Traffic Engineering (CIV-349)

Design and evaluation of pretimed traffic signals

Nikolas Geroliminis

nikolas.geroliminis@epfl.ch

EPFL

ENAC School of Architecture, Civil and Environmental Engineering

Intersection Design

- Main Objectives:
  - Minimize potential conflicts among different traffic streams (e.g., vehicles of all modes and pedestrians)
  - Provide smooth flow of traffic across the intersection
- The design should incorporate the operating characteristics of both the vehicles and pedestrians using the intersection.

Design Considerations

- Human
  - Driving habits, decision/reaction time
- Traffic
  - Demand, capacities, turning movements, delay, vehicle speeds, size and types of vehicles
- Physical
  - Adjacent property, sight distance, geometric features, control devices, environmental factors, etc…
- Economic
  - Cost, benefits, energy consumption

Traffic Signal Devices

- One of the most important and effective methods of controlling traffic at an intersection
- Electrically time device that assigns the right-of-way to one or more traffic streams so that these streams can pass through the intersection safely and efficiently
- Suitable for:
  - Excessive delays at stop signs and yield signs
  - Problems caused by turning movements
  - Angle and side collision
  - Pedestrian accidents

History of Traffic Signal Devices

- First traffic signal (1868): London
- First electric signal in the US (1914): Cleveland, Ohio
- First interconnected system of 6 signals (1917): Salt Lake City (manually controlled from a single site)
- First automated electric timer controlled from a central traffic tower (1922): Houston, Texas
- First progressive, pretimed system (1928)
- First actuated controller using pressure detectors (late 20's)
- First analog computer system (1952): Denver, Colorado
- Pilot study using digital computers (1963)
- Urban Traffic Control System (UTCS) Project (1967): Washington, D.C.

Purpose of Traffic Signals

- Improve overall safety
- Decrease average travel time through an intersection, hence increase capacity
- Equalize the quality of services for all or most traffic streams
- Factors to considered: justification must be made based on traffic flow, pedestrian safety, accident experience, and the elimination of traffic conflicts

Advantages of Traffic Signals

- Provide orderly movement of traffic
- Flexibility, allocation of right-of-way responding to changes in traffic flow
- Ability to assign priority treatment to some movements or vehicles
- Feasibility of coordinated control along streets or in area networks
- Provision of continuous flow of a platoon of traffic at a desired speed along a given route by coordination

Disadvantages of Traffic Signals

- May increase total intersection delay and fuel consumption (off-peak period)
- Probable increase in certain types of accidents (rear-end collisions)
- Improperly timed, cause excessive delay, increase driver irritation

Type of Left-Turns

- **Permitted left turns**
  - Vehicles are permitted to make a left turn by selecting an appropriate gap in the opposing traffic stream through which to turn.
- **Protected left turns**
  - Vehicles are protected to make a left turn by prohibiting the opposing traffic
  - Need separate signal phases for left turn

http://www.youtube.com/watch?v=7gCZocOu0EQ&feature=related

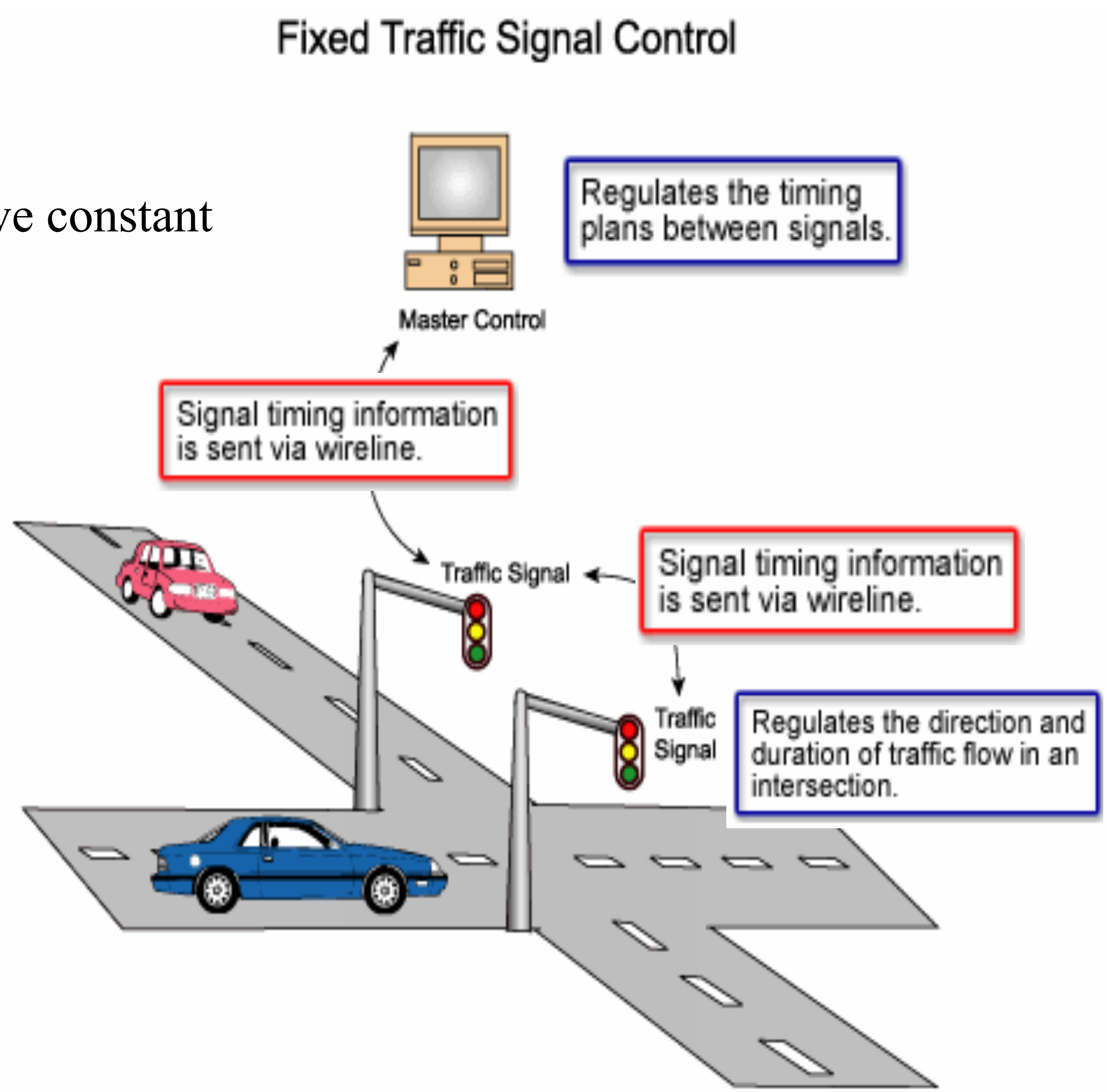
Types of Traffic Signals

- **Pretimed:** Repeat a preset constant cycle.
- **Actuated**:
  - Respond to the presence of vehicles and pedestrians
  - Need to use in conjunction with vehicle detectors
  - **Semi-actuated**
    - Detectors placed only on the minor approach
    - Major approach is interrupted only if vehicle present at the minor approach
  - **Fully actuated**
    - Detectors are installed at all approaches
    - Green time are allocated based on the incoming traffic on each approach

Pre-Timed Control

Pre-timed operations have constant

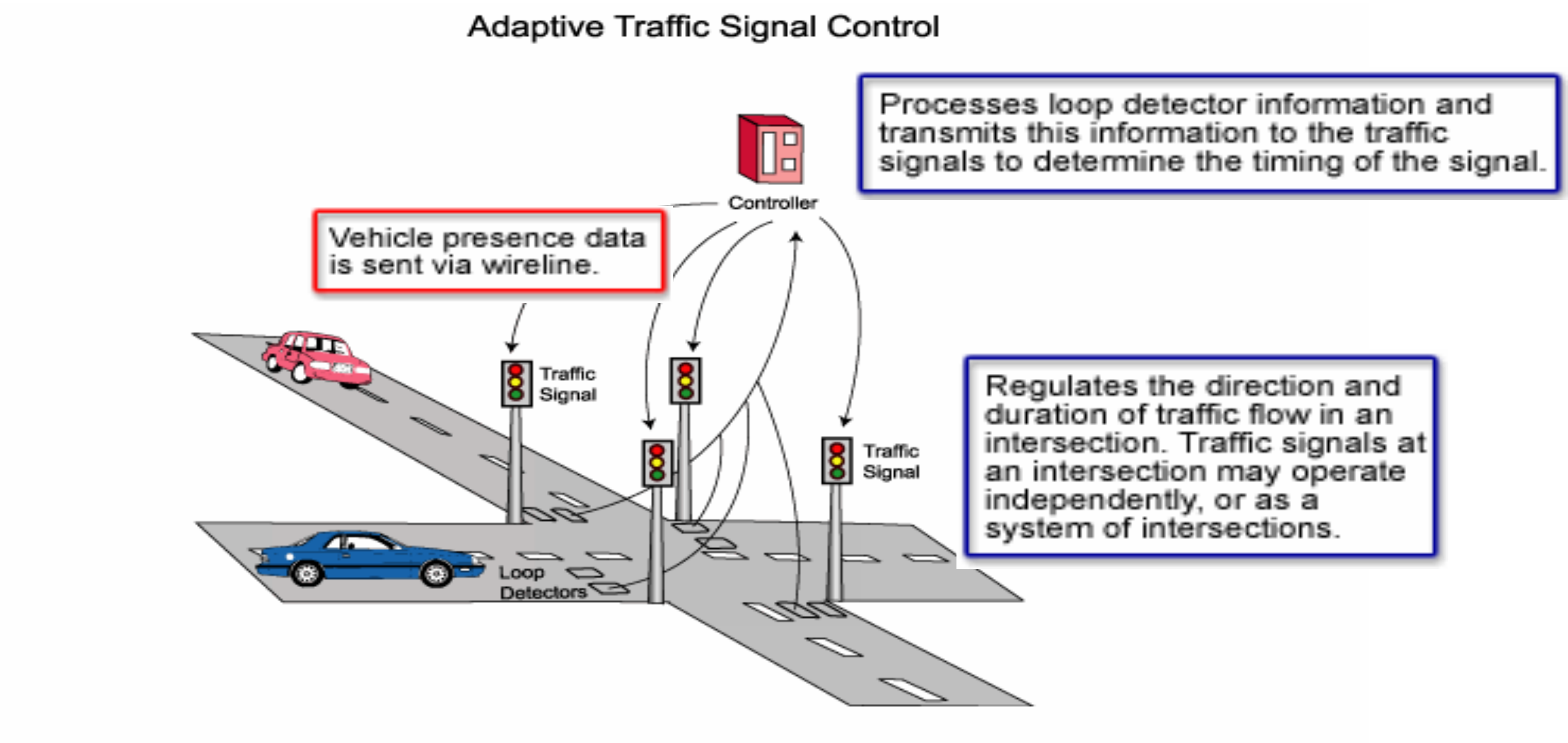
- Cycle length
- Phase sequence
- Green time
- Change interval



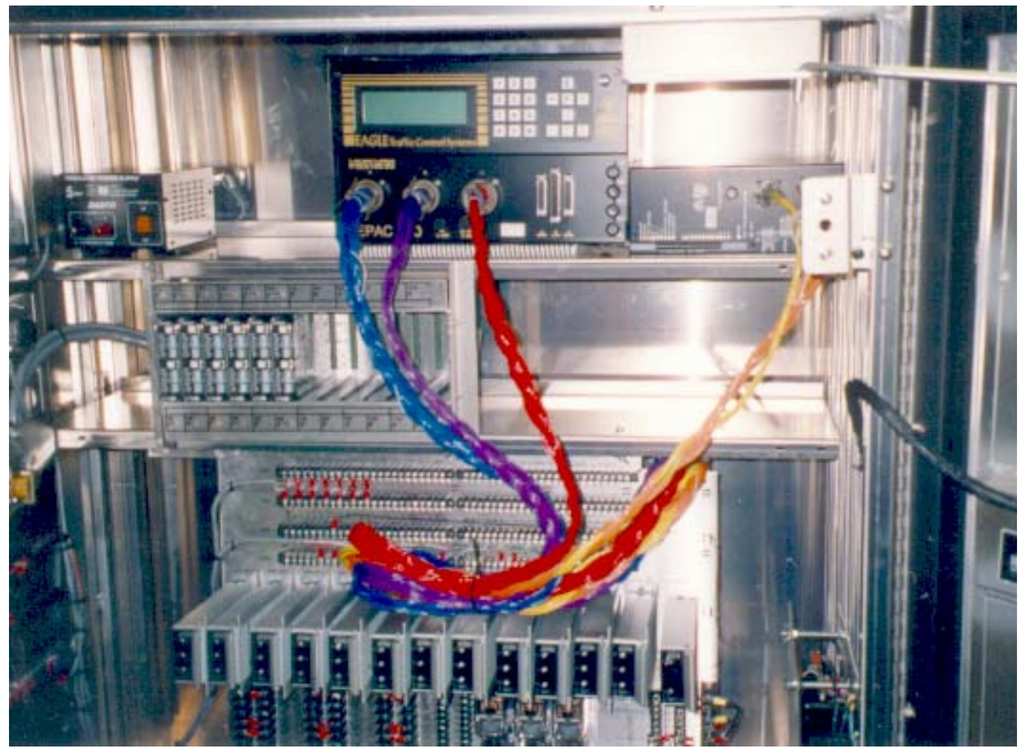
Adaptive Control

Using vehicle detectors & actuated controller, signal can have

- Variable cycle length
- Variable number and phase sequence
- Variable phase lengths



NEMA Controller



Signal Timing Procedure (Steps)

1. Determine “Phasing”
2. Establish analysis lane group
3. Choose “Critical Lane Volumes”
4. Calculate Cycle Length
5. Determine Yellow & Clearance Intervals
6. Proportion Green Time
7. Check Pedestrian Crossing Time
8. Prepare Signal Indication Diagram

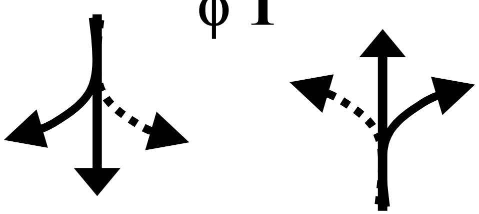
Signal Phasing and the Development of Phase Plans

- Phasing may minimize hazard risks by separating movements, but would often increase delay.
- However, they are situations where the increased number of phases results in lower overall delay (e.g., exclusive LT phase)
- Signal phases must be implemented with appropriate marking and lane assignments
- The plan must be consistent with the intersection geometry, lane-use assignments, volumes and speeds, and pedestrian crossing requirements.

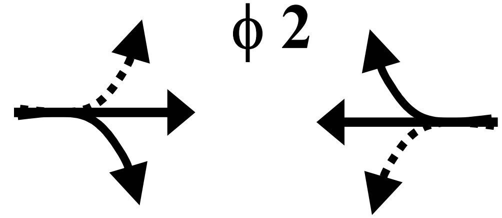
Step 1: Determine phase to use

- Minimum # of phases (two):

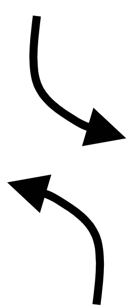
ϕ 1



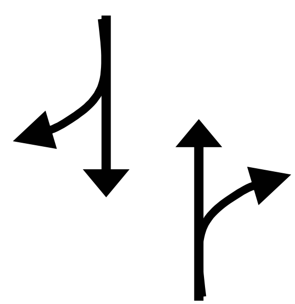
ϕ 2



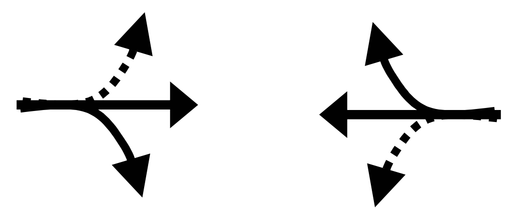
- Three phases:



ϕ 1



ϕ 2

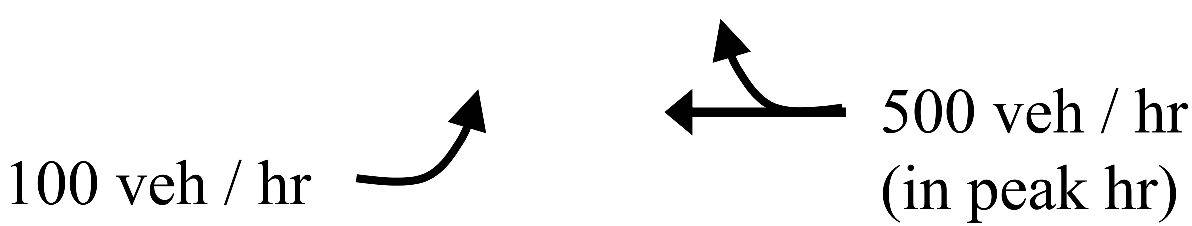


ϕ 3

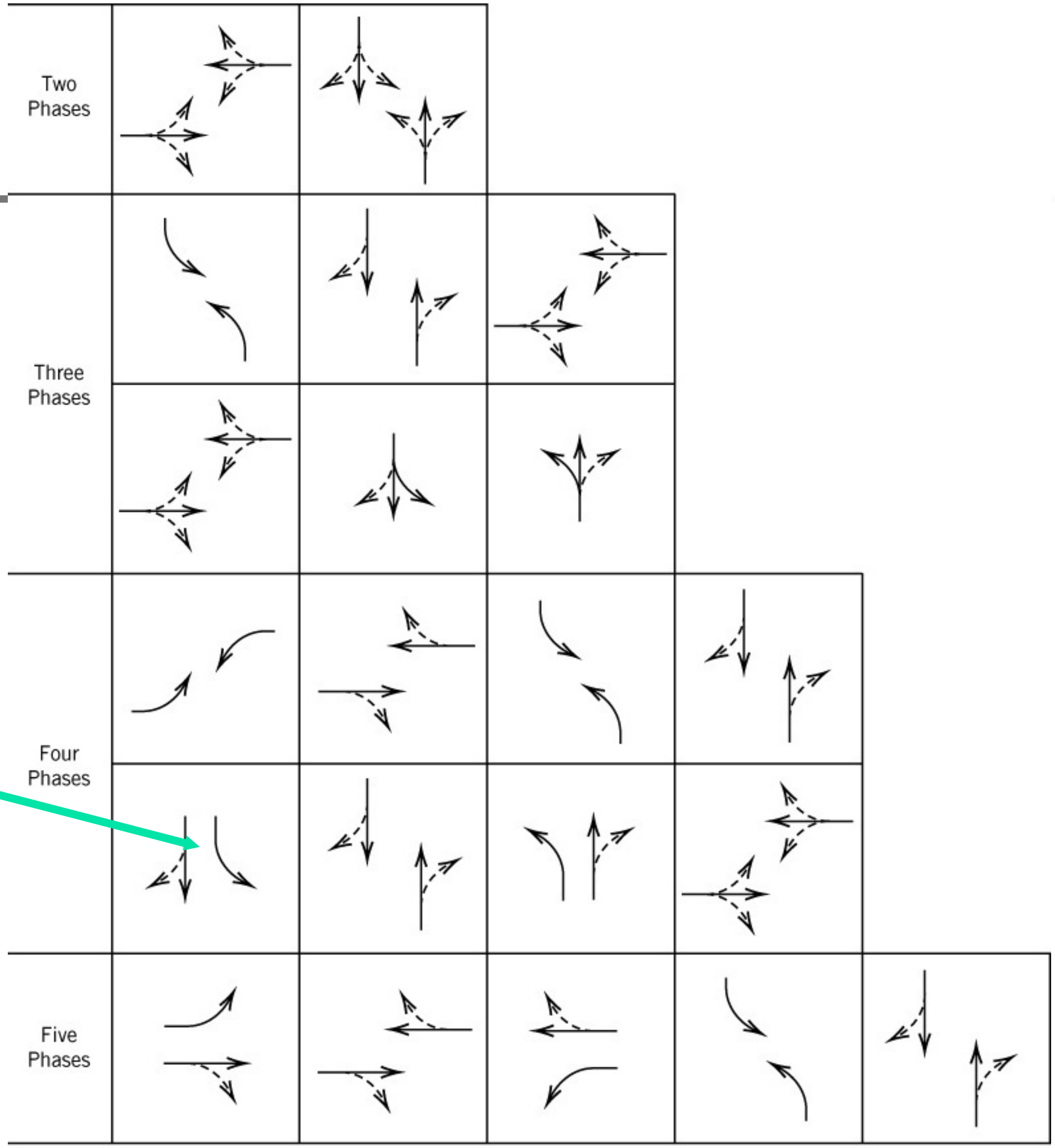
Step 1: Determine phasing to use (cont.)

Left Turn protected phase should be considered if any of the following criteria is met:

1. More than one turning lane is provided;
2. The left turn has a demand over 240veh/h;
3. The cross product of left turn demand and opposing through demand for 1 hour exceeds 50,000 for one opposing lane, 90,000 for two opposing through lanes, or 110,000 for three or more



Signal phase sequences



Leading left turns

Step 2: Establish Analysis Lane Groups

- The methodology for signalized intersections is disaggregate; that is, it is designed to consider individual intersection approaches and individual lane groups within approaches.
- Segmenting the intersection into lane groups is a relatively simple process that considers both the geometry of the intersection and the distribution of traffic movements. In general, the smallest number of lane groups is used that adequately describes the operation of the intersection.

Lane Grouping

Lane groups:

1. Movements from the same lane as one lane group
2. Exclusive turn lane (s) treated as separate lane group.
3. Judgment for shared movement lane (S)

Number of lanes	Movements by lane	Number of possible lane groups
1	LT + TH + RT	1 (Single-lane approach)
2	EXC LT TH + RT	2
2	LT + TH TH + RT	1 or 2
3	EXC LT TH TH + RT	2 or 3

Step 3: determine critical lane groups

- For any combination of lane group movements during a particular phase, one of these lane groups will control the necessary green time. This lane group is referred as “ critical lane group”.
- The lane group with highest traffic intensity v/s
- Allocation of green time for each phase is based on the v/s ratios

Sum of critical v/s and total lost time

$$Y_c = \sum_{i=1}^{n} \left(\frac{v}{s}\right)_{ci}$$

where

Y_c = sum of flow ratios for critical lane groups,
$(v/s)_{ci}$ = flow ratio for critical lane group i, and
n = number of critical lane groups.

$$L = \sum_{i=1}^{n} (t_L)_{ci}$$

where

L = total lost time for cycle in seconds,
$(t_L)_{ci}$ = total lost time for critical lane group i in seconds, and
n = number of critical lane groups.

Discharge Headways and Loss Times

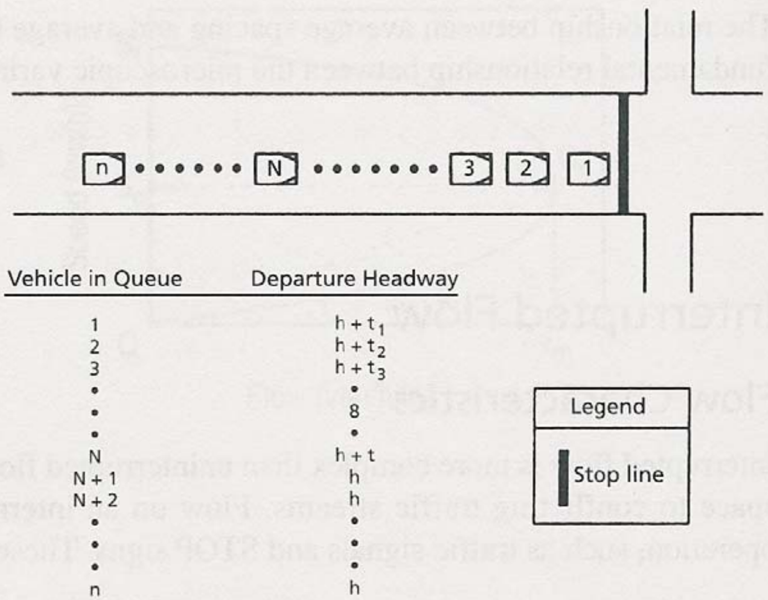


Figure 4–3 Conditions of Traffic Interruption in an Approach Lane of a Signalized Intersection

Source: Transportation Research Board, *Highway Capacity Manual*, Special Report 209, Washington, D.C.: TRB, National Research Council, 1994 (revised 1997).

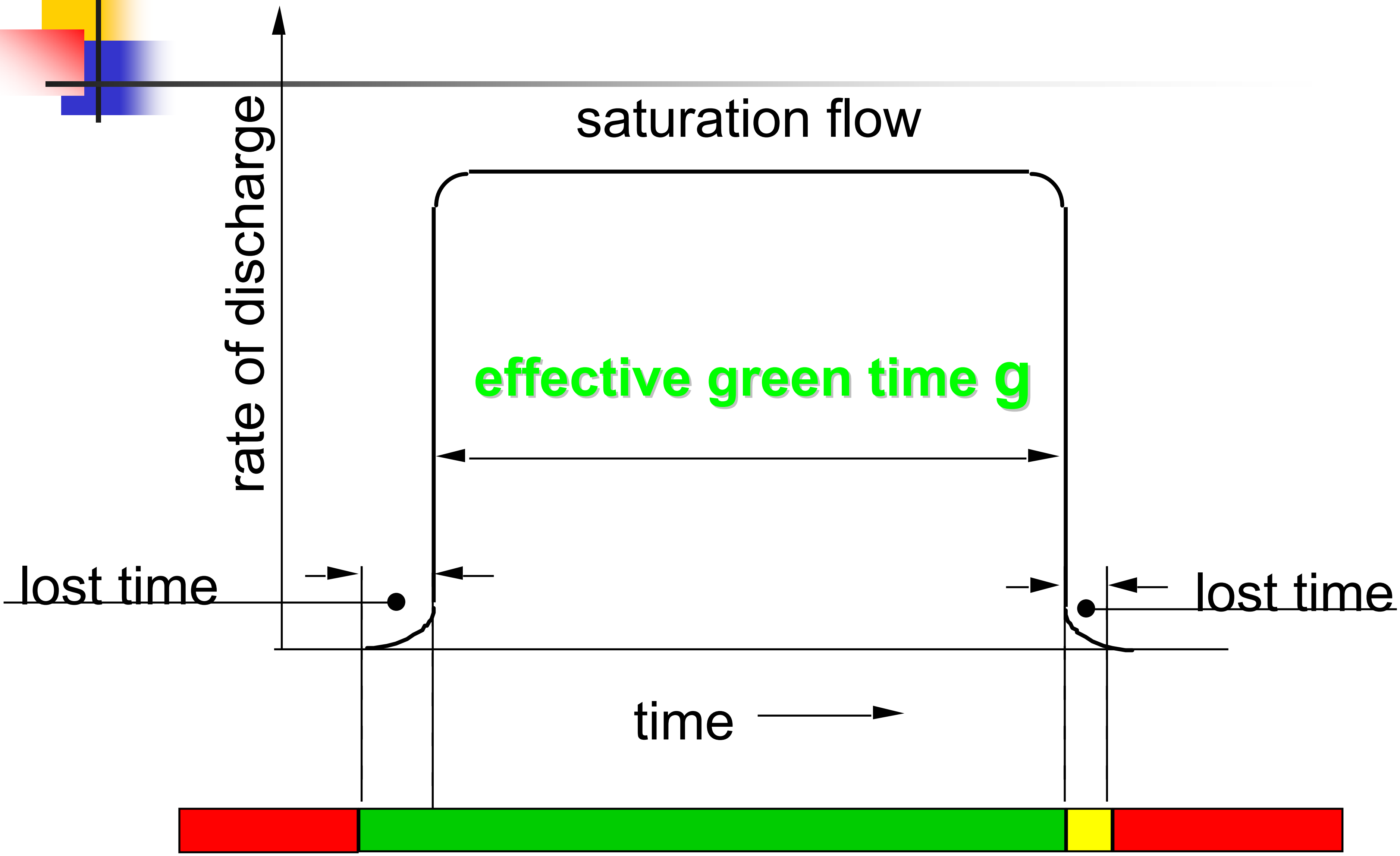
TABLE 20-1 Computations related to Figure 20-1

Queue Position	*Observed Avg. Headway (sec)*	*Estimated Headway ([a])*	*Difference, Observed Minus Actual (sec)*
1	2.61	2.14	0.47
2	3.00	2.14	0.86
3	2.52	2.14	0.38
4	2.37	2.14	0.23
5	2.21	2.14	0.07
> 5	2.14	2.14	0.00
		Start-up lost time =	2.10 sec

[a] Based upon value for queue positions greater than five.

$$l_1 = \sum e(i) = \sum (h_i - h)$$

Effective Green



Minimal Necessary Cycle Length

$$C_{\min} = \frac{L * X_c}{X_c - \sum_{i=1}^{n} Yi}$$

Xc = critical v/c ratio

$$C \cdot q_i \leq s_i \cdot g_i \qquad \Rightarrow \qquad C \cdot \frac{q_i}{s_i} = C \cdot y_i \leq g_i$$

$$C = L + \sum g_i$$

$$C - L \geq C \cdot Y$$

$$C_{\min} = \frac{L}{1 - Y}$$

Step 4: Calculate Cycle Length

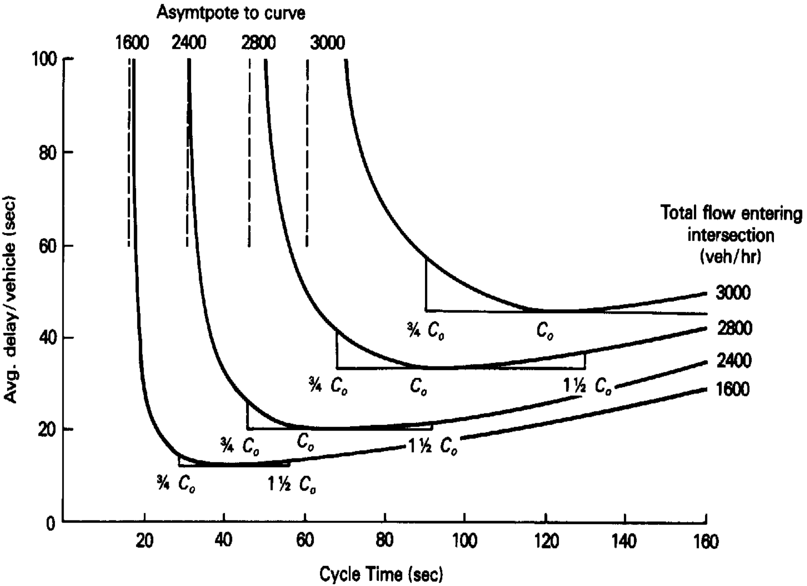
Webster's Delay Formula:

$$C = \left[(1.5 * \mathrm{L}) + 5\right] \; / \; \left(1.0 - \sum_{i=1}^{n} \mathrm{Yi}\right)$$

C = cycle length (optimal)
(round-up to nearest 5 sec. int.)

L = Lost Time / Cycle {seconds}
= sum total yellow + sum all red

$$\mathrm{Yi} = \frac{\Sigma \text{ critical lane volume } \{\text{vph}\}}{\text{saturation flow } \{\text{vph}\}}$$


Asymtpote to curve
1600
2400
2800
3000
100
80
60
40
20
0
Avg. delay/vehicle (sec)
20
40
60
80
100
120
140
160
Cycle Time (sec)
Total flow entering intersection (veh/hr)
3000
2800
2400
1600
¾ C_o
C_o
1½ C_o

Step #5: Allocate Green Time

- Distribute green time such that the v/c ratios are equalized for the critical lane groups

$$X_i = \frac{v_i}{c_i} = \frac{v_i}{s_i * g_i / C} = \frac{v_i / s_i}{g_i / C}$$

$$Equalize\ X_i = X_c$$

$$g_i = (v_i / s_i) * (C / X_c)$$

$$\sum g_i = \sum (v_i / s_i) * (C / X_c) = C - L$$

$$X_c = \sum (v_i / s_i) * \frac{C}{C - L}$$

g_i : effective green for phase i

v_i / s_i : flow ratio for phase i from the critical lane group

C : cycle length

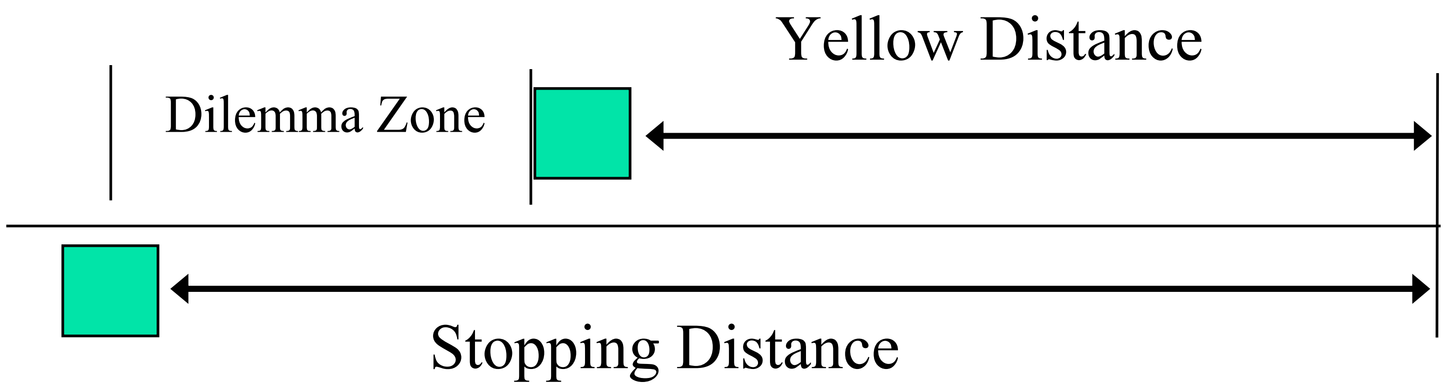
c_i : capacity for phase i

X_c : degree of saturation for the intersection

X_i : v/c ratio (degree of saturation) for phase i

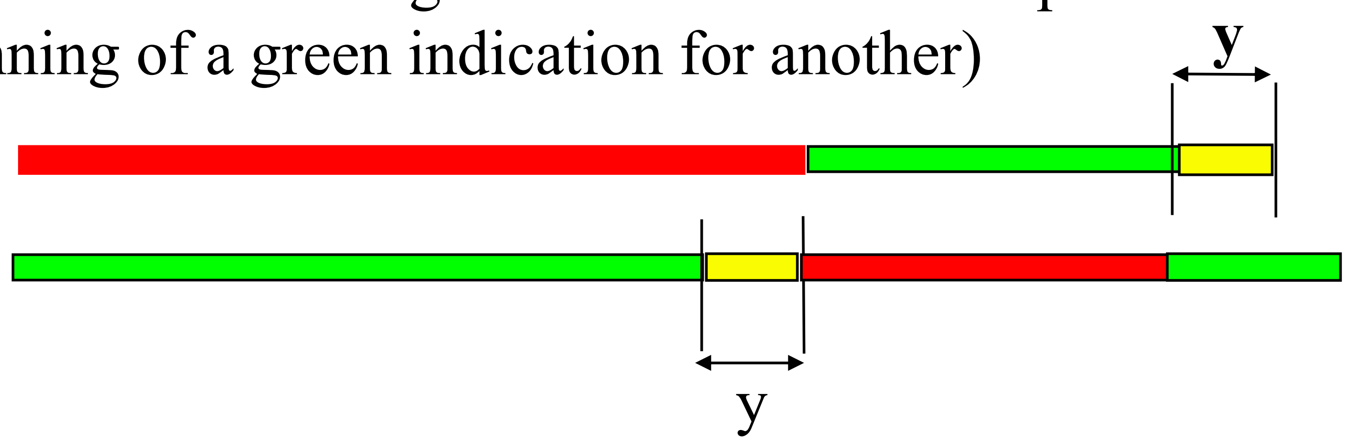
Step 6: Determine Yellow and Clearance Intervals

- "Dilemma Zone" -- driver can neither stop safely nor clear the intersection before the cross street green phase starts!

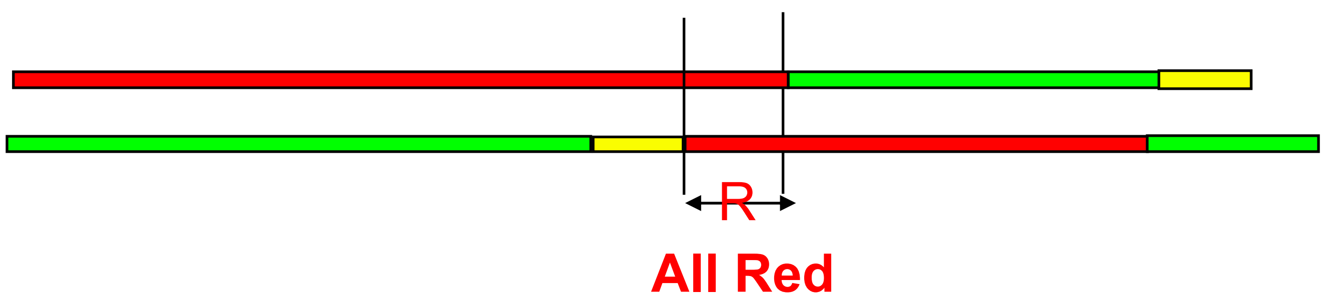


Change and Clearance Intervals

- **Change interval**: identical to the intergreen interval (the time between the end of a green indication for one phase and the beginning of a green indication for another)



- **Clearance interval**: identical to the all-red interval (the display time of a red indication for all approaches)



Determine Yellow & Clearance Intervals

Yellow Time (ITE):

$$y = T + \left(\frac{v}{2a + 2Gg} \right)$$

T = the driver perception / reaction time (1.0 sec)
v = speed of the vehicle in m / s
a = deceleration rate for the vehicle ($3m / s^2$)
G = the percent grade divided by 100
g = acceleration due to gravity ($10m / s^2$)

Determine Yellow & Clearance Intervals

All-Red time:

$$AR = \frac{w + l}{v}$$

AR = the all-red time

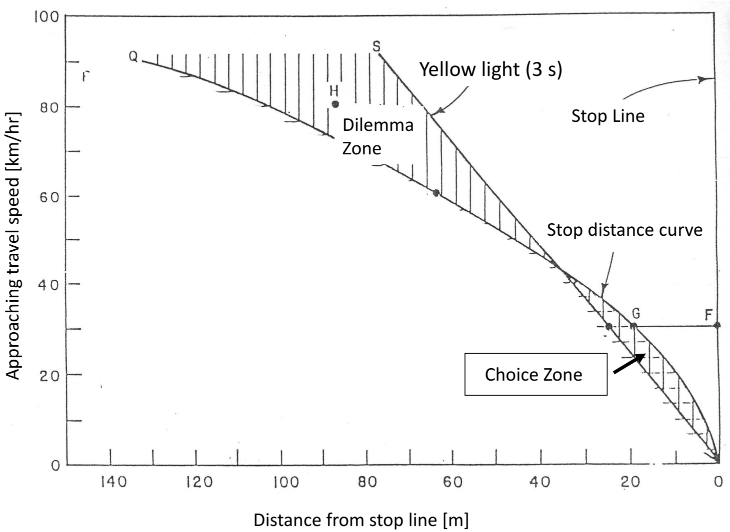
w = the width of the cross street

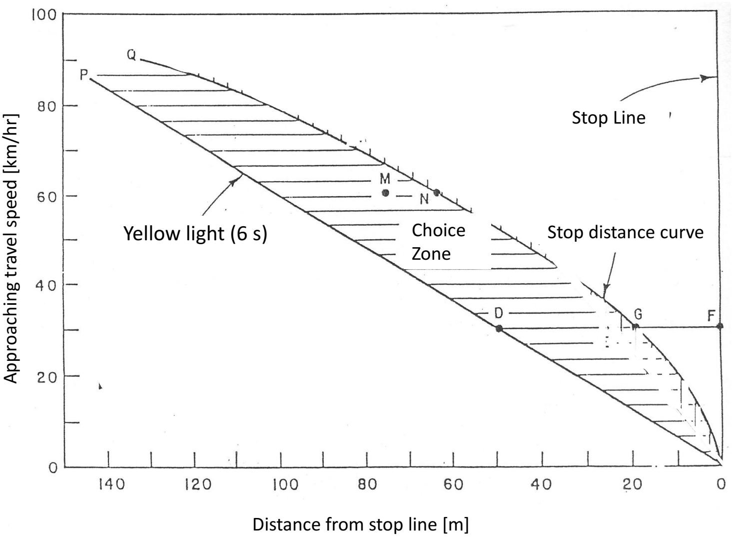
l = effective length of the vehicle

Determine Yellow & Clearance Intervals

- Yellow time: Minimum = 3 sec
  Maximum = 5 sec
  - 3 sec => 16 to 56 k/h
  - 4 sec => 56 to 80 k/h
  - 5 sec => greater than 80 k/h
- If more than 5 sec of yellow is needed => All red must be increased to 2 sec

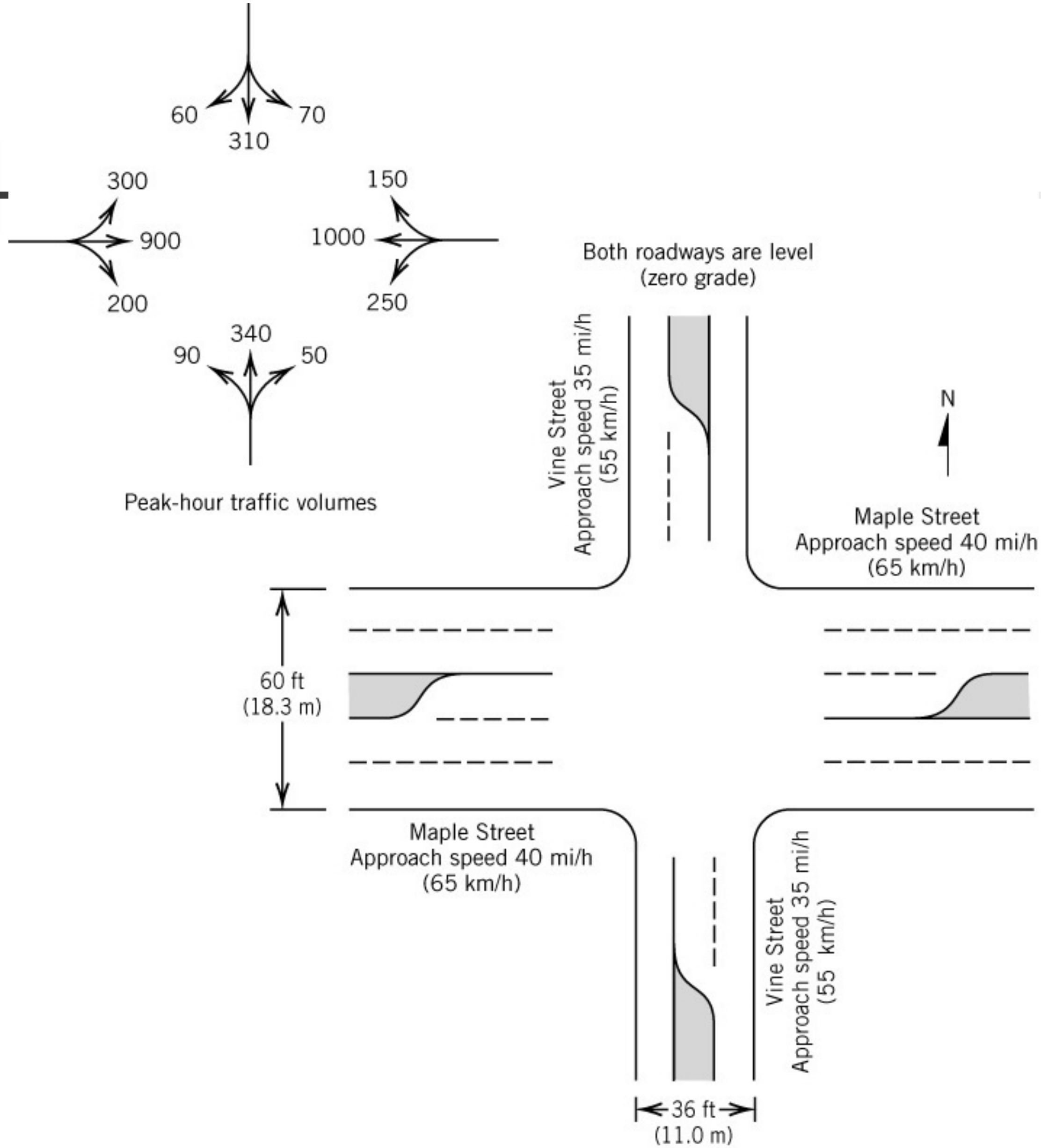
Dilemma zones





Approaching travel speed [km/hr]
100
80
60
40
20
0
140
120
100
80
60
40
20
0
Distance from stop line [m]
Q
P
M
N
D
G
F
Stop Line
Yellow light (6 s)
Choice Zone
Stop distance curve

Signal Timing Example

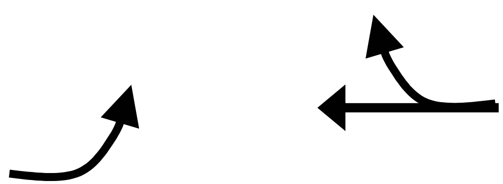


Traffic Signal Timing Example

1. Determine phasing for signal:

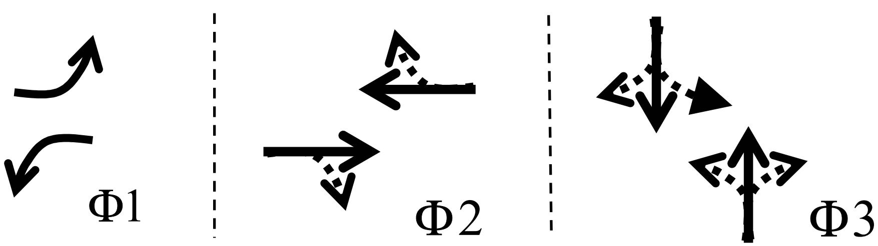
- Eastbound left = 300 veh
  Westbound thru + rt = 1150 veh
- North-South approach volumes are greater than 90,000

300 veh / hr

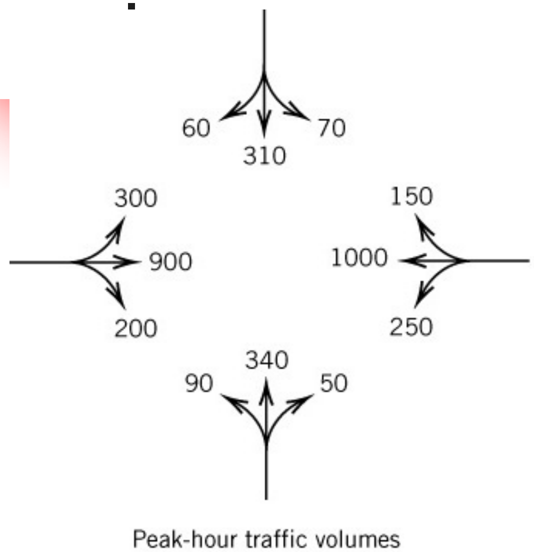


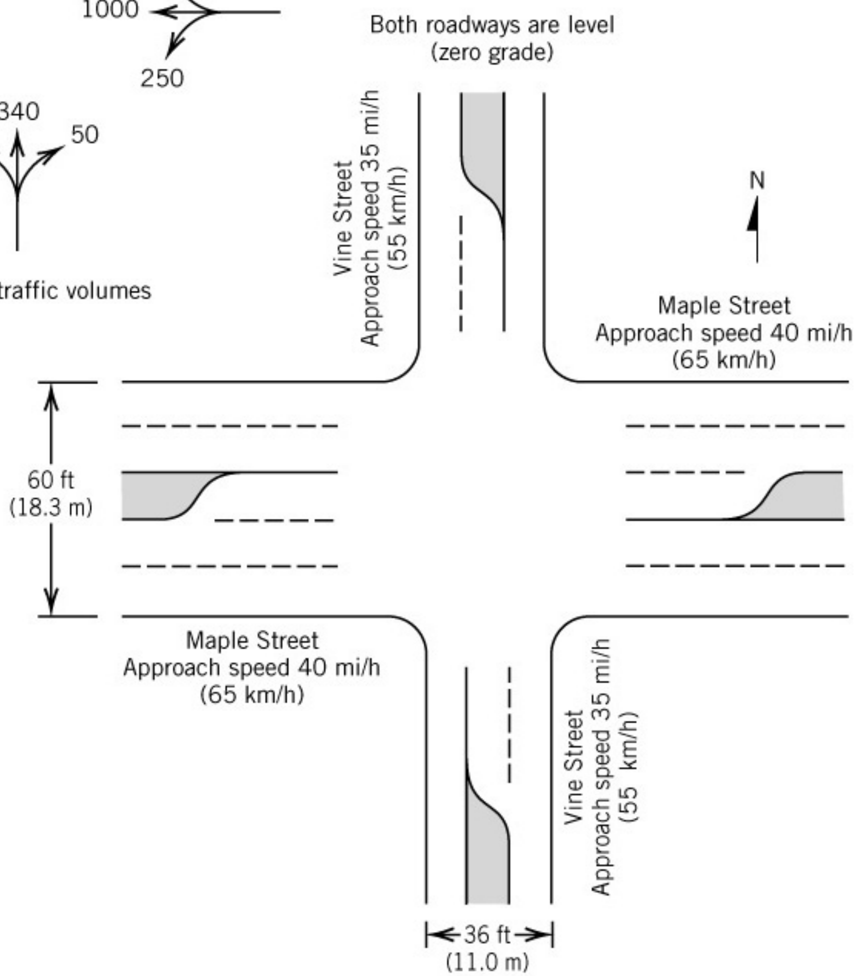
1150 veh / hr
(in peak hr)

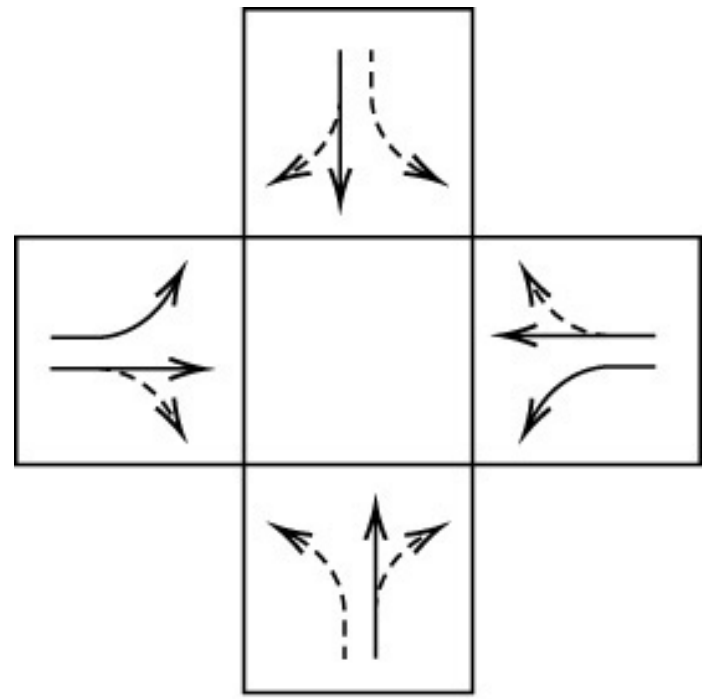
Therefore, left turn phase is suggested.



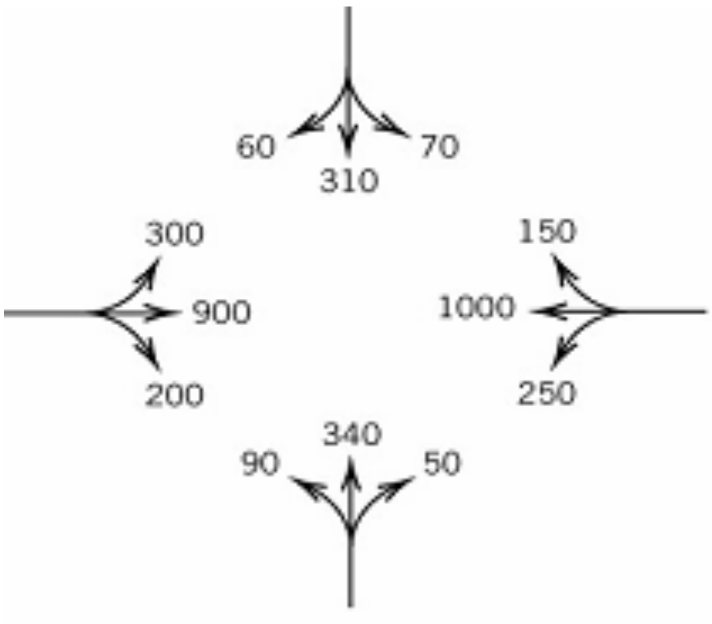
Step #2: determine lane groups



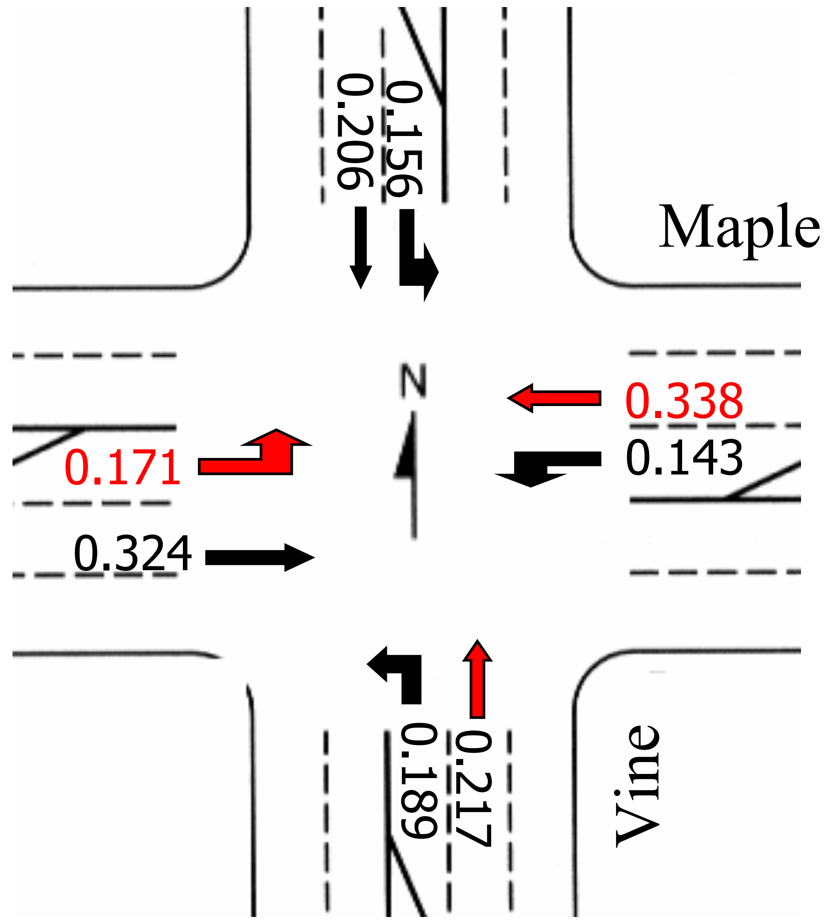




Step #3: Critical Lane Group v/s ratio



Peak-hour traffic volumes



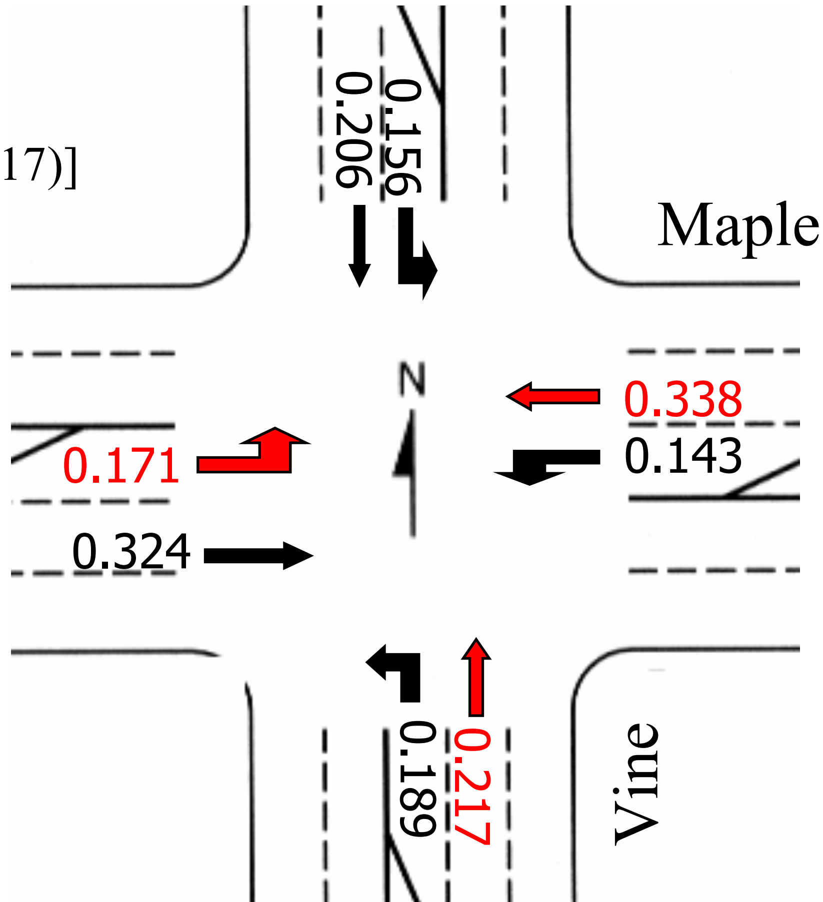
Step #4: Cycle Length

$$C_{opt} = \left[(1.5 * \mathrm{L}) + 5\right] \Big/ \left(1.0 - \sum_{i=1}^{n} \mathrm{Xi}\right)$$

$$= [1.5 * 4 * 3 + 5]/[1.0 - (0.171 + 0.338 + 0.217)]$$

$$= 83.9$$

$$-> 85 \sec onds$$



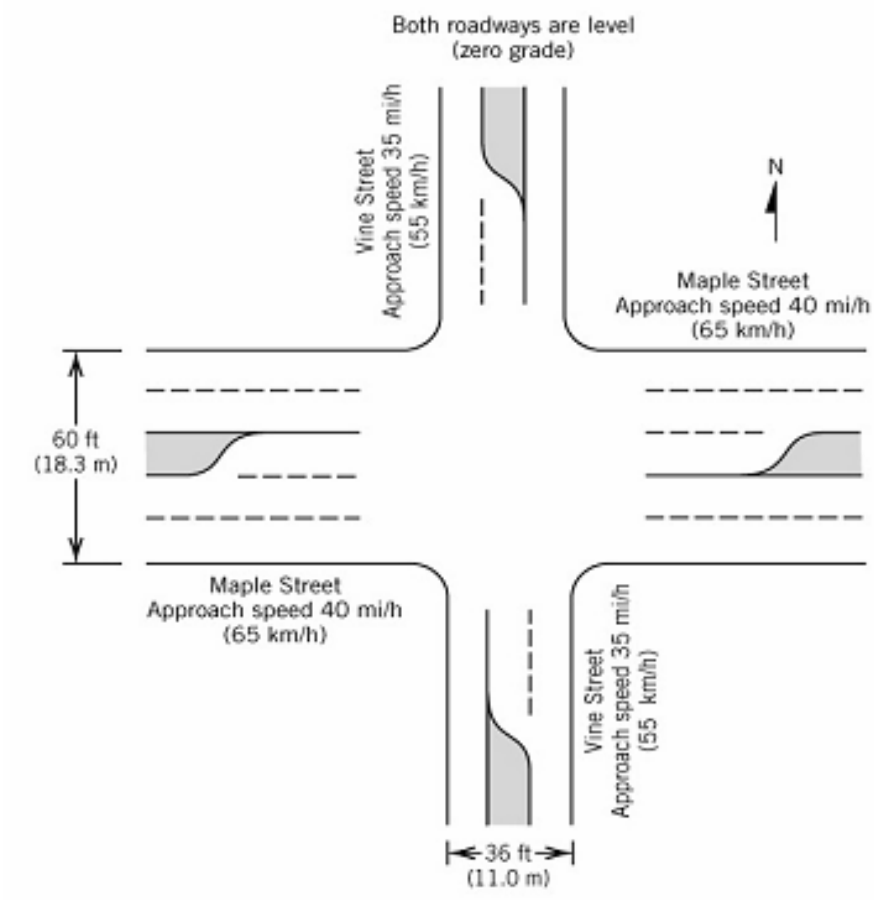
Step #5: Allocate Green Time

- C= 85-second cycle length

$$X_c = \sum (v_i / s_i) * \frac{C}{C-L}$$
$$= (0.171 + 0.338 + 0.217) * 85 / (85 - 4 * 3)$$
$$= 0.845$$

$$g_i = (v_i / s_i) * (C / X_c)$$
$$g_1 = 0.171 * 85 / 0.845 = 17.2s -> 17$$
$$g_2 = 0.338 * 85 / 0.845 = 34s -> 34$$
$$g_3 = 0.217 * 85 / 0.845 = 21.8s -> 22$$
$$g_1 + g_2 + g_3 = 73 = C - L$$

Step #6: Clearance Time Example



Maple Street:

$$y = T + \left(\frac{v}{2a + 2Gg} \right)$$

$$y = 1.0 + \left(\frac{40 * 5280 / 3600}{2 * 10} \right)$$

$$\boxed{y = 3.9 \Rightarrow 4.0\text{sec}}$$

$$AR = \frac{w + l}{v}$$

$$\boxed{AR = \frac{36 + 20}{40 * 5280 / 3600} = 1.0\text{sec}}$$

Step#6 (cont.)

- **<u>Vine Street</u>**

$$y = T + \left(\frac{v}{2a + 2Gg} \right)$$

$$y = 1.0 + \left(\frac{35 * 5280/3600}{2(10)} \right)$$

y = 3.6 say

$$\boxed{\mathbf{Y = 4.0\ sec}}$$

$$AR = \frac{w + l}{v}$$

$$AR = \frac{60 + 20}{35 * 5280/3600}$$

y = 1.6 say

$$\boxed{\mathbf{AR = 2.0\ sec}}$$

Yellow and All Red Time (summary):

	Vine	Maple (Lt)	Maple	
Yellow	4	4	4	
All Red	2	1	1	
	6	5	5	= 16 sec

Step #7: Pedestrian Requirements

- Safety dictates some minimum assured crossing times for pedestrians. This in turn impacts vehicular traffic
- Required time:

  G_p = (4 to 7 sec) + (distance/4.0)

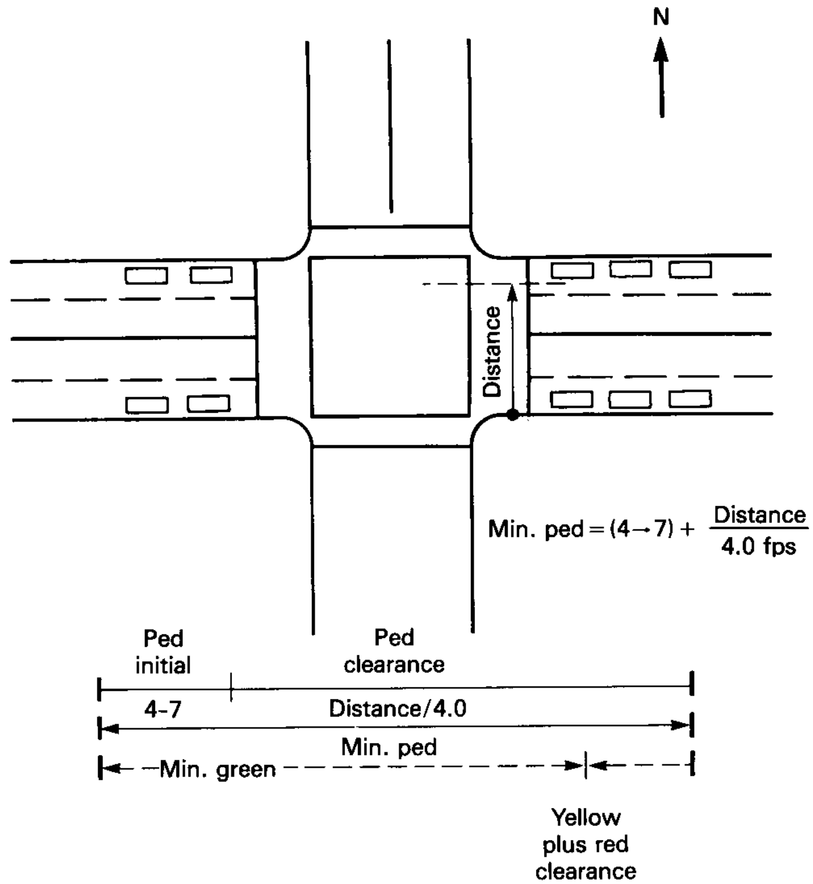


FIGURE 20-19 Measurement of distance for G_p computation.

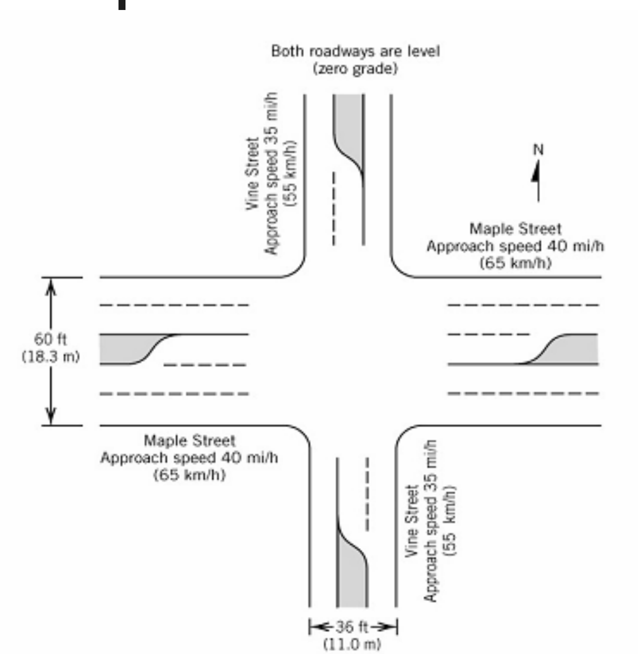
Impact upon Vehicular Traffic

- Alternatively, the minimum green for the movement(s) moving in the same direction as the pedestrian is:

$$G_{\min} + (Y + AR) = G_p \qquad G_{\min} = G_P - (Y + AR)$$

- As the traffic increases, normally, vehicular demand requires a larger minimum cycle length. In low traffic demand, pedestrian traffic dictates the min cycle length

Step #7: Check Pedestrian Time



Assume N_{ped} =15.

Maple

$$Ped\ \mathrm{Grn} = 3.2 + \left(\frac{36}{4.0}\right) + 0.27 * 15 = 16\,\mathrm{sec}$$

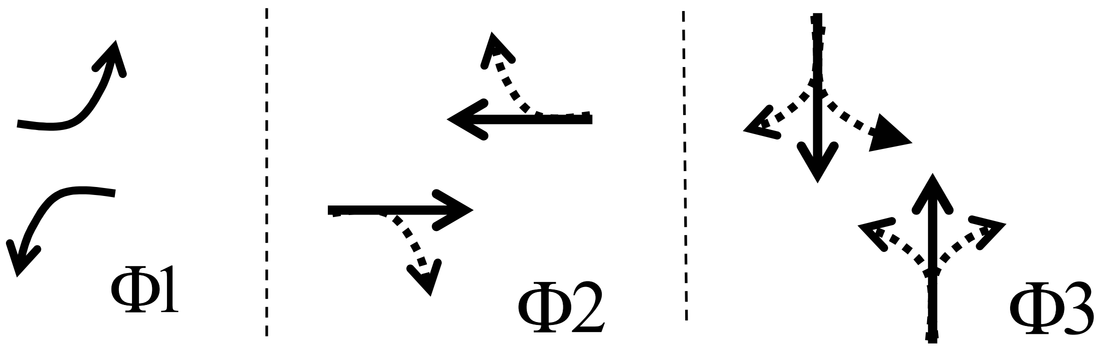
Φ2: 34 sec of Green is OK

Vine

$$Ped\ \mathrm{Grn} = 3.2 + \left(\frac{60}{4.0}\right) + 0.27 * 15 = 22\ \mathrm{sec}$$

Φ3: 22 sec of Green is OK

Step 8: Signal Timing



Green Display = Effective Green + lost time – Y - AR

Φ1: G = 17 + 4 – 4 – 1 =16, Y=4, AR=1
Φ2: G = 34 + 4 – 4 – 1 =33, Y=4, AR=1
Φ3: G = 22 + 4 – 4 – 2 =20, Y=4, AR=2
C = 85 s

Signalized Intersection Level of Service

Introduction

- Level of service (LOS) is a qualitative assessment of facility operations based upon a quantitative performance measure.
- The performance measure that is used to assess level of service for signalized intersections is average control delay per vehicle.

Introduction

- Analysis Procedure (assuming phasing, cycle length, and effective green times have already been determined)
  - Calculate Capacities
  - Calculate Delay
  - Determine Level of Service (LOS)

Calculate Lane Group Capacities

- Capacity is determined on a lane group basis

$$c = s \times g/C$$

Where:

s = adjusted saturation flow rate
g/C = eff. green to cycle length ratio

Uniform Delay

- Delay models when demand is less than capacity

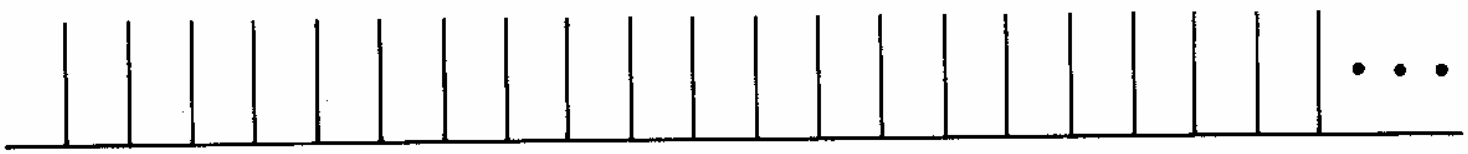
$$UD = \frac{C[1-(g/C)]^2}{2[1-(v/s)]}$$ Average UD

$$X = v/c = \frac{v/s}{g/C}$$ volume-to-capacity ratio or Degree of saturation <= 0.85

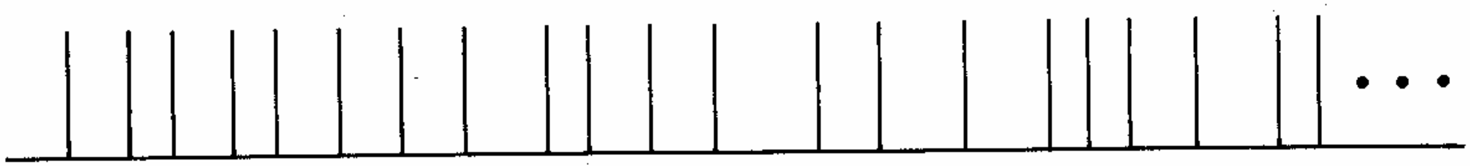
$$UD = \frac{1}{2}C\frac{[1-g/c]^2}{[1-v/s]} = \frac{1}{2}C\frac{[1-g/C]^2}{[1-(v/c)(g/C)]} = \frac{0.5C[1-g/c]^2}{1-(g/C)X}$$

UD is derived from D/D/1 queuing regime

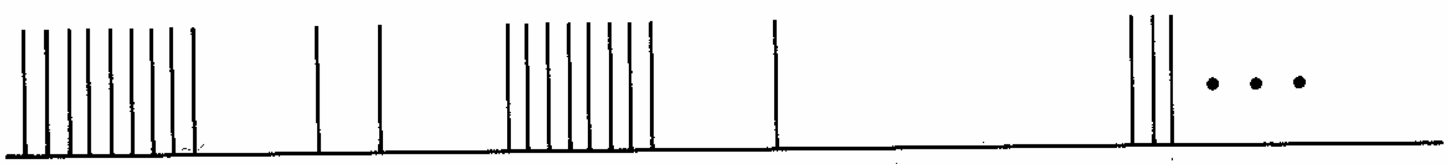
Insights into Webster's Equation



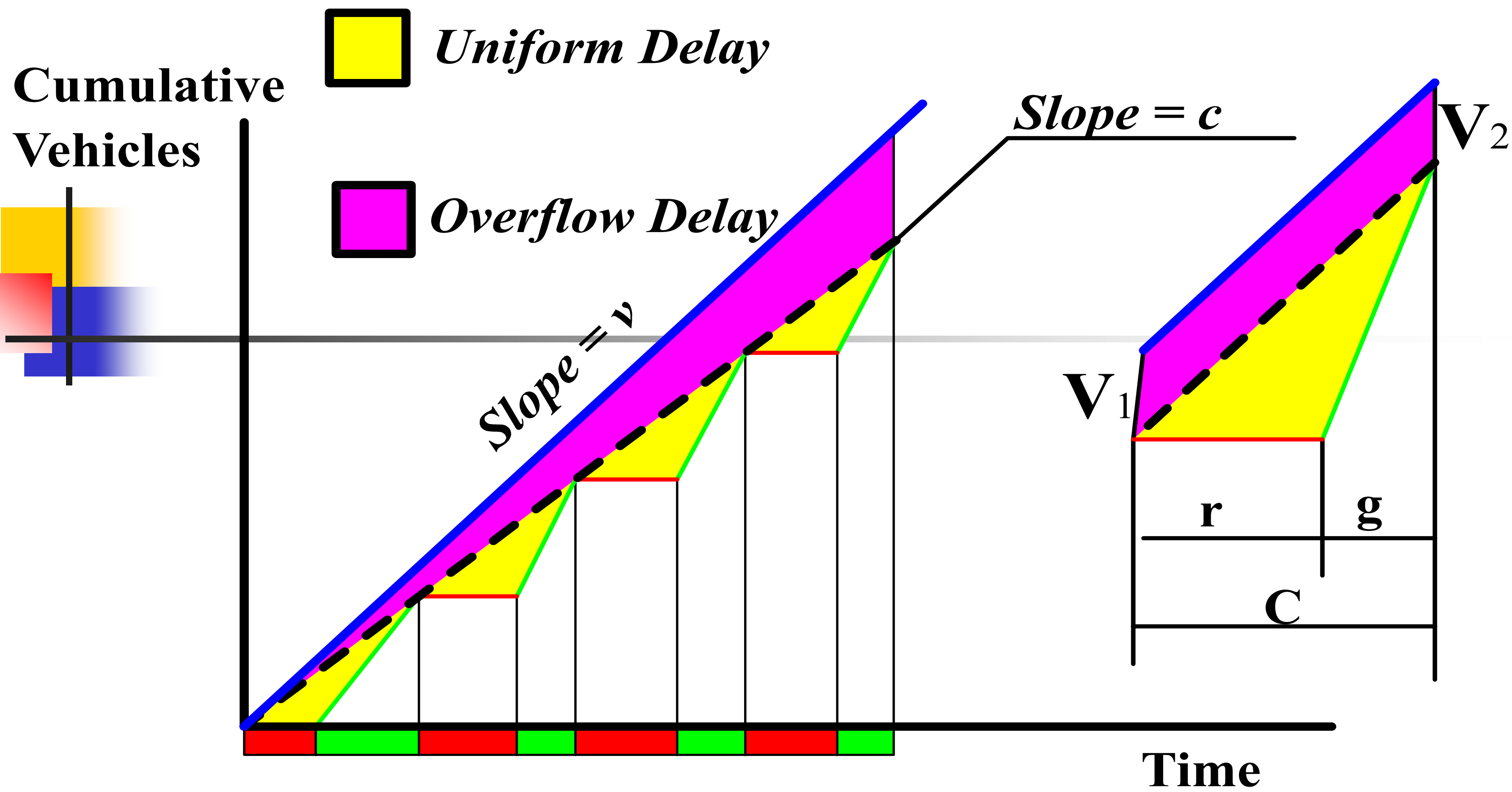
(a) Perfectly uniform arrivals, giving rise to Webster's first term

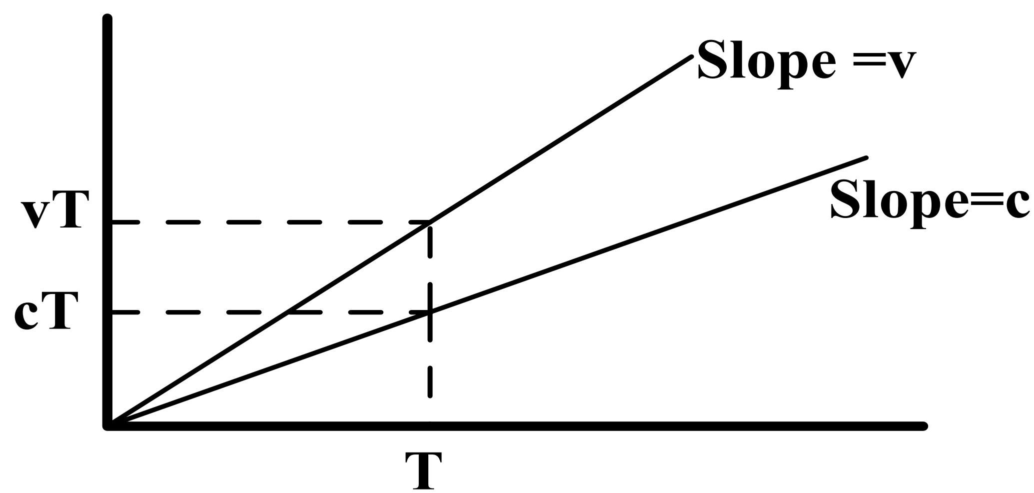


(b) Poisson arrivals (exponential interarrival times), giving rise to Webster's second term



(c) Not covered: platooned arrivals, with or without randomness


Uniform Delay
Overflow Delay
Cumulative Vehicles
Slope = c
Slope = v
V2
V1
r
g
C
Time


Slope =v
Slope=c
vT
cT
T

Determining Delay

- Average control delay per vehicle

$$d = d_1 \times PF + d_2 + d_3$$

Eq. 7.14

Where:

d = average signal delay per vehicle in seconds,

d_1 = average delay per vehicle due to uniform arrivals in seconds,

PF = progression adjustment factor,

d_2 = average delay per vehicle due to random arrivals in seconds, and

d_3 = average delay per vehicle due to initial queue at start of analysis time period, in seconds.

Determining Delay

- Uniform delay

$$d_1 = \frac{0.5C\left(1-\frac{g}{C}\right)^2}{1-\left[\min(1,X)\frac{g}{C}\right]}$$

Eq. 7.15

Where:
d_1 = average delay per vehicle due to uniform arrivals in seconds,
C = cycle length in seconds,
g = effective green time for lane group in seconds, and
X = v/c ratio for lane group.

Determining Delay

- Random delay

$$d_2 = 900T\left[(X-1)+\sqrt{(X-1)^2+\frac{8kIX}{cT}}\right] \qquad \text{Eq. 7.16}$$

Where:
d_2 = average delay per vehicle due to random arrivals in seconds,
T = duration of analysis period in h,
X = v/c ratio for lane group,
k = delay adjustment factor that is dependent on signal controller mode,
I = upstream filtering/metering adjustment factor, and
c = lane group capacity, in veh/h.

Delay Calculation Assumptions

- For problems in this class, all intersections are assumed to be isolated, under pretimed control, and have no initial queue at beginning of analysis period; thus:
  - $d_3 \rightarrow 0$
  - $PF \rightarrow 1.0$
  - $k \rightarrow 0.5$
  - $I \rightarrow 1.0$

Determining Delay

- Aggregating Delays

$$d_A = \frac{\sum_i d_i v_i}{\sum_i v_i} \qquad \text{Eq. 7.27}$$

Where:
d_A = average delay per vehicle for approach *A* in seconds,
d_i = average delay per vehicle for lane group *i* (on approach *A*) in seconds, and
v_i = analysis flow rate for lane group *i* in veh/h.

$$d_I = \frac{\sum_A d_A v_A}{\sum_A v_A} \qquad \text{Eq. 7.28}$$

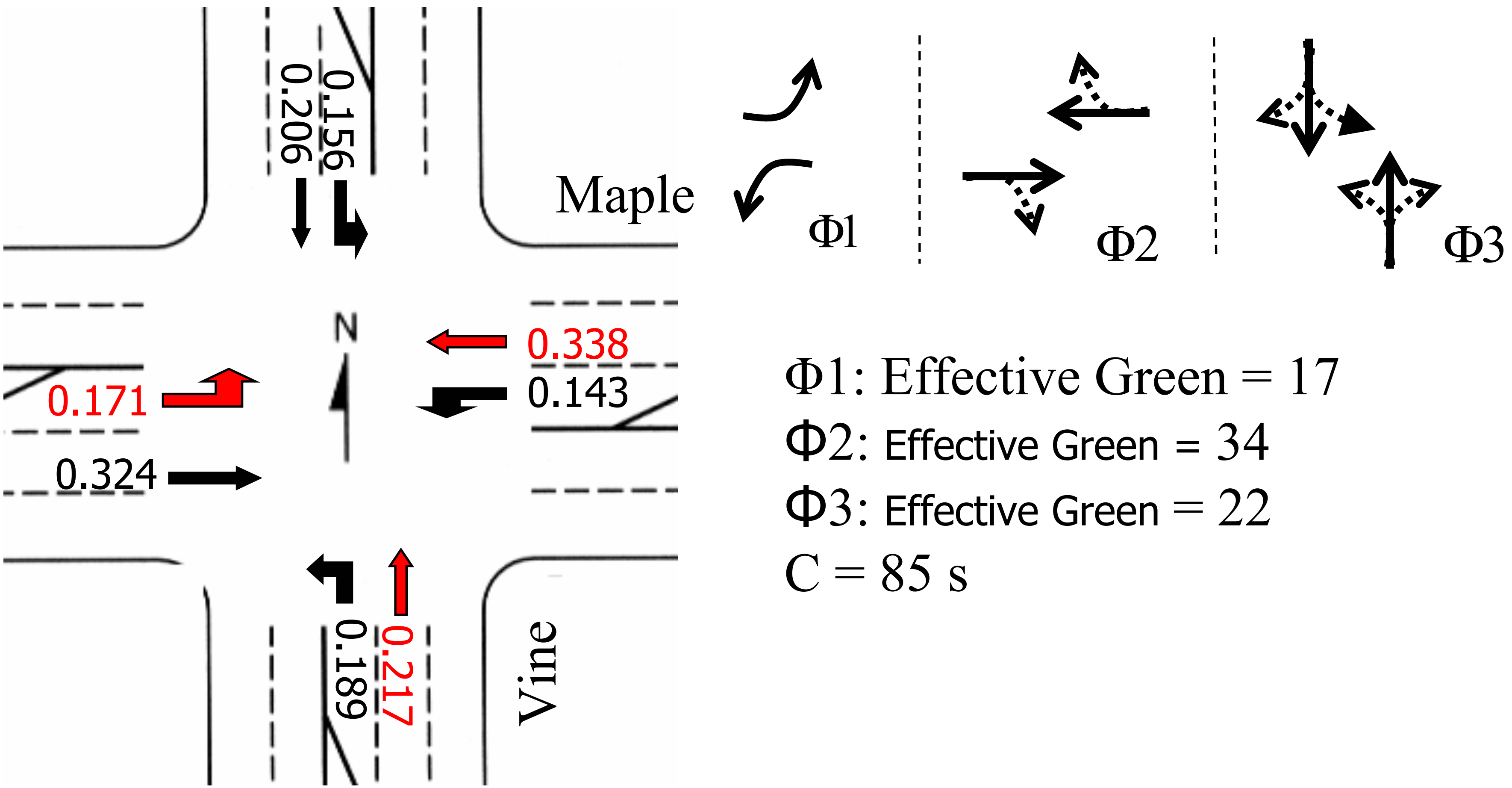
Where:
d_I = average delay per vehicle for the intersection in seconds,
d_A = average delay per vehicle for approach *A* in seconds, and
v_A = analysis flow rate for approach *A* in veh/h.

Level of Service

- Delay Thresholds

LOS	Control Delay per Vehicle (s/veh)
A	≤ 10
B	> 10-20
C	> 20 – 35
D	> 35 – 55
E	> 55 – 80
F	> 80

Example



Φ1: Effective Green = 17

Φ2: Effective Green = 34

Φ3: Effective Green = 22

C = 85 s

Determine Delays & LOS

Calculate EB approach delay

Left turn lane group

$g/C = 17/85 = 0.2$

$c = s \times g/C = 1750 \times 0.2 = 350$

$v/c = 300/350 = 0.857$

Uniform Delay

$$d_1 = \frac{0.5(85)(1-0.2)^2}{1-[0.8572 \times .2]} = 32.8\,\text{sec}$$

Determine Delays & LOS

Random Delay

With:
T = 0.25 (15 min)
X = 0.857 (from above)
k = 0.5 (pretimed control)
I = 1.0 (isolated mode)
c = 350 veh/h (from above)

$$d_2 = 900(0.25)\left[(0.857-1)+\sqrt{(0.857-1)^2+\frac{8(0.5)(1.0)0.857}{(350)0.25}}\right] = 22.76\text{sec}$$

Determine Delays & LOS

Total Delay

With *PF* = 1.0 (for isolated signal)

$$d_{EB\_LT} = 32.8 \times 1.0 + 22.76 + 0 = 55.56\,\mathrm{sec}$$

Level of Service: D