Design of Intersections for Safety and Efficiency

Chapter objectives covered in CE361: By the end of this chapter the student will be able to:

1. Find the critical gap for an unsignalized intersection approach (given data of accepted and rejected gaps)
2. Analyze the sight distances at an intersection for possible installation of stop or yield signs
3. Determine when an intersection warrants the installation of a traffic signal
4. Design signal settings for intersections so that drivers will not face a dilemma zone
5. Estimate the stopped delay for an approach to an intersection

8.1 Analysis of Non-signalized Intersections

By the end of this section, the student will be able to...

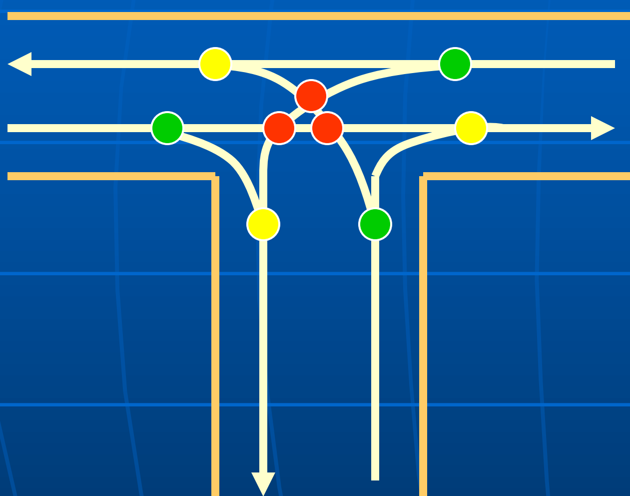
- Objectives of 8.1
  - Determine gaps in traffic that are acceptable to motorists
  - Determine whether to install a yield sign or stop sign, based on critical approach speed

8.1 Analysis of Non-signalized Intersections

- Right of way needs to be assigned to reduce potential conflicts and crashes.
- See the next slide to see how many potential conflict points exists in a T and a 4-leg unsignalized intersection.

Conflict points at unsignalized intersections

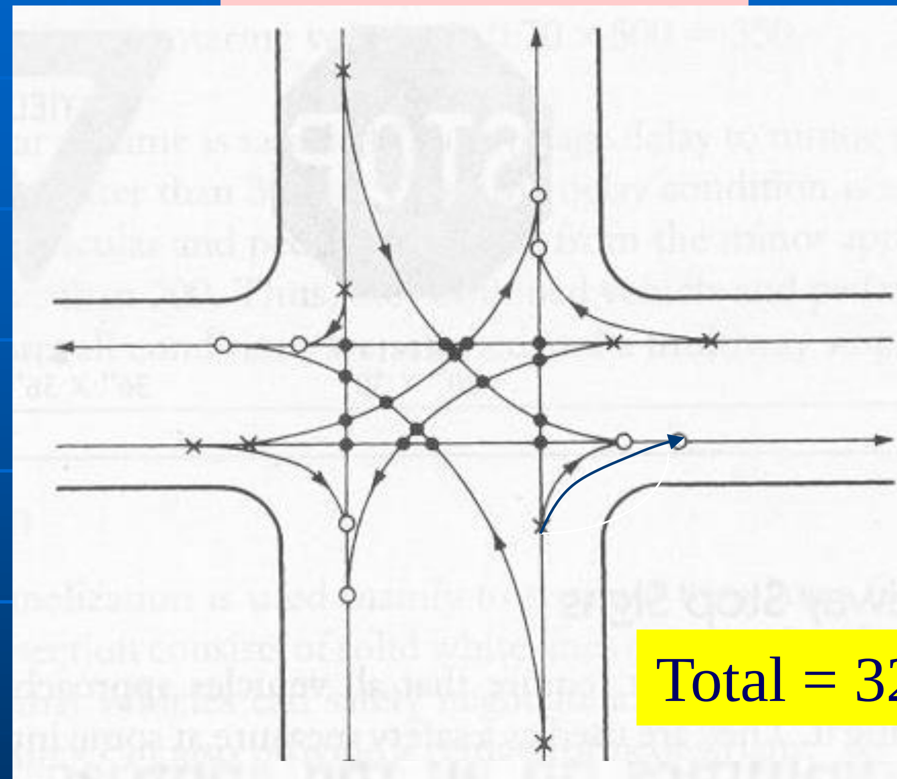
T intersection



- Crossing = 3
- Merging = 3
- Diverging = 3

Total = 9

4-leg intersection

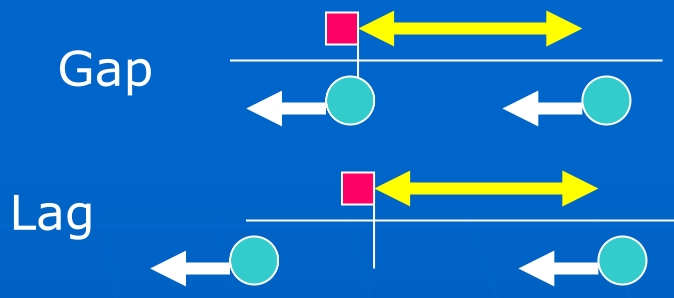


Total = 32

- ○ Merging conflict points = 8
- × Diverging conflict points = 8
- • Crossing conflict points = 16

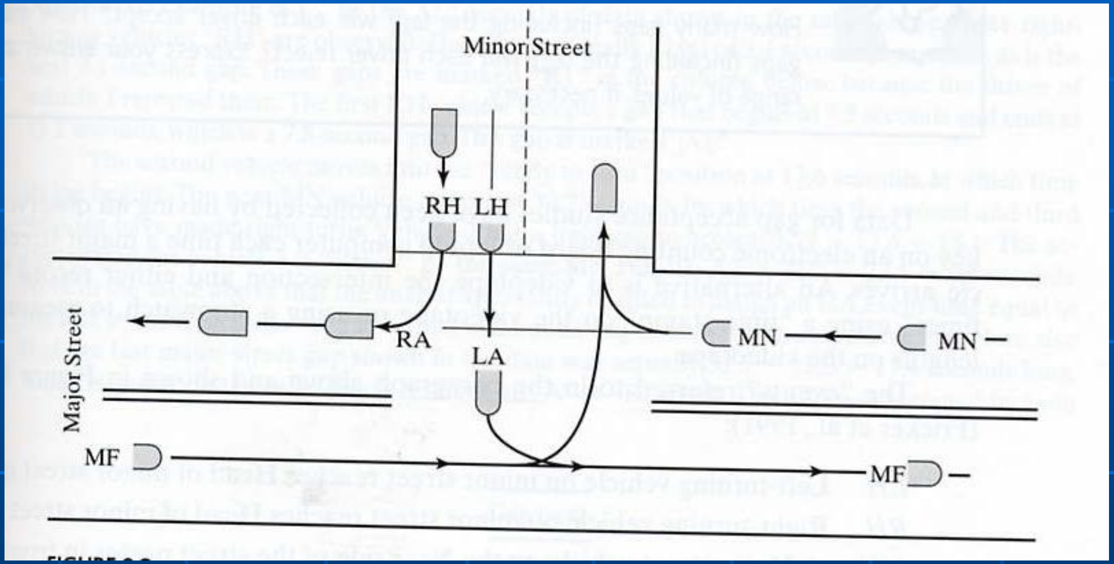
8.1.1 Gap acceptance

First, terminology...



- Headway – time elapsed between the front bumper of one vehicle and the front bumper of the following vehicle passing a given point
- Gap – time elapsed between the rear bumper of one vehicle and the front bumper of the following vehicle passing a given point
- Lag – time elapsed between the arrival of a minor-street vehicle ready to move into the major street and the arrival of the front bumper of the next vehicle in the major traffic stream
- Accepted gap or lag – gap or lag that the driver of a minor street vehicle uses to move into the major street
- Rejected gap or lag – gap or lag that the driver of a minor street vehicle waiting to enter the major street does not accept
- Untested gap – no minor street vehicle was present
- Critical gap – the minimum size gap that a particular driver will accept

Events in gap acceptance analysis



LH = LT veh at Head of minor st. queue

RH = RT veh at Head of minor st. queue

MN = Major st. vehicle on the Near side

MF = Major st. vehicle on the Far side

LA = LH vehicle Accepts the gap

RA = RH vehicle Accepts the gap

Example 8.1

Key for understanding this table → Check the arrival of MN after the arrival of RH.

Time (sec)	Event	Remarks	Time (sec)	Event	Remarks
0	RH	RT veh at head	17.6	RH	RT veh at head
3.4	RH MN	Rejected lag 3.4 sec	17.6	RA	Accepted lag 15.1 sec (32.7-17.6)
7.5	MN	Rejected gap 4.1 sec (7.5-3.4)	23.4	RH	RT veh at head
11.4	RA	Accepted gap 7.8 sec (15.3-7.5)	23.4	RA	Accepted lag 9.3 sec (32.7-23.4)
15.3	MN	MN arrives. Gap 7.8 sec	32.7	MN	MN arrives. Gap 17.4 sec (32.7-15.3)

Mr. Raff's method simplified

Mr. Raff → The gap for which the number of accepted gaps shorter than it is equal to the number of rejected gaps longer than it.

$$t_c = t_1 + \frac{(t_2 - t_1)[R(t_1) - A(t_1)]}{[A(t_2) - R(t_2)] + [R(t_1) - A(t_1)]}$$

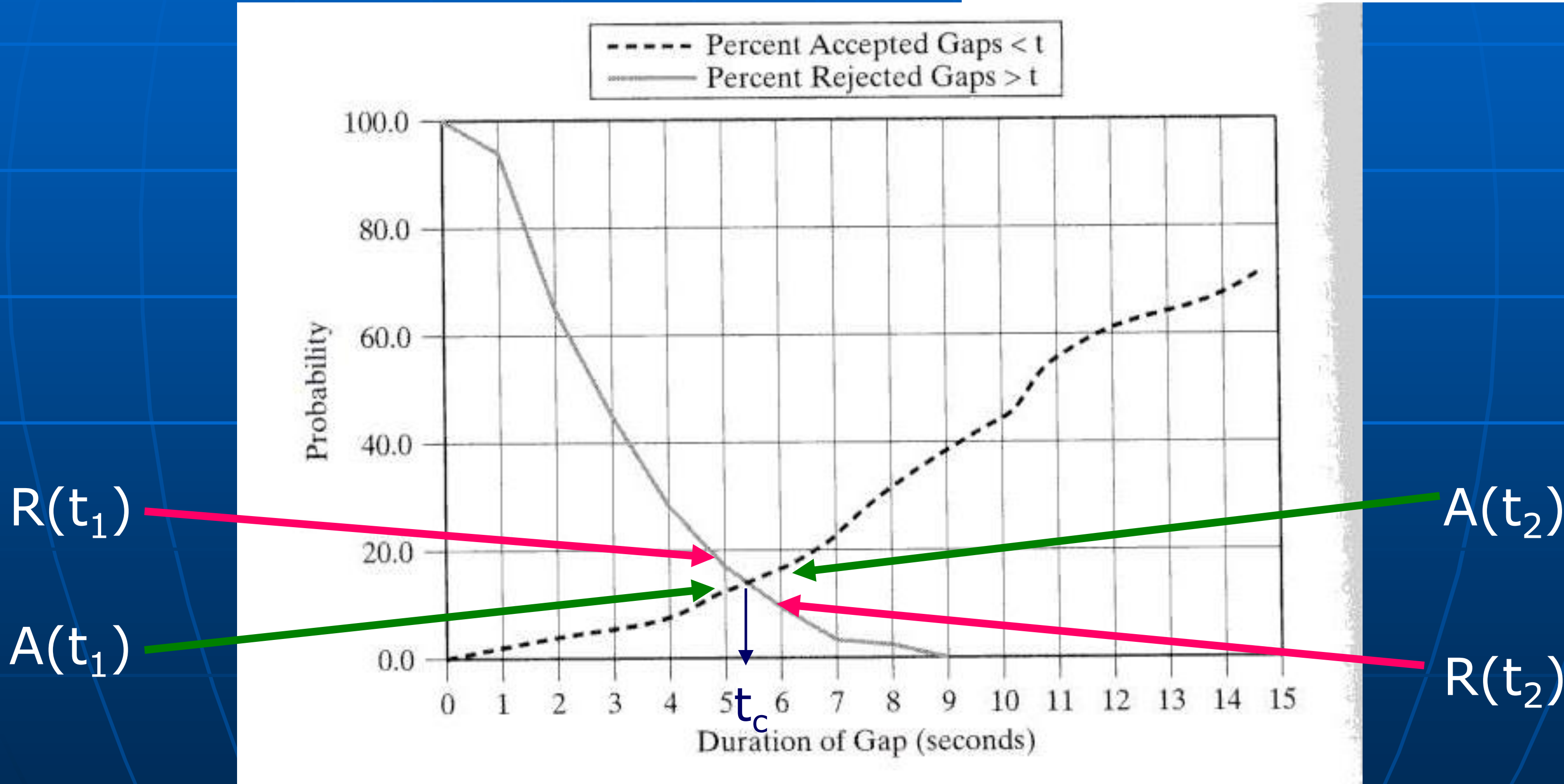


FIGURE 8.3
Cumulative distribution curves for accepted and rejected gaps.

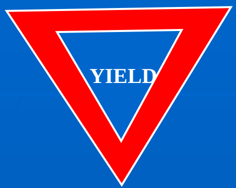
See Table 8.1 for data.

Hierarchy of intersection control

Intersection Control Options: How much judgment can drivers safely exercise to avoid collisions? Three levels of control are available.

Level I	Passive control – basic rules of the road apply ➢ No control ➢ Guide signs only ➢ Warning sings with or without guide signs
Level II	Assignment of ROW to major street or rotational ROW ➢ YIELD control (roundabouts are in this category) ➢ Two-way STOP control ➢ All-way STOP control
Level III	Positive alternate assignment of exclusive ROW ➢ Traffic signals: 2-phase, multiphase ➢ Traffic control agent/officer

Warrants for YIELD sign



The YIELD sign may be warranted:

A. When the ability to see all potentially conflicting traffic is sufficient to allow a road user traveling at the posted speed, 85th percentile speed, or the statutory speed to pass through the intersection or stop in a safe manner.

B. If controlling a merge-type movement on the entering roadway where acceleration geometry or sight distance is not adequate for merging traffic operations.

C. At a second crossroad of a divided highway, where the median width is 30ft or greater. A STOP sign may be installed at the entrance to the first roadway of a divided highway, and a YIELD sign may be installed at the entrance to the second roadway.

D. At an intersection where a special problem exists and where engineering judgment indicates that the problem is susceptible to correction by use of a YIELD sign.

Warrants for two-way STOP sign

Because the STOP sign causes a substantial inconvenience to motorists, it should be used only where warranted. A STOP sign may be warranted where one or more of the following conditions exist:

A. Intersection of a less important road with a main road where application of the normal ROW rule would not be expected to provide reasonably safe operation.

B. Street entering a through highway or street.

C. Unsignalized intersection in a signalized area.

D. High speeds, restricted view, or crash records indicate a need for control by the STOP sign.

http://mutcd.fhwa.dot.gov/HTM/2003r1/part2/part2b1.htm

- The critical approach speed (CAS)
  - If the computed speed is between 10 and 15 mph, a YIELD sign is appropriate.
  - If the computed speed is less than 10 mph, a STOP sign must be installed
  - At computed speeds higher than 15 mph, the CAS does not by itself justify a STOP or YIELD sign. Further analyses may be needed. (MUTCD has a set of warrants for Yield and Stop sign. Approach speed is not the only concern)

After checking the need for a yield or stop sign, check the intersection sight distance (ISD) for vehicles on the major street. If ISD is inadequate, stop signs on the major street may be called for. (see page 426 for t_c values. t_c = 7.5 sec for passenger cars, t_c = 9.5 for single unit trucks, and U, t_c = 11.5 sec for combination trucks)

$$ISD = 1.47 * V * t_c$$

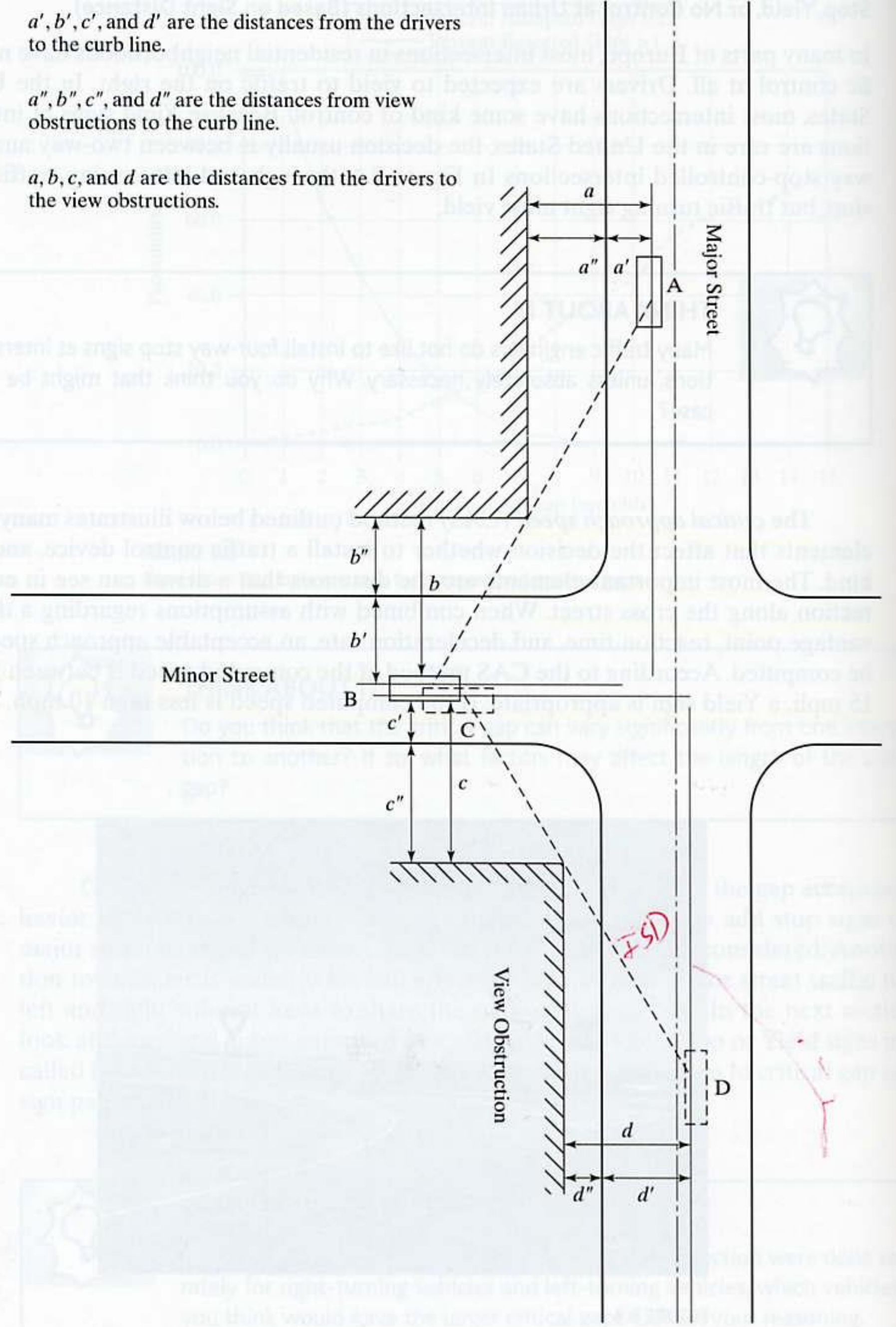


FIGURE 8.5
Typical critical approach speed problem. *Source*: Federal Highway Administration, 1983, p. 2-18.

The CAS Method

a″, b″, c″, and d″ are measured at the site.

a′, b′, c′, and d′ are computed as follows:

- **a′ = 12 ft with parking, a′ = 6′ without parking.**
- **b′ = min{½W + 3 ft; W – 12 ft}**
- **c′ = 12 ft with parking, c′ = 6′ without parking.**
- **d′ = ½W + 3 ft**

3 ft = distance between the centerline and the driver's head.

1/2W = distance between the center line and the curb

W = street width

The CAS Method (cont.)

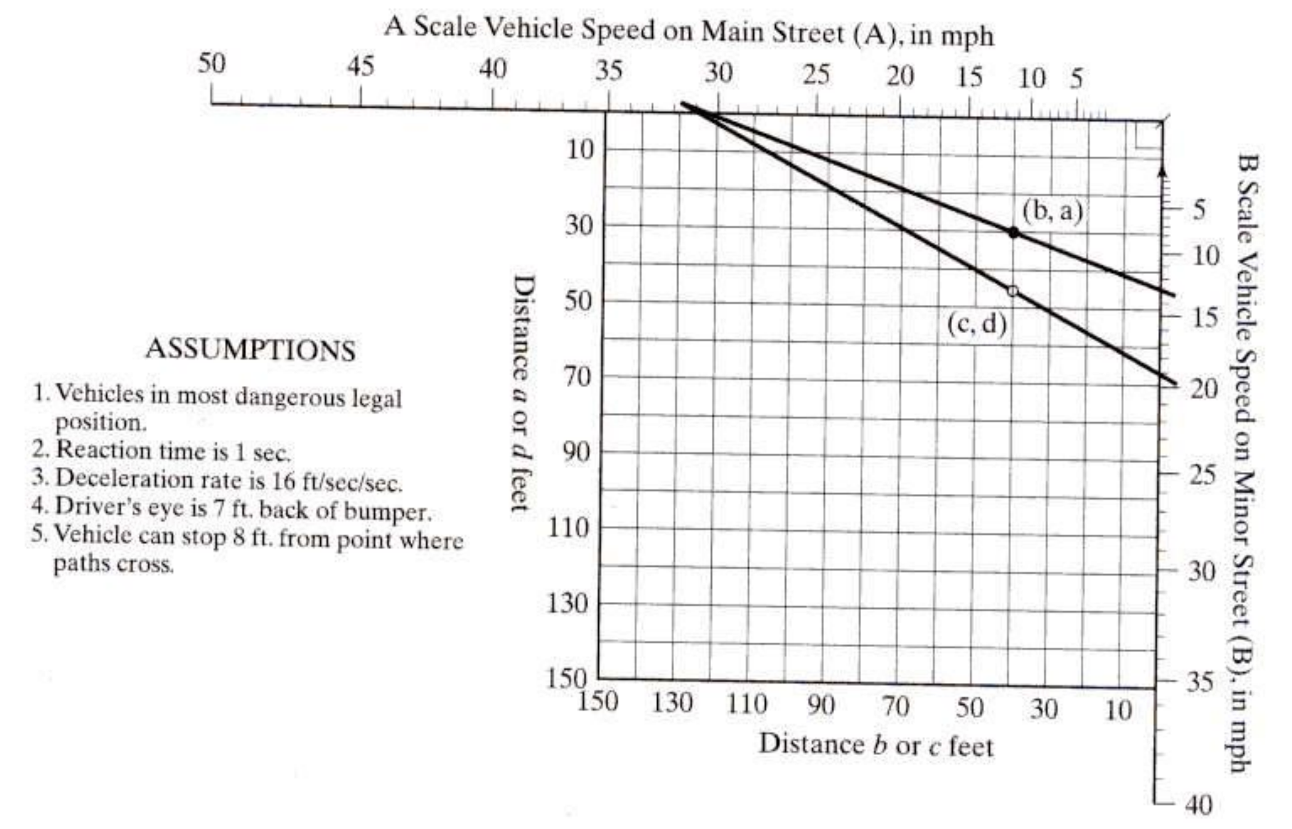


FIGURE 8.6
Critical approach speed chart. *Source*: Federal Highway Administration, 1983, p. 2-17.

Find:

$$a = a' + a''$$
$$b = b' + b''$$
$$c = c' + c''$$
$$d = d' + d''$$

- Place points (b,a) and (c,d) in Fig 8.6.
- Extend lines starting from the 85th-percentile speed on Main St., passing though the two points.
- Read Minor street speed from B scale.
- Use the lower speed to make a decision: <= 10 mph – stop sign; 10 <= speed <=15 mph – yield sign. Otherwise, needs a study

We will walk though Example 8.2.

8.2 Signal Warrants & Stopping Distance at Signalized Intersections

By the end of this section, the student will be able to...

- Objectives of 8.2
  - Determine when to install a traffic signal.
  - Determine whether a dilemma zone exists on the approach to a signalized intersection

8.2 Signal Warrants & Stopping Distance at Signalized Intersections

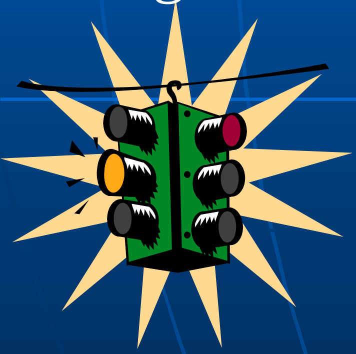
(a)When should traffic signals be installed?

(b)When do signal timings create a hazardous situation for drivers

8.2.1 Warrant Analysis

MUTCD 2000 has 8 warrants for a traffic signal. They are guides, not specsifications. Use professional judgments.

Signals



- **Warrant 1: Eight-hour vehicular volume**
- **Warrant 2: Four-hour vehicular volume**
- **Warrant 3: Peak hour**
- **Warrant 4: Pedestrian volume**
- **Warrant 5: School crossing**
- **Warrant 6: Coordinated signal system**
- **Warrant 7: Crash experience**
- **Warrant 8: Roadway network**

Covered in detail in CE562.

Signal warrant 1A: 8-hour volume

Min. vehicle volume: Principal factor is the intersection traffic volume. Must satisfy for each of any 8 hour of an average day.

Volume Requirements for Minimum Vehicular Volumes Warrant

Number of Lanes for Moving Traffic on Each Approach		Vehicles per Hour on Major Street (total of both approaches)	Vehicles per Hour on Higher-Volume Minor-Street Approach (one direction only)
Major Street	Minor Street		
1	1	500	150
2 or more	1	600	150
2 or more	2 or more	600	200
1	2 or more	500	200

- **May reduce the values by 30% if the 85th percentile speed on the major approach is greater than 40 mph or population is less than 10,000 (built-up area of isolated community).**

Signal warrant 1B

Interruption of continuous traffic: The volume requirements must be met for each of any 8 hours of an average day.

Minimum Vehicular Volumes for Interruption of Continuous Traffic Warrant

Number of Lanes for Moving Traffic on Each Approach		Vehicles per Hour on Major Street (total of both approaches)	Vehicles per Hour on Higher-Volume Minor-Street Approach (one direction only)
Major Street	Minor Street		
1	1	750	75
2 or more	1	900	75
2 or more	2 or more	900	100
1	2 or more	750	100

- **May reduce the values by 30% if the 85th percentile speed on the major approach is greater than 40 mph or population is less than 10,000 (built-up area of isolated community).**

Signal warrant 1C

Combination of warrants: Only in exceptional cases. When none of them are satisfied but when the first two warrants of Warrant 1 are satisfied to the extent of 80% of the stipulated volumes.

Example 8.3

- By overhead transparency

We will walk through this problem.

8.2.2 Reacting to a Changing Traffic Signal – a story of "dilemma zone"

"…, the term "amber" has been changed to "yellow," and the yellow interval simply means "the red interval is coming." The preferred reaction is to try to stop. However, it is possible that there is not sufficient distance for the car to stop, and the car would be in the intersection when the cross traffic gets the green light. The driver could be accused of "running the red light."

Note that currently "running the red light" means the vehicle enters the intersection <u>after</u> the red light was turned on. Once the vehicle is in the intersection, you are not "running the red light" when the cross traffic gets the green light. Most of the signal has an all-red interval after the yellow interval, which was meant to <u>clear</u> the intersection for conflicting movements.

Safely stop at or before the stop bar or clear the intersection & dilemma zone

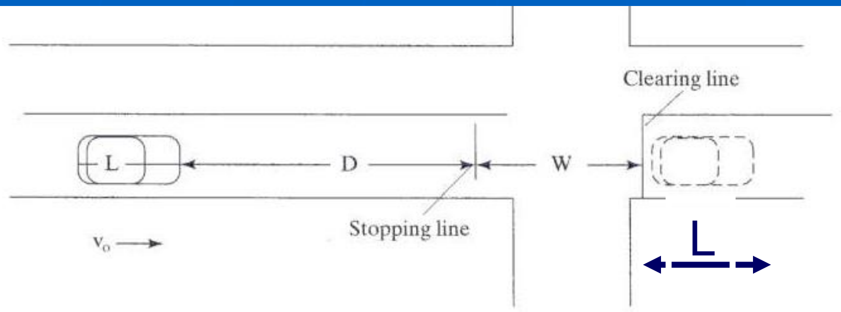


FIGURE 8.9
Vehicle approaching a signalized intersection.

where d_{brake} = the deceleration rate for braking to a stop

t_s = time to stop = $\dfrac{v_o}{d_{brake}}$

a_{acc} = the acceleration rate to increase speed when going through the intersection

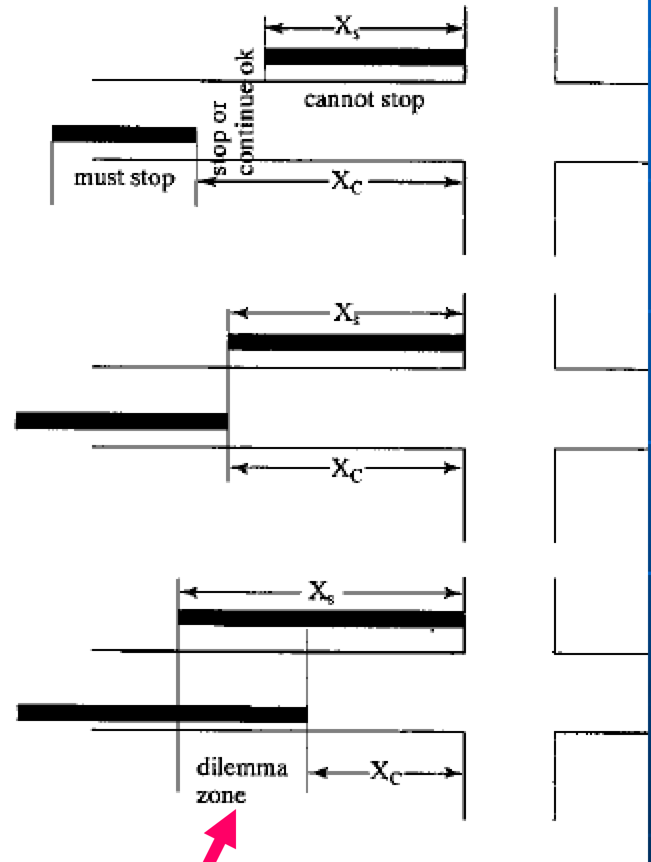
To safely stop:

$$X_S = D \geq v_o t_r + \frac{v_0^2}{2d_{brake}}$$

To safely clear:

$$X_C = D \leq v_o t_Y - (W + L)$$

Usually it is assumed the car will not accelerate (conservative estimate). Add this formula to eq. 8.3.



Dilemma zone: Cannot stop or cannot finish crossing ($X_S > X_C$)

Walk through Example 8.4 & 8.5

Safely stop at or before the stop bar or clear the intersection & dilemma zone (using SSD formula)

Cannot clear but can safely stop

Cannot safely stop but can clear

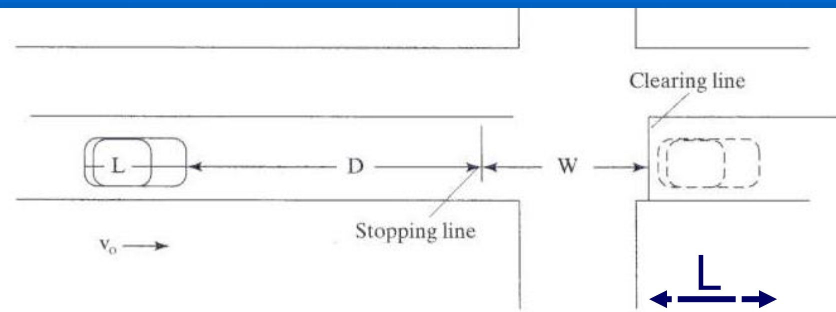
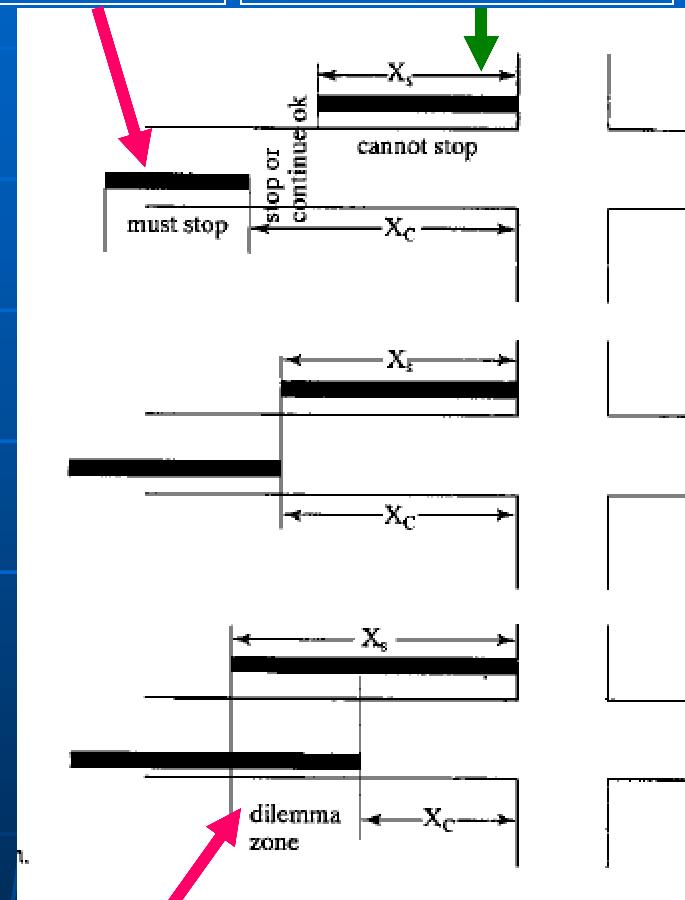


FIGURE 8.9
Vehicle approaching a signalized intersection.

where d_{brake} = the deceleration rate for braking to a stop

t_s = time to stop = $\frac{v_o}{d_{brake}}$

a_{acc} = the acceleration rate to increase speed when going through the intersection



To safely stop:

$$X_S = D \geq v_o t_r + \frac{v_o^2}{2g(f \pm G)}$$

To safely clear:

$$X_C = D \leq v_o t_Y - (W + L)$$

Dilemma zone: Cannot stop or cannot finish crossing ($X_S > X_C$)

Usually it is assume the car will not accelerate (conservative estimate). Add this formula to eq. 8.3.

Eliminating the dilemma zone

When $X_c = X_o$, there is no dilemma zone - at least theoretically.

$$v_o t_Y - (W + L) = v_o t_r + \frac{v_o^2}{2g(f \pm G)}$$

$$v_o t_Y = v_o t_r + \frac{v_o^2}{2g(f \pm G)} + (W + L)$$

$$t_Y = t_r + \frac{v_o}{2g(f \pm G)} + \frac{(W + L)}{v_o}$$

Solution to Example 8.4 using SSD formula

The minimum distance needed to stop X_c is:

$X_S = v_o t_r + v_0^2/[2*g(f \pm G)]$

$= 30*1.47*1.5 + (30*1.47)^2/[2*32.2*0.35]$

$= 66.15 + 86.28 = 152.4$ ft (G = 0, flat profile)

The maximum distance from which the vehicle can safely clear the intersections is:

$X_C = v_o t_Y - (W + L) = 30*1.47*4 - (60 + 16)$

$= 176.4 - 76 = 100.4$ ft

$X_S > X_C$ (152.4 ft > 100.4 ft), hence a dilemma zone exists.

Its length is 152.4 ft – 100.4 ft = 52 ft. The driver's claim cannot be dismissed, but now the issue becomes whether the vehicle was in the dilemma zone when the light changed to yellow.

Solution to Example 8.5 using SSD formula

A)

$$t_Y = t_r + \frac{v_o}{2g(f \pm G)} + \frac{(W+L)}{v_o}$$

$$= 1.5 + \frac{30*1.47}{2*32.2*0.35} + \frac{(60+16)}{30*1.47}$$

$$= 5.18$$

Since t_Y remains to be 4 seconds, AR = 1.18 seconds

B)

$$v_o t_Y = v_o t_r + \frac{v_o^2}{2g(f \pm G)} + (W+L)$$

$$v_o*(4+2) = v_o*1.5 + \frac{v_o^2}{2*32.2*0.35} + (60+16)$$

$$v_o*4.5 = \frac{v_o^2}{22.54} + 76$$

$$0.0444*v_0^2 - 4.5*v_o + 76 = 0$$

Solving for V_0, V_o = 79.93 ft/s or 21.40 ft/sec

or

V_o = 54.4 mph or 14.6 mph

8.3 Analysis of Signalized Intersection

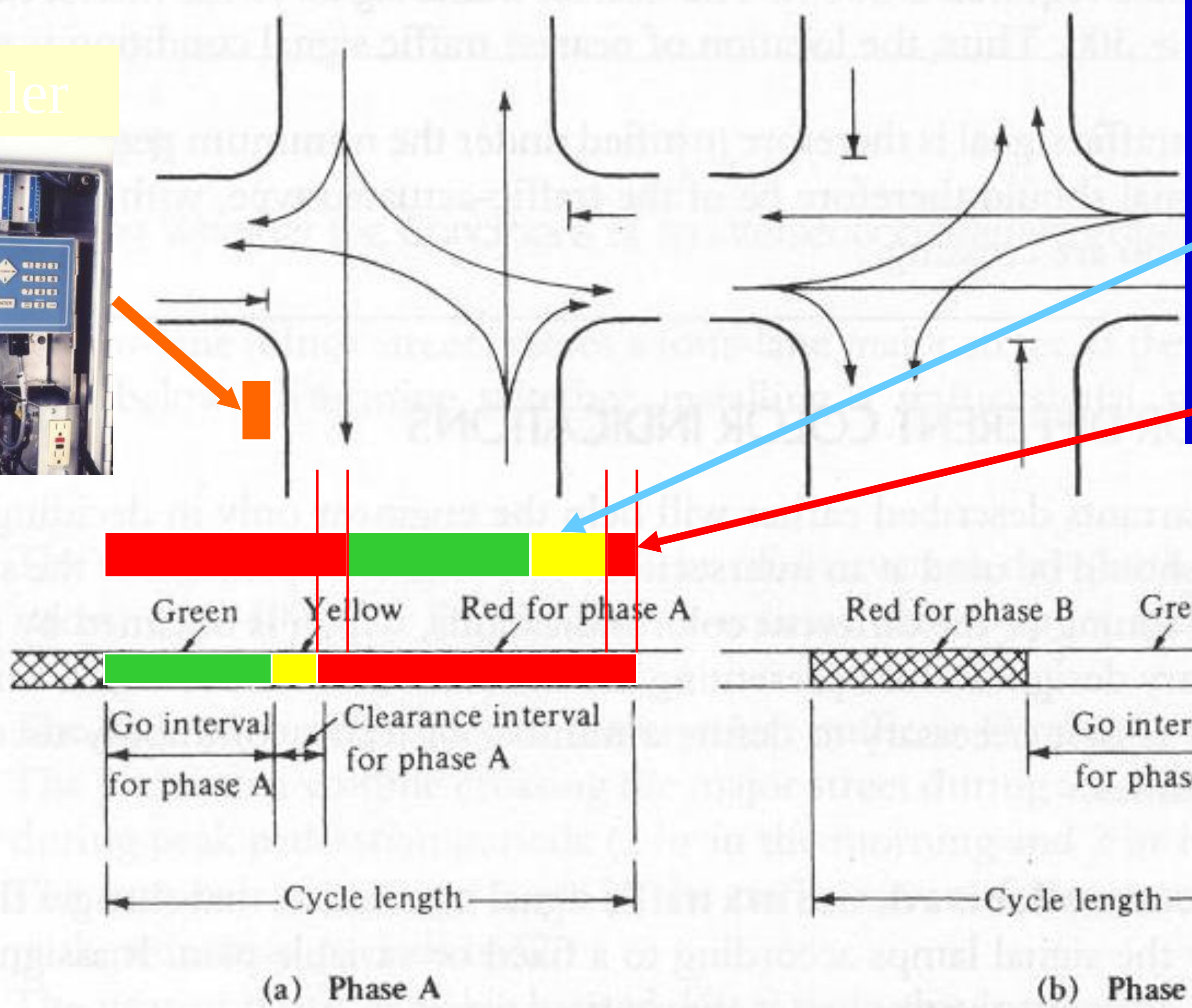
By the end of this section, the student will be able to...

- Objectives of 8.3
  - Summarize a signal timing plan for a given intersection in a concise format.
  - Use time-space diagram to analyze systems of traffic signal settings
  - (Actuated signals, 8.3.3, and delay estimation, 8.3.4. are not covered in CE361. They are discussed in detail in CE562 Traffic Engineering)

8.3 Analysis of Signalized Intersection

8.3.1 Traffic signal timing

Controller



Cycle length

Phase

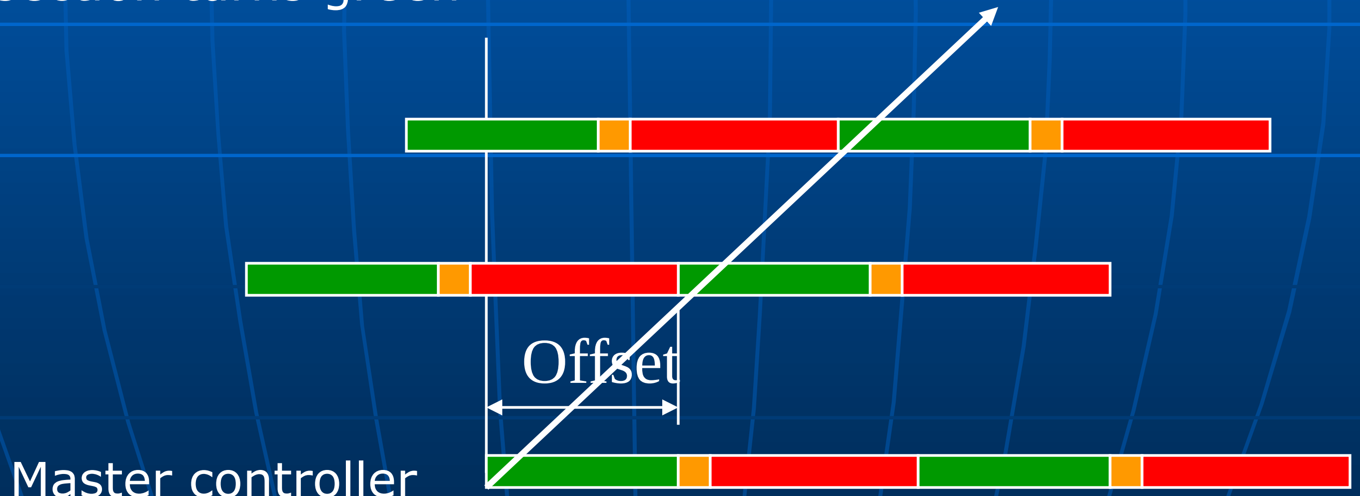
Interval

Change interval

All-read interval (clearance interval)

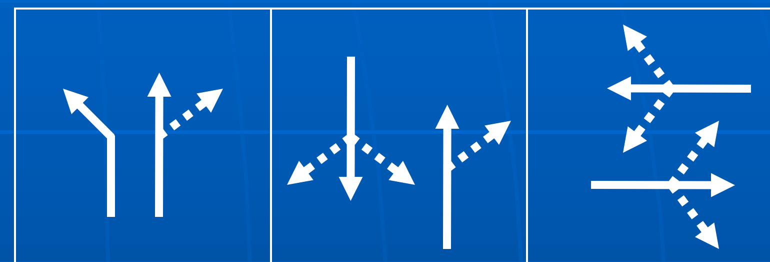
Terms related to signal timing (cont)

- Phase = A signal phase consists of a green interval (G), plus the change (Y) and clearance intervals (AR) that follow it. It is a set of intervals that allows a designated movement or set of movements to follow and to be safely halted before release of a conflicting set of movements.
- Offset = The difference between the time when the upstream intersection turns green and the downstream intersection turns green



		Wildcat Ave.					Coliseum Ave.	
Time(sec)	Interval	Interval legth	Signal Indication	NBLT	NB TH/RT	SB Vehs	EB Vehs	WB Vehs
1				G = 14	G = 38	R = 19	R = 44	R = 44
2								
3								
4								
5								
6								
7								
8								
9								
10								
11								
12								
13								
14	1	14	Green					
15				Y = 4				
16								
17								
18	2	4	Yellow					
19	3	1	All Red?	R = 57				
20						G = 19		
21								
22								
23								
24								
25								
26								
27								
28								
29								
30								
31								
32								
33								
34								
35								
36								
37								
38	4	19	Green					
39					Y = 4	Y = 4		
40								
41								
42	5	4	Yellow					
43					R = 33	R = 33		
44	6	2	All Red					
45							G = 26	G = 26
46								
47								
48								
49								
50								
51								
52								
53								
54								
55								
56								
57								
58								
59								
60								
61								
62								
63								
64								
65								
66								
67								
68								
69								
70	7	26	Green					
71							Y = 4	Y = 4
72								
73								
74	8	4	Yellow					
75	9	1	All Red				R = 1	R = 1
	Total	75 seconds						

Table 8.4 shows a traffic signal-timing form



You can calculate interval lengths from the given G-Y-R data, but a diagram like this gives you a clearer picture of what's happening in the cycle.

Look at these diagrams as you read the explanation of the timing form in the text (Last paragraph of p.436 and Example 8.6).

8.3.2 Time-Space Diagrams

T-S diagram: A scaled chart that shows trajectories of vehicles traveling downstream or upstream

(a) Stopped (distance/time = 0/time = 0 speed)

(b) Traveling downstream at a speed

(c) Stopped again

(d) Traveling downstream again

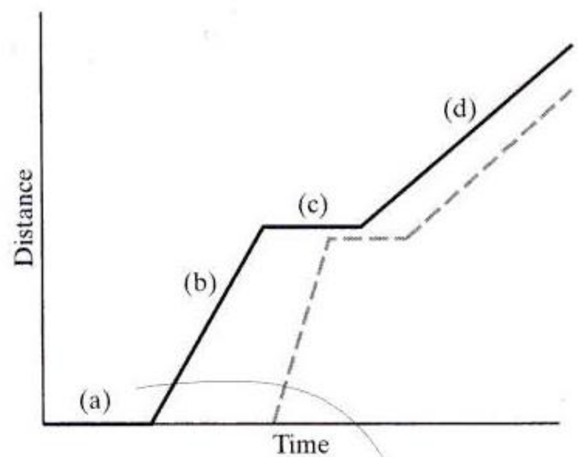


FIGURE 8.13
Vehicle trajectories.

Time-space diagram for signal coordination
(Fig 8.14 is for Example 8.7)

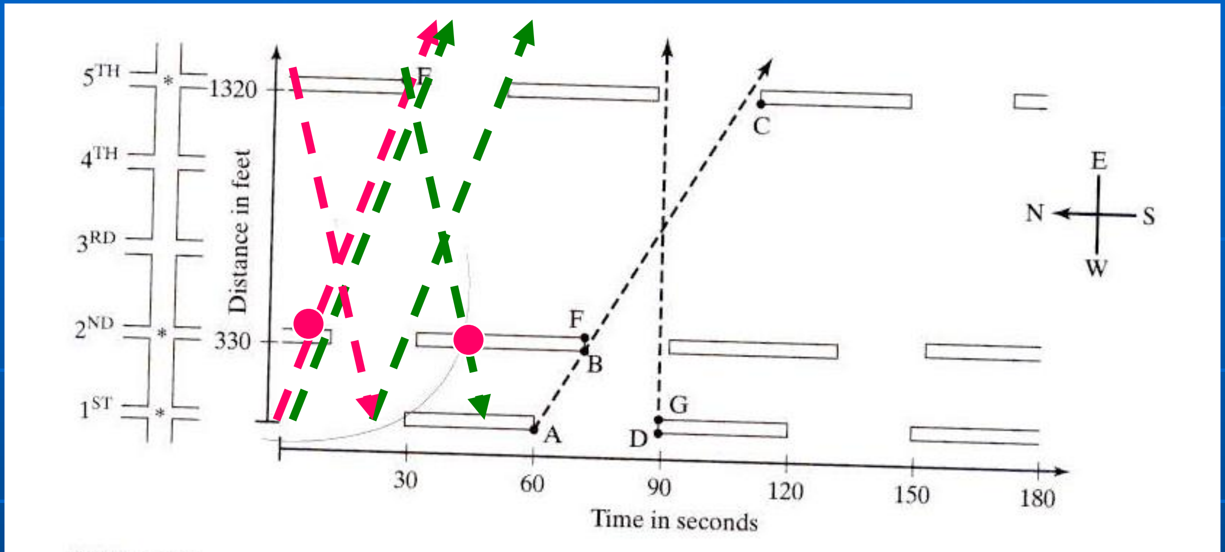
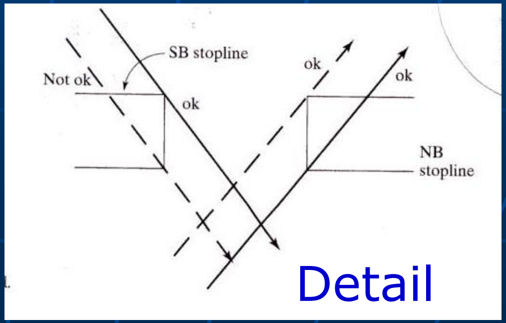
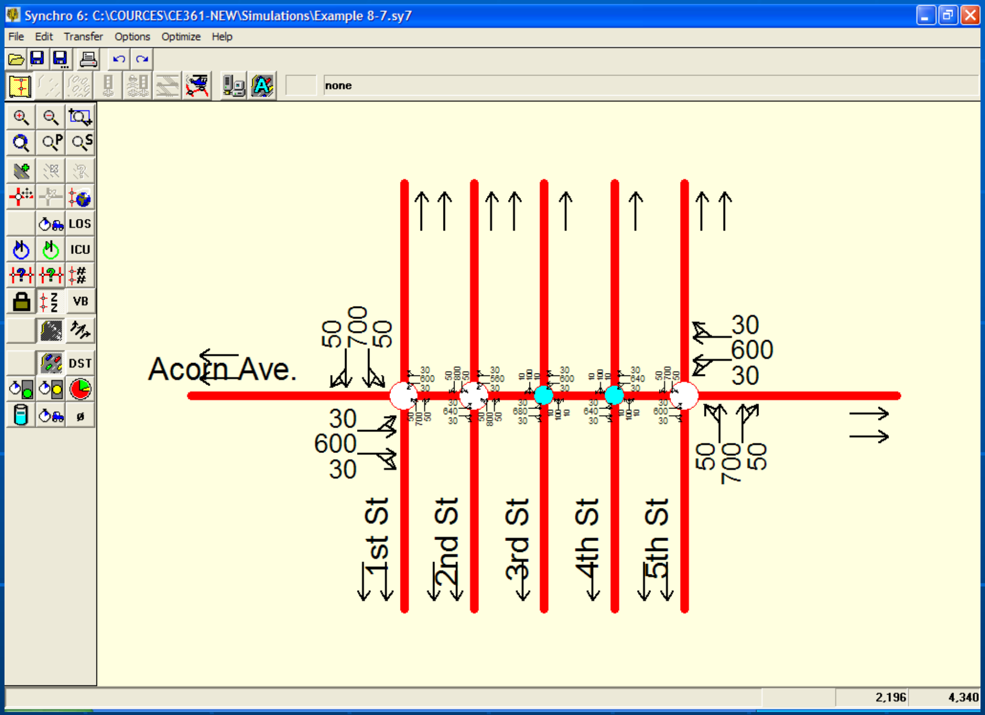


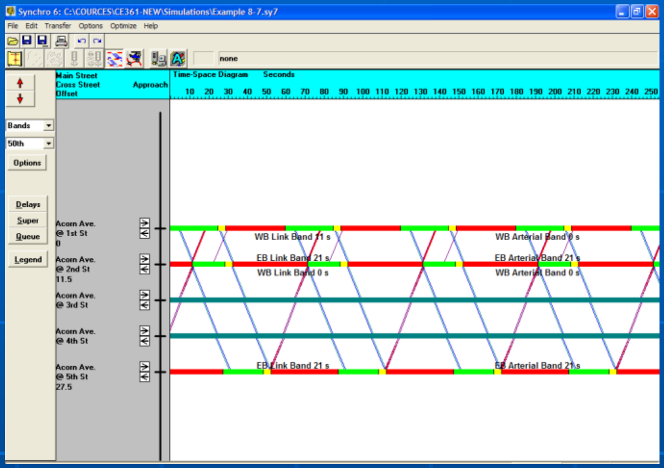
FIGURE 8.14
Time-space diagram for traffic signal timing.

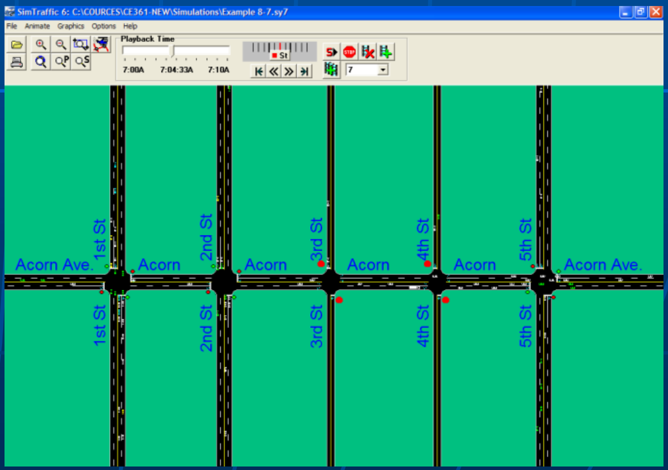
Once the timing design of each signal is completed, offsets of the signals can be adjusted to achieve the speed and green band desired. But depending on the block length and timing, you may not be able to get exactly what you want.



Example 8.7 by Synchro 7 software







We will extensively discuss signal timing issues in CE562.