JCE4600
Fundamentals of Traffic Engineering

Traffic Signal Fundamentals

Agenda

- Use
- Flow Attributes
  - Saturation Flow, Lost Time
  - Clearance Intervals
- Cycle Length
  - Webster's Equation
- Phasing Schemes
- Splits
  - Queuing Theory
  - Capacity, Delay, and Queue Length
- Offset and Coordination
When is it Appropriate to use Traffic Signals?

- Delay
  - Vehicular
  - Pedestrian
- Safety
  - Congestion
  - Sight Distance
  - School Crossing
- Systems Operations
- Can Signals Create Problems?

Guidance from the HCM

EXHIBIT 10–15. INTERSECTION CONTROL TYPE AND PEAK-HOUR VOLUMES
(SEE FOOTNOTE FOR ASSUMED VALUES)

Notes:
- Roundup totals may be appropriate within portion of these ranges.
- Source: Adapted from Traffic Control Devices Handbook 6th ed., p. 4–190, peak = direction. 5+4 volumes converted to two-way peak-hour volumes assuming 427 equals twice the 8-h volume and peak hour is 10 percent of daily. Two-way volume assumed to be 150 percent of peak-direction volume.
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Traffic Signal Timing Components

Major MOE

- Delay
- \(v/c\) (degree of saturation)
- % Stops
- Queue Length
  - 50%
  - 95%
Major Timing Parameters

- **Cycle Length**
  - Time required to display complete sequence

- **Phasing**
  - Control turning movements

- **Splits**
  - Time allocated to a given movement relative to cycle

- **Controller Type**
  - Pre-timed, Actuated, Semi-actuated, Adaptive

- **Coordination/Offset**
  - Start of cycle at one intersection relative to start of cycle at adjacent intersection

Types of Traffic Signal Systems

- **Fixed Time**
  - Low Cost / Easy to Maintain
  - $150,000 per Signal
  - NOT Responsive to Changing Traffic Demands

- **Actuated**
  - $200,000 - $300,000 per Signal
  - Requires traffic detection
    - Loop detectors
    - Video detection
  - Fully Responsive to Traffic Demands at Intersection

- **Semi Actuated**
  - Responsive to Side-Street Demands at Intersection

- **Coordinated**
  - Requires Communication Between Controllers

- **Adaptive**
  - Requires Master Optimization and Detailed Algorithms
  - Intensive Traffic Detection and Communication
  - Responsive to Traffic Demands of Traffic Signal Systems
Traffic Signal Cycle

Traffic Signal Coordination

[Diagrams showing cycle, split (A phase), offset, space, bandwidth, speed, and time relationships]
Other Key Parameters

- Effective Green / Effective Red
- Saturation Flow Rate
- Lost Time = G+Y+AR-g
  - Clearance Interval
  - Start-up Delay
  - Green Extension
- Time Space Diagram
- Capacity of the lane group = sat flow *g/C

Startup Delay and Saturation Flow Rate

<table>
<thead>
<tr>
<th>Δt (sec)</th>
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<th>Min h₁</th>
<th>Δ</th>
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Yellow and All Red Clearance Times

- Yellow Times
  - Dilemma Zone Prevention
  - Typical Guidelines
    - 25 and lower = 3 seconds
    - 30-40 = 3-4 seconds
    - 40-50 = 4-5 seconds
    - 55 and greater = 5 seconds

- Red – Clearance Interval
  - Intersection Width and Speeds

- Do longer clearance intervals make intersections safer?
## Driver Dilemma Zone

**Driver Dilemma Zone at Various Speeds and Yellow Intervals**

<table>
<thead>
<tr>
<th>Vehicle Speed (mph)</th>
<th>Stopping Distance &quot;Xs&quot; (ft)</th>
<th>Clearance Distance &quot;Xc&quot; (ft)</th>
<th>Dilemma Zone (ft)</th>
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## MoDOT Change Intervals

**Table 902.5.3.2 Change Periods**

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<td>5.0</td>
<td>1.3</td>
<td>5.0</td>
</tr>
</tbody>
</table>

Y – Yellow  AR – All Red  CP – Change Period

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**Cycle Length**
Cycle Length

- Minimum Cycle Length
  - Minimum Green Times
  - Minimum Perception Reaction and Start-up Time (5-7 Seconds)
  - Minimum g/C for Capacity
    - $G_{min} = q/s \cdot C$
    - $C_{min} = \text{sum} (G_{min}) + \text{Lost time}$
      - (100% Saturation of Signal)
  - Minimum Pedestrian Clearance Times
  - Clearance Intervals
- Optimal Cycle Length
  - Longer cycle lengths offer higher capacities
  - Critical Lane Groups
  - Longer cycle lengths result in higher delays
  - Delay Equation

Optimal Cycle Length

$$C_o = \frac{1.5L + 5}{1 - \text{sum} (q/s)}$$
Cycle Length
Fact and Fiction

- Fact:
  - Increased cycle length increases intersection capacity
  - Shorter cycle lengths reduce delay
- Fiction:
  - Cycle length has a significant impact on capacity
  - Offset and cycle length are independent
  - Longer cycle lengths always reduce congestion

Longer Cycle Lengths Can Increase Congestion

- Upstream throughput may exceed downstream link capacity
- Turning bay storage can be exceeded
- Increased vehicle headways with long cycle lengths (longer green times)
Cycle Length and Headway

Results for an Isolated Intersection

The “Bottom Line” On Cycle Length
Cycle Length and Capacity

![Graph showing cycle length and capacity for different signal phasing options.

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Signal Phasing
Typical Phasing - (by direction)

Standard 8 Phase Sequence
When to use Protected Left Turn Phasing

- Delay
- Sight Distance
- Types
  - Lead/Lead
  - Lag/Lag
  - Lead/Lag (Left Turn Trap)
  - Split
- What are the trade-offs?
Phasing Impact on Lost Time

EXHIBIT 10-17: DEFAULT LOST TIME PER CYCLE BY LEFT PHASE TYPE

<table>
<thead>
<tr>
<th>Major Street</th>
<th>Minor Street</th>
<th>Number of Phases</th>
<th>( L ) (%)</th>
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</thead>
<tbody>
<tr>
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<td>16</td>
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<tr>
<td>Protected</td>
<td>Permitted</td>
<td>3</td>
<td>12</td>
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<tr>
<td>Permitted</td>
<td>Permitted</td>
<td>2</td>
<td>8</td>
</tr>
</tbody>
</table>

Note:
Protected and permitted relate to left turns.

EXHIBIT 10-11: LOST TIME APPLICATION FOR COMPOUND LEFT-TURN PHASING

- Phase 1a
- Phase 1b
- Phase 1c
- Phase 2

● Indicates lost time applied

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Splits
Basic Facts About Split

- Allocates intersection capacity to conflicting movements
- Directly entered on pretimed controllers
- Implicitly selected for actuated controllers through:
  - Maximum green times
  - Minimum green times

A Correct Split Is Important

![Graph showing the relationship between Delay and Split Error for different vehicle hours per hour (vph): 900 vph, 1100 vph, and 1300 vph. The graph illustrates that as the split error increases, the delay also increases.]
Conclusions About Split

$\text{Split}_i = \text{Cycle} \times (\text{CLF}_i)/(\text{Total CLF})$

- Bad splits produce increased delays particularly at high volumes

CLF = Critical Lane Flow

Continuum Model

- Theoretical Mathematical Model for Representing Capacity, Delay, and Queuing at Signalized Intersections
- Simple Time/Space Diagram
- Basis for HCM Procedures
Continuum Model

Number of Vehicles

Arrival Flow Rate

Saturation Flow Rate

$r$ $g$

Time $t_0$

Continuum Model

Number of Vehicles

Max Back of Queue

Area = Total Delay

$r$ $g$

Time $t_0$
Continuum Model

- How do you find?
  - Average Delay per Vehicle
  - Maximum Length of Queue
  - Percentage of Vehicles Stopped
  - Percentage of the Cycle with a Queue

Timing parameters For Actuated Signal Control

**Initial interval**: Initial green time to allow clearance of vehicles stored in the space between the detector and stop line during the red phase.

**Passage time / Unit extension**: the minimum time the green should be extended for each vehicle arrival at the detector, from the instant the arrival is detected. As a minimum, the unit extension should be equal to the vehicle “passage time” from the detector to the stop line.

**Minimum interval**: the minimum green duration to be provided once the green has been initiated. Typically given as initial interval plus passage time.

**Maximum interval**: total green time allowed for the phase. Typically corresponds to “worst-case” signal operation (i.e. pre-time settings for heavy traffic).

**Phase changing logic**: Signal switches to next phase if either Gap between successive vehicles in green phase is greater than passage time, and there is competing demand (“gap-out”) the maximum interval has been reached (“max-out”)
Actuated Controller Intervals

Variable Green  Yellow Clearance

Initial Interval  Green Clearance (Ped FDW)

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Offset
Offsets Can Produce Smooth Flow

- Offset is the time relationship between intersections
- Offset effectiveness is limited for saturated conditions
- Offset is useful for greater distances between intersections.
- Value of offset depends on mid-block friction

Time-Space Diagram
Platoons Determine Offset Effectiveness

Traffic Coordination Movie
Coordinated Systems

- **Time Base (Via Internal Clock)**
  - Clocks can Drift
  - Inaccurate Following Power Outage
  - Requires Frequent Maintenance

- **7 Wire Interconnect**
  - One Way Communication from Master to Each Local
  - No Means of Monitoring from a Remote Location
  - Requires Citizen Complaints to Identify Malfunctions

- **Closed Loop (Twisted Pair, Fiber Optic, Wireless)**
  - Two Way Communications
  - Data May Be Uploaded/Downloaded Via Telephone
  - Malfunctions can Trigger Alarm

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Coordinated Systems

Advanced Traffic Management Systems (ATMS)
Key Traffic Signal Safety Concepts

- Dilemma Zone
- Left Turn Trap
- Protected Only Phasing
  - Opposing Speeds Higher than 40 mph
  - Sight Distance Issues
  - More than 2 Opposing Lanes
  - Dual Left Turn Lanes
It’s all about Time Video by FHWA

Signal Timing Benefits

- 15 to 40% reduction in delay
- 10 to 40% less stops
- 10% reduction in fuel consumption
- 22% reduction in emissions
- National savings in fuel consumption of 400 million barrels of oil per year

1. The following data applies to the operation of the northbound approach to a signalized intersection:

- Saturation flow rate = 1800 vph
- Arrival Rate = 700 vph
- Cycle Length = 60 Seconds
- Green Interval = 30 Seconds
- Yellow Interval = 5 Seconds
- Start Up Delay = 3 Seconds
- Green Extension = 2 Seconds

a. Plot a time space diagram for two cycle lengths. Be sure to include vehicle headways and the placement of all shock waves. Also include the effective red and effective green intervals as well as the Green, Yellow, and Red intervals. Draw your diagram to scale.
b. From the time space diagram, plot a flow versus time diagram. Be sure to show the excess capacity, to; the effective red and effective green intervals; and Green, Yellow, and Red intervals. Draw your plot to scale.
c. From the above plots, draw a continuum model (# of vehicles versus time.) Show the maximum length of queue, maximum back of queue, saturation flow rate, arrival rate, to, and delay. Be sure to show the effective red and effective green intervals and Green, Yellow, and Red intervals. Draw your plot to scale.
d. Calculate from the above plots, the capacity of the approach, the average delay per vehicle, the average delay per stopped vehicle. Assume the length of the average vehicle is 15 feet and the average spacing of stopped vehicles is 5 feet, how far, on average will the queue extend upstream from the approach?

2. A line of vehicles at a signalized intersection begins to move with the initiation of the green signal. The following values represent the headway between the first 7 vehicles as they cross the intersection.

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Headway (sec)</th>
</tr>
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<tbody>
<tr>
<td>1</td>
<td>3.5</td>
</tr>
<tr>
<td>2</td>
<td>2.9</td>
</tr>
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<td>7</td>
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</table>

a. Assume that G = 35 sec, R = 25 sec, and Arrival Rate = 700 vph. Further assume that Y = 3 sec and Green Extension = 2 sec for all approaches. Plot the continuum model, and calculate total delay for the per cycle. What is $t_o$?
b. What is the saturation flow rate and lost time for this approach?

3. Derive equations for the following, based on the continuum model

- Average Delay per Vehicle
- Maximum Length of Queue
- Percentage of Vehicles Stopped
- Percentage of the Cycle with a Queue