Applications of 1985 *Highway Capacity Manual* for Estimating Delays at Signalized Intersections

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The 1985 *Highway Capacity Manual* (HCM) contains a procedure for estimating stopped delays at signalized intersections. These estimates are to be used to assess the levels of service at an intersection. The assessed levels of service, in turn, provide a basis for making decisions concerning geometric designs and signal operations. To facilitate sound decision making, the HCM procedure must be able to produce accurate delay estimates. This paper evaluates the reliability of the HCM procedure, based on field data, and discusses needed modifications. The evaluation reveals that the procedure tends to overestimate stopped delays at reasonably well-timed signal operations. The discrepancies between the HCM estimates and the observed delays can be very large even when correct cycle lengths and green durations are used as inputs. Such large discrepancies are attributable in part to the progression adjustments recommended in the HCM procedure. Given actual cycle lengths and green durations, the procedure's ability to correctly identify the levels of service is good. However, a reliable method is needed for estimating average cycle lengths and green durations for traffic-actuated signal operations.

The 1985 *Highway Capacity Manual* (HCM) (*1*) is widely used to assist in the planning, design, and operation of highway facilities. In chapter 9 of the HCM, a procedure is provided for estimating stopped delays at signalized intersections. A major element of this procedure is a delay function, which is represented by

$$d = 0.38C(1 - g/C)^2[1 - (g/C)X] + 173X^2\{(X - 1) + [(X - 1)^2 + 16X/c]^{1/2}\} \quad (1)$$

where

d = average stopped delay per vehicle for a lane group (sec/veh),
C = cycle length (sec),
g = effective green for the lane group being considered (sec),
X = volume-to-capacity ratio for the lane group, and
c = capacity for the lane group (vph).

Another major component of the HCM procedure is a set of progression adjustment factors, which are multiplied by the values obtained in Equation 1 to produce the final delay estimates. These adjustment factors attempt to account for the variations in stopped delays as a function of the type of signal control, directional movements, volume-to-capacity ratio, and vehicle arrival type.

The delays estimated from this procedure form the basis for assessing the levels of service at signalized intersections. The level of service assessments, in turn, help engineers make decisions concerning geometric designs and signal operations. Therefore, it is imperative that the HCM procedure be able to consistently produce reliable delay estimates. Little information on the reliability of this procedure has previously appeared in literature.

A major purpose of this paper is to present the findings of a study that compared observed stopped delays with estimates obtained from the HCM procedure. The paper also discusses needed enhancements to the procedure.

Twenty sets of field data were used to evaluate the HCM procedure. These data were collected in the following four urban areas in the state of New York: Canton, Potsdam, Watertown, and Syracuse. The types of signal control represented in the data sets include fixed-time control, semi-actuated control, and full-actuated control. When using the HCM procedure for actuated signal operations, the average observed cycle lengths and effective green durations were used as inputs into Equation 1. Stopped delays were estimated on the basis of 15-min flow patterns.

DATA COLLECTION AND SYNTHESIS

Stopped delays were measured for single-lane movements at seven intersections. To compare the HCM estimates with observed delays, the cycle lengths, green durations, yellow durations, and saturation flow rates were also recorded using video cameras with built-in stopwatches. For the data collection, each traffic lane was divided into two zones. Zone I covered a distance extending from the stopline to a location about 200 ft upstream. Zone II included the entire length upstream of Zone I. Two observers were used in tandem to provide separate accounts of the vehicle movements in these zones. This arrangement was necessary because of the presence of rather long queues at most of the study sites. When possible, the actual time at which a vehicle came to a stop in a queue and the time when a vehicle started moving after the green onset were recorded. For the eight or nine queuing vehicles that could usually be stored in Zone I, this task of data collection was not difficult. However, keeping track of the individual movements of those vehicles further upstream was difficult at times. Therefore, the numbers of stopped vehicles in Zone II were often recorded at 5-sec intervals. The recording interval was occasionally lengthened to 10 sec when very long queues were encountered.

Following the HCM procedure, the field data were synthesized into 15-min flow patterns for analysis. This resulted

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in a total of 20 sets of data. With the exception of one 15-min flow pattern involving opposed left turns, the capacities for the subject movements exceeded the arrival rates. However, spillovers of queuing vehicles from one cycle to another were not uncommon for most of the subject movements.

A summary of the data concerning the signal control, directional movement, flow rate, and capacity of each subject movement is given in Table 1. The average observed stopped delays and the stimates obtained from the HCM procedure are shown in Table 2.

OBSERVED DELAYS VERSUS HCM ESTIMATES

The HCM procedure attempts to estimate the true average stopped delay for a given condition. In contrast, the observed delay for 15-min flow is only a sample, which would invariably deviate from the true average. While discrepancies between the observed delays and the HCM estimates can be expected, the HCM procedure must be able to produce unbiased estimates.

Table 2 shows that the HCM estimates sometimes deviate significantly from the observed delays. For Movements 8 and 11, the HCM estimates were only about one-half of the observed delays. These two movements were associated with a traffic-actuated signal phase at a major intersection in Canton. This signal phase was often prematurely terminated because of the inability of its queuing vehicles to extend the green intervals continuously. In several observed cycles, the green intervals lasted only for about 15 sec when more than 10 queuing vehicles were still moving toward the intersection. Because the HCM procedure is intended for assessing reasonably efficient signal operations, it cannot adequately reflect the delays under such undesirable signal operations. Therefore, the estimates for Movements 8 and 11 do not necessarily signify a real limitation of the HCM procedure.

For most of the other movements, the HCM estimates were within 10 sec/veh of the observed delays. In fact, the HCM estimates for 11 of the 20 movements deviated from the observed values by less than 6 sec/veh. This implies that, with properly timed signals and accurate information on cycle lengths, green durations, and flow characteristics, the HCM procedure has a reasonable chance of producing good estimates for assessing the levels of serve at signalized intersections. Excluding Movements 8 and 11, the HCM procedure resulted in incorrect classifications of the level of service for only three movements.

However, as shown in Figure 1, the HCM procedure appears to have a tendency to overestimate stopped delays. The existence of such systematic errors warrants attention.

TABLE 1 SUMMARY OF MOVEMENT-RELATED DATA

Movement	Turn[1/] Type	Signal[2/] Control	Cycle, C sec	Effective Green, g sec	Arrival Rate, q vph	Arrival Type	Capacity vph
1	PL	semi	50.1	19.5	484	2	660
2	OL	fixed	120.0	39.4	360	2	340
3	OL	fixed	120.0	39.4	231	2	340
4	SR	fixed	90.0	28.0	528	2	565
5	SR	fixed	90.0	28.0	442	3	534
6	PL	fixed	90.0	28.6	432	2	521
7	PL	fixed	90.0	28.6	506	3	560
8	ST	full	103.1	39.7	523	3	561
9	SL	full	90.6	20.1	248	3	337
10	ST	full	86.7	31.7	448	3	516
11	ST	full	73.6	30.0	520	3	563
12	SR	full	159.0	40.0	458	1	506
13	SR	full	168.2	40.0	449	1	506
14	ST	full	125.0	19.2	193	2	243
15	ST	full	107.0	41.0	635	2	682
16	ST	full	116.0	35.0	438	1	485
17	ST	full	99.8	26.9	390	2	411
18	ST	full	116.0	33.3	465	2	478
19	ST	full	112.4	33.5	498	1	536
20	ST	full	114.7	33.3	479	2	536

[1/] OL = opposed left turns; SR = straight plus right turns;
PL = protected left turns; SL = straight plus left turns

[2/] semi = semi-actuated; fixed = fixed-time; full = full-actuated

TABLE 2 COMPARISON OF OBSERVED STOPPED DELAYS AND LEVELS OF SERVICE (LOS) WITH HCM ESTIMATES

Movement	Observed		HCM Estimates		
	Delay sec/veh	LOS	Delay sec/veh	LOS	Overestimate sec/veh
1	15.0	B	12.9	B	-2.1
2	65.6	F	87.7	F	22.1
3	31.1	D	30.2	D	-0.9
4	41.1	E	47.0	E	4.9
5	26.1	D	29.1	D	3.0
6	30.9	D	29.1	D	-1.8
7	27.1	D	35.2	D	8.1
8	64.2	F	33.6	D	-30.6
9	27.7	D	25.9	D	-1.8
10	37.4	D	25.2	D	-12.2
11	44.2	E	26.4	D	-17.8
12	64.3	F	69.4	F	5.1
13	60.6	F	71.2	F	10.6
14	45.2	E	48.9	E	3.7
15	31.0	D	36.3	D	5.3
16	40.8	E	52.6	E	11.8
17	36.8	D	47.7	E	10.9
18	48.6	E	53.1	E	4.5
19	38.4	D	54.1	E	15.7
20	34.7	D	40.2	E	5.5

SOURCE OF ESTIMATION ERRORS

Many factors can contribute to the estimation errors produced by the HCM procedure. One potential contributing factor is

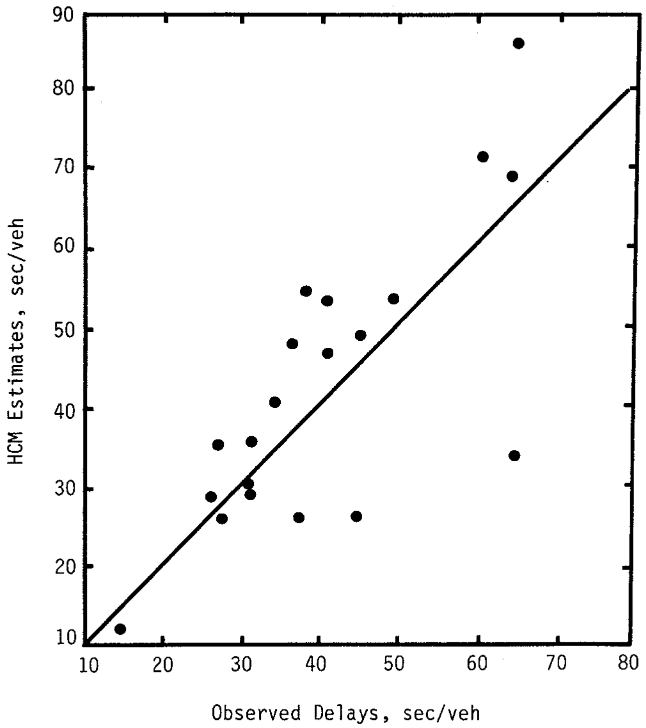

FIGURE 1 Observed stopped delays versus HCM estimates.

TABLE 3 ESTIMATED DELAYS WITH AND WITHOUT PROGRESSION ADJUSTMENT

Movement	Adjustment Factor	Estimated Delays, sec/veh			
		With	Error*	Without	Error*
4	1.19	47.0	4.9	39.5	-1.6
8	0.85	33.6	-30.6	39.5	-24.7
9	0.85	25.9	-1.8	30.5	2.8
10	0.85	25.2	-12.2	29.7	-7.7
11	0.85	26.4	-17.8	30.9	-13.3
12	1.20	69.4	5.1	57.8	6.5
13	1.20	71.2	10.6	59.2	-1.4
14	0.98	48.9	3.7	49.9	4.7
15	0.95	36.3	5.3	38.2	7.2
16	1.20	52.6	11.8	43.8	3.0
17	0.95	47.7	10.9	50.2	13.4
18	0.94	53.1	4.5	56.5	7.9
19	1.19	54.1	15.7	45.5	7.1
20	0.96	40.2	5.5	41.9	7.2

*Estimate - observed delay

the use of the progression adjustment factors for modifying the estimates obtained from Equation 1. Table 3 compares delays estimated with and without applying the progression adjustments. The table reveals that, without the adjustments, most of the large estimation errors can be reduced substantially. By treating the estimates obtained from Equation 1 as the final estimates, the estimation errors for the movements shown in Table 3 can be reduced from an average of 10 to 7.7 sec/veh. Therefore, the progression adjustments given in the HCM require revision and, until revised factors are available, it may be advisable not to apply the adjustment factors to vehicular movements at isolated intersections.

Another factor that may contribute to the estimation errors is the use of a constant coefficient of 0.38 in the first term of Equation 1. This constant implies that, for uniform arrivals with no spillovers of queuing vehicles from one cycle to another, the stopped delays equal 76 percent of the corresponding approach delays.

Referring to Figure 2, the approach delay of a vehicle is defined in this paper as the elapsed time between the expected time of arrival (t_1) at the stopline and the time of departure (t_4) from the stopline. The corresponding stopped delay is measured from time t_2 (at which the vehicle comes to a stop) to time t_3 (when the vehicle begins to move after the green onset). The total approach delay of the vehicles arriving at a uniform rate in a cycle is represented by the area of the triangle ABC in Figure 3. The slope of AC of the triangle equals an arrival rate of q vph. The slope of BC represents a saturation flow rate of S vph in green duration. The base of the triangle, which has a length of r sec, is equal to the effective red interval (cycle length minus effective green).

With no spillovers of queuing vehicles from one cycle to another, it can be shown that the average approach delay for

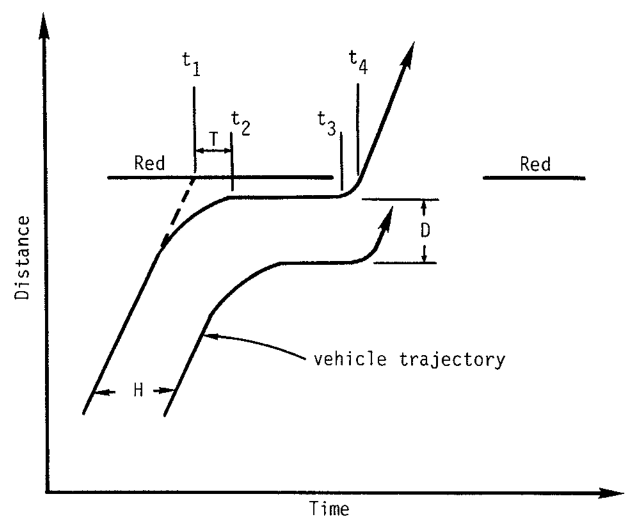

FIGURE 2 Schematic of approach delay and stopped delay.

a uniform arrival pattern can be estimated from

$$d_a = \frac{C(1 - g/C)^2}{[1 - (g/C)X]/2} \tag{2}$$

Conceptually, it is reasonable to assume that, for a given cycle length, the stopped delays will account for a larger proportion of the approach delays as the available green intervals

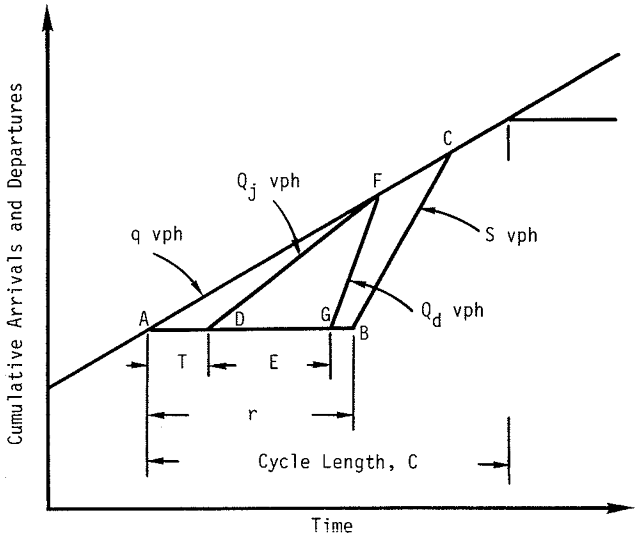

FIGURE 3 Determination of delays per cycle for uniform arrivals.

are shortened. In other words, the constant coefficient of 0.38 used in Equation 1 should be replaced by a variable.

To examine the magnitude of estimation errors attributable to the use of a constant coefficient, assume that vehicles approach the intersection at speed V and, if necessary, decelerate a constant rate B to come to a stop. Based on this assumption, the first queuing vehicle, which is expected to reach the stopline at t_1 (Figure 2) if no deceleration is necessary, will come to a stop at $t_1 + V/(2B)$. The time lag between the expected arrival time and the stop time is denoted as T in Figures 2 and 3. The value of this time lag is

$$T = V/(2B) \quad (3)$$

The second queuing vehicle has an expected arrival time of $t_1 + H$, where H is the uniform headway, in seconds, of the arriving vehicles. The value of H is

$$H = 3{,}600/q \quad (4)$$

This vehicle will come to a stop behind the first queuing vehicle at $t_1 + H - D/V + V/(2B)$, where D is the spacing between two stationary queuing vehicles, measured from the front end of one car to the front end of the other.

Similarly, the third queuing vehicle will join the queue at $t_1 + 2H - 2D/V + V/(2B)$. In other words, the rate at which vehicles come to a stop is one vehicle every $H - D/V$ seconds. If this rate is represented by Q_j vph, then

$$Q_j = 3{,}600/(H - D/V) \quad (5)$$

After the green onset, the queuing vehicles will start moving successively at an average rate of one vehicle per R sec, where R is the driver reaction time. This implies that the queuing vehicles depart from the stationary queue at a rate of

$$Q_d = 3{,}600/R \quad (6)$$

where Q_d is the rate of departure, in vph, from the stationary queue.

Therefore, the total stopped delay for the vehicles arriving in one cycle can be represented by the smaller triangle *DGF* in Figure 3. The base of this triangle can be approximated by a time period of

$$E = C - G - Y - R - T \quad (7)$$

where Y is the yellow interval and G is the green interval. (All units in Equation 7 are in seconds.)

The average stopped delay can then be determined as

$$d_s = \frac{(E^2/C)(Q_j/q)}{(1 - Q_j/Q_d)/2} \quad (8)$$

Based on Equations 2 and 8, it can be shown that the ratio of stopped delay to approach delay can vary from less than 0.4 (when the green interval accounts for a large portion of the cycle) to more than 0.7 (when the green interval is relatively short). This relationship is intuitively correct and can be confirmed by computer simulation.

Figures 4 and 5 compare the simulated delays with the estimates obtained from Equation 2 and Equation 8, respectively. These estimates are based on a driver reaction time of R = 1.2 sec (*2*), a yellow interval of Y = 4 sec, a vehicle approach speed of V = 50 ft/sec, a deceleration rate of B = 6.25 ft/sec^2, and a saturation flow rate of S = 1,630 vphg. The simulation model used in this study generates uniform arrivals and processes the vehicles downstream by updating their positions and speeds once per second of real time. Unlike the analytical model, the simulation model allows the arriving vehicles to move toward and out of the intersection according to probabilistic flow characteristics observed in the field (*2*). The simulation runs performed in this study analyze the delays under various conditions for 1 hr. As shown in Figures 4 and

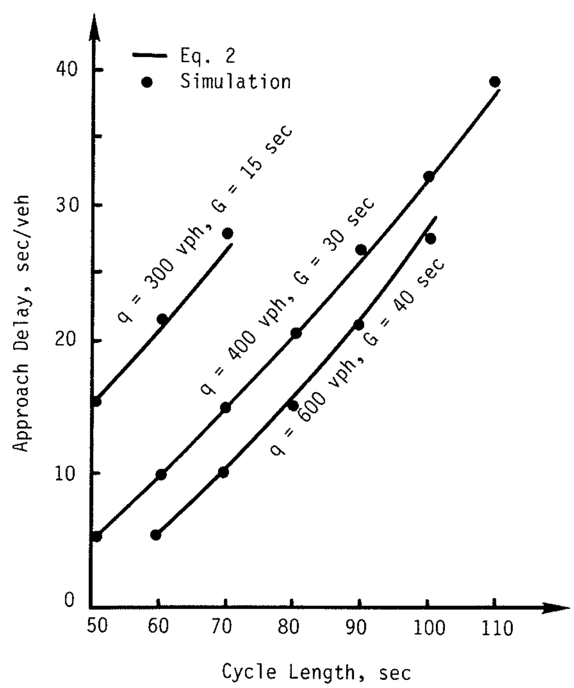

FIGURE 4 Simulated approach delays versus delays determined from Equation 2 for uniform arrivals.

5, the agreement between the simulated delays and the theoretical values is remarkably good.

Figure 6 compares the stopped delays estimated from Equation 8 and the first term of Equation 1 for uniform arrivals. The first term of the HCM delay function tends to overestimate delays when they are under 20 sec/veh. Beyond this level, it tends to underestimate the delays. However, because the estimation errors are mostly less than 3 sec/veh, the first term of the HCM delay function can be considered sufficiently accurate and the modification of Equation 1 should be focused on the second term. To alleviate the tendency to overestimate delays, the second term can be revised to lower its sensitivity to the value of the volume-to-capacity ratio (X).

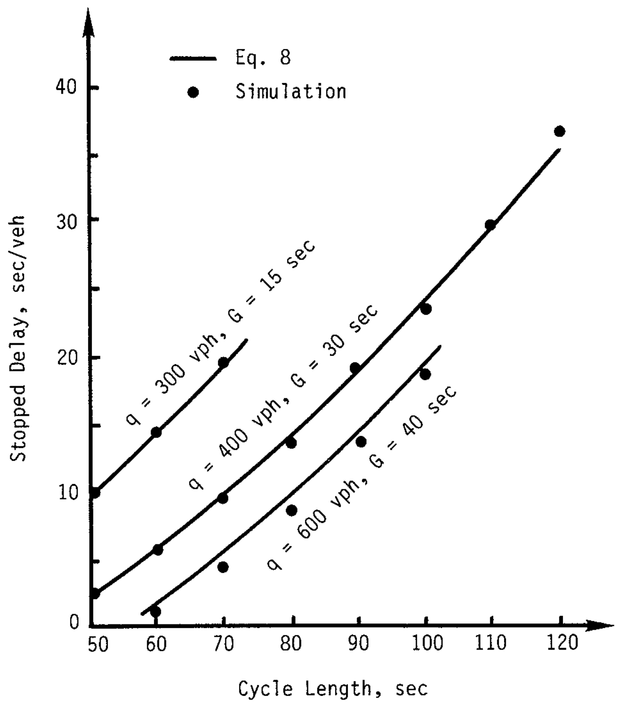

FIGURE 5 Simulated stopped delays versus delays determined from Equation 8 for uniform arrivals.

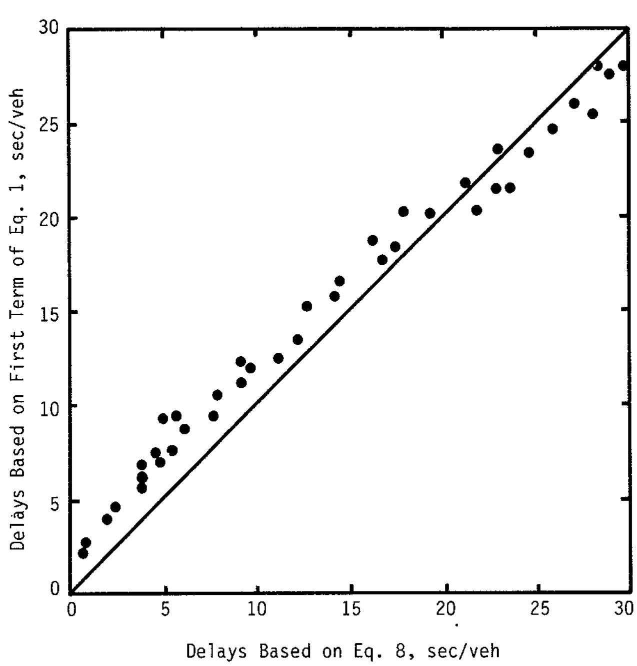

FIGURE 6 Comparison of delays estimated from Equation 8 and the first term of Equation 1 for uniform arrivals.

A WEAK LINK

Although the HCM estimates compare favorably with the observed delays and the levels of service for most of the subject movements, these comparisons use the actual cycle lengths and green durations as inputs into the HCM procedure. In reality, the applications of the HCM procedure are likely to involve unknown cycle lengths and green durations at traffic-actuated signals. This is a major flaw in the HCM procedure.

The HCM suggests that the average cycle length for a traffic-actuated signal operation be estimated from

$$C = LX_c/(X_c - \Sigma(v/S)_{ci}) \quad (9)$$

where

- C = cycle length (sec),
- L = loss time per cycle (sec),
- X_c = critical volume-to-capacity ratio for the intersection,
- v = volume of a lane group (vph),
- S = saturation flow of a lane group (vphg), and
- $(v/S)_{ci}$ = critical flow ratio for lane group i.

In using this equation, a value must be assumed for X_c. The suggested values are 0.85 for semi-actuated control and 0.95 for full-actuated control. These values may be realistic in closely packed platoons. However, at intersections where a signal phase is associated with a number of traffic lanes, the green intervals can be extended for long periods even though the capacity of each individual lane or lane group is far from being fully utilized. This is because traffic-actuated logics combine individual lane flows into a single, equivalent flow to the gaps between successive actuations of detectors. As a result, traffic-actuated operations may have a much smaller X_c than the values suggested for Equation 9. Under such a condition, the use of the suggested values would lead to large errors in estimating average cycle lengths.

The signal operation observed at the T-intersection between Central Avenue and Vly Street in Albany underlines this potential problem. This T-intersection was controlled with a two-phase, semi-actuated signal. The observed total flow rate on Central Avenue was 2,492 vph, which included a critical flow of 1,260 vph and a corresponding saturation flow of 3,260 vphg. The side street had a critical flow of 143 vph and a saturation flow of 1,500 vphg. If Equation 9 is used with a loss time of 10 sec and an X_c of 0.85 as suggested, the estimated average cycle length would be 23 sec. In contrast, the observed average cycle length was 103.4 sec and the corresponding X_c value was about 0.53.

It can be determined from Table 1 that the volume-to-capacity ratios for the subject movements under full-actuated control ranged from 0.73 to 0.95. Because most of these movements represented the critical movements of their respective signal phases, the X_c ratios for the related intersections would have been only as high. Therefore, for the purpose of broadening the applicability of Equation 9, X_c should be treated as a function of cycle length, green interval, flow rate, and saturation flow. This equation can be made even more meaningful for the operational analysis of signal operations if it is enhanced to account for the impact of timing settings and detector configurations.

CONCLUSIONS

Given accurate information on cycle lengths, green durations, and saturation flows, the HCM procedure produces delay estimates that are mostly within 10 sec/veh of the observed values for movements regulated by well-timed signals. However, the discrepancies between the HCM estimates and the observed delays for several movements examined in this study are quite large. Furthermore, it appears that the HCM procedure has a tendency to overestimate delays. Nevertheless, the HCM procedure can correctly identify the levels of service if accurate cycle lengths and green durations are used in Equation 1.

The large discrepancies between the HCM estimates and some of the observed delays can be reduced significantly if no progression adjustments are applied to the estimates obtained from Equation 1. Obviously, the progression adjustments given in the HCM need revision. The first term of Equation 1 was found to be sufficiently accurate for estimating the levels of service. Therefore, the tendency to overestimate delays may be mitigated by reducing the sensitivity of the second term of Equation 1 to the value of X.

Applications of the HCM procedure for assessing traffic-actuated signal operations often involve unknown cycle lengths and green durations. The current method for estimating these factors is a major weakness of the HCM procedure. To provide realistic estimates, the value of X_c in Equation 9 must be treated as a variable rather than as a constant. In addition, to facilitate comparisons of alternative signal operations, Equation 9 should be enhanced to account for the variations in cycle lengths with respect to timing settings and detector configurations.

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