5. INTERSECTIONS, INTERCHANGES, AND TERMINALS

5.1. Intersections

Intersections are areas shared by two or more roads serving conflicting traffic when competing for the same space at the same time when going ahead or changing directions. Intersections vary in complexity from a simple intersection, which has only two roads crossing at a right angle to each other, to a more complex intersection, at which three or more roads cross within the same area. The process of decision making for road users at intersections is complex and this is part of the reason why intersections tend to have a high potential for accidents and delays. The overall traffic flow on any highway depends to a great extent on the performance of the intersections, since intersections usually operate at a lower capacity than through sections of the road.

Intersections are generally classified into three general categories:

- At-grade intersections,
- Grade-separated without ramps, and
- Grade-separated with ramps (commonly known as interchanges).

Grade-separated intersections usually consist of structures that provide for traffic to cross at different levels (vertical distances) without interruption. The potential for accidents at grade-separated intersections is reduced because many potential conflicts between intersecting streams of traffic are eliminated. At-grade intersections do not provide for the flow of traffic at different levels, and therefore there exist conflicts between intersecting streams of traffic.

5.1.1. At Grade Intersections

Most highways intersect at grade, and the intersection area should be designed to provide adequately for turning and crossing movements, with due consideration to sight distance, signs, and alignments. The basic types of at-grade intersections are T, Y or three-leg intersections, which consist of three approaches; four-leg or cross intersections, which consist of four approaches; and multileg intersections, which consist of five or more approaches. A few examples of these types of intersections are given Figure 6-1.

5.1.2. Grade Separations and Interchanges

Intersections at grade can be eliminated by the use of grade-separation structures that permit the cross flow of traffic at different levels without interruption. The advantage of such separation is the freedom from cross interference with resultant saving of time and increase in safety for traffic movements. Grade separations and interchanges may be warranted

1. As part of an express highway system designed to carry high volumes of traffic,
2. To eliminate bottlenecks,
3. To prevent accidents,
4. Where the topography is such that other types of design are not feasible,
Where the volumes to be catered for would require the design of an intersection at grade of unreasonable size, and

Where the road user benefit of reducing delays at an at-grade intersection exceeds the cost of the improvement.

An interchange is a grade separation in which vehicles moving in one direction of flow may transfer by the use of connecting roadways. These connecting roadways at interchanges are called ramps. Many types and forms of interchanges and ramp layouts are used. Some of these are shown Figure 5 - 3. The choice between these intersection types depends on various factors such as traffic, economy, safety, aesthetics, delay, space requirements, etc.
5.2. Design Principles of At-Grade Intersections

The fundamental objectives in the design of at-grade intersections are to minimize delay and the number and severity of potential conflicts among different streams of traffic and between pedestrian and turning vehicles. At the same time, it is necessary to provide for the smooth flow of traffic across the intersection. The design should therefore incorporate the operating characteristics of both the vehicles and pedestrians using the intersection. For example, the corner radius of an intersection pavement or surfacing should not be less than either the turning radius of the design vehicle or the radius required for design velocity of the turning roadway under consideration. The design also should ensure adequate pavement widths of turning roadways and approach sight distances. This suggests that at-grade intersections should not be located at or just beyond sharp crest vertical curves or at sharp horizontal curves.
The basic requirements of intersection design are maximize safety and minimize traffic delay. The design of an at-grade intersection involves:

1. The design of the alignment including profiles, minimum radius and widths of turning roadways,
2. The design of a suitable channelling system for the traffic pattern,
3. The assurance that the sight distances are adequate for the type of control at the intersection.

**Alignment of At-Grade Intersections**

The best alignment for an at-grade intersection is when the intersecting roads meet at right or nearly right angles. This alignment is superior to acute-angle alignments because much less road area is required for turning at the intersection, there is a lower exposure, time for vehicles crossing the main traffic flow, and visibility limitations, particularly for trucks, are not as serious as those at acute-angle intersections. Figure 6-4 shows alternative methods for realigning roads intersecting at acute angles to obtain a nearly right-angle intersection.

![Figure 6-4: Alternative methods of realigning skewed intersections](image)

In designing the profile (vertical alignment) at the intersection, large changes in grade should be avoided; preferably, grades should not be greater than 3 percent. The stopping and accelerating distances for passenger cars on grades of 3 percent or less are not much different from those of cars on flat grades; however, significant differences start to occur at grades higher than 3 percent. When it is unavoidable to use grades of 3 percent or more, design factors such as stopping distances and accelerating distances should be adjusted so that...
conditions equivalent to those on level ground exist. In any case, it is not advisable to use grades higher than 6 percent at intersections.

It should always be remembered that the combination of horizontal and vertical alignments at an intersection should produce traffic lanes that are clearly seen by motorists at all times, without the sudden appearance of potential hazards. Also, motorists should be able to easily understand the path they should take for any desired direction. The angle of turn, the turning speed, the design vehicle, and traffic volume are the main factors governing the design of curves at at-grade intersections. When the turning speed at an intersection is assumed to be 25 km/h or less, the curves for the pavement edges are designed to conform to at least the minimum turning path of the design vehicle. When the turning speed is expected to be greater than 25 km/h, the design speed is also considered. It is also necessary to increase the pavement width of turning roadways when the speed is greater than 25 km/h.

Channelisation of At-Grade Intersections

AASHTO defines channelisation as the separation of conflicting traffic movements into definite paths of travel by traffic islands or pavement markings to facilitate the safe and orderly movements of both vehicles and pedestrians. A traffic island is a defined area between traffic lanes where vehicular traffic is excluded and provided to regulate the movement of vehicles or to serve as a pedestrian refuge. A properly channelised intersection will result in increased capacity, enhanced safety, and increased driver confidence. Properly designed channelisation systems increase intersection capacity and decrease conflicts and accidents.

Islands in an intersection serve one or more of the following purposes:

1. Separation of conflicts
2. Control of angle of conflict
3. Reduction of excessive pavement areas
4. Regulation of traffic flow in the intersection area
5. Arrangements to favour a predominant turning movement
6. Protection of pedestrians
7. Protection and storage of turning and crossing vehicles
8. Location of traffic control devices.

Islands are generally grouped into three major classes: directional or channelised, divisional, and refuge. Islands can be formed by using raised curbs, pavement markings, or the pavement edges. General types and shapes of islands are shown in Figure 5 - 5. Directional islands are designed primarily to guide the motorist through the intersection by indicating the intended route. Where spacious area exists at an intersection and leaves much to the discretion of the driver, islands may be used to channel the motorist into the desired lane by placing a channelling island in the little-used portion of the intersection.

Divisional islands are most frequently used on undivided highways approaching intersections. They serve to alert the driver to the intersection and regulate the flow of traffic into and out of the intersection. Their use is particularly advantageous for controlling left-turning traffic at skewed intersections. A refuge island is located at or near crosswalks to aid and protect pedestrians crossing the roadway. Refuge islands are most generally used on wide streets in urban areas for loading and unloading of transit riders.
Sight Distance at Intersections

The high accident potential at an intersection can be reduced by providing sight distances that allow drivers to have an unobstructed view of the entire intersection at a distance great enough to permit control of the vehicle. At-grade intersections either have no control or are controlled by one of the following methods: yield control, stop control, or signal control. At signalised intersections, the unobstructed view may be limited to the area where the signals are located, but for un-signalised intersections, it is necessary to provide an adequate view of the crossroads or intersecting highways to reduce the potential of collision with crossing vehicles.
Figure 5 - 6 shows a schematic of the sight triangle required for the location of an obstruction that will allow for the provision of the minimum distance \(d_a\) and \(d_b\), the safe stopping sight distance for the give design speed should be used for \(d_a\) and \(d_b\). It can be seen from that triangle ABC and ADE are similar, which gives:

\[
\frac{CB}{AB} = \frac{ED}{AD}
\]

\[
\frac{d_b}{d_a} = \frac{a}{d_a - b}
\]

From this equation, if any of the variables \(d_a, d_b, a,\) and \(b\) are known the fourth can be determined.

**Sight Distance Requirements for No-Control Intersections:** - In this situation the intersection is not controlled by a yield sign, a stop sign, or a traffic signal, but sufficient sight distance is provided for the operator of a vehicle approaching the intersection to see a crossing vehicle and if necessary to adjust the vehicle's speed so as to avoid a collision. This distance must include the distance travelled by the vehicle both during the driver's perception reaction time and during brake actuation or the acceleration to regulate speed. At intersections, 2.0 sec is usually acceptable for perception reaction time, and an additional 1.0 sec is added for the driver to actuate braking or to accelerate to regulate speed. It is, generally, preferable to design uncontrolled intersections such that the driver of each vehicle sees the intersection and the traffic on the crossroad insufficient time for stopping the vehicle before reaching the intersection.

**Sight Distance Requirements for Yield-Control Intersections:** - In this situation the minor road is controlled by a yield sign. Vehicles on the minor road are therefore required to yield to vehicles on the major road, which often requires the vehicle on the minor road to slow down or to stop prior to reaching the intersecting roadway. The sight distance provided on the minor road must therefore be sufficient for the driver to see a vehicle approaching from either the left or right of the major road, and to be able to stop the vehicle before reaching the intersecting roadway, as shown in Figure 6 - 6. The solution is similar to that for the no-control condition except that in this case the minimum stopping sight distances given for the appropriate speeds are always used for \(d_a\) and \(d_b\). It should be noted that the grades of the approaches should be taken into consideration when determining the minimum stopping sight distances.

**Sight Distance Requirement for Stop-Control Intersections:** - When vehicles are required to stop at an intersection, the drivers of such vehicles should be provided sufficient sight distance to be able to stop the vehicle before reaching the intersecting roadway and allow for a safe departure from the stopped position for the three basic manoeuvres that occur at an average intersection. These manoeuvres are:

1. Crossing the intersection, thereby clearing traffic approaching from both sides of the intersection,
2. Turning left onto the crossroad, which requires clearing the traffic approaching from the left and then joining the traffic stream on the crossroad with vehicles approaching from the right, and

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(3) Turning right onto the crossroad by joining the traffic on the crossroad with vehicles approaching from the left.

**Sight Distance at Intersections with Signal Control:** Although the unobstructed view at signalised intersections may be limited to the area of control, it is recommended that the minimum sight distances based on sight distance requirement for stop-control intersections be made available at these intersections. These minimum sight distances are necessary to avoid the hazardous situations resulting from unanticipated conflicts at signalised intersections, including signal failure, vehicles running the red light, use of the flashing red/yellow mode, and right turns on red. The basic principle of signalised intersections is to provide sight distances that will enable the driver to see the signals early enough to take the necessary action indicated by the signals.

### 5.3 Traffic Controls

The purpose of traffic control is to assign the right of way to drivers, and thus to facilitate highway safety by ensuring the orderly and predictable movement of all traffic on highways. Control may be achieved by using traffic signals, signs, or markings that regulate, guide, warn, and/or channel traffic. Complex maneuvering areas of highways such as intersections require properly designed traffic control systems.

Conflicts occur when traffic streams moving in different directions interfere with each other. The three types of conflicts are merging, diverging, and crossing. Figure 5 - 7 shows the different conflict points that exists at a four-approach unsignalized intersection. There are 32 conflict points in this case. The number of possible conflict points at any intersection depends on the number of approaches, the turning movements, and the type of traffic control at the intersection.

![Figure 5 - 7. Conflict points at four-approach unsignalised intersection](image)

The primary objective in the design of a traffic control system at an intersection is to reduce the number of significant conflict points. In designing such a system, it is first necessary to
undertake an analysis of the turning movements at the intersection, which will indicate the significant types of conflicts. Factors that influence the significance of a conflict include the type of conflict, the number of vehicles in each of the conflicting streams, and the speeds of the vehicles in these streams. Crossing conflicts, however, tend to have the most severe effect on traffic flow and should be reduced to a minimum whenever possible.

**Types of intersection control:** - Several methods of controlling conflicting streams of vehicles at intersections are in use. The choice of one of these methods depends on the type of intersection and the volume of traffic in each of the conflicting streams. The different types of intersection control are described below.

**YIELD Signs:** - Yield signs are usually placed on minor-road approaches; where it is necessary to yield the right of way to the major-road traffic. All drivers on approaches with yield signs are required to slow down and yield the right of way to all conflicting vehicles at the intersection. Stopping at yield signs is not mandatory, but drivers are required to stop when necessary to avoid interfering with a traffic stream that has the right of way.

**STOP Signs:** - A stop sign is used where an approaching vehicle is required to stop before entering the intersection. A stop sign may be used on a minor road when it intersects a major road, at an unsignalised intersection, and where a combination of high speed, restricted view and serious accidents indicates the necessity for such a control. Stop signs should not be used at signalised intersections or on through roadways of expressways.

**Roundabouts:** - A roundabout is a means of traffic control where one-way traffic is circulating around a central island. Priority within the roundabout is controlled by GIVE WAY (YIELD) signs for entering traffic, although occasionally traffic signals may be used. It considerably reduces the number and severity of conflicts, makes the traffic flow self-regulatory and continuous, reduces congestion, and promotes safety.

**Traffic Signals:** - One of the most effective ways of controlling traffic at an intersection is the use of traffic signals. Traffic signals can be used to eliminate many conflicts because different traffic streams can be assigned the use of the intersection at different times. Since this results in a delay to vehicles in all streams, it is important that traffic signals be used only when necessary. The most important factor that determines the need for traffic signals at a particular intersection is the intersection's approach traffic volume, although other factors such as pedestrian volume and accident experience may also play a significant role.

The efficient operation of the signal requires proper timing of the different colour indication, which is obtained by implementing the necessary signal timing design. The main objectives of signal timing at an intersection are to reduce the average delay of all vehicles and the probability of accidents. These objectives are achieved by minimizing the possible conflict points when assigning the right of way to different traffic streams at different times. The cycle length for an isolated intersection should be short, preferably between 35 and 60 sec, although it may be necessary to use longer cycles when approach volumes are very high. However, cycle lengths should be kept below 120 sec, since very long cycle lengths will result in excessive delay. Several methods have been developed for determining the optimal cycle length at an intersection and, in most cases, the yellow interval is considered as a component of the green time.

Figure 5 - 8 shows a typical two-phase signal system to illustrate the terminologies commonly used in the design of signal times.
The main purpose of the yellow indication after the green is to alert motorists to the fact that the green light is about to change to red and to allow vehicles already in the intersection to cross it. A bad choice of yellow interval may lead to the creation of a dilemma zone, an area close to an intersection in which a vehicle can neither stop safely before the intersection nor clear the intersection without speeding before the red signal comes on. The required yellow interval is the time period that guarantees that approaching vehicles can either stop safely or proceed through the intersection without speeding.

The yellow interval, which eliminates the dilemma zone, is estimated from the following equations:

\[
\tau_{\text{min}} = \delta + \frac{W + L}{u_0} + \frac{u_0}{2a}
\]

If the effect of grade is added,

\[
\tau_{\text{min}} = \delta + \frac{W + L}{u_0} + \frac{u_0}{2(a + Gg)}
\]

where, \(\tau_{\text{min}}\) = the minimum yellow interval, (sec)
\(\delta\) = perception-reaction time, (sec)
\(W\) = width of intersection, (m)
\(L\) = length of vehicle, (m)
\(u_0\) = speed (m/sec)
\(a\) = deceleration, (m/sec\(^2\))
\(G\) = grade of the approach road, and
\(g\) = acceleration due to gravity.

Yellow intervals of 3 to 5 sec are normally used. When longer yellow intervals than 5 sec are computed from the above equations, an all-red phase can be inserted to follow the yellow
indication, but the change interval, yellow plus all-red, must be at least the value computed from the equations.

**Cycle Lengths**: - The signals at isolated intersections can be pretimed (fixed), semiautomatic, or fully actuated. Pretimed signals assign the right of way to different traffic streams in accordance with a preset timing program. Each signal has a preset cycle length that remains fixed for a specific period of the day or for the entire day. Several design methods have been developed to determine the optimum cycle length, two of which the Webster method is presented here.

Webster Method. Webster has shown that for a wide range of practical conditions, minimum intersection delay is obtained when the cycle length is obtained by the equation

\[
C_0 = \frac{1.5L + 5}{1 - \sum_{i=1}^{n} Y_i}
\]

where,  
- \( C_0 \) = optimum cycle length (sec)  
- \( L \) = total lost time per cycle (sec)  
- \( Y_i \) = maximum value of the ratios of approach flows to saturation flows for all traffic streams using phase \( i \) (i.e., \( V_{ij}/S_j \))  
- \( n \) = number of phases  
- \( V_{ij} \) = flow on lane \( j \) having the right of way during phase \( i \)  
- \( S_j \) = saturation flow on lane \( j \)

**Total Lost Time.** Figure 5 - 9 shows a graph of rate of discharge of vehicles at various times during a green phase of a signal cycle at an intersection. Initially, some time is lost before the vehicles start moving, and then the rate of discharge increases to a maximum. This maximum rate of discharge is the saturation flow. If there are sufficient vehicles in the queue to use the available green time, the maximum rate of discharge will be sustained until the yellow phase occurs. The rate of discharge will then fall to zero when the yellow signal changes to red. The number of vehicles that go through the intersection is represented by the area under the curve. Dividing the number of vehicles that go through the intersection by the saturation flow will give the effective green time, which is less than the sum of the green and yellow times. This difference is considered lost time, since it is not used by any other phase for the discharge of vehicles; it can be expressed as

\[
l_i = G_{ai} + \tau_i - G_{ei}
\]

where,  
- \( l_i \) = lost time for phase \( i \)  
- \( G_{ai} \) = actual green time for phase \( i \) (not including yellow time)  
- \( \tau_i \) = yellow time for phase \( i \)  
- \( G_{ei} \) = effective green time for phase \( i \)

Total lost time is given as

\[
L = \sum_{i=1}^{n} l_i + R
\]

where, \( R \) is the total all-red time during the cycle.
Allocation of Green Times. In general, the total effective green time available per cycle is given by

\[ G_{te} = C - L = C - \left( \sum_{i=1}^{n} l_i + R \right) \]

where, \( C = \) actual cycle length used (usually obtained by rounding off \( C_0 \), to the nearest 5 sec)
\( G_{te} = \) total effective green time per cycle

To obtain minimum overall delay, the total effective green time should be distributed among the different phases in proportion to their \( Y \) values to obtain the effective green time for each phase.

\[ G_{ei} = \frac{Y_i}{Y_1 + Y_2 + \ldots + Y_n} G_{te} \]

and the actual green time for each phase is obtained as

\[ G_{a1} = G_{e1} + l_1 - \tau_1 \]
\[ G_{a2} = G_{e2} + l_2 - \tau_2 \]
\[ G_{ai} = G_{ei} + l_i - \tau_i \]
\[ G_{an} = G_{en} + l_n - \tau_n \]
**Example** Figure 5 - 10 shows peak-hour volumes for a major intersection on an arterial highway. Using the Webster method, determine suitable signal timing for the intersection using a four-phase system and the additional data given in the figure. Use a yellow interval of 3 sec.

- **Figure 5 - 10.** Peak-hour volumes for major intersection on an arterial highway

![Image of a major intersection on an arterial highway with traffic volumes and percentages]

- PHF = 0.95
- Left-turn factor = 1.4
- PCE for buses and trucks = 1.6

<table>
<thead>
<tr>
<th>Traffic Lane</th>
<th>North Approach</th>
<th>South Approach</th>
<th>West Approach</th>
<th>East Approach</th>
</tr>
</thead>
<tbody>
<tr>
<td>Through</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Left</td>
<td>0</td>
<td>0</td>
<td>4</td>
<td>0</td>
</tr>
</tbody>
</table>

Pedestrian volume is negligible.

**a) Data on traffic flow**

- DHV for EB (West approach) through traffic = \( \frac{464}{0.95} = 488 \) vehicles
- PCE = \( 488 - 0.04 \times 488 \times 1.6 = 468 + 31 = 499 \)

**b) Equivalent straight-through passenger cars**
Solution:

First convert the mixed volumes to equivalent straight-through passenger cars. The equivalent volumes are shown in Figure 6 - 10b. The volumes were obtained by dividing by the PHF, and then by applying the relevant factors for trucks and left-turning vehicles as necessary. No factors for right-turning vehicles were used because those volumes were very low. Assume the following phasing system, where the arrows indicate traffic streams that have the right of way:

![Phasing System Diagram]

The critical lane volumes are (see Figure 6 - 10b):

<table>
<thead>
<tr>
<th>Phase, n</th>
<th>Critical Lane Volume</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>499</td>
</tr>
<tr>
<td>B</td>
<td>338</td>
</tr>
<tr>
<td>C</td>
<td>115</td>
</tr>
<tr>
<td>D</td>
<td>519</td>
</tr>
</tbody>
</table>

\[ \Sigma = 1471 \]

Compute the total lost time using. Since there is not an all-red phase—that is, \( R = 0 \) and there are four phases,

\[ L = \Sigma l_i = 4 \times 3.5 = 14 \text{ sec} \]

Determine \( Y_i \) and \( \Sigma Y_i \):

<table>
<thead>
<tr>
<th>Phase A (EB)</th>
<th>Phase B (WB)</th>
<th>Phase C (SB)</th>
<th>Phase D (NB)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lanes:</td>
<td>1 2 3</td>
<td>1 2 3</td>
<td>1 2 3</td>
</tr>
<tr>
<td>( V_{ij} )</td>
<td>335 490 499</td>
<td>189 338 338</td>
<td>115 79 37</td>
</tr>
<tr>
<td>( Vi/Si )</td>
<td>0.17 0.25 0.25</td>
<td>0.09 0.17 0.17</td>
<td>0.06 0.04 0.019</td>
</tr>
</tbody>
</table>

\[ Y_i = 0.25 \quad 0.17 \quad 0.06 \quad 0.26 \]

\[ \Sigma Y_i = 0.74 \]

Determine the optimum cycle length

\[ C_o = \frac{1.5L + 5}{1 - \sum_{i=1}^{n} Y_i} \]
Find the total effective green time:
\[ G_{te} = C - L \]
\[ = (100 - 14) = 86 \text{ sec} \]

Effective time for phase \( i \) is obtained from:

\[
G_a = \frac{Y_i}{Y_1 + Y_2 + \cdots + Y_n} \cdot G_{te}
\]

\[
= \frac{Y_i}{0.25 + 0.17 + 0.06 + 0.26} \cdot 86
\]

\[
= \frac{Y_i}{0.74} \cdot 86
\]

Yellow time \( \tau = 3.0 \text{ sec} \); the actual green time \( G_a \) for each phase is obtained as

\[
G_a = G_{a} + \ell_i - 3.0
\]

- Actual green time for Phase A \( (G_{aA}) \) = \[ \frac{0.25}{0.74} \times 86 + 3.5 - 3.0 \]
  \[ \approx 30 \text{ sec} \]

- Actual green time for Phase B \( (G_{aB}) \) = \[ \frac{0.17}{0.74} \times 86 + 3.5 - 3.0 \]
  \[ \approx 20 \text{ sec} \]

- Actual green time for Phase C \( (G_{aC}) \) = \[ \frac{0.06}{0.74} \times 86 + 3.5 - 3.0 \]
  \[ \approx 7 \text{ sec} \]

- Actual green time for Phase D \( (G_{aD}) \) = \[ \frac{0.26}{0.74} \times 86 + 3.5 - 3.0 \]
  \[ \approx 31 \text{ sec} \]