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Publication of this paper sponsored by Committee on Highway Capacity and Quality of Service.

A Comparison of the 1985 *Highway Capacity Manual* and the Signal Operations Analysis Package 84

DANE ISMART

The primary objective of this paper is to determine if the signalized intersection procedure as described in Chapter 9 of the 1985 *Highway Capacity Manual* (HCM) will give results consistent with the microcomputer version of the Signalized Operations Analysis Package 84 (SOAP 84). Each procedure was used to analyze the intersection in Chapter 9, Calculation 3, of the 1985 HCM. Average stopped delay was calculated for the intersection by each method and was used as the basis for comparing the 1985 HCM and SOAP 84. For through movements and protected–restricted left turns, the two procedures produced similar results for calculating stop delay, X ratios, and effective green ratios. However, for the results to be consistent, the saturation flow as calculated by the HCM method must be used in SOAP 84 as the capacity (saturation flow) for through movements and the protected–restricted left turns. For protected–permissive and unprotected left turns, the two methods produce significantly different results.

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Described is an effort to compare the microcomputer version of SOAP 84 with the methodology in Chapter 9, Signalized Intersections, of the 1985 *Highway Capacity Manual* (HCM).

The Signal Operations Analysis Package (SOAP 84) is a computerized method for developing control plans and evaluating the operations of individual signalized intersections. As the basis for the comparison between SOAP 84 and the 1985 HCM, delay will be calculated by each method. SOAP 84 determines average delay, which includes delay incurred during deceleration and acceleration as well as stop delay. The 1985 HCM calculates average stop delay as the basis for determining level of service. To make a comparison between the two methods, average delay will be converted to average stop delay by using the following formula *(1)*:

$$\text{Average delay}/1.3 = \text{average stop delay} \quad (1)$$

As the first step in the analysis, Calculation 3: Operational Analysis of a Multiphase Actuated Signal from Chapter 9 of the 1985 HCM was chosen as the intersection problem to be used for the comparison. Calculation 3 was selected because it has protected permissive left turns for the north–south approaches and unprotected left turns for east–west approaches. The algorithms used by the HCM and SOAP 84 for Calculation 3 will be evaluated and compared. Because the algorithms used by the HCM and SOAP 84 will not vary for other intersections, the conclusions drawn will be valid whether 1 example or 10 are used. The worksheet for Calculation 3 is shown in Figure 1.

The second step was to develop the saturation flows and adjust volumes so that they are consistent between the two methodologies. SOAP 84 does not include saturation flow adjustment factors (lane width, grade, parking, bus blockage, area type, and right turns), which are incorporated in the 1985 HCM. Therefore, to maintain consistency the north, south, east, and west through-movement adjusted saturation flows calculated from the HCM worksheet (Figure 2) were used as the capacity input (saturation flow) for SOAP 84.

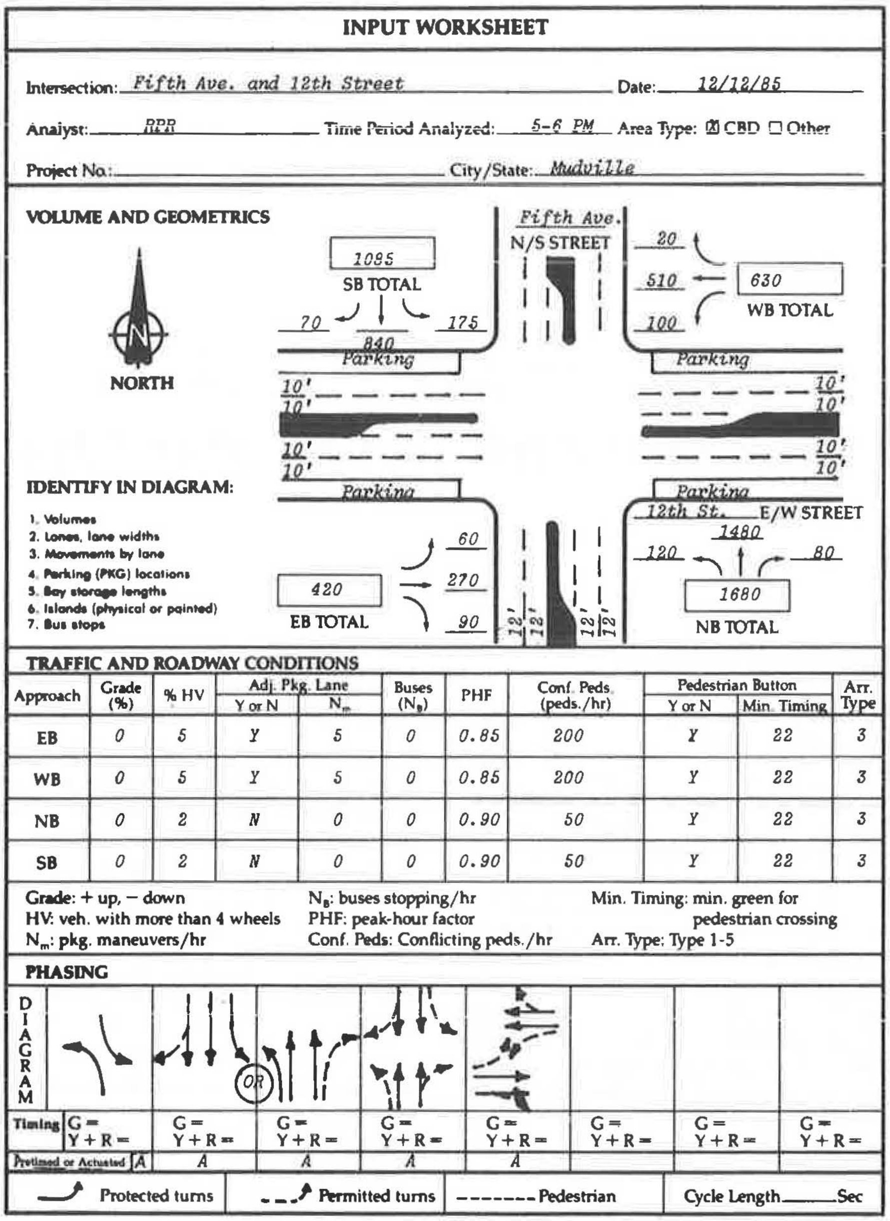
The HCM saturation flow for left turns includes a left-turn factor to account for these movements' not being able to be made at the same saturation flow rates as through movements. In the SOAP 84 program, unprotected left-turn saturation flow will be calculated based on the following equations *(2)*.

Single lane opposing flow:

$$S_L = 1{,}404 - 1.632\ V_o + .0008347\ V_o^2 - .0000002138\ V_o^3 \qquad (2)$$

Multiple lane opposing flow:

$$S_L = 1{,}393 - 1.734\ V_o + .0009173\ V_o^2 - .0000001955\ V_o^3 \qquad (3)$$


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

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

FIGURE 1 Input module worksheet for Calculation 3 in Chapter 9 of the 1985 HCM (*1*,p.9–50, Figure 9–26).

SATURATION FLOW ADJUSTMENT WORKSHEET

LANE GROUPS ① Appr.	② Lane Group Movements	③ Ideal Sat. Flow (pcphgpl)	④ No. of Lanes N	ADJUSTMENT FACTORS 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	.93	.975	1.00	1.00	1.00	.90	1.00	.31	455
EB		1800	2	.93	.975	1.00	.935	1.00	.90	.94	1.00	2582
		1800	1	.93	.975	1.00	1.00	1.00	.90	1.00	.48	705
WB		1800	2	.93	.975	1.00	.935	1.00	.90	.99	1.00	2719
		1800	1	1.00	.99	1.00	1.00	1.00	.90	1.00	.95	1524
NB		1800	2	1.00	.99	1.00	1.00	1.00	.90	.99	1.00	3176
		1800	1	1.00	.99	1.00	1.00	1.00	.90	1.00	.95	1524
SB		1800	2	1.00	.99	1.00	1.00	1.00	.90	.99	1.00	3176

FIGURE 2 Saturation flow rate module worksheet for Calculation 3 in Chapter 9 of the 1985 HCM (*1*,p.9–52, Figure 9–28).

where S_L is the saturation flow for unprotected left turns [vehicles per hour (vph)], and V_o is the opposing through volume (vph).

For the protected portion of left-turn phases, SOAP 84 will use the HCM saturation flow rate without the left-turn factor (Table 1). SOAP 84 left-turn saturation flow for the unprotected portion of the turn will be based on Equation 3. Because the eastbound and westbound left turns have no protected phase, the saturation flow rates from Table 1 for eastbound left turns and westbound left turns will not be used in the calculations for total left-turn capacity of SOAP 84.

In the 1985 HCM, the volume is also adjusted based on peak-hour and lane-use factors. SOAP 84 does not make volume adjustments based on these factors. Rather, SOAP 84 relies on evaluating intersections at 15-min intervals if the user desires. With 15-min analysis periods, the peak-hour factor would be accounted for. In this example, a 1-hr time period is analyzed.

TABLE 1 SATURATION FLOW RATE WITHOUT LEFT-TURN FACTOR

Direction	Saturation Flow Rate
Eastbound left	1,469
Westbound left	1,469
Northbound left	1,603
Southbound left	1,603

Note: In SOAP 84, capacity input is specified in terms of saturation flow (vehicles per hour of green).

To remain consistent, the HCM-adjusted flow shown in Figure 3 (adjusted for peak-hour and lane-use adjustments) will be used as the SOAP volume because the SOAP analysis will be for 1 hr rather than 15-min intervals.

VOLUME ADJUSTMENT WORKSHEET										
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 module worksheet for Calculation 3 in Chapter 9 of the 1985 HCM (*1*,p.9–51, Figure 9–27).

The remaining input (minimum green, headway time, phasing, and permissive left turns) needed to run SOAP 84 does not require any adjustments to remain consistent with the HCM procedure. Timing for the intersection is identified in SOAP 84 approximately as shown in Calculation 3 of the HCM. For this problem, the phasing and cycle length evaluated by SOAP 84 are given in Table 2.

TABLE 2 PHASING AND CYCLE LENGTH EVALUATED BY SOAP 84

Phase	Green Time (sec)
1	7.5
2	6.5
3	73.2
4	31.6

Note: cycle length = 118.8 sec and lost time = 1.5 sec.

By using the HCM methodology and SOAP 84, the intersection was evaluated. The results are shown in Figures 4 and 5. By using Equation 1, the delay calculated by SOAP will be converted to average stop delay. A comparison of the results given in Table 3.

The delay for through movements compares well. However, the permissive left turns are significantly different. For example, for northbound left turns, according to the HCM, delay is calculated at 71.36 sec, whereas with SOAP 84 a delay of 35.5 sec is calculated.

The first step in determining why there is such a significant difference is to look at each method's equation for determining delay. The delay equation of the HCM is as follows.

Uniform arrivals:

$$d_1 = 0.38\ C(1 - g/C)^2/[1 - (g/C)(x)]$$

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		.612	.254	118.8	29.74	116	6.27	1.00	36.01	D	28.6	D
		.678	.254	118.8	30.34	648	1.97	0.85	27.46	D		
WB		.659	.254	118.8	30.61	181	5.83	1.00	35.99	D	41.1	E
		.948	.254	118.8	33.08	682	16.33	0.85	42.00	E		
NB		.936	.653	118.8	13.94	78	57.54	1.00	71.36	F	24.5	C
		.950	.603	118.8	16.65	1915	8.14	0.85	21.07	C		
SB		.944	.690	118.8	12.17	142	42.43	1.00	54.60	E	14.7	C
		.518	.645	118.8	8.54	2049	0.19	0.85	7.42	B		

Intersection Delay 25.1 sec/veh Intersection LOS D (Table 9-1)

FIGURE 4 Level-of-service module worksheet for Calculation 3 in Chapter 9 of the 1985 HCM (*1*,p.9–56, Figure 9–31).

TABLE NO. 31
CALCULATED EFFECTIVE GREEN/CYCLE RATIO FOR EACH MOVEMENT (INCLUDING LEFT TURN RELEASE ADJUSTMENT)

LAMDA	TIME	1 - NBT	2 - NBL	3 - SBT	4 - SBL	5 - EBT	6 - EBL	7 - WBT	8 - WBL
1	1500	.604	.182	.658	.152	.253	.047	.253	.085

TABLE NO. 33
CALCULATED DEGREE OF SATURATION (VOLUME/CAPACITY) (IF X = 999.999, NO GREEN TIME)

X	TIME	1 - NBT	2 - NBL	3 - SBT	4 - SBL	5 - EBT	6 - EBL	7 - WBT	8 - WBL
1	1500	.949	.466	.508	.820	.680	1.037	.951	.955

TABLE NO. 38
AVERAGE UNIT DELAY (SECONDS/VEHICLE)

AVDEL	TIME	1 - NBT	2 - NBL	3 - SBT	4 - SBL	5 - EBT	6 - EBL	7 - WBT	8 - WBL
1	1500	29.935	46.152	10.867	65.156	42.916	186.784	63.887	125.898

*** NOTE ... CYCLE LENGTH COMPUTED FROM TIMING CARD.

FIGURE 5 Calculation 3 SOAP 84 results.

TABLE 3 COMPARISON OF AVERAGE STOP DELAY PER VEHICLE CALCULATED BY USING HCM METHODOLOGY AND SOAP 84

Direction	HCM[a]	SOAP 84
Northbound through	24.79	23.02
Northbound left	71.36	35.50
Southbound through	8.73	8.36
Southbound left	54.60	50.12
Eastbound through	32.31	33.01
Eastbound left	36.01	143.68
Westbound through	49.41	49.14
Westbound left	35.99	96.84

[a]It should be noted that the HCM through movement does not include a .85 progression factor because in SOAP 84 a progression factor of 1.0 is assumed.

Random arrivals

$$d_2 = 173x^2 \{(x - 1) + [(x - 1)^2 + (16x/c)]^{1/2}\}$$

$$d = d_1 + d_2$$

where

- d = average stop delay per vehicle for the subject lane group (sec/veh)
- C = cycle length (sec),
- g/C = green ratio for the subject lane group—the ratio of effective green time to cycle length,
- x = volume-to-capacity (v/c) ratio for the subject lane group, and
- c = capacity of the subject lane group.

The delay equation of SOAP 84 is $D = D_1 + D_2 + D_3$

where

- D = average delay per vehicle (sec/veh),
- D_1 = delay per vehicle for uniform vehicle arrivals, and
- $D_2 + D_3$ = delay per vehicle for random vehicle arrivals.

Uniform arrivals:

$$D_1 = C(1 - \lambda)^2/2(1 - \lambda x)$$

where

- D_1 = delay per vehicle (sec),
- C = cycle length (sec),
- λ = proportion of green time given to the movement (effective green time/cycle length), and
- x = v/c ratio.

Random arrivals:

$$D_2 + D_3 = [(B_n^2/B_d) + (x^2/B_d)]^{1/2} - (B_n/B_d)$$

where

- B_n = $2(1 - x) + xz$;
- z = $(2x/v) \times (60/T) = (2/c) \times (60/T)$;
- v = approach volume (vph);
- T = period length (min), usually 60 min;
- c = capacity; and
- B_d = $4z - z^2$.

The two factors that both equations use are the degree of saturation (x) and the effective green/cycle length. By running both delay equations with the same degrees of saturation and effective green ratios, a comparison was made to determine if the delay equations will produce different results. Figure 6 shows the delay estimates from the models.

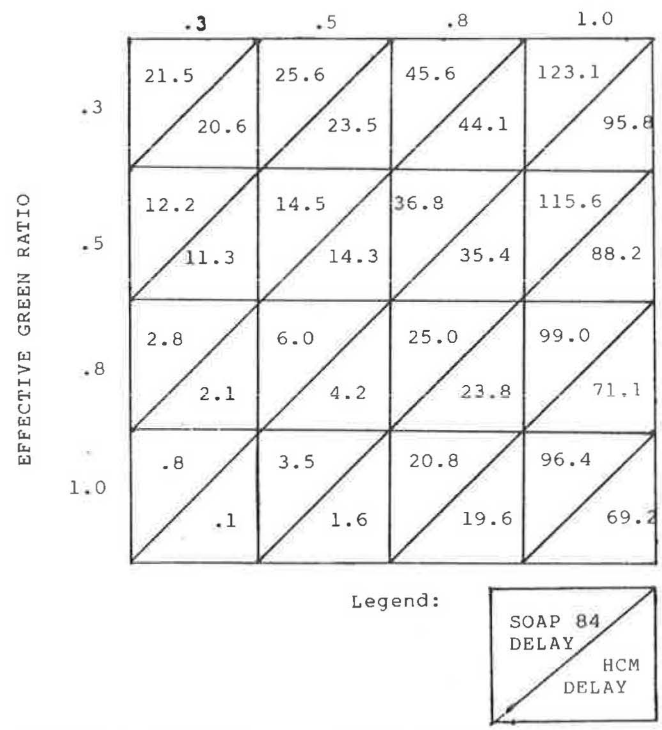


FIGURE 6 SOAP 84 versus HCM delay (x = v/c, for c = 100 sec and v = 100 vehicles).

As can be observed from the data in Figure 6, when the effective green and the v/c ratio are the same in the HCM and SOAP 84 models, the resultant delays are similar except when the v/c ratio approaches 1.0. Because the delay equations give similar results, SOAP 84 and HCM must compute the v/c and effective green ratios differently. Only by having different inputs would the two methods produce different delay estimates for the same problem, as indicated by the data in Table 3.

The next step is to look at how each method calculates the v/c and effective green ratio for left turns in Calculation 3 in Chapter 9 of the HCM. Addressed first are v/c ratios for protected–permissive left turns in the north and south directions. In the HCM methodology, the v/c ratios for the protected portion of a protected–permissive left-turn phase are based on an arbitrary split of demand between the protected and permissive portion of the turn phase.

In Calculation 3, the HCM methodology does not assign any vehicles turning on the permissive portion of the left-turn phase. Only two vehicles per cycle are assumed to turn on the change interval (yellow) of the phase. As indicated in the HCM, a minimum of two vehicles per cycle would be turning, probably as sneakers, during the yellow phase. This assumption of the HCM is conservative because there is excess left-turn capacity in Calculation 3 for the permissive portion of the northbound left-turn and southbound left-turn phases. Because only a minimum amount of demand is assigned to the permissive portion of the left-turn phase, a high amount of left-turn volume remains on the protected left-turn portion of the phase. Thus, the v/c ratio for the protected left turn remains high and the HCM methodology uses the v/c ratio for the protected portion of a protected–permissive left turn in the delay equations.

The approximation of using the v/c ratio computed for the protected portion of the phase to represent the northbound left turns results in an excessive delay computation. The capacity for northbound left turns using the HCM equations can be approximated as follows (HCM Equation 9-22):

CLT = (1,400 – Vo) (g/C) PTL

where

CLT = capacity of the left-turn permissive phase, (vph),
Vo = opposing through plus right-turn movement (vph), and
(g/C) PTL = effective unsaturated green ratio for the permissive left-turn phase (sec/sec).

For NBL turns,

Vo = 1,011
(g/C) PTL = .45
CLT = (1,400 – 1,011) x (.45) = 175

	Capacity (vph)
Protected phase	76
Permissive phase	175
Total	251

With a capacity of more than 250 vph and an adjusted demand of 133, the northbound left-turn phase will not be near saturation, as assumed in Calculation 3 in Chapter 9 of the HCM.

For the southbound direction, the HCM assumption that the protected and permissive portion of the left turns are operating at a high v/c ratio actually reflects the existing operating conditions. The permissive portion of the southbound left turns has a small amount of capacity and the delay estimates for the southbound left turns from the two methodologies are much closer (Table 3).

In the east–west direction, there is no protected left-turn phase. Left turns are made in gaps of the opposing through movements. In the HCM and SOAP 84 methodologies, the volume demand for left turns is the same for permissive-only left turns. However, the two methods do vary in their calculation of capacity for permissive left turns. The HCM methodology for estimating capacity will produce a higher value than will SOAP 84. Although the methodologies produce capacity estimates that may differ by only 40 or 50 vph for the permissive turns, they produce capacity estimates for the permissive turns with significant differences in the v/c ratios. The HCM technique with a high capacity estimates a lower v/c ratio than does SOAP 84. In Calculation 3 of the HCM, SOAP 84 estimates the v/c ratio of eastbound left turns as greater than 1.0. As a result, delay for eastbound left turns is extremely high, as estimated by SOAP 84.

Applying the HCM and SOAP 84 methodologies to Calculation 3 produces the v/c ratios given in Table 4.

As can be observed from the data in Table 4, the SOAP 84 lower estimate of capacity for unprotected left turns produces significantly different v/c ratios for eastbound and westbound left turns. For the northbound and southbound left turns, the HCM procedure of assigning a minimum of two sneakers to the permissive portion of a phase results in a higher v/c ratio than estimated by SOAP 84. Through-movement v/c ratios are almost exactly the same.

TABLE 4 V/C RATIOS ACHIEVED BY APPLYING THE HCM AND SOAP 84 METHODOLOGIES TO CALCULATION 3 IN CHAPTER 9 IN THE HCM

Direction	HCM	SOAP 84
Northbound through	0.950	0.949
Northbound left	0.936	0.466
Southbound through	0.518	0.508
Southbound left	0.944	0.820
Eastbound through	0.678	0.680
Eastbound left	0.612	1.037
Westbound through	0.948	0.951
Westbound left	0.659	0.955

The next step in the analysis is to look at effective green ratios. For left turns with permissive movements, HCM determines the effective green ratio by adding the protected (if any) and permissive phases, subtracting lost time, and dividing the result by the cycle length. SOAP 84 differs significantly in its calculation of effective green ratios for protected–permissive (northbound left and southbound left) and unprotected left turns (eastbound left and southbound left). The SOAP 84 equation is as follows:

$$\text{Left-turn effective green ratio} = [(G_p + 2.5 \times S_n) + (G_u \times C_t)/S_f]/\text{cycle length} \quad (4)$$

where

G_p = effective green time for protected portion of left turn,

S_n = number of sneakers per cycle,
G_u = unsaturated green time for permissive portion of left turn,
C_t = Tanner's capacity for unprotected left turn, and
S_f = adjusted saturation flow for protected left turn.

When the left-turn headway time is equal to 2.5, SOAP Equation 4 for left-turn effective green ratios becomes equivalent to the left-turn capacity (protected, permissive, and sneakers) divided by the saturation flow [3,600/left-turn headway (default 2.5 sec)]. The HCM includes the entire permissive green time in its estimate of effective green time for left turns. From Equation 4 only a portion of the permissive green is included in the SOAP calculation of effective green ratios. As a result, the effective green ratio for unprotected left turns will vary significantly between the two procedures.

For Calculation 3 in Chapter 9 of the HCM, the effective green ratios are given in Table 5. For through movements and protected left turns without permissive left turns, the HCM and SOAP 84 calculate effective green ratios in a similar manner:

[(Green time and clearance time) – lost time]/cycle length

Therefore, as can be observed from the data given in Table 5, all effective green ratios for through movements are the same for both methods.

TABLE 5 EFFECTIVE GREEN RATIOS

Direction	HCM	SOAP 84
Northbound through	.603	.602
Northbound left	.653	.182
Southbound through	.645	.658
Southbound left	.690	.152
Eastbound through	.254	.253
Eastbound left	.254	.047
Westbound through	.254	.253
Westbound left	.254	.083

CONCLUSIONS

Four major conclusions can be made in a comparison of the 1985 HCM and SOAP 84.

1. SOAP 84 does not make any adjustments to the capacity (saturation flow) for factors included in the HCM. Under the current version of SOAP 84, the user must estimate externally from the program the capacity (saturation flow) for each movement. Requiring the user to make an estimation of saturation flow is one of the major weaknesses in SOAP 84. This problem could be avoided if the saturation flow adjustment factors were incorporated in SOAP 84.

2. SOAP 84 and the 1985 HCM can produce similar results when estimating delay, v/c ratios, and effective green ratios for through movements and protected–restricted left turns. If 1985 HCM saturation flow adjustments are used as input, SOAP 84 could be used as a surrogate for the signalized intersection chapter of the 1985 HCM when evaluating through movements and protected–restricted left turns. However, for unprotected left turns and protected–permissive left-turn phasing, the approach taken by the two procedures differs significantly and would not give comparable results unless the procedure's algorithms are modified.

3. The 1985 HCM underassigns the number of vehicles that use the permissive phase of a protected–permissive left turn. In Calculation 3 in Chapter 9 of the HCM, no left-turning vehicles are assigned to the permissive portion of the left-turn phase. Consequently, the protected portion of the left turn is overassigned. This condition creates unrealistically high v/c ratios and delay computations.

A more realistic estimate of delay for protected–permissive left turns would result if the combined v/c ratio for the protected and permissive portion of the left turn were used in the delay computations rather than only the protected portion of the phase.

4. For unprotected left turns, the HCM procedure calculates capacity at a significantly higher value than does SOAP 84.

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Publication of this paper sponsored by Committee on Highway Capacity and Quality of Service.