Empirical Method To Estimate the Capacity and Delay of the Minor Street Approach of a Two-Way Stop-Controlled Intersection

MICHAEL KYTE, B. KENT LALL, AND NASEER MAHFOOD

The results of a study of 12 single-lane approach, two-way stop-controlled intersection sites in the Pacific Northwest region of the United States are summarized. Traffic flow rate and delay data were collected for each site, and 15-min averages were prepared yielding a total of 107 data points. A capacity model was developed for the minor street approach proposing that capacity is a function of the flow rates and the speed on the major street. A delay model was developed proposing that delay increases exponentially as reserve capacity decreases. Although the data base assembled here is limited, both models appear promising. The results produced by the models indicate that the empirical model approach for unsignalized intersections may provide an alternative to the gap acceptance method currently used in the *Highway Capacity Manual*.

The standard U.S. procedure for evaluating the operation and performance of a two-way stop-controlled (TWSC) intersection is described in Chapter 10 of the *Highway Capacity Manual* (HCM) (*1*). This procedure is based on a method developed in Germany by Harders (*2,3*) and validated with a limited set of U.S. data (*4*). A number of problems have been identified with this procedure (*5–8*), three of the most important of which are (*a*) incorrect capacity estimates at both low and high ranges of major street flow rates, (*b*) difficulty in the estimation of the critical gap, and (*c*) lack of a useful measure of effectiveness.

The objective of the research described in this paper is to propose and test an empirically based method for the analysis of one set of traffic movements, the minor street approaches, at a TWSC intersection. Three topics are covered in pursuit of this objective: the data base developed for this study, the development of an empirically based capacity model, and the development of an empirically based delay model.

DATA BASE

Description of the Sites

Data were collected at 12 sites in Oregon, Washington, and Idaho over a period of 15 days. A total of 26.75 hr of intersection operations was observed. Each site had several common characteristics: single lanes on each approach and adequate sight distances for each minor street approach. Major street speeds at the sites varied from 25 to 55 mph. A wide range of traffic flows was observed at the sites. Observed major street flows ranged from 176 to 1,412 veh/hr; observed flows on the minor streets ranged from 56 to 732 veh/hr. Minor street delays ranged from 5.7 to 75.8 sec/veh.

M. Kyte and N. Mahfood, University of Idaho, Moscow, Idaho 83843. B. K. Lall, Portland State University, Portland, Oreg. 97203.

Data Collection and Reduction

Videotapes were made so that a permanent record was available of the traffic operations at each site. A field of view was established so that traffic flows could be clearly observed on each intersection approach and so that queue activity would be visible on one minor street approach.

Data were reduced from the videotapes using the Traffic Data Input Program (TDIP) software. A new version of this program (*9*) was written specifically for this study so that the characteristics of TWSC intersections could be directly accounted for.

As each videotape was observed, certain events were noted using the TDIP software. These events included the passage of each vehicle through the intersection and the times that vehicles on the minor street approach arrived at the end of the queue, arrived first in line at the stop line, and departed from the stop line.

Variables in the Data Base

TDIP produces two data files that were used to construct the traffic flow and delay data base. The first file consists of hourly flow rates for each 15-min period for each of the 12 vehicle movements through the intersection. The second file includes average time in queue, average time in service, and total delay for each 15-min period for vehicles on the minor street approach.

Table 1 gives the variables produced for each 15-min period of intersection operation. The data base includes 107 data points for each of the variables listed. The capacity of the minor street approach was calculated using Equation 1. The reserve capacity was calculated using Equation 2. The remainder of the variables in the table were directly available from the TDIP files.

TABLE 1 Data Base Variables

Category	Dimension	Variable	Description
Flow Rate	veh/hr	q_s q_o $q_{c,L,i}$ $q_{c,R,i}$	Subject approach flow rate Opposing approach flow rate Conflicting approach from the left flow rate Conflicting approach from the right flow rate
Capacity	veh/hr	Q_s $Q_{s,res}$	Subject approach capacity Subject approach reserve capacity
Delay	sec/veh	d_t	Subject approach total delay

$$Q_s = \frac{3{,}600}{d_s} \tag{1}$$

$$Q_{s,res} = Q_s - q_s \tag{2}$$

CAPACITY

Gap-Acceptance Method

The procedure used in the HCM for evaluating the operation and performance of TWSC intersections is based on gap acceptance theory developed by Harders (*2,3*). Harders's model for capacity of the minor street approach of a TWSC intersection is given in Equation 3.

$$Q_s = q_c \left(\frac{e^{-\beta}}{e^{\alpha} - 1} \right) \tag{3}$$

In Equation 3,

$$\alpha = \frac{q_c t_f}{3{,}600} \tag{4}$$

and

$$\beta = \frac{q_c t_g}{9{,}000} \tag{5}$$

where t_g is the critical gap and t_f is the follow-up gap.

Brilon (*2*) notes the following limitations for this equation: (*a*) the major street flow is assumed to be random with headways exponentially distributed, (*b*) all drivers have equal and constant critical gap and move-up times, and (*c*) there is a fixed relationship between critical gap and move-up time, namely $t_f = 0.6t_g$.

Figure 1 shows a plot of the minor street capacity as estimated by the HCM as a function of the major street flow for several values of the critical gap. Field measurements taken for this study are also shown. The plot shows that the HCM method tends to overestimate minor street capacity for low conflicting flows (below 600 vph) and underestimates minor street capacity for high conflicting flows (above 600 vph).

UK Empirical Method

The United Kingdom is the only country today that does not use the gap acceptance method for TWSC intersections. Kim-

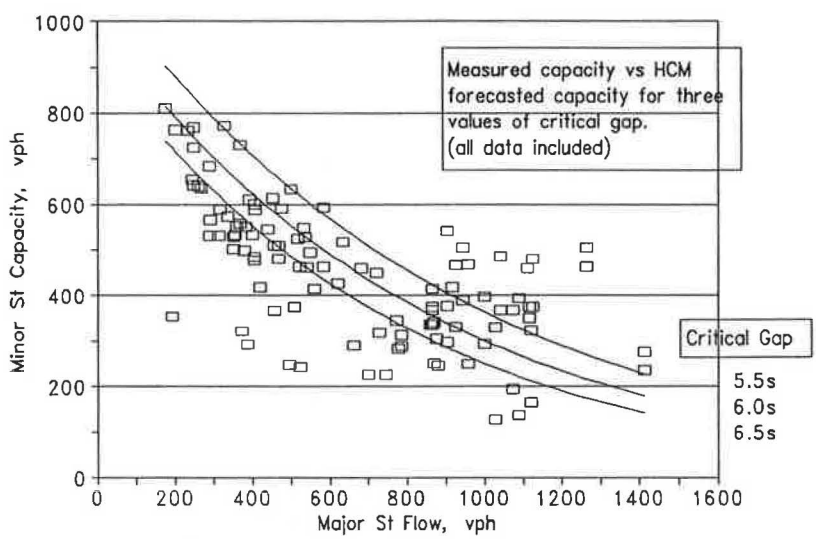


FIGURE 1 Measured capacity versus HCM forecast capacity.

ber and Coombe (*10*), Kimber (*11*), and Semmens (*12*), from the U.K.'s Transport Road Research Laboratory (TRRL), have developed empirically based capacity models based solely on traffic flow rates and site geometry. Kimber identified two potential problems with the gap-acceptance method (*11*, p. 101) that justify the empirical approach.

> Is simple gap acceptance a sufficient description of the vehicle-vehicle interaction process in all common circumstances, and are detailed assumptions of the theory adequate—for example, are the model parameters independent of the magnitude of the priority stream flow.

Kimber also notes that in observation of traffic flow at capacity conditions,

> . . . there were significant periods of priority reversal, during which non-priority vehicles edged into the priority streams, forcing their own gaps. . . . We therefore chose to develop empirical capacity models specified directly in terms of the traffic flows themselves, rather than to assume a priori the completeness of the gap acceptance description. This represents a different level of approach, rather like a thermodynamic description of the properties of a gas as contrasted to a kinetic theory description. (*11*, p. 102)

Kimber and Coombe describe the general equation for the capacity Q of a nonpriority movement:

$$Q = X\left(q_o - \sum_i Y\alpha_i q_i + Z\right) \tag{6}$$

where X, Y, and Z represent functions of the geometric parameters of the intersection.

Effect of Conflicting Flows

The gap acceptance method and the U.K. empirical method agree that the most important factor affecting minor street capacity is the flow rate on the conflicting approaches. This fact presents strong evidence, then, that any model developed here should relate the minor street capacity to the major street or conflicting flow rates. Furthermore, the assertions of Kimber and others from TRRL represent strong motivation to test the empirical method using the data base developed here.

A variety of linear functional forms were investigated using the basic format presented in Equation 7.

$$Q_s = \alpha_1 - \sum_i \alpha_i q_i \tag{7}$$

where q_i is the flow for the ith conflicting movement. Two of the models developed are given in Equations 8 and 9:

$$Q_s = 657.34 - 0.32q_{c,L} - 0.31q_{c,R} \qquad R^2 = 0.44 \tag{8}$$

$$Q_s = 657.44 - 0.31q_c \qquad R^2 = 0.44 \tag{9}$$

Figure 2 shows a plot of both Equation 9 and the actual data for capacity versus the conflicting flow rate.

Examination of Figure 2 shows that the model correctly represents the basic feature of the relationship: minor street capacity decreases as the major street flow increases. The wide dispersion of the data about the linear regression line and the magnitude of the R^2 parameter indicate that the relationship may be nonlinear, different functional forms may be evident for different ranges of conflicting flow rate, and additional variables are required to explain more of the variance.

Effect of Speed

The HCM provides critical gap estimates for two different speed ranges, 30 mph and 55 mph. The differences in the capacity curves for these values indicate at least a theoretical importance of the speed of traffic on the conflicting approaches for the minor street capacity. According to this formulation, the higher the speed, the lower will be the minor

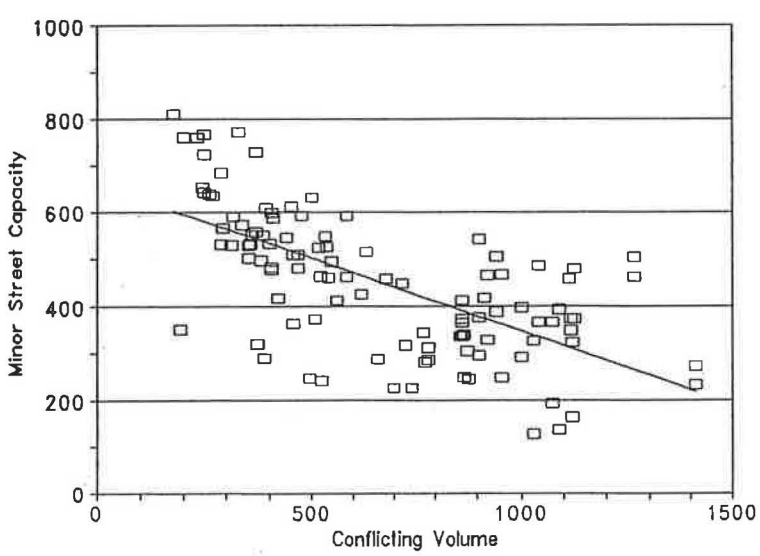


FIGURE 2 Linear capacity model versus measured data.

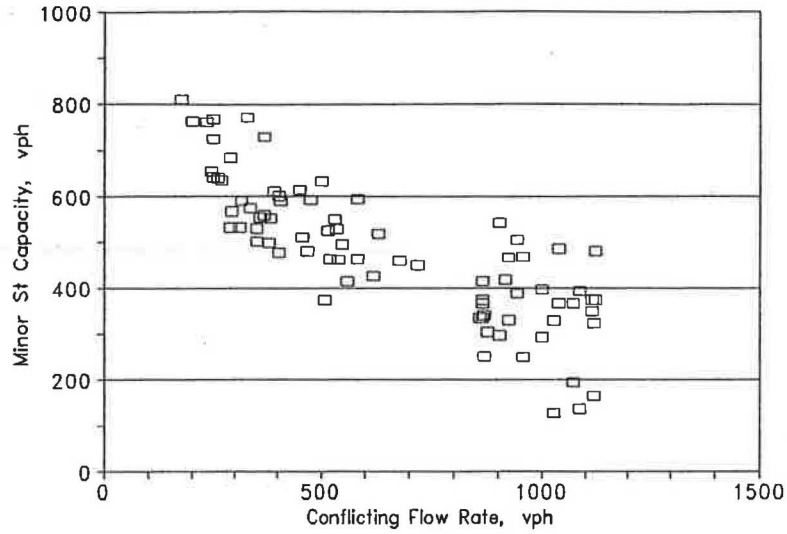
street capacity. This may seem intuitive, since drivers simply need more time to complete their maneuver if they have to make a judgment in higher-speed traffic than in lower-speed traffic.

Figures 3 and 4 show plots of the measured capacity data versus conflicting flow segregated by two speed limit ranges on the major street. Figure 3 includes data in the 25- to 35-mph range, whereas Figure 4 shows data in the 55-mph range.

Multiple regression models were developed to quantitatively determine the effect of major street speed on minor street capacity. The results of this analysis are given in Equations 10 and 11. For the lower speed ranges, typically found on urban arterials (25 to 35 mph), the capacity at low flow rates is about 200 to 250 vph higher than for major streets with higher speeds (55 mph). This difference narrows considerably as the major street flow rates increase. If linear best fit regression lines are drawn through each of these data sets, clear differences in both slope and intercept of the capacity-flow rate relationships appear in these figures. Figure 5 shows a plot of the capacity equation for each speed group.

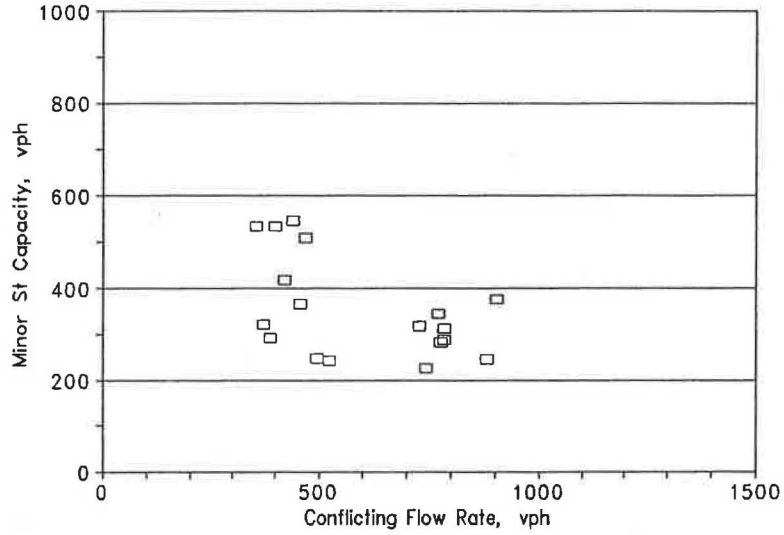
$$Q_s = 740.84 - 0.40q_c \qquad R^2 = 0.68 \tag{10}$$

$$Q_s = 523.99 - 0.29q_c \qquad R^2 = 0.26 \tag{11}$$



Speed Range: 25–35 mph

FIGURE 3 Minor street capacity versus conflicting flow, lower-speed range.



Speed Range: 55 mph

FIGURE 4 Minor street capacity versus conflicting flow, higher-speed range.

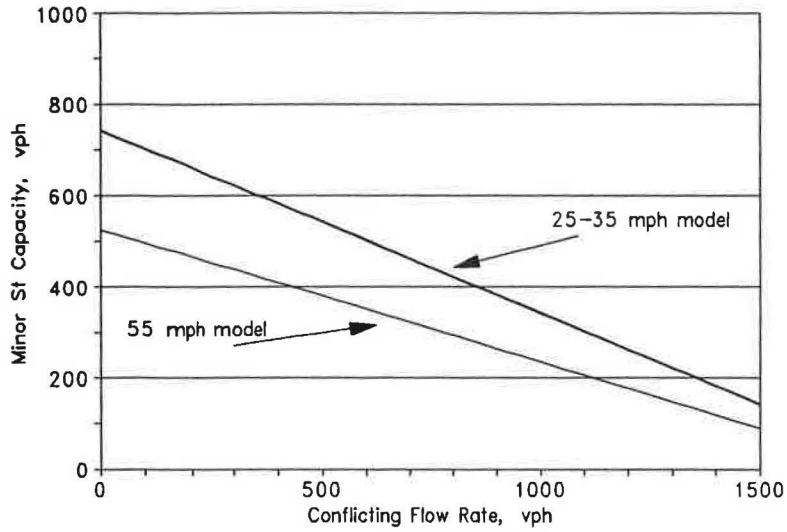


FIGURE 5 Minor street capacity versus conflicting flow, two speed ranges.

Effect of Other Flows

The effects of other flows (i.e., opposing flow and disaggregated conflicting flows) on the minor street capacity were also tested. Three of these models are given in Equations 12, 13, and 14.

$$Q_s = 684.40 - 0.38q_{c,L} - 0.22q_{c,R} - 0.35\,q_o \qquad R^2 = 0.47 \tag{12}$$

$$Q_s = 656.99 - 0.45q_{c,L,LT} - 0.30q_{c,L,TH} - 0.59q_{c,L,RT} - 0.36q_{c,R,LT} - 0.30q_{c,R,RT} \qquad R^2 = 0.42 \tag{13}$$

$$Q_s = 673.64 - 0.50q_{c,L,LT} - 0.27q_{c,L,TH} - 0.45q_{c,L,RT} - 0.31q_{c,R,TH} - 0.41q_o \qquad R^2 = 0.45 \tag{14}$$

Two conclusions can be drawn on the basis of a review of these equations.

1. The models presented in Equations 12, 13, and 14 have R^2 values between 0.4 and 0.5, indicating that improvements in model fit over the models given in Equations 8 through 11 are not gained by disaggregating conflicting flow rates or adding opposing flow rates. This may mean that other factors, such as major street speed or intersection geometry, have a more important effect on capacity than the disaggregated flow variables.
2. Conflicting flows from the left ($q_{c,L}$) have a more significant effect on capacity than conflicting flows from the right ($q_{c,R}$). This is expected, since all minor street movements (left, through, and right) are affected by the conflicting flow from the left, whereas only the left and through minor street movements are affected by the conflicting flow from the right.

Integration of Effects

From the analysis presented, it can be suggested that the capacity of the minor street approach is a function primarily of the conflicting flow rate and the major street speed. Opposing flow rates and disaggregated conflicting flow rates were not shown to significantly improve the capacity model. These factors are now integrated into a recommended capacity model.

The development of the capacity estimation procedure was accomplished incrementally. The steps are summarized below.

Step 1. The data were first segregated according to the speed group of the major street. Two groupings were considered: sites with speeds between 25 and 35 mph and those with speeds between 40 and 55 mph.

Step 2. Figure 6 shows a plot of minor street capacity versus conflicting flow rate for the 25- to 35-mph speed group and for conflicting flows of less than 600 vph. A linear model is fitted through these data, with one additional constraint: the saturation flow rate (when the conflicting and opposing flows are zero), which is just the y-intercept on the curve, is equal to approximately 900 vph. The selection of this constraint can be justified as follows. When the conflicting flow rate is zero, the capacity of the minor street approach is equal to the saturation flow rate of the minor street approach. That is, when there are no vehicles present on the other approaches, vehicles depart from the stop line as rapidly as safety and vehicle performance allow. Whereas this saturation rate has not been measured for TWSC intersections, it has been measured by Kyte (*13*) for all-way stop-controlled intersections. This saturation flow rate is approximately 900 vph.

Step 3. Figure 7 shows a plot of the 25- to 35-mph speed group data for the range of conflicting flows greater than 600 vph. A least squares regression line was fitted through these data.

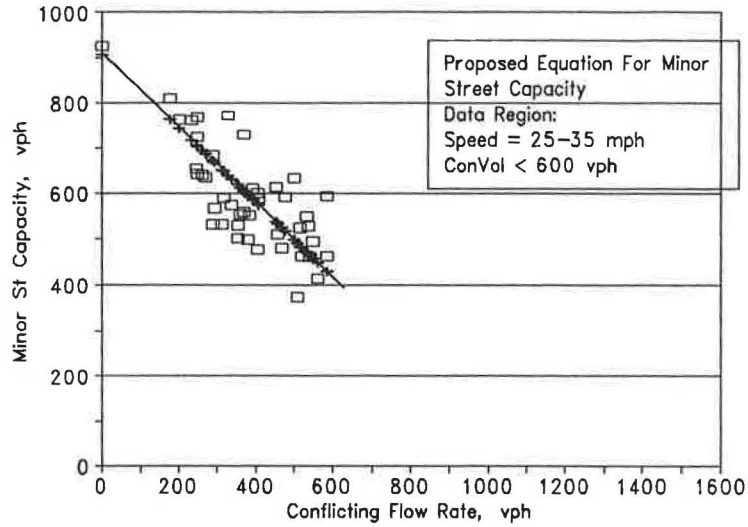


FIGURE 6 Proposed capacity model, lower conflicting flow ranges, lower-speed range.

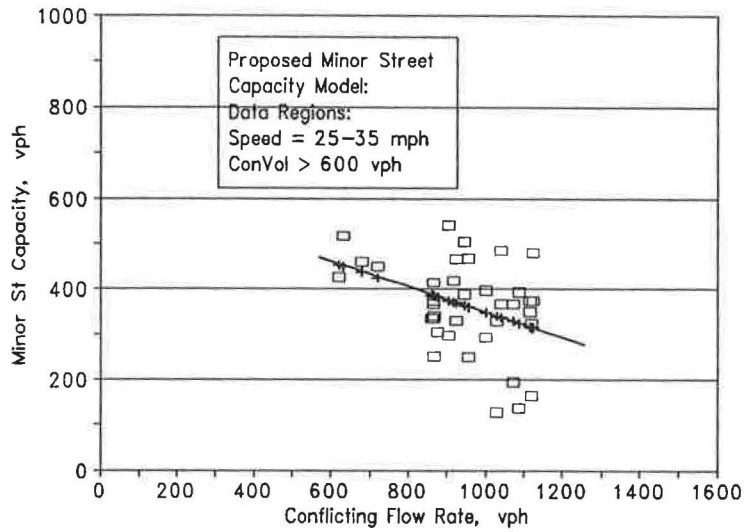


FIGURE 7 Proposed capacity model, higher conflicting flow range, lower-speed range.

Step 4. Figure 8 shows a plot of the 40- to 55-mph data. One equation was fitted through these data and is shown in the figure.

Step 5. Figure 9 shows the three equations together, two for the lower-speed data and one for the higher-speed data. Note, however, that there is an overlap at the higher conflicting flow ranges. To eliminate this overlap, the slopes of the equations were modified slightly; see Figure 10.

Step 6. The final models are shown as Equations 15, 16, and 17.

$$Q_s = 906 - 0.82q_c \quad (15)$$

$$Q_s = 623 - 0.28q_c \quad (16)$$

$$Q_s = 390 - 0.11q_c \quad (17)$$

Comparison of Proposed Method with HCM Procedure

The capacity estimation models proposed here for the two speed groups are compared with the HCM models for similar speed ranges for critical gaps of 6.0 and 7.5 sec, respectively (see Figures 11 and 12).

Figure 11 shows that there is reasonable agreement between the two models for the lower-speed range, with differences of no more than 100 vph, or less than 10 percent. However, the differences are considerable for the higher-speed range, as shown in Figure 12. At lower conflicting flow values, the HCM procedure forecasts capacity values up to 100 percent higher than the new procedures proposed here. The curves intersect at a conflicting flow value of 600 vph; above this value the HCM model forecasts values up to 100 to 150 vph lower than the new procedure.

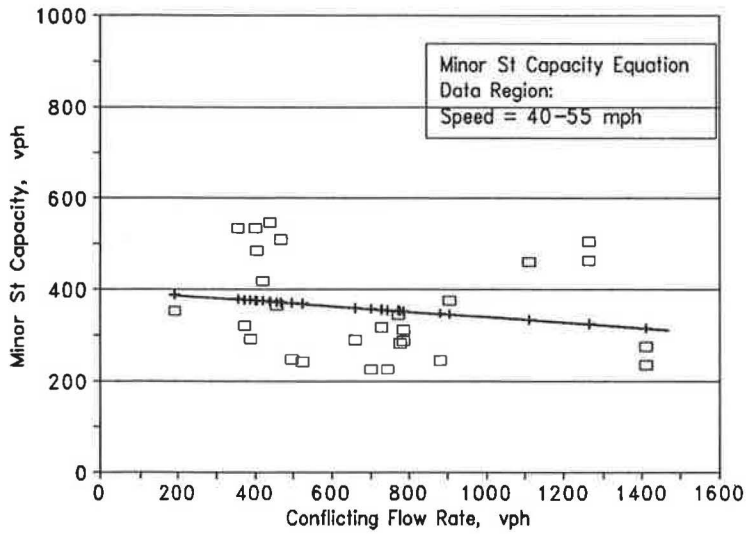


FIGURE 8 Proposed capacity model, higher-speed range.

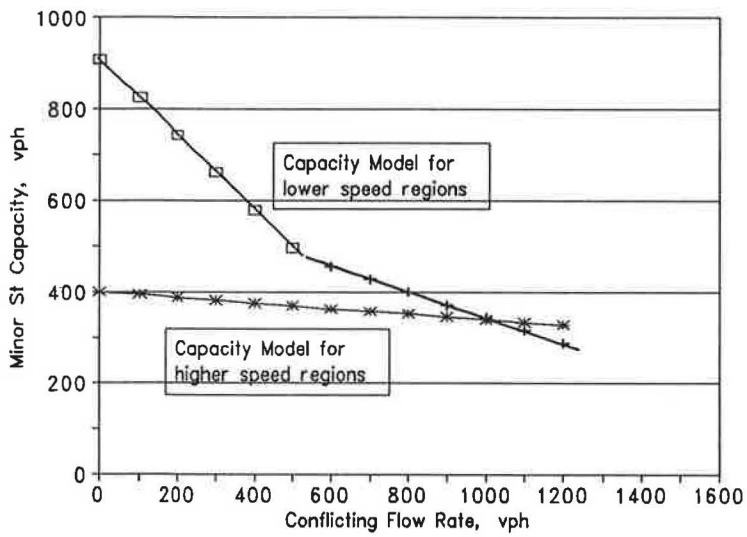


FIGURE 9 Proposed capacity models, preliminary.

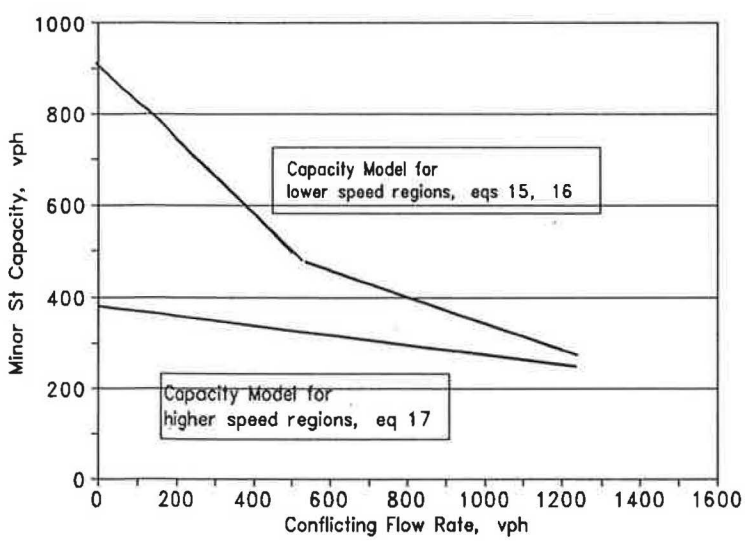


FIGURE 10 Proposed capacity models, final.

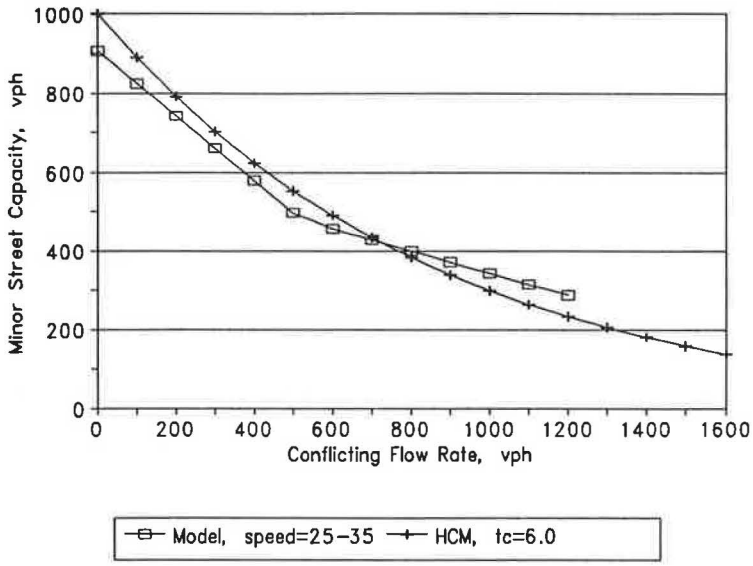


FIGURE 11 Proposed capacity model (lower-speed range) versus HCM model.

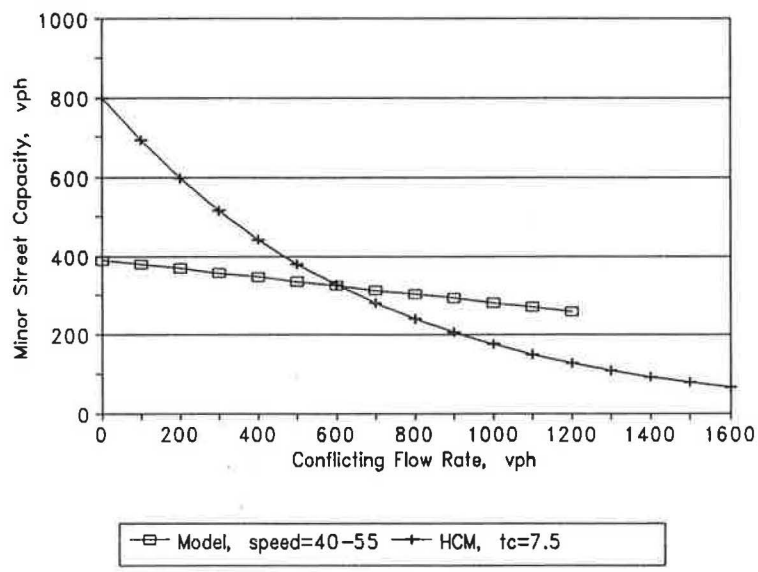


FIGURE 12 Proposed capacity model (higher-speed range) versus HCM model.

DELAY

HCM Method

Reserve capacity is the measure of effectiveness used in the HCM to determine the level of service for a TWSC intersection. Reserve capacity is defined as the unused capacity of a movement, or the difference between the actual capacity for a movement and the flow rate for the movement. The HCM establishes a level of service for each range of reserve capacity and a qualitative description of the delay likely to be experienced (see Table 2).

Reserve capacity, however, has not been a popular parameter with U.S. traffic engineers. It cannot be measured directly in the field, and it is not directly linked with quantifiable delay ranges. Brilon (*2*), however, has shown that reserve capacity is a useful measure and correlates well with the expected delay for a minor street. In fact, reserve capacity is somewhat analogous to the degree of saturation or volume/capacity ratio in that both parameters describe the amount of capacity remaining or available. An example of the relationship of minor street delay to reserve capacity and major street flow is given in Figure 13. The figure is from Brilon (*2*).

Effect of Reserve Capacity

Total delay is the sum of service delay and queue delay. An exponential model relating total delay to reserve capacity was

TABLE 2 Level of Service and Reserve Capacity

Reserve Capacity	Level of Service	Expected Delay to Minor Street Traffic
± 400 vph	A	Little or no delay
300-399 vph	B	Short traffic delays
200-299 vph	C	Average traffic delays
100-199 vph	D	Long traffic delays
0-99 vph	E	Very long traffic delays
< 0	F	-

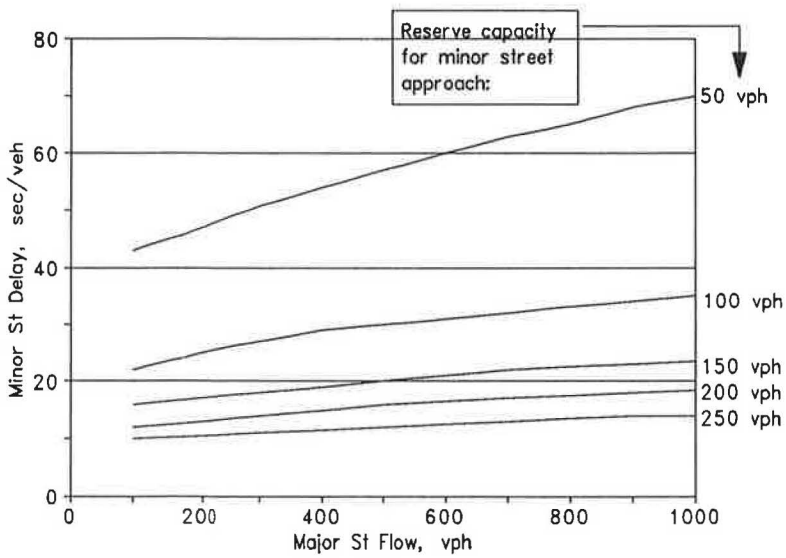


FIGURE 13 Delay as a function of reserve capacity and major street flow, Brilon model.

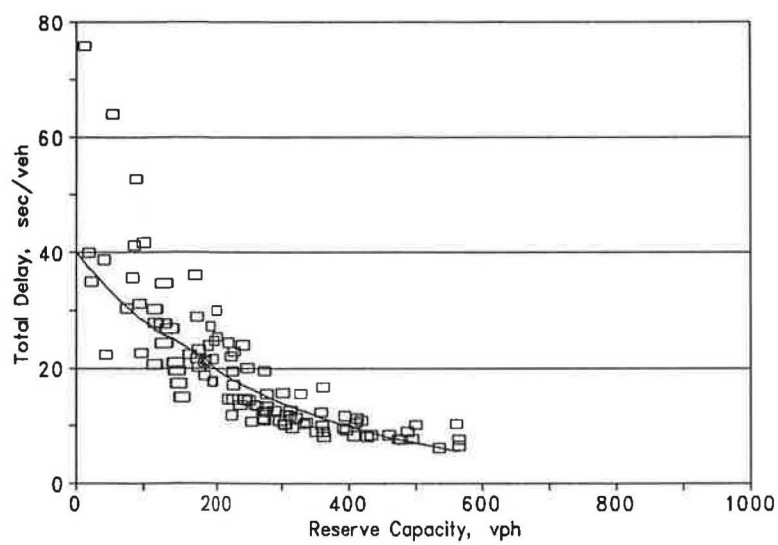


FIGURE 14 Total delay versus reserve capacity.

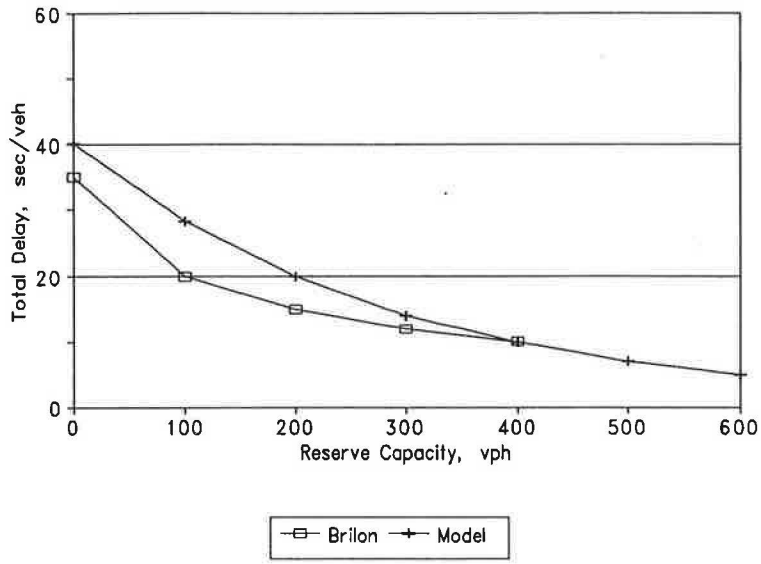


FIGURE 15 Proposed delay model versus Brilon model.

developed and is shown in Equation 18. The plot of Equation 18 is given in Figure 14.

$$d_t = 40.079e^{-0.0035q_{s,rcs}} \qquad R^2 = 0.78 \tag{18}$$

Comparison of Proposed Method with Brilon Model

The proposed delay estimation model is plotted against Brilon's delay model in Figure 15. The Brilon model forecasts somewhat lower delays (in the range of 5 to 10 sec lower) when the reserve capacity is less than 300 vph. The two models nearly coincide for higher values of reserve capacity.

FINDINGS AND CONCLUSIONS

The objective of the research described in this paper is to propose and test empirically based methods to forecast capacity and delay for the minor street approach of a TWSC intersection. This objective has been accomplished. The major findings of this research are summarized as follows.

Data Base

A data base has been assembled from 12 TWSC intersection sites in the Pacific Northwest region of the United States. The data base includes geometric and traffic characteristics from 26.75 hr of intersection operations. The data are summarized over 15-min periods; thus, 107 data points are included in the data base. A video camera was used to film each intersection, and computer software developed for this study was used to enter and reduce the data. Seven traffic variables were produced for each 15-min period of intersection operation: the capacity of the subject approach; flow rates on the subject approach, the opposing approach, and the conflicting approaches; and total delay, service delay, and queue delay on the subject approach.

Proposed Capacity and Delay Models

Proposed methods for estimating capacity and delay are presented. The flow rate on the conflicting approaches is the most important variable affecting capacity on the minor street. The functional form relating minor street capacity to conflicting flow is nonlinear and may depend on the range of conflicting flow rate. The speed on the major street affects the level and slope of the capacity relationship. Delay is affected primarily by reserve capacity. The delay model, an exponential form, provided an excellent fit to the data. The quality of the delay-reserve capacity model provides support to the earlier work of Brilon and others that suggests the importance of the reserve capacity parameter in determining intersection level of service.

Clearly the methods proposed here are only preliminary; both need to be validated with a larger data base. But the results show that the methods may represent a feasible alternative to the gap acceptance approach currently used in the HCM. In short, the empirical approach of directly relating capacity and delay to measured flow rates appears to be feasible and warrants further study.

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