I. Traffic Signal Control

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Outline

- Background: Intersection control
- Traffic Flow at Signalized Intersections
- Performance Measures
- Signal Timing Isolated Traffic Signals
- Signal Coordination
- Actuated Traffic Signals
- Traffic Responsive and Adaptive Control
Background

Intersections: Conflict Points /Control Type

- Merging conflict points = 8
- Diverging conflict points = 8
- Crossing conflict points = 16
Traffic Flow at Signalized Intersections

I₁: Start-up lost time
I₂: Clearance lost time
Lost Time & Effective Green Time (1)

- **Start-up lost time** \((l_1)\): The time lost due to acceleration of the first four vehicles at the beginning of the green.

- **Clearance lost time** \((l_2)\): Portion of the yellow (and all-red) clearance interval that is not used by vehicles to cross the intersection stopline.

- **Total Lost Time**, \(t_L\)
  
  \[ t_L = l_1 + l_2 \]

- **Effective Green/Red Times for a Movement**

  - Actual green plus yellow time - lost time: \(g_i = G_i + Y_i - t_L\)
  
  - Actual red time plus lost time: \(r_i = R_i + t_L\)
**Saturation Flow and Capacity**

**Saturation flow**: the maximum flow rate per lane at which vehicles can pass through a signalized intersection assuming that the signal was green for a full hour and a queue is present.

**Ideal Saturation flow**: 1,900 pce/l/hr/g

**Capacity** = (Saturation flow) * (proportion of time the signal is effectively green)

\[ c = s \frac{g}{C} \text{ (vphl)} \]
Traffic Dynamics
Urban Streets: Vehicle Platoons
## I. MOBILITY

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<td># vehicles in yellow</td>
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The volume to capacity ratio (v/c) for an intersection lane group is also called degree of saturation, $X$:

$$X_i = \left( \frac{v}{c} \right)_i = \frac{v_i}{s_i \left( \frac{g_i}{C} \right)} = \frac{v_i C}{s_i g_i}$$

(16-7)

where

- $X_i = (v/c)_i$ = ratio for lane group i,
- $v_i$ = actual or projected demand flow rate for lane group i (veh/h),
- $s_i$ = saturation flow rate for lane group i (veh/h),
- $g_i$ = effective green time for lane group i (s), and
- $C$ = cycle length (s).
The critical v/c ratio, $X_c$, is the v/c ratio for the whole intersection, considering only the lane groups that have the highest flow ratio (v/s) per signal phase:

$$X_c = \sum \left( \frac{V}{S} \right)_{ci} \left( \frac{C}{C-L} \right)$$

where

- $X_c$ = critical v/c ratio for intersection;
- $\sum \left( \frac{V}{S} \right)_{ci}$ = summation of flow ratios for all critical lane groups i;
- $C$ = cycle length (s); and
- $L$ = total lost time per cycle, computed as lost time, $t_L$, for critical path of movements (s).

**Intersection Spare Capacity = 1-$X_c$**
Delay and Queuing

Time in the queue (sec) \[ t_Q = \frac{sr}{s - v} \]

Queue in the beginning of green (veh) \[ Q_M = \frac{vr}{3600} \]
\[ d = \frac{c(1-g/c)^2}{2[1-(g/c)x]} + \frac{x^2}{2q(1-x)} - 0.65\left(\frac{c}{q^2}\right)^{\frac{1}{3}}x^2 + 5(g/c) \]

where,

\[ d = \text{average delay per vehicle (sec)}, \]
\[ c = \text{cycle length (sec)}, \]
\[ g = \text{effective green time (sec)}, \]
\[ x = \text{degree of saturation (flow to capacity ratio)}, \]
\[ q = \text{arrival rate (veh/sec)}. \]
Delay – Time Dependent Models

Applies to random + saturation delay

Example HCM2000

\[ d_2 = 900T \left[ (X - 1) + \sqrt{(X - 1)^2 + \frac{8kIX}{cT}} \right] \]

- \( T \): analysis period
- \( X \): degree of saturation
- \( c \): capacity
- \( K, I \): adjustment factors
  - \( K \): for coordination
  - \( I \): for controller type

For Isolated fixed time signals

\( K = 0.5, \ I = 1 \)
Back of Queue: Undersaturated Signal
Traffic Signal Operations

Isolated Signals

- **Pretimed (Fixed Time):** duration of cycle length and green times remain fixed throughout the analysis period

- **Actuated:** green times (and cycle length) vary based on the vehicle arrivals subject to a min and max value
  - Semi-actuated
  - Fully-actuated

- **Adaptive:** advanced control based on detection and prediction of traffic arrivals

Arterials and Networks

- Coordinated fixed-time
- Coordinated actuated (semi-actuated)
- Traffic responsive & adaptive Control
**Signal Timing: Definitions**

- **Cycle length**: a complete sequence of signal indications
- **Phase**: portion of time that movements having the right-of-way do not change
- **Interval**: portion of time that signal indication remains unchanged
Clearance Intervals (1)

- **Yellow Time (Yellow Change)**
  Warn drivers of end of phase

\[
Y = T + \frac{S}{2a + 64.4G}
\]

- \(Y\) = yellow change interval (sec)
- \(T\) = driver reaction time (sec) – 1 sec.
- \(S\) = vehicle speed (ft/s) - 85% speed or posted speed limit
- \(a\) = vehicle deceleration rate (f/s²) - 10 ft/s²
- \(G\) = approach grade (%)
Clearance Intervals (2)

- **All Red (Red Clearance)**
  Use to clear vehicles in the intersection prior to changing right-of-way assignment

\[ R = \frac{W + L}{S} \]

- **R** = all-red clearance interval (sec)
- **S** = vehicle speed (fps)
- **W** = distance from stop line to intersection far side (ft)
- **L** = vehicle length (ft)--- 20 ft for passenger cars
Minimum Pedestrian Green Time

- The minimum pedestrian green time for a phase is determined based on typical values of pedestrian walking speed (4 ft/sec or 3.5 ft/sec).

- Example HCM method

\[
G_p = 3.2 + \frac{L}{S_p} + \left(2.7 \frac{N_{ped}}{W_E}\right) \quad \text{for } W_E > 10 \text{ ft}
\]

\[
G_p = 3.2 + \frac{L}{S_p} + \left(0.27N_{ped}\right) \quad \text{for } W_E \leq 10 \text{ ft}
\]

where

- \(G_p\) = minimum green time (s),
- \(L\) = crosswalk length (ft),
- \(S_p\) = average speed of pedestrians (ft/s),
- \(W_E\) = effective crosswalk width (ft),
- 3.2 = pedestrian start-up time (s), and
- \(N_{ped}\) = number of pedestrians crossing during an interval (p).
Signal Phasing

- Permitted phasing: turning movement is made through the opposing vehicle flow.
  
  Example: Left turns concurrent with the opposing through movement, and right-turns concurrent with pedestrian crossings in a conflicting crosswalk.

- Protected phasing: turns are made during an exclusive left-turn phase

- Protected-Permissive Left Turns

- Prohibited Left Turns

- Split Phasing
Typical Phasing Schemes

Two phases

Protected LT

(a)

Exclusive left-turn phase
Three phases

(b)

Leading/lagging green overlapping phases

(c)

Four phases
Two left-turn phases

(d)

Permitted LT
Criteria for Left Turn Phasing (1)

- **Intersection Design Characteristics**
  - # of left-turn lanes
  - # of opposing through lanes
  - Speed of opposing traffic
  - Sight distance

- **Traffic Volumes**
  - Left-turn volume (veh/cycle) $V_{lt}$
  - Opposing through + right-turn volume $V_o$

- **Delay to Left-Turning Vehicles**

- **Accident History**

Example:
$V_{lt} \times V_o > 50,000$
Protected LT
Phase Sequence
Pretimed Controllers: Signal Timing

- **Cycle length:**
  Minimum green time to serve critical traffic demand/phase:

  \[ g = \left(\frac{v}{s}\right)(C - L) = y(C - L) \]

  **Minimum Cycle Time:**
  \[ C = \frac{L}{(1 - Y)} \]

  s.t. sum of min phase lengths

  **Optimum cycle length (Webster):**

  \[ C_o = \frac{1.5L + 5}{1 - \sum_i \left(\frac{v_j}{s_j}\right)_i^c} \]

  \[ C_o = \text{Optimum delay cycle length (sec)} \]

  \[ L = \text{Total lost time per cycle (sec)} \]

  \[ y = (v/s)_i^c = \text{Critical (flow/saturation flow) ratio for phase } i \]
Signal Delay vs. Cycle Length

- Critical Cycle Length, $C_c$
- Minimum-Delay Cycle Length, $C_m$
Signal Timing: Green Splits

- **Phase Green Times**
  
  Effective green time per phase $g_i$
  Equal Degree Of Saturation (EQUISAT)

  $$g_i = \frac{(v/s)_i^c}{\sum_i (v/s)_i^c} (C - L)$$
  $$g = y(C-L)/Y$$

  s.t. min phase lengths for pedvs/veh

$$g_i = G_i + Y - t_L$$

- $G_i$ = actual green time for phase $i$ (sec)
- $Y_i$ = clearance = yellow + all-red time (sec)
- $t_L$ = total lost time for phase (sec)
- $C$ = cycle length (sec)
- $L$ = lost time per cycle (sec)
Coordinated Signals (Arterials/Networks): Signal Control Parameters

System Cycle length \( C \)
Phase sequence \( p_{s_i} \)
Green Times \( g_i \)
Offsets \( O_i \)

Fixed:
# Phases
Yellow (all red) intervals
Minimum green times
Robertson’s platoon dispersion formula:

\[ q_2 (i+t) = F q_1(i) + (1-F) q_2 (i+1+t) \]

where:

\[ F = \frac{1}{1+\alpha t} \]

\[ \alpha = 0.50 \]

\[ t = 0.8TT \]

\( \alpha \) platoon dispersion factor (PDF)
Benefits of Signal Coordination
Concepts: Cycle length

- All signals operate on a common cycle length
- Typically the critical intersection dictates the system cycle length
- Signals may operate on multiples of cycle length (half-cycle)
Concepts: Offsets

- Time difference between two reference points
- Defined by phase and interval
- Value: 0 ~ cycle length (seconds)

The sum of offsets in two directions must be equal to an integer number of cycles

\[ \text{Off}_{ij} + \text{Off}_{ji} = n \, C \]

**Ideal Offsets:**
Offset = \( L/v \)
L: Signal spacing (ft)
V: Speed (ft/sec)
Concepts: Progression

Offset measured at the start of green

Offset measured at the end of green
Common Synchronization Schemes (1)
Common Synchronization Schemes (2)

- Traffic demands per travel direction are balanced
- The signal spacing is approximately equal

**Alternate System**

\[ C = \frac{2L}{v} \]

Bandwidth = green time

**Double Alternate System**

\[ C = \frac{4L}{v} \]

Bandwidth = (green time)/2

\[ C = \text{system cycle length (sec)} \]

\[ L = \text{signal spacing (ft)} \]

\[ V = \text{average link speed (ft/sec)} \]
Select Cycle length for Critical intersection

- Arrival Flow
- Departure Flow
- Red Signal
- Green Signal

1 Cycle

Excess Delay caused by longer cycle
Offsets: Issues

Incorporate Queue Clearance time

Reduce wasted Green time

Reduce upstream blocking & consider Lag Left phasing sequence
Phase Sequence & Arterial Progression (1)

Leading Lefts

EB: 20 sec
WB: 8 sec
Phase Sequence & Arterial Progression (2)

Lead-Lag

EB: 20 sec
WB: 20 sec
Optimization Objective Functions

Maximum Bandwidth

- **Efficiency**: Proportion of the cycle length used by the bandwidth

  \[ \text{Efficiency} \% = \frac{\text{Bandwidth}}{2 \times \text{Cycle Length}} \]

- **Attainability**: Proportion of the through green utilized by the bandwidth (\%)

  \[ \text{Attainability} \% = \frac{\text{Bandwidth}}{\text{Min. Artery Through Green}} \]

Minimum Delay and Stops
## Signal Timing Optimization Models

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<th>Objective Function</th>
<th>Control Parameters</th>
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<td>Min Delay &amp; Stops</td>
<td>C, g, O</td>
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<td>Max Bandwidth</td>
<td>C, ps, O</td>
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<tr>
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<td>Min Delay</td>
<td>C, ps, g, O</td>
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Optimization Objective Function:

Maximize \( B = W_1 b_o + W_2 b_i \)

- \( b_o \) = outbound green band
- \( b_i \) = inbound green band
- \( W \) = weighting factors

subject to:

Minimum green times

Assumptions

- No Platoon Dispersion
- Turning Traffic
- Green Times calculated (Webster formula)
TRANSYT-7F Model

TRAffic Network Study Tool

- Macroscopic Deterministic Simulation
- Optimization of Cycle/Splits/Offsets
- Arterials/Grid Networks
- Multiple Vehicle Classes
INPUT
- Traffic volumes
- Saturation flows
- Network Data
- Timing Plan

TRAFFIC MODEL

OUTPUT
- Link/Network Performance
- Flow profiles
- T-S Diagram

SIGNAL OPTIMIZER

Optimization Reached
- Yes
- No

Optimal Timing Plan

Stop
Modeling Traffic Flow--Stopline

Vehicle Trajectory (Slope is inverse of speed)

Effective Green, $G_e$

Projection of traffic flow rates by time increments

Distance Upstream

Distance Downstream

Stop

Flow Rate (Veh/Step)

Time Increments - Steps (4 Sec/Step)
Modeling Traffic Flow — Platoons (1)
Modeling Traffic Flow – Platoons (2)
TRANSYT-7F: Signal Optimization

\[ PI = \sum_{i=1}^{N} W_{Di} D_i + KW_{si} S_i \]

\( D_i \): delay on link \( i \) (veh-hr)

\( S_i \): number of stops on link \( i \) (veh/sec)

\( K \): system-wide "stop penalty": the weight given to number of stops relative to delay.

\( W \): weighting factors (default = 1)
TRANSYT-7F Optimization Process

- Hill Climbing algorithm
- Global Optimum not guaranteed
SYNCHRO Model

- **Capacity Analysis**
  HCM 2000, ICU, Signal/Stops

- **Signal Timing**
  Actuated Signals
  Optimization – *Minimum Delay*
  Coordination

- www.trafficware.com
SYNCHRO Signal Timing Window
SYNCHRO: Time-Space Diagram
Actuated Signals — Basic Signal Settings

- **Minimum Green**
  Time to serve vehicles in the queue (stopline to detector location)
  - 10 s main street through movements

- **Vehicle Extension (Gap/Passage Time)**
  - Advanced Loop Detectors:
    \[ \text{Vehicle extension (s)} = \frac{DS}{1.47 \cdot V} \]
    \[ DS = \text{detection setback (ft)} \]
    \[ V = \text{speed (mph)} \]
  - **Stopbar Detection**: Vehicle extension close to zero

**Maximum Green**
Max green time allowed for the green phase
Maximum green time = 1.5 x Green time (X = 0.95)
Operation of an Actuated Phase (1)

Case 1: Max Green Not Reached (Gap out)

- Phase Starts
- Detector Actuation
- Passage Time
- Minimum Green
- Extension Green
- Total Green Time
- Maximum Green
- Yellow Interval
- Phase Terminates

Detector Actuation on a Conflicting Phase
Operation of an Actuated Phase (2)

Case 2: Max Green Reached (Max out)

- Maximum Green
- Minimum Green
- Extension Green
- Total Green Time

- Phase Starts
- Detector Actuation
- Passage Time
- Detector Actuation on a Conflicting Phase
- Yellow Interval
- Phase Terminates
NEMA/170/2070 (Volume/Density) Controllers

- **Variable Initial**
  Function of vehicle arrivals during yellow & all-red

- **Vehicle Extension (Gap) Reduction**
  Start with high gap time and reduce once traffic is moving

- **Max I/Max II:**
  Different Settings of Max Green
  Time-of-day or Coordinated/Free operation

**Other Controller Functions**

  - Phase skip
  - Recall: min, max, ped
  - Dual/single entry
  - Conditional service
Min and Max Gap
Time Before Reduction
Time to Reduce
Reduce By/Reduce Every

Min gap = 2-3 sec
Max gap = Min (Veh extension, 5 sec)
Time before reduction = 33 % of max green
Time to reduce = 80 % of max green
Coordination of Actuated Signals

- **Cycle Length (sec):** All signals operate on a common fixed cycle. Typically the cycle length for the critical intersection. Usually determined for $X = 0.95$.

- **Split (sec):** The phase green + yellow + all red intervals.

- **Offset or Yield Point (sec):** the difference between a reference point (system zero) and the end (beginning) of the through (sync) phase green interval at the intersection.

- **Force Off (sec):** fixed point in the signal cycle where actuated phases terminate.

- **Permissive Period (sec):** amount of time (in seconds) within the cycle, during which non-coordinated, phases are allowed to be serviced.
Coordinated Actuated Signals: Operation (1)

a. Phase 2 is "Forced-Off," Phase 3 "Gaps-Out"

- $F_2$ = Phase 2 Ends At The Force-Off Point
- $A$ = Phase 3 Ends Before Force-Off, $F_3$.
- Position Of Point $A$ Depends On Vehicle Headways And Extension Interval (Gap).
- $BF_3$ = Spare Green Time Available To The Sync Phase.

b. Phase 2 "Gaps-Out," Phase 3 "Maxes-Out"

- $B$ = Phase 2 Ends Before Force-off, $F_2$
- $C$ = Phase 3 ends, sync phase starts.
- Position of point $C$ depends on the max green $G_{max}$ for Phase 3.
- $DF_3$ = Spare Green Time Available To The Sync Phase
"Early Return"
To Green Problem
Traffic Flow Variability vs. Control

A
- Fixed-Time Plans
- Time of Day (TOD)
- No Detection
- May be actuated

B
- Fixed time plans
- Traffic responsive plan selection
- System detection

C
- Traffic responsive control
- On-line timing development
- Approach & system detection

D
- Adaptive control
- Measure & predict arrivals per cycle
- Extensive detection
Overview: Traffic Control Strategies

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http://www.signalsystems.org.vt.edu/documents.html
SCOOT: Split Cycle Offset Optimization Technique

Flow

Phases

Demand Profiles

Queues

Split & Offset Optimizer

Current SCOOT Timings

Translation Array

Preferences & Observations

Close Settings

Weights & Bias

All Possible Settings

Traffic Engineer

Cycle Optimiser
Stopline Detection

Network subdivided into Regions
Each region has homogenous flow characteristics
Each region subdivided into links and nodes
Calculate degree of saturation (DS) for all nodes

DS = [green-(unused green)]/green
LADOT’S ATCS
Adaptive Traffic Control System (1)

- Adjust signal timing on a cycle-by-cycle basis:
  - Cycle Length
  - Splits (Critical Intersection Control)
  - Offset (Critical Link Control)

- Data:
  - Detectors located 200-300 ft upstream of the stopline
  - Volume & occupancy data collected every second
  - Data smoothed and used every cycle

- Constraints:
  - Phase sequence is fixed
  - Minimum green times
LADOT ATCS (2)

Intersection Display

Cycle Length
Adaptive Control: Rolling Horizon

Stage 1:
- Projection Horizon
- Head
- Tail

Stage 2:
- Roll Period
- Projection Horizon
- Head
- Tail

Stage 3:
- Roll Period
- Projection Horizon
- Head
- Tail
OPAC/ RHODES
Adaptive Control: No Fixed Cycle

- Measured and Predicted Vehicle Arrivals
- Optimization: Min Queues
- Rolling Horizon

- Upstream detectors can provide an actual history for a short portion of the profile
- Smoothed volume can be used for uniform profiles
- Platoon identification and smoothing can be used for cyclic profiles