Operational Analysis of Exclusive Left-Turn Lanes with Protected/Permitted Phasing

James A. Bonneson and Patrick T. McCoy

With the release of the *1985 Highway Capacity Manual*, a new procedure for analyzing signalized intersections has been introduced. One of the major differences between the 1965 and the 1985 manuals is in the area of left-turn capacity. A general methodology for the analysis of signalized intersections, particularly left-turn operations, is described in the 1985 Manual. Unfortunately, with regard to exclusive left-turn lanes with protected/permitted phasing, the sample calculations provided do not appear to explicitly follow the general methodology. Moreover, the sample calculations introduce many new concepts that are not included in the discussion of the methodology. Calculation 3 in Chapter 9 of the manual is reexamined in this paper. In particular, the left-turn lane groups with protected/permitted phasing are reanalyzed according to the general methodology, but issue is taken with some of the "new" concepts introduced within Calculation 3. On the basis of the findings reported in this paper, it appears that there is a need for some revision of Chapter 9 of the *1985 Highway Capacity Manual*, particularly with regard to the analysis of left-turn lane groups with protected/permitted phasing.

Chapter 9 of the *1985 Highway Capacity Manual* (HCM) *(1)* contains procedures for evaluating the capacity and level of service of signalized intersections. The operational-analysis methodology presented in the HCM accounts for the effect of left-turn movements based on the manner in which they are accommodated. In the case of left turns made from an exclusive left-turn lane controlled by protected/permitted phasing, the HCM recommends an iterative procedure, which is shown in Figure 1. In this procedure, all left turns are initially assumed to occur in the protected phase. If this assumption results in volume-to-capacity ratios that are too high, a portion of the left turns, up to the capacity of the permitted phase, is assigned to the permitted phase, and the saturation-flow-rate and capacity-analysis modules are repeated. The portion of left-turns assigned to the permitted phase is increased on successive iterations until either acceptable volume-to-capacity ratios are obtained or the capacity of the permitted phase is reached.

Unfortunately, only a general description of this procedure is given in the HCM. Also, the sample calculations presented in the HCM do not correctly illustrate the procedure as it is described. Consequently, the generality of its description and the inconsistency between this description and the sample calculation illustrating its use have been sources of confusion to HCM users.

J. A. Bonneson, Traffic Operations Program, Texas Transportation Institute, Texas A&M University System, College Station, Tex. 77843. P. T. McCoy, Civil Engineering Department, University of Nebraska, Lincoln, Lincoln, Neb. 68588.

In an effort to eliminate this confusion, the operational-analysis procedure presented in the HCM for evaluating the capacity and level of service of exclusive left-turn lanes controlled by protected/permitted phasing is reviewed in this paper, and revisions to the procedure are suggested to make it consistent with other procedures in the HCM. The revised procedure is presented within the context of a reanalysis of Calculation 3, which is the sample calculation used in the HCM to illustrate the operational analysis of exclusive left-turn lanes with protected/permitted phasing. The reanalysis of Calculation 3 is presented in the first section of this paper, which includes explanations of the revisions made to the procedure presented in the HCM. The second section includes a summary of the revised procedure recommended. The solution of Calculation 3 is compared with the solution of Calculation 3 presented in the HCM.

REANALYSIS OF CALCULATION 3

Calculation 3, which begins on page 9-50 of the HCM, is the operational analysis of a multiphase-actuated signal located at the intersection of Fifth Avenue and 12th Street. The input worksheet showing the geometric, traffic, and signalization conditions at this intersection is shown in Figure 2. Exclusive left-turn lanes are provided on all four approaches to the intersection. Protected/permitted phasing is provided for the left-turns from the north-south street (Fifth Avenue), and permitted phasing is provided for the left turns from the east-west street (12th Street).

In this reanalysis, the procedure suggested in the HCM is followed except where revisions are noted. All pertinent worksheets are completed and shown in this reanalysis. However, the discussion focuses only on those points in the solution where revisions to the procedure are made. Although this paper is concerned with just the operational analysis of exclusive left-turn lanes with protected/permitted phasing, all worksheets are completed for the entire intersection to better illustrate the consequences of the revisions. A discussion of the reanalysis of Calculation 3 with respect to each of the modules in the operational-analysis procedure follows.

Input and Volume Adjustment Modules

The input and volume adjustment modules are performed in the same way as they were in the original analysis. The worksheets for these modules are shown in Figures 2 and 3. They are

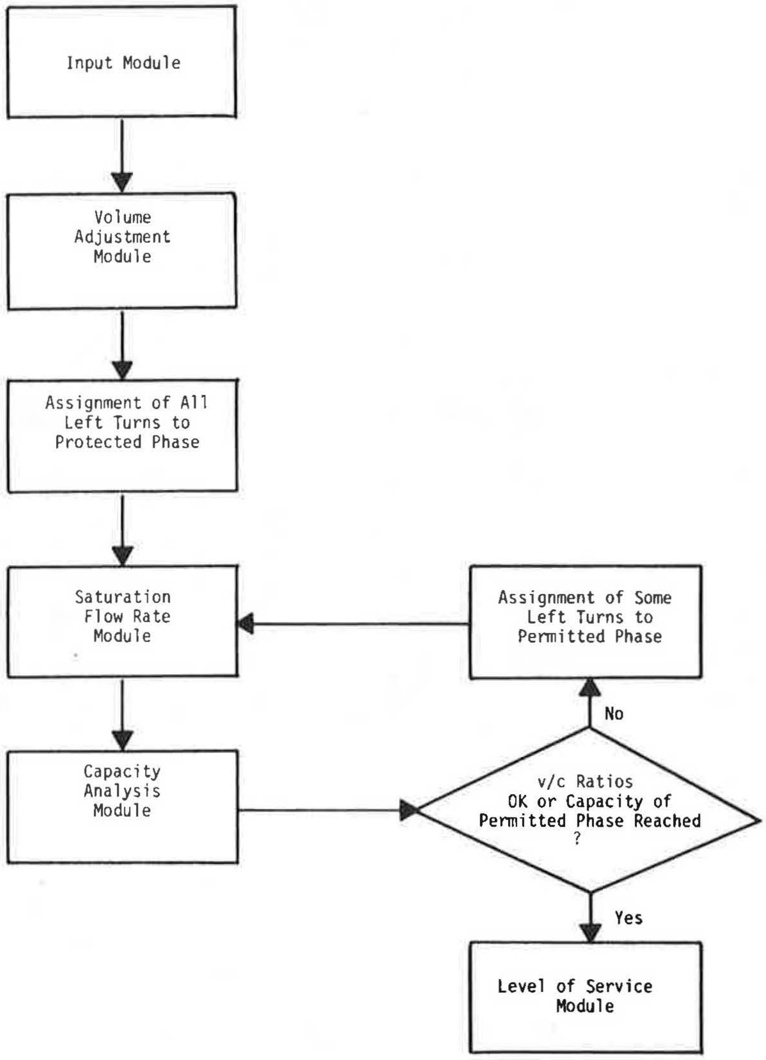


FIGURE 1 Iterative procedure for operational analysis of exclusive left-turn lanes with protected/permitted phasing.

identical to those shown in the HCM and are presented here only for convenience.

Saturation Flow Rate Module

The saturation flow adjustment worksheet is shown in Figure 4. The adjustment factors used are identical to those used in the HCM with one exception: the left-turn adjustment factors for the eastbound (EB) and westbound (WB) permitted left-turns have been modified (i.e., EB: 0.29, not 0.31 and WB: 0.46, not 0.48). The reason for this deviation is explained by the iterative nature of the method for computing left-turn adjustment factors for permitted left turns. In other words, for those situations where the signal timing is not known or where the signal is actuated, as in this case, the corresponding phase durations must be initially estimated and then solved for iteratively. Ultimately, the assumed signal timings will converge to reasonable values, and the result will most accurately reflect the intersection's operation.

In the original analysis of Calculation 3, a 90-sec cycle and a 18.5-sec phase duration were initially assumed for the calculation of the eastbound and westbound left-turn adjustment factors. This represents a good starting solution. But if the analyst had iterated through the analysis procedure, better estimates of these times would have been obtained as shown in Figure 5. Thus, Calculation 3 as presented in the HCM illustrates only the first iteration of the analysis process, whereas the results shown in Figures 4 and 5 are representative of the last iteration and hence the saturation flow rates shown should be more accurate than those shown in Figure 9-28 of the HCM.

It should also be noted that some of the saturation flow rates for other movements differ by 1 or 2 percent. This amount is negligible and can be attributed to the effects of rounding during the analysis process.

For the purposes of comparison between this analysis and that presented in the HCM, a cycle length of 119 sec is used for all subsequent analysis steps. This approach highlights deviations resulting from the analysis process rather than those attributable to different cycle lengths.

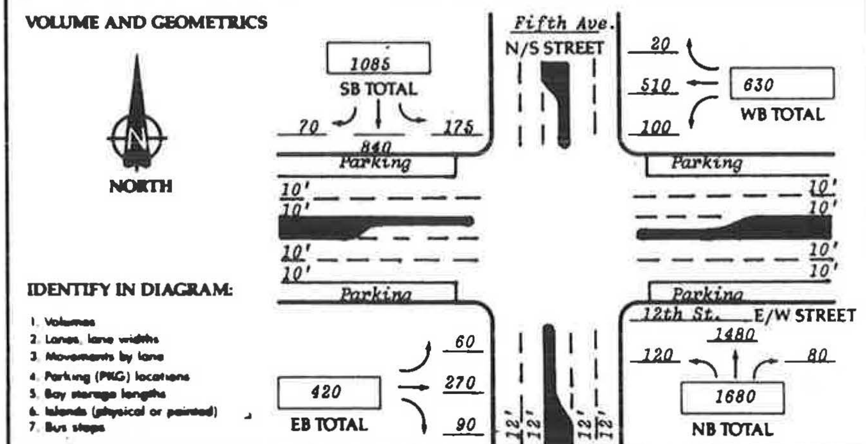
INPUT WORKSHEET

Intersection: *Fifth Ave. and 12th Street* Date: *12/12/85*

Analyst: *RPR* Time Period Analyzed: *5-6 PM* Area Type: ☒ CBD ☐ Other

Project No.: City/State: *Mudville*

VOLUME AND GEOMETRICS



IDENTIFY IN DIAGRAM:

1. Volumes
2. Lanes, lane widths
3. Movements by lane
4. Parking (PKG) locations
5. Bay storage lengths
6. Islands (physical or painted)
7. Bus stops

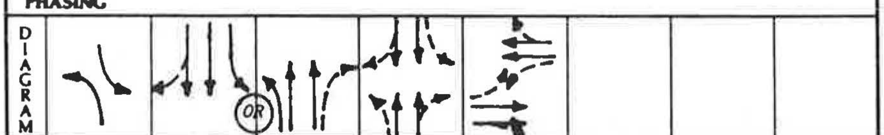
TRAFFIC AND ROADWAY CONDITIONS

Approach	Grade (%)	% HV	Adj. Pkg. Lane Y or N	Adj. Pkg. Lane N_m	Buses (N_B)	PHF	Conf. Peds. (peds./hr)	Pedestrian Button Y or N	Pedestrian Button Min. Timing	Arr. Type
EB	0	5	Y	5	0	0.85	200	Y	22	3
WB	0	5	Y	5	0	0.85	200	Y	22	3
NB	0	2	N	0	0	0.90	50	Y	22	3
SB	0	2	N	0	0	0.90	50	Y	22	3

Grade: + up, − down
HV: veh. with more than 4 wheels
N_m: pkg. maneuvers/hr
N_B: buses stopping/hr
PHF: peak-hour factor
Conf. Peds: Conflicting peds./hr
Min. Timing: min. green for pedestrian crossing
Arr. Type: Type 1-5

PHASING

DIAGRAM



Timing	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =	G = Y + R =
Pretimed or Actuated	A	A	A	A	A			

Protected turns — Permitted turns — ------- Pedestrian — Cycle Length ____ Sec

FIGURE 2 Input worksheet for Calculation 3.

Capacity Analysis Module

The capacity analysis worksheet is shown in Figure 6. Given the phasing plan shown on the input worksheet in Figure 2, the combinations of critical lane groups are found according to the following rule:

$$\begin{bmatrix} \text{EB LT or TH/RT} \\ \text{or} \\ \text{WB LT or TH/RT} \end{bmatrix} + \begin{bmatrix} \text{NB LT + SB TH/RT} \\ \text{or} \\ \text{SB LT + NB TH/RT} \end{bmatrix}$$

Thus, the sum of critical flow ratios results from the combination: WB TH/RT + SB LT + NB TH/RT = 0.24 + 0.09 + 0.57 = 0.90. This represents the percentage of green time needed to adequately serve intersection traffic during the analysis hour.

Average Cycle Length and Lost Time

Using Equation II.9-1 in the HCM, the cycle length is computed as follows:

$$C = LX_c/[X_c - \sum_i (v/s)_{ci}] \qquad (1)$$

where

C = cycle length, in seconds;
L = total lost time per cycle, in seconds;
X_c = critical v/c ratio for the intersection; and
$(v/s)_{ci}$ = sum of critical flow ratios.

① Appr.	② Mvt.	③ Mvt. Volume (vph)	④ Peak Hour Factor PHF	⑤ Flow Rate v_p (vph) ③ ÷ ④	⑥ Lane Group	⑦ Flow rate in Lane Group v_g (vph)	⑧ Number of Lanes N	⑨ Lane Utilization Factor U Table 9-4	⑩ Adj. Flow v (vph) ⑦ × ⑨	⑪ Prop. of LT or RT P_{LT} or P_{RT}
EB	LT	60	0.85	71		71	1	1.00	71	1.0 LT
	TH	270	0.85	318		424	2	1.05	445	0.25 RT
	RT	90	0.85	106						
WB	LT	100	0.85	118		118	1	1.00	118	1.0 LT
	TH	510	0.85	600		624	2	1.05	655	0.04 RT
	RT	20	0.85	24						
NB	LT	120	0.90	133		133	1	1.00	133	1.0 LT
	TH	1480	0.90	1644		1733	2	1.05	1820	0.05 RT
	RT	80	0.90	89						
SB	LT	175	0.90	194		194	1	1.00	194	1.0 LT
	TH	840	0.90	933		1011	2	1.05	1062	0.08 RT
	RT	70	0.90	78						

FIGURE 3 Volume adjustment worksheet for Calculation 3.

According to the HCM, the X_c value for a fully actuated signal can be estimated at 0.95. This estimate is based on the additional assumption that actuated intersections operate efficiently with respect to the allocation of green time. Intuitively, this approach is reasonable and should provide a good approximation of the average signal timing during the analysis hour.

At this point, some discussion is necessary for the determination of total intersection lost time. The HCM states that total lost time per cycle for this intersection and phasing combination is 6.0 sec. This value represents two 3.0-sec increments of lost time corresponding to the two through phases and assumes there is continuous utilization of the time element occurring between overlapped phases. Although this argument appears at first to have validity, it is incorrect. By definition, lost time is the time lost due to start-up, delay, and intersection clearance (totaling approximately 3.0 sec) that is experienced by each critical lane group. Hence, it is experienced by all three critical lane groups associated with Calculation 3 for a total of 9.0 sec of lost time.

Based on the assumption of X_c equal to 0.95 and a total lost time of 6.0 sec, the average cycle length was estimated to be 118.8 sec in the original Calculation 3 analysis. Using this cycle length, the effective green times were estimated by proportionally allocating the total cycle length to the critical lane groups as given in Table 1. However, because of the initially incorrect assumption of total lost time, the sum of the phase lengths given in Table 1 is greater than the cycle length by 3.0 sec, the amount by which the lost time was underestimated.

Assuming that total intersection lost time is 9.0 sec, a more realistic average cycle length can be estimated using Equation 1. For a 9.0-sec lost time and the given X_c of 0.95, the average cycle length is calculated to be 171 sec. This represents a 44

SATURATION FLOW ADJUSTMENT WORKSHEET												
LANE GROUPS				ADJUSTMENT FACTORS								
① Appr.	② Lane Group Movements	③ Ideal Sat. Flow (pcphgpl)	④ No. of Lanes N	⑤ Lane Width f_w Table 9-5	⑥ Heavy Veh f_{HV} Table 9-6	⑦ Grade f_g Table 9-7	⑧ Pkg. f_p Table 9-8	⑨ Bus Blockage f_{bb} Table 9-9	⑩ Area Type f_a Table 9-10	⑪ Right Turn f_{RT} Table 9-11	⑫ Left Turn f_{LT} Table 9-12	⑬ Adj. Sat. Flow Rate s (vphg)
		1800	1	.930	.975	1.0	1.0	1.0	.90	1.0	.291	429
EB		1800	1	.930	.975	1.0	.935	1.0	.90	.942	1.0	2590
		1800	1	.930	.975	1.0	1.0	1.0	.90	1.0	.457	675
WB		1800	2	.930	.975	1.0	.935	1.0	.90	.990	1.0	2734
		1800	1	.99	1.0	1.0	1.0	1.0	.90	1.0	.95	1524
NB		1800	2	.99	1.0	1.0	1.0	1.0	.90	.99	1.0	3180
		1800	1	.99	1.0	1.0	1.0	1.0	.90	1.0	.95	1524
SB		1800	2	.99	1.0	1.0	1.0	1.0	.90	.99	1.0	3166

FIGURE 4 Saturation flow adjustment worksheet for Calculation 3.

percent increase in cycle length over the original estimate of 118.8 sec. Moreover, this illustrates the sensitivity of Equation 1 to estimates of L, $\sum_i (v/s)_{ci}$, and X_c.

But, as previously mentioned, a 119-sec cycle length is used for all subsequent steps in this reanalysis in order to provide a more direct comparison between it and the original analysis of Calculation 3. Hence, to maintain the equality in Equation 1, X_c must be calculated. Given a 119-sec cycle length, a $\sum_i (v/s)_{ci}$ of 0.90, and a 9.0-sec lost time, X_c is found to be 0.97.

The signal timing plan for a 119-sec cycle and a 9.0-sec lost time is given in Table 2. In this case, as expected, the sum of the phase lengths is equal to the cycle length.

Left-Turn Capacity

During the iteration process, the amount of left-turn volume assigned to the protected portion of the protected/permitted left-turn phase is reduced, if possible. This reduction is a function of the theoretical capacity of the permitted phase portion. As specified in the HCM (see Step 10, p. 9-30), the

SUPPLEMENTAL WORKSHEET FOR LEFT-TURN ADJUSTMENT FACTOR, f_{LT}				
INPUT VARIABLES	EB	WB	NB	SB
Cycle Length, C (sec)	119.0	119.0	119.0	119.0
Effective Green, g (sec)	29.3	29.3	80.7	70.0
Number of Lanes, N	1.0	1.0	1.0	1.0
Total Approach Flow Rate, v_a (vph)	494	741	1866	1205
Mainline Flow Rate, v_M (vph)	423	623	1733	1011
Left-Turn Flow Rate, v_{LT} (vph)	70.6	117.6	133	194
Proportion of LT, P_{LT}	1.0	1.0	1.0	1.0
Opposing Lanes, N_o	2.0	2.0	2.0	2.0
Opposing Flow Rate, v_o (vph)	623	423	1011 / 1062	1733 / 1820 (a)
Prop. of LT in Opp. Vol., P_{LTO}	0.0	0.0	0.0	0.0
COMPUTATIONS	EB	WB	NB	SB
$S_{op} = \frac{1800\, N_o}{1 + P_{LTO}\left[\frac{400 + v_M}{1400 - v_M}\right]}$	3600	3600	3600 / 3166	3600 / 3180 (b)
$Y_o = v_o / S_{op}$	0.173	0.118	0.281 / 0.335	0.481 / 0.572
$g_u = (g - CY_o) / (1 - Y_o)$	10.5	17.3	65.7 / 61.4	24.6 / 4.4
$f_s = (875 - 0.625\, v_o) / 1000$	0.485	0.610		
$P_L = P_{LT}\left[1 + \frac{(N-1)g}{f_s g_u + 4.5}\right]$	1.0	1.0		
$g_q = g - g_u$	18.8	12.0		
$P_T = 1 - P_L$	0.0	0.0		
$g_f = 2\frac{P_T}{P_L}\left[1 - P_T^{0.5 g_q}\right]$	0.0	0.0		
$E_L = 1800 / (1400 - v_o)$	2.32	1.84		
$f_m = \frac{g_f}{g} + \frac{g_u}{g}\left[\frac{1}{1 + P_L(E_L - 1)}\right] + \frac{2}{g}(1 + P_L)$	0.291	0.457		
$f_{LT} = (f_m + N - 1) / N$	0.291	0.457		

FIGURE 5 Supplemental worksheet for Calculation 3.

capacity of the permitted left-turn phase is calculated as the maximum of

$$C_{LT} = (1{,}400 - V_o)\,(g/C)_{PLT} \quad (2)$$

or

$$C_{LT} = 2 * 3{,}600/C \quad (3)$$

where

C_{LT} = capacity of the left-turn permitted phase, in vph;
V_o = opposing through plus right-turn flow rate, in vph; and
$(g/C)_{PLT}$ = effective green ratio for the permitted left-turn phase.

Unfortunately, the methodology does not describe in sufficient detail the derivation of the $(g/C)_{PLT}$ ratio. Even more unfortunate is the omission of Equation 2 from the discussion of Calculation 3. The effects of this omission will be more evident in the next few paragraphs.

Further investigation of the effective-green-time term (g) in the $(g/C)_{PLT}$ ratio reveals that it is identical to the unsaturated green time that is used in the calculation of the left-turn satura-

CAPACITY ANALYSIS WORKSHEET									
LANE GROUP		③ Adj. Flow Rate v (vph)	④ Adj. Sat. Flow Rate s (vphg)	⑤ Flow Ratio v/s ③ ÷ ④	⑥ Green Ratio g/C	⑦ Lane Group Capacity c (vph) ④ × ⑥	⑧ v/c Ratio X ③ ÷ ⑦	⑨ Critical ? Lane Group
① Appr.	② Lane Group Movements							
EB		71	429	0.164	0.246 29.3 sec	106	0.669	
		445	2590	0.172	0.246 29.3 sec	637	0.698	
WB		118	675	0.174	0.246 29.3 sec	166	0.709	
		655	2734	0.240	0.246 29.3 sec	672	0.974	X
NB		0	1524	0.0	0.0	0	-	
		133	389	0.343	0.516 61.4 sec	201	0.662	
		1820	3180	0.572	0.588 70.0 sec	1869	0.974	X
SB		134	1524	0.088	0.091 10.7 sec	138	0.974	X
		60	1600	0.038	0.038 4.5 sec	60	1.00	
		1062	3166	0.335	0.678 80.7 sec	2148	0.493	

Cycle Length, C 119 sec

Lost Time Per Cycle, L 9.0 sec

$\Sigma (v/s)_{ci} =$ 0.900

$$X_c = \frac{\Sigma (v/s)_{ci} \times C}{C - L} = 0.974$$

FIGURE 6 Capacity analysis worksheet for Calculation 3.

TABLE 1 SIGNAL TIMING USING HCM CALCULATION OF LOST TIME

Movement	Critical Flow Ratio	Effective Green[a] (sec)	Lost Time (sec)	Phase Length [b](sec)
EB/WB through	0.241	30.1	3.0	33.1
SB left-turn	0.088	11.0	3.0	14.0
NB/SB through	0.573	71.7	3.0	74.7
Total	0.902	112.8	9.0	121.8[c]

NOTE: Cycle length (C) = 118.8 sec, and critical v/c (X_c) = 0.95.
[a]Effective green (g) = (critical flow ratio)(C/X_c).
[b]Phase length (G) = g + lost time.
[c]Greater than cycle length (C = 118.8 sec).

TABLE 2 SIGNAL TIMING USING REVISED CALCULATION OF LOST TIME

Movement	Critical Flow Ratio	Effective Green[a] (sec)	Lost Time (sec)	Phase Length [b](sec)
EB/WB through	0.24	29.3	3.0	32.3
SB left-turn	0.09	10.7	3.0	13.8
NB/SB through	0.57	70.0	3.0	72.9
Total	0.90	110.0	9.0	119.0[c]

NOTE: Cycle length (C) = 119.0 sec, and critical v/c (X_c) = 0.97.
[a]Effective green (g) = (critical flow ratio)(C/X_c).
[b]Phase length (G) = g + lost time.
[c]Equal to cycle length (C = 119.0 sec).

tion flow adjustment factor for permitted left turns. This unsaturated green time, which is calculated on the supplemental worksheet, is computed as follows:

$$g_{\mu} = (g - CY_o)/(1 - Y_o) \quad (4)$$

where

g_{μ} = portion of green not blocked by the clearing of an opposing queue of vehicles, in seconds;
g = effective green time, in seconds;
C = cycle length, in seconds; and
Y_o = flow ratio for opposing approach.

At this point some discussion is warranted on the appropriate values to use in calculating the opposing flow ratio ($Y_o = V_o/S_{op}$) on the supplemental worksheet. According to the methodology, V_o is defined as the "mainline flow rate" on the opposing approach. In Calculation 3, this value was found in Column 5 of the volume adjustment worksheet. However, because this procedure is an attempt to account for the discharge time of the longest opposing queue, it is suggested that the correct value to use in this instance would be the "adjusted flow rate" found in Column 10. This value is identical to that found in Column 5 with the exception that a lane utilization factor has been applied.

Intuitively, this approach is more reasonable for estimating queue discharge time because it would account for any imbalance in lane use. Obviously, the permitted left-turn movement cannot begin until the longest opposing queue has dissipated. If the opposing approach is observed to have unequal utilization among through or right lanes, or both, then this should be accounted for via the lane utilization factor. A review of the literature on left-turn capacity supports this argument *(2, 3)*.

In addition to using the adjusted flow rate, it is also suggested that the derivation of the saturation flow on the opposing approach (S_{op}) be reconsidered. Inspection of the equation used on the supplemental worksheet to compute S_{op} indicates that it does not consider many of the adjustment factors used in the saturation flow adjustment worksheet. For this particular example the corresponding values of S_{op} taken from the saturation flow adjustment worksheet are less than 90 percent of those calculated using the supplemental worksheet. Therefore, it appears redundant to calculate the saturation flow rate again when a more appropriate value has already been computed on the saturation flow adjustment worksheet.

The implications of using the suggested values for V_o and S_{op} instead of those recommended by the HCM are shown in Figure 5. As can be seen in the northbound and southbound columns, the variation between analysis approaches can be significant. In particular, the equation for g increases in sensitivity as the flow ratio (Y_o) nears 1.0. As a result, estimates of g_{μ} for the southbound left-turn differ by more than a factor of 5.

For the remainder of this discussion the values of g_{μ} calculated by using the suggested procedure will be employed in subsequent computations. Hence, the computations of the capacity of the left-turn permitted phase (C_{LT}) are as follows:

Northbound:

$C_{LT} = (1{,}400 - 1{,}011) * 61.4/119$
$= 201$ vph <-- Maximum value

or

$C_{LT} = 2 * 3{,}600/119$
$= 60$ vph

Southbound:

$C_{LT}\ (1{,}400 - 1{,}733) * 4.4/119$
$= 0$ vph

or

$C_{LT} = 2 * 3{,}600/119$
$= 60$ vph <-- Maximum value

According to the HCM, "up to" the maximum value for the permissive flow rate (C_{LT}) may be assigned to the permitted portion of the protected/permitted phase. Because the exact number of vehicles arriving during each phase portion is unique to each intersection and is a function of arrival patterns and upstream progression, the number of vehicles arriving during each phase portion can vary considerably. In the case of uniformly arriving traffic, the number of left-turn vehicles arriving during the protected and permitted phase portions would be proportional to their g/C ratios.

For this reanalysis of Calculation 3, the maximum permitted flow rate is assigned to the permitted phase volume; thus minimizing the time needed for the protected left-turn phase. This approach is assumed to be more reasonable from a minimum total delay standpoint because left-turn phases typically move fewer total vehicles than through phases. Hence, protected left-turn phase lengths are typically kept as short as possible to minimize total intersection delay.

This argument is particularly applicable to pretimed signals where the protected left-turn phase interval would be set as low as practical. On the other hand, vehicular demand at actuated intersections could extend the left-turn phase beyond the minimum required and thus the permitted left-turn phase component would not realize its total potential permitted flow rate. Also it should be noted that this approach assumes that coordination for the left-turn movement is not provided because this is the most common situation.

Once the capacity of the permitted portion of the protected/permitted phase has been calculated, the left-turn volume associated with this lane group can be distributed among the appropriate phase intervals. The capacity of each phase interval is calculated as follows:

Northbound:

NB $\text{Left}_{PERM} = 201$ vph
NB $\text{Left}_{PROT} = 133 - 201 = 0$ vph

Southbound:

SB $\text{Left}_{PERM} = 60$ vph
SB $\text{Left}_{PROT} = 194 - 60 = 134$ vph

One interesting outcome from the preceding calculations is that it now appears that the permitted portion of the northbound left-turn phase has sufficient capacity to adequately serve the left-turn volume. In other words, it appears that the protected portion of the northbound left-turn phase is not necessary. As alluded to at the beginning of the previous section, it now becomes apparent that the omission of Equation 2 in calculating permitted left-turn capacity can have a significant impact on the analysis process. For Calculation 3, it shows that protection for the northbound left-turn is not warranted.

Once the protected and permitted left-turn phase volumes have been calculated, the capacity analysis worksheet can be completed by using the appropriate HCM methodology. The completed worksheet is shown in Figure 6.

Level of Service Module

In this module pertinent values from the capacity analysis worksheet shown in Figure 6 are carried forward and entered on the level of service worksheet shown in Figure 7. From these values, estimates of group delay are calculated and averaged for each approach and the intersection as a whole. Ultimately, these delays are translated into levels of service that describe the quality of traffic flow associated with each group, approach, and intersection.

With respect to calculating delay for protected/permitted left-turn phases with exclusive lanes, the HCM (*1*, p. 9-56) suggests that total delay for the left-turn lane group can be estimated by using approximations for the *g/C* and *v/c* ratios. However, these assumptions are gross estimates and can result in delays that are totally unreasonable.

The difficulty encountered when calculating the delay for left-turn movements with protected/permitted phasing arises from the variation in saturation flows during one signal cycle. This situation is shown in Figure 8 for the southbound left-turn movement. As shown in this figure, the southbound left-turn has two unique saturation flows: one during its designated left-turn phase and the other representing sneaker activity at the end of the through phase. By comparison, the protected left-turn phase for the northbound left-turn was eliminated because of ample time during the through phase for filtering left-turn operations. Hence, this movement has only one saturation flow rate.

The uniform delay incurred by left-turn vehicles can be found by calculating the area under the queue-departure diagram (shaded area) shown in Figure 8. Individual delay components can be separately calculated as that area immediately preceding the particular phase portion (i.e., the protected and permitted phase portions). For this particular example, the

LEVEL-OF-SERVICE WORKSHEET

Lane Group		First Term Delay				Second Term Delay				Total Delay & LOS		
① Appr.	② Lane Group Movements	③ v/c Ratio X	④ Green Ratio g/C	⑤ Cycle Length C (sec)	⑥ Delay d_1 (sec/veh)	⑦ Lane Group Capacity c (vph)	⑧ Delay d_2 (sec/veh)	⑨ Progression Factor PF Table 9-13	⑩ Lane Group Delay (sec/veh) (⑥+⑧) × ⑨	⑪ Lane Group LOS Table 9-1	⑫ Approach Delay (sec/veh)	⑬ Appr. LOS Table 9-1
EB		0.669	0.246	119	30.8	106	9.9	0.85	34.6	D	29.2	D
		0.698	0.246	119	31.0	637	2.3	0.85	28.4	D		
WB		0.709	0.246	119	31.1	166	8.8	0.85	34.0	D	44.7	E
		0.974	0.246	119	33.8	672	21.1	0.85	46.6	E		
NB		0.662		119	16.3	201	5.5	1.00	21.8	C		
		0.974	0.588	119	17.9	1869	11.2	0.85	24.8	C	24.5	C
SB		0.978		119	32.4	199	43.0	1.00	75.4	F		
		0.493	0.678	119	7.0	2148	0.2	0.85	6.1	B	16.8	C

Intersection Delay 26.4 sec/veh Intersection LOS D (Table 9-1)

FIGURE 7 Level-of-service worksheet for Calculation 3.

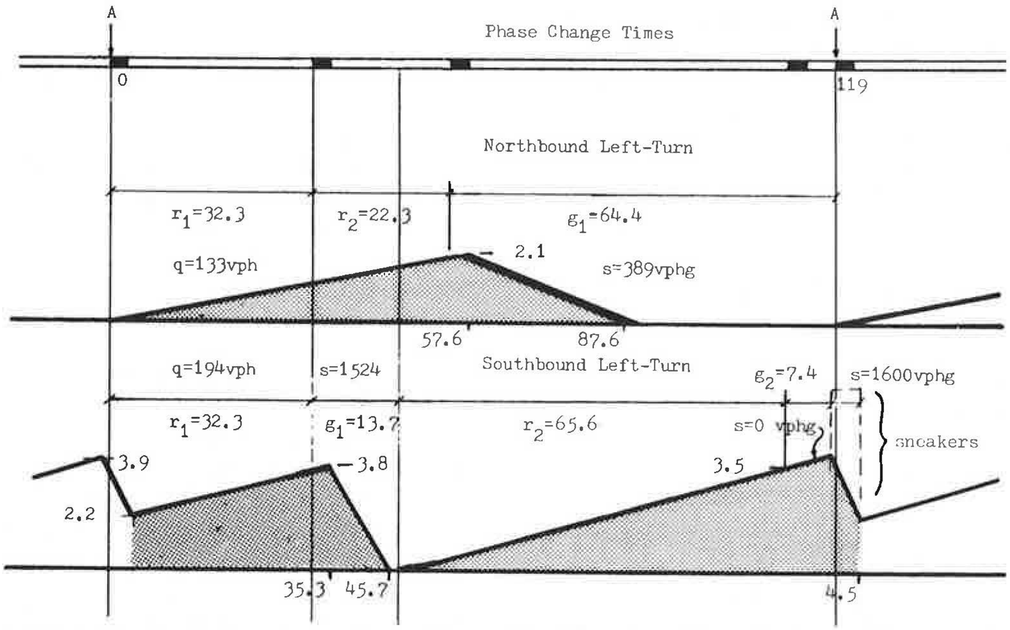


FIGURE 8 Queue departure patterns for northbound and southbound left-turn movements.

southbound left-turn uniform delay was found to incur 32.4 sec per vehicle (14.9 protected, 17.5 permitted) (see Figure 7).

The second term of delay is intended to account for the effects of random arrivals with regard to their creating overflow from one signal cycle to the next. Because this delay is based on overall cycle efficiency, it must account for left-turn operations during all phases that service left-turning vehicles. This is accomplished by calculating the combined protected and permitted capacity for the left-turn movement. As shown in Figure 7, the combined capacity for the southbound left-turn phase components is 199 vehicles per hour and results in an X ratio of 0.978 (= 194/199). Using this X ratio, the overflow delay can be calculated as 43 sec per vehicle.

As shown in Figure 9-31 of the HCM, a progression factor of 1.0 was used for the eastbound and westbound left-turn lane groups in Calculation 3. Although the use of this factor is a subjective determination by the analyst (based on first-hand knowledge of vehicular arrivals), it appears that if Table 9-13 of the HCM was followed explicitly, a factor of 0.85 would be recommended here. In particular, one of the notes accompanying this table states: "All LT^c. This category refers to exclusive LT lane groups with protected phasing only. When LT's are included . . ."

The inference here is that it is reasonable to assume that permitted left-turns have the same arrival pattern as their adjacent through movements. Hence, in the absence of better knowledge about arrival patterns, it is suggested that the progression factors used for the eastbound and westbound left-turn lane groups be the same as those used for the adjacent through movement.

As a means of evaluating the impact of the revised approach, the delays estimated by it can be compared with those from the original analysis of Calculation 3. As can be observed from Table 3, the revised estimates of delay vary considerably from the original HCM estimates.

The most significant change can be observed for the northbound and southbound left-turn groups. The northbound delay has decreased by 69.5 percent whereas the southbound delay has increased by 38.1 percent. The reason for the decrease in northbound delay can be attributed to the additional permitted capacity calculated by Equation 2.

The increase in southbound delay is the result of the revised approach for calculating protected/permitted delay for individual phase components. The original approach reasoned that the total lane group delay could be estimated using the combined *g/C* ratio for the entire protected plus permitted phase (*1*, p. 9-56). However, this ratio will typically overestimate the true *g/C* ratio and result in unrealistically low uniform delay estimates for the left-turn lane group.

TABLE 3 DELAY COMPARISON

Lane Group	HCM Delay	Revised Delay	Change (%)
EB Left	36.0	34.6	-3.9
EB Thru	27.5	28.4	3.3
WB Left	36.0	34.0	-5.6
WB Thru	42.0	46.6	11.0
NB Left	71.4	20.1	-71.8
NB Thru	21.1	24.8	17.5
SB Left	54.6	72.7	33.2
SB Thru	7.4	6.1	-17.6
EB Approach	28.6	29.2	2.1
WB Approach	41.1	44.7	8.8
NB Approach	24.5	24.4	-0.4
SB Approach	14.7	16.4	11.6
Intersection	25.1	26.2	4.4

Differences in delay for other lane groups are not as great as for those of the northbound and southbound left-turn groups. These differences are small and can be attributed to slight changes in the analysis worksheet variables. For instance, the primary reason for the lower delay estimates for the eastbound and westbound left-turn lane groups is the different factor used to account for progression (i.e., 0.85 instead of 1.00).

CONCLUSIONS AND RECOMMENDATIONS

The main implication of this reanalysis is that there are inconsistencies between the original analysis of Calculation 3 and the HCM methodology. These are most likely misinterpretations of the HCM methodology that result from the general nature of the discussion related to protected/permitted left-turn phasing. In particular, the calculation of permitted capacity and unsaturated green time for exclusive, protected/permitted left-turn lane groups needs further clarification. Moreover, there is a need for clarification of the proper approach to use in estimating (a) total lost time, (b) amount of left-turn volume to assign to the permitted portion of protected/permitted left turns, and (c) delay for protected/permitted left-turn lane groups. Finally, it is recommended that Calculation 3 be amended to show both the initial and final worksheets thereby illustrating the iterative process involved in completing the capacity analysis worksheet.

REFERENCES

1. *Special Report 209: Highway Capacity Manual.* TRB, National Research Council, Washington, D.C., 1985.
2. J. H. Shortreed. Left-Turn Equivalencies for Opposed, Shared, Left-Turn Lanes. In *Transportation Research Record 971*, TRB, National Research Council, Washington, D.C., 1984, pp. 14–20.
3. D. B. Fambro, C. J. Messer, and D. A. Anderson. Estimation of Unprotected Left-Turn Capacity at Signalized Intersections. In *Transporiation Research Record 644*, TRB, National Research Council, Washington, D.C., 1977, pp. 113–119.

DISCUSSION

DANIEL F. BEAGAN
Stoner & Webster Engineering Corporation, P.O. Box 2325, Boston, Mass. 02107.

Bonneson and McCoy have made an important contribution toward clarifying the confusing aspects of the methodology for the analysis of signalized intersections as outlined in the *1985 Highway Capacity Manual (1)*. Their recommendations for the total lost time, the progression factor for permitted left turns, and the general need for an iterative process in completing the worksheets should be incorporated directly in future updates of the manual. Their recommendations for opposing volume, the permitted portion of capacity, and for the use of effective green time in the supplemental worksheet for left-turn adjustment factors make valid points but need further discussion.

OPPOSING VOLUME

The authors propose quite reasonably that the opposing volume, V_o, be adjusted by the lane utilization factor, *LU*. It is this V_o that is then used in calculating the unsaturated green time, g_u. However, when the authors later calculate the capacity of the north and southbound left-turn permitted phases the unadjusted opposing volume is used. If this is not simply an error, the reason for using the unadjusted opposing volume at this point should be given.

EFFECTIVE PERMITTED GREEN TIME

In preparing the supplemental left-turn adjustment factor worksheet for the northbound permitted phase, the authors used the value of 80.7 sec, which is the total opposing effective green time including both the protected and permitted left-turn phases. This is necessary to obtain the proper unsaturated green time value because the saturated green includes the opposing southbound volume, which moves on the protected phase. Although the authors did not fill out the complete worksheet, the equations for g_g and f_m, which both involve g, should use the northbound *permitted* left-turn green time of 70 sec, not 80.7. This argues for the need to include a new input variable for the worksheet, g_o, which is equal to the total green time associated with the opposing volume. It would be used in place of g in calculating the unsaturated green time.

CAPACITY OF PERMITTED LEFT-TURN PHASE PORTION

The authors correctly conclude that the term g used to calculate the capacity of the permitted portion of the protected/permitted left turn is actually the unsaturated green time, g_u. This maintains consistency with the left-turn saturation flow adjustment factor for permitted left turns. The authors, however, continue to follow the manual in choosing the maximum of the unsaturated portion or the change interval capacity for the permitted capacity of the protected/permitted left turn. For complete consistency with the supplemental left-turn adjustment factor worksheet, the sum, not the maximum, of these capacities should be used, and that sum should be multiplied by all of the adjustment factors from the saturation flow adjustment worksheet contained in Columns 5 through 11. Failure to do this will result in a different capacity for the permitted left-turn phase, depending on whether it is handled alone or as part of a protected/permitted left turn.

DELAY FOR PROTECTED/PERMITTED LEFT TURNS

The authors display the results of a uniform delay analysis based on calculating the area under the queue-departure diagram as shown in Figure 8. Because this method was actually used in the original formulation of the uniform delay equation, d_1, this is the correct procedure. Those using the method should be cautioned, however, that, to be consistent with the manual, the area must be reduced by 33 percent as the authors have done to account for the conversion from total delay to stopped delay. Further, although not noted in Figure 8, the downward sloping lines are all the difference between the saturation flow rate and the arrival rate.

Finally, in Figure 8 the end of the northbound queue occurs at 83.0 not 100.1 sec as shown, although the average uniform delay is correct. The southbound queue after 32.3 sec is 3.4 not 3.7 vehicles, and the southbound queue is reduced to zero at 41.5 sec, not 44.8 as shown. For the southbound lane group, the area needs to be recalculated. The total average uniform delay for the southbound left-turn lane groups should be 28.5 not 29.8 sec shown in Figure 7.

DISPLAY OF RESULTS

In Figure 7, the level of service worksheet, the authors display the saturation flow rates and green ratios differently for the north-south and the east-west left-turn groups. For the east-west lane groups, they show the total green time ratio and a saturation flow rate accounting for the total green time. For the north-south left-turn lane groups they show the unsaturated green time ratios and a saturation flow rate accounting for the unsaturated green time ratio. Although the delay results obtained will be the same regardless of whether the total or unsaturated green ratios are used if the proper associated saturation flow rates are also used, the different presentations may introduce unnecessary confusion in the review of completed worksheets.

CONCLUSION

The authors have made an important step in correcting the deficiencies of the signalized analysis methodology of the *1985 Highway Capacity Manual.* The methodology for constructing the queue-departure diagram needs to be more fully described in the future. The capacity calculation of the permitted portion of a potential/permitted left turn also needs further discussion.

AUTHORS' CLOSURE

As Beagan notes in his discussion, we have identified several areas in need of clarification or revision to the signalized intersection analysis methodology in the *1985 Highway Capacity Manual* (HCM). Many of our recommendations were for further clarification of areas that were vague in their application toward protected/permitted left-turn phasing. These include the calculation of unsaturated green time and capacity of the permitted phase portion, the progression factor adjustment, assignment of left-turn volume to each phase portion, and the general iterative nature of the capacity analysis. On the other hand, there are some areas that would appear to need revision. These include the calculation of lost time and delay with regard to protected/permitted movements.

Beagan appears to agree with many of our findings while taking issue with others. In general, his discussion highlights several points that perhaps were not discussed as exhaustively in our paper as they could have been. We are hopeful that his comments will provide any further clarification needed in those areas.

With regard to Beagan's discussion, we would like to offer some additional comment. In particular, he suggests that further explanation is required about the use of the unadjusted opposing volume (i.e., not adjusted for lane utilization) in calculating the capacity of the permitted phase portions. The omission of this adjustment was intentional and reflects the authors' understanding of the derivation of the equation used to calculate permitted left-turn saturation flow rates (i.e., Equation 2).

It is believed that this equation is a linear approximation of the negative exponential function derived originally by Major and Buckley to describe the interaction of two traffic streams at a priority intersection *(1)*. This particular equation does not explicitly account for the number of opposing lanes although there are several equations that do *(2)*. More important, however, none of these equations uses a lane utilization factor as a means of addressing the number of opposing lanes.

It should also be noted that a lane utilization adjustment has been traditionally used to account for unequal lane use by a queue of vehicles on an intersection approach. This adjustment is intended to account for the green time required to clear the longest standing queue. It is our opinion that lane utilization adjustments are inappropriate for determining the permitted left-turn saturation flow rate of vehicles filtering through a randomly arriving stream. It should be noted that the approach used is consistent with that of others *(3)*.

Beagan also suggests that the combined capacities of the end-of-phase "sneakers" and the unsaturated phase portion be used for the permitted left-turn capacity instead of simply using the larger of the two. We would agree that in many cases both of these components combine to serve existing left-turn demand and should be analyzed as such. However, the design of a signal timing plan that does not adequately serve the total left-turn demand, without relying on sneakers, should not be recommended. Any timing plan that is designed to take advantage of sneaker activity encourages improper use of the change interval, increases the number of vehicle conflicts, and compromises the safety of all motorists within the intersection.

The approach developed in our paper is consistent with the HCM's methodology and is in recognition of the aforementioned concerns. Using this approach, enough green time would be provided the left-turn phase to serve all left-turn vehicles except those that clear during the unsaturated phase portion. This approach would minimize the amount of "sneaker" activity. However, in special cases where "sneakers" provide the greater permitted capacity (i.e., when $g_u = 0$ or $V_o > 1{,}399$), there will undoubtedly be some vehicles moving at the end of the phase. In this situation, it would be advisable to use protected-only instead of protected/permitted left-turn phasing.

Beagan also comments on the calculation of the uniform and random delay components. In fact, his comments have brought to light the need for some minor changes to the uniform delay estimates and Figures 7 and 8. These revisions were made for the final version of our paper.

REFERENCES

1. N. G. Major and D. J. Buckley. Entry to a Traffic Stream. *Proc., Australian Road Research Board,* Nunawading, 1962.
2. P. G. Michalopoulos, J. O'Connor, and S. M. Nova. Estimation of Left-Turn Saturation Flows. In *Transportation Research Record 667,* TRB, National Research Council, Washington, D.C., 1978, pp. 35–41.
3. D. B. Fambro, C. J. Messer, and D. A. Anderson. Estimation of Unprotected Left-Turn Capacity at Signalized Intersections. In *Transportation Research Record 644,* TRB, National Research Council, Washington, D.C., 1977, pp. 113–119.

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