5. INTERSECTIONS

5.1. INTRODUCTION

Intersections are the physical component of the roadways where two highways intersect. They are the most complex element of roadways, since it requires more than one decision to be performed at any time. Intersections affect significantly the quality and amount of traffic through highways due to its complexity and use of traffic control devices. Intersections are classified as grade-separated or at grade. As the terms imply, for the first group there is physical separation among the traffic streams and they are usually known as interchanges, while the other group are the typical street intersections. This section examines only at grade intersections.

Three basic traffic control devices are used to control flow through an intersection. These are traffic signals, STOP signs, and YIELD signs. The placement of any of these devices is controlled by warrants specified in the Manual of Uniform Traffic Control Devices (MUTCD). Vehicles approaching yield signs have to slow down and yield the right of way to other traffic flows at the intersection. They are usually placed at intersections of minor roads or at channelized movements. In contrast, vehicles approaching stop signs are required to completely stop before entering the intersection. They are used at intersections of minor roads with roads with high speeds or volumes, of areas with restricted sight vision, and at intersections with high accident history. They can be 2-way, stop signs on minor street only, or all-way, stop signs on all approaches. Traffic signals are the most successful device in allocating time and space through an intersection and can alleviate conflicts of movements. There are a number of actors that need to be considered prior to placing a traffic signal and they include traffic volumes, pedestrian volumes, accident experience, and delays.

5.2. TRAFFIC SIGNALS

5.2.1. Terminology

The objective of a traffic signal is to properly allocate time to the respective movements of an intersection without causing undue delays. For a traffic signal to work properly and achieve these objectives, proper timing is required. However, before presenting the timing issues, the definition of a number of terms is presented.

<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cycle</td>
<td>A complete sequence of signal indications</td>
</tr>
<tr>
<td>Cycle Length (C)</td>
<td>Time to complete a cycle</td>
</tr>
<tr>
<td>Phase</td>
<td>Part of cycle allocated to a set of movements</td>
</tr>
<tr>
<td>Interval</td>
<td>Time for a constant display</td>
</tr>
<tr>
<td>Change Interval ($\tau_i$)</td>
<td>Time elapsed between the end of the green of one phase and the beginning of green of the next phase, equal to yellow and (any) all red</td>
</tr>
</tbody>
</table>
Green time \((G_i)\): Time of green display
Lost time \((l_i)\): Time lost due to start up and slow down at the beginning and end of the green interval
Effective green \((g_i)\): Real time allocated for vehicle movement, \(g_i = G_i - l_i + \tau_i\)
Green ratio \((g/C)\): The portion of effective green for each phase
Pretimed signals: All intervals are fixed
Semiactuated signals: Main street maintains green continuously unless a vehicle arrives at the stop-line of the crossroad
Actuated signals: Vehicles in all approaches can activate the signal
Protected movement: Exclusive use of time and uncontested right-of-way
Permitted movement: Has to yield the right-of-way and be completed when traffic "permits"
Discharge headway: Headway after stabilization of flow
Saturation flow: Maximum number of vehicles that can be processed at an intersection approach, if the signal indication remains continuously green
Critical movement: The movement with the highest volume to saturation ratio; there is only one per phase

5.2.2. Basic Concepts

5.2.2.1. Clearance Interval

While establishing the times for specific movements through a signalized intersection, special consideration should be given to the time required for a vehicle to cross the intersection towards the end of the green phase. Traditionally, this time is the yellow interval and any all red indication following. Very short times do not provide adequate time for vehicles to clear the intersection, while long times lead to disrespect of the yellow, and even some times of the red, indication. Improper clearance interval also cause a dilemma to drivers regarding their reaction--drive or stop. Figure 5.1 shows an intersection approach, where a dilemma zone exists. Drivers caught within the overlapping zones are not clear as to what to do.

Distance \(X_c\) is the required stopping distance while distance \(X_o + W + L\) is the required distance to be traveled in the available clearance interval. To eliminate the dilemma zone, the two distances, \(X_o\) and \(X_c\), should be at least equal. Assuming that a vehicle travels with a speed \(u_o\) (m/sec) and there is a clearance interval of \(\tau_{\text{min}}\) seconds, then

\[
X_o = u_o \tau_{\text{min}} - (W + L)
\]  

(1)

Similarly, assuming a deceleration rate of \(\alpha\) m/sec\(^2\) and reaction time of \(t_r\) seconds, distance \(X_c\) is
To eliminate the dilemma zone $X_c$ should be equal to $X_o$ and by using Equations 1 and 2 and rearranging the terms, the minimum clearance interval is

$$
X_c = u_o t_r + \frac{u_o^2}{2\alpha}
$$

To eliminate the dilemma zone $X_c$ should be equal to $X_o$ and by using Equations 1 and 2 and rearranging the terms, the minimum clearance interval is

$$
\tau_{\text{min}} = t_r + \frac{W+L}{u_o} + \frac{u_o}{2\alpha}
$$

Safety considerations indicate the use of no less than 3 seconds of clearance interval. In this case, the clearance interval is set equal to the yellow indication. If longer clearance intervals are needed, they can be accommodated through the use of combination of yellow and all red indications.

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**Example**

Vehicles approaching an intersection with 60 km/h have to cross a 12 m street. If the average reaction time of a driver is 1.5 seconds, the deceleration rate is 3 m/sec$^2$, the average length of a vehicle is 6 m, determine the clearance interval required. If the desired yellow interval is 4 seconds, should there be an all red indication?

Using Equation 3 and a speed of $60(1000)/3600 = 16.7$ m/sec, the minimum required clearance interval is

$$
\tau_{\text{min}} = t_r + (W+L)/u_o + u_o/2\alpha = 1.5 + (12+6)/16.7 + 16.7/2(3) = 5.4 \text{ sec}
$$

Using a 4 second yellow, the remaining 1.4 seconds should be accommodated using an all red indication.

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5.2.2.2. Lost Time

Traffic leaving the approach of an intersection at the beginning of the green indication is not discharged at full rate, since vehicles need to accelerate and drivers do not respond instantly to the change of signal indication. Similarly, at the beginning of the yellow interval vehicles will start decelerating and the discharge rate will drop. Assuming that there are enough vehicles in line to maintain a maximum constant discharge rate throughout the green interval, the times when the discharge rate drops is called *lost time*. This time represents the time that the intersection is not fully utilized to discharge vehicles and is shown in Figure 5.2.
Figure 5.2. Lost time concept at signalized intersections

From this figure, the lost time is

\[ I_i = G_i + \tau_i - g_i \]  

(4)

5.3. CRITICAL MOVEMENT ANALYSIS

The Critical Movement Analysis (CMA) is a process that is based on the basic assumption that a signalized intersection will operate close or at capacity if the sum of critical lane volumes is 1400 vph. This method is used to evaluate alternative phasing plans, approximate the volume distribution by lane, and provide general estimates of capacity and adequacy of the intersection.

To proceed with this method, first the volume of each approach has to be assigned on each of the lanes traveled. The following rules have been established for such lane assignments:

1. Only through traffic: evenly distributed among lanes
2. Right turns: equivalent to through traffic if no exclusive turn lane exists
3. Exclusive Left or Right turn lanes: all turning traffic is assigned in the lane
4. Through and Left turns: utilize through vehicle equivalents and use a special procedure.

Table 1. Through vehicle equivalents

<table>
<thead>
<tr>
<th>Opposing Through &amp; Right Volume (v/h)</th>
<th>Through Vehicle Equivalents</th>
</tr>
</thead>
<tbody>
<tr>
<td>0-199</td>
<td>1.1</td>
</tr>
<tr>
<td>200-599</td>
<td>2</td>
</tr>
<tr>
<td>600-799</td>
<td>3</td>
</tr>
<tr>
<td>800-999</td>
<td>4</td>
</tr>
<tr>
<td>&gt;1000</td>
<td>5</td>
</tr>
</tbody>
</table>

The process for distributing traffic for shared through and left turning traffic is as follows:
1. Determine Passenger Car Equivalents (PCE) for left turning vehicles if left turn movement is opposed by oncoming traffic;
2. Calculate Design Volume ($V_d$) using $V_d = (V_{LT} \times PCE) + V_{TH}$ ($V_{LT}$: left turn volume, $V_{TH}$: through volume);
3. Divide $V_d$ by the number of lanes to evenly distribute the volume;
4. Volume in through lanes will be equal to the one calculated, while the volume in the shared lane will be the left turning volume and the remaining through that was not accommodated by the through lanes.

**Example**

For the intersection shown here determine the number of vehicles using each lane.

Following the rules presented above each approach is analyzed separately:

1. **North-bound traffic**—Exclusive left and right only lanes take all turning movements; through traffic is equally divided between the two lanes and thus $700/2 = 350$ v/h for each lane

2. **South-bound traffic**—Exclusive left turn lane take all left turning traffic; total flow of through and right movements is equally divided between the other two lanes and thus $(800 + 100)/2 = 450$ v/h in each lane. The TH only lane has 450 v/h, RT+TH lane will have 350 v/h TH and 100 v/h RT

3. **East-bound traffic**—One TH+RT and one TH+LT, opposing volume for left turns west-bound TH+RT = 780 v/h therefore PCE for LT 3. The total equivalent through volume will be $V_d = 120(3) + 850 = 1210$ v/h and each lane will have $1210/2 = 605$ v/h. The TH+RT lane will carry 605 v/h (150 RT and 455 TH) and the TH+LT lane will carry 365 v/h (245 v/h TH (700-455) and 120 v/h LT)

4. **West-bound traffic**—One TH+RT and one TH+LT, opposing volume for left turns east-bound TH+RT = 850 v/h therefore PCE for LT 4. The total equivalent through volume will be $V_d = 130(4) + 780 = 1300$ v/h and each lane will have $1300/2 = 650$ v/h. The TH+RT lane will carry 650 v/h (100 RT and 550 TH) and the TH+LT lane will carry 260 v/h (130 v/h TH (680-550) and 130 v/h LT)

To determine the critical lane volumes the following two rules are used:
1. Left turns **only** on **protected phases**: The highest volume lane that receives green for each phase becomes the critical one.
2. Left turns on **permissive phases**: The critical lane volume becomes the highest total of the through single lane with its opposing left movement.

**Example**

For the intersection shown above, determine the critical lane volumes for the phasing diagram shown for each direction.

1. **Critical lane volume for phase 1**
2. **Critical lane volume for phase 3**
Max \( \{LT_{NB}, LT_{SB}\} = 180 \)
Critical lane volume for phase 2
Max \( \{TH_{NB}, TH_{SB}\} = 450 \)

\[
\text{Max } \{LT_{EB} + TH_{WB}, LT_{WB} + TH_{EB}\} = \text{Max } \{130+605, 120+650\} = 770
\]

The determination of the critical lane volumes allows for the evaluation of phasing plans. To achieve this, first the possible phasing schemes need to be identified, then the volumes are assigned to each travel lane with the use of CMA procedures, the critical lanes and their volumes by phase are determined, and the sum of critical volumes for the intersection is calculated. The alternative with the lowest sum is probably the best phasing solution. However, if special considerations should be given for exclusive phases (for example due to high accidents, difficulty of geometric design and so forth), these phases should also be considered.

**Example**

For the intersection in the previous example the sum of critical lane volumes for a three phase signal will be: \( \Sigma_{CV} = 180+450+770 = 1400 \text{ v/h} \)

For the same intersection and a two-phase signal the sum of critical lane volumes will be:
\( \Sigma_{CV} = \text{Max } \{180+350, 450+160\}+770 = 610+770 = 1380 \text{ v/h} \)

Therefore, the two-phase signal will produce a "better" operation because the intersection will operate under the maximum 1400 v/h total. However, other factors, such safety, coordination with other signals, and progression, should be considered before making the final decision.

5.4. SIGNAL TIMING

5.4.1. Pedestrian Requirements

According to Manual of Uniform Traffic Control Devices the WALK indication at a traffic signal should flash for an interval of 4 to 7 seconds. A minimum of a 4-second interval is needed if the pedestrian volume is light (10 ped/cycle or less) while a 7-second interval should be used if there are 20 ped/cycle or more. The required time for pedestrians is estimated as the time needed to walk until the middle of the farthest traveled lane. The average pedestrian speed is 1.2 m/sec and this speed should be adjusted for the prevailing age of pedestrians (older pedestrian walk slower).

If \( W \) denotes the length that a pedestrian has to walk and assuming a speed of 1.2 m/sec, then the minimum total time for the WALK and Flashing DON'T WALK indications should be
To accommodate vehicle traffic while maintaining the minimum pedestrian requirements, then $G_p$ should be at least equal to the red indication of the street that pedestrians need to cross.

### 5.4.2. Vehicular Requirements

Using only the vehicular requirements another formula was developed by Webster that calculates the optimum cycle length for a signalized intersection minimizing delays. The formula utilizes the principles of the Critical Movement Analysis for distributing traffic in the available lanes and determining critical lanes and volumes. Webster's formula calculates the optimum cycle $C_o$ as

$$C_o = \frac{1.5L + 5}{\phi_i \left(1 - \sum_{i=1}^{\phi} Y_i\right)}$$

where $L$ is the total lost time per cycle, $Y_i$ is the critical volume to saturation flow ratio for phase $i$, and $\phi$ is the number of phases. The total lost time $L$ is the sum of all lost times for each phase and the total sum of any all red indications.

The time distribution among the phases is completed by computing the total effective green time as

$$g_f = C_o - L$$

Then, this time is distributed among the phases proportionally to their critical volume to saturation flow ratios $Y_i$. Thus,

$$g_i = \frac{Y_i}{\phi \sum_{i=1}^{\phi} Y_i} g_f$$

Finally, the display times are computed by rearranging Equation 4, and thus

$$G_i = g_f + l_i - \tau_i$$

The process for determining the cycle length and distributing the time among the available phases is summarized in the following steps:

1. Assign traffic volumes to lanes using Critical Movement Analysis (CMA)
2. Identify trial phasing plan(s)
3. Determine critical lane volumes (one for each phase) ($v_i$)
4. Determine if trial phasing plan is likely to be adequate
   - Do critical lane volumes total 1,400 vph or less?
   - Is capacity adequate to accommodate any permitted left-turn movements?
5. Determine requirements for clearance interval at end of each phase
   - Compute $\tau_i$ for each phase
   - Set yellow interval ($y_i$) to 3 or 4 seconds
   - Determine all-red interval ($r_i = \tau_i - y_i$)
6. Determine optimal cycle length using Webster's formula ($C_o$), Equation 6
7. Split cycle length into phases using Equations 7, 8, and 9
8. Adjust green times for pedestrians as necessary using Equation 5
9. Test other phase plans as desirable
10. Prepare timing diagram for both traffic and pedestrian indications

Example

The cycle length for the intersection shown previously in the CMA example is to be determined. It was decided to use a three-phase signal due to accidents. All approaches have 3.0 m lanes and saturation flows are 1800 pcphgl. The average walking speed is 1.0 m/sec and there is light pedestrian volume. Assuming a lost time of 3 sec per phase, approach speed of 45 km/h, 6 m vehicles, deceleration rate of 3 m/sec², and reaction time of 1 sec, determine the cycle length and the timing of each phase to accommodate both vehicular and pedestrian requirements.

a. Determination of critical lane volumes (as computed previously)
   Phase 1 (exclusive LT for N-S): 180 v/h
   Phase 2 (TH and RT for N-S): 450 v/h
   Phase 3 (all E-W traffic): 770 v/h

b. Determination of clearance intervals
   Using Equation 3, vehicles traveling with a N-S direction have to clear 4 lanes, thus (4)(3)=12 mt, with an approach speed of 45(1000)/3600 = 12.5 m/sec. The clearance interval will then be:
   \[ \tau_{NS} = \frac{(12+6)}{12.5} + 1 + \left[ \frac{12.5}{2(3)} \right] = 4.5 \text{ sec or 5 sec} \]

   Vehicles traveling with an E-W direction have to clear 6 lanes, thus (6)(3)=18 m, with an approach speed of 12.5 m/sec. The clearance interval will then be:
   \[ \tau_{EW} = \frac{(18+6)}{12.5} + 1 + \left[ \frac{12.5}{2(3)} \right] = 5.0 \text{ sec} \]

   Since the clearance intervals are longer than the recommended 3 to 4 seconds yellow indications, it was decided to use 4 seconds for yellow and the remaining required clearance time will be as all red. Therefore, all three phases will have a 1 second all red.

c. Determination of cycle length
   The total lost time will be L = 3(3) + 3(1) = 12 sec. Using Equation 6, the optimum cycle is
   \[ C_o = \frac{(1.5(12) + 5)}{(1 - [(180/1800)+(450/1800)+(770/1800)])} = 23/0.222 = 104 \text{ sec} \]

d. Determination of phase splits
   Using Equations 7 and 8, the effective greens for each phase will be
   \[ g_T = 104 - 12 = 92 \text{ sec} \]
   \[ g_1 = 92 \left( \frac{0.100}{0.100+0.250+0.428} \right) = 12 \text{ sec} \]
   \[ g_2 = 92 \left( \frac{0.250}{0.100+0.250+0.428} \right) = 29 \text{ sec} \]
   \[ g_3 = 92 \left( \frac{0.428}{0.100+0.250+0.428} \right) = 51 \text{ sec} \]

e. Determination of pedestrian needs
   Assuming the 1.0 m/sec walking speed and a lead time of 4 seconds (because of light pedestrian volume), the north- and south-bound pedestrians need \[ G_{NSP} = 4 + (12-1.5)/1 = 14.5 \text{ sec} \]. This time is less than the available time of 29 seconds (see part "d" above): therefore the pedestrian needs for this approach are satisfied.
   Similarly, the east- and west-bound pedestrians need \[ G_{EWEP} = 4 + (18-1.5)/1 = 20.5 \text{ sec} \]. This time is less than the available time of 51 seconds (see part "d" above): therefore pedestrian needs are satisfied.

f. Display times
Using Equation 9, the display greens will be
\[ G_1 = g_1 + l_1 - \tau_{NS} = 12 + (3+1) - 5 = 11 \text{ sec} \]
\[ G_2 = g_2 + l_2 - \tau_{NS} = 29 + (3+1) - 5 = 28 \text{ sec} \]
\[ G_3 = g_3 + l_3 - \tau_{EW} = 51 + (3+1) - 5 = 50 \text{ sec} \]

For the pedestrian indications, the flashing DON'T WALK (FDW) indication is taken equal to the minimum pedestrian walking times computed in step e and the WALK indication is taken equal to the remaining green time.

g. Time diagram

Therefore, a 104 second cycle is adequate to satisfy both vehicular and pedestrian needs. The time diagram for the signal of this intersection will be as shown in the following figure.

5.4.3. Signal Timing Issues

5.4.3.1. Left Turn Phasing

Several times the use of exclusive left turn phase is not warranted nor needed. Prior to deciding whether an exclusive left turn phase is needed, an evaluation should be performed that will allow for determining the need for a left turn phase based on vehicular demands. This evaluation is done by determining the capacity of the left turns that could be accommodated as permissive movements. The formula to be used for this computation is

\[ c_{LT,i} = \text{Max} \{(1400 - V_o)(g_i/C), 2 \text{ veh/cycle}\} \]  \hspace{1cm} (10)

where \( c_{LT,i} \): the capacity of left turns for phase I, \( V_o \): the opposing volume (through and right movements), and \( (g_i/C) \) the proportion of the critical volume of the phase to the sum of the critical volumes. The 2 veh/cycle figure is an estimate for the number of vehicles that will turn during the yellow indication.

This figure should be then compared to the left turning volume. If the actual volume is lower than...
the capacity \((c_{LT,i})\) then there is no need for an exclusive left turn phase. Otherwise, a left turn phase should be considered.

The formula given here considers only the vehicular demands of the intersection. Several times local warrants require the use of an exclusive left turn phase. Such warrants may be based on volumes, delays or accidents. These warrants must be considered prior to making a final decision.

5.4.3.2. Traffic Signal Warrants

Traffic signals should be installed **ONLY** when needed. This objective is to provide for a safe and efficient traffic and pedestrian flow at intersections and undue installation of these devices will only increase delays and cause discomfort to drivers and pedestrians. Traffic signals should be installed based on a set of warrants established in the Manual of Uniform Traffic Control Devices. These warrants include a variety of criteria that are to be considered including volumes, pedestrian traffic, school crossings, accident experience, and system requirements. Even though no warrants exist for the removal of a traffic signal, such an action should be seriously considered if there is a need to remove a traffic signal. Criteria to be used for this action include low traffic performance, reduced safety, and increased fuel consumption and environmental pollution.

5.5. ARTERIAL COORDINATION

Traffic signals along an arterial need to be coordinated to increase the progression of flow and reduce delays and fuel consumption. A well coordinated arterial improves mobility, controls speeds, creates safe gaps for cross-street traffic, reduces delays, and decreases fuel consumption and pollutants.

Factors that affect arterial coordination include spacing of intersections, the average running speed of vehicles, the number of cross-streets, the capacity restrictions of the intersections and the streets that connect them, and the geometric and traffic characteristics of the arterial. A basic assumption for the coordination is that all signals have the same cycle length.

Signals are coordinated with the use of offsets, which are the lag in time between the beginning or end of green (for main street movements) and some time reference point. These offsets are usually based on travel time using the average running speed. Arterial coordination is usually depicted in a time-space diagram.

The window of time available to a platoon traveling through the arterial is called bandwidth. The width of this window is controlled by the intersection with the smallest green time. This intersection is called the critical intersection because it controls the time-space diagram.

Coordination is achieved with the use of **simultaneous system**, where all intersections along the arterial have the same color display (therefore no offset), **alternate system**, where every other intersection has the same color display, or **offset coordinated system**, where offsets between successive intersections are used. The simultaneous system is usually used for closely spaced intersections while the alternate system is indicated for equally spaced intersections. The offset coordinated system is used for achieving good progression and maintaining a certain travel speed along the arterial. Examples of these systems are shown in Figure 5.3.
Arterial coordination for one-way streets is an easy task to perform and can be completed even by hand. However, coordination of a two-way arterial is difficult to be performed by hand and computer software is available for completing this task. Such software is PASSER II and TRANSYT-7F, presented in the next section, and each follows a different approach in determining the best coordination for an arterial. PASSER II uses an algorithm that maximizes the width of the bandwidth for the arterial. Sometimes, this is done at the expense of the cross-street traffic which experiences high delays. On the other hand, TRANSYT-7F uses a process that minimizes delays for the arterial and the cross-streets. This allows for better service for the cross-streets but may harm the progression along the arterial.

Example

The arterial shown here has an east-west orientation and has five signalized intersections along its length. All intersections have a 70-second cycle and are timed in a way that provides for a 50-50 signal split at each intersection. Determine:

a. the offsets at each intersection so to maintain an east-bound progression speed of 40 km/h;
b. the progression of the west-bound traffic for the solution in "a"; and
c. the bandwidth for both directions of traffic.

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>D</th>
<th>E</th>
</tr>
</thead>
<tbody>
<tr>
<td>275 m</td>
<td>230 m</td>
<td>125 m</td>
<td>210 m</td>
<td></td>
</tr>
</tbody>
</table>

a. For a 40(1000)/3600 = 11.1 m/sec progression speed the offsets will be \( O_{A,B} = 275/11.1 = 25 \text{ sec} \), \( O_{A,C} = 505/11.1 = 46 \text{ sec} \), \( O_{A,D} = 630/11.1 = 57 \text{ sec} \), and \( O_{A,E} = 840/11.1 = 6 \text{ sec} \) (76-70).
b. West-bound progression is shown in the following figure and it can be observed that there is no progression in this direction.
c. The bandwidth for the east-bound direction is 35 seconds while the bandwidth for the west-bound direction is 0 seconds.