

An aerial photograph of a busy urban intersection. The image shows multiple lanes of traffic, including cars, trucks, and buses. There are buildings, including a gas station, and trees visible around the intersection. The text "CAPACITY ANALYSIS FOR SIGNALIZED INTERSECTIONS" is overlaid in large, yellow, serif capital letters across the center of the image.

CAPACITY ANALYSIS FOR SIGNALIZED INTERSECTIONS

Signalized Intersections

- **CAPACITY ANALYSIS FOR SIGNALIZED INTERSECTIONS :**
- An example of interrupted flow facilities in which external control plays a major role in defining the traffic flow characteristics
- At-grade intersections are locations where different modes of transportation interact, such as cars, trucks, buses, bicycles, and pedestrians. At-grade intersections also represent one of the most complex components of a transportation system. This is because conflicting traffic streams compete for the right-of-way at an intersection

CAPACITY ANALYSIS FOR SIGNALIZED INTERSECTIONS

- When traffic volumes are low, traffic at an intersection could be regulated using basic rules of the road, or using **stop and yield signs**. As traffic **volumes increase**, however, it becomes extremely difficult for drivers to select adequate gaps in conflicting traffic streams for executing their desired maneuvers. When this happens, intersection signalization (i.e. .. the **use of traffic control signals**) becomes a must.

CAPACITY ANALYSIS FOR SIGNALIZED INTERSECTIONS

- Traffic signals play a dramatic role in determining the overall performance level of an arterial system
- Traffic signals can generally be divided into two groups: pretimed signals and actuated signals.
Pretimed signals are typically insensitive to current volumes. The cycle length of a pretimed signal is generally **fixed**, regardless of the current volumes. The operation of actuated controllers **varies according to the observed volume**. Actuated controllers thus need to be connected to traffic **detectors** for sensing traffic demand.

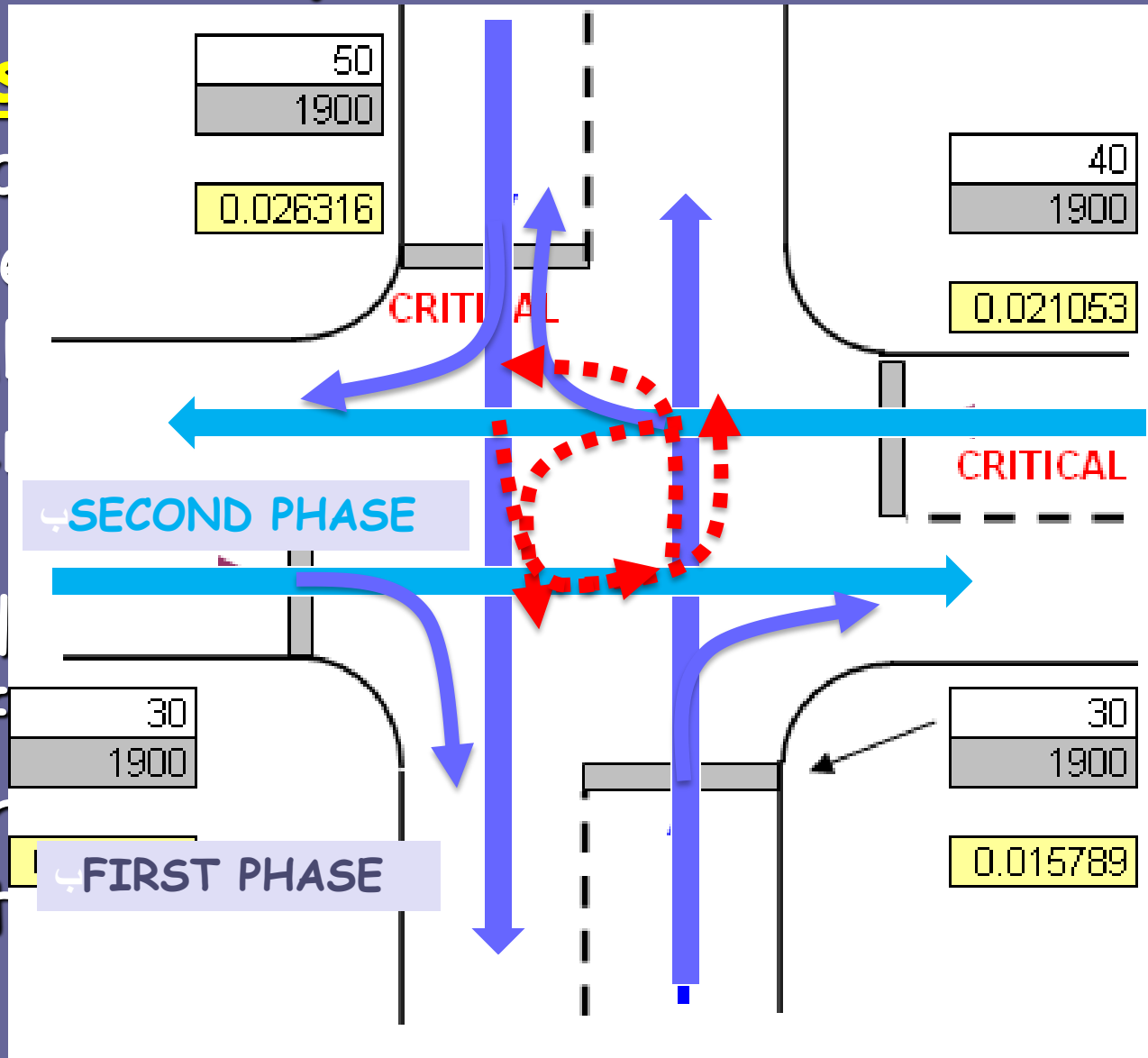
CAPACITY ANALYSIS FOR SIGNALIZED INTERSECTIONS

- Sometimes we can use a pretimed controller. Typically, one would have a timing plan for handling the morning peak period or rush hour, another for the evening peak, and a third for the off-peak period. The pretimed controller would be instructed to use the morning signal plan between the hours of 6:30 and 8:30 A.M., the evening plan between 4:30 and 6:30 P.M., and the off-peak plan during the rest of the day. Within each of these periods, the parameters of a pretimed signal plan remain unchanged. Given this, the use of pretimed controllers is most appropriate when **traffic conditions do not vary significantly within the different peak periods.**

Important Definitions

- **Cycle and cycle length.** A traffic signal cycle is a rotation through all the signal indications at a given intersection. Every legal movement would generally receive the "green" indication only once during a given cycle. **The time it takes for the signal to go through one cycle of indications is the cycle length.**
- **Interval.** A time period during which all the signal indications or **lights remain unchanged.** A cycle generally includes several intervals such as green. change Of yellow, clearance or all-red. and the red interval.

Important Definitions



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Important Definitions

- **Offset**. A term used in conjunction with coordinated systems of signals. It refers to the **time difference between the initiation of green on two adjacent signals**. Typically, the offset is measured in terms of the green initiation time of the downstream (t_d) signal relative to the upstream signal (t_u)-that is, the offset is equal to $t_d - t_u$.

Signal Timing Principles

In order to appreciate the basis behind the methodology for the **analysis and design of signalized intersections**, we need first to discuss the following:

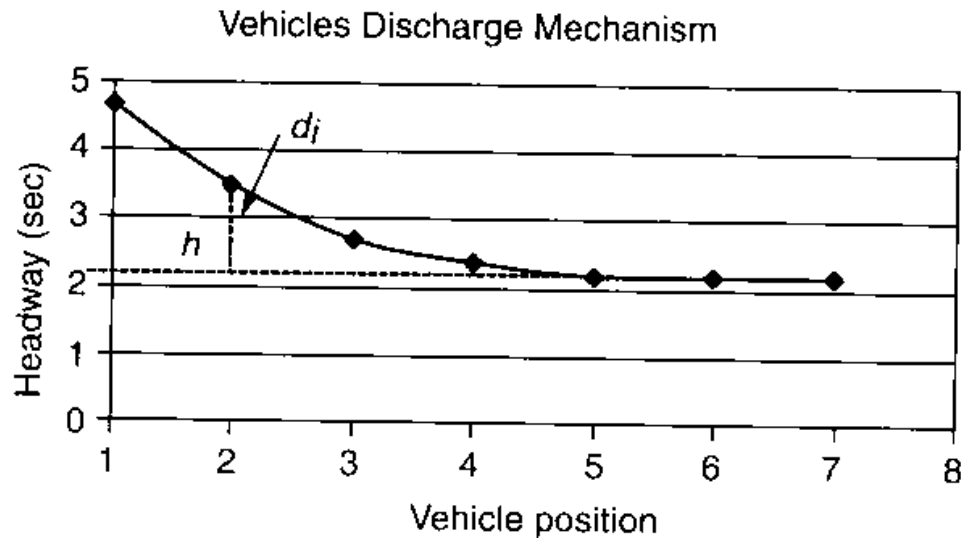
- (1) the mechanism by which vehicles discharge from a queue waiting at a traffic signal;
- (2) the time lost in the process: and
- (3) the concept of the capacity of a given intersection approach.

Discharge Headway and Saturation Flow Rate

- Observations of the way vehicles discharge from a queue (i.e. a line of vehicles) have revealed that if the recorded discharge

FIGURE 4.3

Discharge headways at signalized intersections.

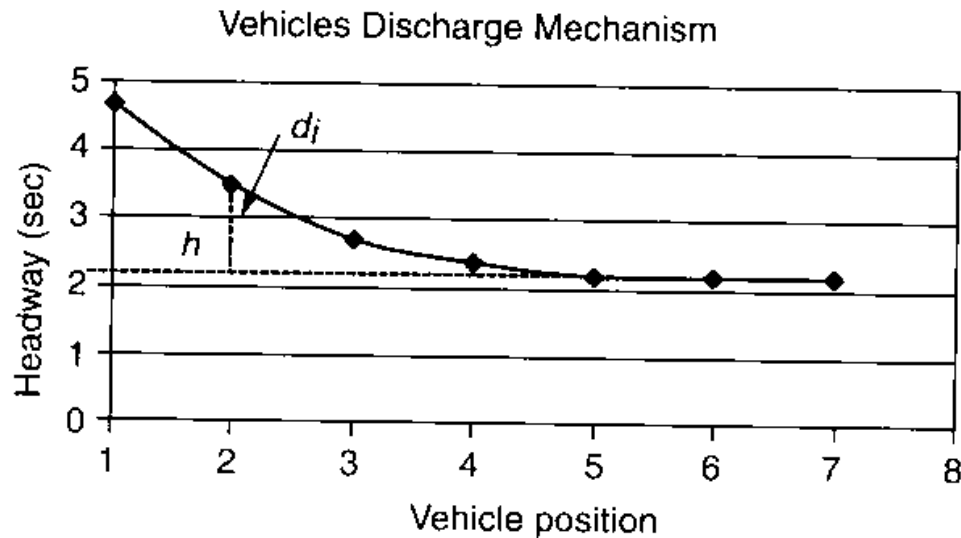


Discharge Headway and Saturation Flow Rate

- This figure explains the mechanism by which vehicles depart from a signalized intersection when it turns green. **The first few headways are relatively long**, then after the fourth or fifth

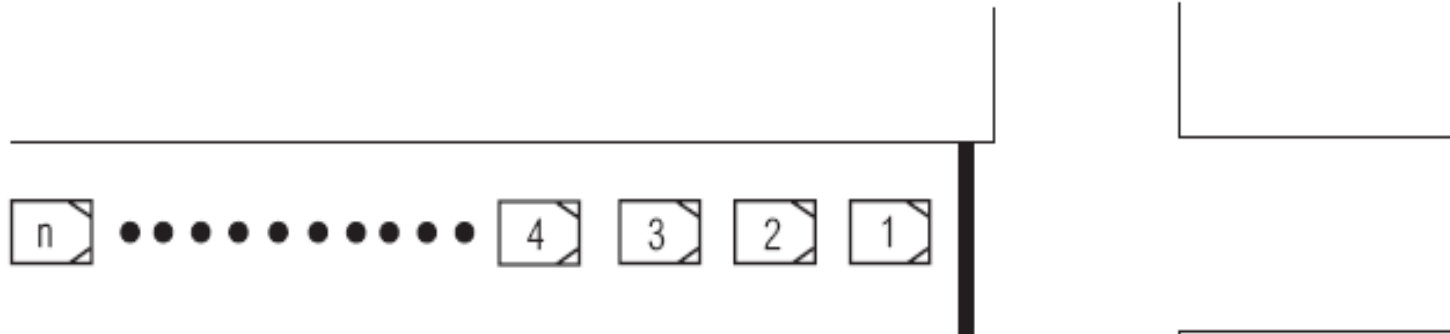
FIGURE 4.3

Discharge headways
at signalized
intersections.



provided that there are vehicles waiting in the queue. The saturation headway is often denoted by h and is typically in the range of 2-3 sec/veh.

Condition at Start-up



Vehicle in Queue Departure in Headway

1	$h + t_1$
2	$h + t_2$
3	$h + t_3$
4	$h + t_4$
.	h
.	h
.	.
.	.
n	h

Queue Position	Observed Avg. Headway	Saturation Headway	Difference (Obs.-Est.)
1	3.14	2.14	1.00
2	2.74	2.14	0.50
3	2.52	2.14	0.38
4	2.37	2.14	0.23
≥ 5	2.14	2.14	0.00
Start-up Lost Time			2.11

Q- Discharge Headway and Saturation Flow Rate

- If we assume that the signal remains green all the time and that we have enough vehicles waiting in the queue and that each one consumes h seconds to enter the intersection (i.e. .. the saturation discharge headway). the total number of vehicles entering in an hour (i.e. .. the saturation flow rate) can be computed easily as

- $s = 3600/h$ (4.9)

where

- s = saturation flow rate in units of veh/hr green/lane (veh/hg/lane)
- h = saturation headway (sec/veh)

Total Lost Time and Effective Green Time

- we have assumed that vehicles enter the intersection every h seconds. In reality, however, the average headway is greater than h . As Figure 4.3 shows, for the first four or five vehicles, the headway is actually greater than h , since the drivers of those first four or five vehicles typically require more reaction time in order to accelerate. Let us denote the difference between the actual headway for those first vehicles and the saturation headway by d_i (see Figure 4.3). The sum of these d_i 's would give us what we call the start-up lost time I_1 .

Total Lost Time and Effective Green Time

- This represents the time lost at the beginning of each phase (i.e. when the signal turns green) as a result of the additional reaction time required by the first four or five vehicles in a queue. We could compute the total time required for a queue consisting of n vehicles to discharge from a signalized intersection as

- $T_n = I_1 + nh$

where

- T_n = green time required for the discharge of n vehicles (seconds)
- I_1 = start-up lost time (sec/phase)
- h = saturation headway (sec/veh)

Total Lost Time and Effective Green Time

- Typically, a signal for a given approach goes through the following sequence of intervals:
(1) green; (2) yellow; (3) allred (this is typically a 1-sec interval in which the signal indications for all approaches at an intersection are red to ensure the clearance of the intersection before the initiation of the green for a second approach); and (4) red.

- Vehicles from a given intersection approach would therefore normally move during **all of the green and part of the yellow** or the clearance interval. The part of the yellow that is not utilized by vehicles plus the all-red interval where everybody is stopped represents time lost, and this is the time that I_2 is designed to capture. Therefore, the total lost time/phase (t_L) is thus equal to the start-up lost time plus the clearance lost time, as follows:

- $$t_L = I_1 + I_2$$

- To facilitate accounting for the lost time/phase in signal analysis and modeling, the **effective green time (g)** was defined. This represents the time during which vehicles are effectively moving at the rate of one every h seconds. This time is given as

- $g_i = G_i + Y_i - t_{Li}$

where

- g_i = effective green time for phase i
- G_i = actual green time for phase i
- Y_i = duration of the yellow interval
- t_{Li} = total lost time during phase i

Capacity of a Given Lane

The saturation flow rate (s) as defined in Equation 4.9 gives us the capacity of a single lane on a given intersection approach, assuming that that approach gets a green indication all the time. For a signalized intersection, each approach typically gets green only during a certain fraction of the total cycle length. Therefore, if a given approach has an effective green time period equal to g and if the total cycle length is C sec, the capacity of that approach is equal to

$$C_i = s_i \frac{g_i}{C}$$

Q- Capacity of a Given Lane

$$C_i = s_i \frac{g_i}{C}$$

where

C_i = capacity of lane i (veh/hr)

s_i = saturation flow rate for lane i (veh/hg)

g_i = effective green time for lane i (sec)

C = cycle length (sec)

Capacity of a Given Lane

- The lane capacity computed could then be **multiplied by the number of lanes** to yield the capacity for the whole lane group (i.e., group of lanes that move together during a given phase and have similar operating characteristics). While Equation 4.13 is useful for computing the capacity of a given approach or a lane group, it does not address how to compute the capacity for a signalized intersection as a whole. The issue of signalized intersection capacity will be addressed in the next section.

EXAMPLE 4.3

Computing the Capacity of a Signalized Approach

- The eastbound approach of a signalized intersection with a cycle length of 80 sec gets 37 sec of green. Studies show that the saturation headway for that approach is equal to 2.2 sec, the start-up lost time is equal to 2 sec, and the clearance lost time is equal to 1 sec. If the duration of the yellow or clearance interval is 3.5 sec, determine the capacity for that approach, assuming that it consists of two through-moving traffic lanes.

EXAMPLE 4.3

Computing the Capacity of a Signalized Approach

- *Solution*

- The saturation flow rate for that approach is first computed from Equation 4.9 as :

$$s = \frac{3600}{2.2} = 1636 \text{ veh/hr/lane}$$

- From Equation 4.11, the total lost time/phase for that approach is computed as :
 - $t_L = I_1 + I_2 = 2.0 + 1.0 = 3 \text{ sec}$
- Next, the effective green time for the approach is computed from Equation 4, 12 as
- $g_i = G_i + Y_i - t_{L,i} = 37.5 + 3.5 - 3.0 = 37.5 \text{ sec}$

EXAMPLE 4.3

Computing the Capacity of a Signalized Approach

- *Solution (con)*
- Finally, the capacity for the approach can be computed from Equation 4.13 as follows:

$$c_i = s_i \frac{g_i}{C} = 1636 \times \frac{37.5}{80} = 767 \text{ veh/hr/lane}$$

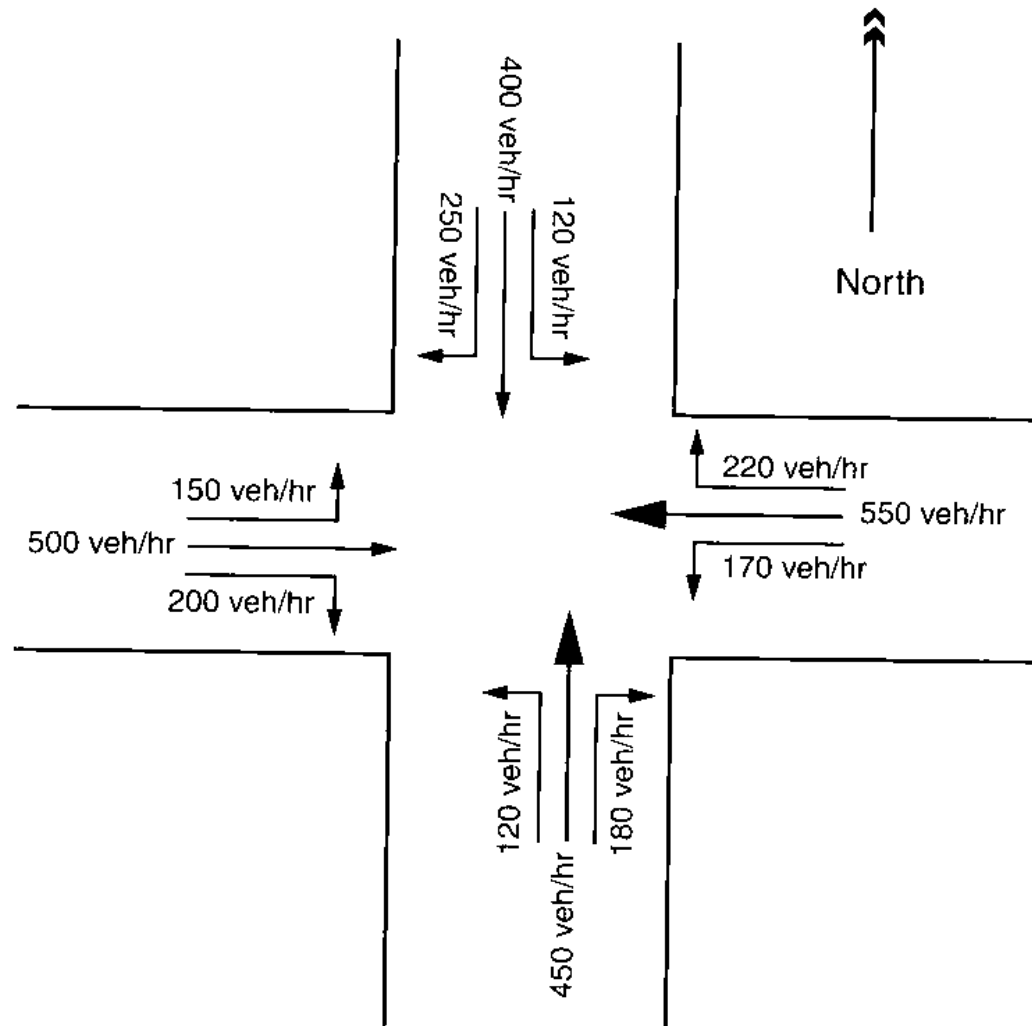
- Therefore, the capacity of the approach or lane group is given by multiplying the preceding figure by 2, since the approach had two lanes, as follows:
- $c = 767 \times 2 = 1534 \text{ veh/hr}$

The Time Budget and the Critical Lane Concepts

- Developing signal timing plans is based upon two concepts, namely **the time budget** and the **critical lane** concepts. The time budget concept is concerned with allocating the available time among the competing vehicular and pedestrian streams at an intersection. The **critical lane** concept states that during any given phase, while several traffic approaches are allowed to move, one particular movement will require the **largest amount of time**. That particular movement is referred to as the critical lane for that given phase. Satisfying the needs of the critical lane movement would automatically satisfy the needs of all other accompanying movements.

FIGURE 4.4

The critical lane concept.



...ing the EB and WB movements needs to be designed so as to satisfy the needs of the heaviest or most intense movement (i.e. .. it should be long enough to accommodate that volume).

The Time Budget and the Critical Lane Concepts

- which in this case is the 550 veh/hr volume. By doing this, the needs of the other lesser volumes would be automatically satisfied. The NB and SB phase needs to be designed for the 450 veh/hr lane, since this is the most intense volume moving in this second phase. The critical lane for phase 1 is the one carrying the 550 veh/hr volume, and the critical lane for phase 2 is the lane with the 450 veh/hr volume. These two movements are shown in bold in Figure 4.4. Therefore, for the intersection shown in Figure 4.4, the available time should be allocated to the vehicles in the critical lane for phase 1 and those in the critical lane for phase 2 while accounting for the time lost in each phase.

Signalized Intersection Capacity

- With the concepts of **time budget** and **critical volumes** defined, we turn our attention to presenting a simplified version of the concept of signalized intersection capacity. In one sense, the maximum sum of critical lane volumes that a signalized intersection can accommodate can be regarded as a measure for the intersection capacity. This is a simplified measure compared to the more elaborate methods described in the HCM. but nevertheless it is quite useful.

The Time Budget and the Critical Lane Concepts

● Signalized Intersection Capacity

- To determine the maximum sum of the critical lane volumes that a signalized intersection can accommodate, first we must determine the time available to allocate for these movements in an hour since there is some time lost in each signal cycle that is not utilized by vehicles. After the available time for allocation is determined, dividing this time by the discharge headway immediately yields the maximum sum of critical lane volumes. The calculation proceeds as follows: First, the total lost time/cycle is computed as :

- $$L = N \times t_L \quad (4.14)$$

The Time Budget and the Critical Lane Concepts

● Signalized Intersection Capacity

$$● L = N \times t_L \quad (4.14)$$

where

● L = lost time/cycle (sec/cycle)

● N = number of phases in the cycle

● t_L = total lost time/phase as defined previously (sec/phase)

● The number of cycles in one hour is given as $3600/C$ cycles. where C is the cycle length in seconds. Therefore. the total lost time in one hour.

L_H is given by

$$L_H = N \times T_L \times \left(\frac{3600}{C} \right)$$

The Time Budget and the Critical Lane Concepts

● Signalized Intersection Capacity

$$L_H = N \times T_L \times \left(\frac{3600}{C} \right)$$

- Therefore, the time available for allocation. T_G . is equal to :

$$T_G = 3600 - N \times t_L \times \left(\frac{3600}{C} \right) \quad (4.16)$$

- Dividing this time by the saturation headway. h would thus give us the maximum sum of critical volumes that the intersection can accommodate, V_c which can be expressed as

$$V_c = \frac{1}{h} \left[3600 - N \times t_L \times \left(\frac{3600}{C} \right) \right] \quad (4.17)$$

Applications

- Equation 4.17 can be used in a number of different ways. **First**, it can be used to determine the maximum sum of critical lane volumes that a given intersection with a given cycle length can accommodate. **Second**, it can be used to determine the number of lanes/intersection approaches required if a certain cycle length is desired. **Finally**, it can be used to determine the minimum cycle length required to accommodate a given set of volumes at a particular intersection. The following examples illustrate these applications of the methodology.

EXAMPLE 4.4

- Determining the Maximum Sum of Critical Volumes at an Intersection
- A signalized intersection having three phases has a cycle length equal to 90 sec. Determine the maximum sum of critical volumes that the intersection can accommodate, given that the lost time/phase is 3.50 sec and that the saturation headway is 2 sec.

EXAMPLE 4.4

- Determining the Maximum Sum of Critical Volumes at an Intersection

Solution

- From Equation 4.17. the maximum sum of critical volumes can be computed as

$$V_c = \frac{1}{h} [3600 - N \times t_L \times (\frac{3600}{C})]$$

$$V_c = \frac{1}{2.0} [3600 - 3 \times 3.5 \times (\frac{3600}{90})] = 1590 \text{ veh/hr}$$

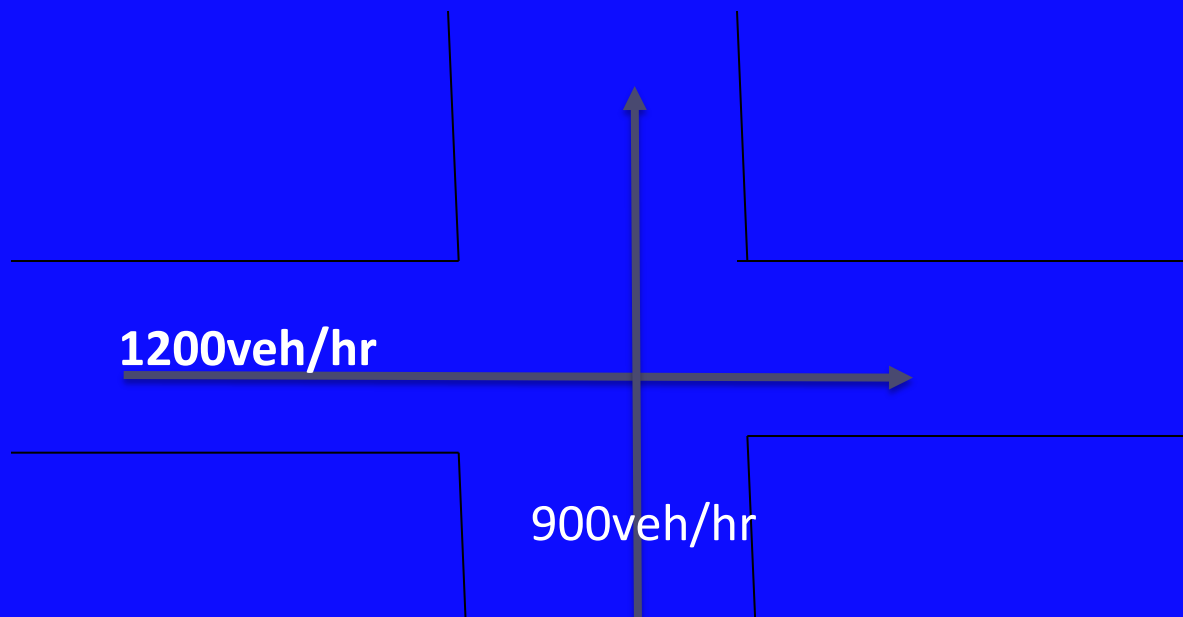
EXAMPLE 4.5

- **Q** - Determining the Number of Lanes at an Intersection Consider the two-phase intersection shown in Figure 4.5. The intersection has a 60-sec cycle length, and the time lost/phase is equal to 4 sec. The critical volumes are shown in the figure. Determine the number of lanes required for each critical movement. Assume a saturation headway of 2.20 sec.

- **Solution**

- The first step is to determine the maximum sum of critical volumes that the intersection with its current cycle length can accommodate. This value is then compared to the observed critical volumes ³⁵

EXAMPLE 4.5

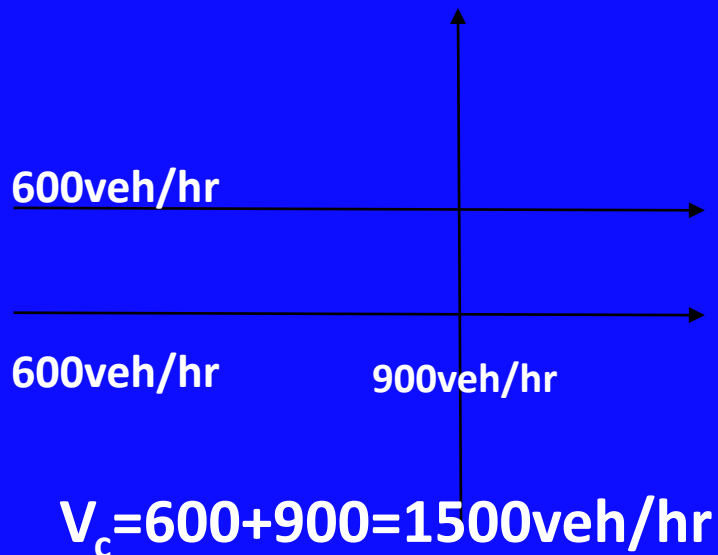


$$V_c = \frac{1}{h} [3600 - N \times t_L \times (\frac{3600}{C})]$$

$$V_c = \frac{1}{2.2} [3600 - 2 \times 4 \times (\frac{3600}{60})] = 1418 \text{ veh/hr}$$

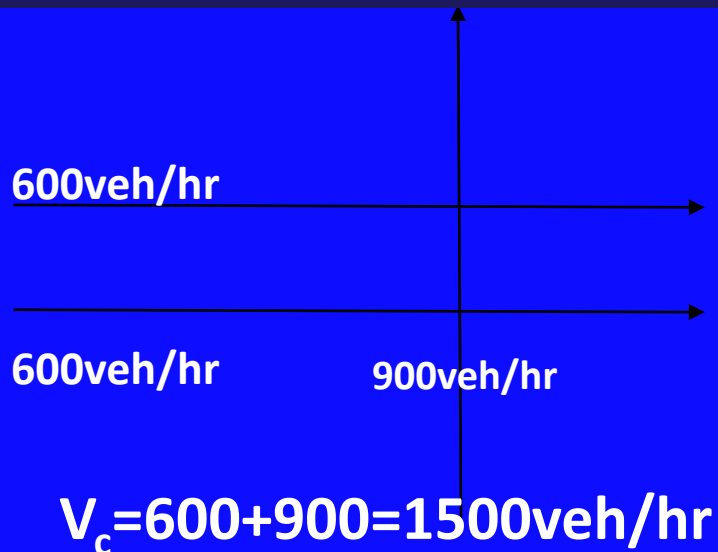
EXAMPLE 4.5

According to Figure 4.5. the sum of critical volumes is equal to $1200 + 900 = 2100$ veh/hr. This means that these volumes have to be distributed over a number of lanes so that the sum of critical volumes observed is less than the maximum sum of critical volume that the intersection can handle as determined from Equation 4,17



EXAMPLE 4.5

We start with two lanes/direction for the east-west street. and one lane/direction for the north-south street. as shown in Figure 4, This gives us a sum of critical volumes of 1500 veh/hr. which is still more than the intersection can handle (i.e. 1418 veh/hr). We then proceed to divide the north-south critical volume as well over two lanes. which gives 1050 veh/hr as the sum of critical volumes, Since 1050 veh/hr is less than 1418 veh/hr, the design is acceptable,



EXAMPLE 4.6

Determining the Minimum Cycle Length

Determine the minimum cycle length for the two-phase intersection shown in Figure 4.7 The intersection's critical volumes are shown in the figure,

Assume a saturation headway of 2,10 sec
and a lost time/phase of 3,50 sec,

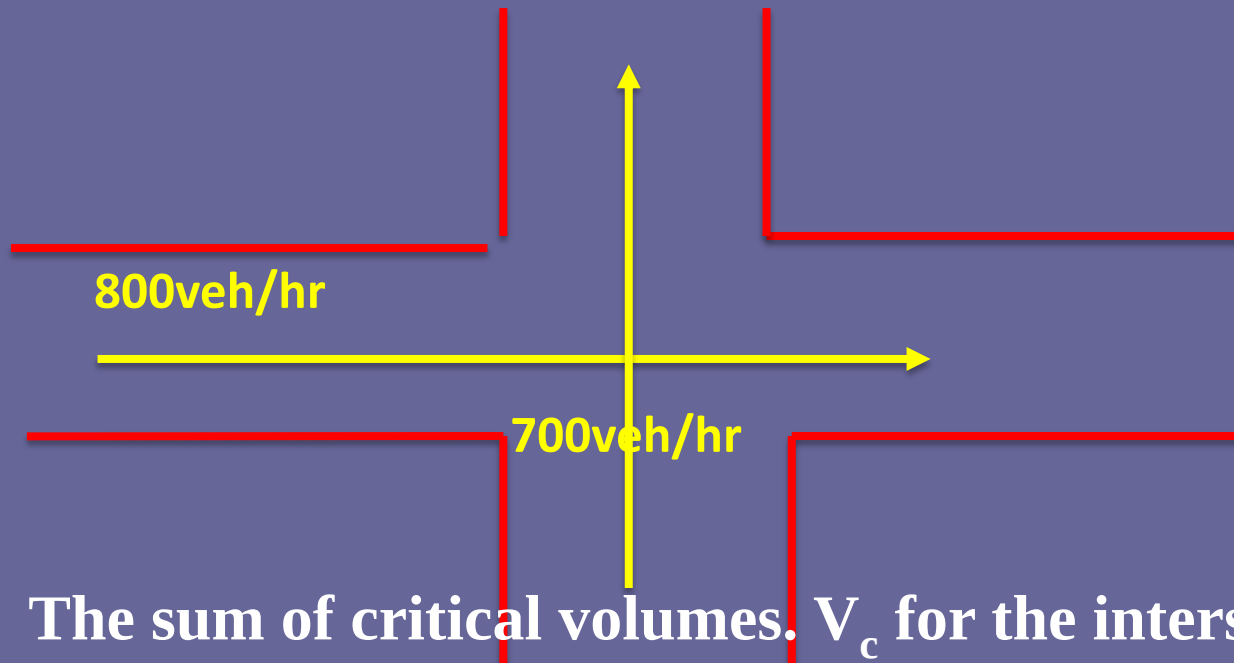
Solution

For this problem. Equation 4,17 is rearranged in order to solve the cycle length, C .

This gives the following equation:

$$C_{\min} = \frac{N t_L}{1 - \left(\frac{V_c}{3600 / h} \right)}$$

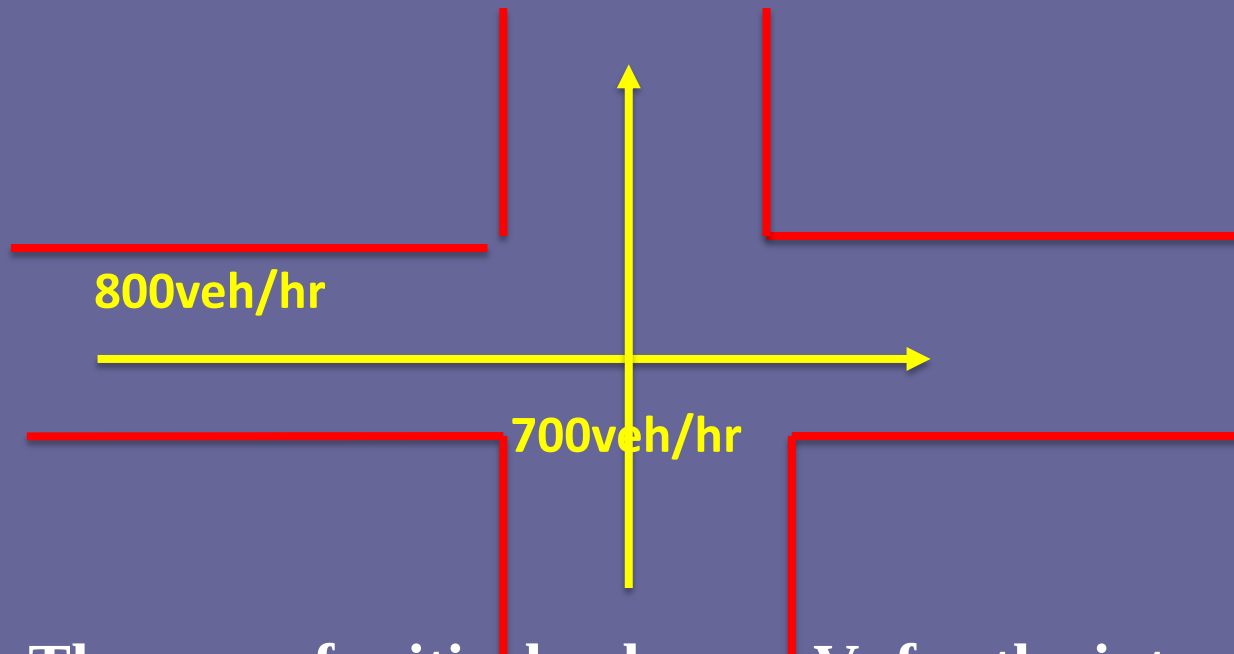
EXAMPLE 4.6



The sum of critical volumes, V_c for the intersection
 $800 + 700 = 1500$ veh/hr. Therefore, the minimum cycle length is given by

$$C_{\min} = \frac{N t_L}{1 - \left(\frac{V_c}{3600 / h} \right)}$$

EXAMPLE 4.6



The sum of critical volumes, V_c for the intersection
 $800 + 700 = 1500$ veh/hr. Therefore, the minimum
cycle length is given as

$$C_{\min} = \frac{2 \times 3.5}{1 - \left(\frac{1500}{3600 / 2.1} \right)} = 56 \text{ sec}$$

Desirable Cycle Length

- In Example 4.6, we solved for the minimum cycle length needed to accommodate a given sum of critical volumes using Equation 4.17. This equation, however, does not account for the within-the-hour variations of traffic volume (which is accounted for using the peak hour factor). In addition, most signals are timed so that between 80 and 95% of the capacity available is utilized (Equation 4.17) assumes that 100% of the capacity is utilized). Providing some excess capacity is important for transportation systems because of the uncertainty associated with predicting traffic demand.

Desirable Cycle Length

- To account for these two factors (namely, within-the-hour variations and the percent utilization of capacity). Equation 4.17 is modified as follows:

$$C_{des} = \frac{N t_L}{1 - \left(\frac{V_c}{(3600/h) \times PHF \times (v/c)} \right)}$$

- Where:
- C_{des} : desirable cycle length as opposed to the minimum cycle length of Equation 4.17
- PHF = peak hour factor
- v/c = desired volume to capacity ratio