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號誌化交叉路口延滯時間計算模式之探討

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摘要

車流於號誌化交叉路口延滯時間的長短，是決定該交叉路口服務水準的重要依據。目前國內外有很多計算延滯時間的方法，在這些方法中，美國公路容量手冊(HCM)的計算模式是常被引用的方法之一。這個模式在1994年年底作了一個重要的修改，績進調整因數不再同時乘於均勻延滯(Uniform Delay, d1)和漸增延滯(Incremental Delay, d2)，改成只應用在均勻延滯部份。然而這個模式的可靠度如何，則需要進一步的分析和探討。

本研究比較三個最被常使用的模式；交通系統模擬模式(TRAF-NETSIM)、1994年版美國公路容量手冊模式和澳洲模式(ARRB)。比較結果發現，在流量小的時候，美國模式和澳洲模式計算出的結果非常接近模擬結果。在流量接近飽和狀況時，澳洲模式較接近模擬結果，美國模式則有較大的差距。本研究同時發現這些差距可藉由改變HCM中的績進調整因數，或TRAF-NETSIM中的車隊到達型態使其減少。這些發現有助於國內專家學者在引用這些模式或發展本土化模式時，提供重要的參考。

INTRODUCTION

Vehicular delay at signalized intersections is a critical component of travel time in an urban road network. Delay results when traffic is impeded by factors beyond the motorist's control. It may be due to interference from other motorists or attributable to the traffic control devices themselves. The Highway Capacity Manual (HCM)[1] uses delay as the sole criterion for determining level of service at signalized intersections. The 1994 version of HCM introduces a change on the delay estimation from the previous HCM methodology (1985 HCM)[2]. Naturally, this change invites comparisons with the existing methods.

This paper attempts to make such a comparison using simulation methodology that have been employed extensively in the word. The comparisons are limited to isolated traffic signal operations. In other words, no consideration is given to the effect of coordination with adjacent signalized intersections. The simulation methodology is the TRAF-NETSIM.

The paper is organized as follows. First the definitions of delay in HCM and TRAF-NETSIM is distinguished along with a regression model is developed to reconcile the delay estimates from TRAF-NETSIM and the HCM. Then, the HCM is compared with TRAF-NETSIM. Several findings are presented and discussed.

RECONCILING DELAY ESTIMATES FROM TRAF-NETSIM AND HCM

In preparation for the comparing of outputs produced by the HCM against TRAF-NETSIM, it is necessary to examine the exact definition of delay used by these two techniques and to reconcile any differences between them. Both methods produce estimates of a variable called "stopped delay per vehicle," but the basis for their computation is entirely different.

TRAF-NETSIM defines stopped delay in terms of the accumulated number of seconds during which a vehicle is actually traveling at zero speed (i.e., "locked wheel" delay). The HCM, on the other hand, defines stopped delay in terms of time spent at a speed of less than 5 mph. It is computed analytically by dividing the total delay by a factor of 1.3. This factor was developed as the average ratio of total delay to stopped delay.

Furthermore, the definition of total delay is different between the HCM and TRAF-NETSIM. In the HCM, total delay is the delay caused by a signal. TRAF-NETSIM's total delay includes two parts. The first is cruise delay, which caused by the interaction of slower vehicles. The second is signal delay.

The various delay definitions can be seen in Figure 1, which shows a graphical representation of the time-space trajectory of an average vehicle delay as it passes through an intersection. Note that the vehicle approaches the intersection at a constant cruise speed and undergoes a period of deceleration before coming to a full stop. The stopped time is represented by the vertical segment of the trajectory since this segment portrays a time interval in which there is no change in the special position. At the end of the stopped-delay interval, the vehicle undergoes a period of acceleration until the cruise speed is reached. The various delays reported by the HCM and TRAF-NETSIM models are indicated on the left and right sides of the intersection, respectively.

In Figure 1, the HCM model considers the total delay to be the vertical distance (time) between the "cruise" lines for entering and leaving the intersection. This is the delay due to the signal. If there is no signal, the HCM total delay will be zero. However, the TRAF-NETSIM's total delay is referenced to the free-flow speed of the approaching vehicles instead of the cruise speed used by the HCM. Free-flow speed is a value referred to as the highest cruise speed a vehicle can travel on a link. As the flow on the link increases, the cruise speed decreases. Specifically, the HCM total delay is the delay only caused by signal (i.e., signal delay), and the TRAF-NETSIM total delay includes signal delay and cruise delay. Therefore, the TRAF-NETSIM total delay is by definition higher than the HCM total delay because it includes the "cruise delay."

A procedure was developed to show how signal delay (HCM's total delay) can be determined using the TRAF-NETSIM model. The procedure requires two steps. The first considers the relationship between input free-flow speed, cruise speed, and volume to saturation flow rate (v/s) ratios. The second constructs a model to differentiate signal delay from TRAF-NETSIM total delay.

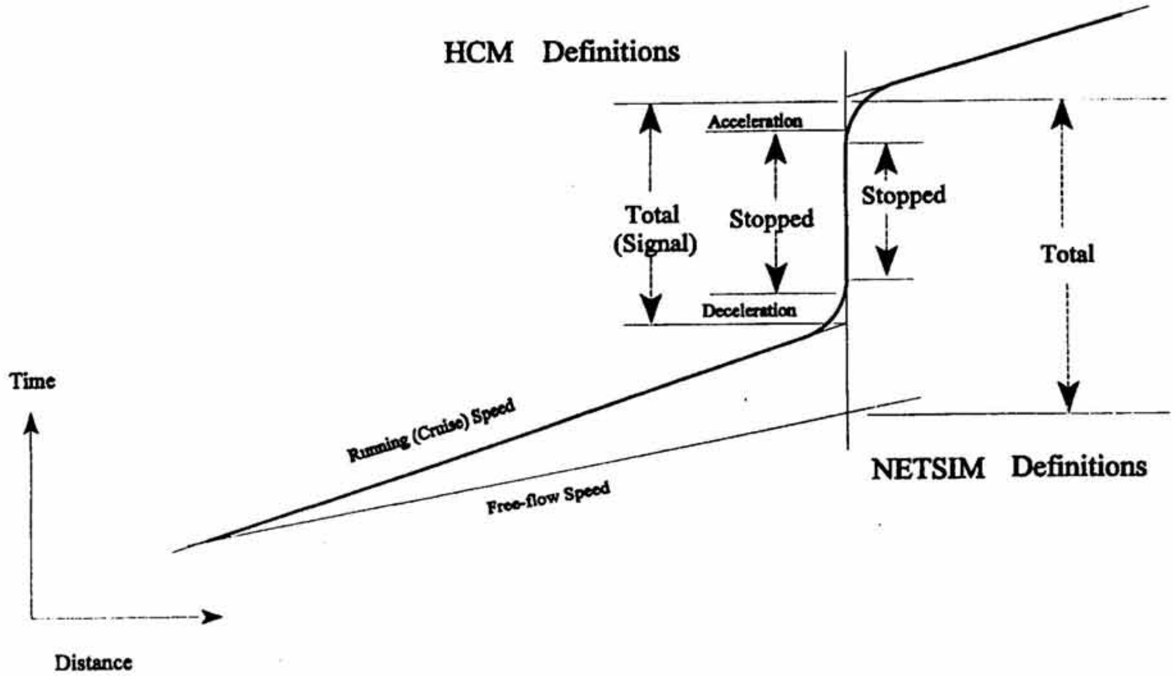

Figure 1. Comparison of delay definition.

Speed-flow Analysis

The study methodology involved a comparison of the input free-flow speed with the modeled average cruise speed at midblock for various v/s ratios. The general relationship is

$$W = a \times S_c \times \left(S_f - S_c\right) \qquad (1)$$

where W = v/s ratio,
S_f = input free-flow speed,
S_c = cruise speed, and
a = model parameter.

so,

$$S_c = \frac{S_f}{2} \pm \frac{\sqrt{a^2 S_f^2 - 4aW}}{2a} \qquad (2)$$

The intersection being studied consists of one lane in each direction. Only thru vehicles are considered in this analysis, i.e., no right- or left-turning vehicles. The link length used was 2640 feet. The phase split was 50/50. A saturation headway of 2 seconds per vehicle (saturation flow rate of 1800 vphpl) and cycle lengths of 60 and 90 seconds were used in this analysis. These values reflect an ideal intersection setup with long link lengths and acceptable real-life values for green times, cycle lengths, and saturation flow rates.

Recent enhancements in TRAF-NETSIM allow for the generation of a series of intermediate preprocessor data files with the extension .F4n (n = 0 to 9). One of these files, .F41, contains the link, vehicle, and blockage data for animation. In every second, one record is written for each link in the network. Each link record may be followed by one or more records containing information about the vehicles existing on the link. The information includes every vehicle's identical number, the traveled distance from the upstream node, turn code (if vehicle will turn left, thru, or turn right), vehicle length, and queue code (if vehicle is in queue). When no vehicles exist on a given link, this vehicle data record is not written. By collecting these data, a time-space diagram with an approach volume of 500 vph is plotted in Figure 2. Every point reflects the location and time of a vehicle traveling on the link every second. The average cruise speed can be obtained by taking the average slope of these trajectories. In this example, the cruise speed is 39.3 feet per second, which is slower than the free-flow speed (44 feet per second). The slower cruise speed is due to the fact that TRAF-NETSIM considers speeds from 75 to 127 percent of the input speed and assigns them to each vehicle randomly. A low-speed vehicle would tend to reduce the speeds of all the following vehicles.

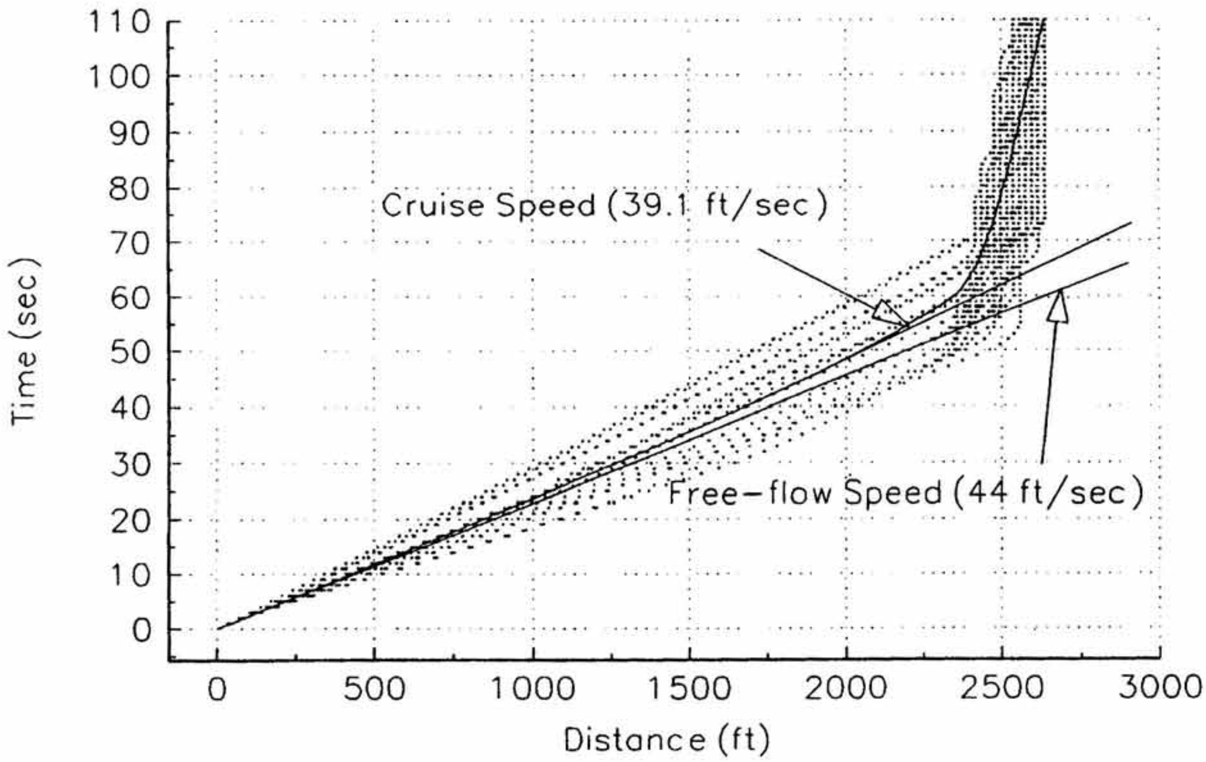

Figure 2. Simulated cruise speed.

By this process, a database was created containing the TRAF-NETSIM cruise speeds, free-flow speed, and v/s ratios. A total of 192 simulation runs were carried out to create the database. The relationship of cruise speed and v/c ratios for the free-flow speed of 30 mph (44 ft/sec) is plotted in Figure 3. Meanwhile, this relationship is sought using regression analysis for all data. The model parameter, a, in Equations (1) and (2) is found to be 0.002295. The coefficient of determination, R-square, was estimated to be 0.93. This means that the equation fits the data reasonably well. The p-value of the estimated coefficient is less than 0.05, indicating that it is significant at the 95 percent confidence level.

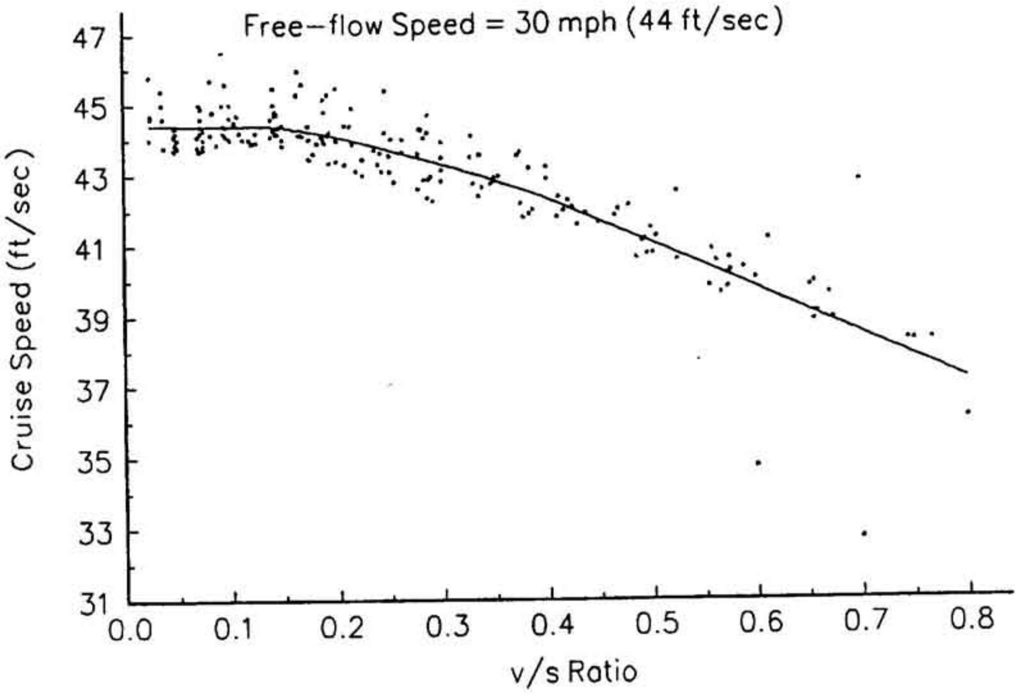

Figure 3. Simulated relationship of cruise speed and v/s ratio.

Signal Delay in TRAF-NETSIM

By definition, the TRAF-NETSIM total delay is equal to the travel time at cruise speed plus intersection signal delay minus travel time at free-flow speed. Thus, signal delay is equal to total delay minus travel time at cruise speed plus travel time at free-flow speed. This relationship can be represented by the following equation:

$$D_s = D - \frac{L}{S_c} + \frac{L}{S_f} \qquad (3)$$

where D_s = TRAF-NETSIM signal delay (sec/veh),
D = TRAF-NETSIM total delay (sec/veh),
L = Link length (ft), and
S_c and S_f were defined previously.

Using the 192 data sets in the speed-flow analysis, the relative accuracy of the recommended model was compared with the HCM model. The results of the comparison are shown in Figure 4. The results indicate that the HCM total delays are higher than those from the TRAF-NETSIM. This finding raises a question: what factor causes this difference. The answer can be demonstrated using more microscopic method in the following section.

TRAFFIC SIGNAL DELAY MODEL

The traditional delay formulation used by virtually all analytical models is based on two components, or terms, which are added together to produce the computed delay per vehicle. The first is uniform delay, which refers to the average vehicle delay experienced assuming that traffic demand is the same for all signal cycles. The second is incremental delay, which occurs because individual cycle failure and the random arrivals of vehicles.

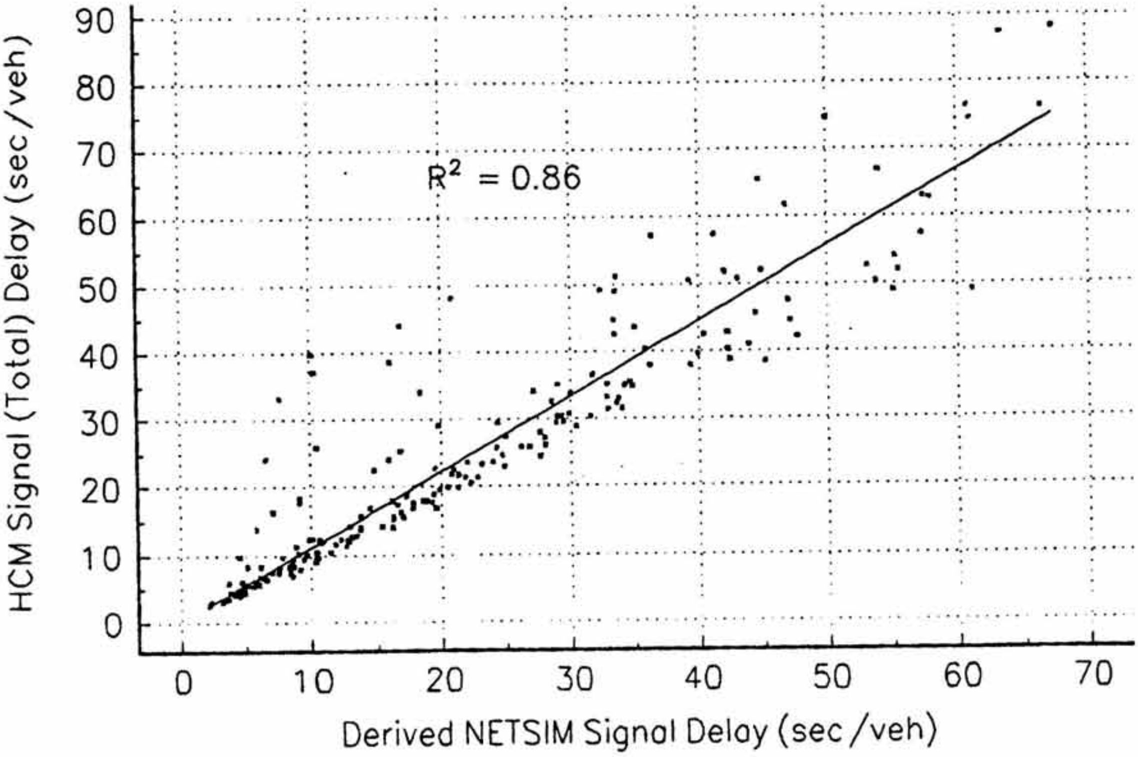

Figure 4. Comparison of HCM and derived TRAF-NETSIM signal delay.

The first delay component D_1 is given by

$$D_1 = \frac{C\left(1-\frac{g}{C}\right)^2}{2\left(1-\frac{g}{C}\times X\right)} \tag{4}$$

where C = cycle length (sec),
g = effective green, and
X = volume-to-capacity ratio.

This formula is valid when the arrival rate is uniform throughout the cycle. It is used in the British and Australian delay calculation methods. Equation (4) is also the basis for delay calculation in the HCM, with two important modifications. The first uses stopped delay rather than total delay as a measure of performance for signalized intersections. Second, stopped delay is defined not in terms of locked wheel delay (i.e., totally stopped) but in terms of time spent at less than a certain speed, such as 5 mph. Total delay also includes the time lost because of deceleration and slower movement through the intersection. According to the HCM, the total delay is 1.3 times the stopped delay.

The incremental delay is called the random-plus-saturation delay because of random arrivals and individual cycle failures in the HCM. Akçelik (3) proposes a generalized time-dependent expression in the form

$$D_2 = 900 \times T \times X^n \times \left[X - 1 + \sqrt{(X-1)^2 + \frac{m_o (X - X_o)}{cT}} \right] \quad (5)$$

where T = flow period (hr),

c = capacity (vph), and

X_o = volume-to-capacity ratio below which overflow delay is negligible. This can be expressed as

X_o = a + bsg

where s = saturation flow rate (vps),

a, b, m_o, n = parameters.

The delay model parameters a, b, m, and n depend on the distribution of arrivals and departures. Model parameters as presented by Akçelik (3) are given in Table 1. Note that the flow period is 15 minutes (T=1/4) in the HCM. Therefor, the incremental delay calibration term, m, is 16 for random arrival condition.

Table 1. Calibration parameters for d2 in analytical models.

Method	Model parameters			
	n	m_o	a	b
HCM	2	4	0	0
ARRB	0	12	0.67	1/600

To demonstrate TRAF-NETSIM modeling the two delay components, several runs were made in which traffic streams with different flow rates were introduced into links with different lengths. The results are shown in Figures 5 and 6 for single-lane and multilane links, respectively. Volume-to-capacity ratios from 0.6 to 1.0 and link lengths of 150, 500, 1,000, 1,500, and 2,000 feet are represented in these figures. The purpose to simulate the 150-foot link is get the TRAF-NETSIM first term delay (D_1). This is because the link length is so short that the cycle failure delay can not occur. Moreover, 100 percent of the free-flow speed was assigned to every type of driver so that the traffic would not be affected by slower vehicles. Figures 5 and 6 illustrate that the delay of the 150 foot link is close to the analytical uniform delay. From these two figures, it is found that the ARRB is closer to the TRAF-NETSIM than the HCM. Specially, when the traffic is undersaturated operation. This is because that the ARRB includes a parameter X_o, a value of the degree of saturation below which the overflow delay is negligible.

To compare the delay for link lengths of 500 to 2,000 feet with the existing models, TRAF-NETSIM underestimates the delay values. For overflow delay, TRAF-NETSIM predicts lower values when the v/c ratio nears 1.0. This is due to the fact that TRAF-NETSIM generates less random fluctuation in the arrival flow rate than the existing models do. This can be illustrated by increasing the range of free-flow speed percentage. Table 2. lists the values assumed for different profiles of free-flow speed percentage. In this table, P_n ($n = 0 \sim 4$) represents different profiles of free-flow speed percentage. P_0 is the default profile. The range of the free-flow speed increases as the n value increasing. Simulations with these profiles were performed and again compared with the HCM total delay. The result is shown in Figure 7. As seen in the figure, the total delay of TRAF-NETSIM approaches the curve of the HCM total delay as the randomness of traffic increased.

Table 2. Profiles of free-flow speed percentage.

Driver Type	Profile of Free-Flow Speed Percentage				
	P_0(default)	P_1	P_2	P_3	P_4
1	75	70	65	60	54
2	81	77	72	67	63
3	91	87	83	78	72
4	94	90	87	82	81
5	97	93	91	89	86
6	100	101	102	104	106
7	107	112	116	119	123
8	111	116	120	126	130
9	117	122	127	133	138
10	127	132	137	142	147

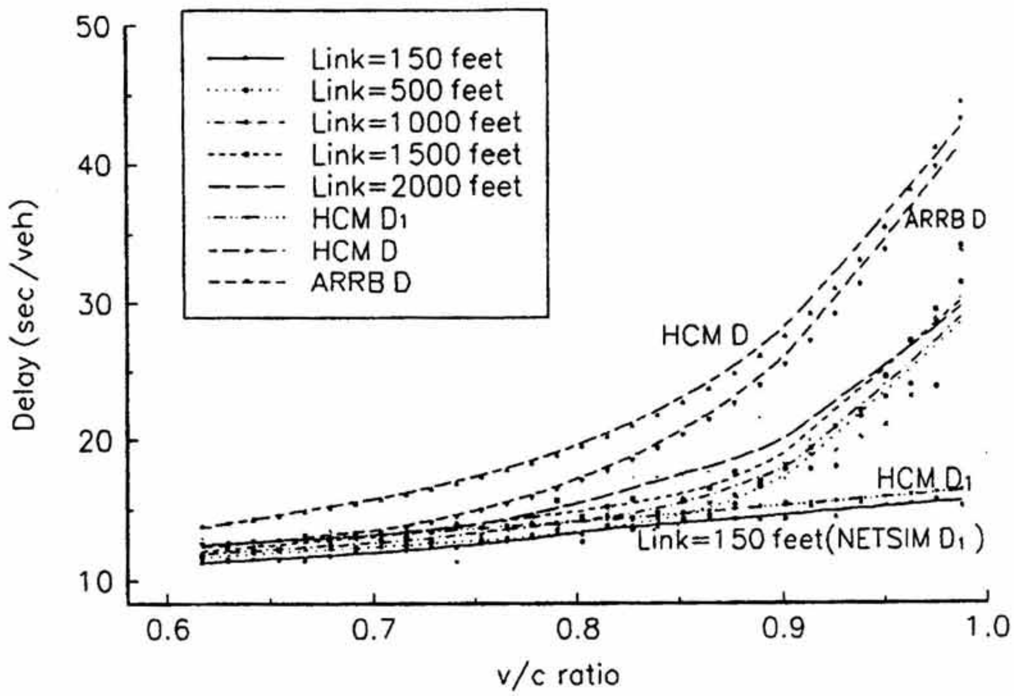

Figure 5. Comparison of HCM's delay with ARRB and TRAF-NETSIM methods for single-lane approach.

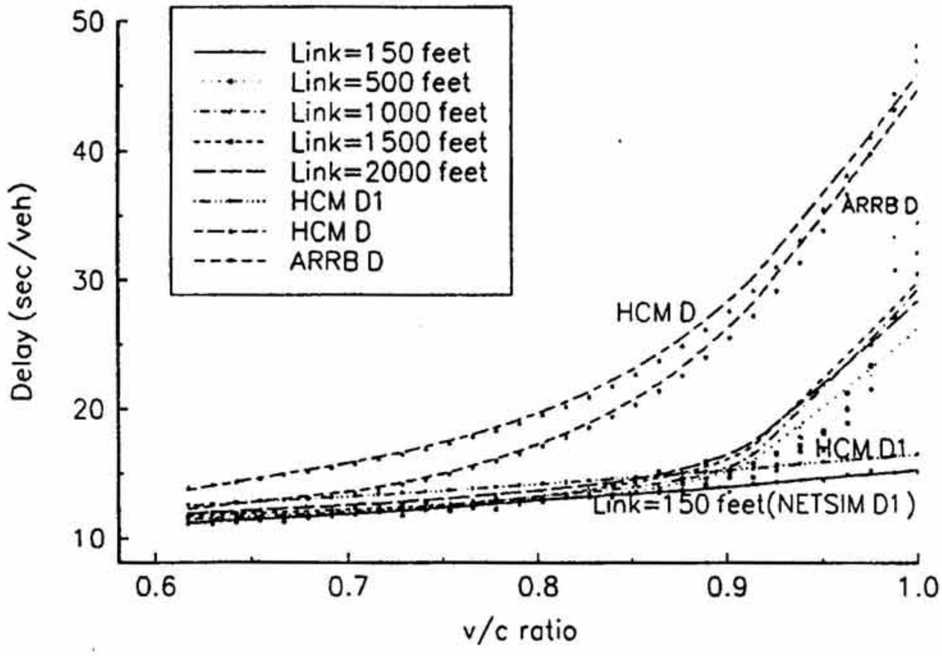

Figure 6. Comparison of HCM's delay with ARRB and TRAF-NETSIM methods for multilane approach.

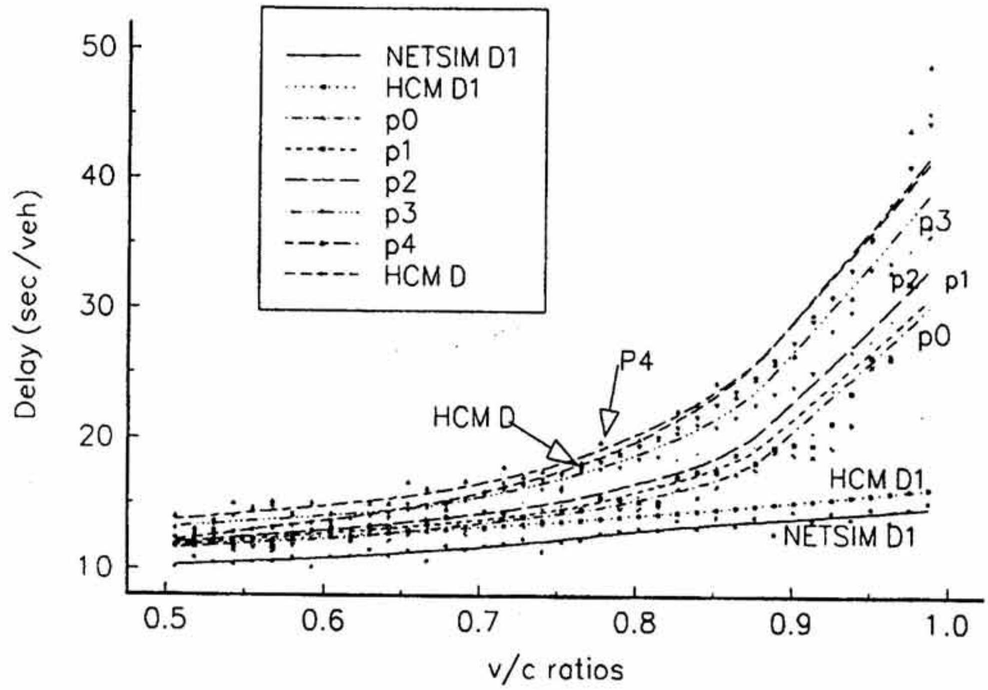

Figure 7. Comparison of HCM's total delay with TRAF-NETSIM total delay for different profiles of free-flow speed percentage.

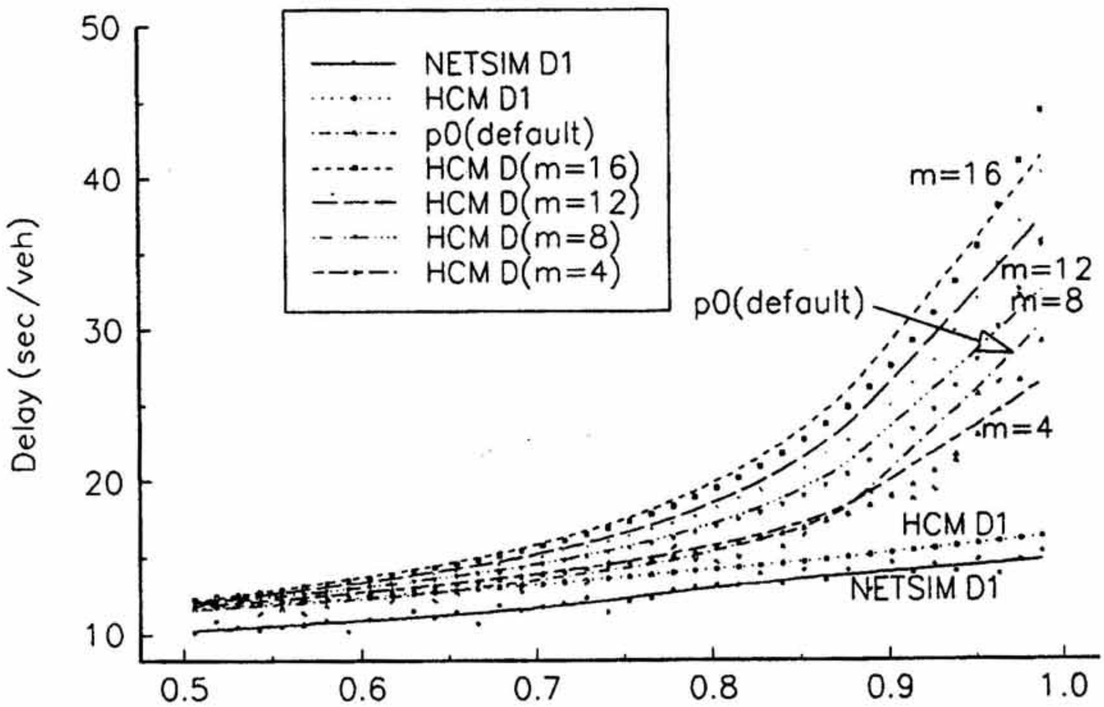

Figure 8. Comparison of TRAF-NETSIM default setting with different HCM m values.

On the other hand, the default values of the free-speed percentage profile can be approached by changing the parameter value of the HCM overflow delay equation. Figure 8 shows a comparison of the default TRAF-NETSIM setting with different HCM m values. As seen in the figure, the default value in TRAF-NETSIM is between m = 4 and m = 8.

CONCLUSIONS

Average vehicle delay is the key indication of intersection performance. This research resulted some interesting observations. Initially, it is observed that the definitions of delay are different between TRAF-NETSIM and the HCM. Furthermore, it was found that, TRAF-NETSIM estimates values of total delay lower than the HCM. By doing more microscopically analysis, it is apparent that the delay model used in the HCM agrees very well with the TRAF-NETSIM model for undersaturated operation. There are significant differences in conditions are oversaturated. TRAF-NETSIM predicts incremental delays less than estimates from HCM procedure. This is because TRAF-NETSIM specifies less randomness of free-flow speed and arrivals. However, it is possible to make the delay values agree by the proper choice of parameters.

REFERENCES

1. *Special Report 209: Highway Capacity Manual, 3rd ed.*, Transportation Research Board, National Research Council, Washington, D.C., 1994.
2. *Special Report 209: Highway Capacity Manual*, Transportation Research Board, National Research Council, Washington, D.C., 1985.
3. Akcelik, R., "The Highway Capacity Manual Formula for Signalized Intersections," ITE Journal, Vol. 58, No. 3, 1988, pp23-27.
4. McShane, W. R., and Roess, R. P., *Traffic Engineering*, Prentice-Hall, Inc., 1990.
5. Tarko, A., Rouphail, N., and Akcelik, R., " Overflow Delay at a Signalized Intersection Approach Influenced by an Upstream Signal: An Analytical Investigation," *Transportation Research Record 1398*, Transportation Research Board, Washington, D.C., 1993.
6. Rathi, A. K., and Venigalla, M. M., "Variance Reduction Applied to Urban Network Traffic Simulation," *Transportation Research Record 1365*, Transportation Research Board, Washington, D.C., 1992.