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

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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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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:

\[ S_L = 1,404 - 1.632 V_o + 0.0008347 V_o^2 - 0.000002138 V_o^3 \]  

(2)

Multiple lane opposing flow:

\[ S_L = 1,393 - 1.734 V_o + 0.0009173 V_o^2 - 0.0000001955 V_o^3 \]  

(3)

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

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.
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

<table>
<thead>
<tr>
<th>Phase</th>
<th>Green Time (sec)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>7.5</td>
</tr>
<tr>
<td>2</td>
<td>6.5</td>
</tr>
<tr>
<td>3</td>
<td>73.2</td>
</tr>
<tr>
<td>4</td>
<td>31.6</td>
</tr>
</tbody>
</table>

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:

\[ d_1 = 0.38 \left(1 - \frac{g}{C}\right)^2 / \left[1 - \left(\frac{g}{C}\right) \times \alpha\right] \]
### TABLE 31
CALCULATED EFFECTIVE GREEN/CYCLE RATIO FOR EACH MOVEMENT (INCLUDING LEFT TURN RELEASE ADJUSTMENT)

<table>
<thead>
<tr>
<th>Lane Group</th>
<th>First Term Delay</th>
<th>Second Term Delay</th>
<th>Total Delay &amp; LOS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>V/C Ratio X</td>
<td>Cycle Length C (sec)</td>
<td>Delay d1 (sec/veh)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>EB</td>
<td>.612 .254</td>
<td>118.8</td>
<td>29.74</td>
</tr>
<tr>
<td></td>
<td>.678 .254</td>
<td>118.8</td>
<td>30.34</td>
</tr>
<tr>
<td>WB</td>
<td>.950 .603</td>
<td>118.8</td>
<td>33.08</td>
</tr>
<tr>
<td></td>
<td>.944 .690</td>
<td>118.8</td>
<td>12.17</td>
</tr>
<tr>
<td>SB</td>
<td>.518 .645</td>
<td>118.8</td>
<td>8.54</td>
</tr>
</tbody>
</table>

**Note:** Cycle length computed from timing card.

### TABLE 33
CALCULATED DEGREE OF SATURATION (VOLUME/CAPACITY)

<table>
<thead>
<tr>
<th>Lane Group</th>
<th>First Term Delay</th>
<th>Second Term Delay</th>
<th>Total Delay &amp; LOS</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Cycle Length C (sec)</td>
<td>Delay d1 (sec/veh)</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
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<td>EB</td>
<td>.612 .254</td>
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<td>8.54</td>
</tr>
</tbody>
</table>

**Note:** Cycle length computed from timing card.

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

### FIGURE 5
Calculation 3 SOAP 84 results.
TABLE 3 COMPARISON OF AVERAGE STOP DELAY PER VEHICLE CALCULATED BY USING HCM METHODOLOGY AND SOAP 84

<table>
<thead>
<tr>
<th>Direction</th>
<th>HCM</th>
<th>SOAP 84</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northbound through</td>
<td>24.79</td>
<td>23.02</td>
</tr>
<tr>
<td>Northbound left</td>
<td>71.36</td>
<td>35.50</td>
</tr>
<tr>
<td>Southbound through</td>
<td>8.73</td>
<td>8.36</td>
</tr>
<tr>
<td>Southbound left</td>
<td>54.60</td>
<td>50.12</td>
</tr>
<tr>
<td>Eastbound through</td>
<td>32.31</td>
<td>33.01</td>
</tr>
<tr>
<td>Eastbound left</td>
<td>36.01</td>
<td>143.68</td>
</tr>
<tr>
<td>Westbound through</td>
<td>49.41</td>
<td>49.14</td>
</tr>
<tr>
<td>Westbound left</td>
<td>35.99</td>
<td>96.84</td>
</tr>
</tbody>
</table>

*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
\[
d_2 = 173x^2 \cdot (x - 1) + \left[(x - 1)^2 + (16x/c)\right]/2
\]
\[
d = d_1 + d_2
\]
where
\[
d = \text{average stop delay per vehicle for the subject lane group (sec/veh)}
\]
\[
C = \text{cycle length (sec)}
\]
\[
g/C = \text{green ratio for the subject lane group—the ratio of effective green time to cycle length}
\]
\[
x = \text{volume-to-capacity (v/c) ratio for the subject lane group}
\]
\[
c = \text{capacity of the subject lane group}
\]

The delay equation of SOAP 84 is
\[
D = D_1 + D_2 + D_3
\]
where
\[
D = \text{average delay per vehicle (sec/veh)}
\]
\[
D_1 = \text{delay per vehicle for uniform vehicle arrivals, and}
\]
\[
D_2 + D_3 = \text{delay per vehicle for random vehicle arrivals}
\]

Uniform arrivals:
\[
D_1 = C(1 - \lambda)^2/2(1 - \lambda x)
\]
where
\[
D_1 = \text{delay per vehicle (sec)}
\]
\[
C = \text{cycle length (sec)}
\]
\[
\lambda = \text{proportion of green time given to the movement (effective green time/cycle length)}
\]
\[
x = \text{v/c ratio}
\]

Random arrivals:
\[
D_2 + D_3 = \left([B_n^2/B_d] + (x^2/B_d)\right) \cdot 1/2 - B_n/B_d
\]
where
\[
B_n = 2(1 - x) + xz;
\]
\[
z = (2x/v) \times (60/T) = (2/c) \times (60/T);
\]
\[
v = \text{approach volume (vph)}
\]
\[
T = \text{period length (min), usually 60 min}
\]
\[
c = \text{capacity}; and
\]
\[
B_d = 4z - x^2
\]

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.

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 sneaks, 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):

$$CLT = (1,400 - Vo) \frac{(g/C)}{PTL}$$

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,

$$Vo = 1,011$$

$$\frac{(g/C) PTL}{(CLTL)} = .45$$

$$CLT = (1,400 - 1,011) \times .45 = 175$$

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:

$$Left-turn\ effective\ green\ ratio = \left[\left(G_p + 2.5 \times S_{th}\right) + \frac{\left(G_u \times C_p\right)}{S_4}\right]/cycle\ length$$

where

- \(G_p\) = effective green time for protected portion of left turn,
Sn = number of sneakers per cycle,
Gu = unsaturated green time for permissive portion of
left turn,
Ct = Tanner's capacity for unprotected left turn, and
Sr = 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 equiv­
alent to the left-turn capacity (protected, permissive, and
sneakers) divided by the saturation flow [3,600/left-turn head­
way (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:

\[(\text{Green time and clearance time}) - \text{lost time}] / \text{cycle length}\]

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**

<table>
<thead>
<tr>
<th>Direction</th>
<th>HCM</th>
<th>SOAP 84</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northbound through</td>
<td>.603</td>
<td>.602</td>
</tr>
<tr>
<td>Northbound left</td>
<td>.653</td>
<td>.182</td>
</tr>
<tr>
<td>Southbound through</td>
<td>.645</td>
<td>.658</td>
</tr>
<tr>
<td>Southbound left</td>
<td>.690</td>
<td>.152</td>
</tr>
<tr>
<td>Eastbound through</td>
<td>.254</td>
<td>.253</td>
</tr>
<tr>
<td>Eastbound left</td>
<td>.254</td>
<td>.047</td>
</tr>
<tr>
<td>Westbound through</td>
<td>.254</td>
<td>.253</td>
</tr>
<tr>
<td>Westbound left</td>
<td>.254</td>
<td>.083</td>
</tr>
</tbody>
</table>

**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.

**REFERENCES**


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