4. Unsignalized intersections
References

• HCM 2000
• web.ics.purdue.edu/~tarko/CE463/Lectures/Lecture18/ce463lec18f01.ppt

Note: - some slides are quoted from given references.
   - text is from HCM.
two-way stop-controlled intersections


Capacity analysis at two-way stop-controlled (TWSC) intersections depends on a clear description and understanding of the interaction of drivers on the minor or stop-controlled approach with drivers on the major street. Both gap acceptance and empirical models have been developed to describe this interaction. Procedures described in this section rely on a gap acceptance model developed and refined in Germany. This model starts with calculation of the conflicting traffic for minor-street movements; as follows.
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CONFLICTING TRAFFIC

Each movement at a TWSC intersection faces a different set of conflicts that are directly related to the nature of the movement. These conflicts are shown in the following Table, which illustrates the computation of the parameter $v_{c,x}$, the conflicting flow rate for movement $x$, that is, the total flow rate that conflicts with movement $x$ (veh/h).

The Table also identifies the conflicting flow rates for each stage of a two-stage gap acceptance process that takes place at some intersections where vehicles store in the median area. If a two-stage gap acceptance process is not present, the conflicting flow rates shown in the rows labeled Stage I and Stage II should be added together and considered as one conflicting flow rate for the movement in question.
HCM Numbering system for traffic & pedestrian movements at road intersections
The following notes apply to the previous Table:

a) If right-turning traffic from the major street is separated by a triangular island and has to comply with a yield or stop sign, $v_6$ and $v_3$ need not be considered.

b) If there is more than one lane on the major street, the flow rates in the right lane are assumed to be $v_2/N$ or $v_5/N$, where $N$ is the number of through lanes. The user can specify a different lane distribution if field data are available.
The following notes apply to the previous Table:

c) If there is a right-turn lane on the major street, $v_3$ or $v_6$ should not be considered.

d) Omit the farthest right-turn $v_3$ for Subject Movement 10 or $v_6$ for Subject Movement 7 if the major street is multilane.

e) If right-turning traffic from the minor street is separated by a triangular island and has to comply with a yield or stop sign, $v_9$ and $v_{12}$ need not be considered.

f) Omit $v_9$ and $v_{12}$ for multilane sites, or use one-half their values if the minor approach is flared.
CRITICAL GAP AND FOLLOW-UP TIME

The critical gap, $t_c$, is defined as the minimum time interval in the major-street traffic stream that allows intersection entry for one minor-street vehicle. Thus, the driver's critical gap is the minimum gap that would be acceptable. A particular driver would reject any gaps less than the critical gap and would accept gaps greater than or equal to the critical gap. Estimates of critical gap can be made on the basis of observations of the largest rejected and smallest accepted gap for a given intersection.

The time between the departure of one vehicle from the minor street and the departure of the next vehicle using the same major-street gap, under a condition of continuous queuing on the minor street, is called the follow-up time, $t_f$. Thus, $t_f$ is the headway that defines the saturation flow rate for the approach if there were no conflicting vehicles on movements of higher rank.
two-way stop-controlled intersections

CRITICAL GAP

Base values of $t_c$ and $t_f$ for passenger cars are given in next Table. The values are based on studies throughout the United States and are representative of a broad range of conditions. Base values of $t_c$ and $t_f$ for a six-lane major street are assumed to be the same as those for a four-lane major street. Adjustments are made to account for the presence of heavy vehicles, approach grade, T-intersections, and two-stage gap acceptance. The critical gap is computed separately for each minor movement by this equation.

$$t_{c,x} = t_{c,\text{base}} + t_{c,\text{HV}} P_{HV} + t_{c,G} G - t_{c,T} - t_{3,LT}$$
two-way stop-controlled intersections

CRITICAL GAP

\[ t_{c,x} = t_{c,\text{base}} + t_{c,HV} P_{HV} + t_{c,G} G - t_{c,T} - t_{3,LT} \]

where

- \( t_{c,x} \) = critical gap for movement x (s),
- \( t_{c,\text{base}} \) = base critical gap from Exhibit 17-5 (s),
- \( t_{c,HV} \) = adjustment factor for heavy vehicles (1.0 for two-lane major streets and 2.0 for four-lane major streets) (s),
- \( P_{HV} \) = proportion of heavy vehicles for minor movement,
- \( t_{c,G} \) = adjustment factor for grade (0.1 for Movements 9 and 12 and 0.2 for Movements 7, 8, 10, and 11) (s),
- \( G \) = percent grade divided by 100,
two-way stop-controlled intersections

CRITICAL GAP

\[ t_{c,x} = t_{c,base} + t_{c,HV} P_{HV} + t_{c,G} G - t_{c,T} - t_{3,LT} \]

\( t_{c,T} \) = adjustment factor for each part of a two-stage gap acceptance process, (1.0 for first or second stage; 0.0 if only one stage) (s), and

\( t_{3,LT} \) = adjustment factor for intersection geometry (0.7 for minor-street left-turn movement at three-leg intersection; 0.0 otherwise) (s).

<table>
<thead>
<tr>
<th>Vehicle Movement</th>
<th>Base Critical Gap, ( t_{c,base} ) (s)</th>
<th>Base Follow-up Time, ( t_{f,base} ) (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Two-Lane Major Street</td>
<td>Four-Lane Major Street</td>
</tr>
<tr>
<td>Left turn from major</td>
<td>4.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Right turn from minor</td>
<td>6.2</td>
<td>6.9</td>
</tr>
<tr>
<td>Through traffic on minor</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Left turn from minor</td>
<td>7.1</td>
<td>7.5</td>
</tr>
</tbody>
</table>
two-way stop-controlled intersections

FOLLOW-UP TIME

The follow-up time is computed for each minor movement using next equation. Adjustments are made for the presence of heavy vehicles.

\[ t_{f,x} = t_{f,\text{base}} + t_{f,\text{HV}} P_{HV} \]

where

- \( t_{f,x} \) = follow-up time for minor movement \( x \) (s),
- \( t_{f,\text{base}} \) = base follow-up time from Exhibit 17-5 (s),
- \( t_{f,\text{HV}} \) = adjustment factor for heavy vehicles (0.9 for two-lane major streets and 1.0 for four-lane major streets), and
- \( P_{HV} \) = proportion of heavy vehicles for minor movement.

Values from the previous table are considered typical. If smaller values for \( t_c \) and \( t_t \) are observed, capacity will be increased. If larger values for \( t_c \) and \( t_t \) are used, capacity will be decreased. (The relationship between the potential capacity and \( t_t \) or \( t_c \) is inverse)
two-way stop-controlled intersections

POTENTIAL CAPACITY

The gap acceptance model used in this method computes the potential capacity of each minor traffic stream in accordance with this equation:

\[
C_{p,x} = V_{c,x} \frac{e^{-v_{c,x}t_{c,x} / 3600}}{1 - e^{-v_{c,x}t_{f,x} / 3600}}
\]

Where

- \(C_{p,x}\) = potential capacity of minor movement \(x\) (veh/h),
- \(V_{c,x}\) = conflicting flow rate for movement \(x\) (veh/h),
- \(t_{c,x}\) = critical gap (i.e., the minimum time that allows intersection entry for one minor-stream vehicle) for minor movement \(x\) (s), and
- \(t_{f,x}\) = follow-up time (i.e., the time between the departure of one vehicle from the minor street and the departure of the next under a continuous queue condition) for minor movement \(x\) (s).
Rank Priority

Four-Leg Intersection

<table>
<thead>
<tr>
<th>Rank</th>
<th>Traffic stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2, 3, 5, 6, 15, 16</td>
</tr>
<tr>
<td>2</td>
<td>1, 4, 13, 14, 9, 12</td>
</tr>
<tr>
<td>3</td>
<td>8, 11</td>
</tr>
<tr>
<td>4</td>
<td>7, 10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Rank</th>
<th>Subscript</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>i</td>
</tr>
<tr>
<td>2</td>
<td>j</td>
</tr>
<tr>
<td>3</td>
<td>k</td>
</tr>
<tr>
<td>4</td>
<td>l</td>
</tr>
</tbody>
</table>
### Traffic Stream Information

<table>
<thead>
<tr>
<th>Rank</th>
<th>Traffic Stream</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2, 3, 5, 15</td>
</tr>
<tr>
<td>2</td>
<td>4, 13, 14, 9</td>
</tr>
<tr>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>

**Intersection**
Base condition for potential capacity

The potential capacity of a movement is denoted as $c_{p,x}$ (for movement $x$) and is defined as the capacity for a specific movement, assuming the following base conditions:

- Traffic from nearby intersections does not back up into the subject intersection.
- A separate lane is provided for the exclusive use of each minor-street movement.
- An upstream signal does not affect the arrival pattern of the major street traffic.
- No other movements of Rank 2, 3, or 4 impede the subject movement.
Impeding Movements

Vehicles use gaps at a TWSC intersection in a prioritized manner.

When traffic becomes congested in a high-priority movement (Stream rank 2 like 1 and 4),

it can impede lower-priority movements (i.e., streams of Ranks 3 like 8 ) from using gaps in the traffic stream (e.g. 2 and 5), reducing the potential capacity of these movements.
Impeding Movements

In other words: Minor traffic streams of Rank 3 must yield not only to the major traffic streams, but also to the conflicting major-street left-turn movement, which is of Rank 2. Thus, not all gaps of acceptable length that pass through the intersection will normally be available for use by Rank 3 traffic streams, because some of these gaps are likely to be used by the major-street left-turning traffic. The magnitude of this impedance depends on the probability that major-street left-turning vehicles will be waiting for an acceptable gap at the same time as vehicles of Rank 3. A higher probability that this situation will occur means greater capacity-reducing effects of the major-street left-turning traffic on all Rank 3 movements.
Movement Capacity

\[ C_{m,x} = C_{p,x} \cdot f_x \]
# Impedance Effect

<table>
<thead>
<tr>
<th>Rank</th>
<th>Minor Movement</th>
<th>Impedance Factor $f_x$</th>
</tr>
</thead>
<tbody>
<tr>
<td>2</td>
<td>1, 4, 9, 12</td>
<td>$f_x = 1$</td>
</tr>
<tr>
<td>3</td>
<td>8, 11</td>
<td>$f_x = \left(1 - \frac{v_1}{c_{m,1}}\right)\left(1 - \frac{v_4}{c_{m,4}}\right)$</td>
</tr>
<tr>
<td>4</td>
<td>7</td>
<td>$p'' = \left(1 - \frac{v_1}{c_{m,1}}\right)\left(1 - \frac{v_4}{c_{m,4}}\right)\left(1 - \frac{v_{11}}{c_{m,11}}\right)$ $p' = 0.65 p'' - \frac{p''}{p'' + 3} + 0.6 \sqrt{p''}$ $f_7 = p'\left(1 - \frac{v_{12}}{c_{m,12}}\right)$</td>
</tr>
<tr>
<td>4</td>
<td>10</td>
<td>$p'' = \left(1 - \frac{v_1}{c_{m,1}}\right)\left(1 - \frac{v_4}{c_{m,4}}\right)\left(1 - \frac{v_8}{c_{m,8}}\right)$ $p' = 0.65 p'' - \frac{p''}{p'' + 3} + 0.6 \sqrt{p''}$ $f_{10} = p'\left(1 - \frac{v_9}{c_{m,9}}\right)$</td>
</tr>
</tbody>
</table>

$$C_{m,x} = C_{p,x} \cdot f_x$$

$p_{0,x} = 1 - \frac{v_x}{c_{m,x}}$ probability of queue-free state for movement $x$
Example of calculating potential capacity

For the shown TWSC intersection, consider the following information:

- percent of truck is 10%,
- the grade 4%.
- The demand flow is in veh/hr.

Calculate the following for all movements (except 2, 3, 5, 6):

- 1- Potential Capacity.
- 2- Impact factor.
- 3- Movement Capacity.
Movements of Rank 2 (1,4,9,12)

1- Capacity of Movement 1

\[ V_{C,1} = V_5 + V_6^a + V_{16} \]
\[ = (350 + 350) + 0 + 0 = 700 \]

\[ t_{C,1} = t_{C,\text{base}} + t_{C,HV} \times P_{HV} + t_{C,G} \times G - t_{C,T} - T_{3,LT} \]
\[ = 4.1 + 2.0 \times 0.1 + 0.0 \times \left( \frac{4}{100} \right) - 0.0 - 0.0 = 4.3 \]

\[ t_{f,.1} = t_{f,\text{base}} + t_{f,HV} \times P_{HV} \]
\[ = 2.2 + 1.0 \times 0.1 = 2.3 \]

\[ C_{P,1} = V_{C,1} \times \frac{e^{-V_{C,1} \times t_{c,1}}}{3600} = 841.3 \text{veh/hr} \]
Movements of Rank 2 (1,4,9,12)

1. Capacity of Movement 4

\[ V_{C,4} = V_2 + V_3^{[a]} + V_{15} \]

\[ = (250 + 250) + 100 + 0 = 600 \]

\[ t_{C,4} = t_{C,\text{base}} + t_{C,HV} \times P_{HV} + t_{C,G} \times G - t_{C,T} - T_{3,LT} \]

\[ = 4.1 + 2.0 \times 0.1 + 0.0 \times \left( \frac{4}{100} \right) - 0.0 - 0.0 = 4.3 \]

\[ t_{f,4} = t_{f,\text{base}} + t_{f,HV} \times P_{HV} \]

\[ = 2.2 + 1.0 \times 0.1 = 2.3 \]

\[ C_{P,4} = V_{C,1} \times \frac{e^{\frac{-V_{C,1} \times t_{c,1}}{3600}}}{1 - e^{\frac{-V_{C,1} \times t_{f,1}}{3600}}} = 920.26 \text{veh} / \text{hr} \]
Movements of Rank 2 (1,4,9,12)

2. Impact factor of Movement 1 and 4

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<th>Rank</th>
<th>Minor Movement</th>
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</tr>
</tbody>
</table>

3. Movement capacity of 1 and 4

$$C_{m,1} = C_{p,1} \cdot f_1$$

$$C_{m,1} = 841.3 \times 1$$

$$C_{m,1} = 841.3 \text{veh/hr}$$

$$C_{m,1} = C_{p,4} \cdot f_4$$

$$C_{m,1} = 920.3 \times 1$$

$$C_{m,1} = 920.3 \text{veh/hr}$$
Movements of Rank 3 (8,11)

1- Capacity of Movement 8

\[ V_{C,8I} = 2V_1 + V_2 + 0.5V_3^c + V_{15} \]
\[ = 2 \times 40 + (250 + 250) + 0^{neg} + 0 = 580 \]
\[ V_{C,8II} = 2V_4 + V_5 + V_6^a + V_{13} \]
\[ = 2 \times 60 + (350 + 350) + 0^{neg} + 0 = 820 \]

Assume one stage
\[ V_{C,8} = 580 + 820 = 1400 \]
\[ t_{C,8} = t_{C,\text{base}} + t_{C,\text{HV}} \times P_{HV} + t_{C,G} \times G - t_{C,T} - T_{3,LT} \]
\[ = 6.5 + 2.0 \times 0.1 + 0.2 \times \left( \frac{4}{100} \right) - 0.0 - 0.0 = 6.708 \]
\[ t_{f,8} = t_{f,\text{base}} + t_{f,\text{HV}} \times P_{HV} \]
\[ = 4.0 + 1.0 \times 0.1 = 4.1 \]
\[ C_{P,8} = V_{C,8} \times \frac{t_{C,8}}{3600} = 129.4 \text{veh/hr} \]
Movements of Rank 3 (8,11)

2. Impact factor of Movement 8

<table>
<thead>
<tr>
<th>Rank</th>
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<tr>
<td>3</td>
<td>8, 11</td>
<td>$f_x = \left(1 - \frac{v_1}{c_{m,1}}\right)\left(1 - \frac{v_4}{c_{m,4}}\right)$</td>
</tr>
</tbody>
</table>

$$f_x = \left(1 - \frac{40}{841.3}\right)\left(1 - \frac{60}{920}\right) = 0.89$$

3. Movement capacity of 8

$$C_{m,8} = C_{p,8} \cdot f_8$$
$$C_{m,1} = 129.4 \times 0.89$$
$$C_{m,1} = 115.166 \text{veh/hr}$$
Shared Lane Capacity

\[ c_{SH,1} = \frac{v_7 + v_8 + v_9}{\left( \frac{v_7}{c_{m,7}} \right) + \left( \frac{v_8}{c_{m,8}} \right) + \left( \frac{v_9}{c_{m,9}} \right)} \]

\[ c_{SH,1} = c_{m,7} \]

\[ c_{SH,2} = \frac{v_8 + v_9}{\left( \frac{v_8}{c_{m,8}} \right) + \left( \frac{v_9}{c_{m,9}} \right)} \]
95\textsuperscript{th} percentile of maximum queue length

\[
Q_{95} \approx 9001 \left[ \frac{v_x}{c_{m,x}} - 1 + \left( \frac{v_x}{c_{m,x}} - 1 \right)^2 + \left( \frac{3600}{c_{m,x}} \right) \left( \frac{v_x}{150T} \right) \right]
\]

where

- \(Q_{95}\) = 95th-percentile queue (veh),
- \(v_x\) = flow rate for movement \(x\) (veh/h),
- \(c_{III,x}\) = capacity of movement \(x\) (veh/h), and
- \(T\) = analysis time period (h) (\(T = 0.25\) for a 15-min period).
Average Delay for Movement

\[ d = \frac{3600}{c_{m,x}} + 900T \left( \frac{v_x}{c_{m,x}} - 1 \right)^2 + \frac{3600}{450T} \left( \frac{v_x}{c_{m,x}} \right) \]\n
where

- \( d \) = control delay (s/veh),
- \( v_x \) = flow rate for movement \( x \) (veh/h),
- \( c_{m,x} \) = capacity of movement \( x \) (veh/h), and
- \( T \) = analysis time period (h) (\( T = 0.25 \) for a 15-min period).
Average Lane Delay

\[ d = \frac{3600}{c} + 900T \left[ \frac{v}{c} - 1 + \sqrt{\left( \frac{v}{c} - 1 \right)^2 + \left( \frac{3600}{c} \frac{v}{c} \right) \left( \frac{v}{c} \right)} \right] + 5 \]

\( T = \) period of analysis in hrs, typically 0.25 hr
Average Approach and Intersection Delays

\[ d_A = \frac{d_{RT}v_{RT} + d_{TH}v_{TH} + d_{LT}v_{LT}}{v_{RT} + v_{TH} + v_{LT}} \]

\[ d_I = \frac{d_{A,1}v_{A,1} + d_{A,2}v_{A,2} + d_{A,3}v_{A,3} + d_{A,4}v_{A,4}}{v_{A,1} + v_{A,2} + v_{A,3} + v_{A,4}} \]
Level of Service

<table>
<thead>
<tr>
<th>LEVEL OF SERVICE</th>
<th>DELAY RANGE</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>≤10</td>
</tr>
<tr>
<td>B</td>
<td>&gt;10 and ≤15</td>
</tr>
<tr>
<td>C</td>
<td>&gt;15 and ≤25</td>
</tr>
<tr>
<td>D</td>
<td>&gt;25 and ≤35</td>
</tr>
<tr>
<td>E</td>
<td>&gt;35 and ≤50</td>
</tr>
<tr>
<td>F</td>
<td>&gt;50</td>
</tr>
</tbody>
</table>

Delays are in seconds
Traffic Volumes in HCM Analysis

- HCM recommends evaluating the traffic quality for the busiest 15-minutes of the design hour.
- The first step of calculations is converting the hourly volume $V_m$ for each traffic movement $m$ into the corresponding peak hour flow rates $\nu_m$:

$$\nu_m = \frac{V_m}{PHF} \text{ (veh/h)}$$