Transportation System Engineering 2 , 10601461

Chapter 5
Intersection Control

AN-NAJAH NATIONAL UNIVERSITY
NABLUS, PALESTINE

Outline: Chapter 5

5.1 Concepts of Traffic Control

5.2 Conflict Points at Intersections

5.3 Types of Intersection Control

5.4 Signal Timing

Intersection Control

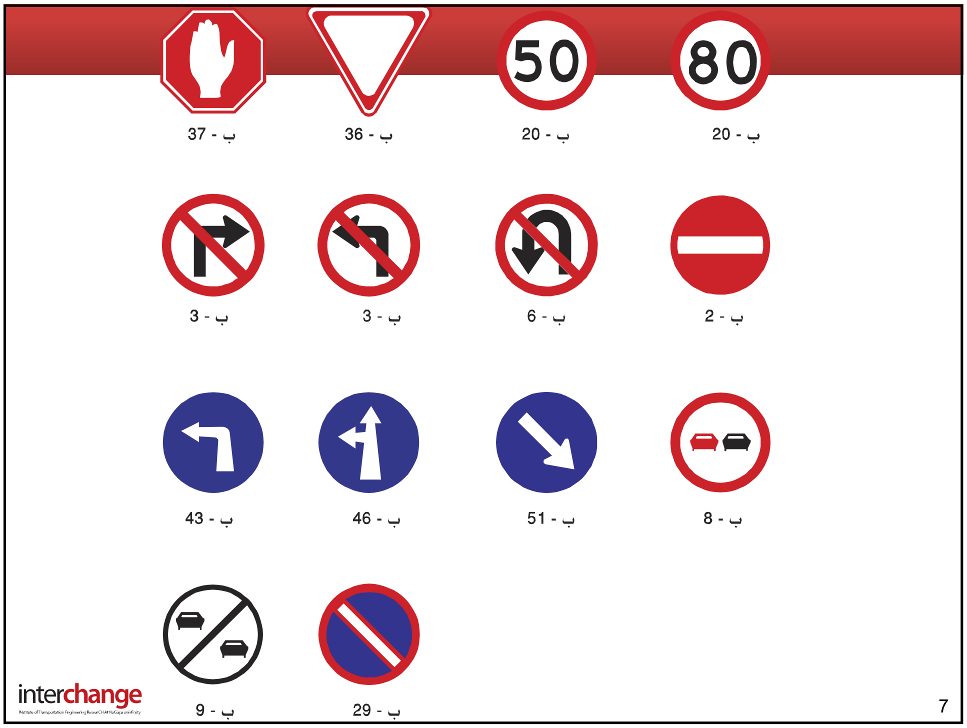
- Intersection is an area shared by two or more roads
  - Its main function is to allow the change of route directions.
- The flow of traffic on any street is greatly affected by the flow of traffic through the intersection points
  - because the intersection usually performs at a level below that of any other section of the road

5.1 Concepts of Traffic Control

Concepts of Traffic Control

- The purpose of traffic control is to assign the right of way to drivers in order to facilitate highway safety
  - by ensuring the **orderly and predictable** movement
- To regulate, guide, warn, and/or channel traffic
- Guidelines are provided in the **Manual on Uniform Traffic Control Devices (MUTCD)**
- To be effective, a traffic-control device must:
  - Fulfill a need
  - Command attention
  - Convey a clear, simple meaning
  - Command the respect of road users
  - Give adequate time for proper response

interch

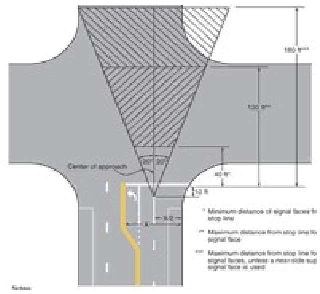

50
80
ب - 37
ب - 36
ب - 20
ب - 20
ب - 3
ب - 3
ب - 6
ب - 2
ب - 43
ب - 46
ب - 51
ب - 8
ب - 9
ب - 29
interchange
7


تحويلــــة
نهايـــة أعمـــال
الطريـــق
END ROAD WORK
نهاية أعمال الطريق
بداية أعمال الطريق
أ - 38
أ - 34
أ - 46
أ - 35
3m
م
50
أ - 49
ب - 18
ب - 20
interchange
8

Concepts of Traffic Control

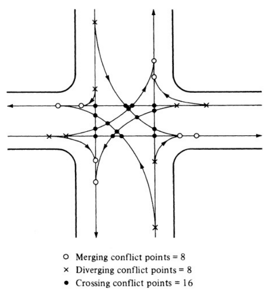
- MUTCD recommends that engineers consider the following five factors:

1. Design
2. Placement
3. Operation
4. Maintenance
5. Uniformity



- Engineers should avoid using control devices that conflict with one another at the same location
  - It is imperative that control devices aid each other in transmitting the required message to the driver

interchange

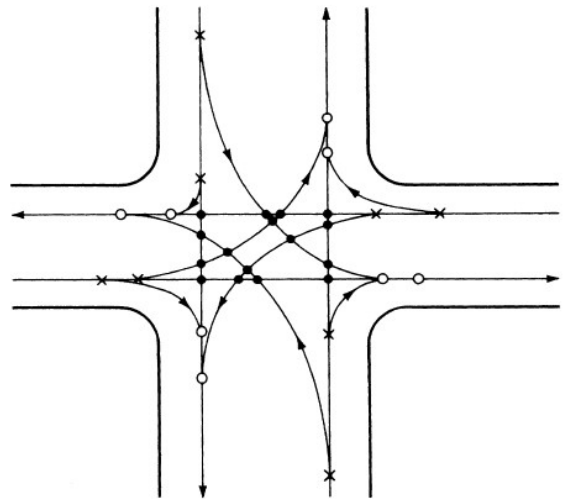


5.2 Conflict Points at Intersections

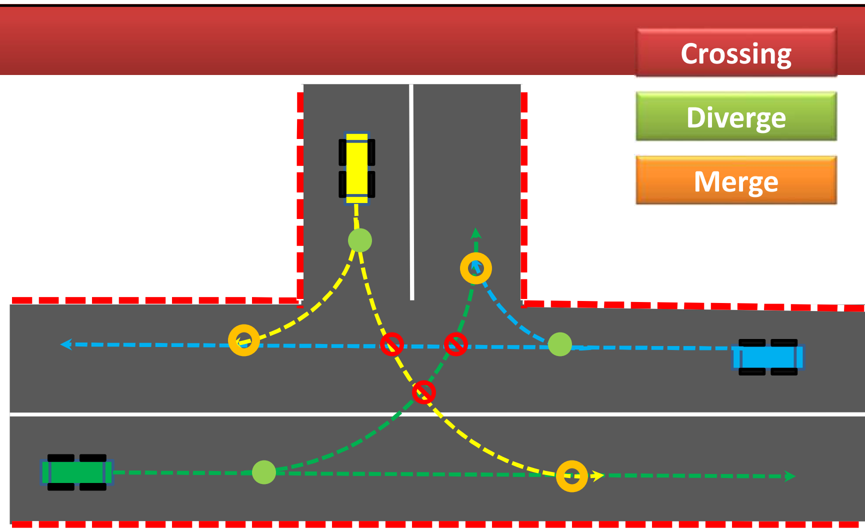
Conflict Points at Intersections

- Conflicts occur when traffic streams moving in different directions interfere with each other
- The number of possible conflict points at any intersection depends on
  - Number of approaches
  - Turning movements
  - Type of traffic control at the intersection
- Factors that influence <u>the significance</u> of a conflict include
  - Type of conflict
  - Number of vehicles in each conflicting stream
  - Speeds of the vehicles in those streams
- **<u>Crossing conflicts</u> tend to have the most severe effect on traffic flow and should be reduced to a minimum**

Conflict Points at Intersections

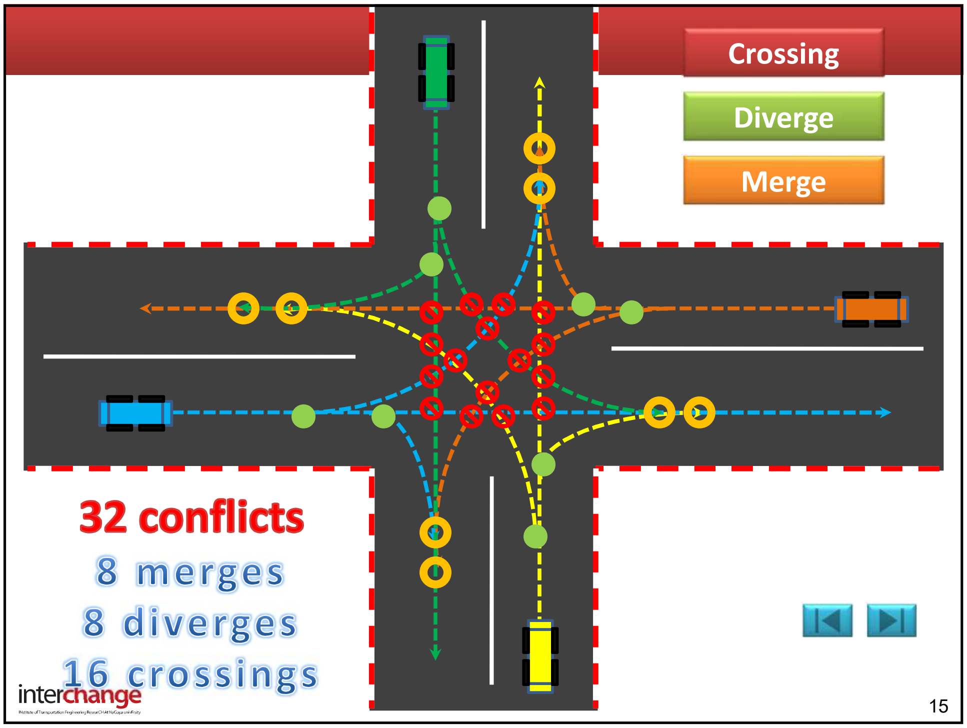


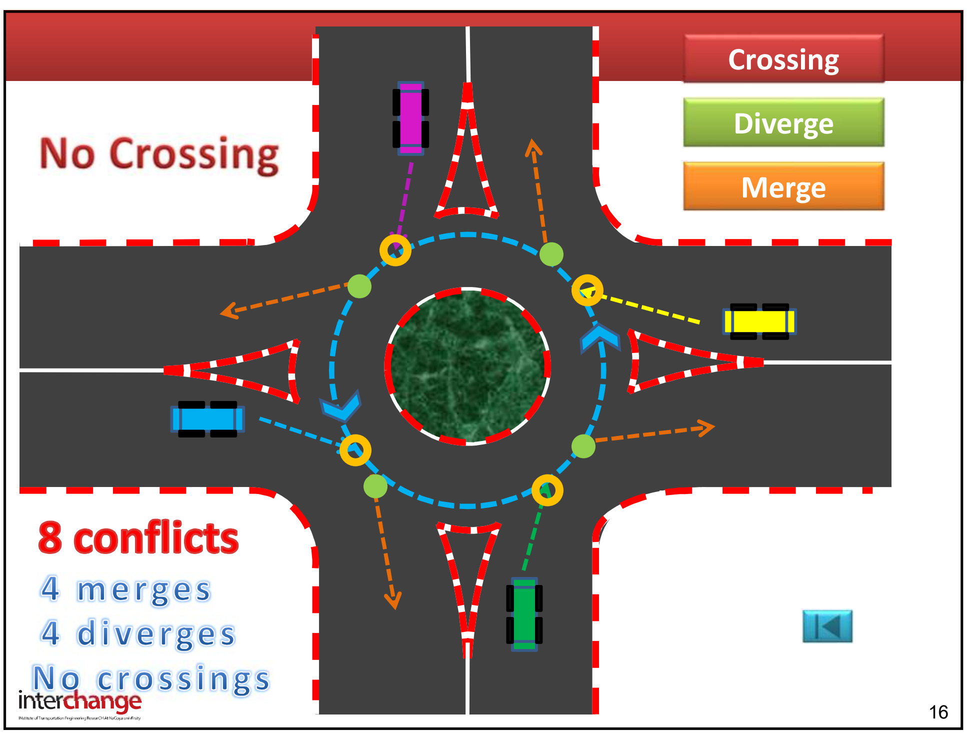
○ Merging conflict points = 8
× Diverging conflict points = 8
● Crossing conflict points = 16



9 conflicts

3 merges
3 diverges
3 crossings


Crossing
Diverge
Merge
32 conflicts
8 merges
8 diverges
16 crossings
interchange
15


No Crossing
Crossing
Diverge
Merge
8 conflicts
4 merges
4 diverges
No crossings
interchange
16

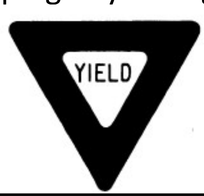
5.3 Types of Intersection Control

Types of Intersection Control

- The selection of a control type depends on
  - type of intersection
  - volume of traffic in each of the conflicting streams
- Types of intersection control:

1. Yield Signs

  - All drivers are required to slow down and stop if necessary to give the right of way to all conflicting vehicles at the intersection
  - Stopping at yield signs is not mandatory



Yield Sign Sizes

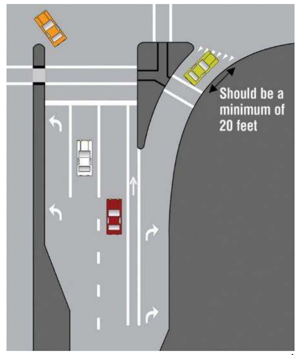
Conventional Roads	36" × 36" × 36"
Expressways	48" × 48" × 48"
Freeways	48" × 48" × 48"
Minimum	30" × 30" × 30"

Types of Intersection Control

1. Yield Signs

– Most significant factor in the warrant for yield signs is **the approach speed on the minor road**

– If there is a separate or channelized right-turn lane without an adequate acceleration lane, the yield sign is warranted



2. Stop Signs

– A stop sign is used where an approaching vehicle is required to stop before entering the intersection

– The use of these signs results in considerable inconvenience to motorists

Types of Intersection Control

2. Stop Signs

– The warrants for stop signs suggest that a stop sign may be used
  – on a minor road when it intersects a major road
  – at an unsignalized intersection
  – where a **combination of high speed, restricted view, and serious crashes** indicates the necessity for such a control

Stop Sign Sizes

Conventional Roads	30" × 30"
Expressways	36" × 36"
Minimum	24" × 24"

R1–1

Types of Intersection Control

3. Multiway Stop Signs

– They require that all vehicles approaching the intersection stop before entering it

– Normally are used when the traffic volumes on all of the approaches are approximately equal
  - However when traffic volumes are high, the use of signals is recommended

– Furthermore, they should be used when:
  1. As an interim measure to control traffic at intersections where a signalized system is justified until the signalized system is in place
  2. **Safety:** **Five or more crashes** occur at an intersection in a 12-month period **or**

interchange

23

Types of Intersection Control

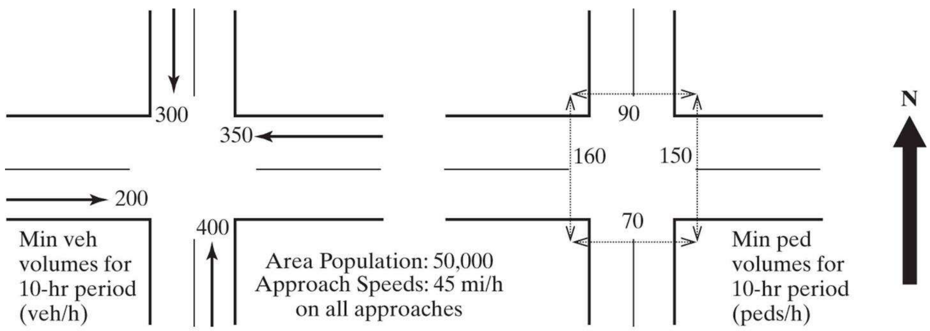
3. Volume and delay:

- For any 8 hours : Total volume on both major street **approaches should not be less than 300 veh/h and** combined volume of vehicles and pedestrians from the minor approaches **should not be less than 200 units/h**
- The average delay of the vehicles on the minor street is more than 30 sec/veh during the maximum hour

- If the 85th-percentile approach speed on the major approach is greater than 40 mi/h, minimum requirement for vehicular volume can be reduced by **30 percent**

If 80 percent of the safety and volume minimum requirements are met, the installation of a multiway stop sign is justified

- Major street **approaches ≥ 300 veh/h**
- **V**olume of vehicles & pedestrians from the minor approaches ≥ **200 units/h**



Time	Main Street Volume (veh/h)			First Ave Volume (veh/h)			Ped Volume (ped/h)
	EB	WB	TOT	NB	SB	High Vol	Xing Main
11 AM–12	400	425	**825**	75	80	**80**	115
12–1 PM	450	465	**915**	85	85	**85**	120
1–2 PM	485	500	**985**	90	100	**100**	125
2–3 PM	525	525	**1,050**	110	115	**115**	130
3–4 PM	515	525	**1,040**	100	95	**100**	135
4–5 PM	540	550	**1,090**	90	100	**100**	140
5–6 PM	550	580	**1,130**	110	125	**125**	120
6–7 PM	545	525	**1,070**	96	103	**103**	108
7–8 PM	505	506	**1,011**	90	95	**95**	100
8–9 PM	485	490	**975**	85	75	**85**	90
9–10 PM	475	475	**950**	75	60	**75**	50
10–11 PM	400	410	**810**	50	55	**55**	25

Types of Intersection Control

3. Multiway Stop Signs

Example 8.1 Evaluating the Need for a Multiway Stop Sign at an Intersection

A minor road carrying 75 veh/h on each approach for eight hours of an average day crosses a major road carrying 145 veh/h on each approach for the same eight hours, forming a four-leg intersection. Determine whether a multiway stop sign is justified at this location if the following conditions exist:

1. The pedestrian volume from the minor street for the same eight hours as the traffic volumes is 40 ped/h.
2. The average delay to minor-street vehicular traffic during the maximum hours is 37 sec/veh.
3. There are an average of four crashes per year that may be corrected by a multiway stop control.

Types of Intersection Control

3. Multiway Stop Signs

Solution:

- Determine whether traffic volume on the major street satisfies the warrant.

  Total vehicular volume entering the intersection from the major approaches is $145 + 145 = 290$ veh/h. The major road traffic volume criterion is not satisfied.
- Determine whether total minor-road traffic and pedestrian volume satisfies the warrant.

  Total minor-road traffic and pedestrian volume $= 2 \times 75 + 40 = 190$.
  Total minor-road and pedestrian volume is not satisfied.
- Determine whether crash criterion is satisfied.

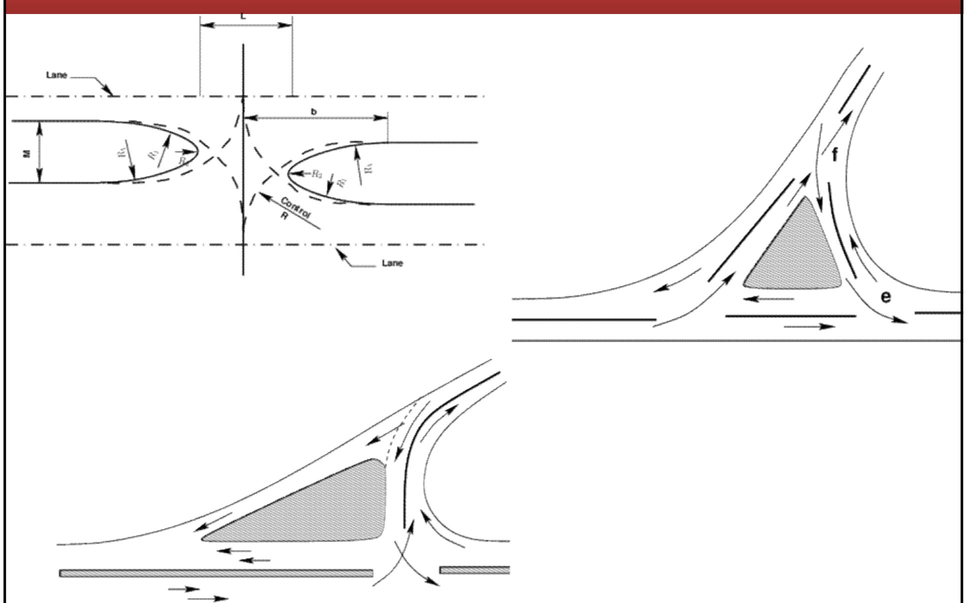
  Total number of crashes per year = 4.
  Crash criterion is not satisfied.
  However, each crash and volume criterion is satisfied up to 80% of the minimum required.

  The installation of a multiway stop control is justified.

Types of Intersection Control

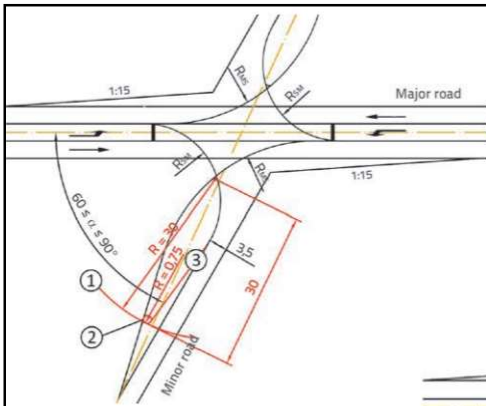
4. Intersection Channelization

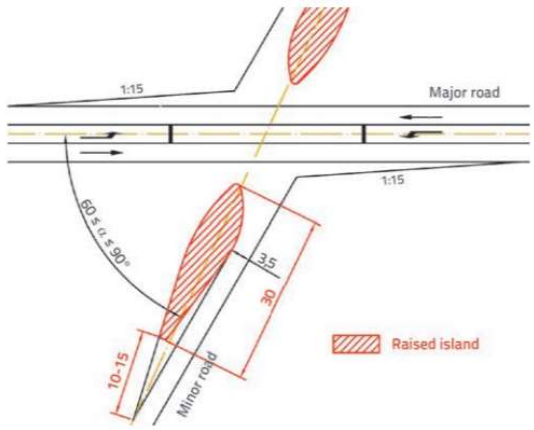
- Intersection channelization is used mainly to separate turn lanes from through lanes
- Guidelines for the use of channels at intersections include:
  - Laying out islands or channel lines to allow a natural, convenient flow of traffic
  - Avoiding confusion by using a few well-located islands
  - Providing adequate radii of curves and widths of lanes for the prevailing type of vehicle



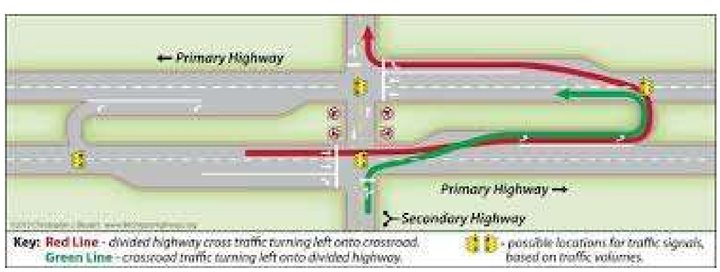
interchange

30





interchange



interchange

32

Types of Intersection Control

4. Traffic Signals

- The use of traffic signals is an effective ways of controlling traffic
  - It can be used to eliminate many conflicts
- Since it results in delay to all vehicles , **it is important that signals be used only when necessary**
- Most important factor that determines the need for traffic signals is approach traffic volume,
  - Also pedestrian volume and crash experience plays an important role

Types of Intersection Control

4. Traffic Signals

Normal Traffic Signal

LED Traffic Signal

Types of Intersection Control

4. Traffic Signals

– Manual Uniform Traffic Control Devices **MUTCD** describes eight warrants
  - **at least one of which should be satisfied to be signalized**

✓ 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

- **Choices are:**
  - Warrant is satisfied / met
  - Warrant is not satisfied
  - Not enough information / cannot be determined
  - Not applicable

interchange

36

Types of Intersection Control

Warant 1, Eight-hour vehicular volume

– **Condition A** (Minimum Vehicular Volume)

- It is satisfied when traffic volumes on the major-street and the **higher** volume minor-street approaches for each of any eight hours of an average day are at least equal to the volumes specified in the 100 percent columns of Table 8.1
- "Average" day is a weekday whose traffic volumes are normally and repeatedly observed at the location

Types of Intersection Control

Warrant 1, Eight-hour vehicular volume

– **Condition A** (Minimum Vehicular Volume)

Table 8.1 Volume Requirements for Warrant 1, Condition A, Eight-Hour Vehicular Volumes

Condition A—Minimum Vehicular Volume									
Number of Lanes for Moving Traffic on Each Approach		*Vehicles Per Hour on Major Street (Total of Both Approach)*				*Vehicles Per Hour on Higher Volume Minor-Street Approach (One Direction Only)*			
Major Street	*Minor Street*	*100%*[a]	*80%*[b]	*70%*[c]	*56%*[d]	*100%*[a]	*80%*[b]	*70%*[c]	*56%*[d]
1	1	500	400	350	280	150	120	105	84
2 or more	1	600	480	420	336	150	120	105	84
2 or more	2 or more	600	480	420	336	200	160	140	112
1	2 or more	500	400	350	280	200	160	140	112

Used after adequate trial of other remedial measures

May be used when the major-street speed exceeds 40 mi/h or in an isolated community with a population of less than 10,000

May be used after adequate trial of other remedial measures when the major-street speed exceeds 40 mi/h or in an isolated community with a population of less than 10,000

Types of Intersection Control

Warrant 1, Eight-hour vehicular volume

- **Condition B** (Interruption of Continuous Flow)
  - It is satisfied when traffic volumes on the major-street and on the **higher** volume minor-street approaches for each of any eight hours of an average day are at least equal to the volumes specified in Table 8.2.
  - Volumes for the major street and the high-volume minor street should be for the same eight hours
    - but the higher volume on the minor street does not have to be on the same approach during each of the eight hours being considered

Types of Intersection Control

Warrant 1, Eight-hour vehicular volume

- **Condition B** (Interruption of Continuous Flow)

Table 8.2 Volume Requirements for Warrant 1, Condition B, Interruption of Continuous Traffic

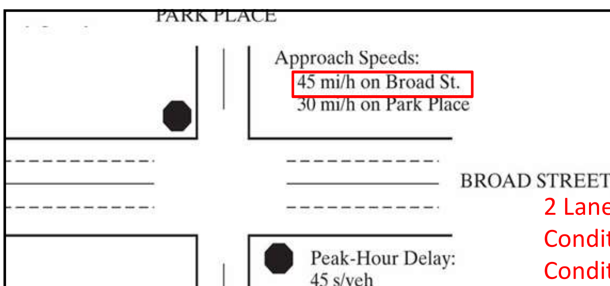
Condition B — Interruption of Continuous Traffic									
Number of Lanes for Moving Traffic on Each Approach		*Vehicles Per Hour on Major Street (Total of Both Approach)*				*Vehicles Per Hour on Higher Volume Minor-Street Approach (One Direction Only)*			
Major Street	*Minor Street*	*100%*[a]	*80%*[b]	*70%*[c]	*56%*[d]	*100%*[a]	*80%*[b]	*70%*[c]	*56%*[d]
1	1	750	600	525	420	75	60	53	42
2 or more	1	900	720	630	504	75	60	53	42
2 or more	2 or more	900	720	630	504	100	80	70	56
1	2 or more	750	600	525	420	100	80	70	56

Used after adequate trial of other remedial measures

May be used when the major-street speed exceeds 40 mi/h or in an isolated community with a population of less than 10,000

May be used after adequate trial of other remedial measures when the major-street speed exceeds 40 mi/h or in an isolated community with a population of less than 10,000

- We consider <u>only entering lanes</u>
- When each of Warrant 1 A and Warrant 1 B is not satisfied, we may use a combination of warrants (80% of 1A and 80% of Warrant B **<u>together</u>**).
- When the major-street speed exceeds 40 mph or is in an isolated community with a population of less than 10,000, then **70% of the original values are used**.
- The 56% values (80% x 70% = 56%) may be used for combination of Conditions A and B after adequate trial of other remedial measures when the major-street speed exceeds 40 mph or is in an isolated community with a population of less than 10,000.



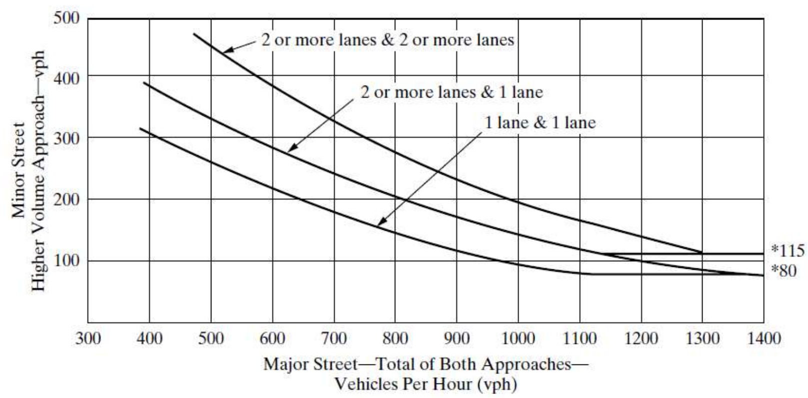
2 Lanes major with 1 lane minor
Condition A: (420 vs. 105)
Condition B: (630 vs. 53)

Time	Broad Street Vol (veh/h)			Park Place Volume (veh/h)			Ped Vol (ped/h) Xing Broad
	EB	WB	TOT	NB	SB	High Vol	
11 AM – 12	300	400	**700**	100	90	**100**	120
12 – 1 PM	325	450	**775**	110	125	**125**	115
1 – 2 PM	400	475	**875**	140	150	**150**	109
2 – 3 PM	450	480	**930**	150	165	**165**	122
3 – 4 PM	455	475	**930**	155	170	**170**	135
4 – 5 PM	445	425	**870**	160	160	**160**	140
5 – 6 PM	400	380	**780**	152	155	**155**	125
6 – 7 PM	385	350	**735**	140	150	**150**	121
7 – 8 PM	350	350	**700**	145	152	**152**	120
8 – 9 PM	350	375	**725**	130	156	**156**	105
9 – 10 PM	325	325	**650**	122	120	**122**	85
10 – 11 PM	300	300	**600**	120	95	**120**	85

Types of Intersection Control

Warrant 2, Four-hour vehicular volume

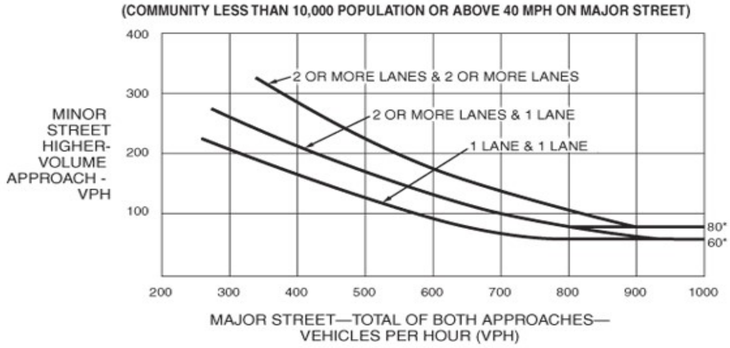
– This warrant is considered at locations where the main reason for installing a signal is the high intersecting volume



Types of Intersection Control

Figure 4C-2. Warrant 2, Four-Hour Vehicular Volume (70% Factor)

(COMMUNITY LESS THAN 10,000 POPULATION OR ABOVE 40 MPH ON MAJOR STREET)



*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.

– This figure can be used when 85th-percentile speed of the major-street traffic is higher than 40 mi/h

– **When the plot for each of any four hours of an average day falls above the standard graph, this warrant is satisfied**

Types of Intersection Control

Warrant 3, Peak Hour

This warrant is used when traffic conditions during one hour of the day or longer result in undue delay to traffic on the minor street **(Either Condition A or B)**

– **Condition A**

- The warrant is satisfied when two conditions are met:

✓Delay during any four consecutive 15-minute periods on one of the minor-street approaches controlled by a stop sign is equal to or greater than specified levels

Delay level: 4 veh-hrs for a one-lane approach and 5 veh-hrs for a two lane approach

Types of Intersection Control

– **Condition A**

✓Same minor-street approach volume and the total intersection entering volume are equal to or greater than the specified levels

For the same minor approach (one direction only) are 100 veh/h for one moving lane of traffic, and 150 veh/h for two moving lanes of traffic.

For total intersection volume are 650 veh/h for intersections with three approaches, and 800 veh/h for intersections with four or more approaches.

- Total Intersection Delay:
  - Approach Volume = 300 Veh/hr
  - Average Delay = 45 sec
  - Total Delay = 45 x 300 / 3600 = 3.75 veh-hr

interchange

47

Types of Intersection Control

Warrant 3, Peak Hour

– **Condition B** (Figure 8.6 and 8.7)

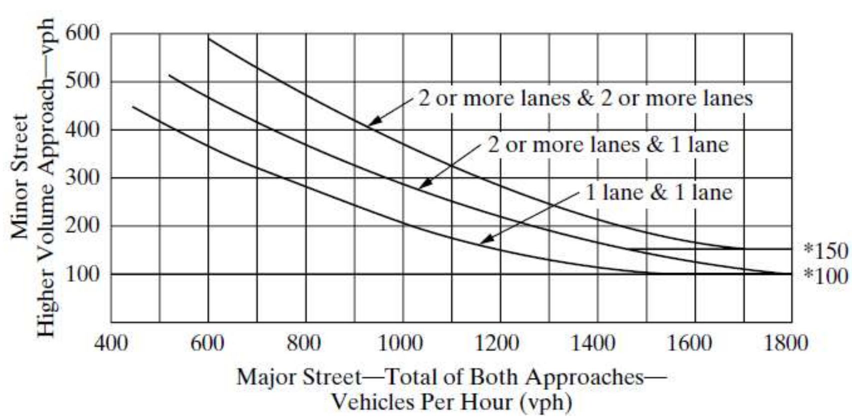


Figure 8.6

Types of Intersection Control

Warrant 3, Peak Hour

– **Condition B** (Figure 8.6 and 8.7)

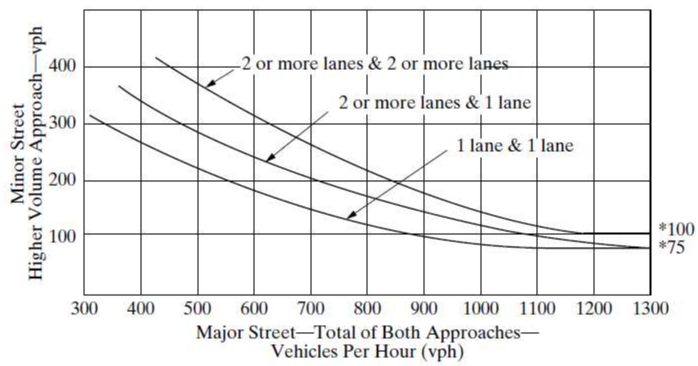


Figure 8.7

For locations where the speed on the major street is higher than 40 mi/h, or where the intersection is within an isolated built-up area with a population less than 10,000

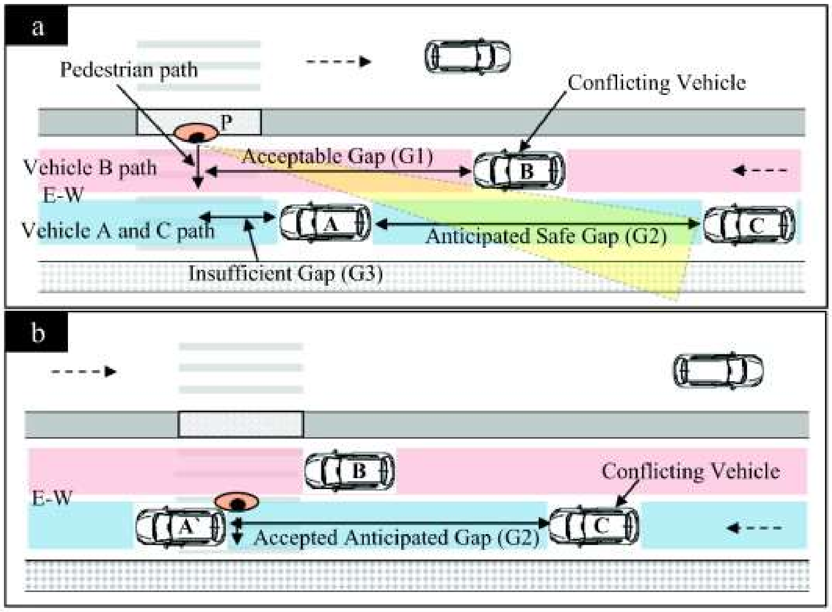
Types of Intersection Control

Warrant 4, Minimum Pedestrian volume

– This warrant is satisfied when:

- Pedestrian volume crossing the major street on an average day is at least 100 for each of any four hours or 190 or higher during any one hour **and**
- There are fewer than 60 acceptable gaps per hour by pedestrians **and**
- The nearest traffic signal along the major street should be at least 90 m (300 ft) away from the proposed intersection.

If only this warrant is satisfied, a pedestrian push button is used.



interchange

51

Types of Intersection Control

Warrant 5, School Crossing

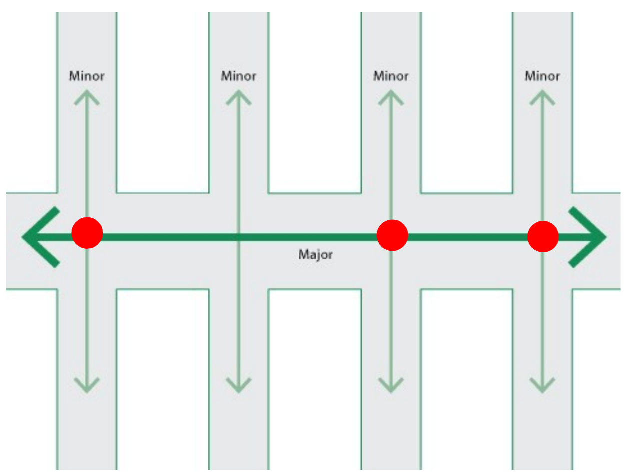
- In this case the main reason for installing a traffic signal control is to accommodate the crossing of the major street by schoolchildren
- This warrant is satisfied if during the period when school children are using the crossing:
  - Number of acceptable gaps is less than the number of minutes in that period and there are at least **20 students** during the highest crossing hour

The signal should be actuated, and all obstructions to view (such as parked vehicles) should be prohibited for at least 100 ft before and 20 ft after the crosswalk

Types of Intersection Control

Warrant 6, Coordinated Signal System

- This warrant may justify the installation if it will enhance the progressive movement of traffic along a highway segment with a coordinated traffic-signal system
- In such case the installation of traffic signal will help maintain a proper grouping of vehicles and effectively regulate group speed.
- **This warrant is not applicable when the resultant spacing of the traffic signal is less than 300 ft**



Types of Intersection Control

Warrant 7, Crash Experience

- This warrant is used when the purpose of installing a traffic signal control is to reduce number and severity of crashes
- This warrant is satisfied if
  - Five or more injury or property-damage-only (PDO) crashes have occurred within a 12-month period and that signal control is a suitable countermeasure for these crashes, and
  - Traffic and pedestrian volumes should not be less than 80 percent of the requirements specified in the
    - minimum vehicular volume warrant (Table 8.1), the interruption of continuous traffic warrant (Table 8.2), or
    - the minimum pedestrian volume warrant

Types of Intersection Control

Warrant 8, Roadway Network

- This warrant may justify the installation if it will help to encourage concentration and organization of traffic networks
- The warrant can be applied at intersections of two or more major roads when
  1) Total entering volume is at least 1000 during the peak hour of a typical weekday **and**
  2) Five-year projected traffic volumes, based satisfy the requirements of the following warrants:
     - ✓ eight-hour vehicular volume,
     - ✓ four-hour vehicular volume,
     - ✓ peak-hour volume during an average weekday

Types of Intersection Control

Warrant 8, Roadway Network

– A major street considered for this warrant should possess at least one of the following characteristics:

- A component of a highway system that serves as the principal roadway network for through traffic flow
- A component of a highway system that includes rural or suburban highways outside, entering, or traversing a city
- It is designated as a major route on an official transportation plan or equivalent standard plots

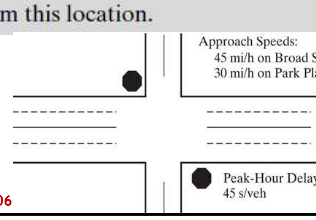
Types of Intersection Control

Example 8.2 Determining Whether the Conditions at an Intersection Warrant Installing a Traffic-Signal Control

A two-lane minor street crosses a four-lane major street. If the traffic conditions are as given, determine whether installing a traffic signal at this intersection is warranted.

1. The traffic volumes for each eight hours of an average day (both directions on major street) total 400 veh/h. For the higher volume minor-street approach (one direction only), the total is 100.
2. The 85th-percentile speed of major-street traffic is 43 mi/h.
3. The pedestrian volume crossing the major street during an average day is 200 ped/h during peak pedestrian periods (two hours in the morning and two hours in the afternoon).
4. The number of gaps per hour in the traffic stream for pedestrians to cross during peak pedestrian periods is 52.
5. The nearest traffic signal is located 450 ft from this location.

2 Lanes major with 1 lane minor
Condition A: (420 vs. 105)
Condition B: (630 vs. 53)



Types of Intersection Control

Options: signal warrant is (a) met, (b) not met, (c) not applicable, or (d) insufficient information given to assess (Cannot be determined).

2 Lanes major with 1 lane minor
Condition A: (420 vs. 105)
Condition B: (630 vs. 53)

- 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

5.4 Signal Timing

Signal Timing: Definition of Terms

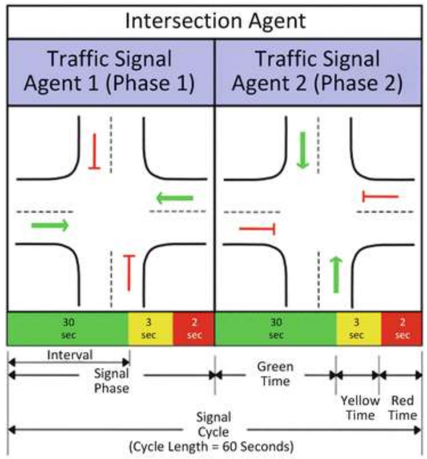
- The efficient operation of the signal requires proper timing of the different color indications
- It is necessary to define a number of terms commonly used in the design of signal times:

① **Controller:** A device in a traffic signal installation that changes the colors indicated by the signal lamps according to a fixed or variable plan

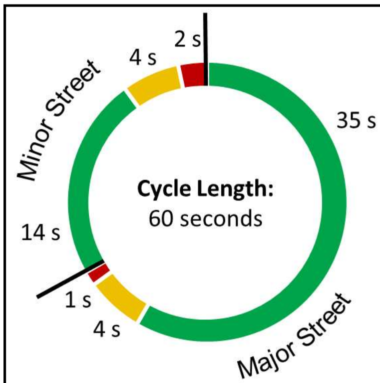
- It assigns the right of- way to different approaches at appropriate times
- It is capable of accommodating coordinated-actuated operation and preemption

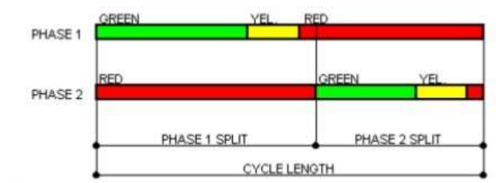
Signal Timing: Definition of Terms

② **Cycle (cycle length):** the time in seconds required for one complete color sequence of signal indication



Cycle





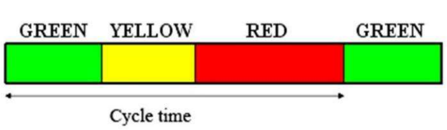


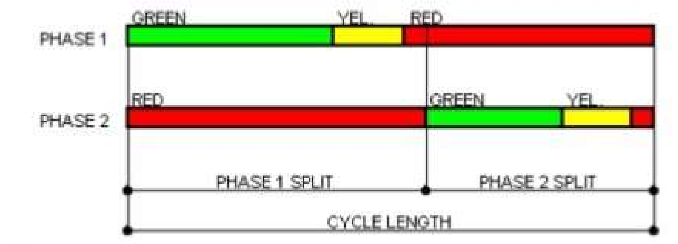
Figure 1: signal timing at a traffic signal

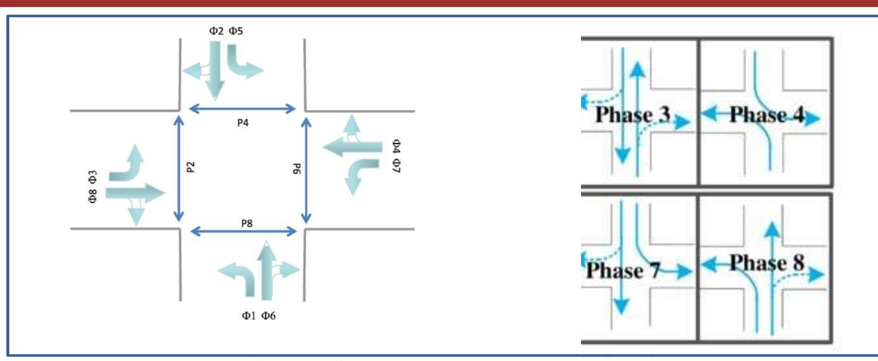
- Minimum and Maximum Cycle length?
- Minimum 35-40 sec
- Regular Max = 120 sec
- Could reach 150-180 sec

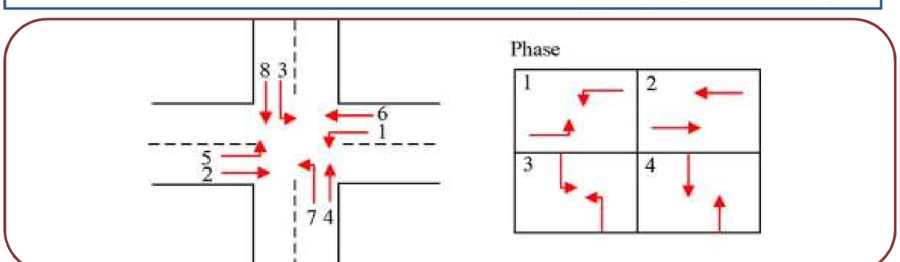
Signal Timing: Definition of Terms

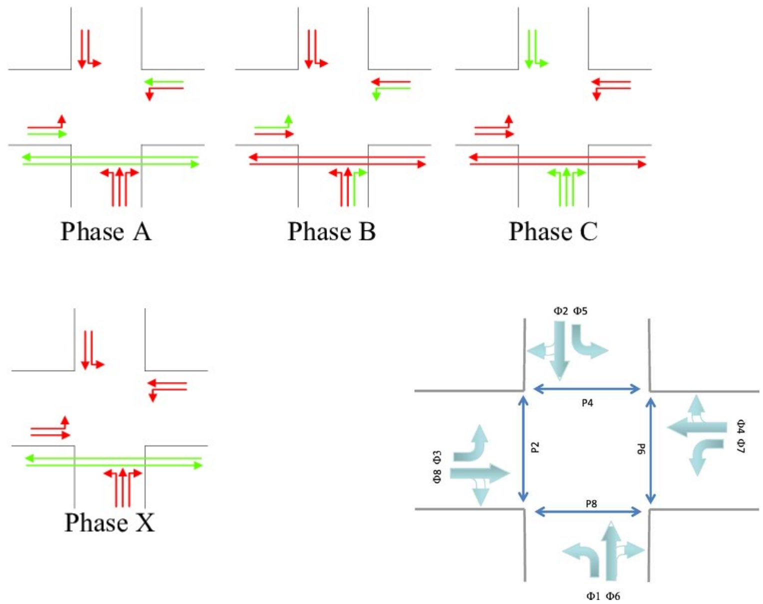
③ **Phase (signal phase):** That part of a cycle allocated to a stream of traffic or a combination of two or more streams of traffic having the right-of-way simultaneously during one or more intervals

④ **Interval:** Any part of the cycle length during which signal indications do not change





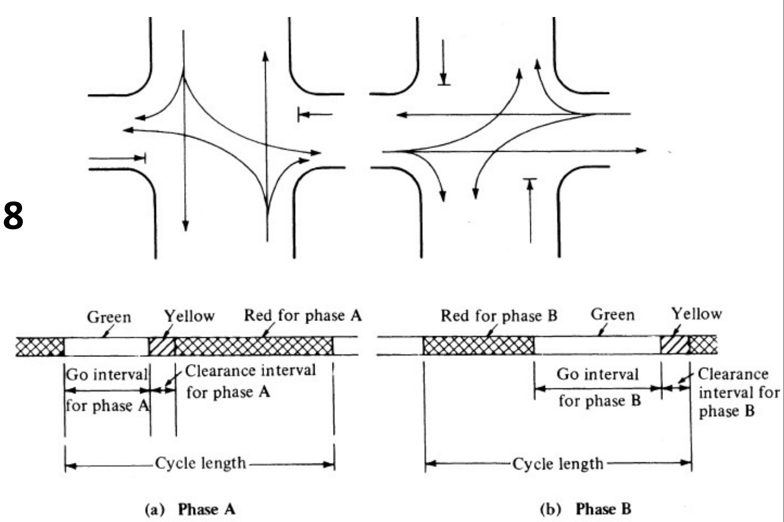




interchange

67

Figure 8.8



interchange

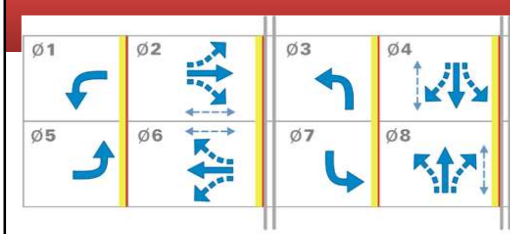
68

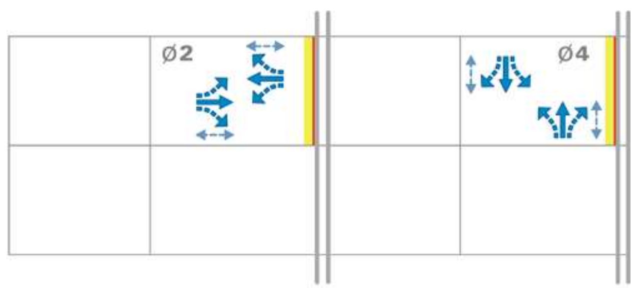
Signal Timing: Definition of Terms

13. Permitted turning movements: are those made within gaps of an opposing traffic stream or through a conflicting pedestrian flow

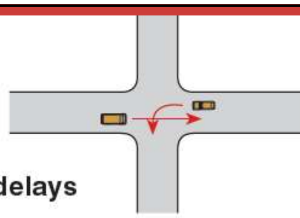
14. Protected turns: are those turns protected from any conflicts with vehicles in an opposing stream or pedestrians on a conflicting crosswalk

- A permitted turn takes more time than a similar protected turn and will use more of the available green time

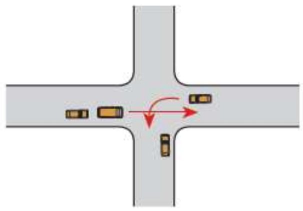




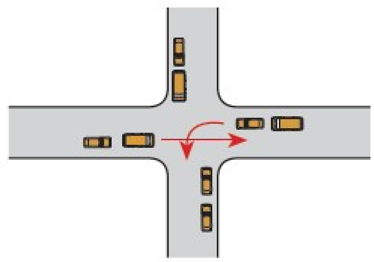
interchange



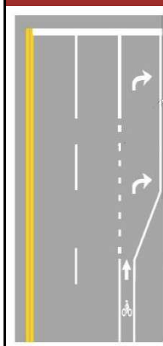
Minimal delays

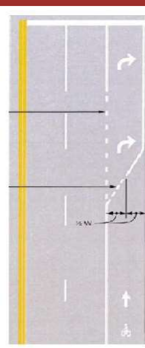


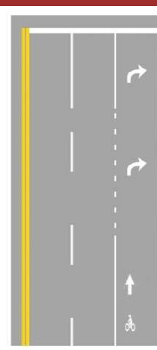
B Low levels of delay and queuing

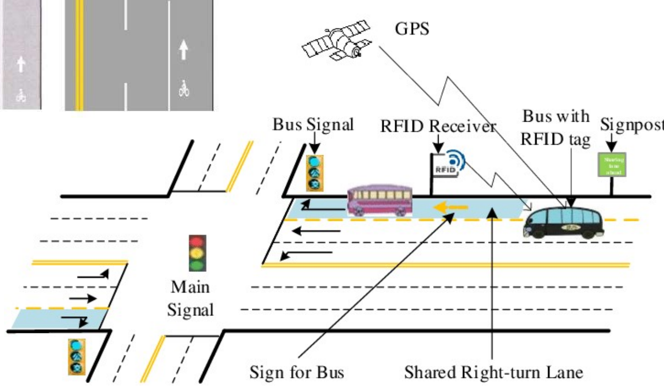


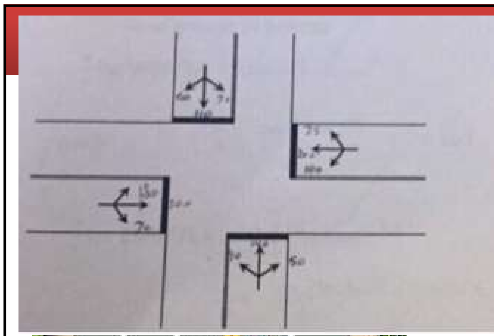
When can use protected (or exclusive) right or left turn phase?











Signal Timing: Definition of Terms

⑥ **Change and clearance interval:** The total length of time in seconds of the yellow and all-red signal indications

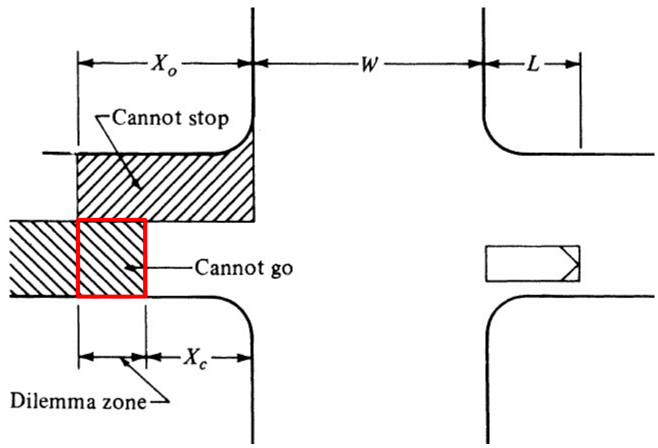
- It is provided for vehicles to clear the intersection after the green interval before conflicting movements are released

⑦ **All-red interval:** The display time of a red indication for all approaches

- It is used to allow vehicles and pedestrians to clear large intersections before opposing approaches are released
- Sometimes, it is used as a phase exclusively for pedestrian crossing

- **Phase Length = G + Amber (yellow, ţ) + All-Red (AR)**

Yellow Interval



Signal Timing: Definition of Terms

⑨ **Peak-hour factor (PHF):** A measure of the variability of demand during the peak hour

- It is the ratio of the volume during the peak hour to the maximum rate of flow during a given time period within the peak hour.
- For intersections, the time period used is 15 min, and PHF is given as

$$\text{PHF} = \frac{\text{Volume during peak hour}}{4 \times \text{volume during peak 15 min within peak hour}}$$

Signal Timing: Definition of Terms

⑨ Peak-hour factor (PHF):

- PHF may be used, to compensate for the possibility that peak arrival rates for short periods during the peak hour may be much higher than the average for the full hour
- Design hourly volume (DHV) can then be obtained as

$$\text{DHV} = \frac{\text{Peak hour volume}}{\text{PHF}}$$

- Some of the known influencing factors on PHF are :
  - ✓ Traffic generators being served by the highway,
  - ✓ Distances between these generators and the highway
  - ✓ Population of the metropolitan area in which the highway is located

---

- Traffic Volumes:
  - 1^{st} 15 min = 150
  - 2^{nd} 15 min = 200
  - 3^{rd} 15 min = 200
  - 4^{th} 15 min = 250
  - One hour = 800 veh/hr
  - Average per 15 min = 200 veh / 15 min
  - Peak 15 min = 250 veh/15 min
  - PHF = 800 / (4*250) = 0.80
  - Design Hourly Volume = PHV / PHF = 800/0.80 = 1000 veh/hr

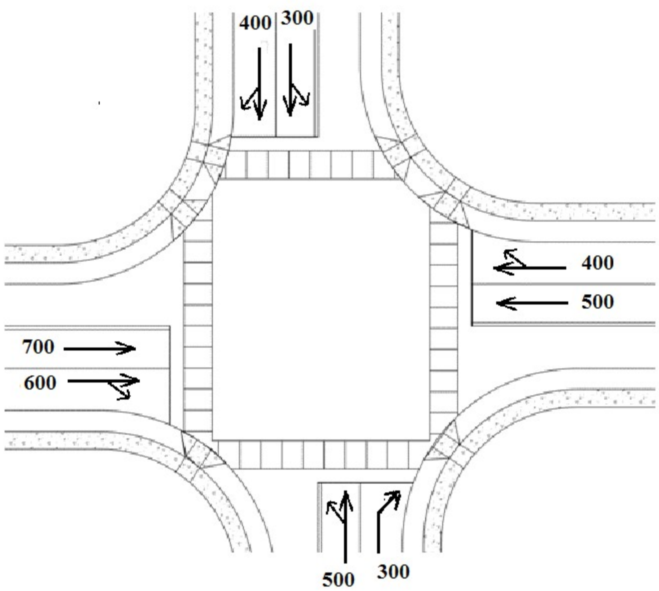
interchange

78

Signal Timing: Definition of Terms

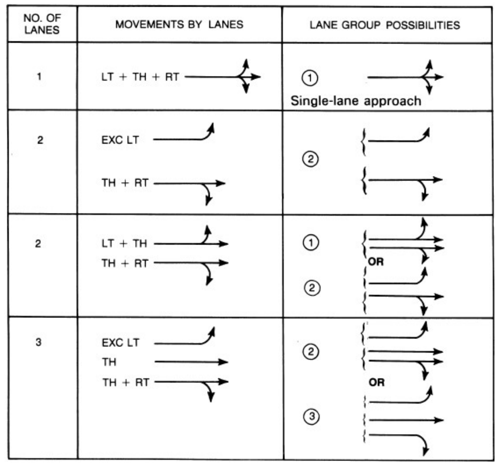
⑩ Lane group:

- A lane group consists of one or more lanes on an approach which have the same green phase
- Lane groups **LG** for each approach are established using the following guidelines:
  A) Exclusive left-turn lane(s) should be in separated LG, unless the approach also contains a shared left-turn and through lane (same for exclusive RT lanes)
  B) When exclusive LT lanes and/or exclusive RT lanes are provided, all other lanes are generally established as a single lane group



Signal Timing: Definition of Terms

⑩ Lane group:



When two or more lanes have been established as a single lane group for analysis, all subsequent computations consider these lanes a single entity

Signal Timing: Definition of Terms

11. Critical Lane group: The lane group that requires the longest green time in a phase, and therefore, determines the green time that is allocated to that phase

12. Saturation flow rate: The flow rate in veh/h that the lane group can carry if it has the green indication continuously, (i.e., if $g/C = 1$)

Signal Timing: Definition of Terms

12. Saturation flow rate: It depends on an ideal saturation flow (so), which is usually taken as 1900 veh/h of green time per lane.

- The ideal saturation flow is then adjusted for the prevailing conditions to obtain the saturation flow for the lane group being considered

$$s = s_o N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$$

Signal Timing: Definition of Terms

12. Saturation flow rate:

$$s = s_o N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb}$$

s = saturation flow rate for the subject lane group expressed as a total for all lanes in the lane group (veh/h)
s_o = base saturation flow rate per lane (pc/h/ln)
N = number of lanes in the group
f_w = adjustment factor for lane width
f_{HV} = adjustment factor for heavy vehicles in the traffic stream
f_g = adjustment factor for approach grade
f_p = adjustment factor for the existence of a parking lane and parking activity adjacent to the lane group
f_{bb} = adjustment factor for the blocking effect of local buses that stop within the intersection area
f_a = adjustment factor for area type
f_{LU} = adjustment factor for lane utilization
f_{LT} = adjustment factor for left turns in the lane group
f_{RT} = adjustment factor for right turns in the lane group
f_{Lpb} = pedestrian adjustment factor for left-turn movements
f_{Rpb} = pedestrian/bicycle adjustment factor for right-turn movements

Signal Timing: Definition of Terms

Table 10.4 Adjustment Factors for Saturation Flow Rates[a]

Factor	Formula	Definition of Variables	Notes
Lane width	$f_w = 1 + \frac{(W - 12)}{30}$	W = lane width (ft)	W ≥ 8.0 If $W > 16$, two-lane analysis may be considered
Heavy vehicles	$f_{HV} = \frac{100}{100 + \%HV(E_T - 1)}$	$\%HV$ = percent heavy vehicles for lane group volume	$E_T = 2.0$ pc/HV
Grade	$f_g = 1 - \frac{\%G}{200}$	$\%G$ = percent grade on a lane group approach	$-6 \leq \%G \leq +10$ Negative is downhill
Parking	$f_p = \frac{N - 0.1 - \frac{18N_m}{3600}}{N}$	N = number of lanes in lane group N_m = number of parking maneuvers/h	$0 \leq N_m \leq 180$ $f_p = \geq 0.050$ $f_p = 1.000$ for no parking
Bus blockage	$f_{bb} = \frac{N - \frac{14.4N_B}{3600}}{N}$	N = number of lanes in lane group N_B = number of buses stopping/h	$0 \leq N_B \leq 250$ $f_{bb} = \geq 0.050$
Type of area	$f_a = 0.900$ in CBD $f_a = 1000$ in all other areas		

Lane utilization	$f_{LU} = v_g/(v_{g1}N)$	v_g = unadjusted demand flow rate for the lane group, veh/h v_{g1} = unadjusted demand flow rate on the single lane in the lane group with the highest volume N = number of lanes in the lane group	
Left turns	Protected phasing: Exclusive lane: $F_{LT} = 0.95$ Shared lane: $f_{LT} = \frac{1}{1.0 + 0.05P_{LT}}$	P_{LT} = proportion of LTs in lane group	See pages 474 through 483 for non-protected phasing alternatives
Right turns	Exclusive lane: $f_{RT} = 0.85$ Shared lane: $f_{RT} = 1.0 - (0.15)P_{RT}$ Single lane: $f_{RT} = 1.0 - (0.135)P_{RT}$	P_{RT} = proportion of RTs in lane group	$f_{RT} = \geq 0.050$
Pedestrian-bicycle blockage	LT adjustment: $f_{Lpb} = 1.0 - P_{LT}(1 - A_{pbT})(1 - P_{LTA})$ RT adjustment: $f_{Rpb} = 1.0 - P_{RT}(1 - A_{pbT})(1 - P_{RTA})$	P_{LT} = proportion of LTs in lane group A_{pbT} = permitted phase adjustment P_{LTA} = proportion of LT protected green over total RT green P_{RT} = proportion of RTs in lane group P_{RTA} = proportion of RT protected green over total RT green	See pages 485 to 490 for step-by-step procedure

Table 10.5 Default Lane Utilization Factors

Lane Group Movements	*No. of Lanes in Lane Group*	*Percent of Traffic in Most Heavily Traveled Lane*	*Lane Utilization Factor (f_{Lu})*
Through or shared	1	100.0	1.000
	2	52.5	0.952
	3[a]	36.7	0.908
Exclusive left turn	1	100.0	1.000
	2[a]	51.5	0.971
Exclusive right turn	1	100.0	1.000
	2[a]	56.5	0.885

[a]If lane group has more lanes than number shown in this table, it is recommended that surveys be made or the largest f_{Lu}-factor shown for that type of lane group be used.

interchange

Signal Timing: Definition of Terms

15. Flow ratio: (**v/s**) is the ratio of the actual flow rate or projected demand ***v*** on a approach or lane group to the saturation flow rate ***s***

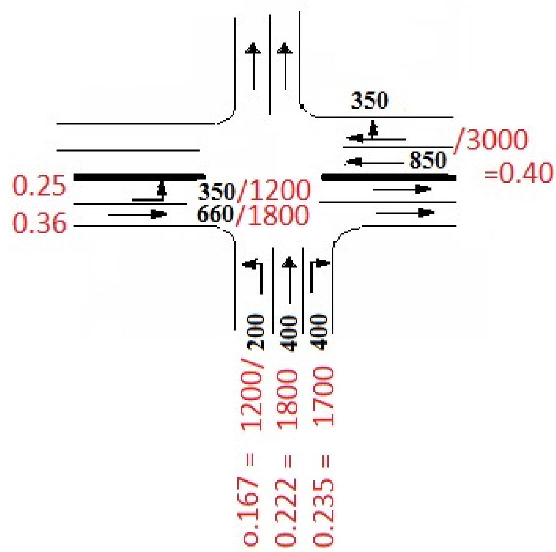
16. Level of Service LOS: is the operational analysis of an existing transportation facility

- For signalized intersections: It is used to determine the level of service at which the intersection is performing in terms of control or signal **delay**

Assume

- $S_L = 1200$
- $S_{TR} = 1200$
- $S_R = 1700$
- $S_T = 1800$

- Then v/s (as shown on figure)



interchange

89

- **Level-of-Service(LOS)** of a traffic facility is a concept introduced to relate the quality of traffic service to a given flow rate.
- Level-of-Service is introduced by **HCM** to denote the level of quality one can derive from a local under different operation characteristics and traffic volume.
- **Level of Service LOS:** is the operational analysis of an existing transportation facility
  - For signalized intersections: It is used to determine the level of service at which the intersection is performing in terms of control or signal **delay**

interchange

90

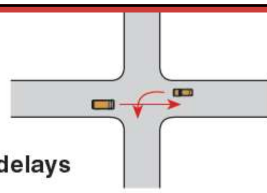
Signal Timing: Definition of Terms

16. Level of Surface LOS for Signalized Intersections

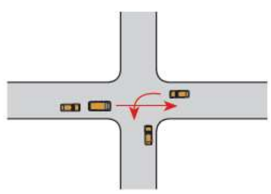
- LOS criteria are given in terms of the average control delay per vehicle during an analysis period of 15 minutes

Table 10.1 Level-of-Service Criteria for Signalized Intersections

Level of Service	*Control Delay Per Vehicle (sec)*
A	≤ 10.0
B	> 10.0 and ≤ 20.0
C	> 20.0 and ≤ 35.0
D	> 35.0 and ≤ 55.0
E	> 55.0 and ≤ 80.0
F	> 80.0

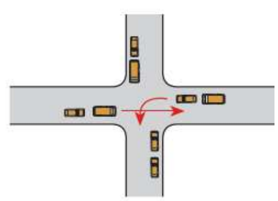


A Minimal delays

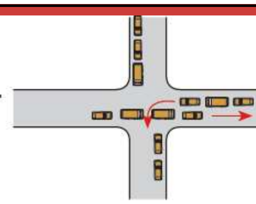


B Low levels of delay and queuing

C Intermittently vehicles wait through more than one signal indication, occasionally backups may develop, traffic flow still stable and acceptable.

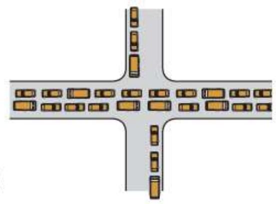


D Delays at intersections may become extensive, but enough cycles with lower demand occur to permit periodic clearance, preventing excessive backups. LOS D has historically been regarded as a desirable design objective in urban areas.



E Traffic fills intersection capacity, long queues and delays, many vehicles need to wait through more than one green indication

F Traffic demand exceeds capacity of intersection, very long queues and delays, most vehicles need to wait through more than one green indication



interchange

93

Signal Timing

Objective of Signal Timing

- The main objectives are to reduce the average delay of all vehicles and the probability of crashes
  - achieved by minimizing the possible conflict points when assigning the right of way
- However, sometime reducing delay conflicts with crash reduction
  - Number of phases should be kept to a minimum to reduce average delay but sometimes we need several phases to separate traffic streams and provide better safety
- **It is recommended to adopt a two-phase system whenever possible**

Signal Timing at Isolated Intersections

- An isolated intersection is one in which the signal time is not coordinated with that of any other intersection and therefore operates independently
- Cycle length usually 35 sec to 60 sec
  - Should be less than 120 sec
- Very long cycle lengths will result in excessive delay
- Two methods for designing cycle length will be discussed:
  1. **Webster method**
  2. **Highway Capacity Method**

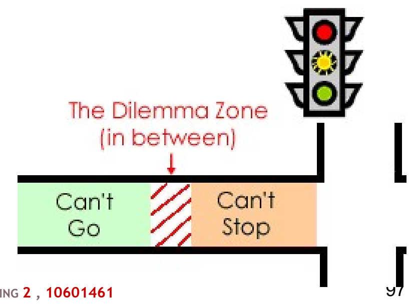
Before discussing these methods, we will discuss the basis for selecting the yellow interval at an intersection

Yellow Interval

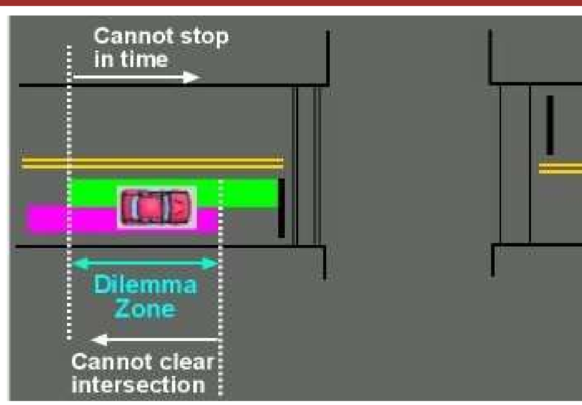
- The main purpose is to **alert motorists to the fact that the green light is about to change to red and to allow vehicles already in the intersection to cross it**

A bad choice of yellow interval may lead to the creation of a ***dilemma zone***

Dilemma zone: an area close to an intersection in which a vehicle can neither stop safely nor clear the intersection without speeding before the red signal comes on

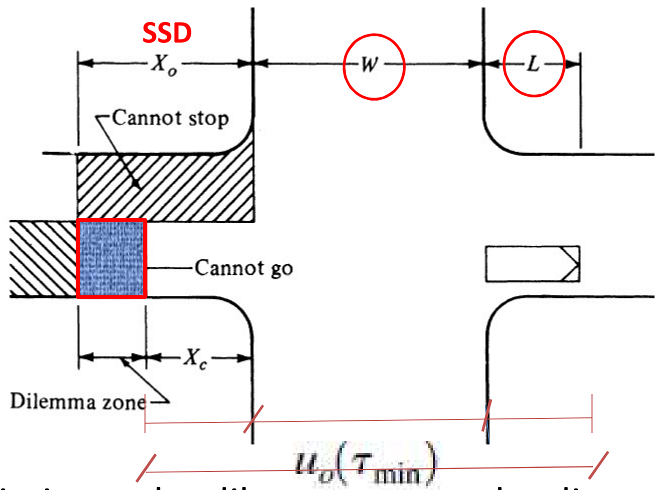


Yellow Interval



- The required yellow interval is the time period that guarantee that an approaching vehicle <u>can either stop safely or proceed through the intersection without speeding</u>

Yellow Interval



- To eliminate the dilemma zone, the distance X_o should be equal to the distance X_c

Yellow Interval

- Assuming t_{min} is the yellow interval (sec), the the distance travelled during it:

$$X_c = u_o(\tau_{min}) - (W + L)$$

- **X_c** is the distance within which a vehicle traveling at the speed limit (**u_o**) during the yellow interval **t_{min}** cannot stop before encroaching on the intersection

$$W = \text{Width of intersection (ft)}$$
$$L = \text{Length of vehicle (ft)}$$

Yellow Interval

- For vehicles to be able to stop:

$$X_o = u_o\delta + \frac{u_o^2}{2a}$$

X_o = the minimum distance from the intersection for which a vehicle traveling at the speed limit u_o during the yellow interval $\tau_{\min}$ cannot go through the intersection without accelerating; any vehicle at this distance or at a distance greater than this has to stop

δ = perception-reaction time (sec)

a = constant rate of braking deceleration (ft/sec^2)

AASHTO recommends a deceleration rate of 11.2 ft /sec^2

3.4 m /sec^2

Yellow Interval

- For the dilemma zones to be eliminated, X_o must be equal to X_c

$$u_o(\tau_{\min}) - (W + L) = u_o\delta + \frac{u_o^2}{2a}$$

$$\tau_{\min} = \delta + \frac{W + L}{u_o} + \frac{u_0}{2a}$$

After adding the effect of grade:

$$\tau_{\min} = \delta + \frac{W + L}{u_o} + \frac{u_o}{2(a + Gg)}$$

Yellow Interval

$$\tau_{min} = \delta + \frac{W + L}{u_o} + \frac{u_o}{2(a + Gg)} \quad \text{..........................} \quad (8.5)$$

- t_{min} is rounded to the nearest 0.5
- Safety considerations, normally preclude yellow intervals of less than **three seconds**
- To encourage motorists' respect for the yellow interval, it is usually not made longer than **five seconds**
- If longer yellow intervals are required, an **all-red interval** can be inserted after the yellow indication

Yellow + all-red ≥ The value of Equation (8.5)

Yellow Interval

Example 8.4 Determining the Minimum Yellow Interval at an Intersection

Determine the minimum yellow interval at an intersection whose width is 40 ft if the maximum allowable speed on the approach roads is 30 mi/h. Assume average length of vehicle is 20 ft.

Solution: We must first decide on a deceleration rate. AASHTO recommends a deceleration rate of 11.2 ft/sec^2. Assuming this value for a and taking δ as 1.0 sec, we obtain

$$\tau_{min} = 1.0 + \frac{40 + 20}{30 \times 1.47} + \frac{30 \times 1.47}{2 \times 11.2}$$
$$= 4.3 \text{ sec}$$

In this case, a yellow period of 4.5 sec will be needed.

Cycle Length Determination

- The signals at isolated intersections can be:
  - **Pre-timed (fixed),**
  - **Semi-actuated, or**
  - **Fully actuated**

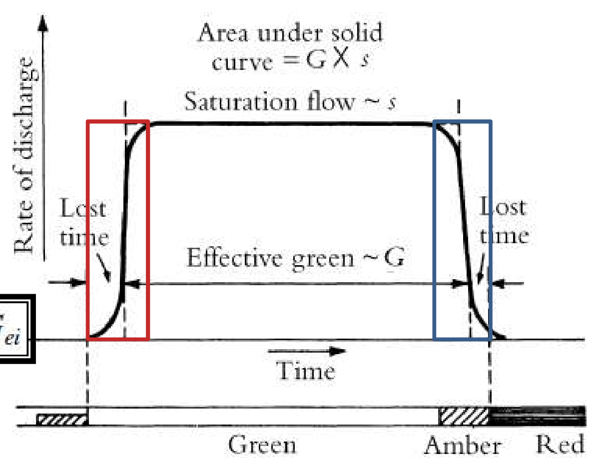
- Pre-timed signals assign the right of way to different traffic streams in accordance with a preset timing program
  - Cycle length that remains fixed for a specific period of the day or for the entire day

Cycle Length Determination

Webster Method

$G_e = G_{ai} + t_i - l_i$

$$\ell_i = G_{ai} + \tau_i - G_{ei}$$



Discharge of Vehicles at Various Times during a Green Phase

Cycle Length Determination

Webster Method

$$C_o = \frac{1.5L + 5}{1 - \sum_{i=1}^{\phi} Y_i}$$

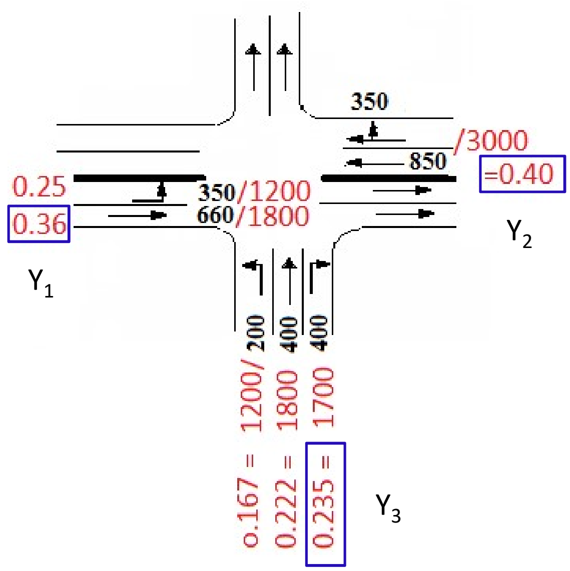
where

C_o = optimum cycle length (sec)
L = total lost time per cycle (sec)
Y_i = maximum value of the ratios of approach flows to saturation flows for all lane groups using phase i (i.e., q_{ij}/S_j)
ϕ = number of phases
q_{ij} = flow on lane groups having the right of way during phase i
S_j = saturation flow on lane group j

Assume

- S_L = 1200
- S_{TR} = 1200
- S_R = 1700
- S_T = 1800

- Then v/s (as shown on figure)



Cycle Length Determination

- The number of vehicles that go through the intersection is represented by the area under the curve
- Dividing the number of vehicles that go through the intersection by the saturation flow will give the effective green time, which is less than the sum of the green and yellow times

$$\ell_i = G_{ai} + \tau_i - G_{ei}$$

ℓ_i = lost time for phase i
G_{ai} = actual green time for phase i (not including yellow time)
τ_i = yellow time for phase i
G_{ei} = effective green time for phase i

Cycle Length Determination

Total lost time is given as

$$L = \sum_{i=1}^{\phi} \ell_i + R$$

where R is the total all-red time during the cycle.

- **Allocation of Green Times:** In general, the total effective green time available per cycle is given by

$$G_{te} = C - L = C - \left(\sum_{i=1}^{\phi} \ell_i + R \right)$$

C = actual cycle length used (usually obtained by rounding off C_o to the nearest five seconds)
G_{te} = total effective green time per cycle

Cycle Length Determination

- To **obtain minimum overall delay**, the total effective green time should be distributed among the different phases in proportion to their Y :

$$G_{ei} = \frac{Y_i}{Y_1 + Y_2 + \cdots Y_\phi} G_{te}$$

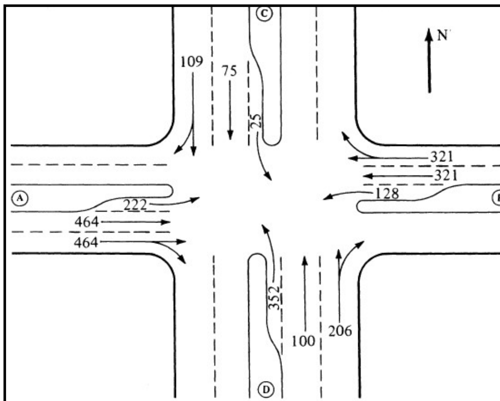
- Actual green time for each phase is obtained as

$$G_{a1} = G_{e1} + \ell_1 - \tau_1$$
$$G_{a2} = G_{e2} + \ell_2 - \tau_2$$
$$G_{ai} = G_{ei} + \ell_i - \tau_i$$
$$G_{a\phi} = G_{e\phi} + \ell_\phi - \tau_\phi$$

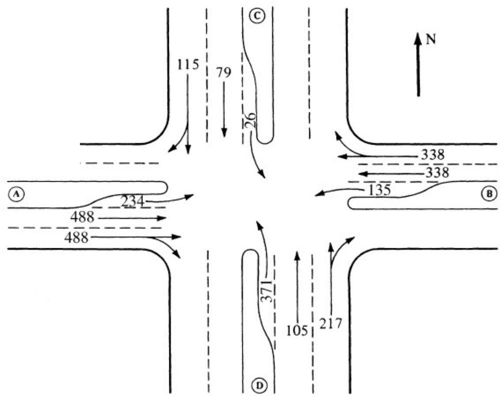
Cycle Length Determination

Webster Method

Example 8.5



PHF = 0.95
Pedestrian volume is negligible.



(b) Equivalent hourly flows

interchange

Example 8.5 Signal Timing Using the Webster Method

Figure 8.12a on page 354 shows peak-hour volumes for a major intersection on an expressway. Using the Webster method, determine a suitable signal timing for the intersection using the four-phase system shown below. Use a yellow interval of three seconds and the saturation flow given.

Phase	*Lane Group*	*Saturation Flow*
A	①	1615
	②	3700
B	①	3700
	②	1615
C	①	1615
	②	3700
D	①	1615
	②	3700

interchange

Phase (ϕ)	Critical Lane Volume (veh/h)
A	488
B	338
C	115
D	371
	Σ 1312

Compute the total lost time using Eq. 8.7. Since there is not an all-red phase—that is, $R = 0$—and there are four phases,

$$L = \sum \ell_i = 4 \times 3.5 = 14 \text{ sec (assuming lost time per phase is 3.5 sec)}$$

	Phase A (EB)		Phase B (WB)		Phase C (SB)		Phase D (NB)	
Lane Group	1	2	1	2	1	2	1	2
q_{ij}	234	976	676	135	26	194	371	322
S_j	1615	3700	3700	1615	1615	3700	1615	3700
Q_{ij}/S_j	0.145	0.264	0.183	0.084	0.016	0.052	0.230	0.087
Y_i	0.264		0.183		0.052		0.230	

- Determine Y_i and ΣY_i.

$$\Sigma Y_1 = (0.264 + 0.183 + 0.052 + 0.230) = 0.729$$

interchange

- Determine the optimum cycle length using Eq. 8.6.

$$C_o = \frac{1.5L + 5}{1 - \sum_{i=1}^{\phi} Y_i} = \frac{(1.5 \times 14) + 5}{1 - 0.729} = 95.9 \text{ sec}$$

Use 100 seconds as cycle lengths are usually multiples of 5 or 10 seconds.

- Find the total effective green time.

$$G_{te} = C - L = (100 - 14) = 86 \text{ sec}$$

Effective time for phase *i* is obtained from Eq. 8.9.

$$G_{ei} = \frac{Y_i}{Y_1 + Y_2 + \ldots + Y_n} G_{te} = \frac{Y_i}{0.264 + 0.183 + 0.052 + 0.230} 86 = \frac{Y_i}{0.729} 86$$

inter

Yellow time $\tau = 3.0$ sec; the actual green time G_{ai} for each phase is obtained from Eq. 8.10 as

$$G_{ai} = G_{ei} + \ell_i - 3.0$$

Actual green time for Phase A

$$(G_{aA}) = \frac{0.264}{0.729} \times 86 + 3.5 - 3.0$$
$$\approx 32 \text{ sec}$$

- 31.6 sec

Actual green time for Phase B

$$(G_{aB}) = \frac{0.183}{0.729} \times 86 + 3.5 - 3.0$$
$$\approx 22 \text{ sec}$$

- 22.1 sec

Actual green time for Phase C

$$(G_{aC}) = \frac{0.052}{0.729} \times 86 + 3.5 - 3.0$$
$$\approx 7 \text{ sec}$$

- 6.6 sec

Actual green time for Phase D

$$(G_{aD}) = \frac{0.23}{0.729} \times 86 + 3.5 - 3.0$$
$$\approx 27 \text{ sec}$$

- 27.6 sec

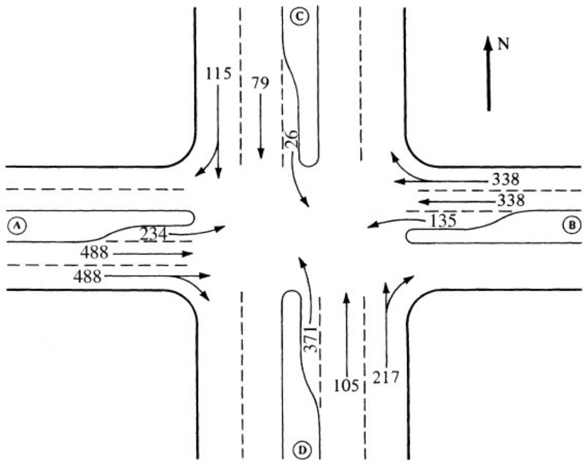
117

- Always check the final cycle length
- C = 32 + 22 + 7 + 27 + 4x3 = 100 sec
- $C = \Sigma G_i + \Sigma t_i + \Sigma AR_i$

interchange

118

Alternative Phasing



(b) Equivalent hourly flows

Phase	Lane Group	Saturation Flow
1	①	1615
	②	1615
2	①	3700
	②	3700
3	①	1615
	②	1615
4	①	3700
	②	3700

	Phase 1		Phase 2		Phase 3		Phase 4	
	EB L	WB L	EB TR	WB TR	NB L	SB L	NB TR	SB TR
q	234	135	976	667	371	26	322	194
S	1615	1615	3700	3700	1615	1615	3700	3700
q/s	**0.145**	0.084	**0.264**	0.180	**0.230**	0.016	**0.087**	0.052
Critical	0.145		0.264		0.23		0.087	

- Σ Yi = 0.145 + 0.264 + 0.230 + 0.087 = 0.726
- C = (1.5 x 14 + 5) / (1 – 0.726) = 94.9 sec (use 95 sec).

interchange

Cycle Length Determination

Minimum Green Time for Pedestrian

- If a significant number of pedestrians exist, it is necessary to provide a **minimum green** time that will allow the pedestrians to safely cross the intersection

$$G_p = 3.2 + \frac{L}{S_P} + \left[2.7\frac{N_{\text{ped}}}{W_E}\right] \qquad \text{for } W_E > 10 \text{ ft}$$

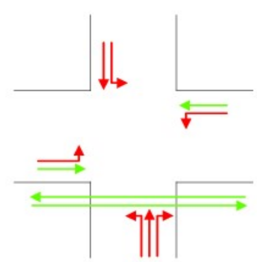
$$G_p = 3.2 + \frac{L}{S_P} + (0.27N_{\text{ped}}) \qquad \text{for } W_E \leq 10 \text{ ft}$$

G_p = minimum green time (sec)
L = crosswalk length (ft)
S_p = average speed of pedestrians, usually taken as 4 ft/sec (assumed to represent 15th percentile pedestrian walking speed)
3.2 = pedestrian start-up time
W_E = effective crosswalk width
N_{ped} = number of pedestrians crossing during an interval

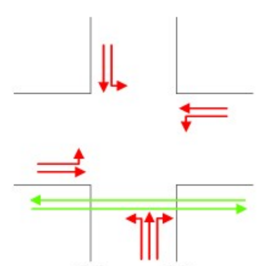
interchange

- When do pedestrians can cross the street?

(during green, yellow, and AR intervals)



Phase A



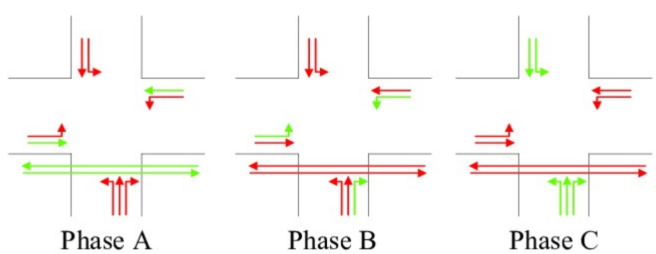
Phase X

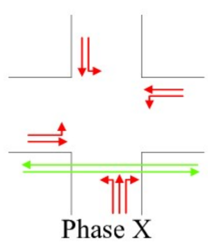
interchange

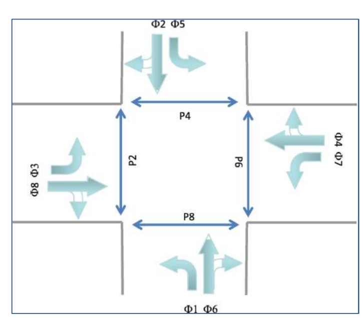
124

- Procedure:
  - Design signal phasing and timing for vehicles
  - Calculate minimum green time for pedestrians
  - Check if available time for pedestrians is sufficient or not for each phase.
  - If yes, then design is OK
  - If not, increase green time in that phase to allow for pedestrians to pass.
  - Double check the cycle length at the end.

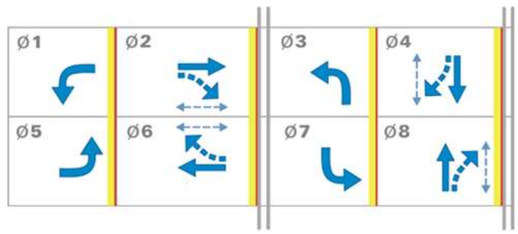
interchange

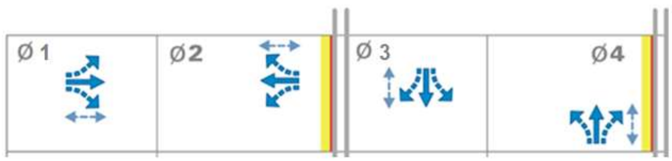




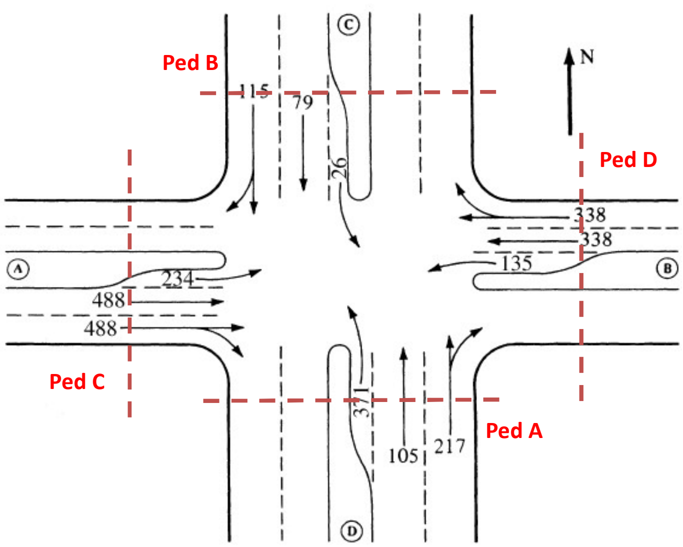


interchange





Check this example for pedestrian time



(b) Equivalent hourly flows

Yellow time $\tau = 3.0$ sec; the actual green time G_{ai} for each phase is obtained from Eq. 8.10 as

$$G_{ai} = G_{ei} + \ell_i - 3.0$$

Actual green time for Phase A

$$(G_{aA}) = \frac{0.264}{0.729} \times 86 + 3.5 - 3.0$$
$$\approx 32 \text{ sec}$$

Actual green time for Phase B

$$(G_{aB}) = \frac{0.183}{0.729} \times 86 + 3.5 - 3.0$$
$$\approx 22 \text{ sec}$$

Actual green time for Phase C

$$(G_{aC}) = \frac{0.052}{0.729} \times 86 + 3.5 - 3.0$$
$$\approx 7 \text{ sec}$$

Actual green time for Phase D

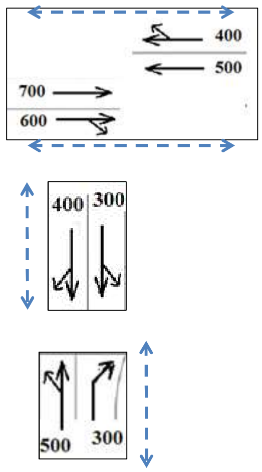
$$(G_{aD}) = \frac{0.23}{0.729} \times 86 + 3.5 - 3.0$$
$$\approx 27 \text{ sec}$$

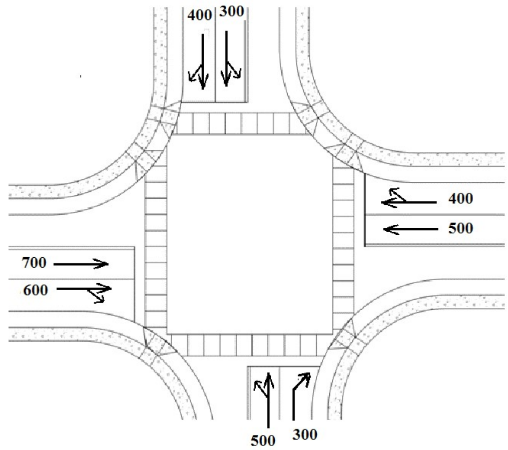
- **Ped time**
  - Design signal phasing and timing for vehicles

$$G_p = 3.2 + \frac{L}{S_p} + (0.27N_{\text{ped}}) \qquad \text{for } W_E \leq 10 \text{ ft}$$

  - G_{pA} = 3.2 + (5x11 + 8)/4 + 0.27 (15) = 23 sec (available time = 32 + 3 = 35 (OK)
  - Assuming the same time required for other phases, then
  - Available time for peds during phase B = 22+3 = 25 OK
  - Available time for peds during phase C = 7+3 = 10 Not OK
  - Available time for peds during phase D = 27+3 = 30 OK
  - So, What to do?
    - Increase green for Phase C ---- waste of time – delay
    - Or change phasing, change pedestrian phase (allow peds to move during another phase)

- Possible Phasing





interchange

Project Reminder

interchange

Cycle Length Determination

The Highway Capacity Method

- It is used to determine the cycle length based on the capacity (the maximum flow based on the available effective green time) of a lane group
- The capacity of an approach or lane group is given as:

$$c_i = s_i(g_i/C)$$

c_i = capacity of lane group i (veh/h)
s_i = saturation flow rate for lane group or approach i (veh/h of green, or veh/h/g)
(g_i/C) = green ratio for lane group or approach i
g_i = effective green for lane group i or approach i
C = cycle length

Cycle Length Determination

The Highway Capacity Method

- Degree of saturation: The ratio of flow to capacity (v/c) can be estimated by:

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

X_i = (v/c) ratio for lane group or approach i
v_i = actual flow rate for lane group or approach i (veh/h)
s_i = saturation flow for lane group or approach i (veh/h)
g_i = effective green time for lane group i or approach i (sec)

Cycle Length Determination

The Highway Capacity Method

- When the overall intersection is to be evaluated with respect to its geometry and the total cycle time, the concept of critical volume-to-capacity ratio (Xc) is used
- **Critical v/c ratio** for the whole intersection is given as

$$X_c = \sum_i (v/s)_{ci} \frac{C}{C - L}$$

X_c = critical v/c ratio for the intersection

$\Sigma_i(v/s)_{ci}$ = summation of the ratios of actual flows to saturation flow for all critical lanes, groups, or approaches

C = cycle length (sec)

L = total lost time per cycle computed as the sum of the lost time, (l_i) for each critical signal phase, $L = \Sigma l_i$

Cycle Length Determination

The Highway Capacity Method

- If the critical (v/c) ratio is less than 1.0, the cycle length provided is adequate for all critical movements to go through the intersection if the green time is proportionately distributed to the different phase
- **The minimum possible cycle length that avoid oversaturation occurs when the critical (v/c) ratio is equal to 1.0**
- Usually in this design method, we find the cycle length by assuming critical (v/c) ratio

Table 10.1 Level-of-Service Criteria for Signalized Intersections

Level of Service	*Control Delay Per Vehicle (sec)*
A	≤ 10.0
B	> 10.0 and ≤ 20.0
C	> 20.0 and ≤ 35.0
D	> 35.0 and ≤ 55.0
E	> 55.0 and ≤ 80.0
F	> 80.0

interchange

Cycle Length Determination

The Highway Capacity Method

Example 8.6

Example 8.7

Chapter 5
Intersection Control