Topic 7
(Chapters 23)
Analyses of Unsignalized Intersections
Types of Unsignalized Intersections

- Uncontrolled
- Stop Sign Controlled
  - TWSC
  - AWSC
- Yield Sign Controlled
- Roundabout
TWSC Intersections

- Priority movements

<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>

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</tr>
<tr>
<td>3</td>
<td>7</td>
</tr>
</tbody>
</table>
Gap Acceptance

- **Critical gap, $t_c$**
  - Minimum gap in the major stream that a minor street vehicle would accept
  - Cannot be measured directly in the field (accepted gap is usually larger, and the rejected gap is usually smaller than critical gap)
  - Drivers behave differently

- **Follow-up time, $t_f$**
  - Minimum headway between two consecutive vehicles in the minor stream
  - Can be measured directly in the field
Gap Acceptance

- Two-way Stop-Controlled Intersections
- Roundabouts
- Can you model this?

IndianTraffic.gvi
$t_c$ and $t_f$

<table>
<thead>
<tr>
<th>Movement</th>
<th>$t_{cb}$, sec</th>
<th>$t_{fb}$, sec</th>
</tr>
</thead>
<tbody>
<tr>
<td>Two-lane Major Street</td>
<td>Four-lane Major Street</td>
<td></td>
</tr>
<tr>
<td>Major LT</td>
<td>4.1</td>
<td>4.1</td>
</tr>
<tr>
<td>Minor RT</td>
<td>6.2</td>
<td>6.9</td>
</tr>
<tr>
<td>Minor TH</td>
<td>6.5</td>
<td>6.5</td>
</tr>
<tr>
<td>Minor LT</td>
<td>7.1</td>
<td>7.5</td>
</tr>
</tbody>
</table>

\[
t_c = t_{cb} + t_{cHV} P_{HV} + t_{cG} G - t_{cT} - t_{3LT}
\]

\[
t_f = t_{fb} + t_{fHV} P_{HV}
\]
Adjustments on $t_c$ and $t_f$

<table>
<thead>
<tr>
<th>Adjustment</th>
<th>Values</th>
</tr>
</thead>
</table>
| $t_{cHV}$  | 1.0, Two-lane major street  
             | 2.0, Four-lane major street |
| $t_{cG}$   | 0.1, Movements 9 and 12  
             | 0.2, Movements 7, 8, 10 and 11  
             | 1.0, Otherwise |
| $t_{cT}$   | 1.0, With two stage process  
             | 0.0, With single stage process |
| $t_{3LT}$  | 0.7, Minor-street LT at T-intersection  
             | 0.0, Otherwise |
| $t_{fHV}$  | 0.9, Two-lane major street  
             | 1.0, Four-lane major street |

\[
\begin{align*}
    t_c &= t_{cb} + t_{cHV} P_{HV} + t_{cG} G - t_{cT} - t_{3LT} \\
    t_f &= t_{fb} + t_{fHV} P_{HV}
\end{align*}
\]
Capacity Model

- **Conflicting volume, \( v_{cx} \)**
  - Figure 23.3 (page 670)

- **Potential capacity, \( c_{px} \)**

\[
c_{px} = v_{cx} \left[ \frac{e^{-(v_{cx}t_{cx} / 3600)}}{1 - e^{-(v_{cx}t_{fx} / 3600)}} \right]
\]

Harder’s Model (*CEE 663)
HCM Capacity Model - Harders

- Discrete minor stream departure

\[ 0 \leq t < t_c \quad \text{Zero departure} \]
\[ t_c \leq t < t_c + t_f \quad \text{One departure} \]
\[ t_c + t_f \leq t < t_c + 2t_f \quad \text{Two departures} \]
\[ t_c + (n-1)t_f \leq t < t_c + nt_f \quad n \text{ departures} \]

Number of possible departures, \( q(t) \)
Harders Model - Continued

- Main stream gap is negative exponential

\[ f(t) = \lambda e^{-\lambda t} \quad F(t) = 1 - e^{-\lambda t} \quad \lambda = \frac{v_c}{3600} \]

\[ P(h \leq t) = F(t) = 1 - e^{-\lambda t} \]

\[ P(t_c \leq h < t_c + t_f) = e^{-\lambda t_c} - e^{-\lambda(t_c + t_f)} \]

\[ P\{t_c + (n-1)t_f \leq h < t_c + nt_f\} = e^{-\lambda\{t_c + (n-1)t_f\}} - e^{-\lambda\{t_c + nt_f\}} \]

\[ c(h) = \sum_{n=0}^{\infty} n* P\{t_c + (n-1)t_f \leq h < t_c + nt_f\} \]

\[ = \sum_{n=0}^{\infty} n* \{e^{-\lambda\{t_c + (n-1)t_f\}} - e^{-\lambda\{t_c + nt_f\}}\} \]
\[ c(h) = \sum_{n=0}^{\infty} n^* \left\{ e^{-\lambda (t_c + (n-1)t_f)} - e^{-\lambda t_c + nt_f} \right\} \]

\[ = 1^* \left\{ e^{-\lambda t_c} - e^{-\lambda (t_c + t_f)} \right\} + 2^* \left\{ e^{-\lambda (t_c + t_f)} - e^{-\lambda (t_c + 2t_f)} \right\} + 3^* \left\{ e^{-\lambda (t_c + 2t_f)} - e^{-\lambda (t_c + 3t_f)} \right\} \]

\[ + \cdots \]

\[ + i^* \left\{ e^{-\lambda [t_c + (i-1)t_f]} - e^{-\lambda [t_c + it_f]} \right\} + \cdots \]
Harders Model - Continued

\[
c(h) = e^{-\lambda(t_c)} + e^{-\lambda(t_c+t_f)} + e^{-\lambda(t_c+2t_f)} + \ldots + e^{-\lambda(t_c+it_f)} + \ldots
\]

\[
= \sum_{i=0}^{\infty} e^{-\lambda(t_c+it_f)} = \sum_{i=0}^{\infty} e^{-\lambda t_c} \ast (e^{-\lambda t_f})^i = e^{-\lambda t_c} \sum_{i=0}^{\infty} (e^{-\lambda t_f})^i
\]

\[
\sum_{i=0}^{\infty} (e^{-\lambda t_f})^i = \frac{1}{1 - e^{-\lambda t_f}}
\]

\[
c(h) = e^{-\lambda t_c} \frac{1}{1 - e^{-\lambda t_f}}
\]

\[
c = v_c e^{-\lambda t_c} \frac{1}{1 - e^{-\lambda t_f}} = v_c \frac{e^{-v_c/3600t_c}}{1 - e^{-v_c/3600t_f}}
\]
Capacity

- **Movement capacity,** $c_{mx}$
  
  $$c_{mx} = f_x c_{px}$$

  $$f_7 = p_{v4} p_{p13} p_{p15}$$

  For minor street LT at T intersection

- **Shared-lane capacity,** $c_{SH}$
  
  $$p_{v4} = 1 - \frac{v_4}{c_{m4}}$$

  $$p_{pi} = 1 - \frac{v_j \left( \frac{w}{S_p} \right)}{3600}$$

  $$c_{SH} = \frac{\sum_y v_y}{\sum_y \frac{v_y}{c_{my}}}$$
Delay and LOS

\[
d_x = \frac{3600}{c_{mx}} + 900T \left[ \frac{v_x}{c_{mx}} - 1 \right] + \sqrt{\left( \frac{v_x}{c_{mx}} - 1 \right)^2 + \frac{3600}{c_{mx}} \left( \frac{v_x}{c_{mx}} \right)} + 5
\]

<table>
<thead>
<tr>
<th>LOS</th>
<th>Average Control Delay, ( \text{sec/veh} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>0-10 (0-10)</td>
</tr>
<tr>
<td>B</td>
<td>&gt;10-15 (10-20)</td>
</tr>
<tr>
<td>C</td>
<td>&gt;15-25 (20-35)</td>
</tr>
<tr>
<td>D</td>
<td>&gt;25-35 (35-55)</td>
</tr>
<tr>
<td>E</td>
<td>&gt;35-50 (55-80)</td>
</tr>
<tr>
<td>F</td>
<td>&gt;50 (&gt;80)</td>
</tr>
</tbody>
</table>

* (xx) for signalized intersections
Pedestrian walking speed is 4.0 f/s. 10% trucks.
Example - Continued

- **Step 1** – Calculate conflicting flow rates, $v_{cx}$ (Fig. 23.3)

  $v_{c4} = 260$  \hspace{1cm} $v_{c9} = 255$  \hspace{1cm} $v_{c7} = 700$

- **Step 2** – Calculate critical gap, $t_{cx}$, and follow-up time, $t_{fx}$

  $t_{c4} = 4.2$  \hspace{1cm} $t_{c9} = 6.3$  \hspace{1cm} $t_{c7} = 6.5$

  $t_{f4} = 2.29$  \hspace{1cm} $t_{f9} = 3.39$  \hspace{1cm} $t_{f7} = 3.59$

- **Step 3** – Calculate potential capacity, $c_{px}$

  $c_{p4} = 1259$  \hspace{1cm} $c_{p9} = 765$  \hspace{1cm} $c_{p7} = 394$
Example - Continued

- **Step 4** – Calculate impedance factor, \( f_7 = p_{v4} \cdot p_{p14} \cdot p_{p15} \)
  
  \[
  p_{p14} = 0.993 \quad p_{p15} = 0.975 \quad p_{v4} = 1 - \frac{v_4}{c_{m4}} = 0.984
  \]

- **Step 5** – Calculate movement capacity, \( c_{mx} \)
  
  \[
  c_{m4} = 1228 \quad c_{m9} = 741 \quad c_{m7} = 372
  \]

- **Step 6** – Shared lane capacities, \( c_{SH} \)
  
  \[
  c_{SH} = \frac{v_7 + v_9}{\frac{v_7}{c_{m7}} + \frac{v_9}{c_{m9}}} = 500
  \]
Example - Continued

- **Step 7 – Calculate delay, \( d_x \)**

\[
d_4 = \frac{3600}{c_{m4}} + 900T \left[ \left( \frac{v_4}{c_{m4}} - 1 \right) + \sqrt{\left( \frac{v_4}{c_{m4}} - 1 \right)^2 + \frac{3600}{c_{m4}^2} \left( \frac{v_4}{c_{m4}} \right)} \right] + 5
\]

\[= 7.98\]

\[d_{7,9} = 15.40\]

- **Step 8 – Determine LOS**
Complexities

- * Upstream Signal Effect
- Two-stage crossing
- Flared approach
Exercise

Using HCS to solve the sample problem given. After the model is set up, try to answer the following questions.

1. Can you duplicate the results given in the example?
2. How many minor movements are involved in the example?
3. Which minor movements have the same potential capacity and movement capacity, i.e., which minor movements are not impeded by higher priority minor movements?
4. What is the basic critical gap and final critical gap for the minor street LT movement?
5. What is the conflicting flow rate for minor street LT movement? Verify the result manually.
6. What is the probability of major street LT movement not blocking the minor street LT movement (i.e., probability of queue free for major street LT movement)?
7. What is the impedance factor for minor street LT movement? How is this factor used for the calculation?
8. What are the movement capacities for the minor street LT and RT movements?
9. What is the capacity for the minor street approach (shared LT and RT lane)
10. What is the control delay for the minor street approach?
Roundabout

- Roundabout is a special type of *traffic circle*
- Major differences between roundabout and traffic circle
  - Speed
  - Traffic control
  - Priority of circulating traffic
  - Design vehicle
  - Pedestrian access
  - Parking
  - Direction of circulation
- Types of roundabout
  - Mini
  - Urban: compact, single-lane, double-lane
  - Rural: single-lane, double-lane

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Roundabout Design Elements

- Inscribed circle diameter
- Exit width
- Entry width
- Splitter island width
- Circulatory roadway width
Roundabout Operations - HCM

- Roundabouts introduced in 1997 HCM
- Method unchanged in HCM 2000
- Uses analytical method
- Only estimates capacity; no guidance on delay or level of service
- Measured in PCE

<table>
<thead>
<tr>
<th></th>
<th>Critical gap (sec)</th>
<th>Follow-up Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Upper-bound solution</td>
<td>4.1</td>
<td>2.6</td>
</tr>
<tr>
<td>Lower-bound solution</td>
<td>4.6</td>
<td>3.1</td>
</tr>
</tbody>
</table>

\[ C_a = v_c \left[ \frac{e^{-(v_c t_e / 3600)}}{1 - e^{-(v_c t_f / 3600)}} \right] \]
FHWA Method

- Consideration of vehicle types (cars, trucks, motorcycles)
- Empirical regression model
- Delay and LOS

FHWA Method vs. HCM

FHWA

HCM
Steps to Calculate Roundabout Volumes

Turning movements → Roundabout volumes
Steps

- Step 1: Convert trucks and other vehicle types to passenger car equivalents (pce)
- Step 2: PHF volume adjustment
- Step 3: Entry volume
- Step 4: Exit volume
- Step 5: Circulating volume

<table>
<thead>
<tr>
<th>Vehicle Type</th>
<th>Passenger Car Equivalent (pce)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Car</td>
<td>1.0</td>
</tr>
<tr>
<td>Single-unit truck or bus</td>
<td>1.5</td>
</tr>
<tr>
<td>Truck with trailer</td>
<td>2.0</td>
</tr>
<tr>
<td>Bicycle or motorcycle</td>
<td>0.5</td>
</tr>
</tbody>
</table>
Entry Volume

- Entry volume = sum of entering turning movements
Exit Volume

- Exit volume = sum of turning movements as shown
Circulating Volume

- Circulating volume = sum of turning movements as shown
Example: Volume Conversion

Turning movements

Roundabout volumes

PHF = 0.94

East/west:
2% SU trucks/buses

North/south:
4% SU trucks/buses,
2% combo trucks
Example Step 1: PCE Calculation

- SB TH: 530 veh (4% SU/bus, 2% combo)
  
  \[
  \begin{align*}
  \text{% cars (0.94) } & \times 1.0 \text{ pce/veh} = 0.94 \\
  \text{% SU/bus (0.04) } & \times 1.5 \text{ pce/veh} = 0.06 \\
  \text{% combo (0.02) } & \times 2.0 \text{ pce/veh} = 0.04
  \end{align*}
  \]

  \[
  f_{hv} = 1.04 \times 530 \text{ veh} = 551 \text{ pce}
  \]
Example Step 1: Completed PCE Calculation

Raw Counts → PCEs

Diagram showing the process of converting raw counts to PCEs with numbers and arrows indicating the flow.
Example Step 2: PHF Factor

PCEs (hourly) → PCEs (peak 15 minutes)

141 / 0.94 = 150
Example Step 3: Calculate Entry Volume

- Entry volume = sum of entering turning movements
Example Step 4: Calculate Exit Volume

- Exit volume = sum of turning movements as shown
Example Step 5: Calculate Circulating Volume

- Circulating volume = sum of turning movements as shown
Example: Solution

**Turning movements**

- North/south: 4% SU trucks/buses, 2% combo trucks
- East/west: 2% SU trucks/buses

**Roundabout volumes**

- PHF = 0.94
- East/west: 2% SU trucks/buses
- North/south: 4% SU trucks/buses, 2% combo trucks
Example: Capacity Calculation

Roundabout volumes

Roundabout category?

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Example: Capacity Calculation

Check capacity of each entry.
Example: Capacity check

Entering and circulating flow = 1800 veh/h

Urban & Rural Single-Lane Roundabouts
Urban Compact Roundabouts

Maximum Entry Flow (veh/h)
Circulatory Flow (veh/h)
Example: Capacity Check

- Entering volume = 645 pce/h
- Capacity of entry:
  - Single-lane: 762 pce/h
  - Urban compact: 607 pce/h
- Volume-to-capacity ratio:
  - Single-lane: \( \frac{645}{762} = 0.85 \) AT
  - Urban compact: \( \frac{645}{607} = 1.06 \) OVER
- What to do when \( v/c > 1.0 \)?
  - Repeat calculation for other approaches
Solution: Capacity Calculation

Urban Compact

Single-Lane

OVER CAPACITY

0.90

0.57

0.85

0.74

OK (TODAY)

0.83

0.85

0.49

1.06

0.57

0.49

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Delay

- **Control delay**
  - Includes initial deceleration delay, queue move-up time, stopped delay, and final acceleration delay

- **Geometric delay**
  - Delay experienced by a single vehicle with no conflicting flows
  - Caused by geometric features

- **Total delay = Control + Geometric**

- **Typical measure used: control delay**
AWSC Intersections

Five cases of vehicle presence
- Case 1 – Subject approach only
- Case 2 – Subject and opposing approaches
- Case 3 – Subject and conflicting approaches
- Case 4 – Subject and two other approaches
- Case 5 – All approaches

Service time depends on traffic on all the approaches

Capacity = 3600/service time

Require iteration to obtain estimate on service time