

CEE 370

Transportation Engineering

Intersection Capacity and LOS



Oct 29, 2007

Professor Jessica Guo

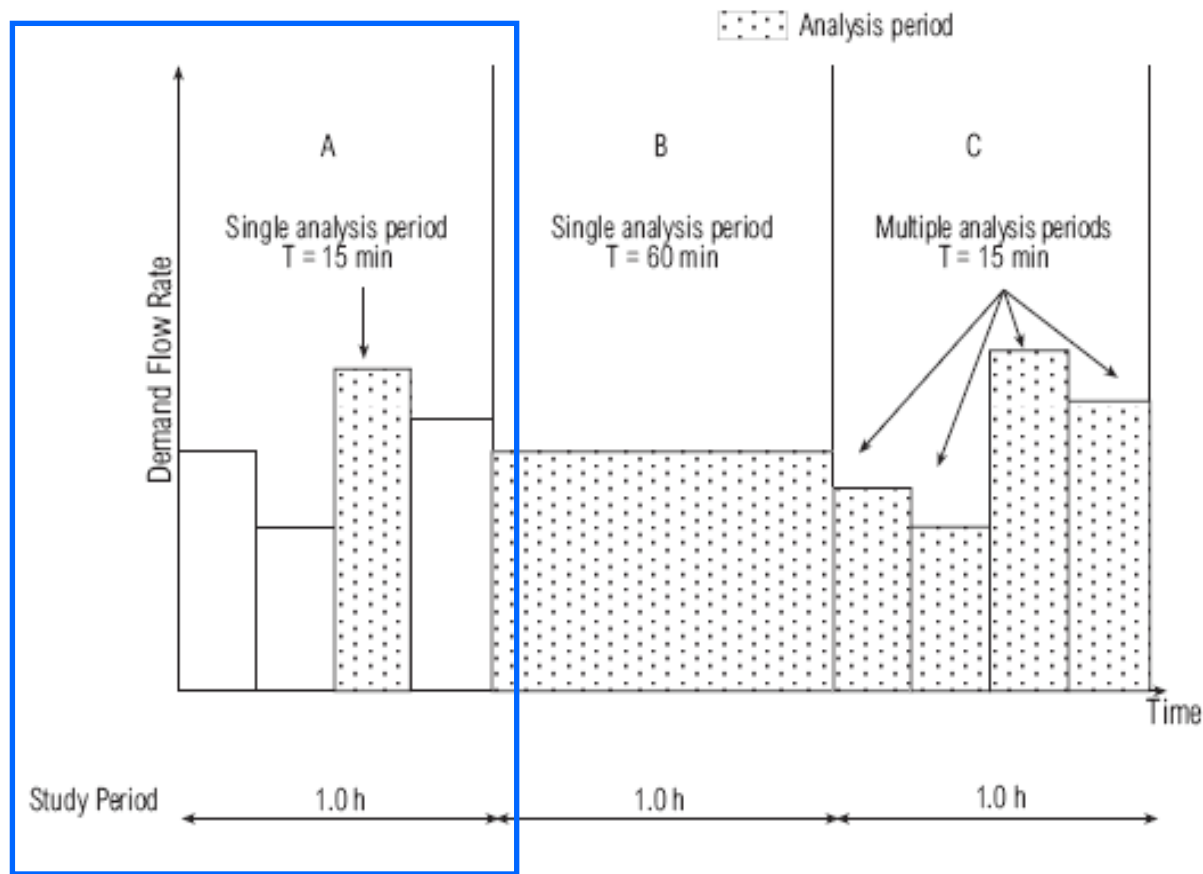
Learning Objectives

- To define capacity and LOS for intersections
- To define fundamental concepts such as critical lane group and critical path
- To analyze the capacity and LOS for pretimed signalized intersections
(HCM Ch. 16; K&L Ch. 9.1~9.5.2)

Overview

- Analysis period is usually 15 min long

EXHIBIT 16-6. THREE ALTERNATIVE STUDY APPROACHES



Overview

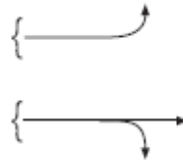
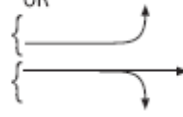
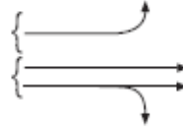
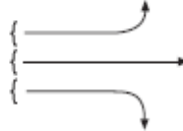
- Physical unit of analysis is **lane group**
 - Consider
 - geometry of the intersection
 - distribution of traffic movements
 - Use as few as needed
 - Exclusive left-turn lane
 - De facto left-turn lane



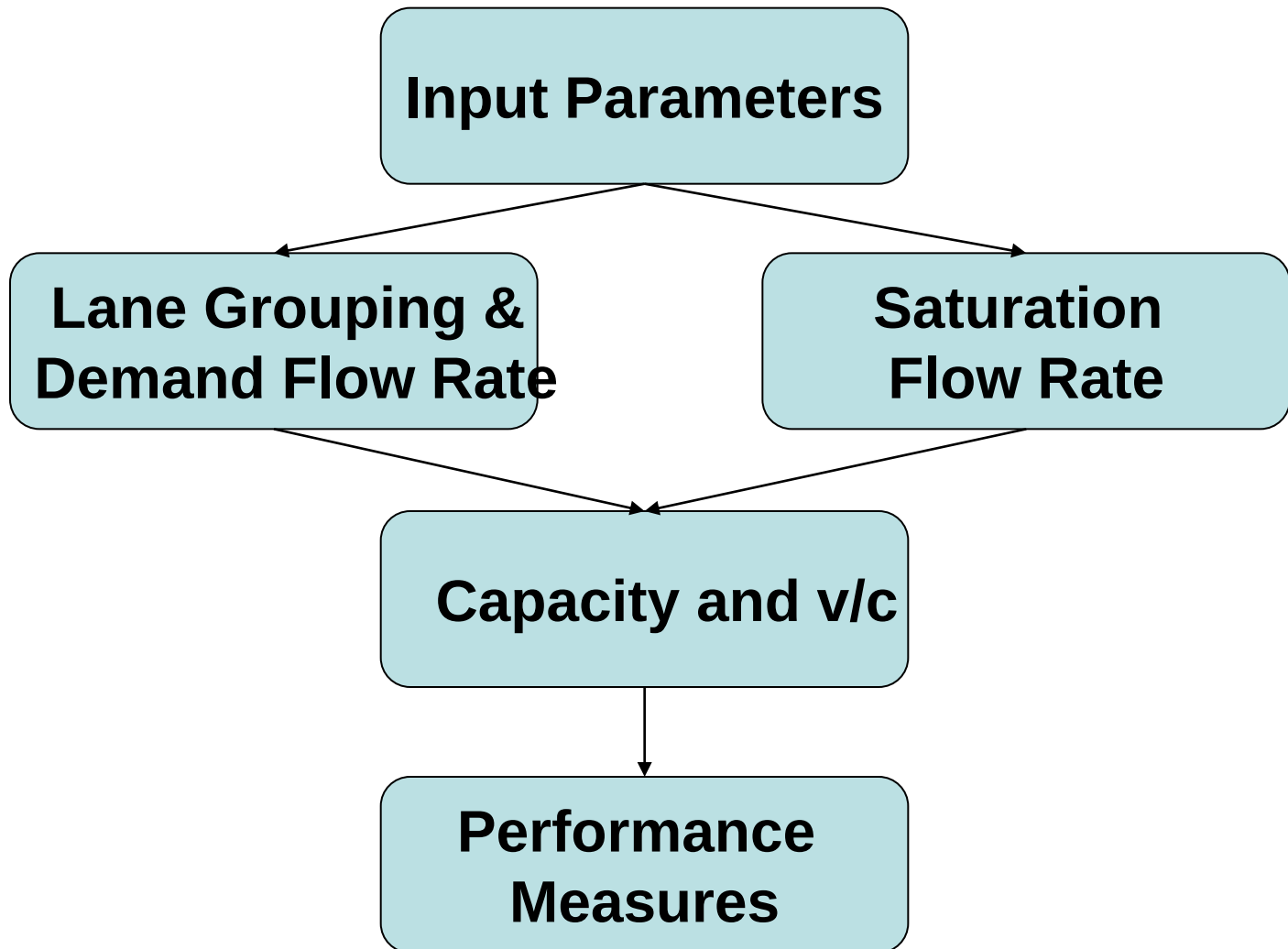
Overview

Typical lane groups

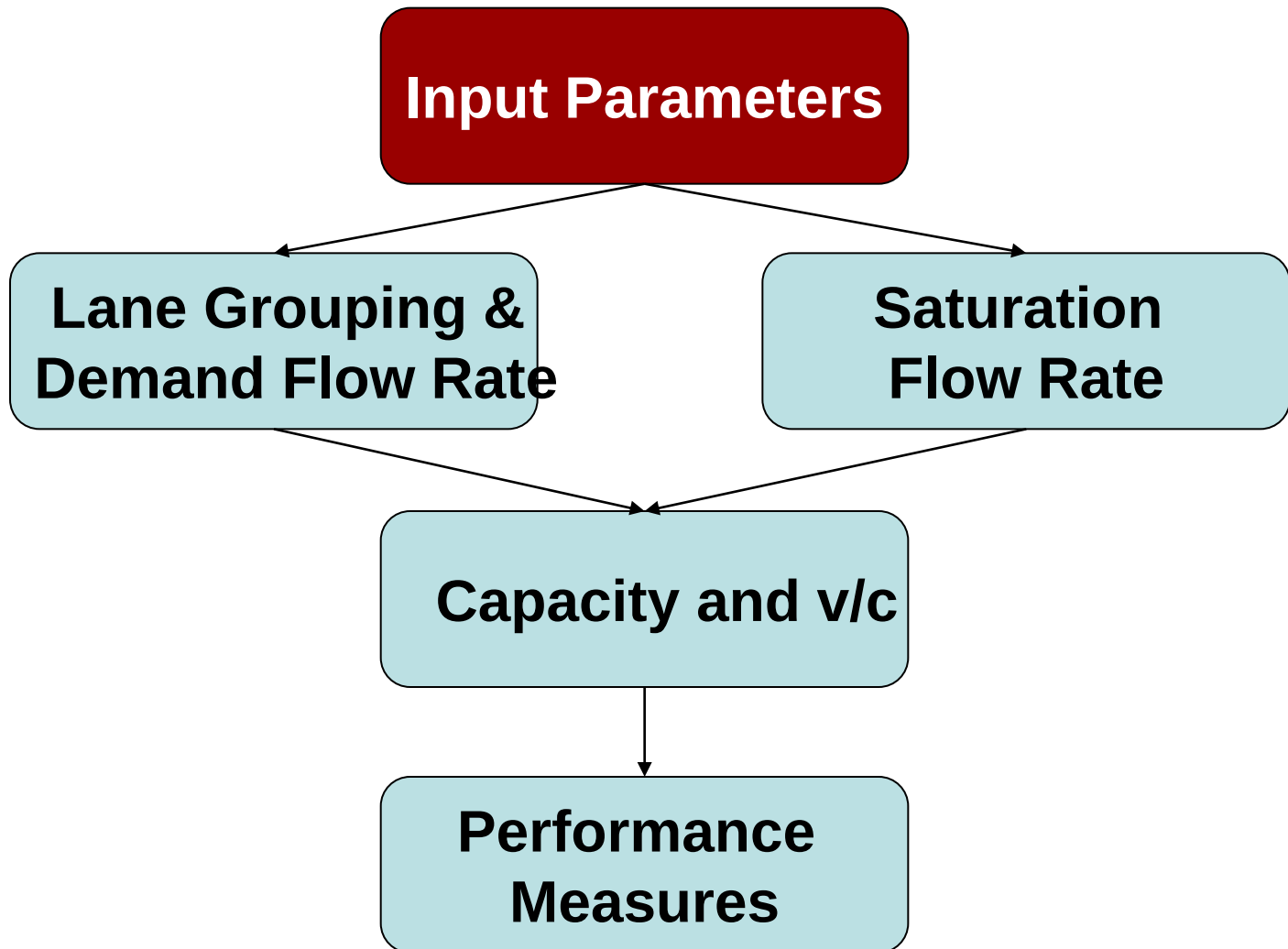
EXHIBIT 16-5. TYPICAL LANE GROUPS FOR ANALYSIS

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 

Signalized Intersection Methodology



Signalized Intersection Methodology



Input Parameters

EXHIBIT 16-3. INPUT DATA NEEDS FOR EACH ANALYSIS LANE GROUP

Type of Condition	Parameter
Geometric conditions	Area type Number of lanes, N Average lane width, W (ft) Grade, G (%) Existence of exclusive LT or RT lanes Length of storage bay, LT or RT lane, L_s (ft) Parking
Traffic conditions	Demand volume by movement, V (veh/h) Base saturation flow rate, s_o (pc/h/ln) Peak-hour factor, PHF Percent heavy vehicles, HV (%) Approach pedestrian flow rate, v_{ped} (p/h) Local buses stopping at intersection, N_B (buses/h) Parking activity, N_m (maneuvers/h) Arrival type, AT Proportion of vehicles arriving on green, P Approach speed, S_A (mi/h)
Signalization conditions	Cycle length, C (s) Green time, G (s) Yellow-plus-all-red change-and-clearance interval (intergreen), Y (s) Actuated or pretimed operation Pedestrian push-button Minimum pedestrian green, G_p (s) Phase plan Analysis period, T (h)

- Three categories: geometric, traffic, and signalization
- When studying an existing intersection, use field data
- When considering future conditions, use forecasted traffic data and proposed geometric and signal designs

Input Parameters

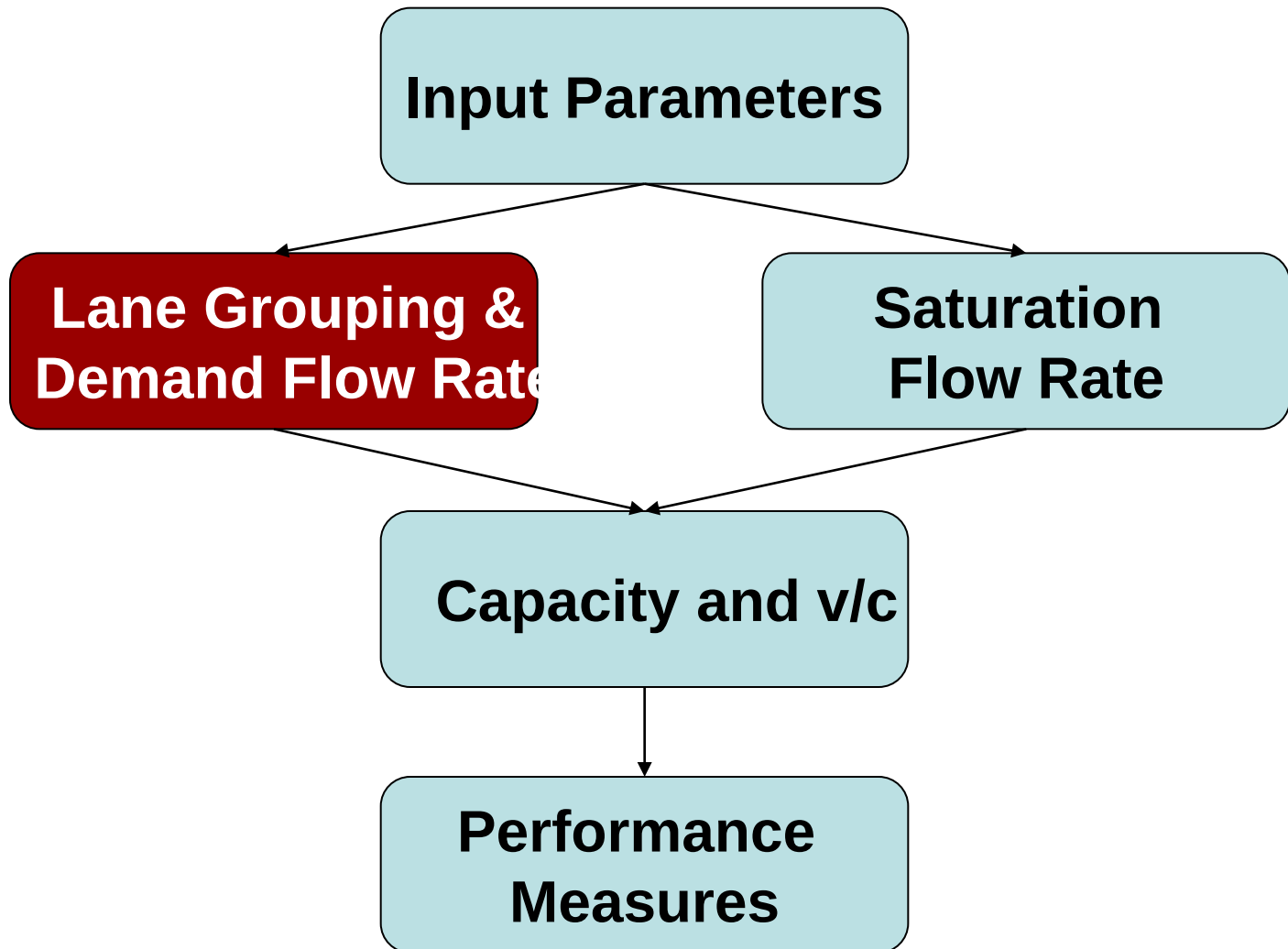
- Number of lanes
- Lane widths
- Grade
- Traffic movements using each lane (shown by arrows)
- Existence and location of curb parking lanes
- Existence and location of bus stops
- Existence and length of storage bays
- Other features such as channelization

EXHIBIT 16-20. INPUT WORKSHEET

INPUT WORKSHEET												
General Information						Site Information						
Analyst _____						Intersection _____						
Agency or Company _____						Area Type ☐ CBD ☐ Other						
Date Performed _____						Jurisdiction _____						
Analysis Time Period _____						Analysis Year _____						
Intersection Geometry												
Volume and Timing Input												
	EB			WB			NB			SB		
	LT	TH	RT ¹	LT	TH	RT ¹	LT	TH	RT ¹	LT	TH	RT ¹
Volume, V (veh/h)												
% heavy vehicles, % HV												
Peak-hour factor, PHF												
Prefixed (P) or actuated (A)												
Start-up lost time, l_s (s)												
Extension of effective green time, e (s)												
Arrival type, AT												
Approach pedestrian volume, ² v_{ped} (p/h)												
Approach bicycle volume, ² v_{bicy} (bicycles/h)												
Parking (Y or N)												
Parking maneuvers, N_p (maneuvers/h)												
Bus stopping, N_b (buses/h)												
Min. timing for pedestrians, ³ G_p (s)												
Signal Phasing Plan												
D	01	02	03	04	05	06	07	08				
I												
A												
G												
R												
A												
M												
Timing	G = Y =	G = Y =	G = Y =	G = Y =	G = Y =	G = Y =	G = Y =	G = Y =				
	Protected turns			Permitted turns			Cycle length, C = _____ s					
Notes												
1. RT volumes, as shown, exclude RTOR.												
2. Approach pedestrian and bicycle volumes are those that conflict with right turns from the subject approach.												
3. Refer to Equation 16-2.												

Each box shows a single phase or subphase during which the allowable movements remain constant

Signalized Intersection Methodology



Demand Flow Rate

- Obtain peak hour flow rate (v_p) based on field observation or using:

$$v_p = \frac{V}{PHF}$$

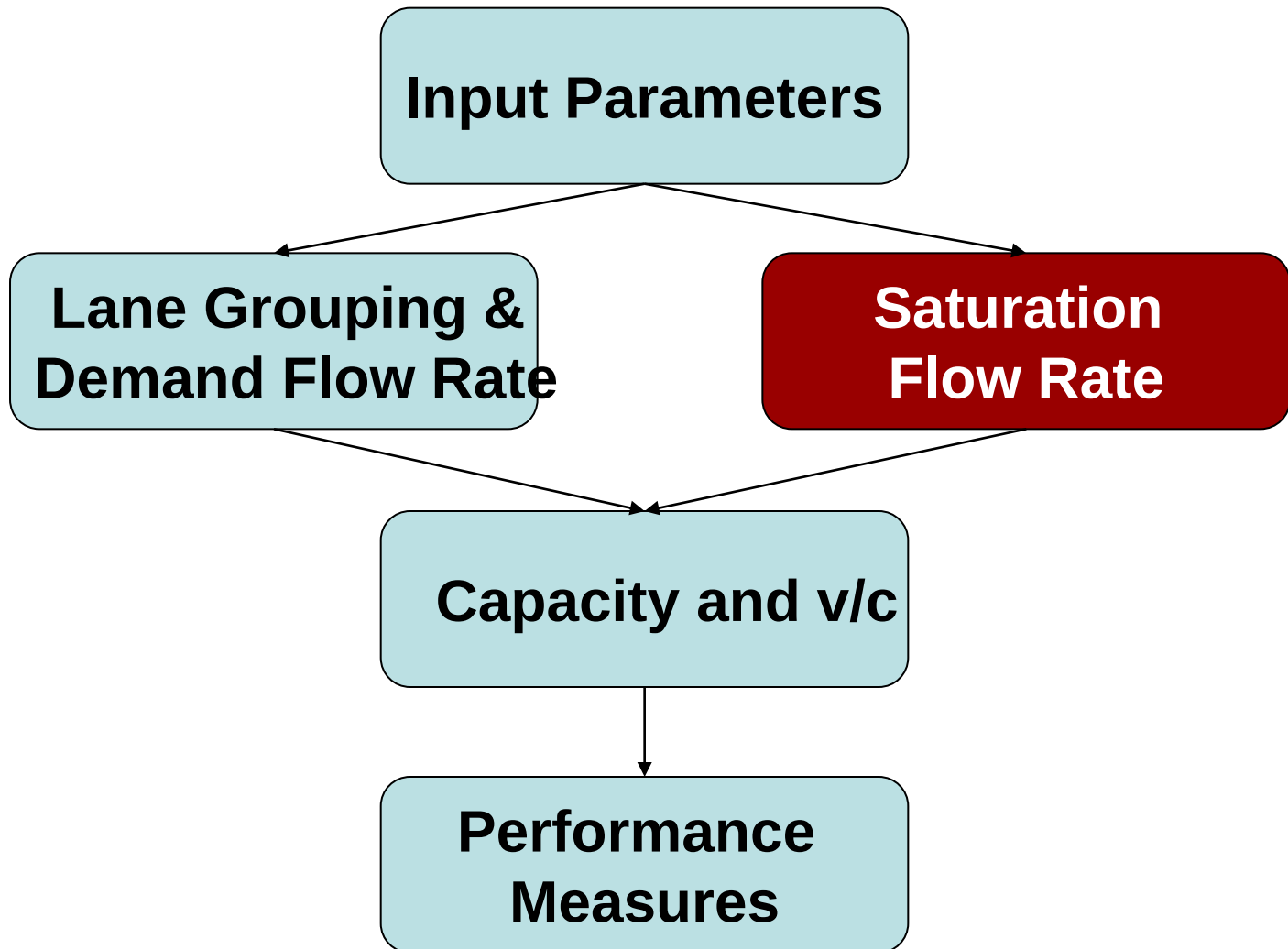
where

v_p = flow rate during peak 15-min period (veh/h),
 V = hourly volume (veh/h), and
 PHF = peak-hour factor.

Demand Flow Rate

- Adjust flow rate for Right-Turn on Red (RTOR):
 - Subtract RTOR volume from RT volume
 - If field data are not available, ignore RTOR, except in special cases
 - Remove free flowing RTs from RT volume

Signalized Intersection Methodology



Saturation Flow Rate

Flow (vph) that can be accommodated by the lane group assuming 100 % green time

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

where

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

Base Saturation Flow Rate

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

- Usually 1,900 passenger cars per hour per lane (pc/h/ln)

Number of Lanes

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

- In the lane group
- To give base saturation flow for the lane group

Adjust for Lane Width

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

Lane width	$f_w = 1 + \frac{(W - 12)}{30}$	W = lane width (ft)	W ≥ 8.0 If W > 16, a two-lane analysis may be considered
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- Accounts for an reduced (increased) flow rate on narrow (wide) lanes
- Standard is 12 ft

Adjust for Heavy Vehicle

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

Heavy vehicles	$f_{HV} = \frac{100}{100 + \%HV(E_T - 1)}$	% HV = % heavy vehicles for lane group volume	$E_T = 2.0 \text{ pc/HV}$
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- Accounts for the additional space occupied by these vehicles and for the difference in operating capabilities of heavy vehicles compared with passenger cars
- 1 HV = 2.0 PCU

Adjust for Grade

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

Grade	$f_g = 1 - \frac{\%G}{200}$	% G = % grade on a lane group approach	-6 ≤ % G ≤ +10 Negative is downhill
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- Account for the effect of grades on the operation of all vehicles

Adjust for Parking

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

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
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- N_m is number of maneuvers in parking areas directly adjacent to the lane group and within 250 ft upstream from the stop line

Adjust for Bus Blockage

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

Bus blockage	$f_{bb} = \frac{N - \frac{14.4 N_B}{3600}}{N}$	N = number of lanes in lane group N_B = number of buses stopping/h	$0 \leq N_B \leq 250$ $f_{bb} \geq 0.050$
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- When stopping buses block traffic flow in the subject lane group
- Assume an average blockage time of 14.4s during a green indication

Adjust for Area Type

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

Type of area	$f_a = 0.900$ in CBD $f_a = 1.000$ in all other areas
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- Account for the relative inefficiency of intersections in business districts in comparison with those in other locations

Adjust for Lane Utilization

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

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
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- Actual lane volume distributions observed in the field should be used, if known
- For Default values, see K&L Table 9-12

Adjust for Left Turns

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

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 Exhibit C16-1, Appendix C, for nonprotected phasing alternatives
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- $f_{LT} = 1.0$ if the lane group does not include any left turns
- 6 cases:

Phasing	Left Turn Adjustment Cases	
	Lane	
	LT Excl	LT Share
Protected	1	4
Permitted	2	5
Prot/Perm	3	6

Adjust for Left Turns

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

EXHIBIT C16-1. ADJUSTMENT FACTORS FOR LEFT TURNS (f_{LT})

Case	Type of Lane Group	Left-Turn Factor, f_{LT}
1	Exclusive LT lane; protected phasing	0.95
2	Exclusive LT lane; permitted phasing	Special procedure; see worksheet in Exhibit C16-9 or C16-10
3	Exclusive LT lane; protected-plus-permitted phasing	Apply Case 1 to protected phase; apply Case 2 to permitted phase
4	Shared LT lane; protected phasing	$f_{LT} = 1.0 / (1.0 + 0.05 P_{LT})$
5	Shared LT lane; permitted phasing	Special procedure; see worksheet in Exhibit C16-9 or C16-10
6	Shared LT lane; protected-plus-permitted phasing	Apply Case 4 to protected phase; apply Case 5 to permitted phase

Adjust for Right Turns

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

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	$f_{RT} \geq 0.050$
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- $f_{RT}=1.0$ if the lane group does not include any right turns
- Right-turn volume may be reduced by permitted RTOR volume

Adjust for Pedestrians and Bicyclists

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

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 LT green P_{RT} = proportion of RTs in lane group P_{RTA} = proportion of RT protected green over total RT green	Refer to Appendix D for step-by-step procedure
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Adjust for Pedestrians and Bicyclists

EXHIBIT D16-3. OUTLINE OF COMPUTATIONAL PROCEDURE FOR f_{Rpb} AND f_{Lpb}

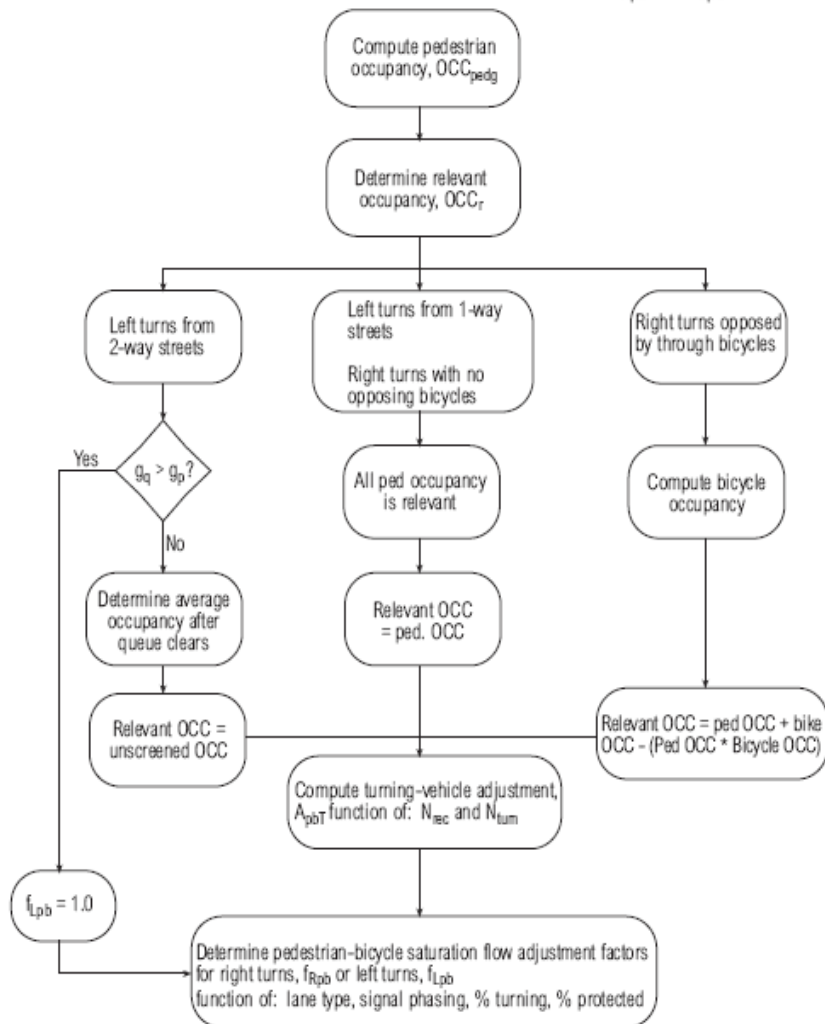
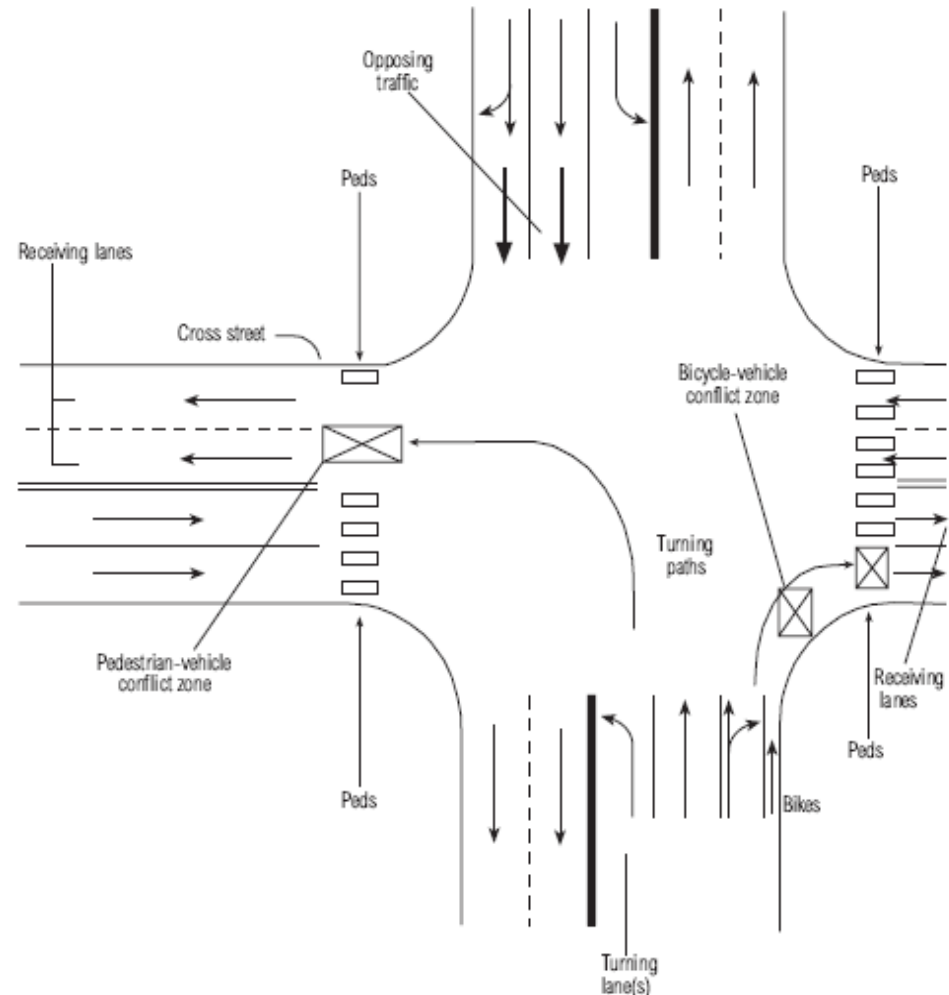
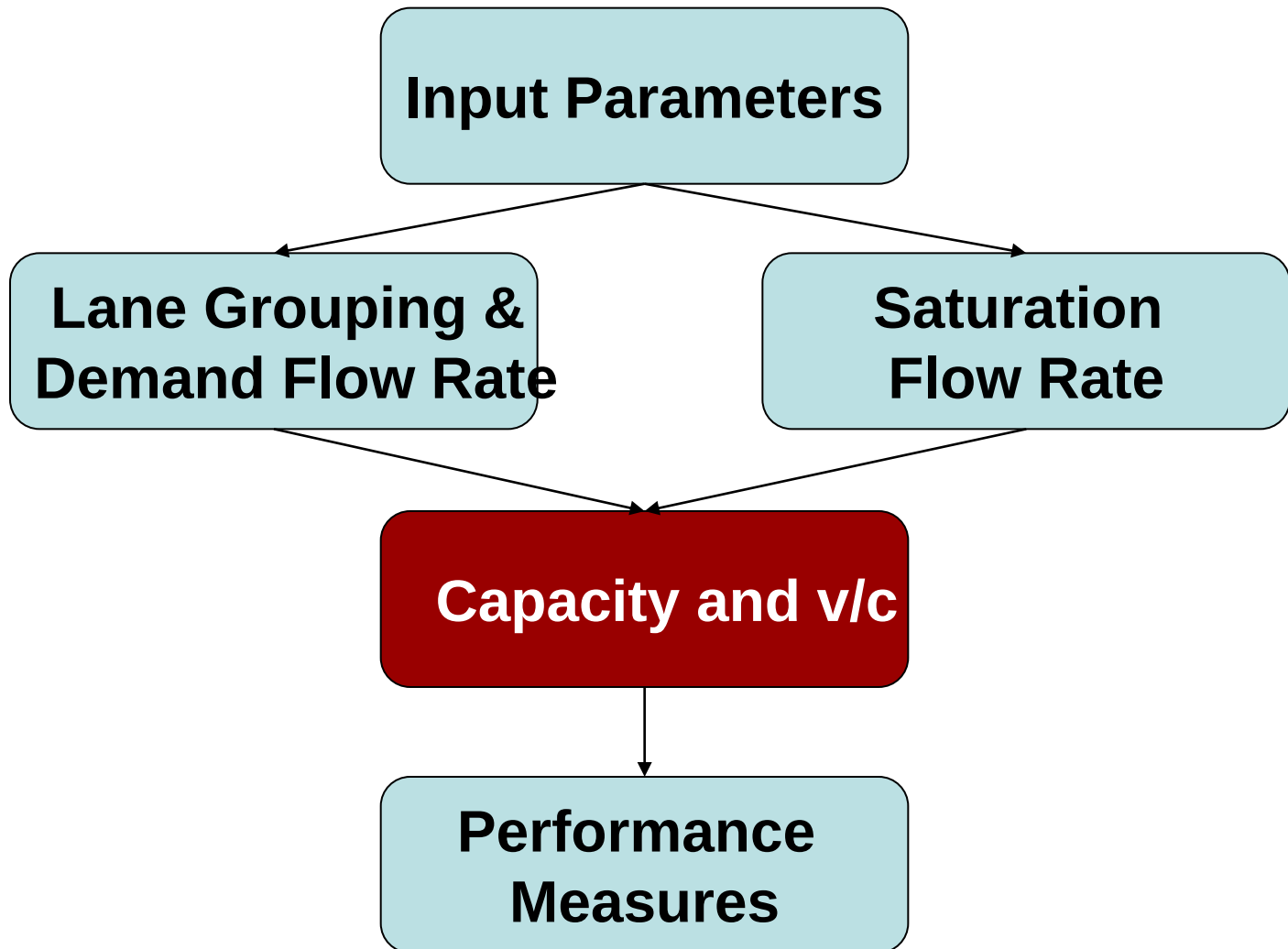


EXHIBIT D16-1. CONFLICT ZONE LOCATIONS



Signalized Intersection Methodology



Capacity Analysis

- **Flow (v/s) ratio**

$$\frac{v_i}{s_i}$$

- **Capacity**

$$C_i = s_i \frac{g_i}{C}$$

- **Volume to capacity (v/c) ratio**

$$X_i = \left(\frac{v_i}{C_i} \right) = \frac{v_i}{s_i \frac{g_i}{C}} = \frac{v_i C}{s_i g_i}$$

X_i = $(v/c)_i$ = ratio for lane group i,

v_i = actual or projected demand flow rate for lane group i (veh/h),

s_i = saturation flow rate for lane group i (veh/h),

g_i = effective green time for lane group i (s), and

C = cycle length (s).

Capacity Analysis

- **Critical v/c ratio**

- v/c ratio for the intersection as a whole

$$X_c = \sum \left(\frac{v}{s} \right)_{ci} \left(\frac{C}{C - L} \right)$$

where

X_c = critical v/c ratio for intersection;

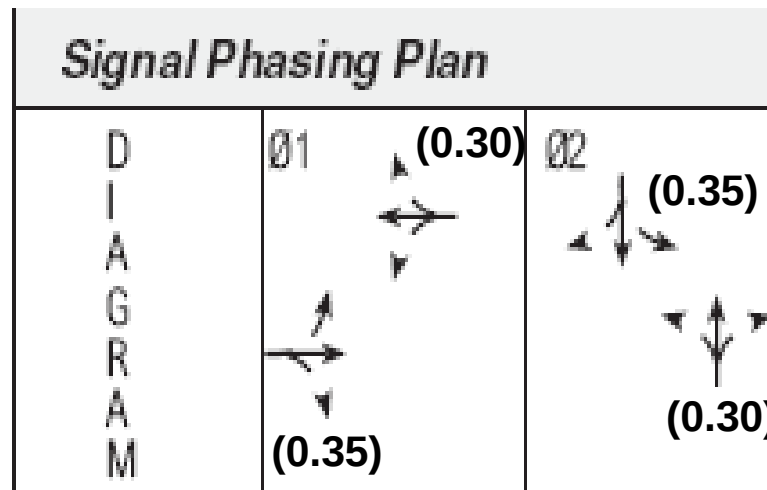
$\sum \left(\frac{v}{s} \right)_{ci}$ = summation of flow ratios for all critical lane groups i ;

C = cycle length (s); and

L = total lost time per cycle, computed as lost time, t_L , for critical path of movements (s).

Capacity Analysis

- Determining **critical lane group** and **critical path**
 - Where phases do not overlap
 - The lane group in each signal phase with the highest v/s ratio is the critical lane group
 - Critical path includes the critical lane groups from all signal phases



$$\sum \left(\frac{v}{s} \right)_{ci} = 0.70$$

$$L = 2t_L$$

Capacity Analysis

- Determining **critical lane group and critical path**
 - Where phases overlap
 - Excluding lost times, one critical lane group must be moving at all times during the signal cycle
 - At no time in the signal cycle may more than one critical lane group be moving
 - The critical path has the highest sum of v/s ratios

Capacity Analysis

Phase 1 is discrete:

- Critical path is NB (0.3)

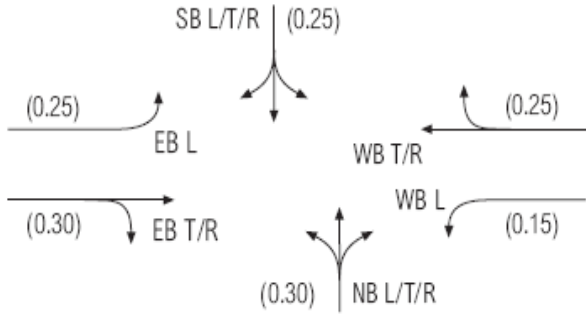
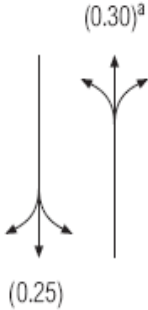
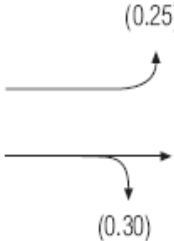
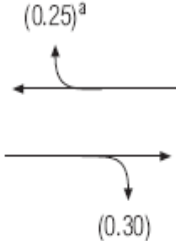
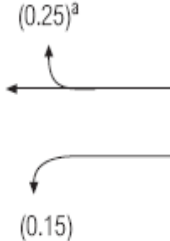
Phase 2 has 2 possible paths:

- EB T/R (0.3) + WB L (0.15)
⇒ Total v/s ratio = 0.45
- EB L (0.25) + WB T/R (0.25)
⇒ Total v/s ratio = 0.50
⇒ This is the critical path

Over total of critical v/s ratio

$$\sum \left(\frac{v}{s} \right)_{ci} = 0.80$$

EXHIBIT 16-8. CRITICAL LANE GROUP DETERMINATION WITH PROTECTED LEFT TURNS

Lane Groups		(v/s ratios)			
					
Signal Phasing					
					
Phase 1	Phase 2A	Phase 2B	Phase 2C		

Note:

a. Critical v/s.

Capacity Analysis

- Lost time t_L is applied when a movement is initiated
 - Thus, t_L is applied to
 - NB in Phase 1
 - EB L in Phase 2A
 - WB T/L in Phase 2B
 - None in Phase 2C!!!
- ⇒ Total lost time $L = 3t_L$

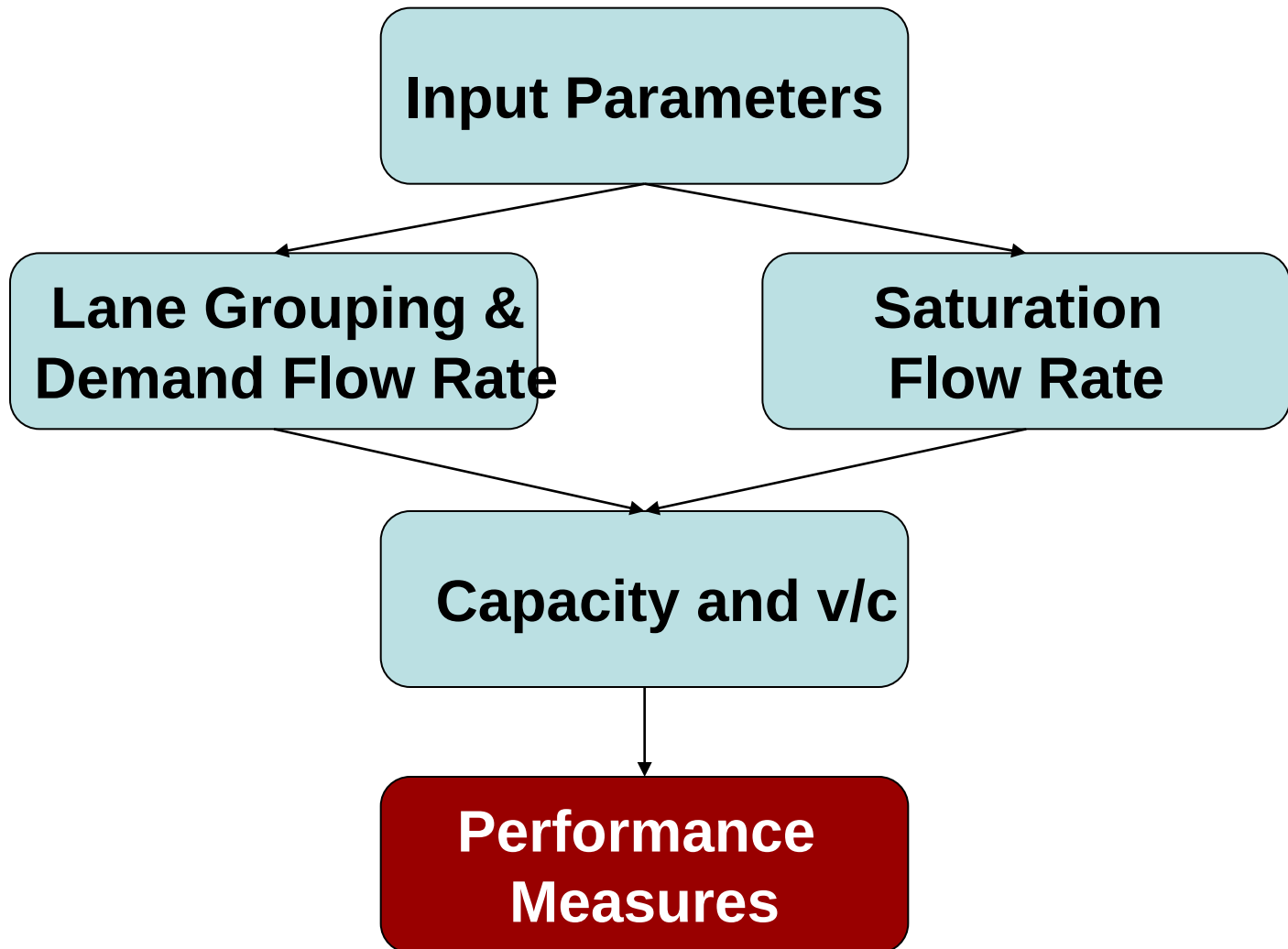
EXHIBIT 16-8. CRITICAL LANE GROUP DETERMINATION WITH PROTECTED LEFT TURNS

Lane Groups		(v/s ratios)			
Signal Phasing					
Phase 1	Phase 2A	Phase 2B	Phase 2C		

Note:

a. Critical v/s.

Signalized Intersection Methodology



Average Control Delay

- The basis for LOS determination
- For a given lane group:

$$d = d_1(PF) + d_2 + d_3$$

where

- d = control delay per vehicle (s/veh);
- d_1 = uniform control delay assuming uniform arrivals (s/veh);
- PF = uniform delay progression adjustment factor, which accounts for effects of signal progression;
- d_2 = incremental delay to account for effect of random arrivals and oversaturation queues, adjusted for duration of analysis period and type of signal control; this delay component assumes that there is no initial queue for lane group at start of analysis period (s/veh); and
- d_3 = initial queue delay, which accounts for delay to all vehicles in analysis period due to initial queue at start of analysis period (s/veh) (detailed in Appendix F of this chapter).

Adjust for Progression

$$d = d_1(PF) + d_2 + d_3$$

$$PF = \frac{(1 - P)f_{PA}}{1 - \left(\frac{g}{C}\right)}$$

where

PF = progression adjustment factor,

P = proportion of vehicles arriving on green,

g/C = proportion of green time available, and

f_{PA} = supplemental adjustment factor for platoon arriving during green

- P is either measured in the field or estimated from the **arrival type**

Adjust for Progression

EXHIBIT 16-4. ARRIVAL TYPES

Arrival Type	Description
1	Dense platoon containing over 80 percent of the lane group volume, arriving at the start of the red phase. This AT is representative of network links that may experience <u>very poor</u> progression quality as a result of conditions such as overall network signal optimization.
2	Moderately dense platoon arriving in the middle of the red phase or dispersed platoon containing 40 to 80 percent of the lane group volume, arriving throughout the red phase. This AT is representative of <u>unfavorable</u> progression on two-way streets.
3	<u>Random arrivals</u> in which the main platoon contains less than 40 percent of the lane group volume. This AT is representative of operations at isolated and noninterconnected signalized intersections characterized by highly dispersed platoons. It may also be used to represent coordinated operation in which the benefits of progression are minimal.
4	Moderately dense platoon arriving in the middle of the green phase or dispersed platoon containing 40 to 80 percent of the lane group volume, arriving throughout the green phase. This AT is representative of <u>favorable</u> progression on a two-way street.
5	Dense to moderately dense platoon containing over 80 percent of the lane group volume, arriving at the start of the green phase. This AT is representative of <u>highly favorable</u> progression quality, which may occur on routes with low to moderate side-street entries and which receive high-priority treatment in the signal timing plan.
6	This arrival type is reserved for <u>exceptional</u> progression quality on routes with near-ideal progression characteristics. It is representative of very dense platoons progressing over a number of closely spaced intersections with minimal or negligible side-street entries.

Adjust for Progression

EXHIBIT 16-12. PROGRESSION ADJUSTMENT FACTOR FOR UNIFORM DELAY CALCULATION

Green Ratio (g/C)	Arrival Type (AT)					
	AT 1	AT 2	AT 3	AT 4	AT 5	AT 6
0.20	1.167	1.007	1.000	1.000	0.833	0.750
0.30	1.286	1.063	1.000	0.986	0.714	0.571
0.40	1.445	1.136	1.000	0.895	0.555	0.333
0.50	1.667	1.240	1.000	0.767	0.333	0.000
0.60	2.001	1.395	1.000	0.576	0.000	0.000
0.70	2.556	1.653	1.000	0.256	0.000	0.000
f_{PA}	1.00	0.93	1.00	1.15	1.00	1.00
Default, R_p	0.333	0.667	1.000	1.333	1.667	2.000

Notes:

$PF = (1 - P)f_{PA} / (1 - g/C)$.

Tabulation is based on default values of f_{PA} and R_p .

$P = R_p * g/C$ (may not exceed 1.0).

PF may not exceed 1.0 for AT 3 through AT 6.

R_p = platoon ratio.

Uniform Delay

$$d = d_1(PF) + d_2 + d_3$$

Assuming uniform arrivals, stable flow, and no initial queue

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

- d_1 = uniform control delay assuming uniform arrivals (s/veh);
- C = cycle length (s); cycle length used in pretimed signal control, or average cycle length for actuated control (see Appendix B for signal timing estimation of actuated control parameters);
- g = effective green time for lane group (s); green time used in pretimed signal control, or average lane group effective green time for actuated control (see Appendix B for signal timing estimation of actuated control parameters); and
- X = v/c ratio or degree of saturation for lane group.

Incremental Delay

$$d = d_1(PF) + d_2 + d_3$$

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

d_2 = incremental delay to account for effect of random and oversaturation queues, adjusted for duration of analysis period and type of signal control (s/veh); this delay component assumes that there is no initial queue for lane group at start of analysis period;

$K=0.50$ for pre-timed signals

T = duration of analysis period (h);

k = incremental delay factor that is dependent on controller settings;

I = upstream filtering/metering adjustment factor;

c = lane group capacity (veh/h); and

X = lane group v/c ratio or degree of saturation.

$I=1.0$ for isolated intersection

Initial Queue Delay

$$d = d_1(PF) + d_2 + d_3$$

If there is no residual queue from a previous time period to cause additional delay to vehicles arriving in the period of analysis

$$d_3 = 0$$

Otherwise, calculate using the procedure given in HCM, Chapter 16, Appendix F

Aggregated Delay Estimates

Delay for an Approach

$$d_A = \frac{\sum d_i v_i}{\sum v_i}$$

where

- d_A = delay for Approach A (s/veh),
- d_i = delay for lane group i (on Approach A) (s/veh), and
- v_i = adjusted flow for lane group i (veh/h).

Delay for an Intersection

$$d_I = \frac{\sum d_A v_A}{\sum v_A}$$

where

- d_I = delay per vehicle for intersection (s/veh),
- d_A = delay for Approach A (s/veh), and
- v_A = adjusted flow for Approach A (veh/h).

Determine LOS

- measure of the acceptability of delay levels to motorists
- Use the total control delay for the given intersection:

EXHIBIT 16-2. LOS CRITERIA FOR SIGNALIZED INTERSECTIONS

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

Interpretation of Results

- A critical v/c ratio of greater than 1.0 indicates that the signal and geometric design cannot accommodate the combination of critical flows at the intersection. The condition may be ameliorated by increased cycle length, changes in the phasing plan, and basic changes in geometrics.
- When the critical v/c ratio is acceptable but the v/c ratios for critical lane groups vary widely, the green-time allocation should be reexamined, because disproportionate distribution of available green is indicated.

Interpretation of Results

- LOS measure is somewhat subjective: what might be acceptable in a large city is not necessarily acceptable in a smaller city or rural area
- When delay levels are acceptable for the intersection as a whole but are unacceptable for certain lane groups, the phase plan, allocation of green time, or both might be examined to provide for more efficient handling of the disadvantaged movement(s)
- When delay levels are unacceptable but v/c ratios are relatively low, the cycle length may be too long for prevailing conditions, the phase plan may be inefficient, or both.
- When both delay levels and v/c ratios are unacceptable, the situation is critical. The full range of potential geometric and signal design improvements should be considered.