Capacity of Shared Left-Turn Lanes—A Simplified Approach

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This paper develops a simple and readily usable formula for estimating the capacity of a shared left-turn lane. It also derives a left-turn blockage factor for use in the formula. The capacity of a through lane at a signalized intersection is reduced by factors that reflect (a) opposing left turns or (b) the blockage effect of left turns on through traffic in the same lane. The capacity of a shared lane represents the minimum of these computations. Thus, the capacity of a shared lane is reduced by the number of left turns using the lane, as well as the traffic volumes in the opposing direction. Opposing left turns reduce the capacity of both shared left-turn lanes and through lanes. When there are five or more left turns per cycle in a shared lane, they preempt that lane for all practical purposes. Short signal cycles appear preferable where shared left-turn lanes dominate.

Computing the capacity of shared left-turn lanes continues to be a complex and elusive task. It is generally agreed that (a) left-turning vehicles have longer headways than through traffic and (b) opposing through vehicles reduce left-turn capacity. There is growing recognition that left turns may impede (or block) through vehicles in the shared lane and that the combined effects of opposing traffic flow and left turns reduce the capacity of a shared lane. While these factors are contained in various capacity guides, the methodologies are complex. There are no simple, practical relationships for ready use.

This paper develops an analytical approach to the capacity of left-turn lanes that considers the nature, magnitude, and interaction of the opposing traffic. It derives simple and readily usable formulas for estimating the capacity of a shared left-turn lane, and it shows how the formulas can be applied. The formulas relate capacity to traditional variables such as green time, cycle length, starting-clearing losses, and vehicle headways (or saturation flows). However, they also include the number of left turns, the proportion of through traffic that is blocked by left turns, and the opposing traffic flow.

The formulas are based on the assumption that only one vehicle can cross a conflict point at any given time. Thus, they build on the critical movement analysis of vehicles across a conflict point. They also build on the 1985 *Highway Capacity Manual* (HCM) concept of "free" and "blocked" green time (*1*). They are interactive since they reflect the impact of the opposing traffic flow.

BACKGROUND

The basic formula for intersection capacity under ideal conditions relates capacity to green time, lost time, and vehicle headways (or saturation flow). The number of through passenger vehicles per lane per cycle can be obtained from the following formula:

$$c = \frac{G - \text{lost time per cycle}}{h_i} = \frac{g}{h_i} \tag{1}$$

where

G = total green + yellow time per cycle,
g = effective green time per cycle,
h_i = ideal headway at saturation flow (sec),
lost time = starting and clearing lost time (sec), and
c = capacity (veh/lane/cycle).

This formula is modified in practice to reflect prevailing roadway and traffic conditions. A series of adjustment (or reductive) factors are applied to account for lane width, traffic composition, and turn interferences.

The general formula becomes

$$c = \frac{g}{h_i} \prod F_i \tag{2}$$

where ΠF_i equals the product of adjustment factors.

This formula can be rearranged to separate the reductive effects of left turns from other effects. One possible form for the formula is as follows:

$$c = \frac{g}{h_i} \prod F_i' - \frac{\text{lost time per cycle due to left turns}}{h_i} \tag{3}$$

Therefore,

$$c = \frac{g}{h} - \text{lost vehicles per cycle due to left turns} \tag{4}$$

where

$\prod F_i'$ = product of all reductive factors other than left turns, and
h = actual or adjusted headway based on these factors.

Hence,

$$c = \frac{g}{h_i} \prod F_i' \tag{4'}$$

This concept reduces the capacity for time losses resulting from left-turn delays rather than adjusting the saturation flow.

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The following sections develop a series of analytical expressions for computing the lost capacity due to left turns.

CONCEPTS AND ASSUMPTIONS

Two sets of formulas were derived for what might be termed a "conflict/blockage" approach. They were keyed to traffic operations through a typical right-angle, two-phase, signal-controlled intersection (see Figure 1) and reflect the following assumptions:

- The time required across a point of conflict represents the sum of the time required by conflicting lane volumes. Conversely, a given green time is shared by the through and conflicting left-turn flows.
- Where through vehicles conflict with opposing left turns, the through vehicles move first.
- Where left turns block through vehicles in the same lane, cars move in the following sequence:
  1. Unblocked through and opposing traffic,
  2. Remainder of opposing traffic,
  3. Left turn(s), and
  4. Blocked through traffic.
- Traffic in each direction moves within a platoon.
- Where through traffic and opposing left turns conflict, some of the left turns will move on the clearance phase if no other time is available. These are defined as "sneakers."
- On opposing single-lane approaches, opposing left turns will move at the same time.
- Right turns form part of the through traffic.
- The headways for through and unblocked left-turning vehicles are the same.

These assumptions result in two sets of criteria for estimating the reductive effect of left turns on capacity (see Figure 2). The capacity of any given approach lane reflects the minimum capacity obtained by applying either the conflict or blockage criteria:

- *Conflict.* Green time is shared between traffic in one direction and left turns in the opposing direction.
- *Blockage.* Green time is lost as a result of delayed left turns waiting for opposing through traffic to clear.

FORMULA DEVELOPMENT

Conflict

The formula for estimating the effect of opposing left turns on the capacity of a lane is straightforward. If there were no

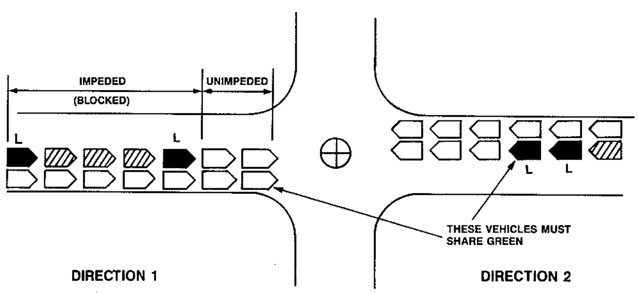

FIGURE 1 Intersection operations.

opposing left turns, the capacity would be g/h. However, since left turns preempt some of the available green time, this amount should be reduced by the number of opposing left turns per cycle (l_2) and increased by the number of sneakers per cycle (s_2). This leads to the following formula:

$$c\ (\text{conflict}) = \frac{g}{h} - l_2 + s_2 \tag{5}$$

subject to

$$s_2 \leq l_2 \leq \frac{g}{h}$$

$$\left(\text{Since } l_2 \leq \frac{g}{h},\ s_2 \text{ is also} \leq \frac{g}{h}\right)$$

This formula is a restatement of the critical lane analysis and applies to both shared and nonshared lanes. It also applies when the opposing left turns operate from an exclusive lane.

Blockage

The capacity of a shared left-turn lane can be viewed as having three basic components in terms of likely blockage effects. These are

1. The through vehicles that precede the first left turn,
2. The through vehicles that follow and are blocked by the left turn, and
3. The left turns.

The expected capacity per cycle is the sum of these three capacities, each weighted by its relative share of the total.

This relationship can be expressed as follows:

$$c_s = p_1c_1 + p_2c_2 + p_3c_3 \tag{6}$$

where

c_s = expected capacity of the shared lane (cars per cycle) (blockage),
c_1 = capacity of shared-lane through vehicles that are not delayed by left turns (cars per cycle),

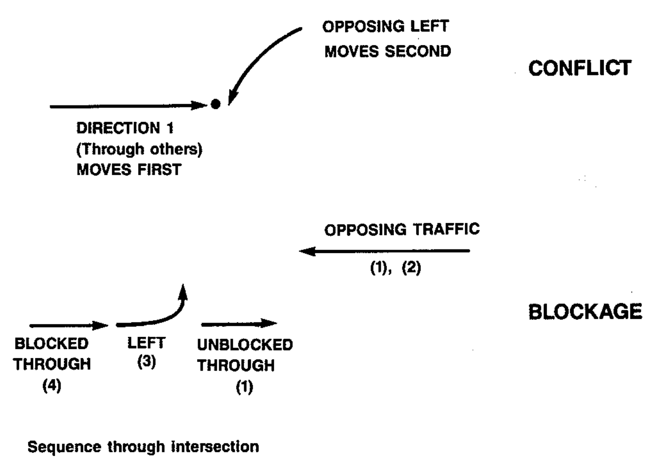

FIGURE 2 The concepts of conflict and blockage.

c_2 = capacity of shared-lane through vehicles that are delayed by left turns (cars per cycle),
c_3 = capacity of shared-lane left turns (left turns are delayed by opposing traffic) (cars per cycle),
p_1 = proportion of capacity used by unimpeded through traffic,
p_2 = proportion of capacity used by impeded (or delayed) through traffic, and
p_3 = proportion of capacity used by left turns.

The proportion of capacity p_1, p_2, and p_3 can be expressed in terms of the total capacity (c_s), and left turns per cycle (l), and the proportion of through vehicles delayed by left turns (K) as follows:

$$p_3 = \frac{l}{c_s} \tag{7a}$$

$$p_2 = \left(1 - \frac{l}{c_s}\right)(K) \tag{7b}$$

$$p_1 = \left(1 - \frac{l}{c_s}\right)(1 - K) \tag{7c}$$

Substituting into Equation 6 yields the following formula:

$$\begin{aligned} c_s = {} & \left(1 - \frac{l}{c_s}\right)(1 - K) \cdot c_1 \\ & + \left(1 - \frac{l}{c_s}\right) K \cdot c_2 + \frac{l}{c_s} c_3 \end{aligned} \tag{8}$$

The capacities c_1, c_2, and c_3 are estimated as follows:

$$c_1 = \frac{g}{h} \qquad \text{(no blockage)} \tag{9a}$$

$$c_2 = \left(\frac{g}{h} - o_L\right) \qquad \text{(blockage)} \tag{9b}$$

$$c_3 = \left(\frac{g}{h} - o_L\right) \qquad \text{(blockage)} \tag{9c}$$

where o_L equals the opposing traffic per lane per cycle.

The blockage condition assumes that the effective green time is shared by the opposing traffic and the blocked vehicles. It also assumes that the opposing traffic moves first and the blocked vehicles move next. This assumption is similar to that used in critical conflict analysis.

Equation 8 was solved algebraically. Equations 9a, 9b, and 9c were then substituted for c_1, c_2, and c_3, respectively. Further simplification produced the following quadratic formula for the expected capacity of a shared left-turn lane:

$$c_s = \frac{\left(\frac{g}{h} - Ko_L\right) + \left[\left(\frac{g}{h} - Ko_L\right)^2 - 4o_L\, l(1 - K)\right]^{1/2}}{2} \tag{10}$$

This formula states that the capacity of a shared lane depends on (a) the effective green time, (b) the vehicle headways, (c) the proportion of through vehicles blocked by left turns, (d) the number of left turns per cycle, and (e) the opposing traffic per lane. The blockage factor (K) depends on the left turns per cycle.

If there are no left turns, $l = 0$ and $K = 0$. The formula simplifies to

$$c_s = \frac{g}{h} \tag{11}$$

If all through vehicles are blocked by left turns, $K = 1$ and $(1 - K) = 0$. The formula simplifies to

$$c_s = \frac{g}{h} - o_L \tag{12}$$

Estimating Two Factors

Application of the formula calls for knowing the values of o_L and K. According to the HCM, for multilane approaches o_L equals [the opposing traffic divided by the number of lanes] times a lane utilization factor. When both approaches of a street have only one lane, o_L becomes the sum of the through and right-turn traffic.

The left-turn blockage factor (K) depends on the number of left turns on the shared approach. It was derived by the following two methods:

1. *Simulation*. Random number tables were used to generate the position of left turns and through vehicles in 10-car platoons. Fifty platoons were analyzed for each of four cases, in which left turns represented 10, 20, 30, and 40 percent of the total traffic in the platoon, respectively. The average number of through vehicles and the proportion of through vehicles delayed were then computed.
2. *Positional Probabilities*. Probability theory was used to estimate the likelihood of the first, second, third, and ith vehicles in line being left turns. Conditional probabilities were computed, assuming that the first left turn was the ith car in line based on sampling with replacement. The probability (p) that the first ($i - 1$) cars were through vehicles and the ith vehicles were left turns is given by the formula:

$$\left(\frac{T}{l + T}\right)^{i-1} \cdot \frac{l}{l + T} \tag{13}$$

where T equals through vehicles per cycle.

The computed values of K are shown in Table 1 and Figure 3. The simulation and sampling methods yield similar results.

An inspection of Table 1 shows that the K values can be approximated by a single set of numbers that are a function of the number of left turns per traffic signal cycle or platoon. As shown in Table 2 and Figure 4, the suggested K values based on left turns per cycle provide a reasonable approximation of left-turn blockage for most conditions:

- When there is one left turn per cycle, approximately 40 percent of the through vehicles in the shared lane would be blocked.
- When there are three left turns per cycle, approximately 70 percent of the through vehicles in the shared lane would be blocked.

TABLE 1 COMPUTED VALUES FOR K

Left Turns as Percent of Total Traffic in Shared Lane	Length of Platoon (veh/cycle)			
	5	10	15	20
1	.029	.053	.076	.094
10	.247	.388 [.322][a]	.495	.576
20	.390	.584 [.607]	.690	.757
30	.527	.694 [.647]	.783	.834
40	.608	.761 [.747]	.834	.874
50	.670[b]	.806	.866	.900
60	.720	.838	.889	.916
70	.770	.860[b]	.905	.929
80	.800	.880	.917	.938
90	—	.900	.929[b]	.945
95	—	—	—	.950

[a]Brackets signify a simulation.
[b]Computed value adjusted slightly.

TABLE 2 SUGGESTED K VALUES FOR APPLICATION

Left Turns Per Cycle	Computed	Suggested Value Rounded
0.5	0.25	0.25
1	0.39	0.40
2	0.58	0.60
3	0.69	0.70
4	0.76	0.75
5	0.81	0.80
6	0.84	0.84
7	0.86	0.86
8	0.88	0.88
9	0.89	0.89
10	0.90	0.90

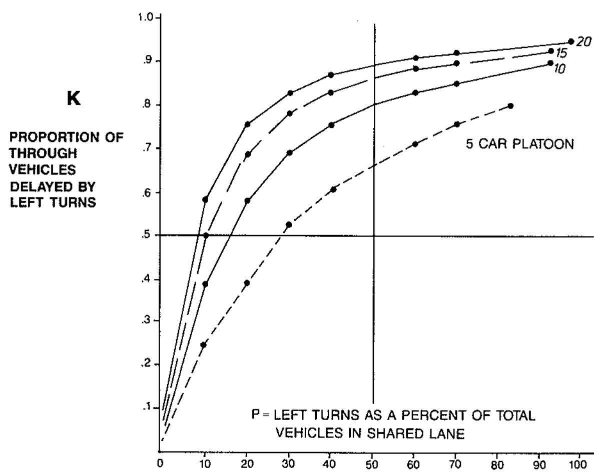

FIGURE 3 ***K* as a function of *p*.**

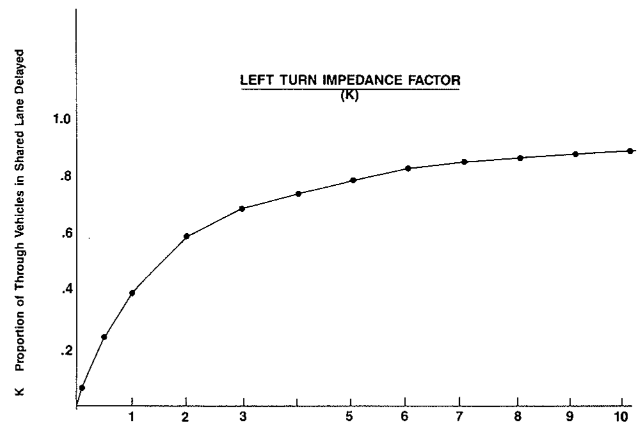

FIGURE 4 Left-turn impedance factor (*K*).

• When there are five left turns per cycle, approximately 80 percent of the through vehicles in the shared lane would be blocked.

These values simplify the computational procedures and are in a form suitable for use in Equation 10.

It is interesting to note that the K values are generally less than those obtained by the relationship

$$K = \frac{l}{l + 1}$$

Simplifying the Formula

The basic quadratic formula for the capacity of a shared lane as a result of blockage is straightforward to use. However, it can be closely approximated by the following simplified formula:

$$c_s = \frac{g}{h} - 1.2Ko_L \quad (14)$$

In this equation, $1.2K \leq 1$. If $1.2K > 1$, use 1.

Sample comparisons between the basic quadratic formula and the simplified formula are shown in Table 3. In most cases, the differences are small—usually less than 0.5 cars per cycle.

The simplified formula can be expressed as

$$c_s = \frac{g}{h} - Bo_L \quad (15)$$

where B, the modified blockage factor, equals $1.2K$ or 1, whichever is smaller.

Table 4 and Figure 5 show how the modified blockage factors (B) compare with the initial K factors. These exhibits can be used in applying Equation 15.

FORMULAS FOR APPLICATION

The capacity of any traffic lane will be reduced by two factors:

1. The time required by the opposing left turns, and
2. The time loss that results from blockage by left turns in the same direction.

The lane capacity will represent the minimum capacity resulting from these two conditions. Suggested formulas reflecting these conditions are shown in Table 5. These for-

TABLE 3 SELECTED COMPARISONS OF THE BASIC AND SIMPLIFIED FORMULAS

	Vehicles Per Cycle	
Left Turns Per Cycle	Basic Quadratic Formula (Eq. 13)	Simplified Formula (Eq. 15)
g/h = 12, o_L = 6		
0.5	10.28	10.20
1	9.21	9.12
2	7.78	7.68
3	7.03	6.46
4	6.59	6.60
5	6.24	6.24
6	6.00	6.00
g/h = 12, o_L = 8		
0.5	9.69	9.60
1	8.20	8.16
2	6.16	6.24
3	4.94	5.28
4	4.00	4.80
g/h = 15, o_L = 6		
0.5	13.33	13.20
1	12.31	12.12
2	10.96	10.68
3	10.27	9.46
4	9.89	9.60
5	9.57	9.24
6	9.34	9.00
7	9.20	9.00
8	9.04	9.00
9	9.00	9.00
g/h = 15, o_L = 8		
0.5	12.76	12.60
1	11.38	11.16
2	9.53	9.24
3	8.56	8.28
4	8.00	7.80
5	7.54	7.32
6	7.22	7.00
7	7.00	7.00
g/h = 15, o_L = 10		
0.5	12.19	12.00
1	10.42	10.20
2	8.00	7.80
3	6.65	6.60
4	5.77	6.00
5	5.00	5.40
g/h = 20, o_L = 6		
0.5	18.38	18.20
1	17.39	17.12
2	16.10	15.68
3	15.45	14.96
4	15.10	14.60
5	14.74	14.24
6	14.56	14.00
7	14.43	14.00
8	14.32	14.00
9	14.24	14.00
10	14.18	14.00
g/h = 20, o_L = 8		
0.5	17.83	17.60
1	16.51	16.16
2	14.77	14.24
3	13.88	13.28
4	13.40	12.80
5	12.98	12.32
6	12.67	12.00
7	12.49	12.00
8	12.34	12.00
9	12.23	12.00
10	12.14	12.00

TABLE 3 (*continued next column*)

TABLE 3 (*continued*)

	Vehicles Per Cycle	
Left Turns Per Cycle	Basic Quadratic Formula (Eq. 13)	Simplified Formula (Eq. 15)
g/h = 20, o_L = 10		
0.5	17.28	17.00
1	15.62	15.20
2	13.40	12.80
3	12.27	11.60
4	11.64	11.00
5	11.10	10.40
6	10.70	10.00
7	10.46	10.00
8	10.26	10.00
9	10.12	10.00
10	10.00	10.00

TABLE 4 INITIAL AND MODIFIED IMPEDANCE FACTORS

Left Turns Per Cycle	Initial *K* Factor	Modified *B* Factor[a]
0.5	0.25	0.300
1	0.40	0.480
2	0.60	0.720
3	0.70	0.840
4	0.75	0.900
5	0.80	0.960
6	0.84	1.000
7	0.86	1.000
8	0.88	1.000
9	0.89	1.000
10	0.90	1.000

[a]1.2K or 1, whichever is less.

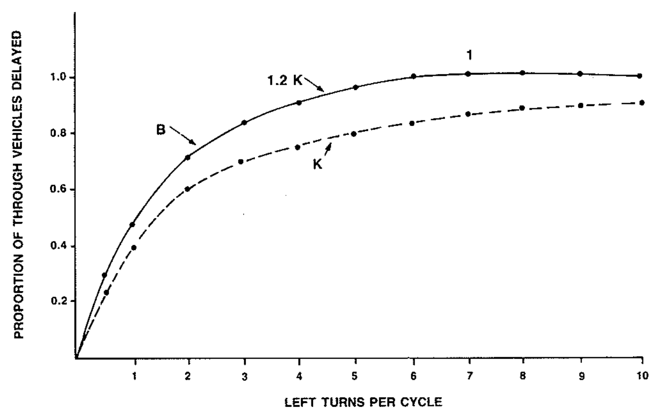

FIGURE 5 Modified impedance factor (*B*).

mulas show how the lane capacity per cycle can be computed on a lane-by-lane basis for four typical conditions:

1. Through lane with no opposing left turns or shared lane with no opposing traffic,
2. Through lane with opposing (conflicting) left turns,
3. Shared lanes with opposing traffic on two-lane streets, and
4. Shared lanes with opposing traffic on multilane streets.

TABLE 5 LANE CAPACITY FORMULAS

Case	Description	Lane Capacity Per Cycle	Constraints[a]
1.	Through lane with no opposing (conflicting) left turns or shared lane on one-way street	(A) $c = \frac{g}{h}$	
2.	Through lane with opposing (conflicting) left turns	(B) $c = \frac{g}{h} - (l_2 - s_2)$	$l_2 \geq s_2$
3.	Single shared lane (on two-lane street)	Minimum of	
	Conflict	(C) $c = \frac{g}{h} - (l_2 - l_1 - s_2)$	$(l_2 - l_1 - s_2) \geq 0$
	Blockage	(D) $c_s = \frac{g}{h} - B(o_2 - l_2)$	
4.	Shared lane on multi-lane street	Minimum of	
	Conflict	(E) $c = \frac{g}{h} - (l_2 - s_2)$	$l_2 \geq s_2$
	Blockage	(F) $c_s = \frac{g}{h} - Bo_2$	

NOTES:
g = effective green time (sec/cycle)
h = headway, adjusted for factors other than left turns (sec/veh)
l_1 = left turns per cycle in given direction
l_2 = opposing left turns per cycle
s_2 = opposing sneakers per cycle (always $\leq l_2$)
o_2 = opposing traffic per lane per cycle
B = modified blockage (impedance factor)
c = capacity (veh/lane/cycle)
c_s = capacity, veh/lane/cycle (shared lane—blockage)
[a]When these conditions are not met, apply Formula A.

Cases 3 and 4 involve the application of a pair of formulas. The formulas are similar, but Case 3 takes into account the cancelling effect of opposing left turns on a two-lane street. In both of these cases, it is necessary to check for the capacity losses caused by opposing left turns. They may be the actual capacity constraints when the number of left turns per cycle is light and the opposing left turns are heavy.

Figure 6 illustrates how the dual blockage and conflict criteria would apply. In this example, the conflict criteria apply only when the opposing left turns are substantially heavier than the left turns in the given direction of travel. Further computational examples are contained in Figure 7.

The number of sneakers per cycle can be assumed to be equal to 1 when there is a shared lane and 2 when there is an exclusive left-turn lane. However, the sneakers can never be more than the actual number of left turns.

The formulas should be applied on a lane-by-lane basis. The headways used for each lane may vary, depending on the effects of right turns and other impedances.

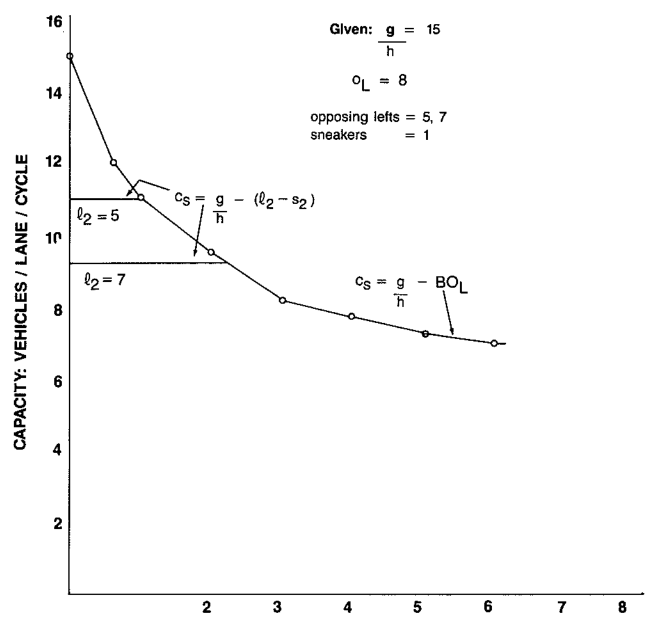

FIGURE 6 Sample computation for multilane approach showing application of dual criteria.

Leading or Lagging Green

The formulas shown in Table 5 can be used to compute the capacities of a shared lane with a leading or lagging green. The effective leading (or lagging) green time should be treated as unimpeded (see Formula A). The remaining green time should be based on Formulas C and D for a single-lane approach or Formulas E and F for a multilane approach. However, the number of left turns per cycle used for computing Formula B should be reduced proportionately to reflect the left turns moving in the leading (or lagging) period. This adjustment is computed as follows:

$$l_1' = \frac{g_2}{g_1 + g_2} l_1 \quad (16)$$

where

g_1 = effective green, normal part of phase;
g_2 = effective green, leading or lagging part of phase;
l_1 = actual left turns per cycle; and
l_1' = left turns per cycle, normal part of phase.

Hourly Capacities

The formulas can also be expressed in vehicles per hour. This is accomplished by substituting $(g/C)\,S$ for g/h, where C equals the cycle length and S equals the adjusted saturation flow.

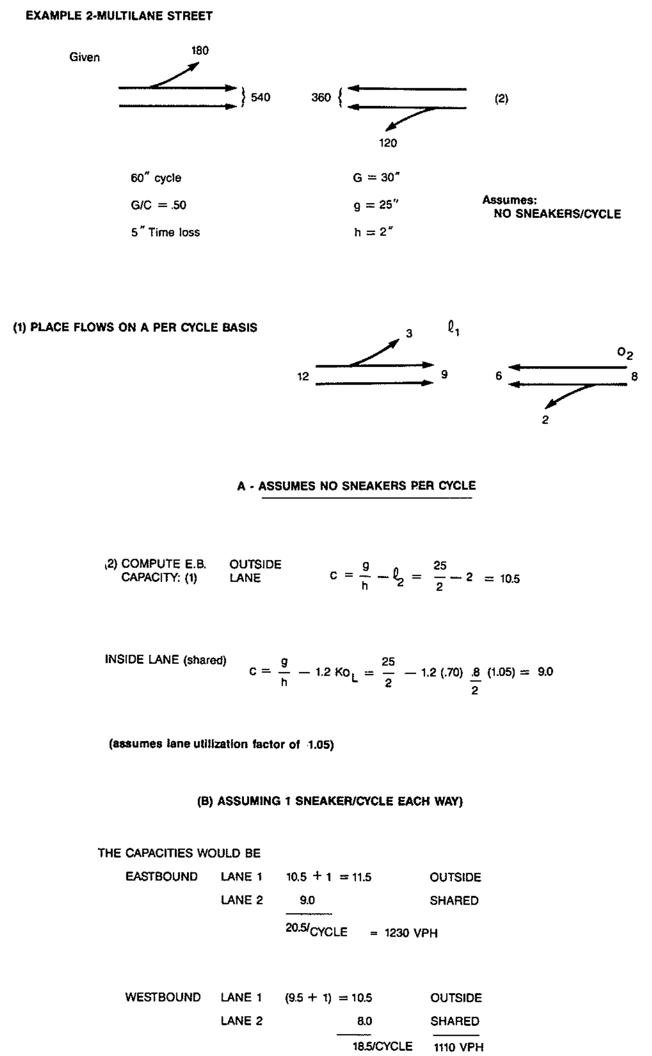

FIGURE 7 Illustrative application.

Thus, for the multilane approaches, the shared-lane capacities (Case 4) would become

$$C_s\ (\text{conflict}) = \frac{g}{C}\,S - (L_2 - S_2)$$
$$C_s\ (\text{blockage}) = \frac{g}{C}\,S - B\,O_L \qquad (17)$$

where

L_2 = opposing left turns (vph),
O_L = opposing traffic/lane/hour,
S_2 = sneakers per hour, and
C_s = shared lane capacity (vph).

COMPARISONS

Pilot comparisons were made with the capacities obtained in Example 1 of the HCM. The two analytical methods produced generally consistent results. The total intersection capacity obtained by the conflict/blockage method was about 7 percent less than that computed by the HCM (see Table 6). The multilane capacities were comparable, while the single-lane capacities produced by the suggested method were about 15 percent lower.

IMPLICATIONS

This paper has developed practical analytical approaches for dealing with left turns at intersections, particularly shared left turns. The formulas are simple and straightforward to use. They include the relevant variables, and they produce reasonable limits and values. They are user friendly and can be solved manually or by computerized methods. They apply on a lane-by-lane basis, and they produce results on the same order of magnitude as the HCM.

The formulas are dynamic in that they consider the effects of the opposing traffic flow on intersection capacity. They reflect the blockage effect of opposing vehicles in a systematic and predictable way, and they take cycle length into consideration.

A suggested blockage factor has been derived from probability and simulation analysis. However, the formulas can use other blockage factors that may emerge from further research or field tests.

The significant findings are as follows:

- The capacity of a shared left-turn lane is reduced by both the number of left turns using the lane and the traffic volume

TABLE 6 COMPARATIVE CAPACITIES (*1*)

Approach	This Paper	Example 9-1 in HCM	Percent Difference[a]
Northbound (one lane)	648	753	−14
Southbound (one lane)	669	807	−17
Eastbound (two lanes)	878	843	4
Westbound (two lanes)	951	995	−4
Total	3,146	3,398	−7.4

[a]From HCM example.

in the opposing direction. Where opposing left turns are heavy, they, too, will limit the capacity of a shared lane.

- When there are five or more left turns per cycle in a shared lane, they preempt that lane for all practical purposes.
- Short signal cycles are preferable to maximize the capacity of shared left-turn lanes since they reduce the left turns per cycle and their blockage effects. They also allow more sneakers per hour on the yellow signal.
- Capacity of a nonshared lane (through vehicles only) is reduced by the opposing left turns.

Additional field studies are desirable to verify the analysis and to adjust the suggested formulas. Their ease of application warrants such efforts. The formulas and factors provide, at minimum, a viable method for use in planning applications.

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