2019 NSF RET Project

Modeling of Signalized Intersection Design and Impacts

Section 3

Fundamentals to Pre-timed Signal Design

Concept: Terminology (1)

- **Flow Rate** -- The rate, in vehicles per hour or passenger car units per hour, at which traffic is entering an intersection.
- **Flow Ratio** -- The ratio of the actual flow rate to the saturation flow rate.
- **Critical Flow Ratio** -- The flow ratio of the critical lane group within a phase. The actual or design flow rate for the critical movement divided by the saturation flow rate for that movement.
- **Critical Movement or Lane** -- The lane or movement for each phase, depending on how you choose to subdivide you intersection, that requires the most green time.
- **Critical Volume** -- A volume, or combination of volumes, which produces the greatest utilization of capacity for the street or lane in question, given in terms of passenger car units per hour per lane or mixed vehicles per hour per lane.
- **Cycle** -- A complete sequence of signal indications. Each phase has been serviced and the cycle is beginning again.
- **Cycle Length** -- The time required for one full cycle of signal indications, given in seconds.
- **Delay** -- The stopped time per vehicle (in seconds per vehicle), usually calculated separately for each lane group.

Concept: Terminology (2)

- **Green Interval** -- The portion of a signal phase in which the green signal is illuminated.
- **Green Time** -- The length of the green interval and its change interval, given in seconds.
- **Green Ratio** -- The ratio of the effective green time to the cycle length.
- **Intersection Flow Ratio** -- The sum of all the critical flow ratios--one from each phase.
- **Effective Green Time** -- The green time that is actually used by traffic. Some lost time occurs initially while traffic responds to the green signal and begins to accelerate. Some time is also lost during the intergreen period as vehicles stop in anticipation of the next phase.
- **Intergreen** -- The time interval between the end of a green indication for one phase and the beginning of green for the next phase. It is the sum of the yellow and all-red intervals.
- **All-red interval** -- Any portion of a signal cycle in which a red indication is observed by all approaches.

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Concept: Terminology (3)

- **Lane Group** -- Any group of lanes. Lanes can be combined during the signal timing design process in order to simplify the calculations.
- **Lost Time** -- The time during a given phase in which traffic could be discharging through the intersection, but is not. This is the period during the green interval and change intervals that is not used by discharging traffic.
- **Pedestrian Crossing Time** -- The time that is required for a pedestrian to cross the intersection. This is used to calculate the intergreen interval and the minimum green time for each phase.
- **Pedestrian WALK Interval** -- the portion of time during which the pedestrian signal says WALK. This period usually lasts around 4-7 seconds and is completely encompassed within the green interval for vehicular traffic. Some pedestrian movements in large cities are separate phases unto themselves.
- **Phase** -- The portion of the cycle that is devoted to servicing a given traffic movement.
- **Phase Sequence** -- The predetermined order in which the phases of a cycle occur.

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Concept: Terminology (4)

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- **Roadway Conditions** -- The physical aspects of the roadway, such as lane-width, number of lanes, easements, bike lanes, shoulder width, and any other aspect of the roadway.
- **Traffic Conditions** -- The qualities of traffic, such as traffic speed, density, vehicle types, and traffic flow rate.
- **Saturation Flow Rate** -- The maximum number of vehicles from a lane group that would pass through the intersection in one hour under the prevailing traffic and roadway conditions if the lane group was given a continuous green signal for that hour. This assumes that there is a continuous queue of vehicles with minimal headways.

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Concept: Isolated Signal Timing Design

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- Concepts of Timing Elements
  - The basic timing elements within each phase include:
    - Green time interval (and the effective green time)
    - Yellow (or amber interval), or Intergreen interval (sum of yellow and all-red intervals).
    - All-red interval
    - Pedestrian WALK interval
    - Pedestrian crossing time
- Some movements are allowed to proceed during a phase even though they cause conflicts.
  - Pedestrians are commonly allowed to proceed across intersections even though right-turn movements are occurring. These movements are called permitted, while protected movements are those without any conflicts. This might be one phase of a multi-phase cycle.
  - Permitted left turn with conflict of the opposing straight traffic is another common example

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Concept: NEMA Phasing Convention

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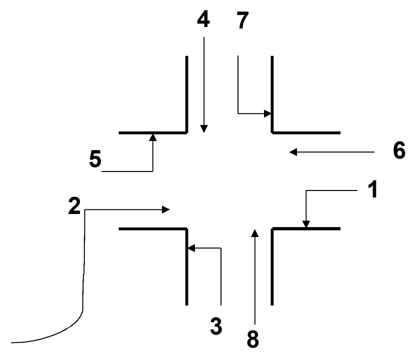
- Through Movements: Even numbers clockwise starting with heaviest movement
- Left Turn Movements: Odd numbers one less than opposing through movement designation



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Concept: NEMA Standards for Phasing

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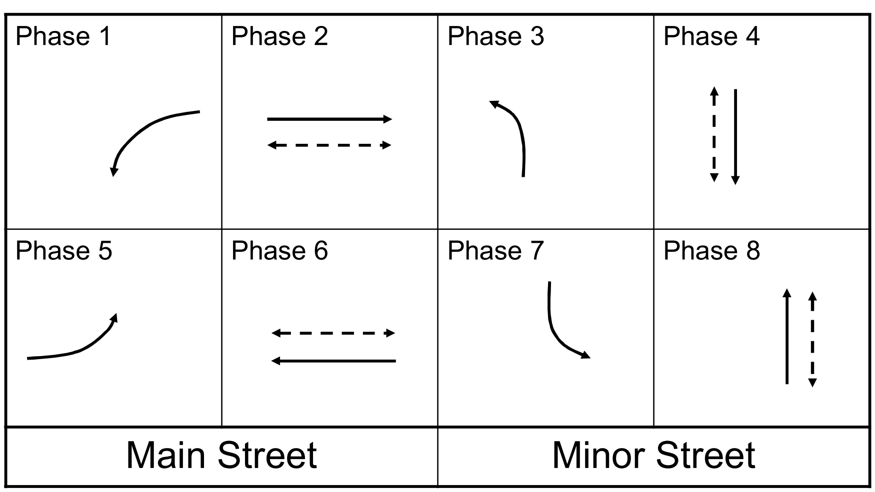

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Isolated Signal Timing Design

- Principle of cycle time design for normal (unsaturated) conditions
  - A joint consideration of many factors
  - Short cycle cause less delays, more stops, less desirable for pedestrian. 30-sec is considered to be practical minimum
  - Long cycle can handle higher volume, but cause more delay and longer queues. 120-sec is a practical maximum
- Some frequently used cycle time design alternatives
  - Design for pedestrian approach
  - The British (Webster's minim delay) method
  - The minimum capacity approach used in the U.S.
  - The cycle performance concept approach
  - The computer aided design approach

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General Factors Affected by Cycle Time

- Vehicular delay
- Frequency of stops
- Pedestrian safety
- Capacity
- Length of queue
- Fuel consumption
- Emission-related Air pollution

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Methods for Determining Cycle Length

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- Optimization Approach (e.g. British or Webster's minim delay method)
- Minimum Cycle Length Approach (assuming full utilization of the intersection)
- Desirable Cycle Length Approach (projected utilization of the intersection)
- Critical Volumes and Critical Lane Grouping Approaches

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Isolated Signal Timing Design

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- The British Method for Estimating Optimum Cycle Length (e.g. minimize overall delay)
  - *Derive optimum cycle length from intersection delay expression by differentiating it:*

$$\boxed{d = \frac{c(1-\frac{g}{C})^2}{2(1-\frac{g}{S})} + \frac{x^2}{2q(1-x)} - 0.65\left(\frac{C}{g^2}\right)^{\frac{1}{3}} x^{(2+5\frac{g}{C})}}$$

  - *To minimize delay, set differential* $\frac{\partial d}{\partial C} = 0$ *and after some simplifications*
  - Where, C_0 = optimum cycle length

L = total lost time; x_i = volume for phase i

$$\boxed{C_0 = \frac{1.5L + 5}{1 - \sum_{i=1}^{n} y_i}}$$

$y_i = \frac{x_i}{s_i}$ = Critical volume/saturation flow ratio for phase i;

S_i = 2000 for metropolitan area and 1900 for others

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Isolated Signal Timing Design:
British Method (Webster's Method)

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- The British Method for Estimating Saturation Flow
  - Saturation flow related to approach width

Width of Intersection Approach (ft)	Saturation Flow Rate (p.c.u./hour of effective green time)
17	2700
15	2250
13	1950
12	1900
10	1850

- In the US, the following thresholds are used:
  - Saturation flow: 2000 for metropolitan areas; 1900 otherwise

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Isolated Signal Timing Design

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- The British Method for Estimating Saturation Flow
  - Effect of composition of traffic. The effect of large vehicles and motorcycles is accounted for by making the following conversions:

    1 heavy or medium commercial vehicle = 1.75 p.c.u.
    1 light commercial vehicle = 1.00 p.c.u.
    1 bus = 2.25 p.c.u.
    1 passenger car = 1.00 p.c.u.
    1 motorcycle = 0.33 p.c.u.
  - Effect of left-turning vehicles. Left-turning vehicles which must cross an opposing traffic stream are allowed for by the following equation (or follow local manual):

    1 left-turning vehicle = 1.75 straight-ahead vehicles

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Isolated Signal Timing Design

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- The British Method for Estimating Saturation Flow
  - Effect on parked vehicle. The reduction is saturation flow depends on the distance between the first parked vehicle and the front stop line. The effect is expressed as a loss of available roadway width in the approach by the formula:
  - *Loss of roadway width (ft)* $= 5.5 - \dfrac{0.9(z-25)}{K}$
  - Where, z = distance from the parked car to the stop line, but if z < 25 ft, then use z = 25 ft (loss of width = 5.5 ft)

    K = green time, seconds

    If the entire expression becomes negative, loss of width = 0

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- The British Method for Estimating Saturation Flow
  - *Effect of grade. For downgrades on the approach up to 5%, increase saturation flow value by three times the grade percentage. For upgrades up to 10%, decrease the saturation flow value by three times the grade percentage.*
  - *Saturation flow values recommended for applications in US.*
    - *No standard estimate, but saturation rate calculated with 2000/2010 HCM is a good number*
    - *A value of 1900/pcplphg is often used*
    - *A value of 2000/pcplphg may be acceptable for intersections in large metropolitan areas*

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- The British Method for Estimating Saturation Flow
  - *Estimate of input parameters*
    - Y_i = *Yellow time (amber time) for phase i; generally 2-4 seconds*
    - L_i= *Lost time for phase i; 2 second in Webster's method; Pignataro suggested 3.7 seconds from Greenshield's starting delay values: 3.8, 3.1, 2.7, 2.4, 2.2, 2.1, ……*
    - *R = all red time*
    - $L = \sum_{i=1}^{\phi} l_i + R$ = *Total lost time*

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Isolated Signal Timing Design

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- The British Method for Estimating Saturation Flow
    - *C = cycle length (seconds)*
    - $Ge = C - L = C - (\sum_{i=1}^{\phi} l_i + R)$ = *Total effective green time*
    - $Ge_i = \frac{y_i}{\sum_{i=1}^{\phi} y_i} Ge$ = *Effective green time for phase i*
    - $Ga_i = Ge_i + l_i - Y_i$ = *Actual green time for phase i*
    - *Relationship of actual and effective green times, yellow time and lost time:* $l_i = Ga_i + Y_i - Ge_i$

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Isolated Signal Timing Design

- Example of Pre-timed Signal Timing Design (Webster's Method)
  - Lane configuration and traffic conditions are shown in the attached figure. The task is to design a four-phase traffic signal timing plan as shown in the figure. Assuming yellow time per phase is 3 seconds, and lost time per phase is 3.5 seconds.
  - Initial traffic condition:

    PHF = 0.95

    Left-turn factor = 1.4

    PCE for buses and trucks = 1.6

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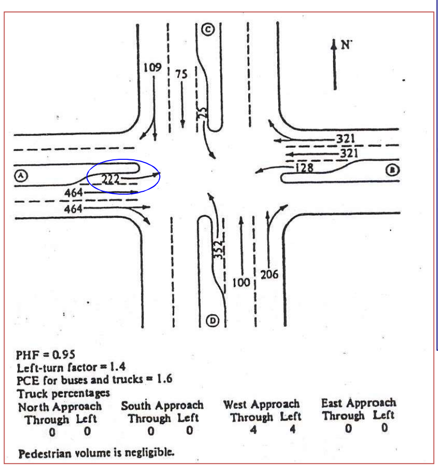
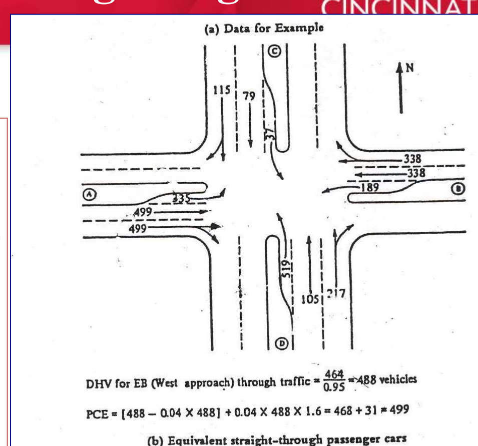
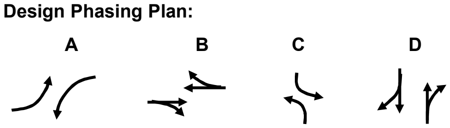
Isolated Signal Timing Design

Geometry and Traffic Conditions





Design Phasing Plan:



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Isolated Signal Timing Design

- Example of Pre-timed Signal Timing Design (Webster's Method)
  - **Step 1**: Convert traffic counts into straight-through passenger car equivalent unit, as shown in the following table.
  - **Step 2**: Identify critical volumes measured in PCE.

Items	Phase A		Phase B				Phase C		Phase D			
Lane	EB Left -turn	WB Left -turn	EB Through	EB Str-right	WB Through	WB Str -right	NB Left -turn	SB Left -turn	NB-Through	NB Str-right	SB Through	SB Str-right
Count	222	128	464	464	321	321	352	25	100	206	75	109
DHV	234	135	488	488	338	338	371	26	105	217	79	115
PCE	335	189	499	499	338	338	519	37	105	217	79	115
yi												
Critical *yi*												

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Isolated Signal Timing Design

- Example of Pre-timed Signal Timing Design (Webster's Method)
  - Notes:

    (1) Straight-Through Passenger Car Equivalent

    (2) Example 1 of conversion:
    - Design Hour Volume (DHV) for West Approach Left-turn Traffic = count/PHF = 222/0.95 = 234 veh.
    - PCE (converting DHV into straight-through volume) = [(234-0.04×234)+0.04×234×1.6)]×1.4 = 335 pc

    (3) Example 2 of conversion:
    - DHV for West Approach Through Traffic = count/PHF = 464/0.95 = 488 veh.
    - PCE (converting DHV into straight-through volume = (488-0.04×488)+0.04×488×1.6) = 499 pc

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Isolated Signal Timing Design

- Example of Pre-timed Signal Timing Design (Webster's Method)
  - **Step 3**: Identify critical volume/saturation ratio as shown in the following table.

Items	Phase A		Phase B				Phase C		Phase D			
Lane	EB Left -turn	WB Left -turn	EB Through	EB Str-right	WB Through	WB Str -right	NB Left -turn	SB Left -turn	NB-Through	NB Str-right	SB Through	SB Str-right
Count	222	128	464	464	321	321	352	25	100	206	75	109
DHV	234	135	488	488	338	338	371	26	105	217	79	115
PCE	335	189	499	499	338	338	519	37	105	217	79	115
yi	**0.17**	**0.09**	**0.25**	**0.25**	**0.17**	**0.17**	**0.26**	**0.02**	**0.05**	**0.11**	**0.04**	0.06
Critical *yi*	**0.17**			**0.25**			**0.26**			**0.11**		

Note: *yi* = (PCE volume)/2000; saturation flow rate is assumed 2000 pcplphg in this example

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Isolated Signal Timing Design

- Example of Pre-timed Signal Timing Design (Webster's Method)
  - **Step 4**: Determine optimum cycle length

Total lost time $L = \sum_{i=1}^{\phi} l_i + R = 4 \times 3.5 + 0 = 14$ seconds

Total critical volume/saturation flow ratio $\sum_{i=1}^{4} y_i$

$= 0.17 + 0.25 + 0.26 + 0.11 = 0.79$

Optimum cycle length $C_o = \dfrac{1.5L+5}{1-\sum_{i=1}^{4} y_i} = \dfrac{1.5 \times 14 + 5}{1-0.79} = 123.8$

say 120 s

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Isolated Signal Timing Design

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- Example of Pre-timed Signal Timing Design (Webster's Method)
  - **Step 5**: Determine total effective green time

$$Ge = C - L = C - (\sum_{i=1}^{\phi} l_i + R) = 120 - 14 = 106 \text{ seconds}$$

  - **Step 6**: Determine effective green time and actual green time for each phase

    Effective green time for phase A:

$$Ge_A = \frac{y_A}{\sum_{i=A}^{D} y_i} Ge = \frac{0.17}{0.79} \times 106 = 22.5 \quad \text{seconds}$$

    Actual green time for phase A:

$$Ga_A = Ge_A + l_A - Y_A = 22.5 + 3.5 - 3 = 23 \text{ seconds}$$

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Isolated Signal Timing Design

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- Example of Pre-timed Signal Timing Design (Webster's Method)
  - The following table summarizes the results for all phases

Timing Type	Phase A	Phase B	Phase C	Phase D
Green (sec)	23	34	35	14
Yellow (sec)	3	3	3	3
Red (sec)	94	83	82	103
Total (sec)	120	120	120	120

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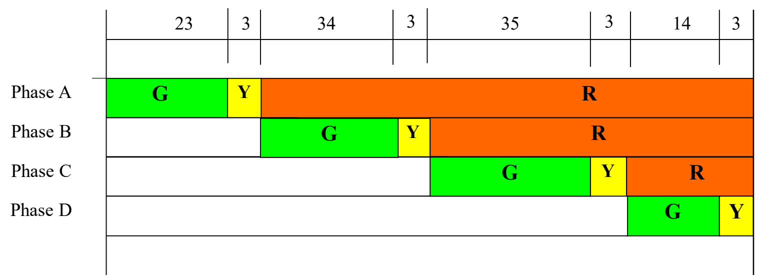
Isolated Signal Timing Design

- Example of Pre-timed Signal Timing Design (Webster's Method)
  - Phase Timing Diagram is shown below:



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Isolated Signal Timing Design

- **Minimum Cycle Length Approach**
  - Assume that the intersection is <u>100% utilized</u> (at capacity)

$$C_{\min} = \frac{N \times t_L}{1 - \left(\frac{V_c}{3600/h} \right)}$$

N: # phases in the cycle; t_L: lost time for each phase (sec); Vc: maximum sum of critical-lane volumes (veh/hr); h: saturation headway (sec).

- **Desired Cycle Length Approach**
  - Assume that the intersection <u>is utilized at a certain degree</u> (e.g. 80% of the capacity)

$$C_{des} = \frac{N \times t_L}{1 - \left(\frac{V_c}{(3600/h) \times PHF \times (v/s)} \right)}$$

  - *PHF: Peak Hour Factor; v/s: volume to saturation ratio.*

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Methods for Determining Cycle Length

Desirable Cycle Length Approach (Assume that the intersection is utilized at a certain degree)

$$C_{des} = \frac{N \times t_L}{1 - \left(\dfrac{V_c}{(3600/h) \times PHF \times (v/c)} \right)}$$

Example

t_L = 4 s/phase, h = 2.2 s, PHF =m 0.90, V_c = 1200 veh/h. What's desirable cycle length as v/c ratio varies from 1.00 ~ 0.90?

when v/c = 1.00 $$C_{des} = \frac{3 \times 4}{1 - \left(\dfrac{1200}{(3600/2.2) \times 0.90 \times 1.00} \right)} = 65\,\text{sec}$$

when v/c = 0.95 C_{des} = 85 sec
when v/c = 0.90 C_{des} = 130 sec
when v/c = 0.85 C_{des} = 290 sec (somewhat to long cycle)
when v/c = 0.80 C_{des} = -648 sec (definitely not applicable)

Proper acceptable range of v/c (1.00, 0.90) ← engineering experience, 30 ~ 120 sec

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Basics of Phasing Design

Traffic Signal Timing

- Vehicle Change Interval

Intergreeen Length

- The Length of the Vehicle Change Interval Can be Determined Using the Following Equation:

Y+AR = t + V/(2a+64.4g) + [(W+L)/V]

- Where:
  - Y+AR = Sum of the Yellow and All-Red
  - [(W+L)/V] = All Red Interval
  - t = Perception/Reaction Time of the Driver - Typically 1 Second
  - V = Approach Speed (ft/s)
  - a = Deceleration Rate (ft/s^2) – Typically 10 ft/s^2
  - W = Width of Intersection
    - Measured from the Near Side Stop Line to the Far Edge of the Conflicting Traffic Lane, Along the Actual Vehicle Path
  - L = Length of Vehicle (ft) – Typically 20 feet
  - g = Approach Grade
    - Percent of Grade Divided by 100
    - Plus for Upgrade & Minus for Downgrade

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Basics of Phasing Design

- Vehicle Change Interval
  - ITE – Manual of Traffic Signal Design (2nd Edition)
    - Table 11-1

TABLE 11-1
Theoretical Minimum Clearance Intervals

Approach Speed, mph	*Yellow Change Interval, s*	*Total Clearance Interval[a] (Yellow Plus All-Red Clearance) for Crossing-Street Widths, Feet*				
		30	*50*	*70*	*90*	*110*
20	3.0	4.2	4.9	5.5	6.2	6.9
25	3.0	4.2	4.7	5.3	5.8	6.4
30	3.2	4.3	4.8	5.2	5.7	6.2
35	3.6	4.5	4.9	5.3	5.7	6.1
40	3.9	4.8	5.1	5.5	5.8	6.1
45	4.5	5.1	5.4	5.7	6.0	6.3
50	4.7	5.3	5.6	5.9	6.2	6.4
55	5.0	5.7	5.9	6.2	6.4	6.7

[a]Using Eq. 11-3, with $t = 1$ s, $a = 10$ ft/s^2, and $L = 20$ ft.

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Lane Grouping

EXHIBIT 16-5. TYPICAL LANE GROUPS FOR ANALYSIS

Number of Lanes	Movements by Lanes	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

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Intersection Channelization

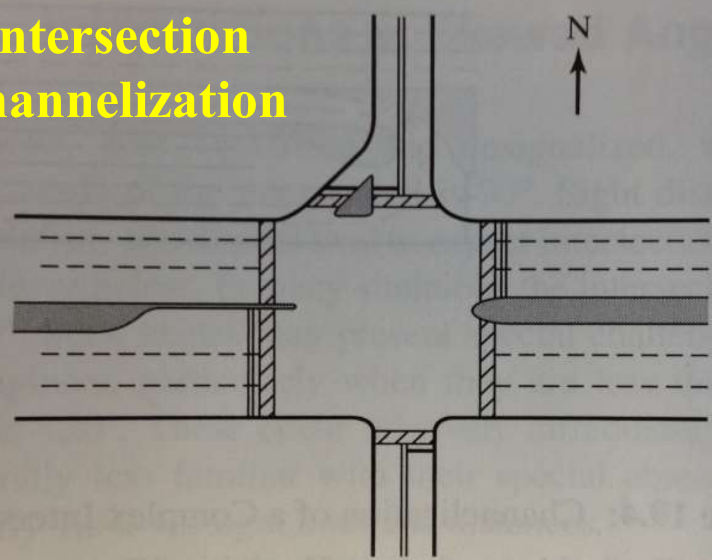

Figure 19.1: A Four-Leg Intersection with Partial Channelization for SB-EB and EB-SB Movements

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Treatment of Left Turns & Right Turns

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- Permitted left turn: the movement that is permitted to cross through the opposing flow but must select an appropriate gap in the opposing traffic stream through which to turn. It usually used where left-turn volumes are reasonable and where gaps in the opposing flow are adequate to accommodate left turn safely.
- Protected left turn: the left-turn vehicles are given a specific phase to allow them turn left while stopping the opposing through movement.
- Compound left turns: this is more complicated signal timing design in which left turn are protected for a portion of the signal cycle and are permitted in another portion of the cycle. Protected and permitted portions of the cycle can be provided in any order. Such phasing is also referred to as protected plus permitted or permitted plus protected, depending on the order of the sequences

End

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