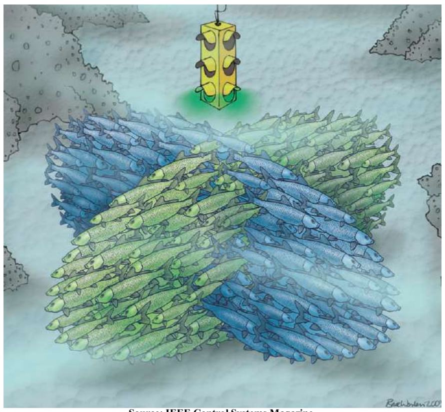
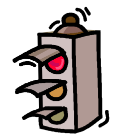


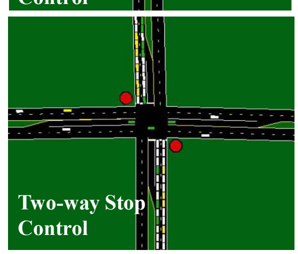
Source: IEEE Control Systems Magazine

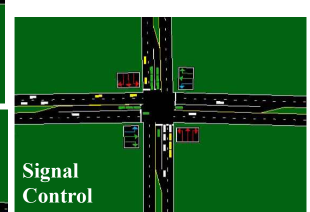
Introduction
Traffic Signal Control



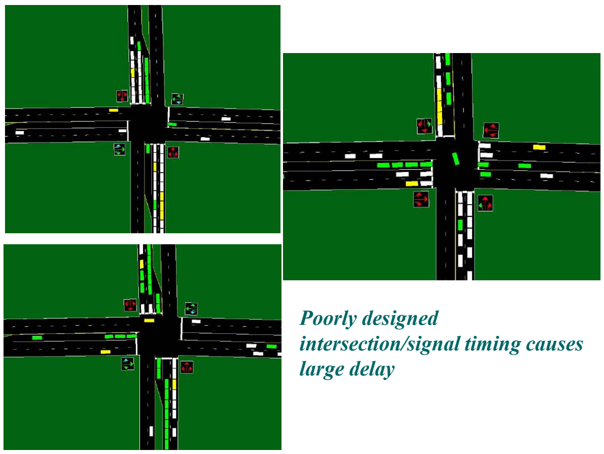
Safe and orderly movement at intersection?

Signals help orderly movement of traffic





Signals help reduce delay/stops and increase capacity



Poorly designed intersection/signal timing causes large delay

Benefits of (Properly Installed) Signals

- Provide orderly movement of traffic
- Increase the handling capacity of the intersection
- Reduce ~~accidents~~ crashes
- Provide coordinated continuous movement along a route
- Interrupt heavy traffic at intervals to permit other traffic to cross

Benefits of (Properly Installed&Timed) Signals

- A signal management program in California demonstrated a benefit-cost ratio of 17:1, with reductions of 14 percent in delay, 8 percent in fuel consumption, 13 percent in stops, and 8 percent in travel time.
- A coordination program in Texas demonstrated a benefit-cost ratio of 62:1, with reductions of 24.6 percent in delay, 9.1 percent in fuel consumption, and 14.2 percent in stops.

Unwarranted, Poorly-designed, Improperly-operated Signals

- Cause excessive delay to vehicles/pedestrians
- Increase ~~accidents~~/Crashes
- Cause disobedience
- Increased use of infrequent routes

Signal Warrants

- Chapter 4C of MUTCD
  - MUTCD is available online at http://mutcd.fhwa.dot.gov/
  - (2009 version with revisions 1&2, updated in 2012)
- Chapter 4C or 16.4.3 of the text (p454-463)

W. 1, Eight-Hour Vehicular Volume
W. 2, Four-Hour Vehicular Volume
W. 3, Peak Hour
W. 4, Pedestrian Volume
W. 5, School Crossing
W. 6, Coordinated Signal System
W. 7, Crash Experience
W. 8, Roadway Network
W. 9, Intersection Near a Grade Crossing

Signal Warrants Examples

Table 4C-1. Warrant 1, Eight-Hour Vehicular Volume

Condition A—Minimum Vehicular Volume

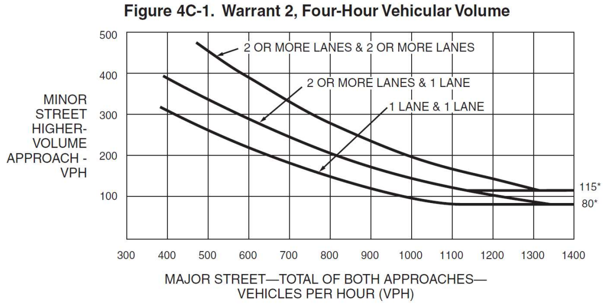
Number of lanes for moving traffic on each approach		Vehicles per hour on major street (total of both approaches)				Vehicles per hour on higher-volume minor-street approach (one direction only)			
Major Street	Minor Street	100%[a]	80%[b]	70%[c]	56%[d]	100%[a]	80%[b]	70%[c]	56%[d]
1	1	500	400	350	280	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

Condition B—Interruption of Continuous Traffic

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	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

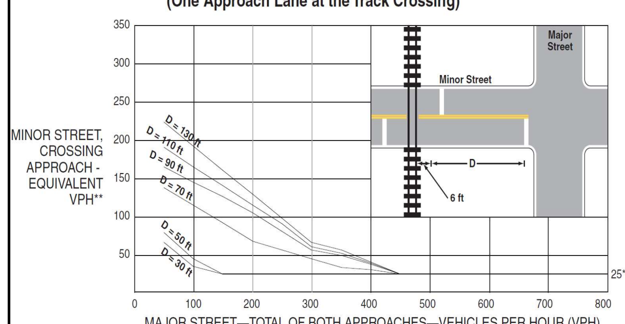
Signal Warrants Examples

Figure 4C-1. Warrant 2, Four-Hour Vehicular Volume



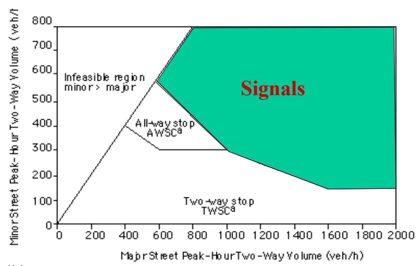
Signal Warrants Examples (new)

Figure 4C-9. Warrant 9, Intersection Near a Grade Crossing (One Approach Lane at the Track Crossing)



Intersection Control Types

EXHIBIT 10-15. INTERSECTION CONTROL TYPE AND PEAK-HOUR VOLUMES
(SEE FOOTNOTE FOR ASSUMED VALUES)



Notes
a. Roundabouts may be appropriate within portion of these ranges.
Source: Adapted from *Traffic Control Devices Handbook* (8, pp. 4-18) - peak-direction, 8-h warrants converted to two-way peak-hour volumes assuming ADT equals twice the 8-h volume and peak hour is 10 percent of daily. Two-way volumes assumed to be 150 percent of peak-direction volume.

(Source: HCM 2000)

Control Types and Delay

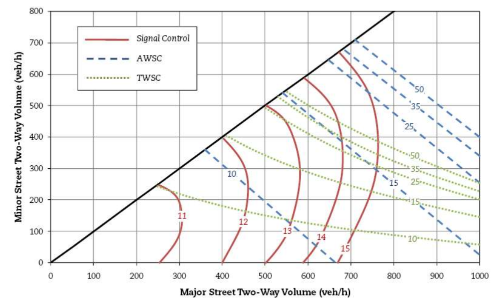


Figure 2. Contours of Control Delay (in seconds) for Signal, AWSC, and TWSC with 20% Left Turn

(Source: Han et al., 2008)

Selection of Control Type

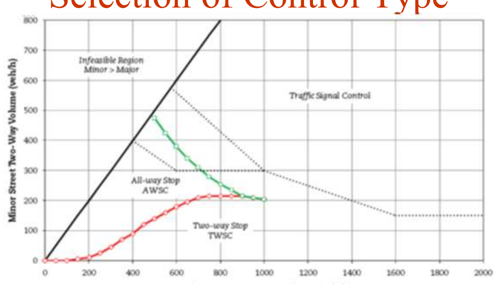


Figure 8. Comparison of Control Types to Exhibit 10-15 with 15% Left Turn

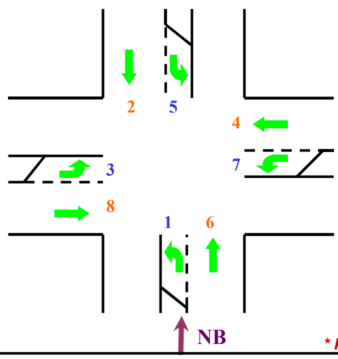
(Source: Han et al., 2008)

Dual-Ring Eight-Phase Traffic Signal Control

- Traffic signal controllers types:
  - actuated
  - pretimed
- Signals can be operated isolated or as part of coordinated systems
- Many traffic signal controllers today use a quad-left, eight-phase, dual-ring traffic-actuated NEMA-based signal controller.

NEMA - National Electrical Manufacturers Association

NEMA Phases (Movements)



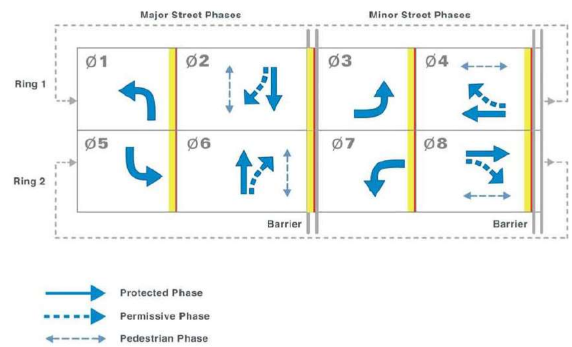
Use **Odd** numbers to indicate **left turns**, goes clockwise typically starting from NB

Use **Even** numbers to indicate through movements, goes clockwise typically starting from SB

2 & 6 are typically for main street through while 4 & 8 for side street

** Phase Number=movements*

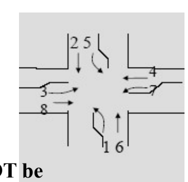
Ring-and-Barrier Diagram



NEMA Phases & Ring Diagram

R1	1	2	3	4
R2	5	6	7	8

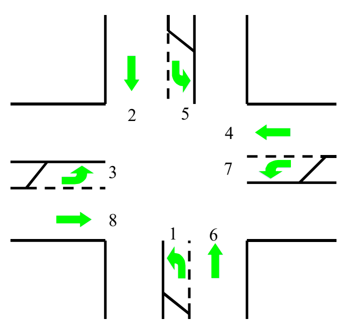
Barrier

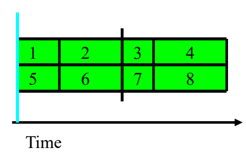


- **Numbers in the same row (ring) can NOT be Used to create feasible phase**
- **Feasible combinations can be created with phases not on the same row but on the same side of the barrier** **(Conflicting pairs of movements/phases on the same street, but on opposing approaches, are placed in the same ring; only one movement in a ring can be active)**

Feasible: **1&5, 1&6, 2&5, 2&6, 3&7, 3&8, 4&7, and 4&8**
Infeasible: **1&2,1&3, 2&3,1&7, ……**

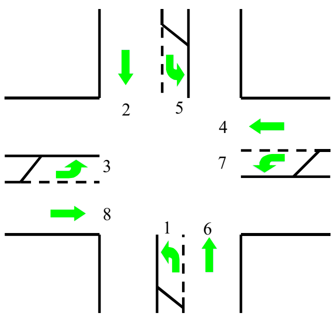
Phase Operation Example 1

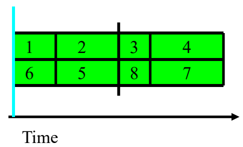




4-phase, left leading

Phase Operation Example 2





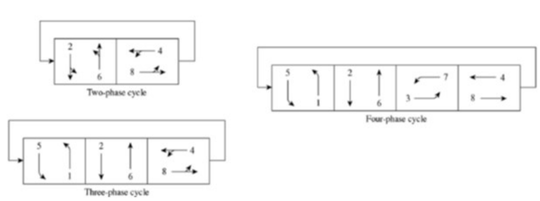
Split phasing

Signal Timing Methods

- Signal Timing Terms & Definitions
- Signal Timing Plan Calculation
  - Webster's Method
  - HCM Method

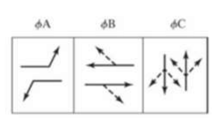
NEMA Phases vs HCM Phasing

- Highway Capacity Manual (HCM) phasing: – The part of the signal cycle allocated to any combination of traffic movements receiving the ROW simultaneously during one or more intervals
- NEMA phase is a number (movement)



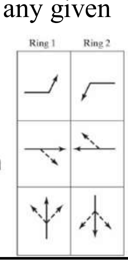
Phase Diagram vs. Ring Diagram

- Phase diagram: all movements being made during any given (HCM) phase
- Ring diagram: individual movements in a controller ring that are active at any given point

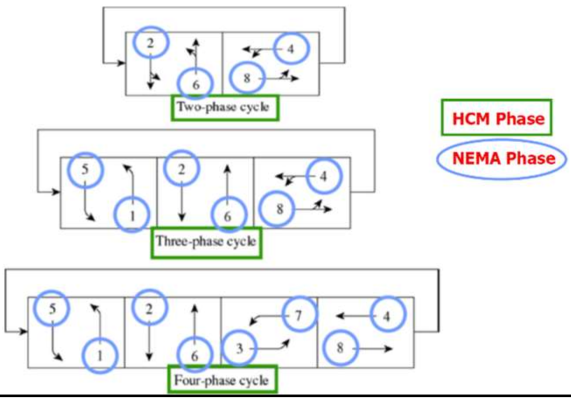


Phase Diagram

Ring Diagram



NEMA and HCM Phasing



Signal Timing Plan

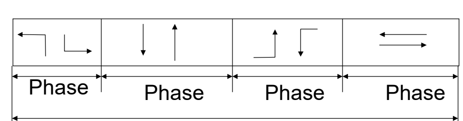
- Cycle length
- Phasing
- Split
- Green, yellow, all red interval
- Offset

Cycle

- One complete sequence of indications serving all movements at an intersection
- The length of time needed to perform one cycle of signal indications ➔ Cycle length

Phase

- A part of the traffic signal time cycle allocated to any combination of traffic movements receiving ROW simultaneously during one or more intervals



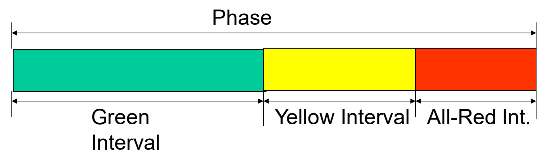
Do not confuse this HCM phase definition with NEMA phase number

Split

- A percentage of the cycle length allocated to each of the various phases in a signal sequence.

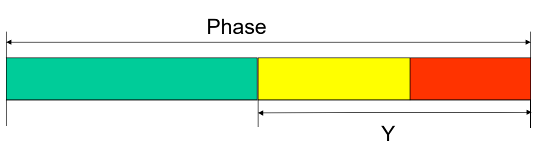
Interval

- A discrete portion of the signal cycle during which the signal indications do not change



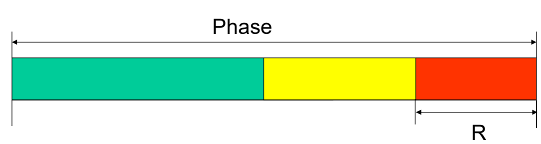
Intergreen (change and clearance interval):

- The end of green and the start of next green indication (Y)



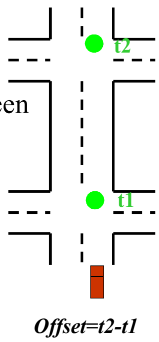
All-Red interval

- Red indication for all approaches
- All red interval is the *clearance interval*



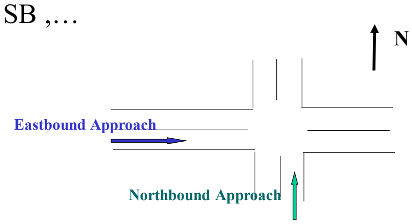
Offset

- the time lapse in seconds, bet. The beginning of a green phase at the intersection and the beginning of green phase at the next intersection
- *Offset can be determined to achieve coordination*



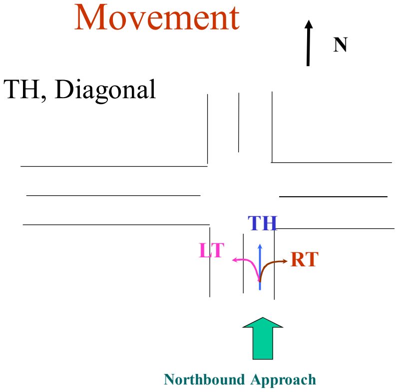
Approach

- the portion of an intersection leg that is used by traffic approaching an intersection
- E.g.: EB, SB ,…



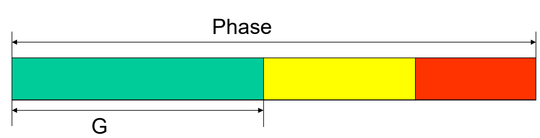
Movement

- LT,RT TH, Diagonal



Green Time

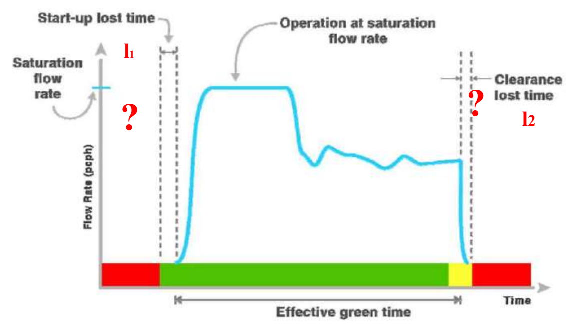
- the time within a given phase during which the indication is green (G)



Lost Time & Effective Green Time

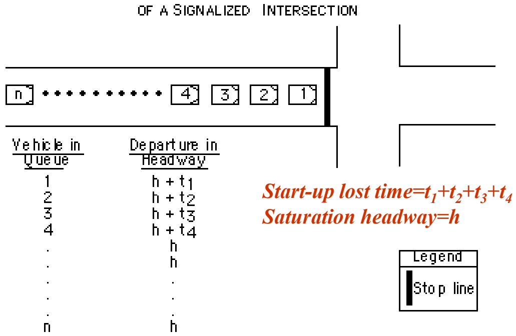
- Lost Time (L): time during which the intersection is not effectively used by any movement, which occurs during the change-and-clearance interval （clearance lost time） and the beginning of each phase (start-up lost time)
- $L=(l_1+l_2)=Y$ (typically)
- Effective green: $g=G+Y-L=G+Y-(l_1+l_2)=G$

Lost Time & Effective Green Time



Start-Up Lost Time & Saturation Flow

EXHIBIT 7-3. CONDITIONS AT TRAFFIC INTERRUPTION IN AN APPROACH LANE OF A SIGNALIZED INTERSECTION



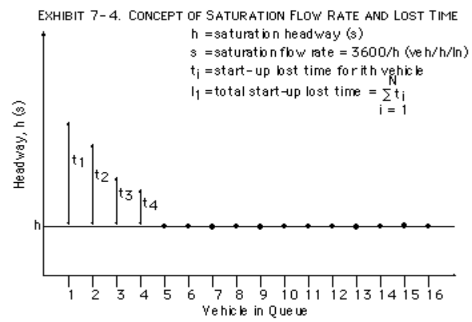
Start-up lost time=$t_1+t_2+t_3+t_4$

Saturation headway=h

Saturation Flow Rate (s)

- Flow rate that would be obtained if there were a continuous queue of vehicles that were given 100% green time (vphgpl, pcphgpl)

Measuring Saturation Flow



Determine saturation flow rate *s* based on saturation headway *h*

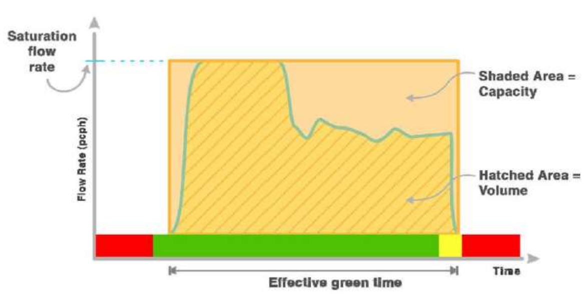
Saturation Flow Rate Estimation (HCM)

$$S = S_o N f_w f_{hv} f_g f_p f_{bb} f_a f_{RT} f_{LT}$$

S_o: typically 1900 pcphgpl
N: # lanes
Adjustment factors

f_w: lane width	f_{hv}:heavy vehicle
f_g: approach grade	f_p:parking
f_{bb}: bus blockage	f_a: area type
f_{RT}: right turn	f_{LT}: Left turns

Volume and Capacity of a Signal Movement



S for Turning Movements

- Right turn S slightly lower depending on RT%
- Left turn S can vary significantly because of multiple scenarios (combinations):
  - Turning from shared or exclusive lane
  - Turning while LT is protected or permitted
  - Also, opposing flow affects s if unprotected
- LT always consumes more effective green time than through=>smaller s than through
- Many models use “through vehicle equivalents (TVEs)” to consider LTs

Critical Lane Group*

- The lane group receiving green in a phase that has the highest *v*/s ratio
- Related to phasing

Development of Phase Plan

- Is the most critical aspect of signal design
- Involves the engineering judgment as well as predefined rules (from research)
- Several feasible approaches could work effectively

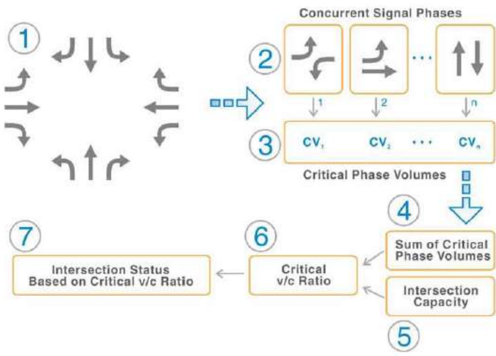
Critical Phases (Movements)

- The conflicting movements between barriers that are in the ring requiring the most time to service the traffic demand at saturation are said to be “critical phases.”
- The identification of all critical phases in the signal cycle must be determined for efficient signal timing.

v/s ratio

- v/s ratio represents demand of a movement
- Critical v/s ratio for a lane group determines required green time
  - Largest (v/s) ratio➔critical

Critical Movement Analysis



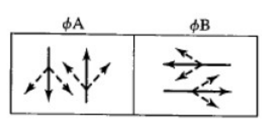
Left Turns

- Determination of left-turn treatments is the most critical aspect of a phasing scheme.
- They could be protected, permitted, or protected-permitted (compound)
- Remember, additional phases add lost time to the cycle, but might be considered for the efficiency and safety of left turners

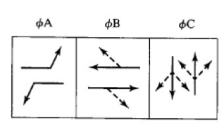
Left-Turn Treatments

- Affects safety
- Affects capacity
- Protected vs. permitted

Protected vs. Permitted



Permitted L.T.



Protected L.T. (Phase A)
Phase B may allow permitted L.T.

Why not always protected?

- Protected left turns are safer
- Remember, additional phases add lost time to the cycle, but might be needed for the efficiency and safety of left turners

General Guidelines for Prot. L.T.

- Are only starting points for consideration of protected left turns

$$v_{LT} \geq 200 \text{ veh/h} \qquad (18\text{-}1a)$$

$$v_{LT} * \left({}^{v_o}/_{N_o} \right) \geq 50{,}000 \qquad (18\text{-}1b)$$

where: v_{LT} = left-turn flow rate, veh/h

v_o = opposing through movement flow rate, veh/h

N_o = number of lanes for opposing through movement

Fully Protected Lefts Rules

- Fully-protected lefts are recommended when any two of the following criteria are satisfied:
  - Left turn flow is > 320 veh/hr
  - Opposing flow is > 1,100 veh/hr
  - Opposing speed is >= 45 mph
  - There are two or more left turn lanes

Fully Protected Lefts Rules

- Fully protected lefts are recommended when any one of the following criteria is met:
  - There are three opposing lanes and the opposing speed is 45 mph or greater
  - Left turn flow is > 320 vph and percent of heavy vehicles exceeds 2.5%
  - Opposing flow is > 1,100 vph and percent of heavy vehicles exceeds 2.5%

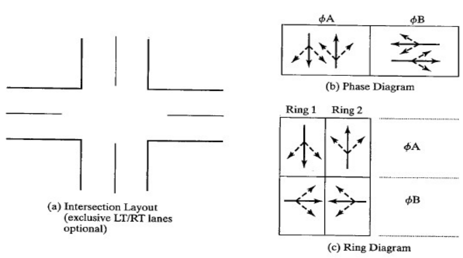
Fully Protected Lefts Rules

- Seven or more left-turn accidents has occurred with protected-permitted phasing during the last three years
- The average stopped delay to protected left turners is acceptable and engineer judges that protected-permitted phasing might cause additional left-turn accidents

Additional rules

- You can not provide protected-left phases unless you have left-turn bays
- All phase plans must be implemented in accordance with the MUTCD
- Plans must be accompanied by signs, markings, and necessary hardware to identify proper lane use

Basic Two-Phase Signalization



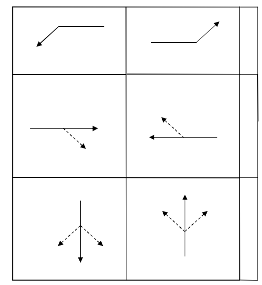
Left Turn Sequence

- Leading
- Lagging
- Leading Lagging
- Concurrent or with overlapping

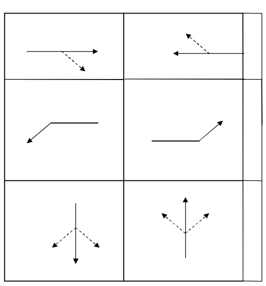
Leading and Lagging Phases

- Leading lefts occur when all movements in one direction get the green together while movements in the opposing directions are stopped
- When the left of the opposing direction gets the green, it's lagging

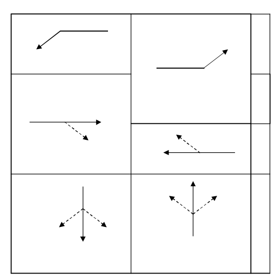
Left Turn Leading



Left Turn Lagging



Left Turn Leading w. Overlapping



More Phases or Fewer Phases?

For a given cycle length

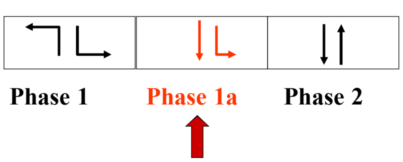
- More phases => more lost times
  - Not good
- Fewer phases?
  - What about left turn delay?
  - What about safety?
- What is the best phasing?

Phasing

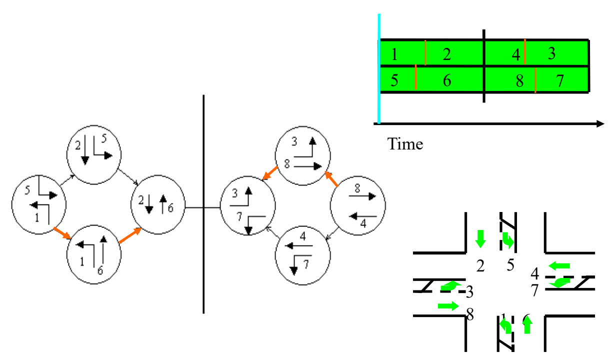
- Number of phases depends on demand
- Key to phasing is the handling of left turns
  - No left turn (one-way streets, or prohibit left turn on two-way streets)
  - Protected left turn
  - Permitted left turn
- Phase overlapping sometimes used for better efficiency

Overlapping Phase

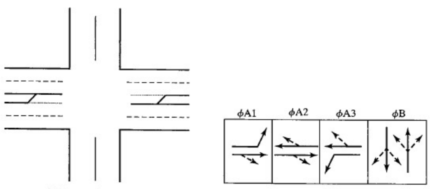
- When critical movements for the exclusive left turn and through are from the same approach
- No lost time for the overlapping phase



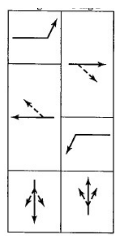
Overlapping Phases



Overlapping Phase



(a) Intersection Layout (b) Phase Diagram



- **How many phases are in this plan?**