Design of Traffic Control

Design Principles of Traffic Signal

Overview

Traffic signals are one of the most effective and flexible active control of traffic and is widely used in several cities worldwide. The conflicts arising from movements of traffic in different directions is addressed by time sharing principle. The advantages of traffic signal includes an orderly movement of traffic, an increased capacity of the intersection and requires only simple geometric design. However, the disadvantages of the signalized intersection are large stopped delays, and complexity in the design and implementation. Although the overall delay may be lesser than a rotary for a high volume, a user may experience relatively high stopped delay. This chapter discuss various design principles of traffic signal such as phase design, cycle length design, and green splitting. The concept of saturation flow, capacity, and lost times are also presented. First, some definitions and notations are given followed by various steps in design starting from phase design.

Definitions and notations

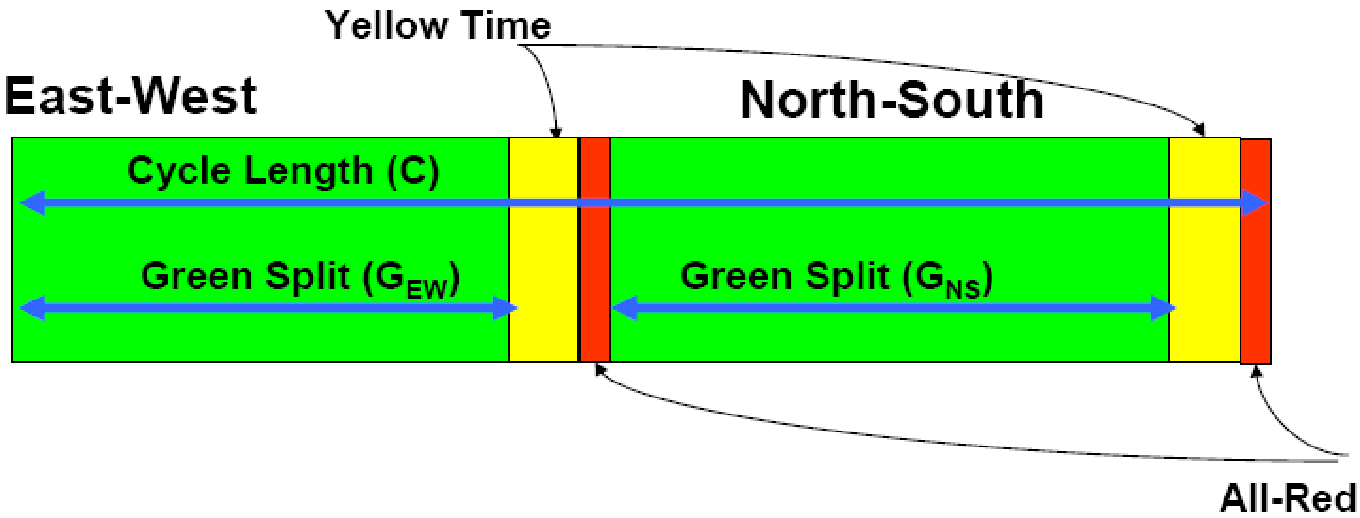
A number of definitions and notations need to be understood in signal design. They are discussed below:

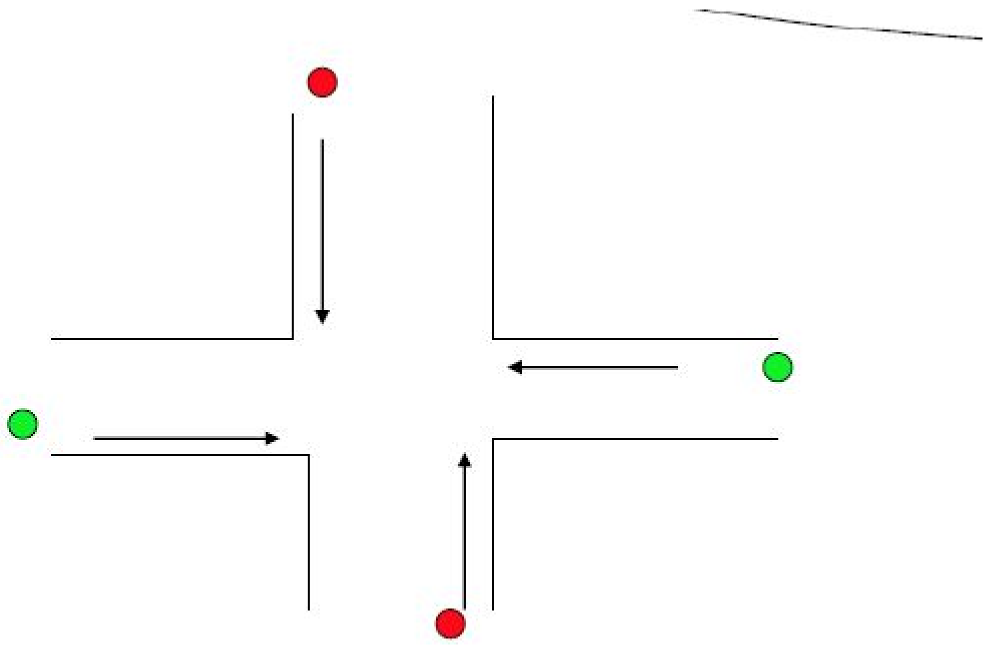
- **Cycle**: A signal cycle is one complete rotation through all of the indications provided.
- **Cycle length**: Cycle length is the time in seconds that it takes a signal to complete one full cycle of indications. It indicates the time interval between the starting of of green for one approach till the next time the green starts. It is denoted by C.
- **Interval**: Thus it indicates the change from one stage to another. There are two types of intervals - change interval and clearance interval.
- **Change interval** is also called the yellow time indicates the interval between the green and red signal indications for an approach.
- **Clearance interval** is also called all red and is provided after each yellow interval indicating a period during which all signal faces show red and is used for clearing off the vehicles in the intersection.
- **Green interval**: It is the green indication for a particular movement or set of movements and is denoted by G_i. This is the actual duration the green light of a traffic signal is turned on.
- **Red interval**: It is the red indication for a particular movement or set of movements and is denoted by R_i. This is the actual duration the red light of a traffic signal is turned on.
- **Phase:** A phase is the green interval plus the change and clearance intervals that follow it. Thus, during green interval, non conflicting movements are assigned into

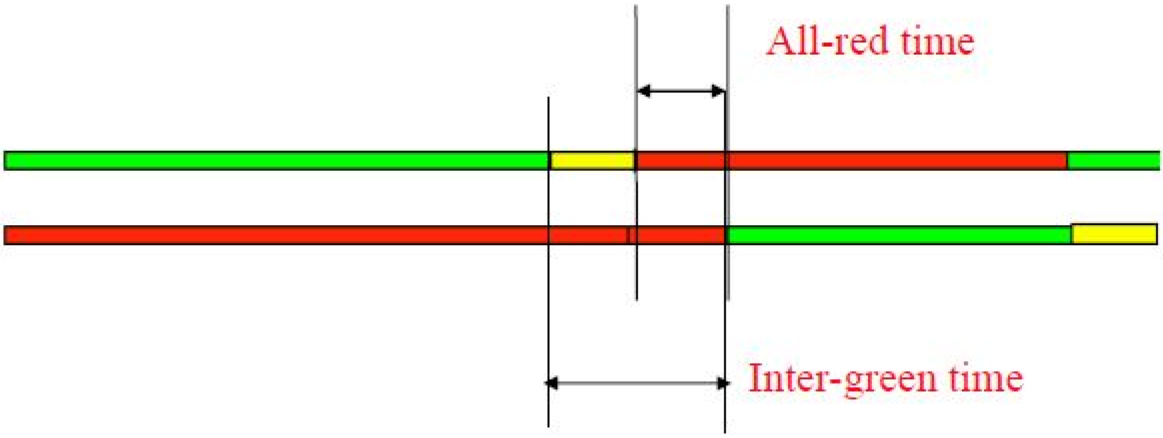
each phase. It allows a set of movements to flow and safely halt the flow before the phase of another set of movements start.

- **Lost time**: It indicates the time during which the intersection is not effectively utilized for any movement. For example, when the signal for an approach turns from red to green, the driver of the vehicle which is in the front of the queue, will take some time to perceive the signal (usually called as reaction time) and some time will be lost before vehicle actually moves and gains speed.

Two-Phase Example



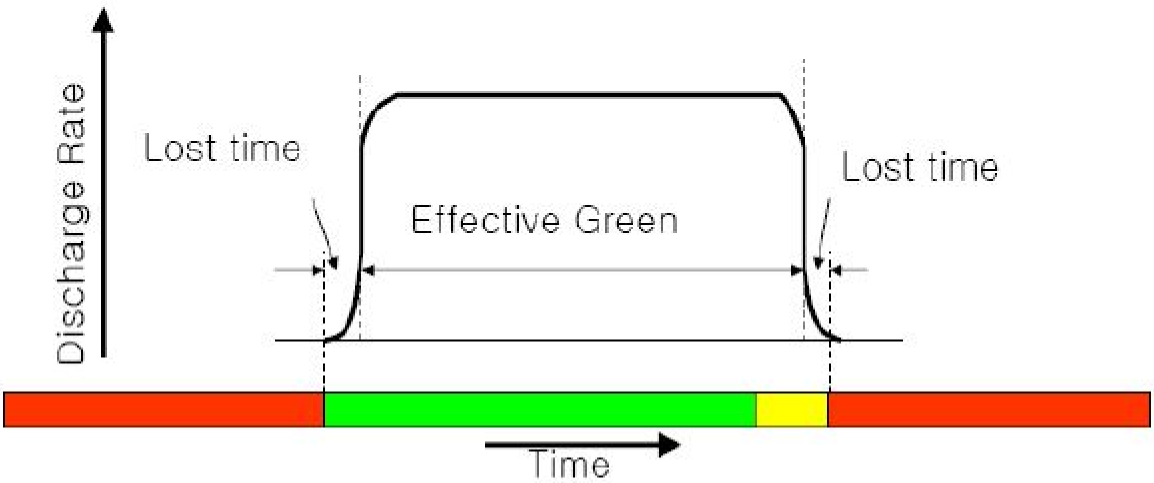




Effective Green Time

- Effective Green (g)=Green Time + Change Interval–Lost Time

- Lost Time (LT)=Start-up delays
- the time during a given phase in which traffic could be discharging through the intersection, but is not. This is the period during the green interval and change intervals that is not used by discharging traffic
- Effective Red (r) = Cycle Length –Effective Green



Capacity and Saturation Flow

- **Capacity**: the maximum number of vehicles that can reasonably be expected to pass over a given roadway or section of roadway, in one direction, during a given time period and under the prevailing roadway, traffic, and signalization conditions.

- **Saturation flow**: The maximum number of vehicles from a lane group that would pass through the intersection in one hour under the prevailing traffic and roadway conditions if the lane group was given a continuous green signal for that hour.

<u>Phase design</u>

The signal design procedure involves six major steps. They include:

(1) phase design,

(2) determination of amber time and clearance time,

(3) determination of cycle length,

(4) apportioning of green time,

(5) pedestrian crossing requirements, and

(6) performance evaluation of the design obtained in the previous steps.

The objective of phase design is to separate the conflicting movements in an intersection into various phases, so that movements in a phase should have no conflicts. If all the movements are to be separated with no conflicts, then a large number of phases are required. In such a situation, the objective is to design phases with minimum conflicts or with less severe conflicts.

There is no precise methodology for the design of phases. This is often guided by the geometry of the intersection, the flow pattern especially the turning movements, and the relative magnitudes of flow. Therefore, a trial and error procedure is often adopted. However, phase design is very important because it affects the further design steps. Further, it is easier to change the cycle time and green time when flow pattern changes, where as a drastic change in the flow pattern may cause considerable confusion to the drivers. To illustrate various phase plan options, consider a four legged intersection with through traffic and right turns. Left turn is ignored. See Figure below.

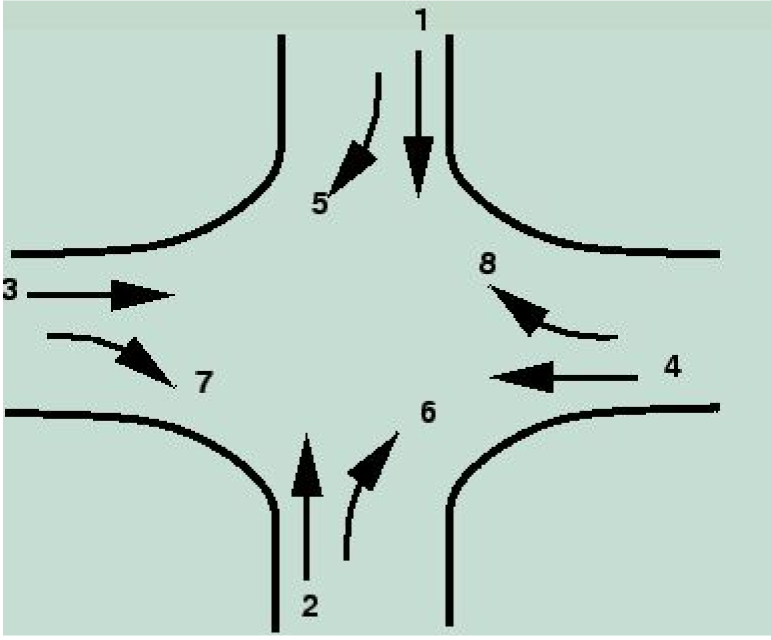


Figure: Four legged intersection.

The first issue is to decide how many phases are required. It is possible to have two, three, four or even more number of phases.

Two phase signals

Two phase system is usually adopted if through traffic is significant compared to the turning movements. For example in Figure below, non-conflicting through traffic 3 and 4 are grouped in a single phase and non-conflicting through traffic 1 and 2 are grouped in the second phase.

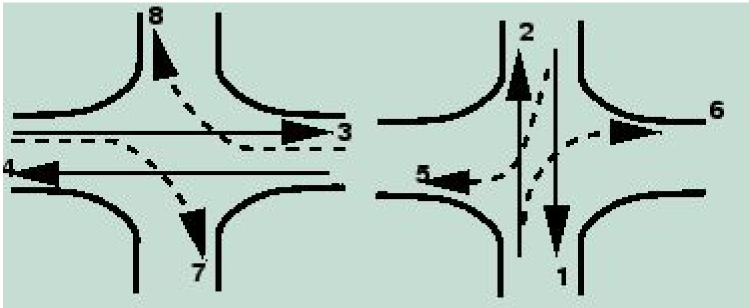


Figure: Movements in two phase signal system.

However, in the first phase flow 7 and 8 offer some conflicts and are called permitted right turns. Needless to say that such phasing is possible only if the turning movements are relatively low. On the other hand, if the turning movements are significant, then a four phase system is usually adopted.

Four phase signals

There are at least three possible phasing options. For example, figure below shows the most simple and trivial phase plan.

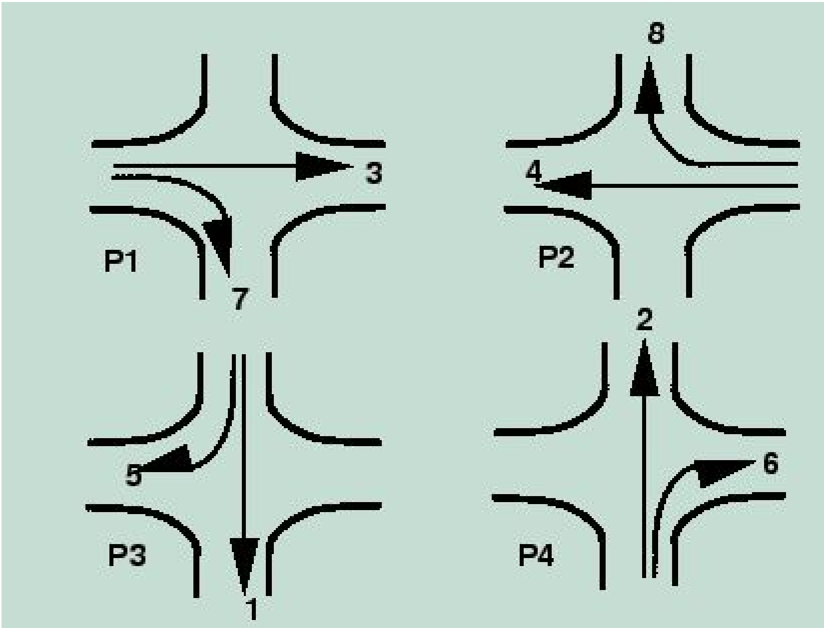


Figure: Movements in four phase signal system: option 1.

where, flow from each approach is put into a single phase avoiding all conflicts. This type of phase plan is ideally suited in urban areas where the turning movements are comparable with through movements and when through traffic and turning traffic need to share same lane. This phase plan could be very inefficient when turning movements are relatively low.

Figure below shows a second possible phase plan option where opposing through traffic are put into same phase.

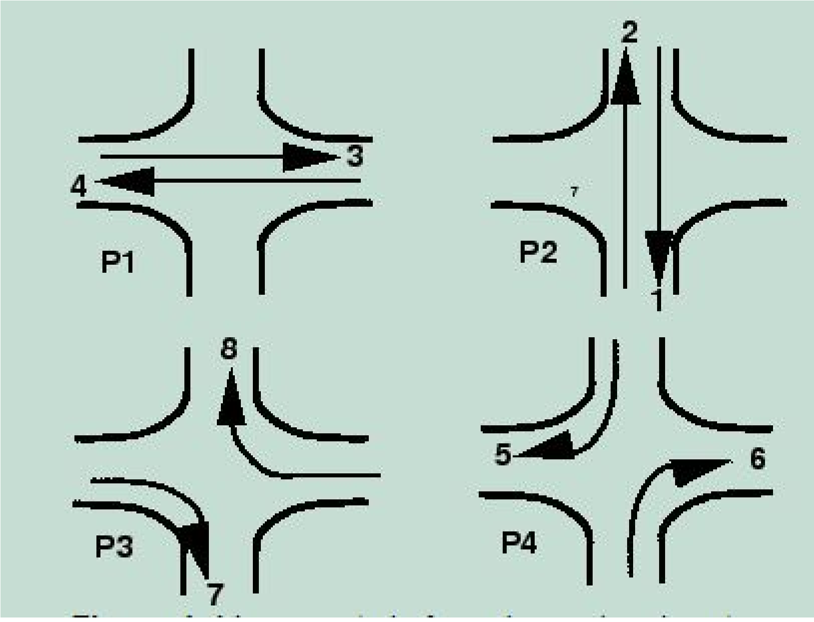


Figure: Movements in four phase signal system: option 2.

The non-conflicting right turn flows 7 and 8 are grouped into a third phase. Similarly flows 5 and 6 are grouped into fourth phase. This type of phasing is very efficient when the intersection geometry permits to have at least one lane for each movement, and the through traffic volume is significantly high. Figure below shows yet another phase plan. However, this is rarely used in practice.

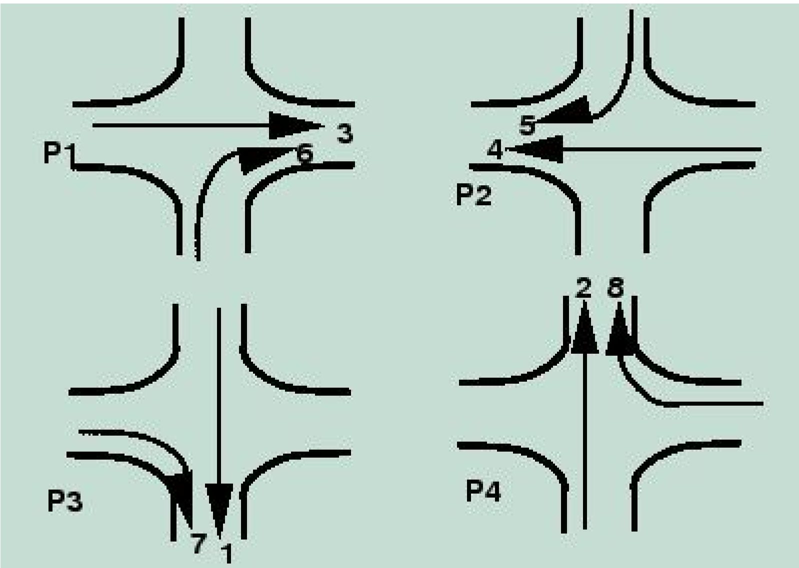


Figure: Movements in four phase signal system: option 3.

There are five phase signals, six phase signals etc. They are normally provided if the intersection control is adaptive, that is, the signal phases and timing adapt to the real time traffic conditions.

Cycle time

Cycle time is the time taken by a signal to complete one full cycle of iterations. i.e. one complete rotation through all signal indications. It is denoted by C. The way in which the vehicles depart from an intersection when the green signal is initiated will be discussed now. Figure 1 illustrates a group of N vehicles at a signalized intersection, waiting for the green signal.

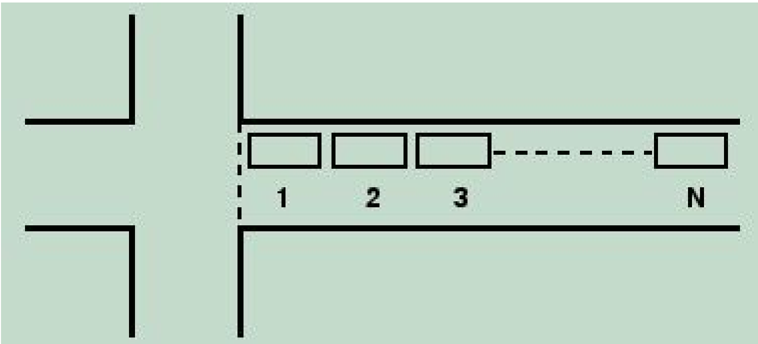


Figure: Group of vehicles at a signalized intersection waiting for green signal.

As the signal is initiated, the time interval between two vehicles, referred as headway, crossing the curb line is noted. The first headway is the time interval between the initiation of the green signal and the instant vehicle crossing the curb line. The second headway is the time interval between the first and the second vehicle crossing the curb line. Successive headways are then plotted as in figure below.

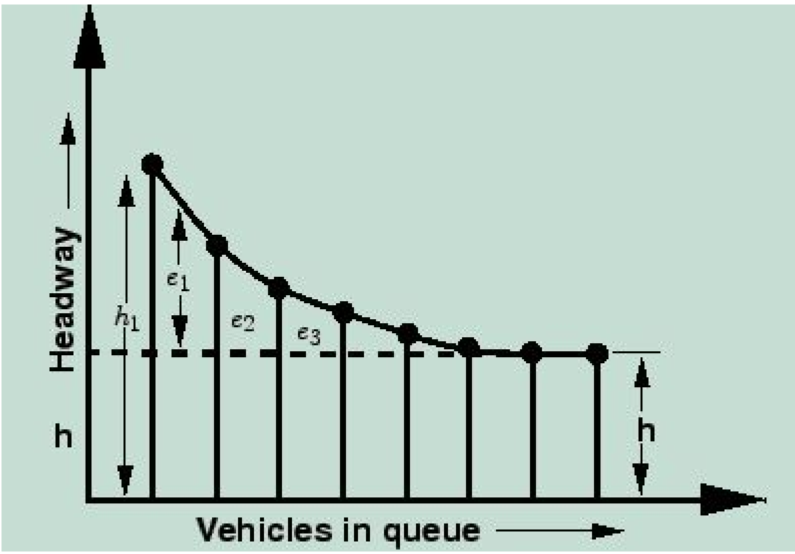


Figure: Headways departing signal.

The first headway will be relatively longer since it includes the reaction time of the driver and the time necessary to accelerate. The second headway will be comparatively lower because the second driver can overlap his/her reaction time with that of the first driver's. After few vehicles, the headway will become constant. This constant headway which characterizes all headways beginning with the fourth or fifth vehicle, is defined as the saturation headway, and is denoted as h. This is the headway that can be achieved by a stable moving platoon of vehicles passing through a green indication. If every vehicles require h seconds of green time, and if the signal were always green, then s vehicles per hour would pass the intersection. Therefore,

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

where s is the saturation flow rate in vehicles per hour of green time per lane, h is the saturation headway in seconds. As noted earlier, the headway will be more than h particularly for the first few vehicles. The difference between the actual headway and h for the i^{th} vehicle and is denoted as e_i shown in figure 2. These differences for the first few vehicles can be added to get start up lost time, l_1 which is given by,

$$l_1 = \sum_{i=1}^{n} e_i \qquad (2)$$

The green time required to clear N vehicles can be found out as,

$$T = l_1 + h.N \qquad (3)$$

where T is the time required to clear N vehicles through signal, l_1 is the start-up lost time, and h is the saturation headway in seconds.

Effective green time

Effective green time is the actual time available for the vehicles to cross the intersection. It is the sum of actual green time (G_i) plus the yellow minus the applicable lost times. This lost time is the sum of start-up lost time (l_1) and clearance lost time (l_2) denoted as t_L. Thus effective green time can be written as,

$$g_i = G_i + Y_i - t_L$$

Lane capacity

The ratio of effective green time to the cycle length ($\frac{g_i}{C}$)is defined as green ratio. We know that saturation flow rate is the number of vehicles that can be moved in one lane in one hour assuming the signal to be green always. Then the capacity of a lane can be computed as,

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

where c_i is the capacity of lane in vehicle per hour, s_i is the saturation flow rate in vehicle per hour per lane, C is the cycle time in seconds.

Numerical example

Let the cycle time of an intersection is 60 seconds, the green time for a phase is 27 seconds, and the corresponding yellow time is 4 seconds. If the saturation headway is 2.4 seconds per vehicle, the start-up lost time is 2 seconds per phase, and the clearance lost time is 1 second per phase, find the capacity of the movement per lane?

Solution

Total lost time, t_L = 2+1 = 3 seconds. From equation 4 effective green time, g_i = 27+4-3 = 28 seconds. From equation 1 saturation flow rate, $s_i = \frac{3600}{h} = \frac{3600}{2.4}$ = 1500 veh per hr. Capacity of the given phase can be found out from equation 5 as $C_i = 1500 \times \frac{28}{60}$ = 700 veh per hr per lane.

Critical lane

During any green signal phase, several lanes on one or more approaches are permitted to move. One of these will have the most intense traffic. Thus it requires more time than any other lane moving at the same time. If sufficient time is allocated for this lane, then all other lanes will also be well accommodated. There will be one and only one critical lane in each signal phase. The volume of this critical lane is called critical lane volume.

Determination of cycle length

The cycle length or cycle time is the time taken for complete indication of signals in a cycle. Fixing the cycle length is one of the crucial steps involved in signal design.

If t_{Li} is the start-up lost time for a phase i, then the total start-up lost time per cycle, $L = \sum_{i=1}^{N} t_{Li}$, where N is the number of phases. If start-up lost time is same for all phases, then the total start-up lost time is $L = N t_L$. If C is the cycle length in seconds, then the number of cycles per hour = $\frac{3600}{C}$. The total lost time per hour is the number of cycles per hour times the lost time per cycle and is = $\frac{3600}{C} L$. Substituting as $L = N t_L$, total lost time per hour can be written as = $\frac{3600\ N\ t_L}{C}$. The total effective green time T_g available for the movement in a hour will be one hour minus the total lost time in an hour. Therefore,

$$T_g = 3600 - \frac{3600\ N\ t_L}{C}$$

$$= 3600 \left[1 - \frac{N\ t_L}{C}\right]$$

Let the total number of critical lane volume that can be accommodated per hour is given by V_c, then $V_c = \frac{T_g}{h}$. Substituting for T_g from equation 1 and s_i from equation in the expression for the the maximum sum of critical lane volumes that can be accommodated within the hour and by rewriting, the expression for C can be obtained as follows:

$$V_c = \frac{T_g}{h},$$

$$= \frac{3600}{h} \left[1 - \frac{N\ t_L}{C}\right],$$

$$= s_i \left[1 - \frac{N\, t_L}{C}\right],$$

$$\therefore\ C = \frac{N\, t_L}{1 - \frac{V_c}{s}}.$$

The above equation is based on the assumption that there will be uniform flow of traffic in an hour. To account for the variation of volume in an hour, a factor called peak hour factor, (PHF) which is the ratio of hourly volume to the maximum flow rate, is introduced. Another ratio called v/c ratio indicating the quality of service is also included in the equation. Incorporating these two factors in the equation for cycle length, the final expression will be,

$$C = \frac{N\, t_L}{1 - \frac{V_c}{s_i \times PHF \times \frac{v}{c}}}$$

Highway capacity manual (HCM) has given an equation for determining the cycle length which is a slight modification of the above equation. Accordingly, cycle time C is given by,

$$C = \frac{N\ L\ X_C}{X_C - \sum\left(\frac{V_{c_i}}{s_i}\right)}$$

where N is the number of phases, L is the lost time per phase, $\left(\frac{V_{c_i}}{s_i}\right)$ is the ratio of critical volume to saturation flow for phase i, X_C is the quality factor called critical $\frac{v}{c}$ ratio where v is the volume and c is the capacity.

<u>Numerical example</u>

The traffic flow in an intersection is shown in the figure

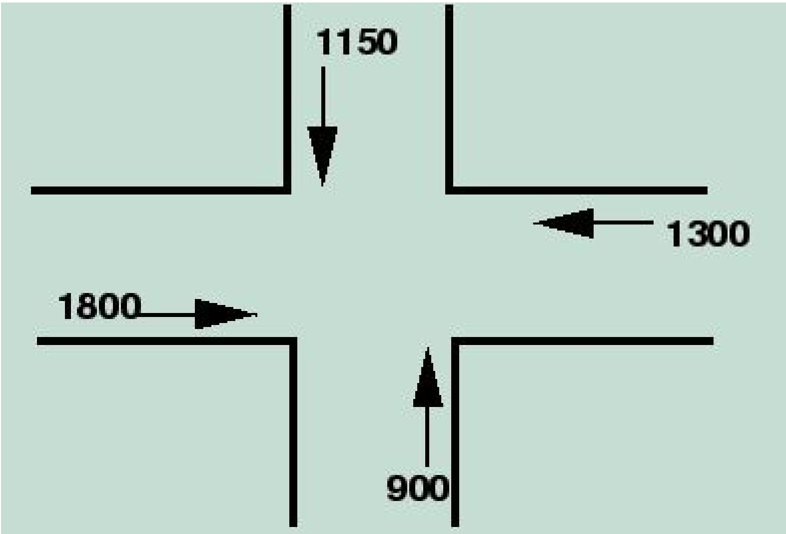


Figure: Traffic flow in the intersection.

Solution

1. If we assign two phases as shown below figure below, then the critical volume for the first phase which is the maximum of the flows in that phase = 1150 vph.

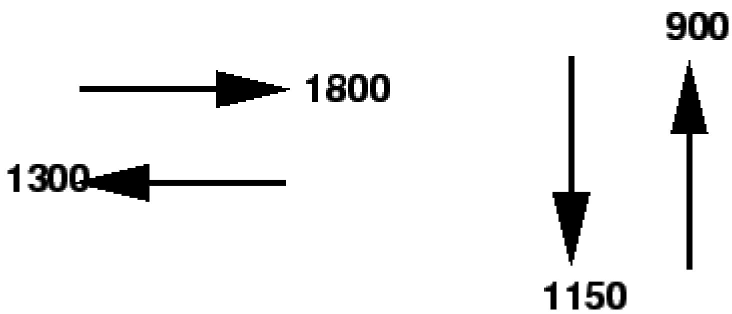


Figure : One way of providing phases

2. Similarly critical volume for the second phase = 1800 vph. Therefore, total critical volume for the two signal phases = 1150+1800 = 2950 vph.
3. Saturation flow rate for the intersection can be found out from the equation as $s_i = \frac{3600}{2.3}$ = 1565.2 vph. This means, that the intersection can handle only 1565.2 vph. However, the critical volume is 2950 vph . Hence the critical lane volume should be reduced and one simple option is to split the major traffic into two lanes. So the resulting phase plan is as shown in figure below.

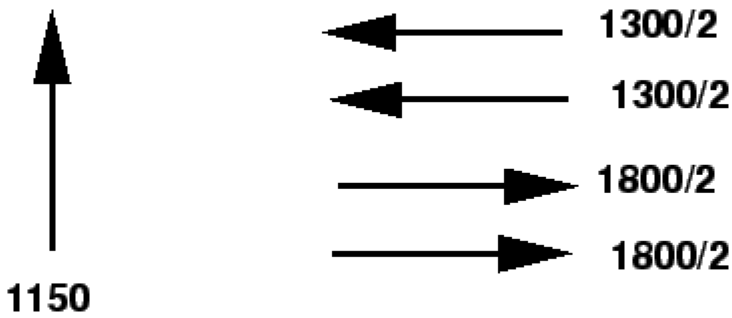


Figure : second way of providing phases

4. Here we are dividing the lanes in East-West direction into two, the critical volume in the first phase is 1150 vph and in the second phase it is 900 vph. The total critical volume for the signal phases is 2050 vph which is again greater than the saturation flow rate and hence we have to again reduce the critical lane volumes.
5. Assigning three lanes in East-West direction, as shown in figure 4, the critical volume in the first phase is 575 vph and that of the second phase is 600 vph, so that the total critical lane volume = 575+600 = 1175 vph which is lesser than 1565.2 vph.

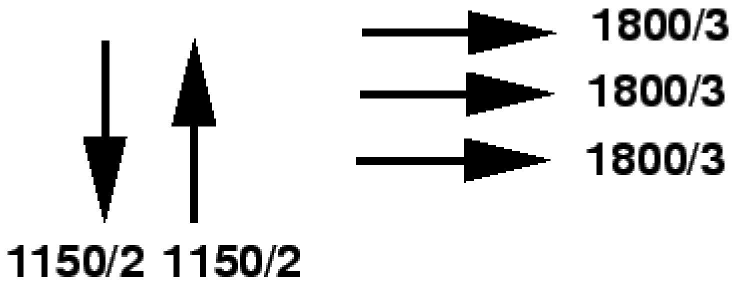


Figure : Third way of providing phases

6. Now the cycle time for the signal phases can be computed from equation 1 as:

$$C = \frac{2 \times 3}{1 - \frac{1175}{1565.2}} = 24 \text{ seconds.}$$

Green splitting

Green splitting or apportioning of green time is the proportioning of effective green time in each of the signal phase. The green splitting is given by,

$$g_i = \left[\frac{V_{c_i}}{\sum_{i=1}^{N} V_{c_i}} \right] \times t_g \qquad (1)$$

where V_{c_i} is the critical lane volume and t_g is the total effective green time available in a cycle. This will be cycle time minus the total lost time for all the phases. Therefore,

$$t_g = C - N\, t_L \qquad (2)$$

where C is the cycle time in seconds, n is the number of phases, and t_L is the lost time per phase. If lost time is different for different phases, then effective green time can be computed as follows:

$$t_g = C - \sum_{i=1}^{N} t_{L_i} \qquad (3)$$

where t_{L_i} is the lost time for phase i, N is the number of phases and C is the cycle time in seconds. Actual green time can be now found out as,

$$G_i = g_i - y_i + t_{L_i} \qquad (4)$$

where G_i is the actual green time, g_i is the effective green time available, y_i is the amber time, and L_i is the lost time for phase i.

Numerical example

The phase diagram with flow values of an intersection with two phases is shown in figure below.

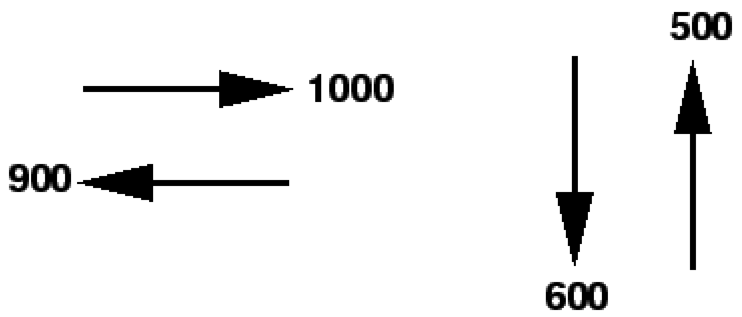


Figure: Phase diagram for an intersection

The lost time and yellow time for the first phase is 2.5 and 3 seconds respectively. For the second phase the lost time and yellow time are 3.5 and 4 seconds respectively. If the cycle time is 120 seconds, find the green time allocated for the two phases.

Solution

1. Critical lane volume for the first phase, V_{C_1} = 1000 vph.
2. Critical lane volume for the second phase, V_{C_2} = 600 vph.
3. Total critical lane volumes, $V_C = V_{C_1} + V_{C_2}$ = 1000+600 = 1600 vph.
4. Effective green time can be found out from equation 2 as T_g =120-(2.5-3.5)= 114 seconds.
5. Green time for the first phase, g_1 can be found out from equation 1 as $g_1 = \frac{1000}{1600} \times 114$ = 71.25 seconds.
6. Green time for the second phase, g_2 can be found out from equation 1 as $g_2 = \frac{600}{1600} \times 114$= 42.75 seconds.
7. Actual green time can be found out from equation 4. Thus actual green time for the first phase, G_1 = 71.25-3+2.5 = 71 seconds (rounded).
8. Actual green time for the second phase, G_2 = 42.75-4+3.5 = 42 seconds (rounded).
9. The phase diagram is as shown in figure below.

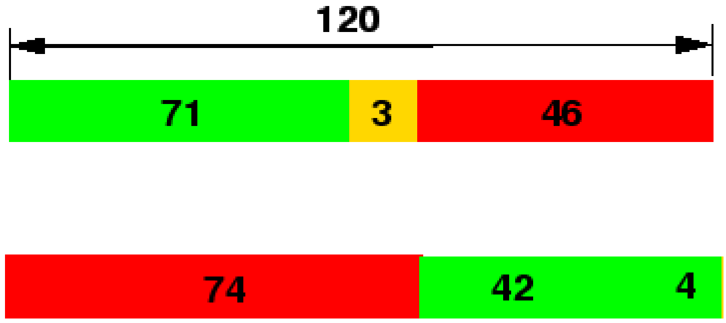


Figure: Timing diagram

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