, **C**=$g_{NS} + g_{NS\_L} + g_{EW} + g_{EW\_L} + L$=115+4*2.5=**125 seconds**

Example 4 (Solution continued):

d) Light Sequence Diagram