Chapter 37

Capacity and LOS Analysis of a Signalized I/S

37.1 Overview

The Highway Capacity Manual defines the capacity as the maximum howdy rate at which persons or vehicle can be reasonably expected to traverse a point or a uniform segment of a lane or roadway during a given time period, under prevailing roadway, traffic and control conditions. 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.

37.2 Methodology

37.2.1 Scope

This chapter contains a methodology for analyzing the capacity and level of service (LOS) of signalized intersections. The analysis must consider a wide variety of prevailing conditions, including the amount and distribution of traffic movements, traffic composition, geometric characteristics, and details of intersection signalization. The methodology focuses on the determination of LOS for known or projected conditions. The capacity analysis methodology for signalized intersections is based on known or projected signalization plans.

37.2.2 Limitation

The methodology does not take into account the potential impact of downstream congestion on intersection operation. Nor does the methodology detect and adjust for the impacts of turn-pocket overflows on through traffic and intersection operation.

37.2.3 Objective

This method uses wide range of operational configuration along with various phase plans, lane utilization, and left-turn treatment alternatives.

- Geometric condition
- Traffic condition
- Signalization condition

The primary output of the method is level of service (LOS). This methodology covers a wide range of operational configurations, including combinations of phase plans, lane utilization, and left-turn treatment alternatives. The below figure shows the signalized intersection methodology.

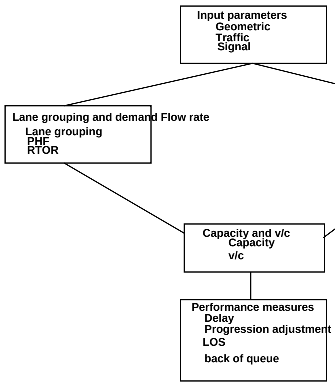

Figure 37:1: signalized intersection methodology

37.3 Input parameters

To conduct operational analysis of signalized intersection, no. of input parameters are required. The data needed are detailed and varied and fall into three main categories: geometric, traffic, and signalization.

37.3.1 Geometric condition

Intersection geometry is generally presented in diagrammatic form and must include all of the relevant information, including approach grades, the number and width of lanes, and parking conditions.

Table 37:1: Input data needs for each analysis of lane group

Condition	Parameter
Geometric	Area type
	Number of lanes, N
	Average lane width, W (m)
	Grade, G (%)
	Existence of exclusive LT or RT lanes
	Length of storage bay, LT or RT lane, L s (m)
	Parking
Traffic	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, vped (p/h)
	Local buses stopping at intersection, NB (buses/h)
	Parking activity, Nm (maneuvers/h)
	Arrival type, AT
	Proportion of vehicles arriving on green, P
	Approach speed, S A (km/h)
Control	Cycle length, C (s)
	Green time, G (s)
	Yellow-plus-all-red change-and-clearance interval (inter green), Y (s)
	Actuated or pre-timed operation
	Pedestrian push-button
	Minimum pedestrian green, Gp (s)
	Phase plan
	Analysis period, T (h)

AT	Description
1	Dense platoon- 80% arrived at start of red
2	Moderately dense- 40-80% arrived during red
3	Less than 40% (highly dispersed platoon)
4	Moderately dense, 40-80% arrived during green
5	Dense to moderately dense- 80% arrive at start of green
6	Very dense platoons progressing over a no. of closed space I/S

37.3.2 Traffic condition

Traffic volumes (for oversaturated conditions, demand must be used) for the intersection must be specified for each movement on each approach. In situations where the v/c is greater than about 0.9, control delay is significantly affected by the length of the analysis period.

- If v/c exceeds 1.0 during the analysis period, the length of the analysis period should be extended to cover the period of oversaturation in the same fashion, as long as the average flow during that period is relatively constant.

- An important traffic characteristic that must be quantified to complete an operational analysis of a signalized intersection is the quality of the progression. The parameter that describes this characteristic is the arrival type, AT, for each lane group. The arrival type should be determined as accurately as possible because it will have a significant impact on delay estimates and LOS determination. It can be computed as

$$R_p = P/(g_i/C) \tag{37.1}$$

  where, R_p = platoon ratio, P = proportion of all vehicles in movement arriving during green phase, C = cycle length (s) and g_i = effective green time for movement or lane group (s).

37.3.3 Signalization condition :

Complete information regarding signalization is needed to perform an analysis. This information includes a phase diagram illustrating the phase plan, cycle length, green times, and change-and-clearance intervals. If pedestrian timing requirements exist, the minimum green time for the phase is indicated and provided for in the signal timing. The minimum green time for a phase is estimated as,

$$G_P = 3.2 + L/S_p + 0.81(N_{ped}/W_E) \; for \; W_E > 3.0m \quad (37.2)$$

$$G_P = 3.2 + L/S_p + 0.27N_{ped} \; for \; W_E \leq 3.0m \quad (37.3)$$

where, G_p = minimum green time (s), L = crosswalk length (m), S_p = average speed of pedestrians (m/s), W_E = effective crosswalk width (m), 3.2 = pedestrian start-up time (s), and N_{ped} = number of pedestrians crossing during an interval (p).

37.4 Determining flow rate

The methodology for signalized intersections is disaggregate; that is, it is designed to consider individual intersection approaches and individual lane groups within approaches. Segmenting the intersection into lane groups is a relatively simple process that considers both the geometry of the intersection and the distribution of traffic movements. Demand volumes are best provided as average flow rates (in vehicles per hour) for the analysis period. However, demand volumes may also be stated for more than one analysis period, such as an hourly volume. In such cases, peaking factors must be provided that convert these to demand flow rates for each particular analysis period. In that case,

$$V_P = V/PHF \quad (37.4)$$

37.5 Determining saturation flow rate

A saturation flow rate for each lane group is computed according to above equation. The saturation flow rate is the flow in vehicles per hour that can be accommodated by the lane group assuming that the green phase were displayed 100 percent of the time (i.e., g/C = 1.0).

$$S = S_O \times N f_w f_{HV} f_g f_p f_{bb} f_a f_{LU} f_{LT} f_{RT} f_{Lpb} f_{Rpb} \quad (37.5)$$

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.

37.5.1 Base saturation flow rate :

For the analysis of saturation flow rate, a fixed volume is taken as a base called base saturation flow rate, usually 1,900 passenger cars per hour per lane (pc/h/ln). This value is adjusted for a variety of conditions. The adjustment factors are given below.

37.5.2 Adjustment for lane width:

The lane width adjustment factor fw accounts for the negative impact of narrow lanes on saturation flow rate and allows for an increased flow rate on wide lanes. The lane width factor can be calculated for lane width greater than 4.8m. The use of two narrow lanes will always result in higher saturation capacity than one single wide lane.

$$f_w = 1 + (w - 3.6)/9 \tag{37.6}$$

where, w = width of lane

37.5.3 Adjustment for Heavy Vehicles and Grade :

passenger cars are affected by approach grades, as are heavy vehicles. The heavy-vehicle factor accounts for the additional space occupied by these vehicles and for the difference in operating capabilities of heavy vehicles compared with passenger cars. The passenger-car equivalent (ET) used for each heavy vehicle is 2.0 passenger-car units and is reflected in the formula. The grade factor accounts for the effect of grades on the operation of all vehicles.

$$f_{HV} = 100/[100 + \%HV(E_T - 1)] \tag{37.7}$$

$$f_g = 1 - \%G/200 \tag{37.8}$$

where, % HV = % heavy vehicles for lane group volume, E_T = 2.0, % G = % grade on a lane group approach

37.5.4 Adjustment for Parking

Parking maneuver assumed to block traffic for 18 s. Use practical limit of 180 maneuvers/h. The parking adjustment factor, f_p, accounts for the frictional effect of a parking lane on flow in an adjacent lane group as well as for the occasional blocking of an adjacent lane by vehicles moving into and out of parking spaces. Each maneuver (either in or out) is assumed to block traffic in the lane next to the parking maneuver for an average of 18 s.

$$f_P = [N - 0.1 - (18N_m/3600)]/N \tag{37.9}$$

where, N_m = number of parking maneuvers/h, N = no. of lanes

37.5.5 Adjustment for Bus Blockage

The bus blockage adjustment factor, f_{bb}, accounts for the impacts of local transit buses that stop to discharge or pick up passengers at a near-side or far-side bus stop within 75 m of the stop line (u/s or d/s). If more than 250 buses per hour exist, a practical limit of 250 should be used. The adjustment factor can be written as,

$$f_{bb} = [N - (14.4N_B/3600)]/N \tag{37.10}$$

where, N_B = no. of buses stopping per hour

37.5.6 Adjustment for Area Type

The area type adjustment factor, fa, accounts for the relative inefficiency of intersections in business districts in comparison with those in other locations. Application of this adjustment factor is typically appropriate in areas that exhibit central business district (CBD) characteristics. It can be represented as, $f_a = 0.9$ in CBD (central business district) and = 1.0 in all others

37.5.7 Adjustment for Lane Utilization

The lane utilization adjustment factor, fLU, accounts for the unequal distribution of traffic among the lanes in a lane group with more than one lane. The factor provides an adjustment to the base saturation flow rate. The adjustment factor is based on the flow in the lane with the highest volume and is calculated by Equation 10.

$$f_{LU} = V_g/(V_{g1}N) \tag{37.11}$$

where, V_g = unadjusted demand flow rate for lane group (veh/ h), V_{g1} = unadjusted demand flow rate on single lane with highest volume in the lane group and N = no. of lanes in the group.

37.6 Determining capacity and v/c ratio:

Capacity at signalized intersections is based on the concept of saturation flow and defined saturation flow rate. The flow ratio for a given lane group is defined as the ratio of the actual or projected demand flow rate for the lane group (v_i) and the saturation flow rate(s_i). The flow ratio is given the symbol (v/s)i for lane group i. Capacity at signalized I/S is based on the saturation flow and saturation flow rate.

$$C_i = s_i \times (g_i/c) \tag{37.12}$$

where c_i = capacity of lane group i (veh/h), s_i = saturation flow rate for lane group i (veh/h) and g_i/C = effective green ratio for lane group i.

37.6.1 v/c ratio:

The ratio of flow rate to capacity (v/c), often called the volume to capacity ratio, is given the symbol X in intersection analysis

$$X_i = (\frac{v}{c})_i = \frac{v_i}{s_i(\frac{g_i}{C})} = \frac{v_i c}{s_i g_i} \tag{37.13}$$

where, 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)

37.6.2 Critical lane group:

Another concept used for analyzing signalized intersections is the critical v/c ratio, X_c. This is the v/c ratio for the intersection as a whole, considering only the lane groups that have the highest flow ratio (v/s) for a given signal phase. For example, with a two-phase signal, opposing lane groups move during the same green time. Generally, one of these two lane groups will require more green time than the other (i.e., it will have a higher flow ratio). This would be the critical lane group for that signal phase. The critical v/c ratio for the intersection is determined by using Equation,

$$X_c = \sum \left(\frac{v}{S}\right)(\frac{C}{C-L}) \tag{37.14}$$

where, X_c = critical v/c ratio for intersection; The above eqn. is useful in evaluating the overall i/s w.r.t the geometric and total cycle length. A critical v/c ratio less than 1.0, however, does indicate that all movements in the intersection can be accommodated within the defined cycle length.

Table 37:2: Relation between arrival type (AT) and platoon ratio

AT	Ration	Default R_p	Progression quality
1	$\leq$ 0.50	0.333	very poor
2	0.50-0.85	0.667	Unfavorable
3	0.85-1.15	1.000	Random arrivals
4	1.15-1.50	1.333	Favorable
5	1.50-2.00	1.667	Highly favorable
6	2.00	2.000	Exceptional

37.7 Determining delay

The values derived from the delay calculations represent the average control delay experienced by all vehicles that arrive in the analysis period, including delays incurred beyond the analysis period when the lane group is oversaturated. The average control delay per vehicle for a given lane group is given by Equation,

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

where, d = control delay per vehicle (s/veh); d_1 = uniform control delay assuming uniform arrivals (s/veh); PF = uniform delay progression adjustment factor, d_2 = incremental delay to account for effect of random arrivals and d_3 = initial queue delay, which accounts for delay to all vehicles in analysis period

37.7.1 Progression adjustment factor

Good signal progression will result in a high proportion of vehicles arriving on the uniform delay Green and vice-versa. Progression primarily affects uniform delay, and for this reason, the adjustment is applied only to d1. The value of PF may be determined using Equation,

$$PF = \frac{(1-P)f_{PA}}{1-(\frac{g}{C})} \tag{37.15}$$

where, PF = progression adjustment factor, P = proportion of vehicles arriving on green, g/C = proportion of green time available, f_PA = supplemental adjustment factor for platoon arriving during green. The approximate ranges of RP are related to arrival type as shown below. PF may be calculated from measured values of P using the given values of f_{PA} or the following table can be used to determine PF as a function of the arrival type.

Table 37:3: Progression adjustment factor for uniform delay calculation

Green Ratio (g/C)	Arrival Type (AT)					
	AT1	AT2	AT3	AT4	AT5	AT6
0.2	1.167	1.007	1	1	0.833	0.75
0.3	1.286	1.063	1	0.986	0.714	0.571
0.4	1.445	1.136	1	0.895	0.555	0.333
0.5	1.667	1.24	1	0.767	0.333	0
0.6	2.001	1.395	1	0.576	0	0
0.7	2.556	1.653	1	0.256	0	0
f_{PA}	1	0.93	1	1.15	1	1
Default, R_p	0.333	0.667	1	1.333	1.667	2

37.7.2 Uniform delay

It is based on assuming uniform arrival, uniform flow rate & no initial queue. The formula for uniform delay is,

$$d_1 = \frac{0.5C(1-\frac{g}{C})^2}{1-[min(1,X)\frac{g}{C}]} \tag{37.16}$$

where, d_1 = uniform control delay assuming uniform arrivals (s/veh), C = cycle length (s); cycle length used in pre-timed signal control, g = effective green time for lane group, X = v/c ratio or degree of saturation for lane group.

37.7.3 Incremental delay

The equation below is used to estimate the incremental delay due to nonuniform arrivals and temporary cycle failures (random delay. The equation assumes that there is no unmet demand that causes initial queues at the start of the analysis period (T).

$$d_2 = 900\ T\left[(X-1)+\sqrt{(X-1)^2+\frac{8klX}{cT}}\right] \tag{37.17}$$

where, d_2 = incremental delay queues, 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), X = lane group v/c ratio or degree of saturation, and K can be found out from the following table.

Table 37:4: k-values to account for controller type

Unit	Degree of Saturation (X)					
Extension (s)	≤ 0.50	0.6	0.7	0.8	0.9	≥ 1.0
≤ 2.0	0.04	0.13	0.22	0.32	0.41	0.5
2.5	0.08	0.16	0.25	0.33	0.42	0.5
3	0.11	0.19	0.27	0.34	0.42	0.5
3.5	0.13	0.2	0.28	0.35	0.43	0.5
4	0.15	0.22	0.29	0.36	0.43	0.5
4.5	0.19	0.25	0.31	0.38	0.44	0.5
5.0^a	0.23	0.28	0.34	0.39	0.45	0.5
Pre-timed	0.5	0.5	0.5	0.5	0.5	0.5

37.7.4 Aggregate delay estimates

The delay obtained has to be aggregated, first for each approach and then for the intersection The weighted average of control delay is given as:

$$d_A = \sum d_i v_i / \sum v_i$$

where, d_i = delay per vehicle for each movement (s/veh), d_A = delay for Approach A (s/veh), and v_A = adjusted flow for Approach A (veh/h).

$$d_1 = \sum d_A \times v_A / \sum v_A$$

37.7.5 Determination of LOS

Intersection LOS is directly related to the average control delay per vehicle. Any v/c ratio greater than 1.0 is an indication of actual or potential breakdown. In such cases, multi-period analyses are advised. These analyses encompass all periods in which queue carryover due to oversaturation occurs. A critical v/c ratio greater than 1.0 indicates that the overall signal and geometric design provides inadequate capacity for the given flows. In some cases, delay will be high even when v/c ratios are low.

37.7.6 Sensitivity of results to input variables

The predicted delay is highly sensitive to signal control characteristics and the quality of progression. The predicted delay is sensitive to the estimated saturation flow only when demand

Table 37:5: LOS criteria for signalized intersection in term of control delay per vehicle (s/veh)

LOS	Delay
A	≤ 10
B	10-20
C	20-35
D	35-55
E	55-80
F	>80

approaches or exceeds 90 percent of the capacity for a lane group or an intersection approach. The following graph shows the sensitivity of the predicted control delay per vehicle to demand to capacity ratio, g/c, cycle length and length of analysis period. Assumptions are : Cycle

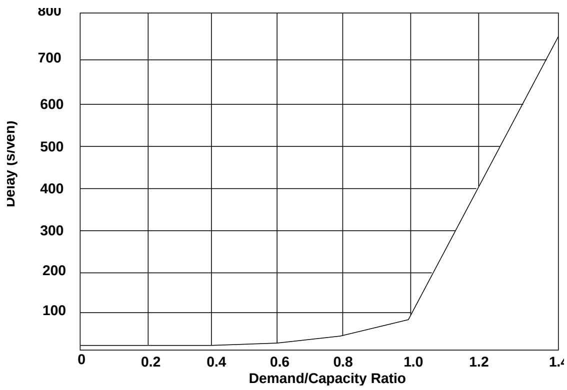

Figure 37:2: sensitivity of delay to demand to capacity ratio

length = 100s, g/c = 0.5, T =1h, k = 0.5, l= 1, s = 1800 veh/hr

37.8 Conclusion

HCM model is very useful for the analysis of signalized intersection as it considers all the adjustment factors which are to be taken into account while designing for a signalized I/S. Though,the procedure is lengthy but it is simple in approach and easy to follow.

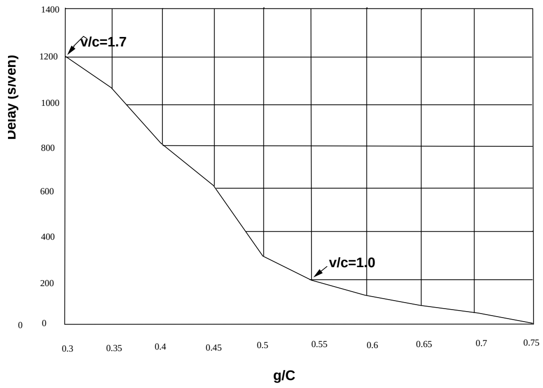

Figure 37:3: sensitivity of delay Vs g/c ratio

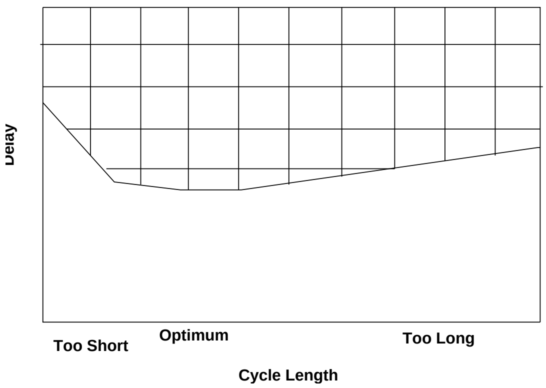

Figure 37:4: sensitivity of delay Vs cycle length

37.9 References

1. Highway Capacity Manual. *Transportation Research Board*. National Research Council, Washington, D.C., 2000.

2. L. R Kadiyali. *Traffic Engineering and Transportation Planning*. Khanna Publishers, New Delhi, 1987.