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REPRINT

A comparison of three delay models for sign-controlled intersections

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NOTE:

This paper is related to the intersection analysis methodology used in the SIDRA INTERSECTION software. Since the publication of this paper, many related aspects of the traffic model have been further developed in later versions of SIDRA INTERSECTION. Though some aspects of this paper may be outdated, this reprint is provided as a record of important aspects of the SIDRA INTERSECTION software, and in order to promote software assessment and further research.

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A comparison of three delay models for sign-controlled intersections

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Abstract

Results of an evaluation of three analytical delay models for unsignalised intersections are presented. The delay models studied are the Highway Capacity Manual Chapter 10 (HCM 94) model, the Akçelik - Troutbeck model, and the SIDRA 5 model. These models are applicable to sign-controlled intersections and roundabouts. The evaluation work reported in this paper is for sign-controlled intersections. Each delay model was used with its associated capacity model. The models were compared by means of extensive tests using the microscopic simulation program ModelC for a basic gap-acceptance case. Delays predicted by the current form of each model were first compared against simulated delays. Modified forms of the three models were then calibrated against the simulation data. Generally, the modified models improved delay predictions to a small extent. Overall, the SIDRA and Akçelik-Troutbeck models indicated similar levels of prediction ability whereas the HCM 94 model displayed poor performance. Improved prediction of capacities appeared to give larger levels of improvement in delay prediction. The HCM 97 delay and capacity models gave similar results compared with the HCM 94 models. Similar model comparison work is recommended using real-life data collected at sign-controlled intersections and roundabouts.

1. INTRODUCTION

This paper presents the results of an evaluation of three analytical models for predicting delay at unsignalised intersections. In increasing level of complexity, the delay models studied are:

- the Highway Capacity Manual Chapter 10 (HCM 94) delay model which is based on a simple queuing theory method (TRB 1994);
- Akçelik - Troutbeck model (1991) based on a delay model originally proposed by Troutbeck (1986, 1989) and is derived by an extension of the simple queuing theory method using a minimum delay parameter based on gap-acceptance modelling; and
- the delay model used in the SIDRA 5 package which is based on gap-acceptance, queuing theory and overflow queue methods (Akçelik 1994; Akçelik and Besley 1998; Akçelik and Chung 1994a; Akçelik, Chung and Besley 1998).

These models are applicable to sign-controlled (two-way stop or give-way) intersections and roundabouts. The evaluation work reported in this paper is for sign-controlled intersections.

Each delay model was evaluated as used with its associated capacity model. The three models were compared by means of extensive simulation tests using the microscopic simulation program ModelC for a basic major-minor gap-acceptance case employing the M3A arrival headway distribution model (Akçelik and Chung 1994b).

While all three models are time-dependent, the evaluation was carried out using their steady-state forms in order to be consistent with the simulation methodology. Accordingly, undersaturated entry traffic conditions (degrees of saturation up to 90 per cent) were considered. Delay predictions by published forms of the models were first compared against simulated delays. Modified forms of the three models were considered and each model was then calibrated against the simulation data. Model calibrations were performed using the statistical analysis package SPSS and Microsoft Excel. The prediction abilities of the original and modified forms of the three models formed the basis of model evaluation (Christensen 1997).

All three models have common elements based on queuing theory. The simple queuing theory (HCM 94) model is widely used in the literature for modelling delay at unsignalised intersections (sign-controlled intersections and roundabouts). It is the basis of delay models used in software packages such as ARCADY (Hollis, Semmens and Denniss 1980) and PICADY (Semmens 1980). The Akçelik-Troutbeck model incorporates the minimum delay parameter based on gap-acceptance modelling. It is used in the Australian roundabout guide for predicting delays at roundabouts (AUSTROADS 1993).

The SIDRA model differs from the other two in the use of the *overflow delay* concept as a basis of model structure and a *signal analogy* method for deriving various gap-acceptance relationships. The same model structure is also used for signalised intersections and roundabouts (Akçelik and Besley 1998; Akçelik and Chung 1994a, 1995; Akçelik, Chung and Besley 1997a,b, 1998). The signal analogy concept converts block and unblock periods in the gap acceptance process into equivalent red and green time periods. Unblock periods occur when headway in the major traffic stream is equal or greater than the critical gap while block periods are continuous intervals of no acceptable gaps (Akçelik 1994; Akçelik, Chung and Besley 1998).

The models given in this paper assume zero initial queued demand. The model structure for the more general case with non-zero initial queue given in Akçelik, Chung and Besley (1997a, 1998) is applicable to all models considered here.

The delay considered in this paper is the *stop-line delay* which includes stopped delay, queue move-up delay and the delay associated with decelerating from the approach negotiation speed to zero speed and accelerating back to the exit negotiation speed. It does not include the geometric delay. Refer to Akçelik, Chung and Besley (1998) for a detailed discussion of different delay definitions.

2. LIST OF SYMBOLS

d	=	average stop-line delay per vehicle considering all vehicles queued and unqueued (s) (not including the geometric delay for the purposes of this paper)
d_1, d_2	=	first (non-overflow) and second (overflow) terms of the delay formula (s)
d_{2s}	=	second-term delay predicted by a steady-state model (s)
d_m	=	minimum delay (s) (the value of d at x = 0)
k_d	=	second-term delay parameter
l	=	lost time in the SIDRA capacity and delay models (s)
n_m	=	minimum number of minor stream vehicles that can depart under heavy major stream flow conditions (veh/min)
q_e	=	arrival flow of the entry (minor stream) lane (veh/h)
q_m	=	total arrival flow of the major stream (pcu/s) (sum of flow rates in all lanes of all higher priority conflicting streams adjusted allowing for any heavy vehicle effects)
Q_e	=	entry lane (minor stream) capacity (veh/h)
Q_g	=	basic gap-acceptance capacity (veh/h)
Q_m	=	minimum capacity (veh/h)
s	=	saturation flow rate of the entry lane (veh/h) ($s = 3600/\beta$)
$s\,g$	=	average capacity per cycle (per unblock period) (veh/cycle)
T_f	=	duration of the demand flow (analysis) period (hours)
x	=	degree of saturation of the entry lane (demand flow rate / capacity = q_e / Q_e)
x_o	=	degree of saturation below which the second-term delay is zero ($d_2 = 0$)
y	=	flow ratio of the entry lane (arrival flow/saturation flow = q_e /s)
α	=	critical gap (s)

β	=	follow-up (saturation) headway (s)
λ	=	a parameter in the exponential arrival headway distribution model
Δ	=	minimum arrival (intra-bunch) headway in the major traffic stream (s); Δ_m for the major stream and Δ_e for the minor (entry) stream
φ	=	proportion of free (unbunched) vehicles in the major traffic stream; φ_m for the major stream and φ_e for the minor (entry) stream

3. CAPACITY MODELS

The assessment of the each delay model was performed using the associated capacity model from the relevant publication. The models are given below (see the Notations section for definitions of parameters used in these expressions).

The SIDRA (Akçelik 1994) capacity formula is expressed by:

$$Q_e = \max(Q_g, Q_m) \tag{1a}$$

$$Q_g = \frac{3600\,\varphi_m\,q_m}{\beta}\left(\frac{1}{\lambda} + \beta - l\right) e^{-\lambda(\alpha-\Delta_m)} \tag{1b}$$

$$Q_m = \min(q_e, 60\,n_m) \tag{1c}$$

$$\lambda = \frac{\varphi_m\,q_m}{(1-\Delta_m\,q_m)} \qquad \textit{subject to}\quad q_m \le \frac{0.98}{\Delta_m} \tag{1d}$$

$$l = 0.5\,\beta \tag{1e}$$

The Akçelik - Troutbeck delay model is used with the following capacity formula described by Troutbeck (1986, 1989):

$$Q_e = \frac{3600\varphi_m\,q_m\,e^{-\lambda(\alpha-\Delta_m)}}{1-e^{-\lambda\beta}} \qquad \textit{for } q_m > 0 \tag{2}$$

$$= 3600/\beta \qquad \textit{for } q_m = 0$$

The HCM 94 capacity formula given in Chapter 10 of the US Highway Capacity Manual for two-way stop sign control (TRB 1994) is expressed by:

$$Q_e = \frac{3600}{\beta}\,e^{-q_m(\alpha - 0.5\,\beta)} \tag{3}$$

The HCM 94 capacity formula assumes a simple negative exponential distribution of arrival headways (Akçelik 1994).

Proportion bunched in the major stream (φ_m) and minor (entry) stream (φ_e) are calculated from:

$$\varphi = e^{-b\,\Delta\,q} \tag{4}$$

where appropriate values of parameters b, Δ (Δ_m or Δ_e), and the flow rate q (q_m or q_e) apply.

For comparison purposes, capacity predictions by the three models for the simulation test cases are given in *Table 1* in *Section 5.*

4. DELAY MODELS

All three delay models assessed in this paper, namely the SIDRA, Akçelik-Troutbeck and HCM 94 delay models use the traditional two-term form ($d = d_1 + d_2$), where d_1 and d_2 have different meanings in each model. The models are described below (see the Notations section for definitions of parameters used in these expressions).

The SIDRA delay model can be stated as:

$$d = d_1 + d_2 \tag{5a}$$

$$d_1 = \frac{d_m \left(1 + 0.3 y^{0.20}\right)}{1 - y} \tag{5b}$$

for x > 1.0, set y = $\beta\, Q_e / 3600$

$$d_2 = 900\, T_f \left[x - 1 + \sqrt{(x-1)^2 + \frac{8\, k_d\, (x - x_o)}{Q_e\, T_f}}\right] \qquad \textit{for } x > x_o \tag{5c}$$

$$= 0 \qquad \textit{otherwise}$$

$$x_o = 0.14 (sg)^{0.55} \tag{5d}$$

$$k_d = 0.17\, \varphi_e\, (sg)^{1.40}\, y^{-0.40}\, (d_m Q_e) \tag{5e}$$

$$d_m = \frac{e^{\lambda(\alpha - \Delta_m)}}{\varphi_m\, q_m} - \alpha - \frac{1}{\lambda} + \frac{\lambda\, \Delta_m^2 - 2\Delta_m + 2\Delta_m\, \varphi_m}{2\,(\lambda\, \Delta_m + \varphi_m)} \tag{5f}$$

$$y = \frac{q_e}{s} = \frac{\beta\, q_e}{3600} \tag{5g}$$

$$sg = \frac{1}{\lambda \beta} + 0.5 \tag{5h}$$

The Akçelik-Troutbeck delay model is expressed by:

$$d_1 = d_m \tag{6a}$$

$$d_2 = 900\, T_f \left[x - 1 + \sqrt{(x-1)^2 + \frac{8\, k_d\, x}{Q_e\, T_f}}\right] \tag{6b}$$

$$k_d = \frac{d_m Q_e}{3600} \tag{6c}$$

d_m from *Equation (5f).*

The HCM 94 delay model is expressed by:

$$d_1 = d_m = \frac{3600}{Q_e} \tag{7a}$$

$$d_2 = 900\, T_f \left[x - 1 + \sqrt{(x-1)^2 + \frac{8\, k_d\, x}{Q_e\, T_f}} \right] \tag{7b}$$

$$k_d = 1.0 \tag{7c}$$

The SIDRA and Akçelik-Troutbeck models use Troutbeck (1986, 1989) minimum delay expression (*Equation 5f*). The HCM 94 model implies a simple relationship for minimum delay (*Equation 7a*).

All three models are *time-dependent* delay models. This is determined by the form of the second-term delay (d_2) expression. In fact, the second-term delay (d_2) expressions in the Akçelik-Troutbeck and the HCM 94 models can be seen as special cases of the SIDRA expression where $x_o = 0$ and k_d as given by *Equations (6c) and (7c)*, respectively.

The SIDRA delay model parameters x_o and k_d (*Equations 5d and 5e*) are for sign control. For roundabouts the same expressions are used with different values of constants as follows:

$$x_o = 0.18\, (sg)^{0.60} \tag{8a}$$

$$k_d = 0.20\, \varphi_e\, (sg)^{1.30}\, y^{-0.40}\, (d_m Q_e) \tag{8b}$$

The results given in this paper for the "current SIDRA model" are based on the use of sign-control models (Equations 5d and 5e).

The *steady-state* form of the second-term delay expression is relevant to an analysis (demand flow) period of indefinite (very long) duration. It yields infinite values of delay as demand flow rate approaches the capacity value. For lower degrees of saturation, both the time-dependent and the corresponding steady-state expressions give similar results. The following expression can be used as a general steady-state model for the three models under consideration:

$$d_{2s} = \frac{3600 k_d\, (x - x_o)}{Q_e\, (1 - x)} \qquad \textit{for } x > x_o \tag{9}$$

$$= 0 \qquad \textit{otherwise}$$

For the SIDRA model, x_o and k_d are given by *Equations (5d) and (5e)*. As in the time-dependent expressions for d_2, the Akçelik-Troutbeck and HCM 94 models can be seen as special cases of the SIDRA expression where $x_o = 0$, and k_d is given by *Equations (6c) and (7c)*, respectively.

As a simple example, *Figure 1* shows delay as a function the degree of saturation as predicted by the steady-state and time-dependent forms of the HCM 94 delay model for a case when $Q_e = 600$ veh/h and $T_f = 1$ h. It is seen in *Figure 1* that, as the degree of saturation increases, the steady-state delay curve approaches the vertical line at capacity ($x = 1$) whereas the time-dependent curve approaches a deterministic oversaturation delay line.

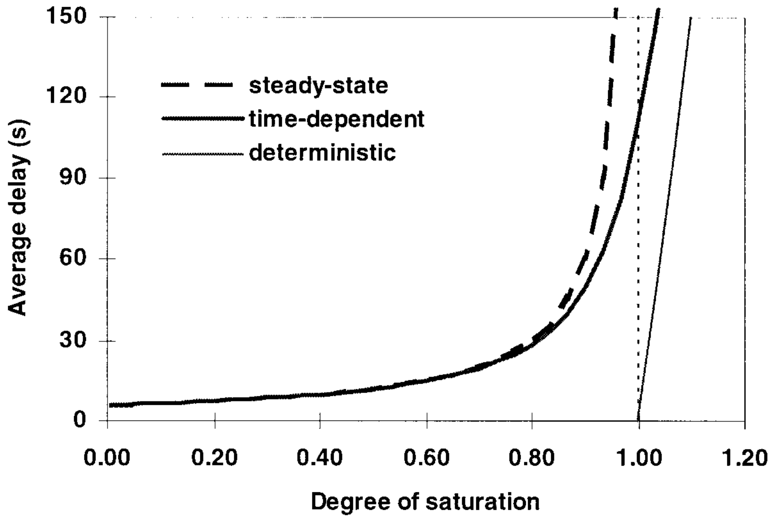

Fig. 1 - Delay as a function of the degree of saturation as predicted by the steady-state and time-dependent forms of the HCM 94 delay model (Q_e = 600 veh/h and T_f = 1 h)

5. MODELC SIMULATION

ModelC (Chung 1993; Chung, Young and Akçelik 1992a,b) is a microscopic (vehicle-by-vehicle) simulation program for the analysis of traffic performance at unsignalised and signalised intersections. It was originally developed for roundabouts, and subsequently extended to simulate simple sign-control and traffic signal control cases (Akçelik and Chung 1994a, 1995).

ModelC is a time-update simulation model, with vehicle movements in individual lanes, based on a car-following model. The conflicts between entering and opposing vehicles (minor and major streams) are resolved by a basic gap-acceptance model as it applies to stop-sign control, give-way sign control and roundabouts. The simulation tests reported in this paper were carried out for a simple gap acceptance (major-minor stream) situation.

The combinations of minor and major stream parameters for the simulation cases used in the evaluation of current models and calibration of modified models are given in *Table 1*. The major traffic stream headway distribution characteristics were specified to represent single-lane and multi-lane cases. In all cases, the minor (entry) traffic stream consisted of one lane, therefore the intra-bunch headway (Δ) and parameter b values for the minor stream was the same as the single lane major stream values in *Table 1*.

Three major stream arrival flow rates were simulated, namely low flow (360 veh/h), medium flow (720 veh/h) and high flow (1080 veh/h). The first two cases in *Table 1* were simulated with low and medium major stream flow rates only due to low capacities. For each major stream flow, five entry flow rates were simulated representing a wide range of degrees of saturation, x = 0.1, 0.3, 0.5, 0.7 and 0.9. The input flow rates to achieve these nominal degrees of saturation were determined by calculating the capacity using the SIDRA capacity formula. The capacities predicted by the three capacity models (*Equations 1, 2 and 3*) are given in *Table 1*. The simulated entry and major stream arrival flow rates, capacities and degrees of saturation differ from the input values.

The duration of the warm-up and main simulation periods were set as 15 and 60 minutes, respectively. The simulation time increment was 0.1 s. Each case was simulated 5 times with different random number streams in order to allow for the effects of random variations. In the analyses, results from individual simulation runs were used directly rather than using an average of the five simulation runs for each case due to problems associated with averaging at higher degrees of saturation. Simulation results were checked carefully and some data were eliminated. Cases that produced degrees of saturation above 0.9 were deleted because steady-state type simulation method does not produce appropriate data for conditions near capacity. After all data elimination, the number of data points used in model evaluation and calibration was 392.

Table 1 - Data for simulation test cases

Minor stream		Major stream				Estimated capacity (veh/h)		
Critical gap, α (s)	Follow up headway, β (s)	Number of lanes	Intra-bunch headway, Δ (s)	Param. b	Flow rate q_m (pcu/h)	SIDRA (Akçelik)	Troutbeck	HCM 94
8.0	4.0	>2	0.5	0.8	360 720	481 245	487 255	494 271
7.0	3.5	>2	0.5	0.8	360 720	596 332	601 342	608 360
6.0	3.5	>2	0.5	0.8	360 720 1080	659 407 242	665 420 257	672 440 287
5.0	3.0	>2	0.5	0.8	360 720 1080	833 561 366	838 575 385	846* 596* 420*
5.0	3.0	1	1.5	0.6	360 720 1080	813 495 250	819 510 269	846* 596* 420*
4.0	2.0	1	1.5	0.6	360 720 1080	1295 859 495	1300 873 515	1333 988 732
3.0	2.0	1	1.5	0.6	360 720 1080	1442 1091 751	1447 1108 781	1474 1207 988

* The HCM 94 model is not sensitive to the number of major stream lanes.

6. PREDICTIONS BY CURRENT DELAY MODELS

Figure 2a shows a comparison of the simulated degrees of saturation with those predicted using the SIDRA (Akçelik) capacity model (*Equation 1*) using the simulated entry and major stream flow rates. Linear trendline and associated statistics indicate very good correspondence between the simulated and predicted values. The degrees of saturation predicted by the Troutbeck model (*Equation 2*) are very similar to the SIDRA predictions. The HCM capacity model (*Equation 3*) generally underestimated degrees of saturation (overestimated capacities) as seen in *Figure 2b.*

Figures 3, 4 and 5 present the graphs of delays predicted by the SIDRA, Akçelik-Troutbeck and HCM 94 delay models plotted against simulated delay values with linear trendlines and associated statistics. The HCM 94 delay model is seen to give poor performance. The SIDRA and Akçelik-Troutbeck models give similar performance.

7. MODIFIED DELAY MODELS

Modified SIDRA model: Several modified forms of the SIDRA delay model were tested and the following form was found to give the best results. For the first delay term:

$$d_l = \frac{d_m \left(1 + a_l \, (sg)^{b_l} \, y^{c_l}\right)}{1 - y} \qquad (10a)$$

$$\text{for } x > 1.0, \text{ set } y = \beta \, Q_e / 3600$$

where a_l, b_l, c_l are calibration parameters, and d_m is the minimum delay given by:

$$d_m = \left(1 - \frac{\beta \, Q_e}{3600}\right) \left(\frac{e^{\lambda(\alpha - \Delta_m)}}{\varphi_m \, q_m} - \frac{1}{\lambda} - \beta + l \right) \qquad (10b)$$

where $l = 0.5 \, \beta$ as in *Equation (1e).*

Equation (10b) will be referred to as the Akçelik minimum delay formula.

For the second delay term (*Equation 5c* applies):

$$x_o = a_2 \, (sg)^{b_2} \qquad (10c)$$

$$k_d = a_3 \, (sg)^{b_3} \, y^{c_3} \qquad (10d)$$

where a_2, b_2, a_3, b_3, c_3 are the calibration parameters.

This model differs from the current SIDRA model in eliminating Troutbeck's minimum delay (d_m) parameter from the second delay term. As such, the model conforms with the general SIDRA model structure more directly. The minimum delay, d_m used in the first delay term is calculated from *Equation (10b)* rather than Troutbeck's formula (*Equation 5f*). The derivation of Akçelik's minimum delay formula is based on the signal analogy concept, and as such conforms with the general SIDRA model structure.

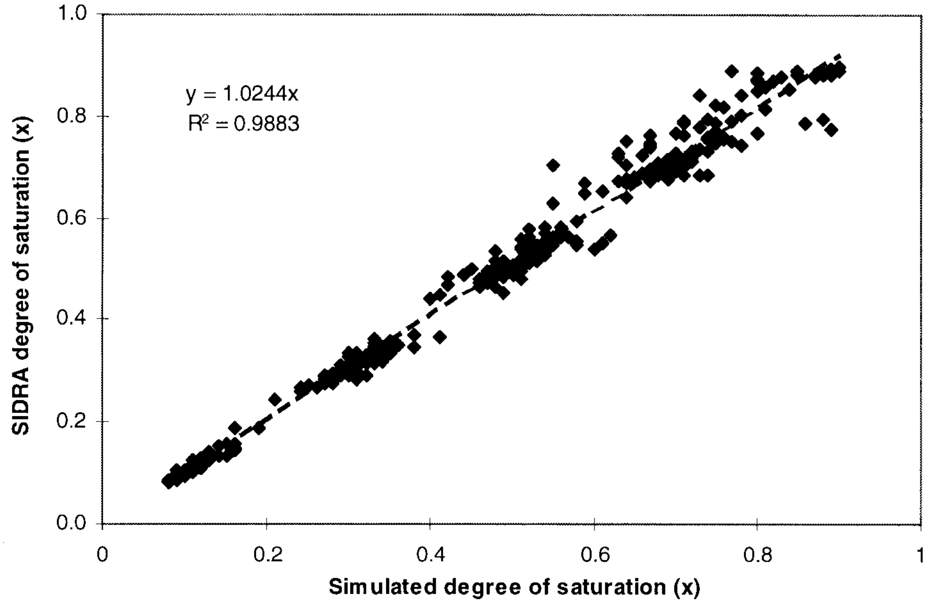

Fig. 2a - Comparison of simulated and predicted (SIDRA) degrees of saturation

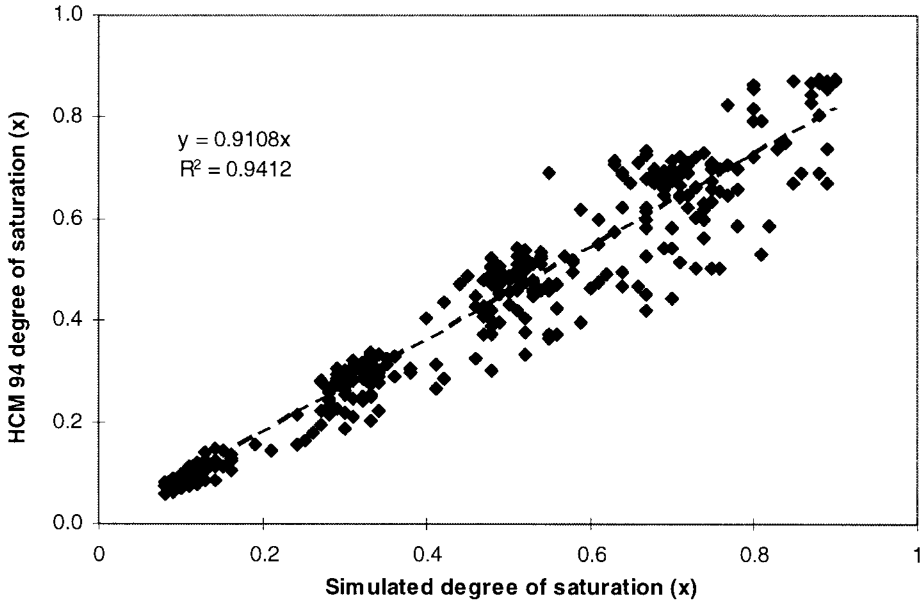

Fig. 2b - Comparison of simulated and predicted (HCM 94) degrees of saturation

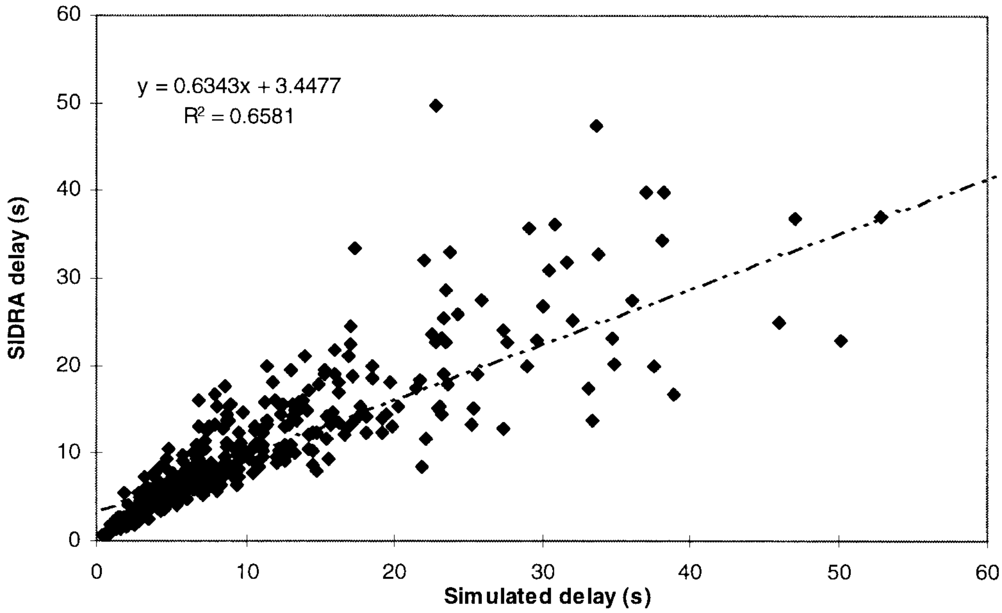

Fig. 3 - Predicted vs simulated delay for the *current SIDRA* delay model using the *SIDRA / Akçelik capacity* model

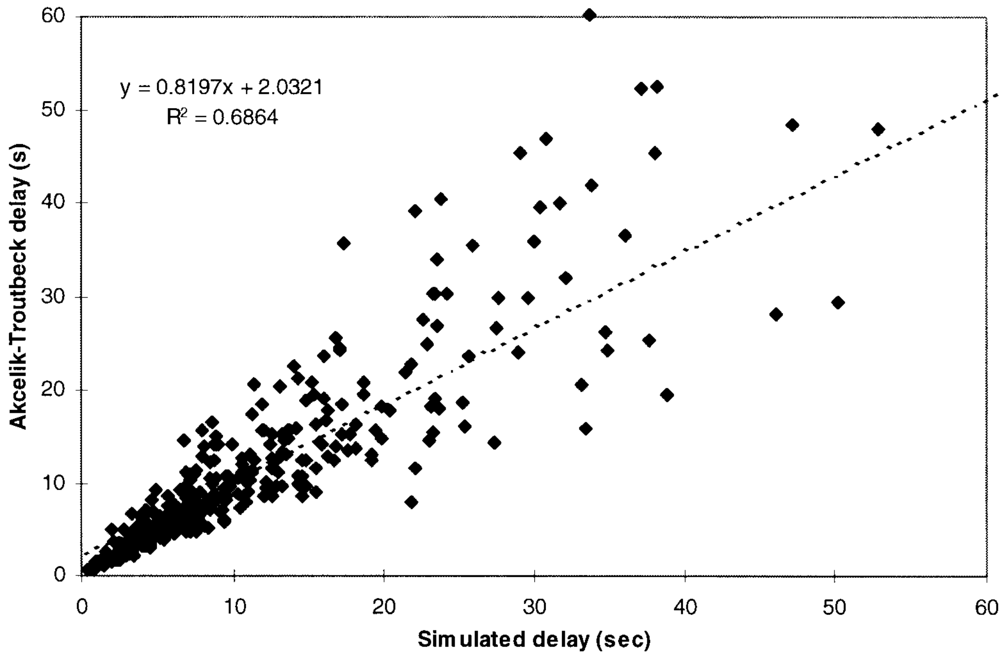

Fig. 4 - Predicted vs simulated delay for the *current Akçelik-Troutbeck* delay model using the *Troutbeck capacity* model

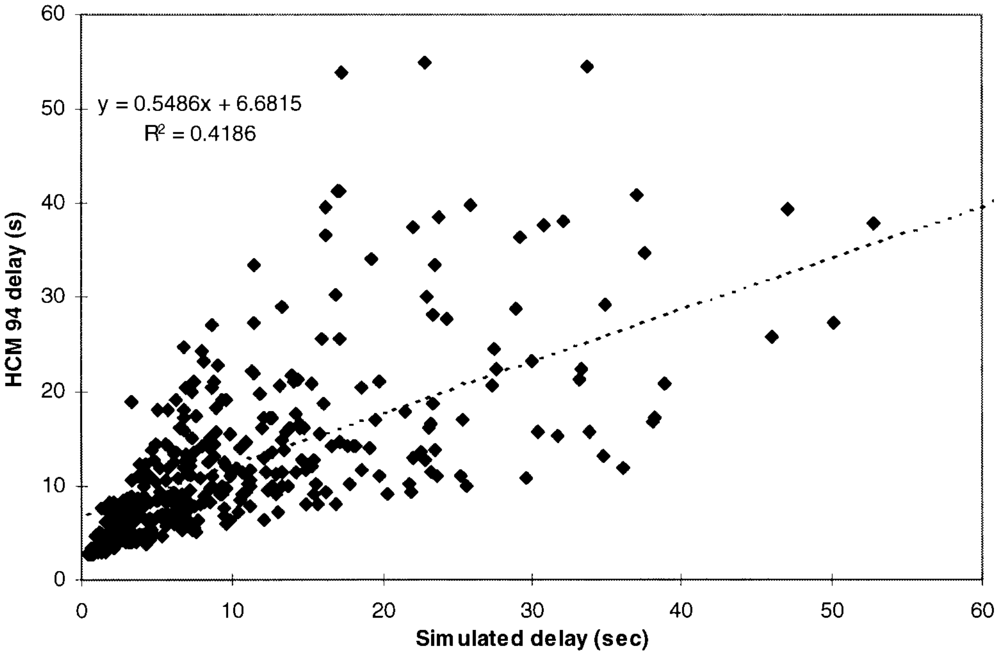

Fig. 5 - Predicted vs simulated delay for the *current HCM 94* delay model using the *HCM 94 capacity* model

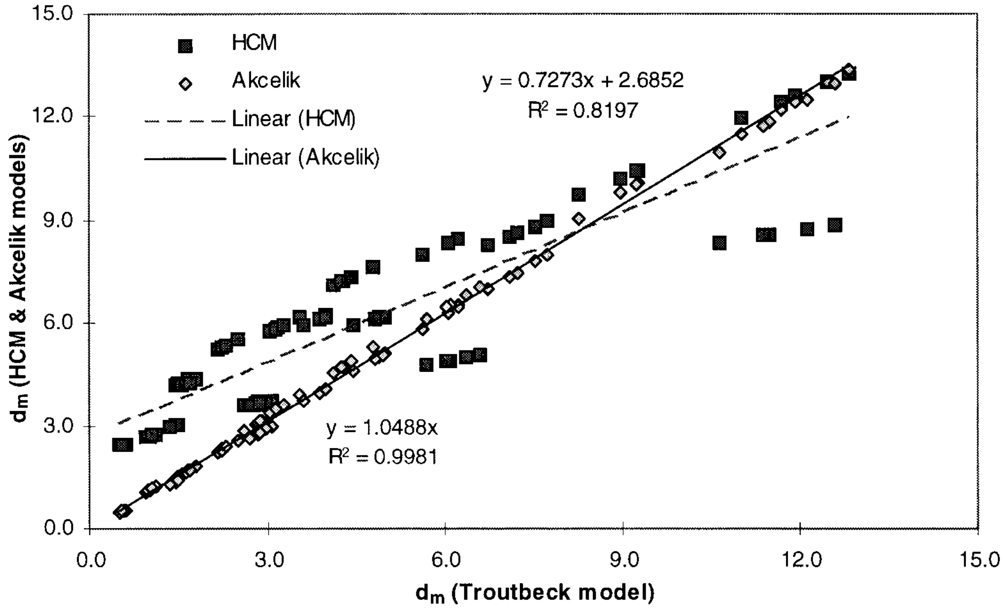

Fig. 6 - Comparison of the minimum delays (seconds) predicted by the Troutbeck model with those by the HCM and Akçelik models

A comparison of minimum delay estimates from the Troutbeck and Akçelik models as well as the HCM minimum delay values (*Equation 7a*) is given in *Figure 6.* The Troutbeck and Akçelik minimum delay predictions are seen to be very close.

Parameter φ_e was also eliminated from the second-term delay expression due to the limited effect it had on regression results.

The ***modified Akçelik-Troutbeck model*** form considered for calibration is as follows:

$$d_l = d_m = a\left[\frac{e^{\lambda(\alpha-\Delta_m)}}{\varphi_m\, q_m} - \alpha - \frac{1}{\lambda} + \frac{\lambda\,\Delta_m^2 - 2\Delta_m + 2\Delta_m\,\varphi_m}{2\,(\lambda\,\Delta_m + \varphi_m)}\right] \quad (11a)$$

$$k_d = b\left(\frac{d_m Q_e}{3600}\right)^c \quad (11b)$$

where a, b and c are the calibration parameters.

The ***modified HCM 94 model*** form considered for calibration is as follows:

$$d_l = d_m = a\,\frac{3600}{Q_e} \quad (12a)$$

$$k_d = b \quad (12b)$$

where a and b are the calibration parameters.

8. CALIBRATION OF MODIFIED DELAY MODELS

The calibrations were performed using the non-linear regression analysis method offered by the statistical analysis package SPSS.

SPSS results were further analysed by means of the trendline facility and visual inspection of graphs in Excel spreadsheets. In some cases, minor manual adjustments were made to the calibration parameters in order to fine-tune the SPSS results. The calibration method is described in detail in Christensen (1997). The calibration results are given below.

Modified SIDRA delay model:

$$a_1 = 0.5 \quad (13a)$$
$$b_1 = -0.4$$
$$c_1 = 0.1$$

$$a_2 = 0.15 \quad (13b)$$
$$b_2 = 0.5$$

$$a_3 = 0.25 \quad (13c)$$
$$b_3 = 0.3$$
$$c_3 = -0.5$$

Figure 7a presents the delay predictions from the modified SIDRA delay model with the above parameter values against the simulated delay values. Comparison of *Figures 3 and 7a* indicates that the modified model offers a small amount of improvement. *Figure 7a* is based on the use of capacities predicted by the SIDRA / Akçelik model (*Equation 1*).

Further improvements to the capacity and delay prediction were obtained when the lost time parameter was calculated from the following formula rather than *Equation (1e)*:

$$l = 0.4 + 0.9\,\beta - 0.35\,\alpha \qquad (13d)$$

Using the lost time from *Equation (13d)* in *Equation (1b)* for capacity and *Equation (10b)* for minimum delay, $R^2 = 0.990$ for degree of saturation (compare with $R^2 = 0.9883$ in *Figure 2a*) and $R^2 = 0.7417$ for delay (compare with $R^2 = 0.7161$ in *Figure 7a*) were obtained.

Improved delay predictions were obtained when the modified SIDRA delay model was used with simulated capacities and slightly different calibration parameters ($a_3 = 0.3$, $b_3 = 0.4$, $c_3 = -0.6$). The results are shown in *Figure 7b*. In this case, comparison of predicted and simulated delays gave $R^2 = 0.8766$. This indicates the importance of accurate capacity prediction for improving the accuracy of delay predictions. Although the capacity predictions by the SIDRA model are very good as seen from *Figure 2a*, delays are sensitive to small differences in capacities, especially at high degrees of saturation.

Modified Akçelik-Troutbeck delay model:

$$\begin{aligned} a &= 1.0 \\ b &= 0.8 \\ c &= 0.6 \end{aligned} \qquad (14)$$

Figure 8 shows the average delays predicted by the modified Akçelik-Troutbeck model plotted against the simulated delays. Comparison of *Figures 4 and 8* indicates that the modified model offers negligible improvement over the original model.

Modified HCM 94 delay model:

$$\begin{aligned} a &= 0.9 \\ b &= 0.7 \end{aligned} \qquad (15)$$

Figure 9a shows the average delays predicted by the modified HCM 94 model (using the HCM 94 capacity model) plotted against the simulated delays. Comparison of *Figures 5 and 9a* indicates that the modified model offers negligible improvement over the original model.

Delay predictions by the modified HCM 94 model was improved substantially when the model was used with capacities predicted by the SIDRA capacity model (*Equation 1b*) as seen in *Figure 9b*. In this case, $R^2 = 0.6568$ was obtained (compare with $R^2 = 0.4388$ in *Figure 9a*). This improvement indicates that performance of the HCM delay model can be improved to a good extent by using a better capacity model.

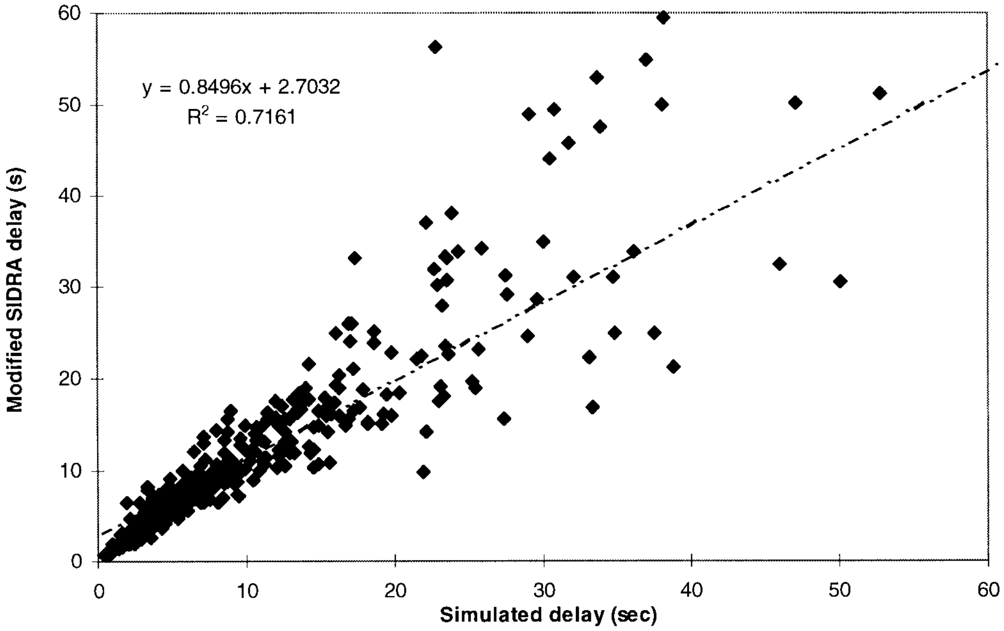

Fig. 7a - Predicted vs simulated delay for the *modified SIDRA* delay model using *SIDRA / Akçelik capacit*y values

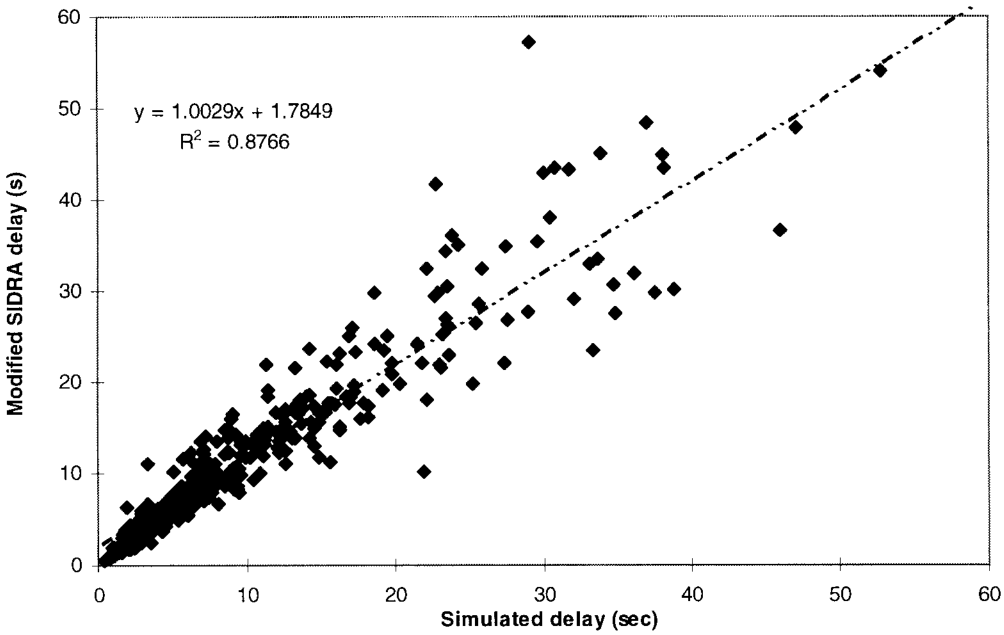

Fig. 7b - Predicted vs simulated delay for the *modified SIDRA* delay model using *simulated capacity* values

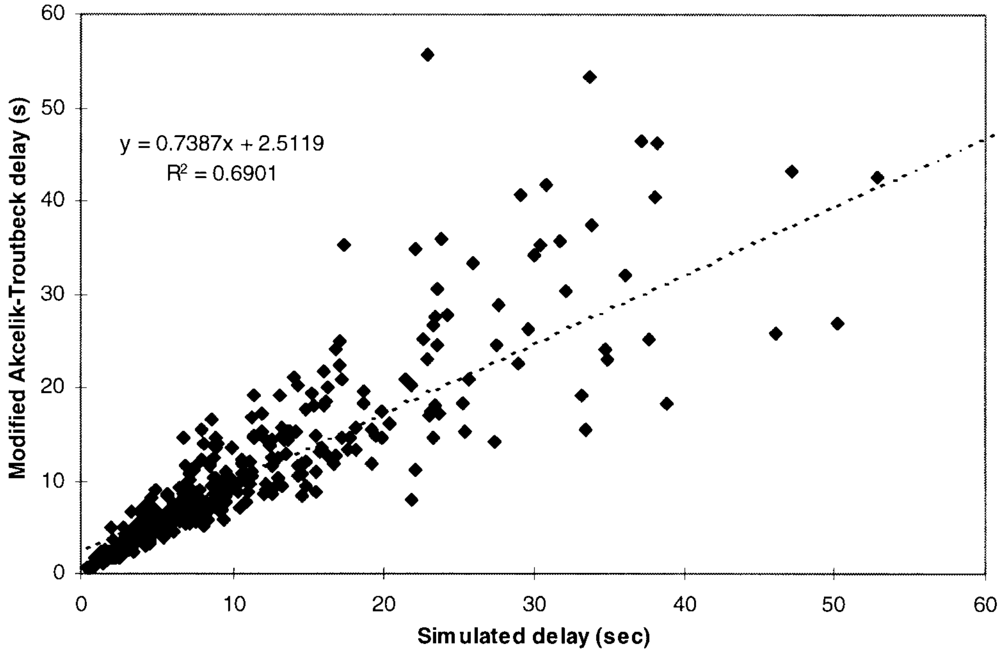

Fig. 8 - Predicted vs simulated delay for the *modified Akçelik-Troutbeck* delay model using the *Troutbeck capacity* model

9. RESULTS FOR THE HCM 97 MODEL

The 1997 version of the Highway Capacity Manual Chapter 10 (HCM 97) retains the HCM 94 delay model for two-way stop sign control but modifies the capacity model (Kyte 1997):

$$Q_e = \frac{3600\, q_m\, e^{-\alpha q_m}}{1 - e^{-\beta q_m}} \tag{16}$$

where q_m is in pcu/s.

This model can be derived from the Troutbeck capacity model (*Equation 2*) assuming a negative exponential distribution model for major stream headways ($\Delta_m = 0$, $\varphi_m = 1.0$, therefore $\lambda = q_m$).

A comparison of the delay predictions by the HCM 97 delay model (same as HCM 94 model) with the simulated delays is shown in *Figure 10.* For major stream flows used in the simulation tests reported in this paper, the predictions by the HCM 97 capacity model (*Equation 16*) are found to be very similar to those by the HCM 94 capacity model (*Equation 3*) as seen in *Figure 11.* As a result, the delay predictions using the HCM 94 and HCM 97 capacity estimates are similar as seen from the comparison of *Figures 5 and 10.*

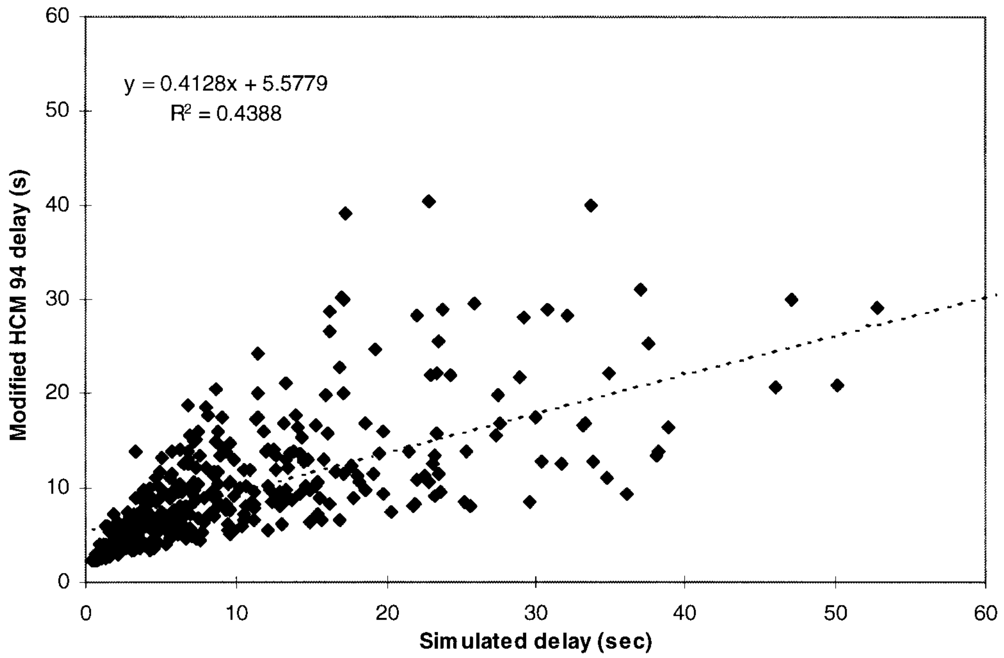

Fig. 9a - Predicted vs simulated delay for the *modified HCM 94* delay model using the *HCM 94 capacity* model

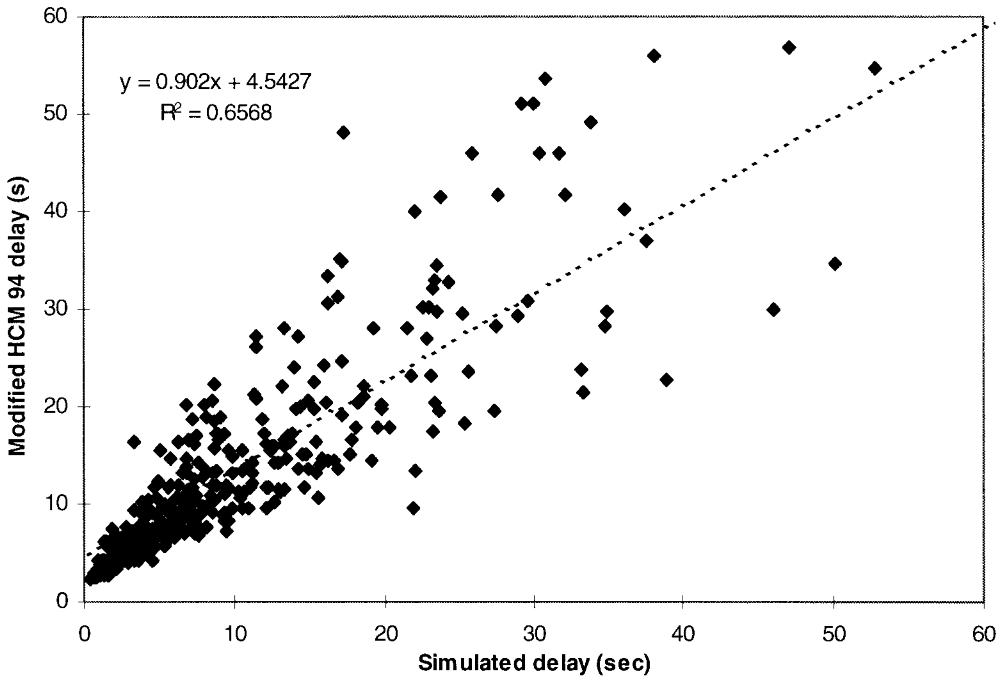

Fig. 9b - Predicted vs simulated delay for the *modified HCM 94* delay model using the *SIDRA / Akçelik capacity* model estimates

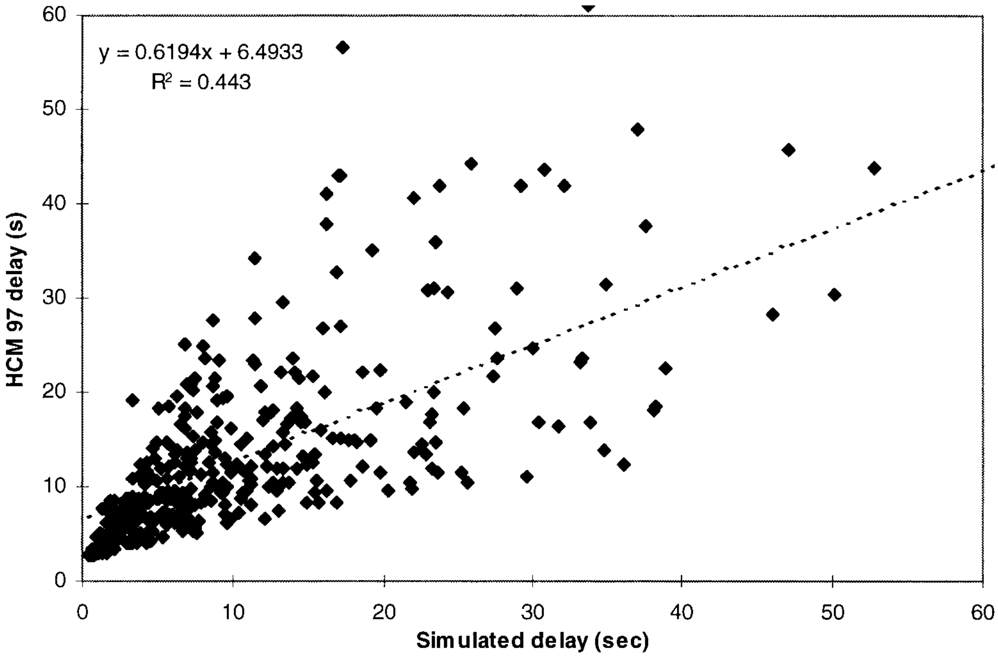

Fig. 10 - Predicted vs simulated delay for the *HCM 94 / 97* delay model using the *HCM 97 capacity* model

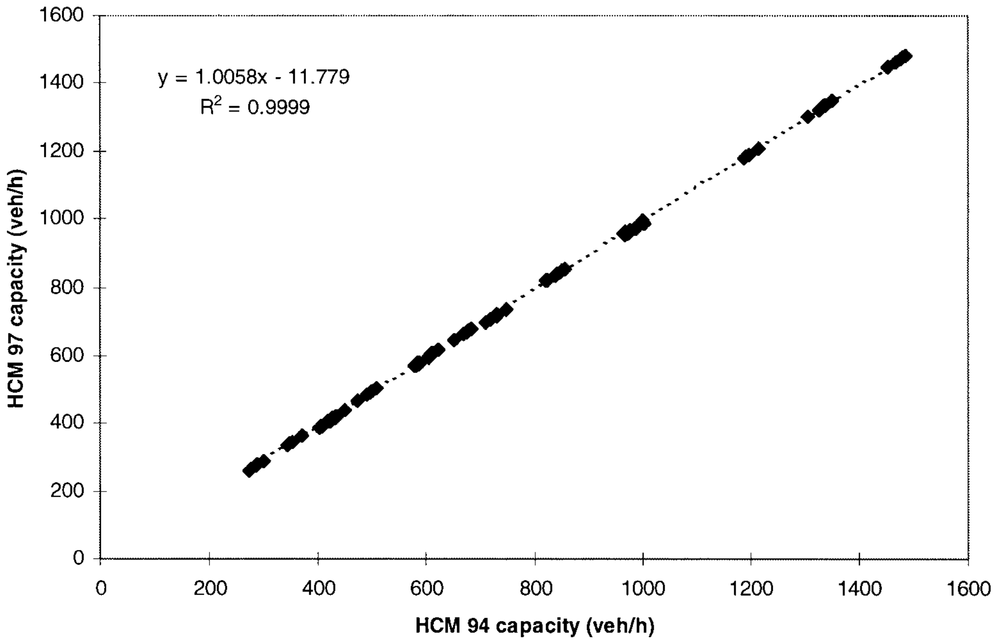

Fig. 11 - Comparison of capacity estimates from *HCM 94 and HCM 97* models

10. CONCLUSION

An evaluation of three existing delay models for unsignalised intersections, namely the SIDRA, Akçelik-Troutbeck and HCM 94 models, has been presented. The models are applicable to sign-controlled (two-way stop or give-way) intersections and roundabouts. The evaluation work reported in this paper is for sign-controlled intersections. Data from ModelC simulation for a basic gap-acceptance situation at a sign controlled intersection were used. Each delay model was evaluated as used with its associated capacity model. Modified forms of the three delay models were calibrated using the same simulation data set.

Generally, the modified models offered small or negligible improvements over the original models. Overall, the SIDRA and Akçelik-Troutbeck models indicated similar levels of prediction ability whereas the HCM 94 (or HCM 97) model displayed poor performance. Improved prediction of capacities appeared to give larger levels of improvement in delay prediction as evident by the improvements obtained when simulated capacities were used to predict delays. In particular, the HCM delay model would benefit from the use of a better capacity model (SIDRA / Akçelik or Troutbeck).

The study presented in this paper supports the delay, capacity and minimum delay formulae developed by Troutbeck using gap-acceptance modelling. It also supports the corresponding formulae developed by Akçelik using a signal analogy concept for gap-acceptance modelling and the well-known overflow concept for delay model formulation. Interestingly, the delay, capacity and minimum delay predictions from the two sets of formulae are very close, with slightly better delay predictions from the modified SIDRA model.

While the Akçelik-Troutbeck delay model has fewer parameters than the SIDRA delay model, an important advantage of the SIDRA model is its consistency with models for *back of queue* and *stop rates* at both unsignalised and signalised intersections. Work was also undertaken to study modified forms of the current SIDRA model for back of queue prediction. The findings were similar to the SIDRA delay model evaluation (Christensen 1997).

This paper has presented simulation results for a basic gap-acceptance process with a single opposing movement (major street through traffic) at two-way sign control assuming known follow-up headway and critical gap values. Applicability of results to roundabouts is limited since both the capacity and delay models for roundabouts have differences in various parameter values, and simulation of complicated interactions among approach flows is needed for roundabouts.

Real-life situations where the basic gap acceptance process with a single opposing movement at a sign-controlled intersection is relevant include the following (assuming driving on the right-hand side of the road as in the USA and Europe):

(i) right turning traffic from minor street at 3-way or 4-way intersections when there is no effect of the adjacent exit flow,

(ii) left-turning traffic from major street when the opposing right-turn movement is controlled by give-way (yield) or stop sign, and

(iii) left-turning traffic from minor street after moving into the median storage area of a 3-way intersection (where two-stage crossing is possible).

In terms of HCM 94, these are Rank 2 movements with a single opposing movement.

Evaluation of alternative delay and capacity models as reported in this paper is recommended for more complicated gap-acceptance situations with multiple opposing movements at sign-controlled intersections and with approach flow interactions at roundabouts.

Importantly, it is recommended that the current and modified forms of the three delay models considered here are tested against real-life delay data (rather than simulation) collected at sign-controlled intersections and roundabouts.

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