Permitted Left-Turn Capacity of Exclusive Lanes: Simulation-Based Empirical Method

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An exploratory procedure for analyzing the permitted left-turn capacity with exclusive lanes is presented, including several empirical models for opposing queue length prediction, permitted saturation flow of mixed traffic, and effect of bay length on the left-turn capacity. Some critical factors, such as the number of opposing lanes and the interactions between upstream and downstream green time–cycle length ratios, have been incorporated in the proposed procedures for capacity estimation. A discrete choice modeling methodology has been applied to predict the fraction of time in a cycle during which the through queue length may be over a certain distance. Such a model enables traffic engineers to determine the left-turn bay length from a cost-benefit perspective. It should be noted that all proposed empirical models are grounded on the simulation experiments with TRAF-NETSIM. Hence, adjustments or modifications may be necessary after extensive field observations are conducted to calibrate TRAF-NETSIM.

The presence of left-turning vehicles at signalized intersections tends to cause excessive delay, increase accident potential, and lower intersection capacity. Hence, accommodating left-turning vehicles with effective signal control strategies has long been a source of concern for traffic engineers. In practice, depending on the use of shared or exclusive lanes for left-turning vehicles, traffic engineers must select a left-turn phasing that best satisfies the left-turn demand and minimizes the operational difficulties incurred by left turns. An appropriate tool or procedure to evaluate the proposed design strategies (i.e., permitted, protected, protected/permitted) thus becomes essential.

Over the past several decades, although highway agencies and research institutions have developed various guidelines for analyzing left-turn capacity, the most widely used are the procedures included in Chapter 9 of the 1985 *Highway Capacity Manual* (HCM). In fact, the 1985 HCM has been used by more traffic and transportation engineers in the past 7 years since it was published than the 1965 HCM was in 20 years.

However, because of both the limited resources and the lack of sufficient empirical validation in their developments, many procedures or models recommended by the 1985 HCM are subject to revision. This is particularly true of Chapter 9, "Signalized Intersections." In many situations, the output from an analysis of left-turn capacity either does not agree with field observations or yields vastly different results.

In view of various technical deficiencies identified with given applications for using the HCM signalized intersection methodology, a number of attempts have been made to modify or enhance the current procedures. This is one of several such projects sponsored by FHWA, with an emphasis on the operational analysis of exclusive left-turn lanes.

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LITERATURE REVIEW

Most existing methods for left-turn analysis start with the estimation of left-turn saturation flow rate. The capacity under various conditions can thus be obtained with appropriate adjustments of the effective green time, cycle length, and other related factors. Prominent studies in this area include the Illinois method (*1*), the revised HCM draft (*2,3*), the Canadian methods (*4*), the U.K. method (*5*), the Swedish approaches (*6,7*), and Australian Road Research Board procedures (*8*). Despite the increasing attention on improving the accuracy for left-turn analysis, existing methods still face some of the following critical issues:

1. The trade of theoretical rigorousness with analytical tractability, such as using simplified assumptions or ignoring some vital elements, in deriving a convenient closed-form solution;
2. The representation of complex population data with limited field observations, such as fitting an empirical model from selected location data without reliable parameter stability analyses; and
3. The demand for very extensive field data, such as directly applying a simulation program for capacity estimation. A detailed review of these methods or procedures has been conducted by a research team at the University of Maryland, and is available elsewhere (*9*).

One of the promising ways to circumvent the aforementioned difficulties is to develop empirical models from a well-calibrated simulation model. Conceivably, such models may not be so appealing as analytical formulations in terms of their mathematical elegance, but they can realistically incorporate related critical factors and their complex interactions though the results of simulation experiments. The stochastic nature of a traffic system as well as the impact of driver behavior on the resulting capacity can also be explored with a proper design of simulation experiments. Hence, this study, as recommended by FHWA, intends to take full advantage of TRAF-NETSIM in the development of operationally convenient yet theoretically reliable models for estimating the capacity of exclusive left-turn lanes.

FRAMEWORK FOR EXCLUSIVE LEFT-TURN CAPACITY ESTIMATION UNDER PERMITTED PHASING

As indicated, the proposed method for estimating left-turn capacity intends to maximize the use of traffic simulation models so that the complex interactions among driver behavior, geometric conditions, and signal control strategies can be fully considered. The simulation-based analyses also allow for assessment of various

input data quality on the capacity estimation. To facilitate the illustration, the entire process for analyzing the exclusive left-turn capacity (ELTC) under permitted phasing is divided into the following principal steps (Figure 1), including both the empirical models and the computation procedures.

Before each step is described in detail, it should be noted that all employed regression models have been through rigorous evaluation, including the following tests for their required properties:

- The residual of any proposed regression model is a random variable.
- The mean value of the residuals in any particular period is 0.
- The variance of the residuals is constant in each period.
- The residuals follow a normal distribution of 0 mean and constant variance.
- All residuals are independent.
- The model residuals are independent of any explanatory variables.
- The model explanatory variables are not perfectly linearly correlated.
- The macrovariables are correctly aggregated.
- All model parameters are independent of the selected sample size (i.e., stability).

An in-depth discussion of these tests is not within the scope of this paper but is available in most econometrics books. Definitions of all variables used in the following analyses are given in Table 1. Note that all empirical equations presented hereafter are based on the simulation experiments of uncoordinated, pretimed intersections with no queue spillback to the upstream intersection.

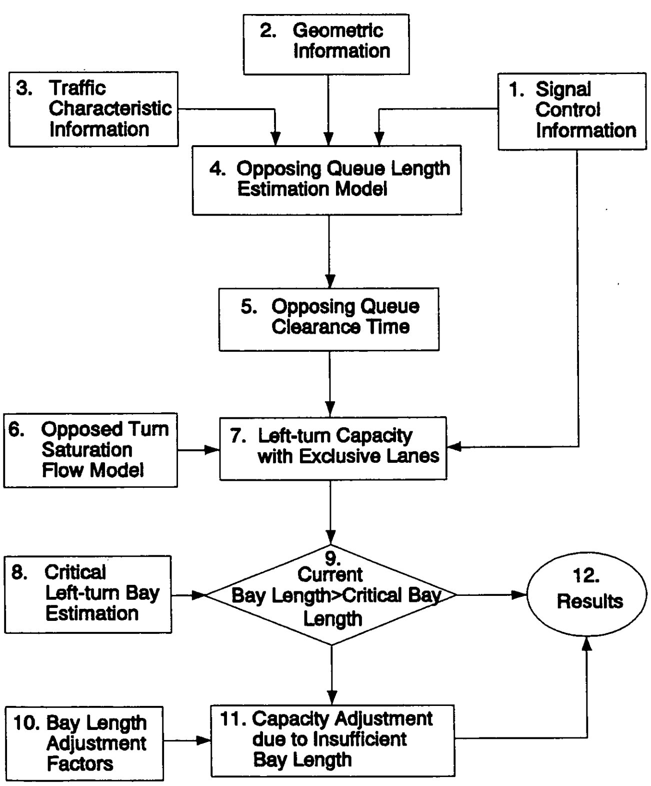

FIGURE 1 Permitted left-turn capacity estimation process (exclusive lane).

Steps 1–3: Preparation of Input Data

As required in the HCM, the first three steps are designed to provide all necessary information for capacity estimation, including signal control plans, geometric conditions, traffic volume, and flow characteristics.

Step 4: Opposing Queue Length Estimation

Since all left-turn vehicles under permitted phasing will be blocked by the opposing discharging vehicles, it is essential to have an accurate estimation of the queue length under the given environment. The available portion of green time can thus be computed according to the observed queue discharging headway. Conceivably, the maximum opposing queue length varies with the arrival traffic patterns, discharge rate, and signal control strategies at both the upstream and the target intersections. A realistic representation of their interactions with analytical formulations would be too complex for use in practice. Hence, the following hybrid model, which is based on extensive simulation experiments, is proposed for this study:

$$N_q = \left[X_5 \cdot (1 - X_3) \cdot \left(\frac{X_1}{X_4 \cdot 3{,}600 \cdot X_2}\right)\right]^{0.6755} \cdot \left(\frac{X_2}{X_3}\right)^{0.7951} \cdot X_1^{0.2235} \cdot X_3^{0.4044} \cdot X_5^{-0.2597} \qquad R^2 = .94, N = 352 \tag{1}$$

where

- N_q = number of queue vehicles to be discharged at beginning of green phase;
- X_1 = total opposing flow rate per hour (vph), 200 vph $\leq X_1 \leq$ 2,700 vph;
- X_2 = green time–cycle length ratio (G/C) for through movement at upstream intersection, $0.3 \leq X_2 \leq 0.8$;
- X_3 = G/C for through movement at target intersection i, $0.3 \leq X_2 \leq 0.8$;
- X_4 = number of opposing through lanes to discharge queue vehicles, $1 \leq X_4 \leq 3$; and
- X_5 = cycle length of target intersection, 60 sec $\leq X_5 \leq$ 120 sec.

Note that the first term approximates the platoons entering the link during the upstream green phase and arriving at the target intersection during the red phase. The effects of G/C at both upstream and downstream intersections and the cycle length on the traffic patterns are then incorporated in the multiplicative adjustment terms.

Step 5: Computation of Opposing Queue Clearance Time

Given the estimated queue length, N_q, from Equation 1, the total opposing queue discharging time can thus be computed by

$$g_0 = N_q \times \overline{H} \tag{2}$$

where $\overline{H}$ is the average queue discharging headway obtained from either field observations or a default empirical value. The unsaturated portion of a green phase for permitted left turns is thus given by

$$g_e = g - g_0 - t_L - a_m$$

TABLE 1 Definition of Model Variables

Variable	Definition
X_1	The total opposing flow rate per hour (vph)
X_2	The G/C ratio at the upstream intersection
X_3	The G/C ratio at the target intersection
X_4	The number of opposing lanes to discharge queue vehicles
X_5	The cycle length of the target intersection
X_6	The total flow rate for the through movement
X_7	The number of lanes for the through movement

where

g = allocated green time,
t_L = loss time, and
a_m = yellow time.

Step 6: Estimation of Permitted Left-Turn Saturation Flow Rate

The primary purpose of Step 6 is to estimate the maximum left-turn flow rate during the effective green phase that has unsaturated opposing flows. Conceivably, factors associated with the maximum permitted left turns include the opposing flow rate, number of opposing lanes, and upstream *G/C* that captures, to some extent, the arrival patterns. To take advantage of TRAF-NETSIM's capabilities, the authors have conducted extensive simulation experiments and have produced the following model for estimating the saturation flow of permitted left turns:

$$S_{pm} = 1{,}723.47 + 0.00017(X_1^*)^2 - 1.0627X_1^* - 300.45X_4 \qquad R^2 = .90, N = 547 \tag{3}$$

where $S_{pm} \geq 0$ and X_1^* is the effective opposing volume to left-turning vehicles, rather than the average opposing flow, and is defined as follows:

$$X_1^* = [Z - Q] \cdot [3{,}600/g_e]$$
$$Z = X_1/[3{,}600/C],\ Q = \alpha \cdot N_4 \tag{3a}$$

where

Z = average opposing vehicles per cycle,
Q = total number of queue vehicles per cycle that exhibit some relation with maximum queue length (N_q), and
α = parameter to capture interrelation between average and maximum queue length per cycle.

The key notion underlying Equation 3a is that after clearing the initial queue on each lane, $(Z - Q)$ vehicles per cycle arrive at the intersection and thus block the left-turning vehicles; if the intersection is not oversaturated, all opposing $(Z - Q)$ vehicles will be discharged during the effective green period. Hence, the actual average gap available for left-turning vehicles is $g_e/(Z - Q)$, and the equivalent opposing flow conflicted with left-turning vehicles under such a condition is X_1^* rather than X_1.

Note that this specification, selected from nine possible function forms, captures the nonlinear relation between the opposing flows and the allowable left-turning vehicles; all parameters are statistically significant at the 0.001 level. Such a specification satisfies all assumptions not only for multivariate regression but also for the stability test (i.e., the estimated results are independent of the selected sample size). Hence, even though TRAF-NETSIM may need to update its key parameters from field observations, the exploratory analysis results remain promising.

Step 7: Computation of Left-Turn Capacity Under Permitted Phasing

Given the opposing queue discharging time and saturation flow rate from Steps 5 and 6, the left-turn capacity under permitted phasing is given by

$$\text{CA}_{pm}(\text{capacity}) = \left(\frac{3{,}600}{C}\right)\left[(g_e) \cdot \left(\frac{S_{pm}}{3{,}600}\right) + N_f\right]$$
$$= S_{pm}\left(\frac{g_e}{C}\right) + \left(\frac{3{,}600}{C}\right) \cdot N_f \tag{4}$$

where g_e denotes the effective green time for permitted left-turns (i.e., after discharging the opposing queue), or the unsaturated portion of the green phase for opposing vehicles, and N_f is the number of sneakers per cycle.

Note that the aforementioned procedures apply only for estimating the left-turn capacity with an exclusive lane and under non-coordinated signals. Additional adjustments will be necessary if a left-turn bay, instead of lanes, is used. As such, the authors have proposed the following five steps to account for the impact of bay length on the available left-turn capacity.

Step 8: Estimation of Required Bay Length for Permitted Left-Turn

The primary purpose of Step 8 is to ensure that the available capacity for permitted left-turns can be achieved with the given bay length. Hence, it should be considered from both the "demand" and "supply" sides. To some extent, the available permitted capacity, based on the opposing traffic conditions, can be viewed as the supply-side maximum permitted left-turn flows. The maximum allowable arriving vehicles for left turns, on the other hand, function like the demand-side flows. With a simple deterministic analysis, the approximate left-turn bay length under permitted phasing can be computed with the following variables:

CA_{pm} = permitted left-turn capacity with an exclusive lane,
S_T = saturation flow rate for through lane,
Q_T = arriving flow rate for through vehicles in left-turn lane,
Q_L = arriving flow rate for left-turn vehicles, and
$\bar{L}$ = average occupied space per vehicle.

The relations between S_T, Q_T, and Q_L are illustrated in Figure 2.

Basically, the required bay length from the capacity perspective is given by

$$L_{pm} = \max(L_S, L_D) \tag{5}$$

where

$$L_S = \bar{L} \cdot \left[\mathrm{CA}_{pm} \cdot \left(\frac{C}{3{,}600}\right)\right] \tag{6}$$

$$L_D = \bar{L} \cdot \left[\frac{Q_L}{3{,}600} \cdot C\right] \qquad \text{if } Q_L < S_T - Q_T \tag{7}$$

$$L_D = \bar{L}\left[\left(\frac{S_T - Q_T}{3{,}600}\right) \cdot C\right] \qquad \text{if } Q_L > S_T - Q_T \tag{8}$$

Note that Equation 5 represents the average queue length necessary for taking advantage of available left-turn gaps, where C denotes the cycle time. The left-turn capacity may not be fully used if the queue length during the green phase is less than the minimum required size. On the other hand, the bay length may be unnecessarily long if the approach has only very few left-turn vehicles that cannot fully use the available bay length. Hence, Equation 7 represents the required bay length based on the arriving left-turn vehicles per cycle, if the through lanes have enough capacity to accommodate the arriving left-turn vehicles. However, under some conditions, not all left-turn vehicles can merge to the left-turn bay because of the larger number of through vehicles. The required bay length is thus given by Equation 8.

As illustrated in Figure 2, the required bay length to use all of the available left-turn capacity depends not only on its own supply and demand levels, but also on the through flow rate. A left-turn vehicle may be blocked by the through queue vehicles and thus miss the turning opportunity. Hence, the left-turn bay must also be longer than the maximum through queue length per cycle. More specifically, considering the impact of the through flow rate, Equation 5 should be restated as follows:

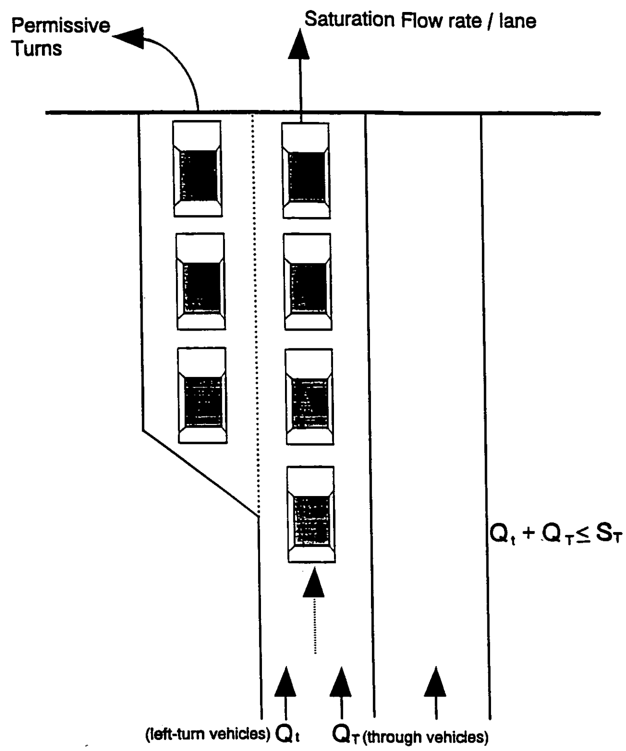

FIGURE 2 Graphical representation of interrelations among bay length and through and left-turn vehicles.

$$L_{pm} = \max(L_S, L_D, L_T) \tag{9}$$

where L_T is the maximum queue length of through vehicles per cycle over 1 hr. In most cases, Equation 1 can be used to predict the maximum queue length as long as the network is not oversaturated.

Step 9: Comparison Between Actual and Required Bay Length

In principle, the left-turn bay can be viewed as a left-turn lane if it is longer than the required length (i.e., $L_A > L_{pm}$). Otherwise some adjustments will be necessary, as the actual usable capacity will be less than the capacity estimated on the basis of opposing traffic conditions. A discrete model to generate the approximate adjustment factor is thus proposed in the next step.

Step 10: Bay Length Adjustment Factors

The purpose of Step 10 is to estimate the fraction of green time in a cycle during which the through queue length is so long that it blocks the left-turn vehicles from entering the left-turn bay. One can then adjust the available capacity on the basis of total blocked duration. With extensive simulation experiments, the authors have developed a discrete choice model for prediction of such a blocked period:

$P(\lambda \geq 120 \text{ ft})$

$$= \frac{\exp\left(a \cdot \frac{X_6}{X_7} + b \cdot X_2 + c \cdot X_3 + d \cdot X_5 + e \cdot \frac{X_2}{X_3}\right)}{\exp(f) + \exp\left(a \cdot \frac{X_6}{X_7} + b \cdot X_2 + c \cdot X_3 + d \cdot X_5 + e \cdot \frac{X_2}{X_3}\right)} \quad (10)$$

where

$a = 0.0011$ ($t = 3.1$),
$b = 2.6464$ ($t = 2.3$),
$c = -1.3985$ ($t = 1.1$),
$d = -0.0005$ ($t = 1.9$),
$e = -0.0870$ ($t = 1.0$),
$f = 2.7285$ ($t = 0.32$), and
$\rho^2 = 0.44$

$P(\lambda \geq 160 \text{ ft})$

$$= \frac{\exp\left(a \cdot \frac{X_6}{X_7} + b \cdot X_2 + c \cdot X_3 + d \cdot X_5 + e \cdot \frac{X_2}{X_3}\right)}{\exp(f) + \exp\left(a \cdot \frac{X_6}{X_7} + b \cdot X_2 + c \cdot X_3 + d \cdot X_5 + e \cdot \frac{X_2}{X_3}\right)} \quad (11)$$

where

$a = 0.0028$ ($t = 5.0$),
$b = 1.1475$ ($t = 1.8$),
$c = -3.6854$ ($t = 2.0$),
$d = 0.0119$ ($t = 3.2$),
$e = 0.2550$ ($t = 6.1$),
$f = 3.7108$ ($t = 3.4$), and
$\rho^2 = 0.63$.

$P(\lambda \geq 200 \text{ ft})$

$$= \frac{\exp\left(a \cdot \frac{X_6}{X_7} + b \cdot X_2 + c \cdot X_3 + d \cdot X_5 + e \cdot \frac{X_2}{X_3}\right)}{\exp(f) + \exp\left(a \cdot \frac{X_6}{X_7} + b \cdot X_2 + c \cdot X_3 + d \cdot X_5 + e \cdot \frac{X_2}{X_3}\right)} \quad (12)$$

where

$a = 0.0028$ ($t = 81.5$),
$b = 1.5931$ ($t = 289$),
$c = -4.4462$ ($t = 276$),
$d = 0.0072$ ($t = 1,200$),
$e = 1.3047$ ($t = 361$),
$f = 5.2287$ ($t = 27.8$), and
$\rho^2 = 0.97$

where

$P(\lambda \geq \alpha \text{ ft})$ = fraction of time in a given cycle during which through queue length is longer than α ft,
X_6 = total flow rate for through movement,
X_7 = total number of lanes for through movement, and
ρ = goodness-of-fit indicator for discrete models.

With these functions, one can predict the fraction of time during which the queue exceeds a certain distance.

Step 11: Capacity Adjustment

Given an insufficient bay length, L^*, its permitted left-turn capacity can thus be computed according to the following expression:

$$\text{CA}_{pm}(L^*) = \text{CA}_{pm} \times [1 - P(\lambda \geq L^*)] \quad (13)$$

where

$\text{CA}_{pm}(L^*)$ = left-turn capacity under permitted phasing and bay length of L^* ft;
CA_{pm} = same capacity with a full left-turn lane;
$P(\lambda \geq L^*)$ = total fraction of time in a cycle during which through queue length exceeds given left-turn bay.

NUMERICAL EXAMPLES

To evaluate the performance of the proposed models and procedures, the following four test scenarios have been designed:

- Scenario A:
  –Number of opposing lanes = 1,
  –Cycle length = 100 sec,
  –G/C = 0.5,
  –G/C^* at the upstream intersection = 0.5,
  –Opposing volume: from 100 to 700 vph (seven cases).
- Scenario B:
  –Number of opposing lanes = 2,
  –Cycle length = 100 sec,
  –G/C = 0.5,
  –G/C^* = 0.5, and
  –Opposing volume: from 100 to 1,000 vph (10 cases).
- Scenario C:
  –Number of opposing lanes = 3,
  –Cycle length = 100 sec,
  –G/C = 0.5,
  –G/C^* = 0.5, and
  –Opposing volume: from 100 to 1000 vph (10 cases).
- Scenario D:
  –Number of opposing lanes = 4,
  –Cycle length = 100 sec,
  –G/C = 0.5,
  –G/C^* = 0.5, and
  –Opposing volume: from 100 to 1000 vph (10 cases).

Since the G/C at both up- and downstream intersections may contribute to the variation of traffic patterns, the authors have also investigated additional 30 cases of similar scenarios but different G/C's.

Field data collection is not the focus of research at this stage, so it is assumed that TRAF-NETSIM is capable of yielding a reasonably reliable capacity estimation, and thus its results are used as the reference base for evaluation.

With such a criterion, the proposed model, as shown in Figures 3 through 6, outperforms the HCM approach in 7 out of 7 cases in Scenario A, 7 out of 10 cases in Scenario B, 7 out of 10 cases in Scenario C, and 8 out of 10 cases in Scenario D. Of the 69 cases overall, the proposed model yielded results better than the HCM in 55 cases.

The research team recognizes that the left-turn capacity obtained with TRAF-NETSIM needs to be validated with field data and that some adjustments may be necessary. An extensive design of experiments will also be needed to examine the proposed procedures under various conditions. Nonetheless, the preliminary performance results indeed indicate the promising future of the proposed model as well as procedures. Hence, with rigorous data validation,

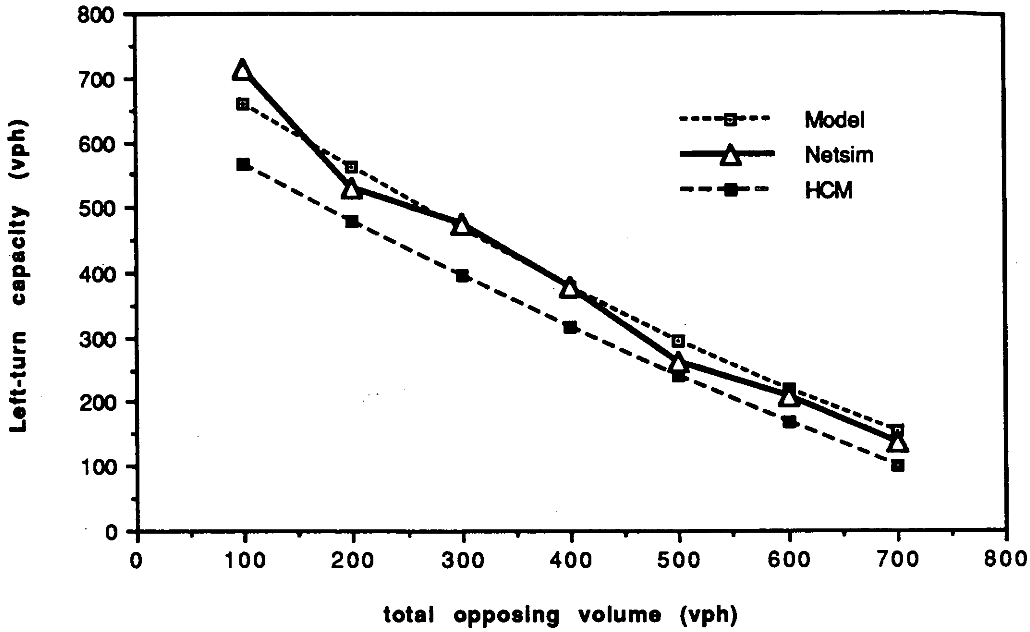

FIGURE 3 Results of Scenario A.

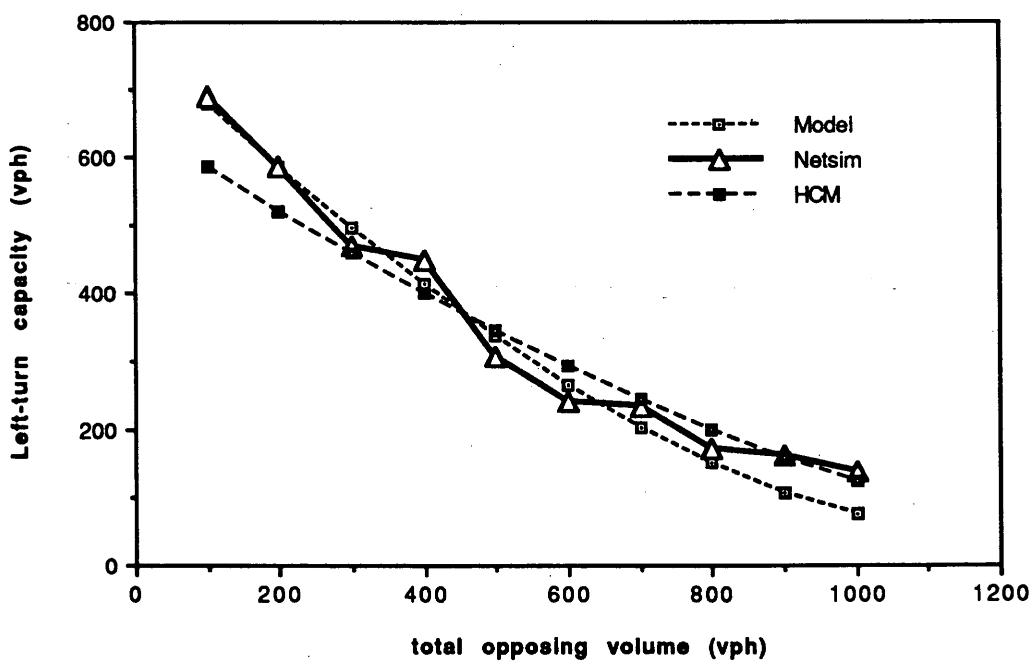

FIGURE 4 Results of Scenario B.

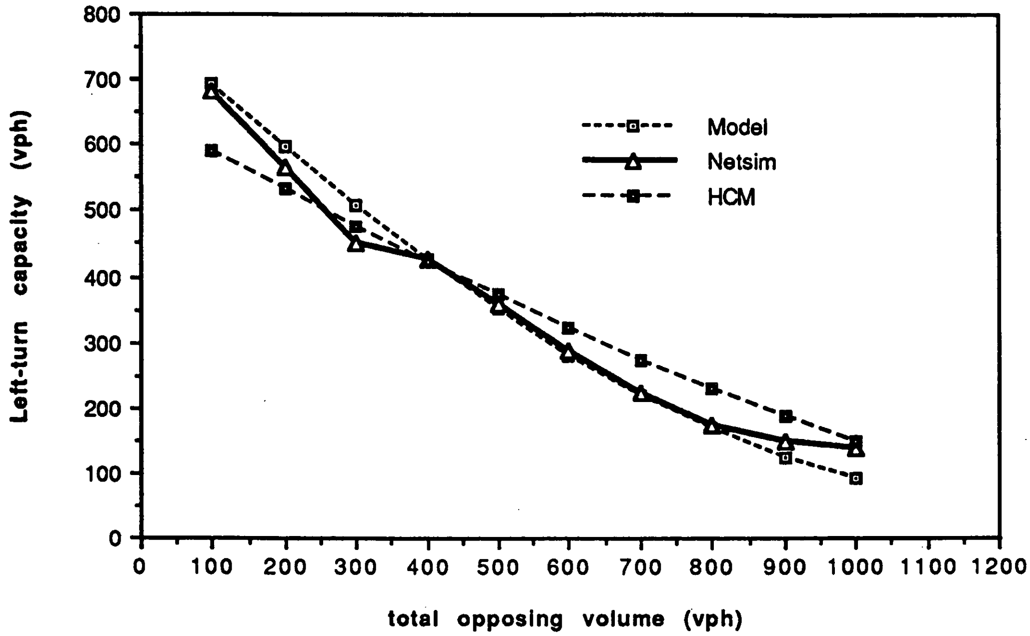

FIGURE 5 Results of Scenario C.

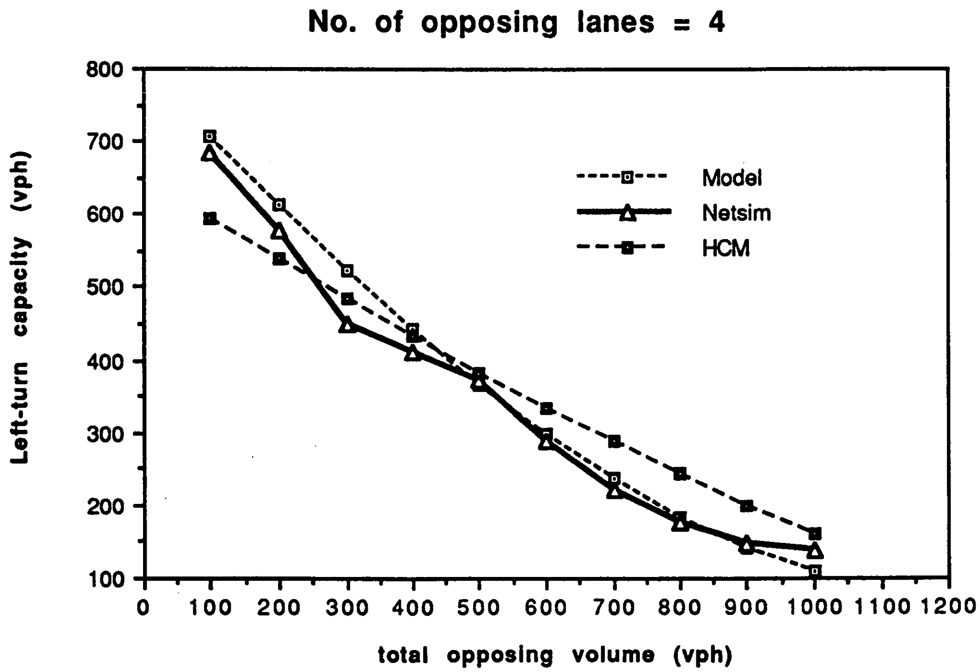

FIGURE 6 Results of Scenario D.

a convenient yet reliable empirical model for left-turn analysis may be achieved.

CONCLUSION

This paper has presented an exploratory procedure for analyzing the permitted left-turn capacity with exclusive lanes, including several empirical models for opposing queue length prediction, permitted saturation flow of mixed traffic, and effect of bay length on left-turn capacity. Some critical factors such as the number of opposing lanes and the interactions between upstream and downstream *G/C*'s have been incorporated in the proposed procedures for capacity estimation. A discrete choice modeling methodology has been applied to predict the fraction of time in a cycle during which the through queue length may be over certain distance. Such a model enables traffic engineers to determine the left-turn bay length from a cost-benefit perspective.

It should be noted that all proposed empirical models are grounded on the simulation experiments with TRAF-NETSIM. Hence, adjustments or modifications may be necessary after extensive field observations have been conducted to calibrate TRAF-NETSIM, which is one of the major tasks in the research project. Some capacity-related parameters, such as discharging headway and truck left-turn processing time, can be estimated from the field data.

Ongoing research along this line includes the development of (a) an analytical model for permitted saturation flow, considering both platoon size and the number of lanes; (b) an operational analysis procedure for protected/permitted and permitted/protected control; and (c) some guidelines for selection of critical capacity-related variables from field data.

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