

# A DISCHARGE CAPACITY FORMULA FOR PRIORITY T-INTERSECTION AND ITS APPLICATION TO MACROSCOPIC SIMULATION OF URBAN NETWORKS

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The current practice in macroscopic simulation of urban networks is to treat minor road discharge at priority T-intersection as arrivals at the junction. Present capacity formulas do not explicitly consider type of control, i.e. stop or yield sign. This study is composed of three parts. The first part deals with the development of a priority intersection capacity formula that is sensitive to control type. The second part discusses the application of the developed capacity formula into a macroscopic simulation model. Finally, in order to deal with the yield-controlled movement to approximate stop control operation, the capacity formula was further modified assuming a linear shift of operational discipline from yield to stop control.

*Key Words* : priority intersection, discharge capacity, macroscopic simulation, urban network

## 1. INTRODUCTION

Application of macroscopic model to urban networks has been gaining interest due to the simplicity of modeling<sup>1),2),3)</sup> and computational efficiency. A difficulty in the modeling of an urban network lies in its inherent nature to describe the traffic movements at an intersection, in particular at an unsignalized intersection. Macroscopic traffic flow models assume a homogeneous traffic stream; thereby, traffic behavior that is primarily governed by inter-vehicle interactions is somewhat complex to describe. For example, MAKSIGRA<sup>1)</sup> does not pay any special consideration to traffic phenomena at unsignalized intersections.

Typical priority intersections are T-intersections with minor and major roads, where the traffic on minor road is controlled by either stop or yield sign. In macroscopic simulation models, priority T-intersections are usually not considered and the traffic flows are simply taken as the arrival/departure volume at the end of link or within the link. For a large urban network with a lot of priority T-intersections, such as in Bangkok, where a unique road network system based on U-turn

control at medians and priority control at T-intersections is widely adopted, traffic simulations would be unrealistic not to consider their effects on the network's over-all performance. Queuing at minor roads could not be accounted for and would result in underestimation of delay without consideration to the allowable discharge or capacity.

The important aspect in macroscopic simulation of priority intersections is the capacity formula used. Michalopoulos<sup>2)</sup> proposed to determine the discharge rate of a minor road at priority T-intersections as the minimum of arrival and capacity to account for queuing. At present, capacity formulas for priority intersections like those developed by Tanner<sup>4)</sup>, Plank<sup>5)</sup>, Plank and Catchpole<sup>6)</sup>, Major and Buckley<sup>7)</sup>, Al-Masaeid<sup>8)</sup> abound. However, these capacity formulas do not consider the effect of control type, either stop or yield.

The *Highway Capacity Manual*<sup>9), 10), 11), 12)</sup> (HCM) provides the comprehensive knowledge for estimating the capacity of unsignalized intersection. The knowledge behind the procedures has greatly advanced for the last decade<sup>13), 14)</sup>. However, no parameters for yield control have been presented in each version except for the critical gap in the 1985

version<sup>9</sup>). Even the latest HCM<sup>12</sup>) provides neither a detailed method nor parameters for yield sign control. It just suggests the applicability to yield-controlled intersections with appropriate change in the values of key parameters.

The fundament concept of the HCM capacity formula for unsignalized intersections is to treat the critical gap and follow-up time as a constant. However, such constant critical gap and follow-up time cannot deal with the substantial shift of operation from yield control to stop control under heavy traffic conditions as discussed below.

This study is organized into three parts. The first part introduces a new discharge capacity formula, which is sensitive to the difference of type of control, either stop sign or yield sign. The capacity formula is based on a fluid approximation of the gap acceptance mechanism. A parameter was integrated into the formula to account for the type of control. The parameter was then calibrated and validated using actual data from stop/yield signed T-intersection and empirical data from yield-controlled T-intersection. The developed capacity formula was compared with the one of the 1994 HCM to emphasize the effect of control type. The second part is the application of the developed capacity formula in macroscopic simulation of urban networks. The capacity formula was integrated into a macroscopic traffic simulation model developed to analyze the traffic capacity at priority T-intersections. The traffic data generated by a simulation program, TRAF-NETSIM, validated that the macroscopic model was able to simulate minor road discharge in both stop and yield control priority T-intersection with reasonable accuracy. Finally, in order to deal with the tendency of yield control operation to approximate stop control operation when traffic conditions mandate a high percentage of stoppage, the capacity formula was further modified assuming a linear shift of operational discipline from yield to stop control.

## 2. GAP ACCEPTANCE MODELING

Gap acceptance models are used to formulate the capacity of a priority intersection. They assume that an infinite queue of vehicles exists at a non-priority or minor road, intending to merge into a priority or major road. The lead vehicle on non-priority road will merge into the major stream by waiting at the stop line for an acceptable gap between succeeding vehicles on priority road. Once the gap is greater than a certain critical gap, the lead vehicle on minor road leaves from the stop line to merge into the priority stream. The next non-priority vehicle will then follow up the queue and reach stop line at the instant the lead vehicle fully discharges from the

minor road. Thus, there will always be a minor road vehicle waiting at the head of the minor road queue. The capacity of a single stream of minor vehicles has been so far studied by various researchers<sup>4),5),6),7),8)</sup>. There are two approaches to derive capacity formula for priority intersections: The first one is a discrete approach and the other is a fluid or continuous analogue approach.

### (1) Discrete Approach

In the discrete gap-acceptance modeling, as reviewed by Plank<sup>5)</sup> and Plank and Catchpole<sup>6)</sup>, given a headway,  $h$ , that will allow,  $n$ , number of vehicles to merge into the major stream, the following expression can be formulated:

$$g + (n - 1)M \leq h \leq g + nM \quad (1)$$

where  $M$  is the follow-up time which is taken to be constant and assumed to be equal to the reciprocal of the saturation discharge flow rate of the minor road and  $g$  is critical gap. The probability that exactly  $n$  vehicles can merge into the major stream can then be given by:

$$\Pr[n] = F_h(g + nM) - F_h(g + (n - 1)M) \quad (2)$$

where  $F_h$  is the probability distribution function of major road headways,  $h$ . Assuming the headways at the major road to be a negative exponential distribution (M1), the discharge rate on minor road,  $cap_D$ , is formulated as

$$cap_D = \frac{\lambda \exp(-\lambda g)}{1 - \exp(-\lambda M)} \quad (3)$$

where  $\lambda$  is traffic flow at the major road<sup>7)</sup>. Assuming a more realistic headway assumption, the Tanner-type regular-random distribution (M3T), which accounts for the bunching effect of traffic, the discrete capacity formula reduces to the Tanner's capacity formula<sup>4)</sup>:

$$cap_D = \frac{\lambda(1 - \lambda\Delta) \exp[-\lambda(g - \Delta)]}{1 - \exp(-\lambda M)} \quad (4)$$

where  $\Delta$  is the minimum allowable headway at the major traffic stream. However, the formulations of the capacity formula using the discrete approach required complex mathematical modifications to characterize the type of control at priority T-intersections.

## (2) Fluid Approximation

Plank<sup>5</sup> proposed a continuous analogue of the discrete gap acceptance modeling in the priority intersection capacity problem. In the fluid approximation approach, it is assumed that queued vehicles at the non-priority road behave like a fluid merging into the priority stream. Headways,  $h$ , at the priority road greater than an assumed constant critical gap,  $g$ , can then be thought of as a series of time intervals, which the fluid traffic stream at the non-priority road may discharge. The discharge capacity,  $cap$ , can thus be expressed as the proportion of time that the priority stream is non-blocking, i.e.  $h > g$ , times the saturation discharge flow rate. The capacity of a priority intersection can be formulated as

$$cap = Pr[h > g] \times \text{saturation discharge flow rate} \\ = [1 - F_h(g)] \times 3600/M \quad (5)$$

where  $M$  is the follow-up time. Assuming an M1 and M3T headway distribution at the major stream, Eq. (5) simplifies to the capacity formulas of Eqs. (6) and (7).

$$cap_F = \frac{3600}{M} \exp(-\lambda g) \quad (6)$$

$$cap_F = \frac{3600}{M} (1 - \lambda \Delta) \exp(-\lambda(g - \Delta)) \quad (7)$$

## (3) Highway Capacity Manual Approach

The *Highway Capacity Manual* (HCM) defines the discharge rate of minor traffic stream at unsignalized intersections as the potential capacity. The method is originated in Germany<sup>15,16</sup>. The 1994 HCM employed Siegloch's<sup>15</sup> formula:

$$cap = (3600/M) \times \exp\left(-\lambda\left(g - \frac{M}{2}\right)\right) \quad (8)$$

Eq. (8) is valid only for  $g$  and  $M$  being constant and the headway on a major stream being exponentially distributed. The latest HCM 2000<sup>12</sup> adopts a formula similar to Eq. (3):

$$cap = \frac{v_c \exp\left(-\frac{v_c g}{3600}\right)}{1 - \exp\left(-\frac{v_c M}{3600}\right)} \quad (9)$$

where  $v_c$  is the conflicting flow rate on major road. The critical gap and follow-up time are adjusted to account for geometric and traffic conditions, such as grade, the number of lanes, proportion of heavy vehicles, and vehicle movement. The potential

capacity thus computed is further adjusted to consider the impedance by higher-priority vehicle movements, pedestrians, and so on. However, the control type is not taken into account in these procedures. Recently, Weitner<sup>17</sup> analyzed the influence of control type on critical gap and follow-up time based on the measurement data at 30 rural intersections in Germany.

## 3. DISCHARGE FORMULA WITH TYPE OF CONTROL PARAMETER

Traffic behavior at a priority T-intersection controlled by stop sign is different from the one controlled by yield sign. In the fluid model, the drivers are assumed to start to merge into the major stream at the instant the on-coming major vehicle passes the intersection. Drivers, however, have the tendency to anticipate the on-coming acceptable gap and would start discharging before the actual passage of the on-coming major vehicle. Thus, as illustrated by Plank<sup>5</sup>, the fluid approximation model underestimates capacity on both the M1 and M3T headway distribution assumption. Nonetheless, the simple formulation of the fluid approximation makes it a preferred approach to the formulation of a capacity formula that deals with the type of control used. Thus, the fluid model was adapted here.

As an improvement of the fluid approximation of the gap acceptance model, a time,  $\sigma$ , is integrated into the formulation to describe how fast non-priority drivers prematurely depart from the stop line, assuming that they enter the major stream as promptly as possibly allowed by the intersection control. From the fluid approximation approach in Fig. 1, the non-priority vehicle is assumed to behave as a fluid entering the priority stream when the gap at the major road allows for movement, i.e.  $gap > critical\ gap$ . Further assuming that drivers anticipate the next acceptable on-coming gap, the utilized time,  $u$ , used for discharging by non-priority vehicles, can be formulated as

$$u = h + \sigma - g = h - (g - \sigma) \quad (10)$$

where  $\sigma$  is the time which the lead minor vehicle starts to discharge before the actual passage of the major vehicle in anticipation of the on-coming gap. In the original fluid approximation formula,  $\sigma$  is taken as zero. Here  $\sigma$  is regarded as greater than zero and is dependent on the type of control at the intersection. Moreover, it is evident from Fig. 1 that  $\sigma$  is minimum at zero and maximum at follow-up time,  $M$ . Thus,  $\sigma$  can be expressed as  $\kappa M$ , at which  $\kappa$  is a constant parameter

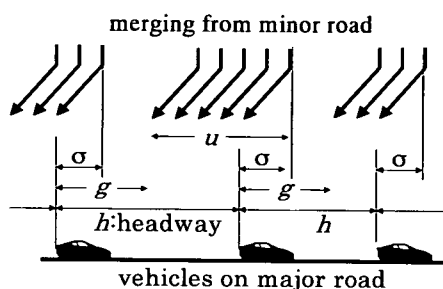


Fig. 1 Fluid approximation of gap-acceptance modeling.

between zero and one. Thus, the proportion of time utilized by the minor road stream for discharging is

$$u/h = [h - g + \kappa M]H(h - g + \kappa M) \quad (11)$$

where  $H(h)$  is a step function integrated into the numerator to prevent the expression from becoming negative. Defining the mean proportion of time utilized by non-priority road vehicles for movement or discharging, the capacity of a priority intersection can be formulated as

$$cap = E[(h - (g - \kappa M))H(h - (g - \kappa M))]/E[h] \times \frac{3600}{M} \quad (12)$$

Assuming the M1 and M3T headway distributions on major roads, Eq. (12) simplifies to

$$cap = \left(\frac{3600}{M}\right) \times \exp(-\lambda(g - \kappa M)) \quad (13)$$

$$cap = \frac{3600}{M} (1 - \lambda \Delta) \exp(-\lambda(g - \kappa M - \Delta)) \quad (14)$$

The  $\kappa$ -parameter in the capacity formulas indicates the degree of how drivers are allowed to prematurely start merging; thus, it can be taken as a function of the type of control used. With yield control, drivers are allowed to negotiate the intersection without full stoppage; consequently, it can then be expected that the  $\kappa$ -parameter of yield control is higher than the one of stop control, where full stoppage is mandated. Thereby, by specifying specific values for the  $\kappa$ -parameter for yield control and for stop control, one can be able to explicitly address the type of control used. This feature is not present in other capacity formulas for priority T-intersection. The developed capacity formula has a similar structure with the fluid approximation capacity formula of Plank<sup>5)</sup> since both formulas are developed based on the percentage of the full capacity available for movement. However, the

current formula has a  $\kappa$ -parameter to account for drivers anticipating on-coming gaps greater than the critical gap. When the  $\kappa$ -parameter is set to zero, the capacity formula reverts to the Plank fluid approximation model. The previous HCM formula of Eq. (8) corresponds to a special case of  $\kappa$ -parameter 0.5. For the remainder of this study, only Eq. (13) was used to directly compare with the HCM formula, Eq. (8).

In this study, the interference to the major traffic by the minor traffic was not taken into account as in the HCM. That is a fundamental hypothesis in dealing with the capacity at priority intersections.

## 4. DATA COLLECTION

### (1) Field Data

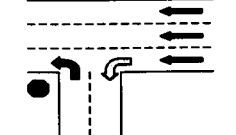
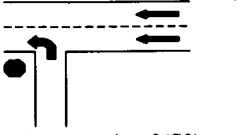
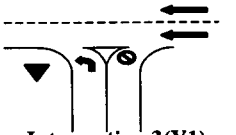
Field data were observed by videotaping three priority intersections in Bangkok from a high vantage point. Among them two intersections are operated by stop sign and the remaining is by yield sign. **Table 1** summarizes the properties and configuration of each intersection. The shoulder lane at intersection 1 is in the exclusive use for left turn traffic and discharging vehicles from minor road conflict with the vehicles on the middle lane. The inflow lane on minor road at intersection 3 was closed due to the construction work. The critical gaps in **Table 1** were calculated by means of the 1985 HCM method, where the critical gap was defined as the median of accepted gaps.

Vehicle arrivals on major and minor roads at these intersections vary over a short period of time so that it is not plausible to simply assume a constant flow for a time period on major road and to determine the capacity of minor road by the number of discharge vehicles during the time period. Therefore, an alternative method of analysis was adopted: The traffic flow at the conflicting lane at the major road was determined every 20 seconds and was plotted over time. The time each vehicle reaches the stop line of minor road and the time it fully discharges from the minor road were also noted and imposed on the conflicting flow versus time graph as illustrated on **Fig. 2**. The outflow or discharge at the minor road was then determined as

$$\text{discharge (veh/hr)} = \frac{3600}{\text{time out} - \text{time in}} \quad (15)$$

where "time in" is the time the lead vehicle in the minor road arrives at the head of the queue and "time out" is the time the lead vehicle fully discharges from the minor road.

Table 1 Property and configuration of data collected sites

 <p>Intersection 1 (S1)</p>	<p>Location: Control: Conflicting lane: Left from major road: Critical gap: Saturation flow rate:</p>	<p>Rachada-Suttisan Intersection, Bangkok Stop Middle lane 300 vph 4.5 seconds 1200 vph</p>
 <p>Intersection 2 (S2)</p>	<p>Location: Control: Conflicting lane: Left from major road: Critical gap: Saturation flow rate:</p>	<p>Sukhumvit Soi 93, Bangkok Stop Shoulder lane None 3.3 seconds 850 vph</p>
 <p>Intersection 3 (Y1)</p>	<p>Location: Control: Conflicting lane: Left from major road: Critical gap: Saturation flow rate:</p>	<p>Talad Bangkhan, Bangkok Yield Shoulder lane None – road closure due to construction work 3.6 seconds 1300 vph</p>

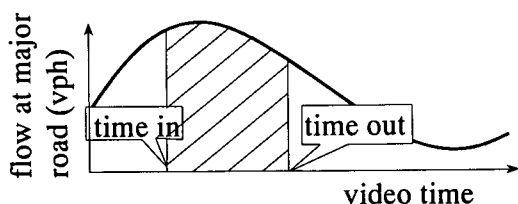


Fig. 2 Time-in and time-out period superimposed on the major road flow diagram.

The vehicle on minor road was considered to have fully discharged when the next queued vehicle has reached the head of the queue. The point, where the lead minor vehicle was considered fully discharged, was determined by observing the average point the discharging vehicle has reached at the instant the next queued vehicle arrives at the head of the queue. The flow rate on the major road was then averaged within the time period between the time-in and time-out and was paired with the corresponding minor road discharge rate. The whole process was repeated for each minor road vehicle using a computer search algorithm, deriving 320 or more data pairs from each location. The data pairs were then grouped into classes every 50-vph of traffic flow on major road. The capacity of minor road for the corresponding class of major road flow was then taken as the average minor road discharge within the class.

## (2) Empirical Data

The process of videotaping and synthesizing data

from the videotapes requires a lot of time and effort. More importantly, it is almost impossible to cover extensive traffic conditions only from field data. In general, the traffic conditions observed at a certain site are limited. To avoid such a bias in traffic flow data, the empirical model developed by Al-Massaied<sup>8)</sup> for estimating capacity of yield controlled streams at a one-way minor street crossing a one-way major was used.

The model was developed with the data measured at thirty-two intersections in Jordan. The critical gaps and follow-up times were calculated following the 1985 HCM method. The formula is defined as

$$cap = C \left( \frac{vis}{sp} \right)^{0.11} \left[ 1 + \frac{(W_m - 9)}{3.6} \right]^{0.94} \left[ 1 + \frac{(w - 3.6)}{3.6} \right]^{0.30} \left( \frac{1}{1 + F^2} \right)^{0.82} \quad (16)$$

where *cap* is the capacity of right turn stream (PCU/hr) and the value of 835 pcu/hr is assumed in this analysis. Similarly, *vis/sp* is the visibility to speed ratio (meter/kph) and 2.0 m/kph is used here. *W<sub>m</sub>* and *w* are width of major and minor streets (m), respectively. Then, *F* is the flow of through traffic in major street (1,000 PCU/hr) and *C* is the capacity under ideal conditions (PCU/hr). In addition, the critical gap of 4.8 sec. was measured at the intersections in Jordan. It should be noted here that the experiment data was not used for developing a capacity model for Bangkok but just for examining how influential the type of control was on the capacity of unsignalized intersections.

## 5. CALIBRATION OF $\kappa$ -PARAMETER

It was theorized that the  $\kappa$ -parameter is dependent upon the type of control used, thus,  $\kappa$  for yield control should be higher than the one for stop control. To confirm this hypothesis, the data from two stop control intersections and one yield control intersection in Bangkok were analyzed along with the empirical data for yield-controlled intersection. As shown in Fig. 3, the capacity-priority flow curves were plotted while changing  $\kappa$ -parameter. The optimum  $\kappa$ -parameter was then determined based on a regression analysis for each case. The best fitted curve lies between the curves of  $\kappa$ -parameter of 0.30 to 0.45 for Intersection 1 (S1), whose range is somewhat larger than that for S2. The optimum curve for S2 is between the curves of 0.35 to 0.38. The left-turning vehicles on the shoulder lane at S1 might have influenced on the merging movements from the minor road. This eventually resulted in a large deviation of the parameter. In addition, the major traffic might have been affected by the minor flows, as shown in a large deviation of the capacity at the minor roads when the major roads were congested. Nevertheless, the difference in the optimum value is very small, i.e. 0.37 for S1 and 0.36 for S2. The multiple correlation coefficient was also fairly good, 0.80 for S1 and 0.81 for S2.

For the yield-controlled intersection in Bangkok, Intersection 3, the optimum value of  $\kappa$ -parameter was 0.72 with the range of 0.70 to 0.75. To examine further this tendency at yield-controlled intersection, the  $\kappa$ -parameter was then estimated using the experimental formula of Eq.(16). The optimum value was 0.67 with range of 0.60 to 0.75. As shown clearly in Fig. 3 (4), the best-fitted curve converges to the curve with  $\kappa$ -parameter of 0.60 at low flow rate region and to the curve with  $\kappa$ -parameter of 0.75 at high flow rate region. Despite the difference in the source of traffic data, the optimum parameters are very similar for both intersections.

It should be noted here that the optimum values for stop control are smaller than the value, 0.5, adopted in the previous HCM formula of Eq. (8) but on the contrary those for yield control are larger than 0.5. In other words, the HCM formula represents an intermediate situation between stop and yield controls. Fig. 4 compares the capacity values estimated by the new fluid formula with those by the HCM model for both stop and yield controls, whereby the fluid formula takes the optimum  $\kappa$ -value. The HCM formula overestimates the discharge capacity for stop-control and underestimates the capacity for yield control.

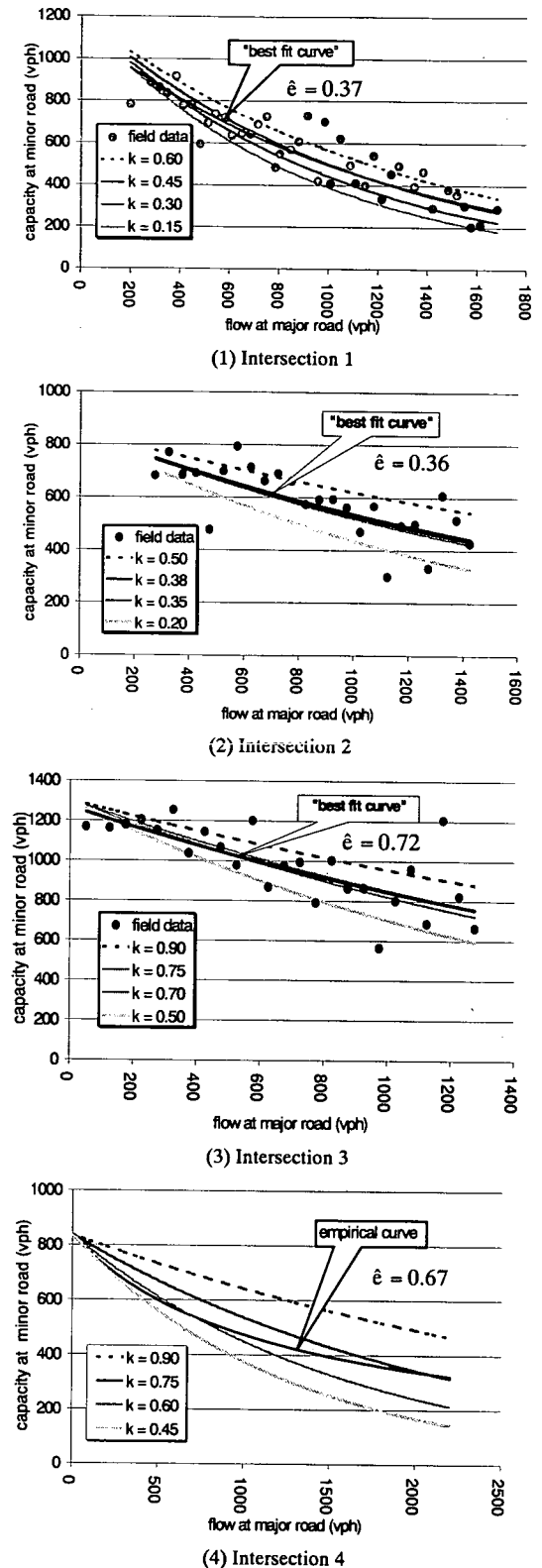
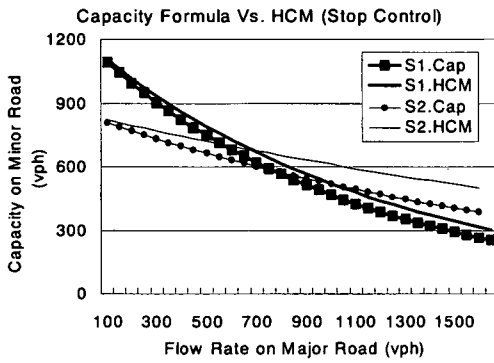
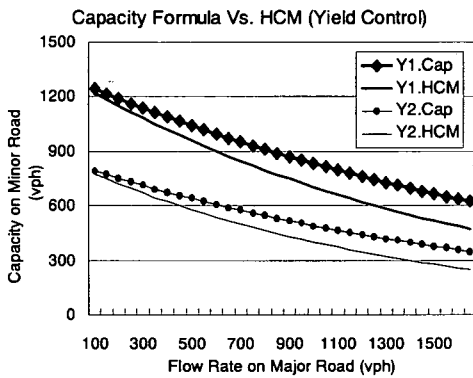


Fig. 3 Calibration of the  $\kappa$ -parameter



(1) Stop control



(2) Yield control

Fig. 4 Comparison of formula with HCM model

## 6. INTERGRATION INTO AN URBAN TRAFFIC CONTINUUM MODEL

### (1) Traffic Continuum Model

For application to macroscopic simulation of an urban network, the capacity formula needs to be integrated into a traffic continuum model. The model proposed by Cremer et. al.<sup>1),18)</sup> was a simplified traffic continuum model, which intended for fast simulation of large urban networks and has the following model equations:

$$k_i^{t+1} = k_i^t + \frac{\Delta t}{\Delta x} (q_{i-1}^t - q_i^t + s_i^t) \quad (17)$$

$$q_i^t = k_i^t \times v_i^t \quad (18)$$

$$v_i^t = \beta v_i^t + (1 - \beta) V(\bar{k}(k)) \quad (19)$$

with  $\bar{k} = \alpha k_i^t + (1 - \alpha) k_{i+1}^t$

where  $k_i^t, v_i^t, q_i^t$  are density, mean speed, and flow at segment  $i$  at time  $t$ .  $\Delta x$  and  $\Delta t$  are segment length and time interval, respectively.  $V(k)$  is

speed-density relationship.  $\alpha$  and  $\beta$  are weighting factors.  $s_i^t$  is source/sink flow. At a link with a priority T-intersection, the exit end of the minor road coincides with the beginning of a major road segment. The source volume in the continuity equation, Eq. (17), was then taken as the minimum of either arrival or capacity; wherein, the modified capacity formula was used for the latter.

### (2) Validation with TRAF-NETSIM

Ideally, it is the best to validate the developed macroscopic simulation model based on field data. However, in this case, it was difficult to find such an observable test site that encompassed a wide range of traffic conditions and with a stable non-priority road demand. Moreover, the desired test on the performance of the developed simulation model on stop and yield intersection cases further complicated the validation process using field data. The change in the control type, i.e. stop sign or yield sign, was necessary but such a change was difficult and sometime dangerous to implement in real life. Therefore, it was decided to generate the test data by means of computer simulation. The macroscopic model of Eq. (17) to (19) was examined using the simulated data. What is important in the selection of the simulation model is that the concept of the model should be different from the macroscopic model developed here. Hence, TRAF-NETSIM, a microscopic model, was adopted due to the diversity in the simulation function and the sophisticated interface in handling the input and output files. The model is widely used and verified by lots of practitioners. TRAF-NETSIM independently simulates each vehicular movement thus traffic operations at a priority intersection are easily and realistically simulated by the use of a gap acceptance function.

To ascertain that the traffic behavior in TRAF-NETSIM was representative of field conditions, TRAF-NETSIM was calibrated for the S1 data set. The parameters of free flow speed, mean saturated headway, and start-up lost time were specified from the observed data while some parameters, such as reaction time, maximum acceleration and deceleration rates, were adjusted based on a trial-and-error technique so as to stay within a certain reasonable range specified for each parameter<sup>18)</sup> and achieve the desired discharge characteristics. Fig. 5 shows the result of calibration with TRAF-NETSIM underestimating field data by 6.9% on average. At this stage no further improvement was realized and the error was taken to be small enough because the error would bring the similar tendency in the subsequent comparative

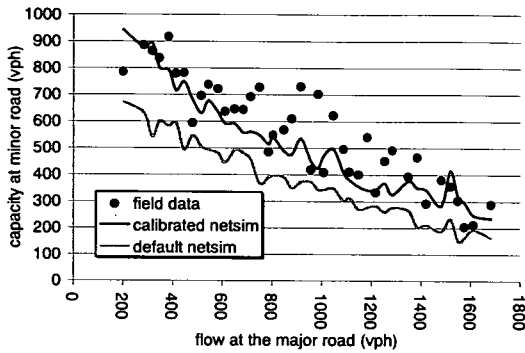


Fig. 5 Calibration of TRAF-NETSIM

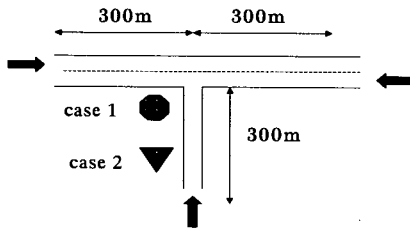


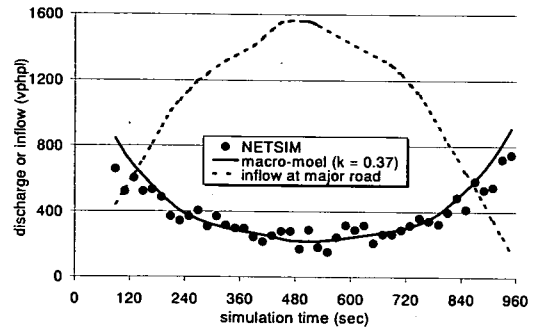
Fig. 6 Virtual intersection configuration.

analysis between both microscopic and macroscopic models. Then from the calibrated TRAF-NETSIM, the required parameters of Cremer model are also approximated.

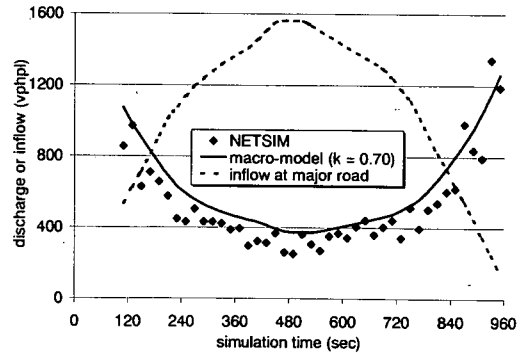
## 7. NUMERICAL RESULTS

For the comparison tests, identical inflow patterns were applied to both macroscopic and TRAF-NETSIM models for the simple urban network illustrated in Fig. 6. Then the discharge rate at the minor road was compared over the whole simulation time. The inflow volume at the major road, illustrated as a dotted line in Fig. 7, was assumed to vary from 25 vphpl at the beginning, 1600 vphpl after 480 sec., and 100 vphpl at the end of 960 sec. The variation of inflow was set up to test the performance of the model over a broad range of traffic conditions. The minor road was made to operate at capacity level. The simulation was started with an empty network. Thus, the first 80 seconds of simulation was eliminated from the analysis to compensate for the lack of initialization. A total of 20 independent simulation runs were made on TRAF-NETSIM. The results were then averaged for comparison with the ones estimated by the macroscopic model of Eqs.(17), (18), and (19).

As the first case, a stop controlled priority T-intersection was analyzed with  $\kappa$  equal to 0.37. The simulation results, as shown in Fig. 7 (1),



(1) Stop control



(2) Yield control

Fig. 7 Simulation results of stop and yield control at virtual intersection.

indicate a good fit with an overestimation error of 31 vph, 7%, on average and with an  $R^2$  of 0.91. As the second case, the control at the intersection was changed from stop to yield with  $\kappa$  equal to 0.70, taking the average of both Y1 and Y2 cases. The results are shown in Fig. 7 (2) with the macroscopic model overestimating TRAF-NETSIM results by 93 vph, 21%, on average and with an  $R^2$  of 0.87.

Compared with the fairly good fit for the stop control case, the results for the yield control case reveals an overestimation, particularly during the 250 to 700 second period when the flow at the major is high (1200 to 1600 vph) but with a reasonably good fit outside that period when the flow at the major road is low. As shown in Fig. 8, the discharge flows for the yield control are rather close to those for the stop control for the congested time period. This is explained by the substantial shift of operational control from yield to stop due to high percentage of non-priority vehicle stoppage at this condition when conflicting flow at the priority road is high. The real lines in Fig. 8 are the approximated curves simulated by NETSIM for each control. Both curves approach each other for the congested period.



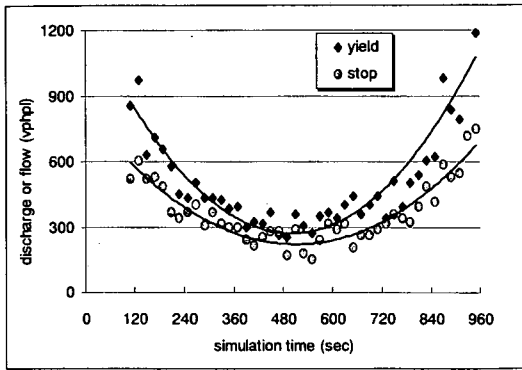


Fig. 8 Comparison of TRAF-NETSIM results with stop and yield control.

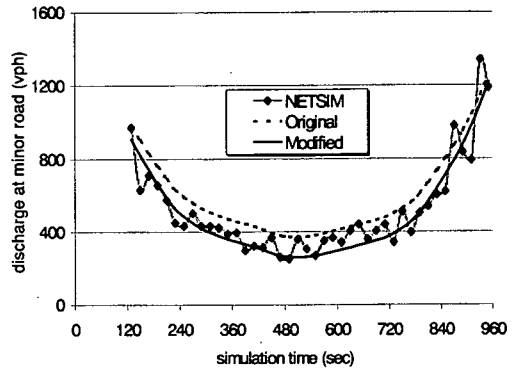


Fig. 9 Discharges by yield control with the modified formula.

## 8. FURTHER MODIFICATION OF CAPACITY FORMULA

To further improve accuracy for the yield control case, the capacity formula for yield control was modified to account for the shift of operational characteristic from yield control to stop control. Assuming that the shift in operational characteristic is linear with respect to flow at the major road normalized over the critical flow, the modified capacity formula was formulated as

$$cap_y = sat_m \times \exp[-\lambda(g - \kappa_m M)] \quad (20)$$

$\kappa_m$  and  $sat_m$  are the modified  $\kappa$  parameter and saturation flow rate given as

$$\kappa_m = \kappa_y - (\kappa_y - \kappa_s) \frac{\lambda}{\lambda_{crit}} \quad (21)$$

$$sat_m = sat_y - (sat_y - sat_s) \frac{\lambda}{\lambda_{crit}} \quad (22)$$

where  $sat_y$  and  $\kappa_y$  are the saturation discharge flow rate and  $\kappa$ -parameter estimated earlier for yield control. Similarly,  $sat_s$  and  $\kappa_s$  are those at stop control.  $\lambda_{crit}$  is the maximum flow of the major road. Using the modified capacity formula, the simulation results, as shown in Fig. 9, reveal an improvement in discharge prediction with the modified formula underestimating NETSIM discharge results by 14 vph on average and with an  $R^2$  of 0.90.

## 9. CONCLUSIONS

Traffic operation at a stop-controlled intersection is different from that of a yield-controlled intersection so that it would be inaccurate to assume the same

capacity formula for both control types.

Presented in this study is how to formulate a new priority capacity equation that is able to differentiate operational characteristics of the type of control used. Such a unified capacity formula for priority T-intersection has not been found in other models.

Quantification of the type of control is determined based on a parameter that accounts for the degree of minor road drivers prematurely starting to move in anticipation of an on-coming acceptable gap. Calibration by field and experiment data indicated that the parameter takes larger value in yield-controlled intersections than the one used in the 1994 HCM and smaller value in stop-controlled intersections; thus, confirming the tendency initially assumed.

A macroscopic traffic simulation model was then developed featuring the new capacity formula into the Cremer model. The new capacity formula, with its favorable properties, was effective in precisely simulating the discharging flows at priority T-intersection. Validation of the model using TRAF-NETSIM data presented accurate results in the stop control case but with mediocre results in the yield control case.

Further examinations with TRAF-NETSIM, indicated that discharge characteristics of yield-controlled intersections approximate stop control discipline at high conflicting flows due to the high percentage of stoppage at near critical condition. To account for the shift of control, the capacity formula for yield-controlled intersections was further modified by assuming the control shift to be linear with respect to the major road flow normalized over the flow at critical state. The modification greatly improved accuracy in the yield control case.

The results in this study indicate that treatment of priority T-intersections need not be neglected in macroscopic simulation of urban networks. Simple

modifications and extension of the algorithm of macroscopic simulation programs can yield more realistic and accurate results without significantly increasing computational burden.

The subject of movement at priority T-intersections is broad and more complex as it seems. Reverse priority, spillback, and multi-lane approaches are common in real life and play an important aspect in the discharge behavior of vehicles at priority T-intersections. The scope of this study is limited only to the left turn movement on minor road at priority T-intersections with the major road operating under free flow conditions. More importantly, the parameters identified here for the new formula are not so precise due to the lack of actual field data. Thus, further study and extensions of the modeling at priority intersections is needed to realize more realistic results.

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## 無信号 T 字交差点の容量算定式とマクロ交通流シミュレーションモデルへの適用

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HCM 等これまでに提案されている無信号交差点における容量算定式は、一時停止制御と譲れ制御の相違を明確には考慮していない。無信号交差点を含む市街地道路へのマクロ交通流モデルの適用にあたっては、容量算定式が不可欠であることから、T 字交差点を対象として両制御の相違を考慮したパラメータを新たに含む容量算定式の開発を行った。次に、当該算定式を組み込んだ高次項を含むマクロ交通流モデルの作成を行い、主道路における交錯交通量を变化させたシミュレーション解析を行った。その結果、パラメータ値は、一時停止制御では旧 HCM 式より小さく、譲れ制御では大きくなることを明らかにした。さらに、渋滞時には、譲れ制御も実質的に一時停止制御状態となる現象を表現するよう算定式の改良を行った。