Topic 7
Interrupted Facilities
(Part I)
Intersection Control (Chapter 8)

- Hierarchy of intersection control
  - Unsignalized
    - Uncontrolled
    - Yield
    - Stop controlled
      - TWSC
      - AWSC
    - Roundabout
  - Signalized
Traffic Signals

Is Signal Control Always Better?
- Advantages
- Disadvantages

MUTCD Signal Warrants
- What does a warrant mean?
- Eight signal warrants (Textbook is from old MUTCD)
  - #1: Eight-hour vehicular volume (Old MUTCD #1~3)
  - #2: Four-hour vehicular volume
  - #3: Peak-hour vehicular (volume and delay)
  - Others: Pedestrian, School crossing, Coordinated signal system, Crash experience, Roadway Network
Signal Warrants

Warrant #1: Eight-hour vehicular volume

- Volume: Major - both directions; Minor - highest approach
- Any 8 hour, but the same period for both streets
- Two conditions: A, B
- Either A or B at 100% level
- Either A or B at 70% level with rural communities
- Both A and B at 80% level
### Table 4C-1. Warrant 1, Eight-Hour Vehicular Volume

#### Condition A - Minimum Vehicular Volume

<table>
<thead>
<tr>
<th>Major Street</th>
<th>Minor Street</th>
<th>Vehicles per hour on major street (total of both approaches)</th>
<th>Vehicles per hour on higher-volume minor-street approach (one direction only)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>100%&lt;sup&gt;a&lt;/sup&gt; 80%&lt;sup&gt;b&lt;/sup&gt; 70%&lt;sup&gt;c&lt;/sup&gt;</td>
<td>100%&lt;sup&gt;a&lt;/sup&gt; 80%&lt;sup&gt;b&lt;/sup&gt; 70%&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>500 400 350</td>
<td>150 120 105</td>
</tr>
<tr>
<td>2 or more...</td>
<td>1</td>
<td>600 480 420</td>
<td>150 120 105</td>
</tr>
<tr>
<td>2 or more...</td>
<td>2 or more...</td>
<td>600 480 420</td>
<td>200 160 140</td>
</tr>
<tr>
<td>1</td>
<td>2 or more...</td>
<td>500 400 350</td>
<td>200 160 140</td>
</tr>
</tbody>
</table>

#### Condition B - Interruption of Continuous Traffic

<table>
<thead>
<tr>
<th>Major Street</th>
<th>Minor Street</th>
<th>Vehicles per hour on major street (total of both approaches)</th>
<th>Vehicles per hour on higher-volume minor-street approach (one direction only)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
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<td>100%&lt;sup&gt;a&lt;/sup&gt; 80%&lt;sup&gt;b&lt;/sup&gt; 70%&lt;sup&gt;c&lt;/sup&gt;</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
<td>750 600 525</td>
<td>75 60 53</td>
</tr>
<tr>
<td>2 or more...</td>
<td>1</td>
<td>900 720 630</td>
<td>75 60 53</td>
</tr>
<tr>
<td>2 or more...</td>
<td>2 or more...</td>
<td>900 720 630</td>
<td>100 80 70</td>
</tr>
<tr>
<td>1</td>
<td>2 or more...</td>
<td>750 600 525</td>
<td>100 80 70</td>
</tr>
</tbody>
</table>

<sup>a</sup> Basic minimum hourly volume.

<sup>b</sup> Used for combination of Conditions A and B after adequate trial of other remedial measures.

<sup>c</sup> May be used when the major street speed exceeds 70 km/h (40 mph) or in an isolated community with a population of less than 10,000.
Signal Warrant Example

East-west is the major street with two lanes on each direction. North-south is the minor street with one lane on each direction. Determine if the intersection meets the 8-hr volume warrant (assume the intersection is located in an urban area)

<table>
<thead>
<tr>
<th>Time</th>
<th>Major Street Volume, vph</th>
<th>Minor Street Volume, vph</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>EB</td>
<td>WB</td>
</tr>
<tr>
<td>11 am-12</td>
<td>400</td>
<td>425</td>
</tr>
<tr>
<td>12-1PM</td>
<td>450</td>
<td>465</td>
</tr>
<tr>
<td>1-2 PM</td>
<td>485</td>
<td>500</td>
</tr>
<tr>
<td>2-3 PM</td>
<td>525</td>
<td>525</td>
</tr>
<tr>
<td>3-4 PM</td>
<td>515</td>
<td>525</td>
</tr>
<tr>
<td>4-5 PM</td>
<td>540</td>
<td>550</td>
</tr>
<tr>
<td>5-6 PM</td>
<td>550</td>
<td>580</td>
</tr>
<tr>
<td>6-7 PM</td>
<td>545</td>
<td>528</td>
</tr>
<tr>
<td>7-8 PM</td>
<td>505</td>
<td>506</td>
</tr>
<tr>
<td>8-9 PM</td>
<td>485</td>
<td>490</td>
</tr>
<tr>
<td>9-10 PM</td>
<td>475</td>
<td>475</td>
</tr>
<tr>
<td>10-11 PM</td>
<td>400</td>
<td>410</td>
</tr>
</tbody>
</table>
**Signal Warrant Example**

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<td>475</td>
<td>475</td>
</tr>
<tr>
<td>10-11 PM</td>
<td>400</td>
<td>410</td>
</tr>
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Signal Warrants

- **Warrant #2: Four-hour vehicular volume**
  - (Similar to 8-hr volume warrant)
  - **Volume:** Major - both directions; Minor - highest approach
  - Any 4 hour, but the same period for both streets
  - 100% level and 70% level
  - A minimum minor street volume threshold
Figure 4C-1. Warrant 2 - Four-Hour Vehicular Volume

MAJOR STREET - TOTAL OF BOTH APPROACHES - VPH

*Note: 115 vph applies as the lower threshold volume for a minor street approach with two or more lanes and 80 vph applies as the lower threshold volume for a minor street approach with one lane.
Figure 4C-2. Warrant 2 - Four-Hour Vehicular Volume (70% Factor)
(COMMUNITY LESS THAN 10,000 POPULATION OR ABOVE 70 km/h (40 mph) ON MAJOR STREET)

MAJOR STREET - TOTAL OF BOTH APPROACHES - VPH

*Note: 80 vph applies as the lower threshold volume for a minor street approach with two or more lanes and 60 vph applies as the lower threshold volume for a minor street approach with one lane.
Signal Warrants

Warrant #3: Peak-hour

- **Volume**
  - Similar to 4-hour volume

- **Delay**
  - Stop control
  - one lane: 4 veh-hr; two-lane: 5 veh-hr
**Figure 4C-3. Warrant 3 - Peak Hour**

**MAJOR STREET - TOTAL OF BOTH APPROACHES - VPH**

*Note: 150 vph applies as the lower threshold volume for a minor street approach with two or more lanes and 100 vph applies as the lower threshold volume for a minor street approach with one lane.*
Figure 4C-4. Warrant 3 - Peak Hour (70% Factor)

(COMMUNITY LESS THAN 10,000 POPULATION OR ABOVE 70 km/h (40 mph) ON MAJOR STREET)

MAJOR STREET - TOTAL OF BOTH APPROACHES - VPH

*Note: 100 vph applies as the lower threshold volume for a minor street approach with two or more lanes and 75 vph applies as the lower threshold volume for a minor street approach with one lane.
Figure 4C-1. Warrant 2 - Four-Hour Vehicular Volume

Based on Previous Example

MAJOR STREET - TOTAL OF BOTH APPROACHES - VPH

*Note: 115 vph applies as the lower threshold volume for a minor street approach with two or more lanes and 80 vph applies as the lower threshold volume for a minor street approach with one lane.
Signal Timing Terminologies

- Basic signal terms
  - Cycle and cycle length
  - Phase and Phasing Sequence
    (*A signal phase is associated with a particular traffic movement*)
  - Interval
    - Change interval (yellow)
    - Clearance interval (all-red)
    - Green interval
    - Red interval
Traffic Movements

One-way Streets

Main Street

Side Street

EB

N

Main Street

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Traffic Movements

One-way Streets

Side Street

Main Street

N

EB

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Traffic Movements
One-way Streets

Side Street

Main Street

EB

N

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Traffic Movements

One-way Streets

Main Street

Side Street

EB

N

Main Street

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Traffic Movements

One-way Streets

Side Street

Main Street

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Two-Phase Operation

\[ \phi_1 \quad \phi_2 \]
Traffic Movements
Full Intersection

Side Street
SB

Main Street
WB

N

NB

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8-Phase Quad Left Control (NEMA)
Phasing Sequence

- **Left-turn Treatment**
  - Permitted (no phase)
  - Protected
  - Protected/Permitted

- **Left-turn Sequence**
  - Dual LT Leading (preferred)
  - Dual LT Lagging
  - Split
  - Lead/Lag
Phasing Sequence

Left-turn Leading

- φ1
- φ2
- φ3
- φ4
- φ5
- φ6
- φ7
- φ8

Ring 1

Ring 2

Barrier

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Phasing Sequence

Lead-Lag

Ring 1

Barrier

ϕ2
ϕ1
ϕ3
ϕ4
ϕ5
ϕ6
ϕ7
ϕ8

Ring 2
Phasing Sequence

Lagging Left-Turn

\[ \phi_2 \rightarrow \phi_1 \rightarrow \phi_6 \rightarrow \phi_5 \rightarrow \phi_3 \rightarrow \phi_7 \rightarrow \phi_4 \rightarrow \phi_8 \]
Phasing Sequence

Split

Barrier

Ring 1

Ring 2

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Example

Determine the appropriate signal phasing and control, assuming left-turn is protected wherever exclusive left-turn lanes are provided.
Right-Turn Phase

- SB: φ8 φ3
- EB: φ1 φ6
- WB: φ2 φ5
- NB: φ4 φ7
- φ4+ φ5

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Right-Turn Phase

- Right-turn Treatment
  - Permitted (same with adjacent through)
    - Right-turn-on-red (RTOR)
    - No RTOR
  - Protected
    - Right-turn arrow display
    - Overlap phase (adjacent through phase + right-side cross street left-turn phase)
Pedestrian Phase

- Pedestrian phase (WALK + FDW) is usually concurrent with the through movement phase.
- WALK and FDW normally show only when pedestrian crossing button is pushed.

<table>
<thead>
<tr>
<th>WALK</th>
<th>FDW</th>
<th>G</th>
<th>y</th>
<th>AR</th>
</tr>
</thead>
<tbody>
<tr>
<td>![Pedestrian Symbol]</td>
<td>![Don't Walk Symbol]</td>
<td>![Green Signal]</td>
<td>![Yellow Signal]</td>
<td>![Red Signal]</td>
</tr>
</tbody>
</table>
Pedestrian Phase

- **WALK** time is usually between 5~7 sec
- **FDW** is also called the pedestrian clearance time, which is to allow pedestrians entering the crosswalk to safely cross

\[ G \geq WALK + FDW \]
Change and Clearance Intervals

- **Change interval (yellow)**
  - Can safely stop when green ends and yellow starts
  - Or can enter the intersection at the end of yellow
  - About 3~4 seconds
Change and Clearance Intervals

- Change interval (yellow) – ITE
  
  \[ y = t + \frac{1.47u_{85}}{2d + 64.4*G} \]

- Clearance Interval (all-red)
  
  \[ ar = \frac{w + L}{1.47u_{15}} \]
Table 7.2.1 Uniform Acceleration Formulas

<table>
<thead>
<tr>
<th>to find</th>
<th>given these</th>
<th>use this equation</th>
</tr>
</thead>
<tbody>
<tr>
<td>$a$</td>
<td>$t, v_0, v$</td>
<td>$a = \frac{v - v_0}{t}$</td>
</tr>
<tr>
<td>$a$</td>
<td>$t, v_0, s$</td>
<td>$a = \frac{2s - 2v_0 t}{t^2}$</td>
</tr>
<tr>
<td>$a$</td>
<td>$v_0, v, s$</td>
<td>$a = \frac{v^2 - v_0^2}{2s}$</td>
</tr>
<tr>
<td>$s$</td>
<td>$t, a, v_0$</td>
<td>$s = v_0 t + \frac{1}{2} a t^2$</td>
</tr>
<tr>
<td>$s$</td>
<td>$a, v_0, v$</td>
<td>$s = \frac{v^2 - v_0^2}{2a}$</td>
</tr>
<tr>
<td>$s$</td>
<td>$t, v_0, v$</td>
<td>$s = \frac{1}{2} t (v_0 + v)$</td>
</tr>
<tr>
<td>$t$</td>
<td>$a, v_0, v$</td>
<td>$t = \frac{v - v_0}{a}$</td>
</tr>
<tr>
<td>$t$</td>
<td>$a, v_0, s$</td>
<td>$t = \frac{\sqrt{v_0^2 + 2as} - v_0}{a}$</td>
</tr>
<tr>
<td>$t$</td>
<td>$v_0, v, s$</td>
<td>$t = \frac{2s}{v_0 + v}$</td>
</tr>
<tr>
<td>$v_0$</td>
<td>$t, a, v$</td>
<td>$v_0 = v - at$</td>
</tr>
<tr>
<td>$v_0$</td>
<td>$t, a, s$</td>
<td>$v_0 = \frac{s}{t} - \frac{1}{2} a t$</td>
</tr>
<tr>
<td>$v_0$</td>
<td>$a, v, s$</td>
<td>$v_0 = \sqrt{v^2 - 2as}$</td>
</tr>
<tr>
<td>$v$</td>
<td>$t, a, v_0$</td>
<td>$v = v_0 + at$</td>
</tr>
<tr>
<td>$v$</td>
<td>$a, v_0, s$</td>
<td>$v = \sqrt{v_0^2 + 2as}$</td>
</tr>
</tbody>
</table>

The table can be used for rotational problems by substituting $\alpha$, $\omega$, and $\theta$ for $a$, $v$, and $s$, respectively.
Dilemma zone is a distance area when a vehicle can neither safely stop nor safely pass the intersection.
Assume the 85th percentile speed is 57 mph, and the 15th percentile speed is 43 mph.

(a) Calculate the yellow change interval, clearance interval

(b) If a vehicle is traveling at 50 mph, determine the dilemma zone if any
Dilemma Zone

\[ x_2 = 313 \]
\[ x_1 = 346 \]
\[ x_2 = 397 \]
\[ x_1 = 397 \]
\[ x_2 = 572 \]
\[ x_1 = 488 \]

\[ u = 50 \text{ mph} \]
\[ u = 57 \text{ mph} \]
\[ u = 70 \text{ mph} \]
Clearance Intervals and Lost Times

- Clearance interval (all-red)
  - vehicles entering in yellow can clear the intersection
  - about 1.0~2.5 sec

- Lost times
  - time that cannot be effectively used by vehicles
  - start-up lost time, \( I_1 \), 2 sec (default in HCM)
  - use of end of green, \( e \), 2 sec (default in HCM)

\[
t_L = I_1 + y + AR - e
\]
Actuated Signal Operation

- Types of signal control
  - Fixed or pre-timed
  - Fully actuated
  - Semi-actuated

- Fully actuated signal
  - Based on vehicle detection
  - Varied green and cycle

- Types of detectors
  - Inductive loop
  - Video image
Actuated Signal Operation

- Types of detection
  - Passage or point detection
  - Presence or area detection

- Passage detection
- Presence detection at stop line
Terms for Actuated Operation

- **Controller terms**
  - Minimum green (5~10 sec)
  - Minimum initial (min. initial + Unit Extension = Min Green)
  - Unit or vehicle extension or passage gap (0.0~4.0 sec)
  - Maximum green
  - Min Recall and Max Recall
Terms for Actuated Operation

- Actuated controller operations

Diagram showing the relationship between Total Green, Minimum Green, and Extension Period.
Saturation Headway and Saturation Flow Rate

\[ s = \frac{3600}{h} \]
Effective Green and Capacity

- Effective green of $\Phi_i$, $g_i$

$$g_i = G_i + y_i + (ar)_i - t_{Li}$$

- Phase capacity, $c_i$

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

- Demand-to-capacity ratio, $x_i$

$$x_i = \frac{v_i}{c_i} = \frac{v_i}{s_i \left( \frac{g_i}{C} \right)} = \frac{v_i}{s_i} \times \frac{C}{g_i}$$
Example

- **Given the following:**
  - \( C = 60 \text{ s} \)
  - \( G = 27 \text{ s} \)
  - \( y = 2.5 \text{ s} \)
  - \( ar = 0.5 \text{ s} \)
  - \( h = 2.4 \text{ s} \)
  - Start up lost time \( l_1 = 2.0 \text{ s} \), Clearance lost time \( l_2 = 1.0 \text{ s} \)

What is the capacity for an approach with two lanes of identical traffic flow characteristics?
Required Green and Phase Time

- Required effective green, \( g_i \) to achieve degree of saturation, \( x_i \)

\[
g_i = \frac{v_i}{s_i} \times \frac{C}{x_i} = y_i \frac{C}{x_i}
\]

- Minimum effective green, \( g_i \)

\[
g_i = y_i C
\]

- Minimum phase, \( \Phi_i \)

\[
\phi_i = g_i + \ell_i = y_i C + \ell_i
\]
Critical Phases

- **Critical phases**: conflicting phases that require the most time

- **Possible critical phases**
  - $\phi_1, \phi_2, \phi_3, \phi_4$
  - $\phi_1, \phi_2, \phi_7, \phi_8$
  - $\phi_5, \phi_6, \phi_3, \phi_4$
  - $\phi_5, \phi_6, \phi_7, \phi_8$
**Example**

**Determine critical phases**

<table>
<thead>
<tr>
<th>$\Phi_i$</th>
<th>Direction</th>
<th>$v_i$, vph</th>
<th>$s_i$, vph</th>
<th>$y_i$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>WBL</td>
<td>120</td>
<td>1710</td>
<td>0.070</td>
</tr>
<tr>
<td>2</td>
<td>EBT</td>
<td>616</td>
<td>3600</td>
<td>0.171</td>
</tr>
<tr>
<td>5</td>
<td>EBL</td>
<td>147</td>
<td>1710</td>
<td>0.086</td>
</tr>
<tr>
<td>6</td>
<td>WBT</td>
<td>512</td>
<td>3600</td>
<td>0.142</td>
</tr>
<tr>
<td>3</td>
<td>NBL</td>
<td>78</td>
<td>1710</td>
<td>0.046</td>
</tr>
<tr>
<td>4</td>
<td>SBT</td>
<td>318</td>
<td>3600</td>
<td>0.088</td>
</tr>
<tr>
<td>7</td>
<td>SBL</td>
<td>174</td>
<td>1710</td>
<td>0.102</td>
</tr>
<tr>
<td>8</td>
<td>NBT</td>
<td>412</td>
<td>3600</td>
<td>0.114</td>
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</tbody>
</table>