

# Comparison of the HCM and Singapore Models of Arterial Capacity

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## ABSTRACT

The paper compares two methods of modelling the relationship between arterial travel speed and traffic flow. The *Highway Capacity Manual* method relies on estimating delay at individual intersections and requires a lot of detailed input data. The model developed by CTS in Singapore requires only two input parameters: intersection spacing and minimum signal delay. Both models show similar trends in travel speed but the HCM method generally predicts lower speeds for uncongested traffic. The Singapore survey data show that arterial running time per kilometer depends on flow rate as well as on intersection spacing. Suggestions are made on how to improve the existing models by using more precise definitions of arterial flow, capacity and running time. It seems that aggregate models such as the CTS model are more appropriate for planning applications when detailed information on signal timing is not available.

## 1. INTRODUCTION

Arterial roads form the backbone of any urban road system. Information on arterial road capacity and performance under different traffic conditions is vital for transportation planners and traffic engineers. Capacity of an arterial depends mainly on its geometry (number of lanes) and on characteristics of traffic control at signalised intersections. The U.S. Highway Capacity Manual (HCM) provides a method of analysing arterial performance, based on detailed calculation of delay incurred at signalised intersections. A study of arterial road capacity in Singapore conducted at the Centre for Transportation Studies (CTS) used a different approach: a direct relationship was established between travel time and traffic density. The speed-flow model derived in this way had only two parameters: intersection spacing and the minimum intersection delay. The CTS model is useful for planning applications as it does not require the input of detailed signal timing data.

The objective of this paper is to compare travel speeds predicted by the two models for a typical range of parameters such as intersection spacing, traffic flow and signal characteristics. Suggestions are made as to the possible improvements of both models. In particular, a relationship between running time and traffic flow is investigated based on empirical data — this relationship has so far been ignored in the HCM method.

## 2. EXISTING MODELS OF ARTERIAL CAPACITY

### 2.1 The Highway Capacity Manual Model

The U.S. Highway Capacity Manual (1997) provides a well-known method of analysing arterial performance. Arterials are classified into categories according to their characteristics

and free-flow speed. Arterial performance or level of service is defined on the basis of the average travel speed for through vehicles.

Arterial speed is the reciprocal of travel time per unit distance. Travel time consists of running time and delay incurred at signalised intersections. This can be expressed as:

$$t = t_r + (\sum d_i) / L \quad (1)$$

where:  $t$  = travel time per km (sec/km),  
 $t_r$  = running time per km (sec/km),  
 $d_i$  = control delay at intersection  $i$  (sec),  
 $L$  = length of an arterial section (km).

The HCM model assumes that the running time is constant and depends only on arterial class (free-flow speed) and the average intersection spacing. When traffic flow along an arterial increases, it causes increased delay at intersections and therefore has an indirect effect on travel time and speed. Thus, a speed-flow model can be formulated by combining Equation (1) with the well-known formula for intersection delay. In the latest HCM (1997) update, the “control delay” concept is used which consists of time lost when vehicles are stopped as well as deceleration-acceleration delay. The uniform delay component is further adjusted depending on the quality of signal progression.

While the HCM method allows one to study the effect of arterial flow on performance, the procedure is complicated and requires a large number of input parameters for each intersection, such as signal cycle time, green time, saturation flow as well as the progression adjustment factors. This makes the procedure cumbersome and not practical for planning applications when the required signal timing details are not known. To overcome these problems default values are assumed for many parameters.

## 2.2 The Singapore CTS Model

A study of arterial road capacity in Singapore was conducted in 1994 at the Centre for Transportation Studies (CTS). Details of this study are given in Fan et al. (1995) and Lum et al. (1998). After investigating several existing speed-flow-density models, the following direct relationship between travel time and traffic density was formulated:

$$t = \alpha \exp(\beta k) + d_{\min} f \quad (2)$$

where:  $k$  = density in pcu per km per lane,  
 $d_{\min}$  = minimum stopped delay per intersection under free-flow conditions(s),  
 $f$  = number of signalised intersections per km, and  
 $\alpha, \beta$  = model parameters.

The first term in Equation (2) represents the variable component of travel time which is the sum of running time and incremental delay at traffic signals. It is a function of traffic density. The second term represents minimum stopped delay which does not depend on traffic density but on the number of signals per kilometer and on the quality of

progression. Thus, the model separates the effects of congestion and signal timing characteristics on travel speed.

Calibration of Equation (2) using field data from all five arterials gave the following parameter values:  $\alpha = 57.96$  and  $\beta = 0.0208$ . The model was then transformed into the following speed-flow relationship:

$$q = 48.08 u \left[ \ln \left( \frac{1}{u} + \frac{d_{\min} f}{3600} \right) + 4.13 \right] \quad (3)$$

where:  $u$  = average arterial travel speed (km/h),  
 $q$  = mid-block traffic flow rate in pcu/h/lane (15-minute flow rate).

By substituting into Equation (3) the appropriate values of  $d_{\min}$  and  $f$ , models for specific arterials can be obtained. The estimated capacity (maximum 15-min flow rate) of typical arterials in Singapore was found to be around 1000 pcu/h/lane under favourable progression and 900 pcu/h/lane without progression.

The CTS model has been further studied and validated by Mak (1997), who found that the predicted speeds were 3 to 4 km/h lower than the observed values.

### 2.3 Other Arterial Speed-Flow Models

The problem of modelling speed-flow relationships for urban arterials is not new and one should briefly mention here the other approaches used. Several direct speed-flow relationships were developed in the early seventies in UK, US and Australia. For example, Beard and McLean (1974) used regression to relate travel speed on four-lane arterials to flow, intersection spacing and environmental factors such as parking and land use. The problem with direct modelling of speed-flow relationship is that it does not allow one to estimate capacity. The characteristics of arterials in those days were also quite different from what is considered typical today.

A lot of research has been done on calibrating and improving the travel time-flow model proposed originally by Davidson (Taylor 1977; Akcelik 1991). The model is based on queuing theory and has the following general form:

$$t_l = t_o \left( 1 + \frac{J q}{Q - q} \right) \quad (4)$$

where:  $t_l$  = link travel time,  
 $t_o$  = free-flow link travel time,  
 $Q$  = link capacity,  
 $J$  = calibration “delay” parameter.

The problem with the original Davidson’s formula was that it predicted infinite travel time as flow approached capacity. This issue was resolved by developing a time-dependent modification of the model (Akcelik 1991, 1996). However, its practical use is made

difficult by the fact that capacity is one of the input parameters. To estimate the capacity of a particular arterial, one would have to rely on HCM or similar method, which requires detailed signal timing information.

### 3. MODEL COMPARISON

#### 3.1 Speed-Flow Relationships

The speed-flow relationships obtained from the HCM and CTS models were compared for typical Singapore conditions. A typical arterial in Singapore is divided (or one-way), with three or more lanes in each direction and little side interference. Intersections are normally flared, with additional lanes for left and right turns. Due to high density of land development, the proportions of turns are usually higher than those observed in other cities. Therefore, a four-phase signal control is quite common.

Table 1 gives the summary of input parameters used in calculations. The running time per kilometer was obtained from HCM Table 11-4, interpolated for the free-flow speed of 60 km/h. Two cases were considered:

1. favourable signal progression (arrival type 5 assumed to represent typical favourable conditions), which resulted in a low minimum delay value of 9.4 s, and
2. unfavourable progression (arrival type 2), resulting in a minimum delay of 21.1 s.

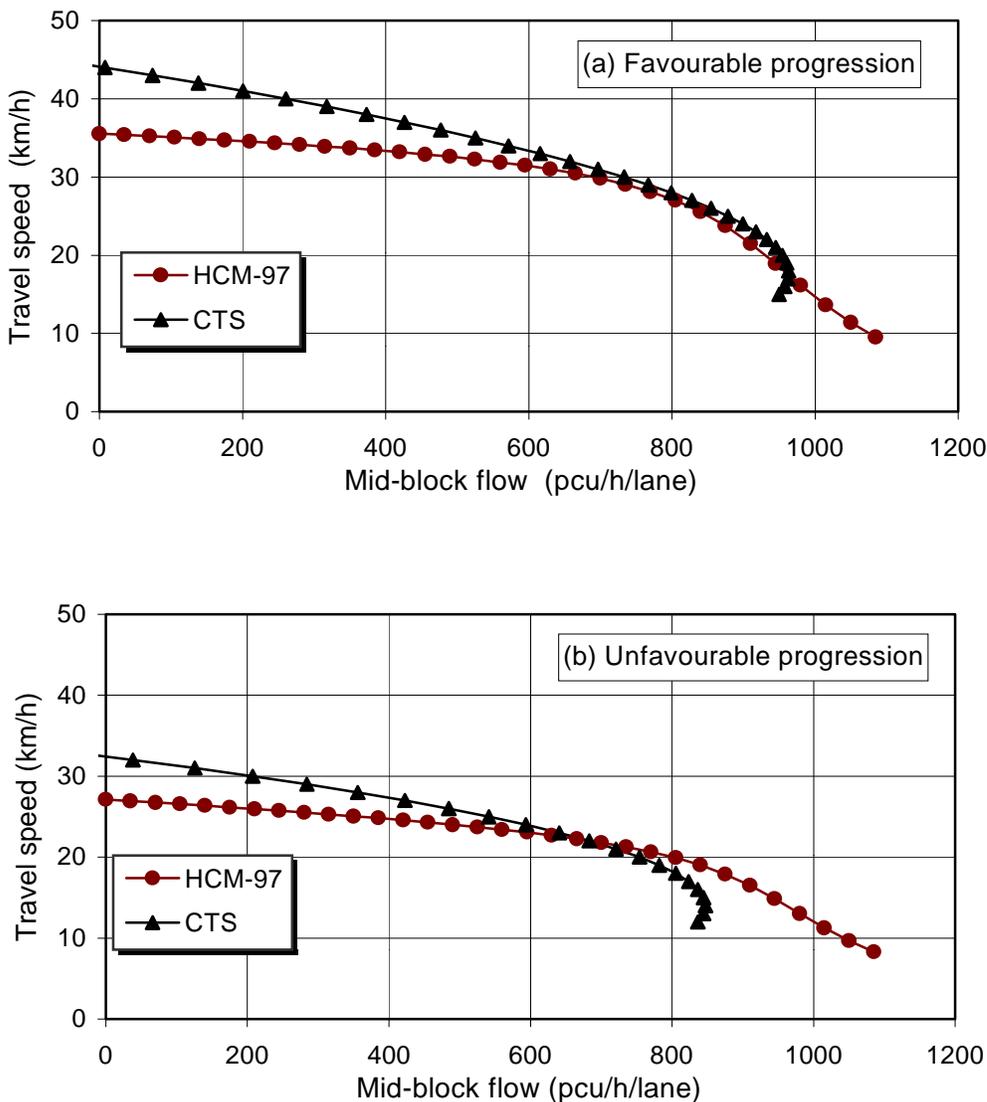
The minimum delay values were calculated from uniform stopped delay formula, using degree of saturation  $x = 0.05$ . The analysis period used was 0.25 h and all flow rates and capacities shown refer to that period.

**TABLE 1 Summary of Input Parameters**

Progression Case	Input parameter	Units	Model	
			HCM	CTS
Both	Arterial class		II	
	Free-flow speed	km/h	60	
	Running time	sec/km	71.3	
	Intersection spacing	signals/km	2.5	2.5
	Saturation flow	pcu/h/ln	1900	
	Cycle time	sec	120	
	Green time ratio		0.4	
	Through flow percentage	%	80	
Favourable	Arrival type		5	
	Progression factor PF		0.555	
	Minimum stopped delay	sec		9.44
Unfavourable	Arrival type		2	
	Progression factor PF		1.136	
	Minimum stopped delay	sec		21.15

Figure 1 shows the comparison of the resulting curves. For flow levels less than 700 pcu/h/ lane, the HCM model predicts lower travel speed. According to the CTS model, arterial speed is much more sensitive to flow, especially under uncongested conditions. This is not surprising as in the HCM method flow is only affecting the speed indirectly, through the value of vehicle delay at intersections. In the case of unfavourable progression, the differences between the two models are also large when flow is near capacity. While the HCM model allows for oversaturation (i.e., flows temporarily greater than capacity), the CTS model predicts reduced flows associated with very low speeds (severely congested conditions).

The two models also differ in the predicted effect of progression quality on free-flow speed and capacity (Table 2). Capacity predicted by CTS model is called “overall” arterial capacity as it reflects the maximum flow measured between intersections (inclusive of turning flows). The corresponding HCM overall capacity was obtained by dividing the approach



**FIGURE 1** Speed-flow curves based on the HCM and CTS models.

**TABLE 2 Summary of Model Output**

Progression case	Output parameter	Units	Model	
			HCM	CTS
Favourable	Overall capacity	pcu/h/ln	950	963
	Approach capacity	pcu/h/ln	760	
	Free-flow speed	km/h	35.5	44.2
Unfavourable	Overall capacity	pcu/h/ln	950	848
	Approach capacity	pcu/h/ln	760	
	Free-flow speed	km/h	27.1	32.6

capacity for through traffic by the through flow proportion (0.8). The gain in free-flow speed due to favourable progression is 11.4 km/h and 8.6 km/h according to the CTS and HCM models, respectively. Interestingly, the CTS model predicts that bad signal progression leads to a decrease in overall arterial capacity by about 115 pcu/h/lane. However, the CTS model is not very sensitive to signal timing parameters such as the green split ratio.

### 3.2 Model Sensitivity to Intersection Spacing

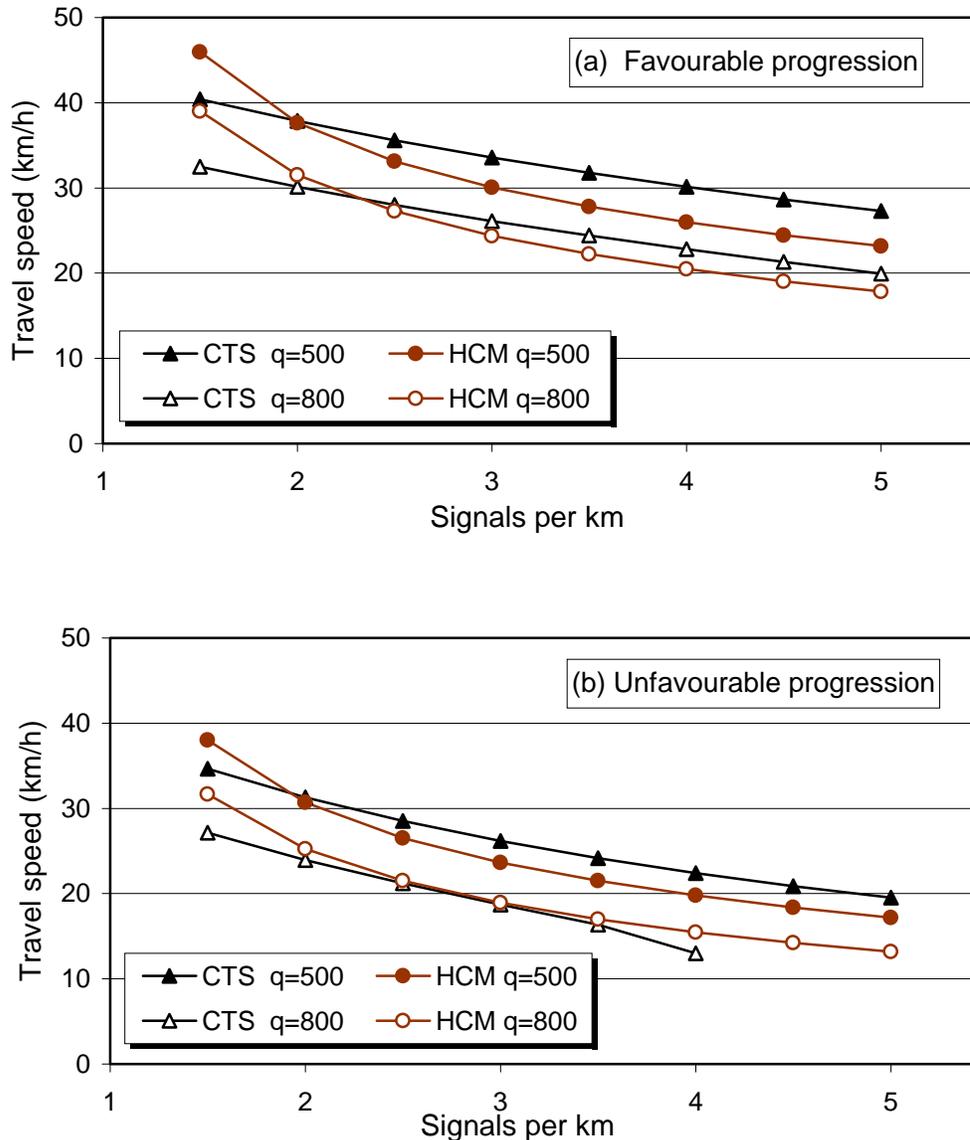
The two models were also compared over a range of intersection spacing between 200 m and 667 m ( $f$  between 5 and 1.5 signals per km). Travel speeds were calculated for two values of mid-block flow: 500 and 800 pcu/h/lane. All the other input parameters were the same as shown in Table 1. Again, two progression quality cases were considered. Figure 2 presents the results.

The sensitivity of both models to the value of  $f$  is similar, except for the very long spacing: when  $f = 1.5$ , the HCM model predicts higher speeds in all cases. The results are very close when  $f = 2$ . For shorter intersection spacing, the CTS model predicts travel speeds of up to 4 km/h higher. Under unfavourable progression, capacity is reached when  $f = 4$  signals/km and CTS model gives a reduced speed.

## 4. INVESTIGATION OF FACTORS AFFECTING RUNNING TIME

The HCM method relies on tabulated values of arterial segment running time (*Highway Capacity Manual 1997*, Table 11-4). These values are assumed constant and depend only on segment length, arterial class and its free-flow speed. The assumption that running times do not depend on arterial flow is illogical and contrary to HCM methodology for uninterrupted flow facilities. The assumption has been recently questioned by Prassas (1999) who used simulation to demonstrate that running speed does change with flow.

The empirical data set from the CTS study was used to investigate factors affecting the observed running times per kilometer. The survey covered 24 one-way arterial sections, with the average intersection spacing ranging from 240 m to 935 m (i.e.,  $f$  ranging from 1.1 to 4.1 signals per km). The data set consisted of 570 observations of 15-min classified traffic volumes and the corresponding running times and travel times measured by probe vehicles. The volumes were converted to flow rates in pcu/h using passenger car equivalents calibrated from the same data by Mak (1997).



**FIGURE 2** Sensitivity of arterial travel speed to intersection spacing.

To test the hypothesis that running time is not affected by the flow rate and intersection spacing, a multiple linear regression was performed with significant (Table 3). The hypothesis that running time is not two independent variables:  $q$  and  $f$ . Both variables proved to be statistically dependent on flow can be rejected at 99.9% level of confidence. The results indicate that, on average, over 1 km arterial length each additional intersection adds 6.8 seconds to the running time while each 100 pcu/h flow increment adds 2 seconds. However, the relationship is not necessarily linear and there is a large unexplained variability in observed running times as indicated by the low  $R^2$  value.

There is a fundamental problem here with the exact definition of running time. In the CTS survey, it was measured as the total time when a probe vehicle was moving (i.e., running time is equal to travel time less stopped delay). However, the observed running time includes periods when vehicles move slowly before and after stopping. This extra time,

**TABLE 3 Regression of Running Time vs. Flow and Intersection Spacing**

Dependent variable	Independent variables				$R^2$	No. of observations
	Flow rate $q$ (pcu/h/lane)		Intersections per km $f$ (signals/km)			
	Regression coefficient	$T$ -value	Regression coefficient	$T$ -value		
Observed running time (sec/km)	0.0201	6.91	6.79	8.60	0.15	570
Net running time (sec/km)	0.0169	5.68	4.44	5.51	0.08	570

known as the deceleration-acceleration delay, is the difference between control delay and stopped delay. The HCM method implies that it should be excluded from the running time as it is already included in the control delay (see Equation 1). Thus, the running time corresponding to the HCM Table 11-4 should be a “net running time” which is very difficult to measure in practice. It could be argued that perhaps the “net running time” is independent of the flow rate. To test this hypothesis, the net running times were estimated by subtracting 30% of stopped delay from the measured running time. This estimation is based on the well-known assumption that control delay is approximately equal to 1.3 times the stopped delay.

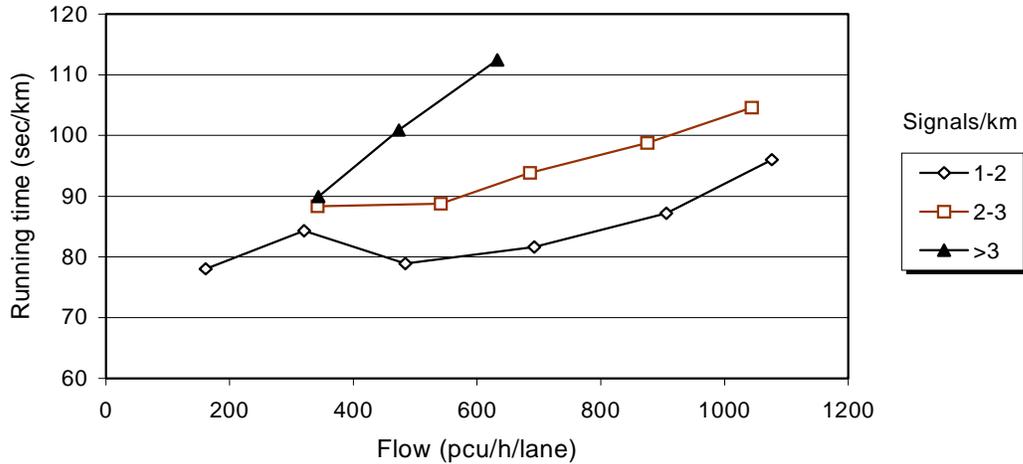
The results of the second regression performed are also shown in Table 3. Again, the hypothesis that the net running time is independent of flow and the number of intersections per kilometer is rejected at 99% level of confidence. The effect of both variables is less strong than in the case of measured running time but it is still highly significant.

To investigate the nature of the relationship between running time and flow, the observations were aggregated in 3 classes of intersection spacing (1–2, 2–3 and more than 3 signals per kilometer) and 6 flow ranges in 200 pcu/h increments. The observed running times averaged in each classification cell are presented in Figure 3. The corresponding estimated net running times are shown in Figure 4. It is clear that the effect of both flow and intersection spacing is non-linear. Running time increases rapidly when flow exceeds 600 pcu/h/lane. The effect is visibly stronger with more intersections per kilometer.

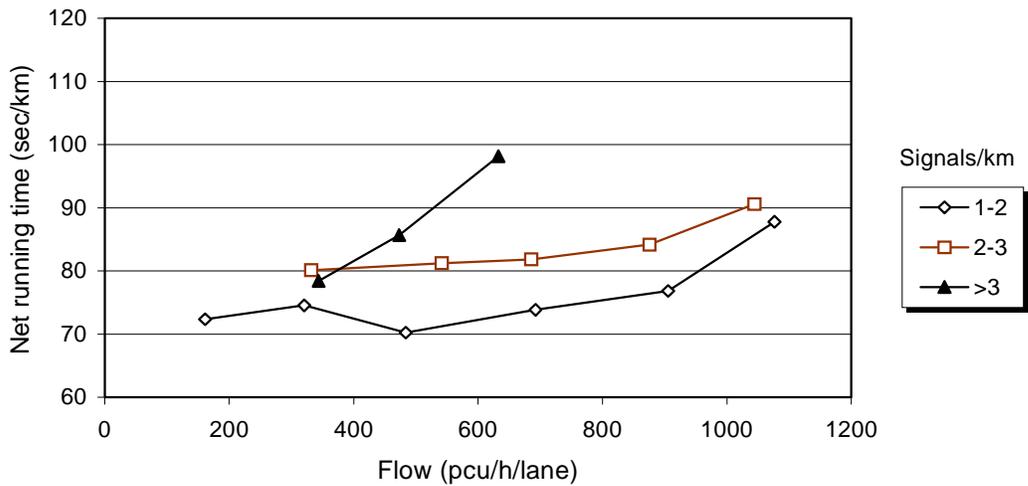
## 5. DISCUSSION

### 5.1 Modelling Approach

It seems that modelling arterial capacity is a complicated process because an arterial is really a system of connected linear elements (links) and barrier elements (signalised intersection approaches). Both the linear elements and barrier elements have their specific speed-flow characteristics which are not the same. While the signalised approach capacity for through traffic flow is relatively well defined, the overall arterial capacity at a mid-block location where through flow combines with turning flows, is more difficult to define and measure.



**FIGURE 3** Observed arterial running time vs. mid-block flow rate.



**FIGURE 4** Estimated net running time vs. mid-block flow rate.

Therefore, attempts to model the arterial speed-flow relationship with a single function are prone to problems and inaccuracies.

Two modelling approaches are possible:

- *Aggregate approach* in which the arterial is treated as one system. A relationship is sought between average performance (travel speed) and average flow. The CTS model is an example of such an approach.
- *Component modelling approach* in which the performance of all the arterial system components (links and intersections) is modelled separately and then averaged. The HCM method is an example of such an approach except that the link performance (running times) is assumed constant.

The modelling approach should be dictated by the expected application of the model. It seems that for planning applications, the aggregate approach (CTS model) is more appropriate whereas the operational analysis should logically be done using the component approach (HCM model). There are several reasons for this. First, the detailed information on signal timing will not be available for planning applications. Second, assuming a single value for cycle time and green time, independent on arterial flow, is conceptually not correct. As traffic flow along an arterial increases and congestion occurs, one is likely to see increased cycle times and green ratios (either through adaptive signal control or through manual signal timing adjustments).

## 5.2 Need for More Precise Definitions

In order to improve model accuracy, it is necessary to use more precise definitions of arterial flow and capacity. A practical problem arises in reconciling measurements of flow and number of lanes at an intersection approach and at a mid-block location. Most arterial intersection approaches are flared, i.e., additional turning and through lanes are added at signals. This can be expressed as a “through lane ratio”  $R_L$ :

$$R_L = N_a / N_m \quad (5)$$

where:  $N_a$  = number of through lanes at a signalised approach,  
 $N_m$  = number of arterial lanes between intersections (mid-block).

Arterial flow measured between intersections includes turning movements whereas HCM analysis involves the through movement only. It may be useful to introduce a “through flow ratio” parameter  $R_q$  to express the ratio of through movement flow at an intersection to flow measured at a mid-block location.

$$R_q = q_a / q_m \quad (6)$$

where:  $q_a$  = approach through flow rate,  
 $q_m$  = mid-block arterial flow rate.

Given these definitions and the fact that signalised approach capacity is normally the limiting factor, the following relationship can be derived between overall arterial capacity and approach capacity:

$$Q_m = Q_a R_L / R_q \quad (7)$$

where:  $Q_m$  = overall (mid-block) arterial capacity per lane,  
 $Q_a$  = approach capacity per lane.

## 5.3 Possible Improvements to the HCM Model

The difficulty of using the present HCM methodology for planning applications has been pointed out by Prassas and McLeod (1999). It seems that an aggregate arterial speed-flow relationship could be developed for typical arterial parameters, based on HCM method.

The main problem with the current HCM method is the lack of linkage between the magnitude of traffic flow and arterial running time. It is understood that such a relationship (suggested by Prassas, 1999) will be incorporated in a future HCM update. It is important to note that in this updated model a consistent definition of running time should be used. If running time is measured as the time when vehicle moves, there is a danger of double-counting the deceleration-acceleration delay in Equation (1). This is because the time lost due to slow movement before and after a stop, although technically part of the running time, is also included in control delay. One way to obtain the net running time from the measured running time would be to subtract 8.6 sec for each stop. This is the average value of deceleration-acceleration delay found by the author in another study (Olszewski 1993). However, this method ignores partial stops, that is cases when vehicles slow down without coming to a full stop.

#### **5.4 Possible Improvements to the CTS Model**

The CTS model has been shown to be able to replicate travel speeds over the range of conditions found in Singapore but its transferability has not been proven. To be useful for planning applications elsewhere, it needs to be calibrated and tested using local data.

Any future study could investigate the effect of new factors such as the through flow ratio and through lane ratio (as defined above). While the inclusion of green split ratio may not be helpful (as its value may change with increased flow), other general parameters reflecting the type of signal control along the arterial, such as the number of phases, could be used.

A practical problem in using the CTS model is the choice of the minimum intersection delay parameter. Its value depends on signal timing and the quality of progression. A recent survey of 5 intersections (Rojas 1999) revealed that the minimum stopped delay varied between 3 and 25 seconds, depending on the duration of green/red periods and the proportion of vehicles arriving during green. The value of minimum delay can be estimated from the standard delay formula using a low value of degree of saturation (say, 5%). The HCM delay formula gave predictions which were close to observations (root-mean-square error of 2.9 sec).

## **6. CONCLUSIONS**

Comparison of the CTS and HCM arterial speed-flow relationships shows that both models predict similar trends in travel speed with respect to changing traffic flow rate, intersection spacing and progression quality. The HCM model generally predicts lower speeds for uncongested traffic. The comparison shows that the aggregate modelling approach which requires very little input information can be useful for planning applications.

Analysis of the Singapore survey data set shows that arterial running time depends both on traffic flow and intersection spacing. More research is needed to model this relationship and to explore possible ways of improving both models. As the number of arterial lanes and traffic flow can be different at mid-block location and at an intersection approach,

care should be taken to use precise definitions of flow and capacity. There is also a potential problem with measuring arterial running time which should be done in such a way as not to double-count the deceleration-acceleration delay.

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