Examination of Shared Lane Operations

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The shared use of a single traffic lane by through and left-turn movements is one of the more complex operations that can occur at signalized intersections. A closed-form solution for evaluating the effect of shared lane use is described in the *Highway Capacity Manual* (HCM). This paper investigates the methodology of the HCM shared lane analysis. It also extends that methodology to recognize the operational interdependence of saturation flow rate and lane use on opposing approaches. This extension is in the form of an iterative modification wherein the saturation flow rate and lane use on opposing approaches are incrementally updated. Using the modified methodology, several investigations were undertaken to determine the behavior of shared lane operations. These investigations included comparing the modified methodology with the original HCM methodology; studying convergence trends; evaluating the effects of various timing and volume conditions; isolating a maximum volume threshold; and identifying the shared versus de facto left-turn lane regime. As a result of this examination, it was found that the HCM methodology consistently estimated slightly lower saturation flow rates than the final flow rate converged upon. A major outcome of the sensitivity analysis and evaluation study was a graphical technique for estimating the operational nature of a shared traffic lane.

The operation of traffic in a lane shared by left-turning and through vehicles is difficult to describe both in general and mathematical terminology. Other authors (*1, 2, 3, 4*) have described the complex combination of events that occur in shared lanes. However, the sensitivity of shared lane operations to various timing and volume conditions has yet to be adequately described or understood. This paper offers another look at opposed, shared lane operations at traffic signals.

The recent publication of the *Highway Capacity Manual* (HCM) (*5*) has heightened the need for a better understanding of shared lane operations. Chapter 9 of this manual presents a methodology for estimating the saturation flow rate of an intersection approach having a shared lane. Although this methodology has been well documented in the HCM, a basic understanding of the effects of each of the input variables (*e.g.*, volume and signal timing) is still greatly needed. In essence, without understanding the trends and tendencies of the methodology, the analyst cannot be confident of the results or their implication.

One goal of this paper is to examine the theoretical sensitivity of shared lane operations (as modeled by the HCM methodology) to changes in several control variables. Another goal is to examine the interdependent relationships among operations on opposing approaches. Finally, the realm of de facto left-turn lane operation (*i.e.*, a shared lane operating as exclusive left-turn lane) will be quantified and described in terms of the conditions that induce its occurrence.

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APPROACH

An intersection having two opposing, two-lane, shared lane approaches was considered to be the typical shared lane situation. This intersection, shown in figure 1, has two lanes on each approach; the inside lane could be shared by through and left-turn vehicles, while the outside, or curb, lane would be used exclusively by through vehicles. The intersection is served by a two phase signal, that is, one phase for each street. For the sake of simplicity, neither cross street nor right-turn traffic volumes were considered.

The variables considered for their effect on shared lane operation are shown in table 1. They include the approach volume (V_a), the opposing approach volume (V_o), the proportion of approach traffic that turns left (P_{LT}), the proportion of opposing traffic that turns left (P_{LTO}), the cycle length (C), and the total green plus yellow time (G). These variables were selected because they were felt to have the greatest influence on shared lane operation.

Each variable was independently varied over a range of typical values to determine its effect on the overall operation of a shared lane. The measures used to monitor these variational effects were the lane group saturation flow rate (S_a) and the proportion of left-turns on the inside lane (P_L). For each of the variables studied, a pair of figures was generated to illustrate the trends and sensitivities of S_a and P_L. These figures are included below in the discussion of sensitivity analysis.

It should be noted that one variable affecting shared lane operation, the saturation flow rate for through traffic (S_T), was not varied in this study. Although it is recognized that this variable could have a significant effect on shared lane operations, it was reasoned that investigation of the other variables would be more pertinent and relevant to the goals of this paper. The saturation flow rate used for this study was less than the ideal rate of 1,800 vehicles per hour of green time per lane (vphgpl). This was deliberately done to illustrate the effects of a less-than-ideal saturation flow rate on shared lane operations.

SHARED LANE MODELS

As noted above, several models have been offered for the analysis of shared lane operations. All of these models are based on a probabilistic approach wherein the opportunities for left-turn or through movement departures are quantified in terms of expected or average rates. This type of model has the advantage of providing both a logical and tractable solution, but the disadvantages of being both complex and iterative, by nature of its dependency on opposing lane operations. Of these models, the shared lane methodology identified

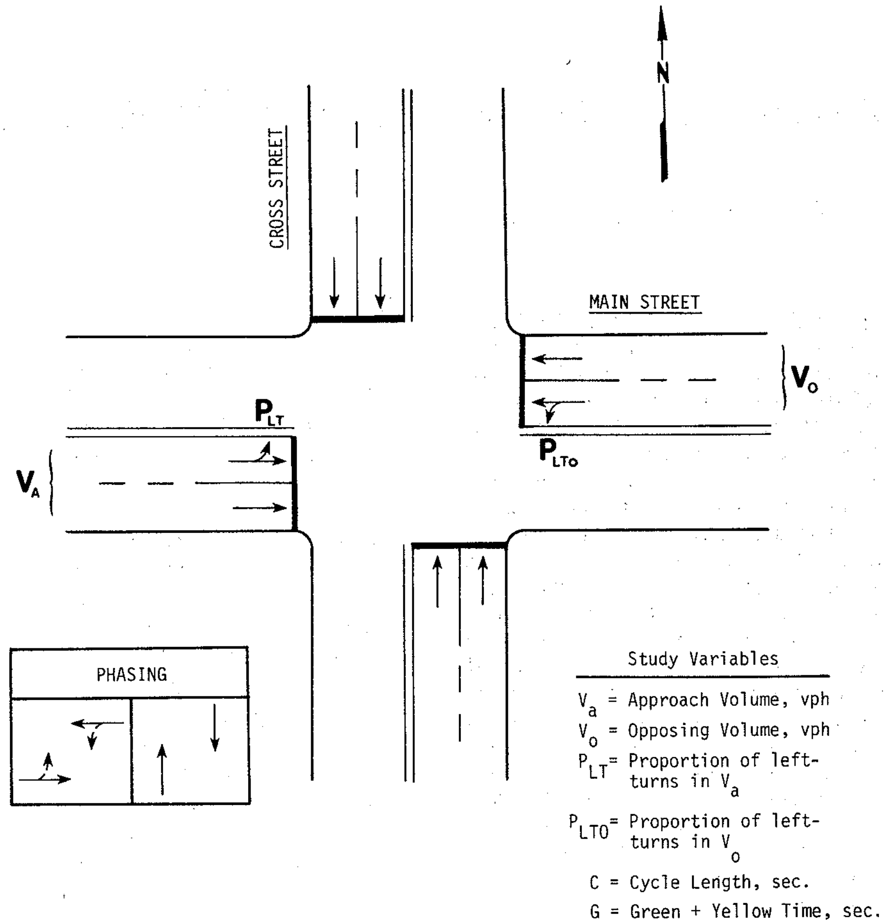

FIGURE 1 Typical shared lane configuration.

in chapter 9 of the HCM was selected for this evaluation for two reasons: its publication in the HCM makes it the more popular methodology, and its simplicity with respect to other probabilistic models provides a reasonable balance between theory and practicality.

HCM Model

The HCM methodology should theoretically provide a good estimate of shared lane operations. As shown in figure 2, the process has been reduced to a series of intermediate calculations. The final result is a factor that can be used to calculate the approach saturation flow rate.

TABLE 1 STUDY VARIABLES

P_{LT}	G/C	C (sec)	V_a, V_o[a] (vph)	P_{LT}, P_{LTO}[b]	S_T[c] (vphgpl)
0.01	0.20	50	200	0.01	1650
0.10	0.30	60	600	0.10	
0.15	0.40	70	800	0.15	
0.20	0.50	80		0.20	
0.30	0.60	90		0.30	
	0.80	100			
		110			
		120			

NOTE: Underlined values represent the base condition. These values were fixed during the sensitivity analysis of a particular variable.
[a]All volume elements were set equal unless otherwise noted.
[b]Proportion of left-turns on the subject and opposing approaches were set equal. For each volume level, P_{LT} and P_{LTO} were varied through their entire range.
[c]Saturation flow rate was not varied.

The HCM model evaluates shared lane operation in terms of three components. These components, as they occur from the commencement of green, are

- Period 1—an initial portion, wherein some through vehicles can proceed before the first, blocking left-turn vehicle arrives at the head of the queue,
- Period 2—an interval subsequent to the clearance of the opposing queue wherein both through and left-turn vehicles can depart, and
- Period 3—a final period wherein left-turn vehicles clear the intersection before the initiation of the cross street phase.

Several authors have proposed the existence of other capacity components (*1, 2*). The contribution of these components, however, is generally small. As a result, the increased complexity of calculation of these components does not appear to be justified, given the overall accuracy of the process.

The HCM method should provide a good estimate of shared lane operations. However, the calculated saturation flow rate can only be taken as an estimate, due to several assumptions and simplifications embedded in the methodology. In particular, assumptions are embedded in the equations for calculating the opposing saturation flow rate (S_{op}) and the pro-

SUPPLEMENTAL WORKSHEET FOR LEFT-TURN ADJUSTMENT FACTOR, f_{LT}				
INPUT VARIABLES	**EB**	**WB**	**NB**	**SB**
Cycle Length, C (sec)	70	70	70	70
Effective Green, g (sec)	27	27	37	37
Number of Lanes, N	2	2	1	1
Total Approach Flow Rate, v_a (vph)	800	833	466	667
Mainline Flow Rate, v_M (vph)	800	833	433	623
Left-Turn Flow Rate, v_{LT} (vph)	72	33	33	44
Proportion of LT, P_{LT}	0.09	0.04	0.07	0.07
Opposing Lanes, N_o	2	2	1	1
Opposing Flow Rate, v_o (vph)	833	800	623	433
Prop. of LT in Opp. Vol., P_{LTO}	0.04	0.09	0.07	0.07
COMPUTATIONS	**EB**	**WB**	**NB**	**SB**
$S_{op} = \dfrac{1800\,N_o}{1 + P_{LTO}\left[\dfrac{400 + v_M}{1400 - v_M}\right]}$	3333	3012	1698	1648
$Y_o = v_o / S_{op}$	0.250	0.266	0.367	0.263
$g_u = (g - CY_o) / (1 - Y_o)$	12.67	11.42	17.87	25.24
$f_s = (875 - 0.625\,v_o) / 1000$	0.354	0.375	—	—
$P_L = P_{LT}\left[1 + \dfrac{(N-1)\,g}{f_s g_u + 4.5}\right]$	0.360	0.163	0.070	0.070
$g_q = g - g_u$	14.33	15.58	19.13	11.76
$P_T = 1 - P_L$	0.640	0.837	0.930	0.930
$g_f = 2\,\dfrac{P_T}{P_L}\left[1 - P_T^{\,0.5\,g_q}\right]$	3.41	7.70	13.29	9.22
$E_L = 1800 / (1400 - v_o)$	3.17	3.00	2.32	1.86
$f_m = \dfrac{g_f}{g} + \dfrac{g_u}{g}\left[\dfrac{1}{1 + P_L\,(E_L - 1)}\right] + \dfrac{2}{g}(1 + P_L)$	0.490	0.690	0.859	0.950
$f_{LT} = (f_m + N - 1) / N$	0.75	0.85	0.86	0.95

FIGURE 2 Shared lane analysis worksheet (*5*).

portion of left-turn vehicles in the left lane (P_L). In both of these equations, estimates must be made regarding shared lane operations on the opposing and subject lane groups before the evaluation can be completed.

Other assumptions inherent in the formulation are the use of ideal saturation flow rates (*i.e.*, 1,800 vphgpl) in the equations for the initial portion of green time (g_f), left-turn equivalency (E_L), opposed saturation flow rate (S_{op}), and the left-turn factor (f_m). It will be shown later that the use of ideal saturation flow rates tends to yield conservative estimates of shared lane capacity. This was an intentional adjustment in recognition of the closed-form computational approach recommended by the HCM.

Iterative Model

Recognizing the limitations of the aforementioned assumptions in the HCM formulation, a modification was proposed and investigated for its effect on the calculated saturation flow rate. This modification was directed towards an iterative approach wherein the values of S_{op} and P_L were recalculated based on previous results, or iterations. This procedure has the advantage of being able to incorporate better estimates of S_{op} and P_L during each iteration, which is particularly important in those instances where the opposing approach also has shared lane operations. The proposed model is described below as a sequence of calculation steps.

- Step 1. $Y_o = V_o / S_{op}(i-1)$
- Step 2. $g_u = (g - C * Y_o) / (1 - Y_o)$
- Step 3. $P_L = P_{LT} * [\ 1 + (N - 1) / f_m(i-1)\ ]$
- Step 4. $g_q = (g - g_u)$
- Step 5. $g_f = 2.0 * [(1 - P_L) / P_L] * [1 - (1 - P_L) * (g_q * S_T 3600)]$
- Step 6. $E_L = S_T / (1400 - V_o)$
- Step 7. $f_{m(i)} = [g_f + g_u / (1 + P_L * (E_L - 1)) + 3600 * (1 + P_L) / S_T] / g$
- Step 8. $f_{LT} = (f_{m(i)} + N - 1) / N$
- Step 9. $S_{a(i)} = ST * f_{LT} * N$

where

C = cycle length, sec.
E_L = through-vehicle equivalent for opposed left-turns.
$f_{m(i)}$ = left-turn factor for the shared lane (Note: $f_{m(i)}<1.0$).
g = effective green time, sec.
g_f = duration of initial portion of green phase, sec.
g_q = portion of green phase blocked to left-turning vehicles by the clearing of an opposing queue of vehicles ($= g - g_u$),sec.
g_u = portion of green not blocked by the clearing of an opposing queue, sec.
i = current calculation sequence.
N = number of lanes on approach.
P_L = proportion of left-turn vehicles in shared lane.
P_{LT} = proportion of left-turn vehicles on the approach.
$S_{a(i)}$ = saturation flow rate for subject lane group, vphg.
$S_{op(i-1)}$ = saturation flow rate on opposing approach taken from the previous calculation, vphg.
S_T = through-vehicle saturation flow rate on subject approach ($= 1800 * f_w * f_{HV} * f_g * f_a$), vphgpl.
V_o = opposing flow rate, vph.
Y_o = flow ratio on the opposing approach.

As shown in the preceding steps, the proposed model adopts the same format and sequence of calculation as that of the HCM methodology. The only deviations are the use of information from preceding calculations and the use of a less-than-ideal saturation flow rate where ideal values had previously been assumed.

In recognition of the iterative nature of the proposed procedure, the methodology was programmed in BASIC to automate the analysis process. The function of this program was to make an initial calculation using the original HCM methodology and to use the modified methodology for second and subsequent iterations.

For this study, a fairly strict convergence criterion was selected such that the nature of the solution process could be fully explored. In fact, a solution was said to have "converged" when the difference between approach saturation flows for two successive iterations was less than 0.5 vphg. While the allowable deviation for the final calculations was quite small, experience with the procedure indicates that the likelihood of arriving at a convergence solution is almost certain.

Using this criterion, the number of iterations was found to range from one to thirty iterations. Convergence was commonly achieved, however, in less than ten iterations for the conditions of this study. In general, two iterations beyond the initial HCM solution would typically yield a saturation flow rate that was very near the convergence flow rate.

Two conclusions were drawn from this study of convergence. First, it appeared that the HCM methodology would generally yield a conservative estimate of the saturation flow rate for a shared lane. This tendency is consistent with the intent of its formulation. However, it should also be noted that for some near-capacity conditions the HCM solution was found to overestimate the shared lane saturation flow rate. Second, the saturation flow rate from the first (HCM) iteration was almost always found to be within 5% of the final solution.

SENSITIVITY ANALYSIS

This section examines the sensitivity of shared lane operations to variations in volume and signal timing. For each of the variable combinations identified in table 1, an iterative analysis was performed which included an initial calculation of saturation flow using the original HCM methodology. All subsequent calculations used the modified methodology wherein information from the last iteration was used as a better estimate of actual conditions. The iterations were stopped when the approach saturation flow rate (S_a) between two successive calculations did not change by more than 0.5 vphg. It should be noted that the results reported in this paper reflect under-capacity conditions for all approaches.

Left-Turn Percentage

The sensitivity of the shared-lane methodology to variation in left-turn percentage was investigated for this analysis. As shown in figure 3, the effect of an increase in left-turn percentage caused a reduction in saturation flow rate for the subject approach. In particular, the flow rate varied between 3,300 vphg and 2,400 vphg for a left-turn percentage in the range of 1% and 30%, respectively. It should also be noted that when the percentage of left-turns was increased, lane use on the interior, shared lane approached that of an exclusive left-turn lane (*i.e.*,P_L = 1.0). This result is reasonable and consistent with general expectation.

Concerning the first (HCM) solution versus the final (convergence) solution, the trends in convergence—noted above in the discussion of the modified methodology—were well illustrated. Not only did the HCM and final solution "track" one another, but it appeared that the HCM solution would yield a conservative, or lower, estimate of saturation flow rate.

Cycle Length

For this investigation, a range of typical of cycle lengths was considered to determine the effect of cycle length on shared-

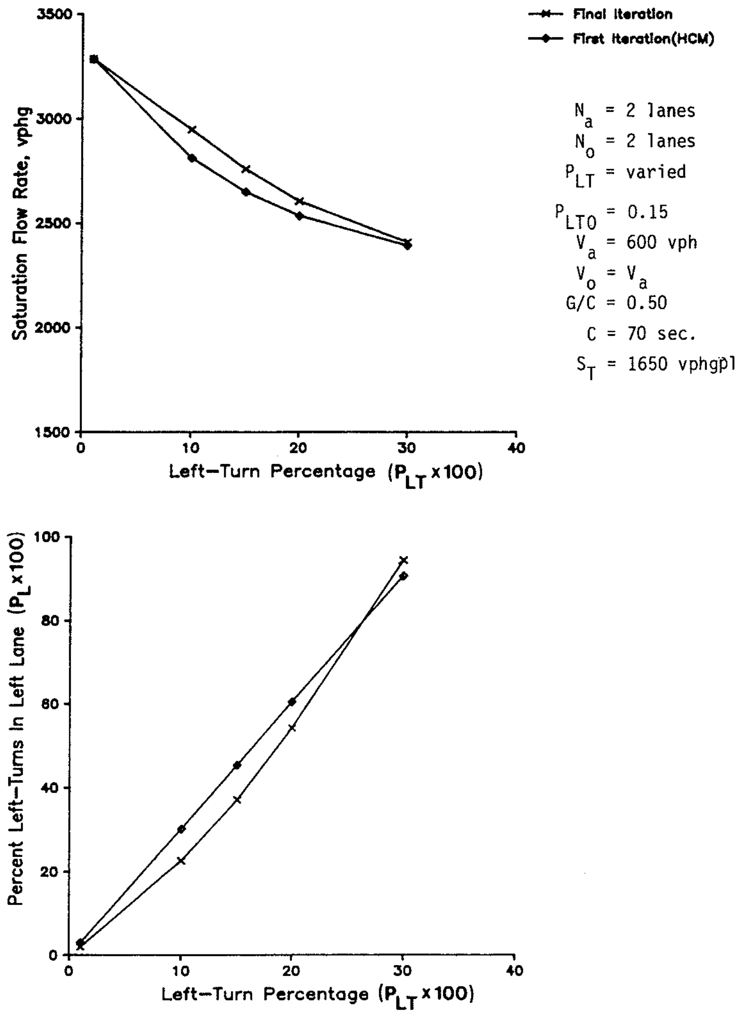

FIGURE 3 **Effects of left-turn percentage.**

lane operations. As shown in figure 4, the convergence trends appear to be consistent with those found in the investigation of left-turn percentage. In particular, the HCM solution again yielded a slightly lower value of saturation flow rate than the convergence solution. In addition, a positive relationship was again found to exist between the two solutions regarding their general agreement with trends in the changes in cycle length.

One of the more interesting results of this sensitivity analysis was the lack of any significant change in flow rate with cycle length. This result implies that the duration of the cycle length has a minimal effect on the operation of shared lanes. This can be explained as the result of two secondary effects. One is the increase in capacity per cycle during period 2 with an increase in cycle length. Vehicular capacity per cycle during this period is a direct function of the amount of unsaturated green time (g_u) available. This green time increases almost linearly with cycle length when the green-to-cycle-length (*G*/*C*) ratio is held constant.

The other secondary effect is the lower number of cycles and hence, clearance opportunities that can occur each hour when cycle length is increased. These two effects tend to cancel one another and thereby minimize the influence of cycle length on saturation flow. It should be noted that the capacity of period 1 was not found to vary significantly with cycle length.

Green-to-Cycle-Length Ratio

For this analysis, the effects of a change in the green time for a given cycle length were investigated. As shown in figure 5, changes in the *G*/*C* ratio were found to have an effect on the operation of the shared lane approach. This was evidenced by the wide variation in saturation flow rates for *G*/*C* ratios of less than about 0.40. In addition to this wide variation, there also appeared to be a deviation from the expected conservative nature of the HCM methodology.

Further investigation of the conditions that created the observed anomalies revealed that as *G*/*C* varies from larger to smaller ratios, the volume-to-capacity ratio (*v*/*c*) of the approach neared 1.0. In fact, for *G*/*C* ratios less than 0.35, both approaches were found to be over capacity. Hence, it appeared that, for some near-capacity conditions, the saturation flow rate found using the HCM methodology could be greater than the iterated solution (*i.e.*, not conservative). It was also noted that, for *G*/*C* ratios greater than 0.40, the

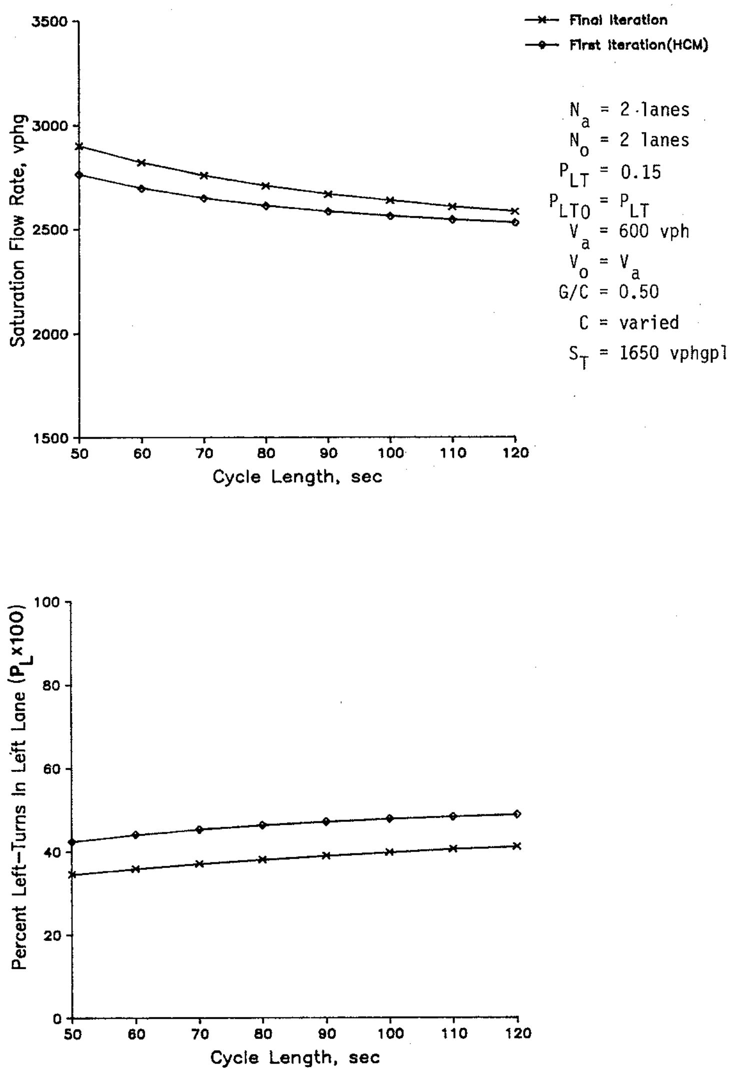

FIGURE 4 Effects of cycle length.

effect on saturation flow rate did not appear to be as significant.

Entering Volume and Left-Turn Percentage

The investigation of entering volume presented many possible combinations of opposing and subject approach volumes. Moreover, it was resolved that a thorough examination should consider effects of changes in both through and left-turn volumes. In recognition of the need for variation in these volumes, it was felt that a balanced volume condition would be the most reasonable compromise. Hence, for all volume conditions reported in this section, the volumes and left-turn proportions on each approach were held equal throughout all analyses.

As a result of equalizing the volumes and left-turn proportions, the investigation was reduced to an analysis of symmetric supply and demand conditions. In other words, the operation of the shared lane on either side of the intersection was identical given the same geometry, volume, and timing conditions. For each value of entering volume, five values of left-turn proportion were examined for their effect on approach saturation flow rate. This approach was taken to ensure a consistency with the preceding analyses.

Figure 6 illustrates the results from this analysis. Based on these results, it was concluded that combinations of high left-turn and entering volumes would have a definite adverse effect on the saturation flow rates of two opposing shared lane approaches. This conclusion is intuitively reasonable, since the demand on a shared lane approach indirectly affects the capacity of the approach opposing it.

One trend observed in this analysis was that the HCM methodology did give conservative results under a wide range of volume conditions. In the few situations where the HCM solution was not conservative, it was found that the *v/c* ratio of the left-turn or through movement was near 1.0. This trend was consistent with that observed during the sensitivity analysis of the *G/C* ratio.

An explanation of the HCM solution's conservative results lies primarily in its formulation. Several major effects interact within the HCM methodology and result in a lower estimation of saturation flow rate for the shared lane. The first effect is embedded in the equations for S_{op} and P_L (see Figure 2). The

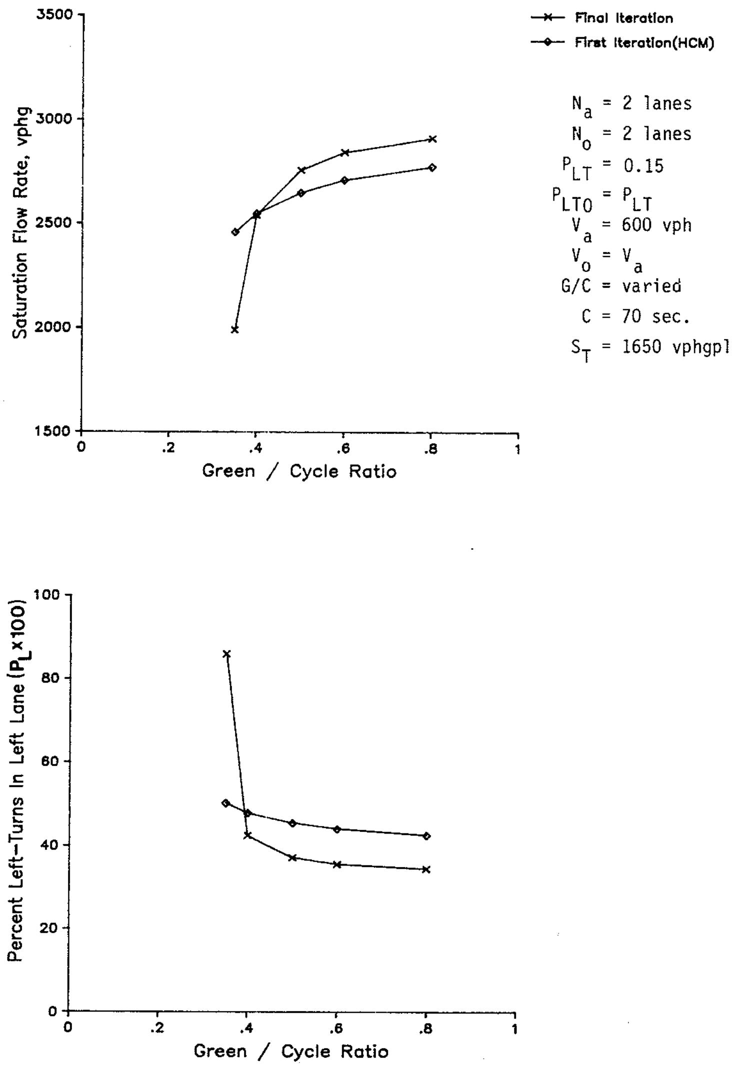

FIGURE 5 Effects of green/cycle ratio.

equation used to estimate S_{op} will almost always yield a higher value than that found in the final iteration. This implies an expectation of higher estimates of unsaturated green time (g_u) and hence, a greater shared lane capacity during period 2. However, this is not generally found because of the effect of another factor, P_L. The equation used to estimate P_L typically overestimates the proportion of left-turn vehicles in the inside, or shared, lane. The implication of this approximate procedure can be found in a lower estimate of through vehicle capacity during period 1.

The effect of overestimating P_L explains some of the conservative nature of the HCM's saturation flow rate estimate. In contrast, the effect of overestimating S_{op} (and thereby g_u) suggests a more liberal flow rate estimate. However, the combination of P_L and g_u in the equation used to calculate the left-turn adjustment factor (f_m) tends to offset the effects of S_{op}. As a result, period 2 capacity is also conservatively estimated in most instances.

Another effect worthy of consideration is the calculation of capacity during period 3. As noted above, the HCM methodology generally overestimates the magnitude of P_L and results in an overestimate of capacity during the clearance interval (*i.e.*, period 3). However, the ultimate indirect factoring of this capacity component by the other saturation flow rate adjustment factors tends to overcompensate for the effect of an overestimated P_L and typically results in a net conservative estimate of period 3 capacity. It should be noted that the capacity of this period has traditionally been calculated as the number of vehicles clearing at the end of the cycle which is totally independent of the saturation flow rate experienced during the green phase.

SHARED LANE RELATIONSHIPS

Based on the preceding sensitivity analysis, it appeared that the four dominant variables (with respect to shared lane operations) were proportion of left-turns (P_{LT}), opposing proportion of left-turns (P_{LTO}), approach volume (V_a), and opposing volume (V_o). Green time and cycle length were found to have a limited effect on shared lane operations.

In an attempt to understand better the interaction of the dominant variables, figure 7 was generated using the modified methodology. In this figure, each axis represents an inde-

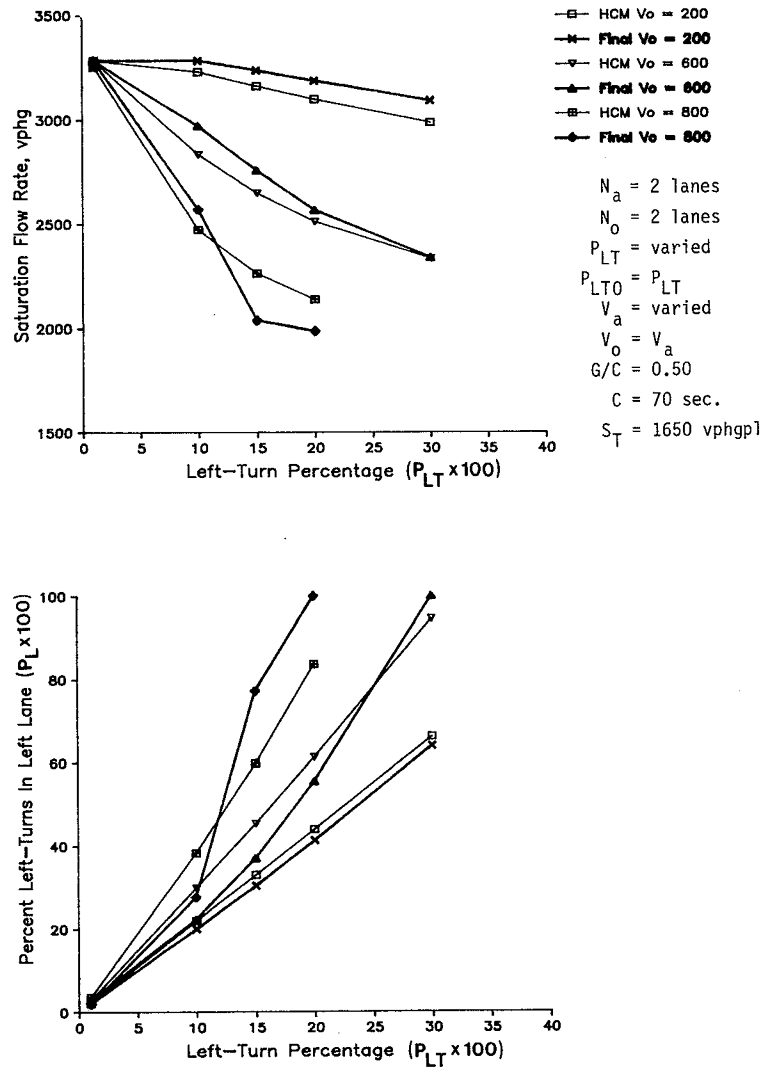

FIGURE 6 Effects of left-turn percentage and entering volume.

pendent variable, while the dependent variable is represented as a shaded region. In general, these variables were chosen to illustrate their interrelated effect on capacity and lane use. As might be expected, opposing and approach volumes were found to have a significant impact on intersection capacity. Similarly, opposing volume and approach left-turn percentage were found to have the greatest influence on approach lane use.

Results of Specific Analyses

Using the modified HCM methodology, the volume-to-capacity (v/c) and shared-exclusive lane relationships shown in figure 7 were developed. The sloping lines shown on each figure represent the unique combination of independent variables such that either the v/c ratio or the proportion of left-turns in the left-lane (P_L) would equal 1.0. These threshold values were selected because they describe a boundary between operational states (*i.e.*, over-under capacity or shared-exclusive lane use).

As suggested by figure 7a, a range of maximum approach and opposing volume combinations was found such that one of the opposed approaches operated at its capacity. Obviously, any combination of approach volumes that had the same proportion of left-turns and intersected below this threshold should experience a v/c ratio less than 1.0.

Two capacity thresholds (P_{LT} = 0.01 and 0.30) are shown in figure 7a. For the case where P_{LT} equaled 0.30, it was found that the combinations of V_o and V_a that produced a v/c equal to 1.0 were less than those found when P_{LT} equaled 0.01. This trend is intuitively reasonable considering the degrading effect that left-turn vehicles have on the capacity of an approach.

Figure 7b illustrates the effect of left-turn proportion (P_{LT}) and opposing volume (V_o) on lane usage. The line A′-A-B identifies the threshold combinations of P_{LT} and V_o that would cause the inner lane to operate an exclusive, or de facto, left-turn lane for an approach volume of 800 vph. Likewise, the line A′-B identifies the exclusive lane threshold for an approach volume of 200 vph. This threshold can be described as an equilibrium condition wherein the volume-to-capacity ratios of the through and left-turn movements are equal and the proportion of left-turn vehicles on the interior lane is 1.0.

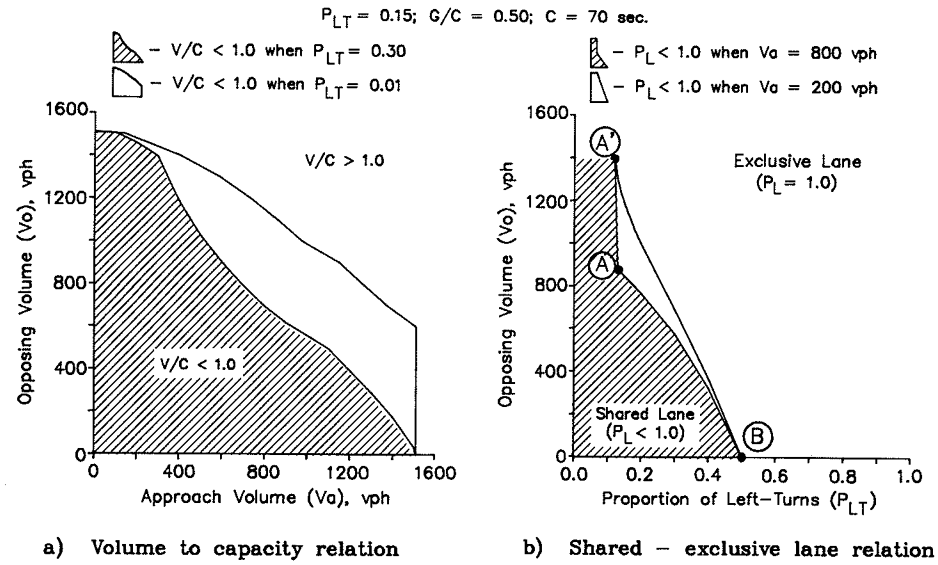

FIGURE 7 Shared lane relationships: specific case.

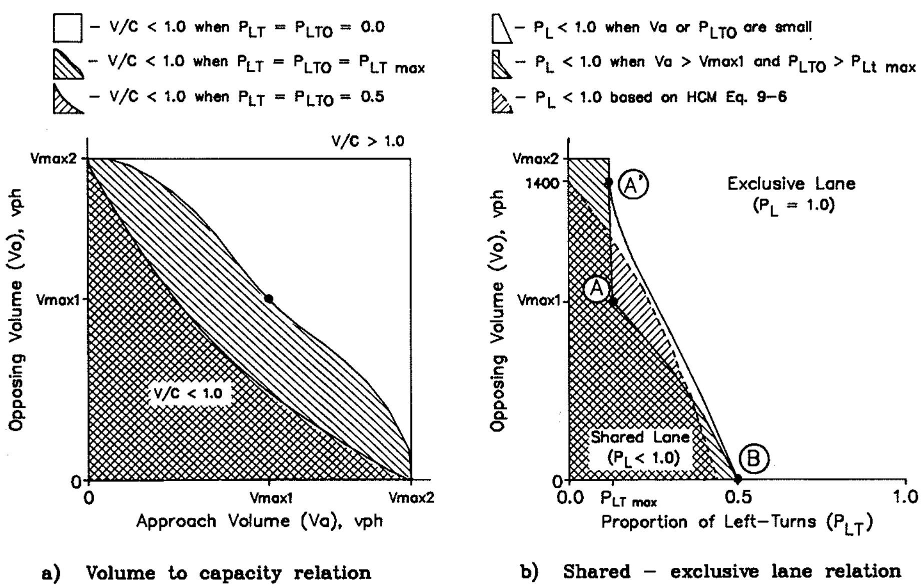

FIGURE 8 Shared lane relationships: general case.

It is reasonable to assume that the equilibrium condition describes the threshold where lane selection becomes movement specific on a shared-lane approach. The essence of this assumption is predicated on the inherent nature of motorists to base their lane selection on minimum travel time. This capacity equilibrium concept is embedded within the formulation of the shared lane analysis methodology.

As shown in Figure 7b, there was a left-turn proportion below which the approach always operated as a shared lane, regardless of opposing volume. For left-turn proportions above this minimum value, operation of the approach was found to be primarily a function of opposing volume. However, approach volume (V_a) and opposing left-turn proportion (P_{LTO}) were also found to affect the location of the equilibrium threshold (*i.e.*, line A′-A-B vs. A′-B). In fact, the secondary effects of V_a and P_{LTO} explain the triangular region A′-A-B wherein the threshold condition was found to vary.

Formulation of General Case

Based on concepts introduced in the preceding section and supplemented with additional analyses, figure 8 was generated to illustrate the basic shared lane relationships. This figure is presented in a general form with only unique points and boundaries described. The intent of the general format was primarily to identify the sensitivity of shared lane use to changes in certain variables. However, it was assumed that the identification of all unique points or boundaries on each figure would aid others in applying these results to different timing and geometric conditions. Each of these points and boundaries is defined below.

V_{max2}—This is the capacity of two through lanes of traffic having no left-turn vehicles.

$$V_{max2} = (N * S_T * [G - l]) / C \quad (1)$$

where

N = number of lanes on the approach.
S_T = through saturation flow rate, vphgpl.
G = total green plus yellow time, sec.
l = lost time, assumed = 3.0 sec.
C = cycle length, sec.

Using the values from figure 7a (*i.e.*, G = 35 sec., S_T = 1650 vphgpl, C = 70 sec., N = 2),

$$V_{max2} = (2 * 1650 * [35 - 3]) / 70 = 1509 \text{ veh/hour.}$$

V_{max1}—This represents the capacity of one lane of through traffic plus the number of left-turn vehicles clearing the intersection during the clearance interval (*i.e.*, sneakers).

$$V_{max1} = [V_{max2} * (N - l) / N] + [S_n * 3600 / C] \quad (2)$$

where

V_{max2} = maximum through lane capacity for N lanes, vph.
N = number of lanes on the approach.
S_n = maximum number of left-turns during the change interval, assumed equal to two under maximum volume conditions.
C = cycle length, sec.

For this example, V_{max1} can be calculated as

$$V_{max1} = [1509 * (2 - 1) / 2] + [2 * 3600 / 70] = 857 \text{ veh/hour.}$$

P_{LTmax}—This value represents the threshold proportion of left-turn vehicles. Any proportion of left-turn vehicles less than this value would theoretically guarantee shared lane operation.

$$P_{LTmax} = (S_n * 3600 / C) / V_{max1} \quad (3)$$

where

V_{max1} = maximum capacity of one lane plus sneakers, vph.
S_n = number of left-turns during the change interval.
C = cycle length, sec.

For this example,

$$PLT_{max} = (2.0 * 3600 / 70) / 857 = 0.12.$$

V_o = 1400 vph—This constant is identified in figure 8 because it represents the opposing volume that would theoretically have insufficient gap size to permit the filtering of left-turn vehicles. Thus, when the opposing volume exceeds 1,400 vph, the only left-turn capacity available would be as sneakers during the clearance interval.

P_{LT} = 0.50—This proportion represents the upper boundary value for shared-lane operation. Theoretically, any left-turn proportion exceeding 0.50 would have exclusive use of the inside lane.

In figure 8a, three separate capacity threshold lines are shown. These lines represent three different combinations of left-turn proportion: 0.0, P_{LTmax}, and 0.50. Of these, 0.0 and 0.50 represent lower and upper boundaries, respectively, on the region of shared lane use. The P_{LTmax} line is also shown because it is related to the shared-exclusive lane threshold and because it can be located using V_{max1}.

The left-turn proportions described in figure 8a are equal for both the subject and opposing approaches. This "symmetric" situation was chosen for two reasons. The first reason was that it more nearly represented the typical intersection where both approaches have roughly the same left-turn proportions. The other reason was based on the results of several analyses, from which it appeared that the symmetric case represented a worst-case combination. Thus, with respect to figure 8a, any volume combination that intersects below the capacity threshold (*i.e.*, $v/c < 1.0$) for a given symmetric left-turn proportion should also be under capacity when one approach has a lesser left-turn proportion. For example, if the proportion of left turns on one approach was 0.05 while the proportion of left-turns on the opposing approach was 0.15 and their volume combination intersected below the $P_{LT} = P_{LTO} = 0.15$ threshold, then it could be concluded that both approaches will operate at a v/c of less than 1.0. In summary, the symmetric left-turn proportion threshold should conservatively predict the under-capacity situation.

When considering figure 8a, it must be remembered that only one left-turn proportion line can describe the capacity threshold. The line chosen should equal or exceed the larger left-turn proportion of either the subject approach or its opposing approach. One of the three threshold lines shown in figure 8a could be used as the capacity threshold or another threshold could be located by interpolation. In recognition of the limitation of the shared lane methodology, the $P_{LT} = P_{LTO} = 0.50$ threshold probably represents a practical boundary for conservatively estimating the volume-to-capacity condition of two, two-lane, opposing approaches.

Figure 8b represents the general relation between the approach left-turn percentage (P_{LT}) and the volume opposing it (V_o). In particular, the line A′-A-B represents the boundary between shared and exclusive lane operation on the subject approach. If the approach left-turn proportion and opposing volume combination intersect below the line A′-A-B, then the subject approach should operate as a shared lane. If the intersection is beyond line A′-B, then the approach should operate as an exclusive lane.

The triangular region A′-A-B bounds the combinations of P_{LT} and V_o that may or may not cause an exclusive lane operation. The location of the exact threshold boundary between point B and a point on line A′-A is a function of approach volume (V_a) and opposing left-turn proportion (P_{LTO}). The reason for this secondary influence is somewhat complex, but is based primarily on the capacity of period 2. In those situations where either the approach volume (V_a) or the opposing left-turn proportion (P_{LTO}) is light, there is a maximum likelihood of unused green time (g_u). This usually results in a maximum left turn capacity. Conversely, if both V_a and P_{LTO} are large, then it is probable that g_u is small. Obviously if g_u equals zero, then period 2 capacity is also zero.

Based on the results of the preceding examination, it was possible to make the following generalization: If the left-turn proportion (P_{LT}) and volume (V_a) of an approach are less than P_{LTmax} and V_{max1}, respectively, then that approach will operate below its capacity and its inner lane will be shared by left and through traffic.

In those cases where P_{LT} and V_a are greater than $P_{LT\max}$ and $V_{\max1}$, but less than 0.50 and $V_{\max2}$, respectively, the operation of the approach must be determined using figures 8a and 8b or by analysis using the HCM methodology (*i.e.*, supplemental worksheet).

Comparison With HCM De Facto Lane Procedure

HCM equation 9-6 (*5*, p. 9-9) describes a simple procedure for determining the operation of a shared lane approach. When the appropriate volume conditions are satisfied, the inside lane can be considered a de facto left-turn lane, and the HCM recommends it be analyzed as such.

The equation 9-6 procedure is compared, in figure 8b, with the threshold curves previously described. As indicated by the dashed curve, there is a general agreement in both shape and orientation. This agreement is particularly good for those situations having low to moderate approach volumes or low opposing left-turn proportions. However, it is also apparent from figure 8 that there are some combinations of opposing volume and left-turn proportion where the simplified procedure could incorrectly predict exclusive or shared lane operation.

CONCLUSIONS

Based on a comparison of the original (HCM) approach and the modified, iterative approach, it was concluded that the saturation flow rate calculated using the HCM methodology would almost always be less than the final, convergence flow rate. In general, the HCM solution was found to be within 5% of the final saturation flow rate.

As a result of the examination of the shared lane sensitivity, several tendencies were noted. One of the more obvious trends observed was the dramatic reduction in saturation flow rate with small increases in the proportion of left-turns. Conversely, the sensitivity of shared lane operations to the magnitude of cycle length or G/C ratio was slight.

The combined effects of the study findings were incorporated into figure 8. Using this figure, it is possible to describe, or predict, the nature of any shared lane operation. By inspection of figure 8, the following generalities were formulated:

1. Only when left-turn percentage is very small does approach capacity near that of two through lanes.
2. When there is a moderate number of left-turn vehicles, the effective number of lanes are reduced from four to roughly two. In other words, the combined maximum volume of two opposing, two-lane approaches, both having a moderate amount of left-turn vehicles, can be conservatively estimated as equal to about 90% of the capacity of two through lanes.
3. If the left-turn percentage and volume of an approach are less than $P_{LT\max}$ and $V_{\max1}$, respectively, then that approach will operate below its capacity, and its inner lane will be shared by left and through vehicles.

The results of this research were based entirely on the assumption of reasonableness of the HCM methodology. Furthermore, these results are limited by the assumptions imbedded in the formulation of the HCM methodology. In recognition of these limitations, it is recommended that field studies be conducted to verify the reasonableness of the HCM methodology and, thereby, the results of this paper.

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