Probabilistic Model for Signalized Intersection Capacity with a Short Right-Turn Lane

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Abstract: The paper presents a capacity estimation model for a signalized intersection approach with a short right-turn lane. The proposed model overcomes one of the major shortcomings of the current capacity estimation methodologies by considering the probabilistic nature of traffic flow and the effect of queue blockage to the short-lane section. The research showed that the capacity of a signalized intersection with a short right-turn lane is strongly related to the length of the short lane, the proportion of through and right-turn vehicles, and cycle length. The study also revealed new findings, through simulation, on the saturation flow rate discharging from the single-lane section where the right-turn lane splits. It was found that the saturation flow rate increases with the increase of the length of the right-turn lane. The proposed model was validated against the results from *CORSIM*, a microscopic traffic simulation model, and found general agreement between the two results. Capacity enhancement is achieved with a short right-turn lane compared to the shared-lane situation. Such a capacity enhancement is contributed by both the short-lane usage and the increased saturation flow rate from the single-lane section. An example of a common application of the proposed model is to provide adequate design of the length of the right-turn lane so that the projected traffic demand can be accommodated at an acceptable service level while minimizing the cost associated with the construction of a full or longer right-turn lane.

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Introduction

At signalized intersections, a right-turn lane often exists in the form of a short lane (also referred to as a right-turn pocket or a flare). While a significant amount of research has been devoted to studying signalized intersections (Olszewski 1993; Kockelman and Shabih 2000), only a limited number of studies exist to address the effect of the short lane on signalized intersection operations, such as the impact on intersection capacity and delay. For example, one impact of the short right-turn lane case is the queue overflow in either the short turn lane or the adjacent full through lane, resulting in blockage to the short-lane section and under utilization of the intersection capacity. In the *Highway Capacity Manual* (HCM) (TRB 2001), the short right-turn lane is basically treated as an exclusive lane. Such a treatment neglects the potential effect of queue blockage in situations where a short turn lane is present. Without queue blockages, the approach would operate as if there were an exclusive lane. However, when traffic flow does cause queue blockage to the short-lane section, the capacity of the approach would be reduced. The current HCM procedure would overestimate the capacity and thus underestimate delay. The lack of an appropriate procedure to evaluate the capacity and delay effects with a short right-turn lane situation often leaves traffic engineers with a dilemma, especially when determining the design of an intersection based on future traffic demands. For example, overdesign of the right-turn lane (i.e., too long) could result in unnecessary cost while underdesign of the right-turn lane would result in insufficient capacity. Such issues become critical when it is expensive (due to topographic or right-of-way constraints) to increase the length of an existing right-turn lane or to construct a new right-turn lane. Although traffic engineers could use simulation models to conduct the analyses, capacity is usually not a direct output from simulation. The significant variations involved in simulation often require multiple simulation runs in order to yield a reasonable mean estimate (Tian et al. 2002).

To our best knowledge, there is only a limited amount of literature that has addressed the short-lane issue. In a study by Simmonite and Moore (1997), they initially pointed out that "the art of modeling (flared approaches) is difficult and, as such, often overlooked by practitioners." Furthermore, they illustrated various cases of the short-lane situation, such as a short exclusive turn lane, and a short shared lane. Their study did not provide specific mathematical models to model the short-lane case. Instead, they recommended several macroscopic simulation models, including *LINSIG* (Simmonite 1985), *TRANSYT 10* (Crabtree et al. 1992), and *LINSAT* (Simmonite and Moore 1997), where the probabilistic nature of queue blocking was taken into consideration in the models. Later in a study by Corby and Hounsell (1998), they pointed out the shortcomings of all the macroscopic models recommended by Simmonite and Moore, and developed a microscopic simulation model called *FLARE*, specifically for modeling the short-lane cases.

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Empirical deterministic models have also been adopted in the *German Highway Capacity Manual* (Brilon et al. 1994) and the *SIDRA* (Akcelik 1997) software package to provide a rough estimate of the effect of a short lane. These models are of deterministic nature in that the effect of the short lane is only considered as a function of the proportion of the turning traffic volumes.

The purpose of this paper is to introduce a probabilistic capacity estimation model for signalized intersections with a short right-turn lane. A model constructed based on probabilistic and statistical theory is presented first. The proposed model was validated using *CORSIM* (FHWA 2002) a microscopic simulation model. Delay estimation under a short right-turn lane situation is not part of this paper.

Proposed Capacity Model

Similar to other types of transportation facilities, the capacity of a signalized approach with a short right-turn lane is defined as the maximum flow rate (measured in vehicle per hour) that the approach can service under prevailing geometry, traffic flow, and signal timing conditions. To obtain the capacity value, an infinite demand on the approach needs to be assumed. In this study, the traffic demand is assumed to be high enough for a queue to exist on the approach at the end of the green interval, and therefore, the short lane section is always blocked at the start of the green interval.

The effect of the short right-turn lane could be addressed from two different perspectives: the capacity reduction from the case of a full exclusive right-turn lane, and the capacity enhancement from the case of a single shared lane. In the HCM procedure, the approach capacity with an exclusive right-turn lane is typically calculated by lane groups instead of by the entire approach. This is simply because an infinite exclusive right-turn lane rarely exists. For this reason, we would investigate the short-lane effect from the perspective of capacity enhancement to the shared lane case.

For the purpose of model derivation, the signalized approach is assumed to include a single through lane with a right-turn pocket. Under the case where the approach has multiple lanes, the proposed model should be applied to estimate a lane-based capacity with some adjustments on the lane-usage balances. The effects of right turn on red and pedestrian crossings are not considered in the proposed model, but these issues will be addressed later in the paper.

The variables and parameters used for the model derivation are given in the Notation. All the vehicles are assumed to be passenger cars.

Overview of Modeling Approach

The steps for deriving the capacity model can be outlined as follows:

1. Calculate the probabilities of blockage to the short-lane section by the through vehicles and by the right-turn vehicles, respectively. When the blockage is by a through vehicle (see Fig. 1), the right-turn lane may not be fully occupied. Similarly, the through lane may not be fully occupied when the blockage is by a right-turn vehicle.
2. Calculate the average number of vehicles in the short-lane section when the blockage occurs. For example, when the blockage is by a through vehicle, the number of vehicles in the right-turn lane can vary each cycle, but the average number of vehicles in the right-turn lane needs to be calculated.
3. Calculate the capacity when the blockage is by a through vehicle. This capacity is obtained through calculating the flow rates or capacities in two portions of the green interval. The first portion of the green interval is to discharge the vehicles in the short-lane section. The time required to discharge these vehicles can also be obtained. The remaining portion of the green interval is to discharge vehicles from the single-lane section, where the capacity is obtained from the basic capacity model based on the green time, the cycle length, and the saturation flow rate.
4. A similar approach is used to calculate the capacity when the blockage is by a right-turn vehicle.
5. The final approach capacity is calculated as the weighted average of the capacities when blocked by a through vehicle and by a right-turn vehicle.

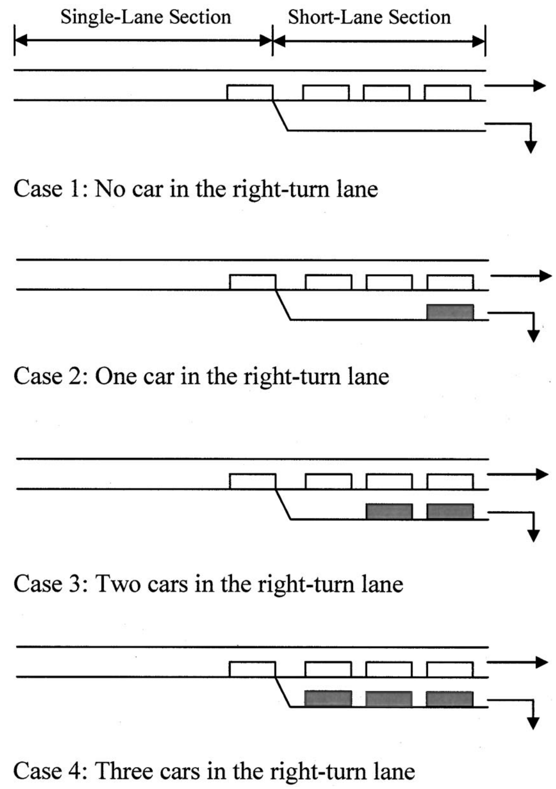

Fig. 1. Number of vehicles in right-turn lane when blocked by through vehicles

Probability of Blockage

There are two general cases that a blockage can occur: (1) a through vehicle blocks the right-turn lane; and (2) a right-turn vehicle blocks the through lane. Consider the cases shown in Fig. 1 where the blockage is by a through vehicle. The length of the right-turn lane is N vehicles ($N=3$ in this case). If we assume that a right-turn vehicle following the Nth through vehicle can still get into the right-turn lane position (design of the transition section for a right-turn lane normally allows enough space for this to occur), then the blockage by a through vehicle is equivalent to the $(N+1)$th (fourth in this case) the through the vehicle arriving at the intersection after the start of the red interval.

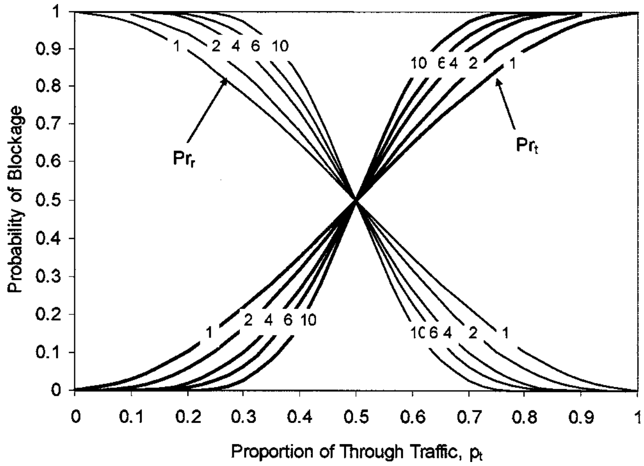

Fig. 2. Probability of blockage by through and right-turn vehicles

The case of $N=0$ (shared lane case) can be considered as a special short-lane case, where the probability of blockage by a through vehicle, Pr_t, is equivalent to the proportion of through traffic (p_t), i.e., the probability that the first vehicle at the stop line is a through vehicle. For $N>0$ this probability can be calculated as follows.

Consider the first $2N+1$ vehicles at the start of the red interval (no more vehicles are needed to cause the blockage). This is equivalent to the fact that a blockage is certain to occur when there are $2N+1$ vehicles arriving after the start of the red interval, regardless of the turning movement types for those vehicles. The number of through vehicles (n_t) among those $2N+1$ vehicles then follows a binomial distribution, where the arrival of a through vehicle can be considered as an event of success. The probability density function for n_t is given by the following equation:

$$f(n_t) = \binom{2N+1}{n_t}(1-p_t)^{2N+1-n_t}p_t^{n_t} \tag{1}$$

The blockage due to a through vehicle includes the cases when n_t is greater than N among $2N+1$ vehicles. Thus, the probability of blockage due to a through vehicle, Pr_t can be calculated using the following equation:

$$\mathrm{Pr}_t = \sum_{n_t=N+1}^{2N+1} f(n_t) \tag{2}$$

Similarly, the probability density function for the number of right-turn vehicles (n_r) is given by the following equation:

$$f(n_r) = \binom{2N+1}{n_r}(1-p_r)^{2N+1-n_r}p_r^{n_r} \tag{3}$$

The probability of blockage due to a right-turn vehicle is then

$$\mathrm{Pr}_r = \sum_{n_r=N+1}^{2N+1} f(n_r) \tag{4}$$

where $\mathrm{Pr}_t+\mathrm{Pr}_r=1$ holds. Fig. 2 illustrates the probabilities of blockage based on the proportion of through vehicles and the length of the right-turn lane.

As can be seen from Fig. 2, the probability of blockage due to a through vehicle, Pr_t, increases as the proportion of through vehicles, p_t increases. As the length of the right-turn lane (N) increases, Pr_t increases when the through traffic is dominant, but decreases when the right turn is dominant.

Average Number of Vehicles in Short Lane

When a blockage occurs due to a through vehicle, there might be $0-N$ vehicles in the right-turn lane as shown in Fig. 1 (where $N=3$). The average number of vehicles in the right-turn lane needs to be calculated for later capacity calculations. The event that a blockage occurs by a through vehicle is equivalent to the event that the $(N+1)$th through vehicle arrives after the start of the red interval. If x denotes the total number of vehicles on both lanes when a blockage occurs, x then follows a negative binomial distribution, and the probability density function of x is given by the following equation:

$$f(x) = \binom{x-1}{N}(1-p_t)^{x-(N+1)}p_t^{n+1} \tag{5}$$

While the expected value of x for a general negative binomial distribution can be calculated using the following equation, a slight modification on the following equation has to be made in this study, because x is only allowed to vary between $N+1$ and $2N+1$. The expected value of x, $E(x)$ should be calculated using Eq. (7)

$$E(x) = \sum_{x=N+1}^{\infty} xf(x) = (N+1)/p_t \tag{6}$$

$$E(x) = \sum_{x=N+1}^{2N+1} xf(x) \tag{7}$$

where

$$f(2N+1) = 1 - \sum_{x=N+1}^{2N} f(x) \tag{8}$$

The variance σ^2 (σ is the standard deviation) of x can then be calculated using the following:

$$\sigma^2 = \sum_{x=N+1}^{2N+1} [x-E(x)]^2 f(x) \tag{9}$$

The average number of vehicles in the right-turn lane can then be obtained by

$$E_r(x) = E(x) - (N+1) \tag{10}$$

Fig. 3 illustrates the relationship among the proportion of through vehicles, p_t, the length of the right-turn lane, N, and the average number of vehicles in the right-turn lane, $E_r(x)$.

As can be seen, $E_r(x)$ increases with increase in N, but decreases with increase in p_t. A nonlinear relationship can be observed among these parameters, contrary to the linear relationship as would be obtained using the German deterministic approach (Brilon et al. 1994).

Fig. 4 illustrates the standard deviations on the average number of vehicles on the right-turn lane. It can be seen that significant variations on $E_r(x)$ exist, especially when p_t is in the range between 0.6 and 0.8.

Using the same methodology, the average number of through vehicles in the short-lane section, $E_t(x)$, when blocked by right-turn vehicles, can be obtained. To ensure the mathematical accuracy of the probabilistic modeling approach, a model validation was conducted against the results from a Monte Carlo simulation model, which was documented in an earlier paper (Tian et al.

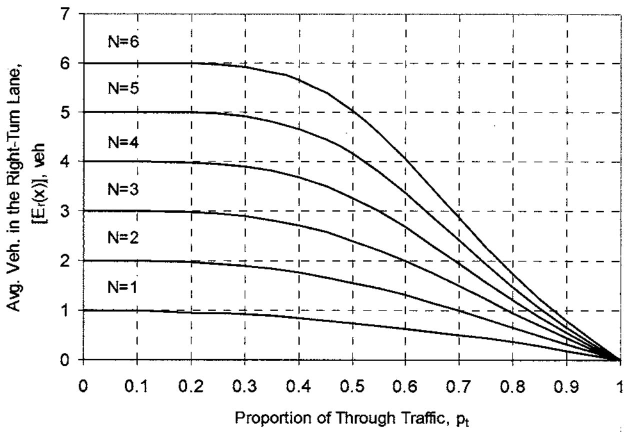

Fig. 3. Average number of vehicles in right-turn lane

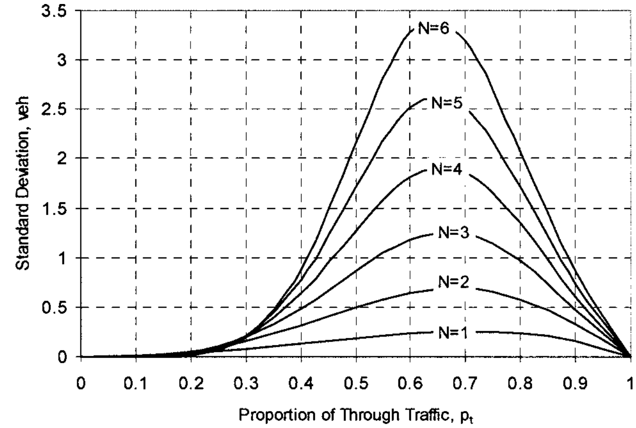

Fig. 4. Variations on average number of vehicles in right-turn lane

2001). Once the average number of vehicles in the short-lane section is obtained, capacity can be calculated based on the procedures described below.

Capacity Model Derivation

The green interval is divided into two portions. The first portion is to discharge the queue in the short-lane section, which includes N through vehicles and $E_r(x)$ right-turn vehicles (when blockage is by a through vehicle). The flow rate measured in vehicle per hour (also considered as the first portion of the total capacity) during the first portion of green, c_1', can be calculated using the following equation:

$$c_1' = \frac{3{,}600}{C}[E_r(x) + N] = \frac{3{,}600}{C}[E(x) - 1] \tag{11}$$

The length of the first portion of green, which is the time required to discharge the queue in the short-lane section, can be calculated using the following equation:

$$g' = \frac{N}{s_t}3{,}600 + t_s \tag{12}$$

An underlying assumption here is that the queue on the right-turn lane is discharged no later than that in the through lane.

The remaining portion of the green interval is to discharge the queue from the single-lane section, and the saturation flow rate from this single-lane section is assumed to be s_N. It is expected that s_N is greater than s_{sh}, the saturation flow rate for a through/right shared lane. Investigation on the flow discharging characteristics from the single-lane section and the determination of s_N are addressed later in the paper based on the results from the *CORSIM* simulation model.

The capacity for the second portion of green, c_1'' can be calculated using the following equation:

$$c_1'' = \frac{1}{C}\left(g - \frac{N}{s_t}3{,}600 - t_s + t_e\right)s_N \tag{13}$$

If the startup lost time t_s is equal to the effective green extension t_e, then

$$c_1'' = \frac{1}{C}\left(g - \frac{N}{s_t}3{,}600\right)s_N \tag{14}$$

Eqs. (13) and (14) are the basic capacity formula for signalized intersections, which include the three basic parameters of green time, cycle length, and saturation flow rate, i.e., capacity =(effective green)/(cycle length)×(saturation flow rate).

The total capacity under the case of blockage by a through vehicle can then be obtained from the following equation:

$$c_1 = c_1' + c_1'' \tag{15}$$

Similarly, the capacity when the blockage is by a right-turn vehicle can be obtained from the following equation:

$$c_2 = c_2' + c_2'' \tag{16}$$

where

$$c_2' = \frac{3{,}600}{C}[E(x) - 1] \tag{17}$$

$$c_2'' = \frac{1}{C}\left(g - \frac{N}{s_r}3{,}600\right)s_N \tag{18}$$

An underlying assumption for calculating c_1 and c_2 is that the green interval is long enough to clear the queues within the short-lane section. When N reaches a level that the green interval is no longer enough to clear the queues within the short-lane section, the capacity reaches its maximum, where c_1 and c_2 can be determined using the following equations. Capacity under such a condition would be close to the separate-lane capacity

$$c_1 = c_1' = \frac{3{,}600}{C}\left[\min\left(g\frac{s_r}{3{,}600}, E_r(x)\right) + g\frac{s_t}{3{,}600}\right]$$
$$= \frac{1}{C}\{\min[gs_r, 3{,}600E_r(x)] + gs_t\} \tag{19}$$

$$c_2 = c_2' = \frac{1}{C}\{\min[gs_t, 3{,}600E_t(x)] + gs_r\} \tag{20}$$

The term of min( ) in the above equations suggests that the minimum should be used between the number of vehicles in the blocked lane [e.g., $E_r(x)$] and the number of vehicles that could be discharged during time g.

The final approach capacity is then obtained from the following equation:

$$c_N = \mathrm{Pr}_t \times c_1 + \mathrm{Pr}_r \times c_2 \tag{21}$$

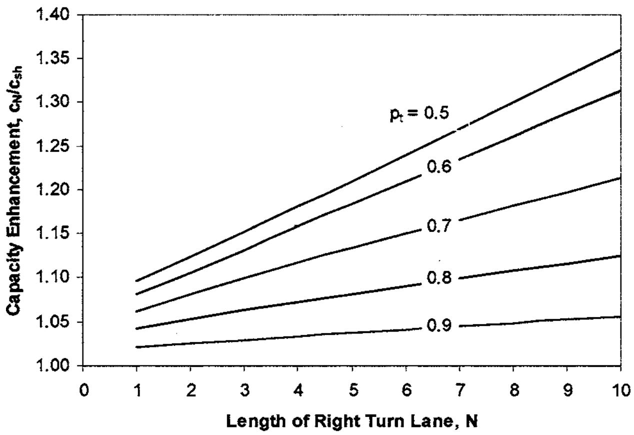

Fig. 5. Capacity enhancements

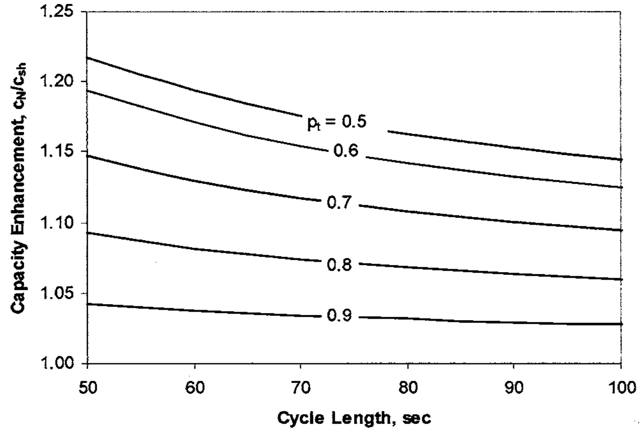

Fig. 6. Effect of cycle length on capacity enhancement (N=3)

Illustration of Capacity Results

To illustrate the effect of a short right-turn lane on capacity, we compare the capacity enhancement to the case with a shared through/right lane. The reason for selecting this approach is that the current capacity estimation procedures such as the HCM do not provide a realistic approach capacity when an exclusive right-turn lane exists. For example, the capacity is usually reported separately for the through lane group and the right-turn lane. The approach capacity where the right-turn lane exists as a pocket is not simply just the sum of the capacities of the two lane groups.

Capacity enhancement is calculated based on the ratio of the two capacity values, one with a short right-turn lane of length N, and the other with a shared through/right lane. The following basic parameters are used to generate the results

effective green, $g = 55$ s

cycle length, $C = 90$ s

saturation flow rate for a through movement,

$s_t = 1{,}900$ vehicles/h

saturation flow rate for a right-turn movement,

$s_r = 1{,}900 \times 0.85 = 1{,}615$ vehicles/h

Since the shared-lane capacity is the basis for capacity enhancement calculations, accurate capacity estimation for the shared-lane situation is critical. Capacity of a shared lane can be calculated using the basic capacity equation as shown in the following equation:

$$c_{sh} = \frac{g}{C} s_{sh} \tag{22}$$

In the HCM, a right-turn adjustment factor, f_{RT}, is used to calculate the saturation flow rate for a shared lane as shown in the following equations:

$$f_{RT} = 1.0 - 0.135 p_r \tag{23}$$

$$s_{sh} = f_{RT} s_t \tag{24}$$

Fig. 5 illustrates the capacity enhancement results based on different N and p_t values. The ideal saturation flow rate of 1,900 vehicles/h was used for s_N to generate the results.

The results in Fig. 5 indicate that the maximum capacity enhancement is achieved when p_t is 0.5, and the capacity enhancement ranges from 10 to 36% with N ranging between 1 and 10. The capacity enhancement is smaller with unbalanced turning movements. For example, with p_t at 0.9, the capacity enhancement ranges between 2 and 6%. The capacity equivalent to the separate-lane capacity would be reached when N is approximately 29 vehicles ($55/3{,}600 \times 1{,}900 = 29$).

The effect of cycle length under the short-lane situation is illustrated in Fig. 6. A constant g/C ratio is used to develop the results in Fig. 6. As can be seen from Fig. 6, the capacity enhancement diminishes with the increase in cycle length, i.e., the effectiveness of the short lane is reduced with longer cycle lengths. This can be explained by the fact that the number of vehicles departing from the short-lane section every cycle is independent to the cycle length [see Eq. (11)]. Therefore, a longer cycle length would result in a lower hourly departing rate (i.e., a lower capacity, c_1).

Model Validation Using Simulation

Validation of the proposed model was conducted using the commercially available *CORSIM* traffic simulation model. *CORSIM* is a microscopic simulation model widely used throughout the United States. Several studies have shown that *CORSIM* is a well-calibrated model to analyze surface street transportation facilities, including capacity and delay analyses at signalized intersections (Rouphail and Eads 1997; Zhang et al. 2001). Model validation using *CORSIM* would provide insight into whether the proposed model would yield reasonable results for practical applications. To be consistent with the proposed model, no right turn on red and no pedestrian crossing are assumed in the simulation.

The traffic volume and geometric data used for model validation is obtained from a real-world case located in Portland, Ore. This study case is described here to simply illustrate the importance of the proposed model in practical applications. The intersection of 162nd Street/Foster Road is a three-leg intersection. The eastbound approach on Foster Road currently has a shared through/right lane. Future projected traffic volumes after a proposed residential development include 990 vehicles/h of through traffic and 190 vehicles/h of right-turn traffic. For simplicity purposes, we assumed 100% passenger cars and ideal traffic conditions. A capacity analysis based on the HCM indicates that the eastbound approach will operate at over capacity with the existing geometry. Based on a 55 s green interval and a 90 s cycle length, the volume-to-capacity ratio for the eastbound approach is calculated at 1.05 based on the HCM method. If an exclusive right-turn lane is provided, the volume-to-capacity (v/c) ratio for through movement, which is the critical movement, would reduce to 0.85. Due to a steep slope and the adjacent property constraints, adding an additional right-turn lane would be very costly, so it was desirable to minimize the length of the right-turn pocket to the extent possible. The objective was to determine the minimum length for the right-turn pocket that would accommodate the projected traffic demand. It is noted that no field data on intersection capacity are available in this case since the study site is for future conditions. The primary reason for using simulation models for model validation is that a significant effort will be involved in data collection when validated using field data. For example, not only the study sites need to have appropriate geometry (e.g., different length of a right-turn pocket), it is also required that a constant queue and lane blockage exist on the intersection approach for the capacity to be measured.

The first task is to calibrate the basic *CORSIM* model for the shared lane and exclusive lane cases, so that the capacity results from *CORSIM* can match that from the HCM. Since *CORSIM* does not directly report capacity values, the capacity of a signalized approach is estimated based on the maximum flow rate that the approach can discharge given an oversaturated condition (Akcelik et al. 1999; Tian et al. 2001). Capacities from *CORSIM* and the HCM are compared for the shared-lane case and the exclusive lane case. Capacity for the exclusive lane case from *CORSIM* is obtained by actually coding a very long right-turn pocket. Consequently, capacity for the exclusive lane case based on the HCM is obtained using the following equation. Capacity obtained in such a way would be more practical since it maintains the fixed proportion of the turning movements

$$c_{ex} = c_T + c_T\frac{v_r}{v_t} \tag{25}$$

where c_{ex}=approach capacity with an exclusive right-turn lane (vehicles/h); and c_T=single lane capacity for the through movement (vehicles/h).

For the particular case used in this study, $c_T = g/C \times s_t = 55/90 \times 1{,}900 = 1{,}161$ vehicles/h and $c_{ex} = 1{,}161 + 1{,}161 \times 190/990 = 1{,}384$ vehicles/h. The shared lane capacity based on the HCM is $c_{sh} = g/C \times s_{sh} = 55/90 \times 1{,}859 = 1{,}136$ vehicles/h.

The calibrated *CORSIM* model yielded capacity with a single lane at 1,109 vehicles/h (versus 1,161 vehicles/h), and with an exclusive right-turn lane at 1,387 vehicles/h (versus 1,384 vehicles/h), which are considered to closely match the HCM results. Based on the calibrated *CORSIM* model, simulation runs were conducted for various lengths of the right-turn pocket (N=1–10). Thirty multiple runs were conducted and the average of these runs was obtained for each scenario. Fig. 7 illustrates the results based on capacity enhancement, a ratio of capacity with a short lane to the capacity with a shared lane. Variations on each run can also be observed.

The results in Fig. 7 indicate that the capacity enhancement appears to be close to a linear relationship. Capacity enhancement ranges between 1.05 (or 5%) and 1.19 (or 19%). These values seem to be much higher than that given by the proposed model, where the capacity enhancement ranges between 1.03 and 1.10.

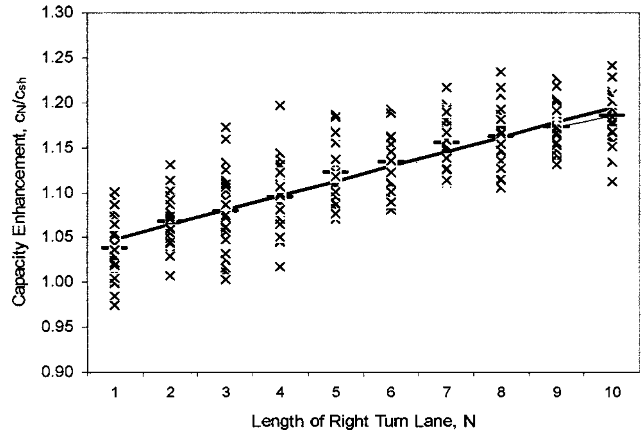

Fig. 7. Capacity enhancements based on *CORSIM*

Two sources might have contributed to such differences. The first possible source is that the average number of vehicles in the short lane in *CORSIM* is higher than what the proposed model predicts. This source of error seems unlikely if the traffic stream generated from *CORSIM* is truly random. Another possible source is that *CORSIM* may have produced higher saturation flow rates from the single-lane section (i.e., s_N is greater than 1,900 vehicles/h).

An investigation on the flow discharging characteristics from the single-lane section was conducted, which is discussed below.

1. Estimate the equivalent saturation flow rate for the single-lane through movement. This is achieved by using 100% through traffic in the calibrated single-lane *CORSIM* model. A capacity of 1,134 vehicles/h is obtained. Based on the green time (55 s) and the cycle length (90 s), the equivalent saturation flow rate for the single-lane through movement, s_t, is obtained using Eq. (22). In this case, s_t is calculated as 1,856 vehicles/h.
2. Estimate the saturation flow rate from the single-lane section. Based on the capacity results from *CORSIM* (C_N) for various N, and the average number of vehicles in the short lane $[E_r(x,N)]$, the saturation flow rate for the single-lane section, s_N, can be estimated using the following equation:

$$s_N = \left[c_N - E_r(x,N)\frac{3{,}600}{C} - N\frac{3{,}600}{C}\right]\frac{C}{\left(g - N\dfrac{3{,}600}{s_t}\right)} \tag{26}$$

Eq. (26) basically estimates the saturation flow rate for the single-lane section based on the capacity during the green portion when the vehicles are discharging from the single-lane section. This capacity, shown in the term

$$\left[c_N - E_r(x,N)\frac{3{,}600}{C} - N\frac{3{,}600}{C}\right]$$

is obtained by subtracting the number of vehicles in the short-lane section from the approach capacity. The length of the green portion is then $g - N(3{,}600/s_t)$. Fig. 8 is a plot of the ratios of $s_N:s_t$.

Fig. 8 indicates that *CORSIM* does yield higher saturation flow rates for the single-lane section. The saturation flow rate appears to increase linearly with the length of the short lane. It is believed that such a flow–discharging characteristic is a result of the car-following logic adopted in the *CORSIM* simulation model. According to various car-following models described by May (1990), saturation flow rate is a function of speed. That is why

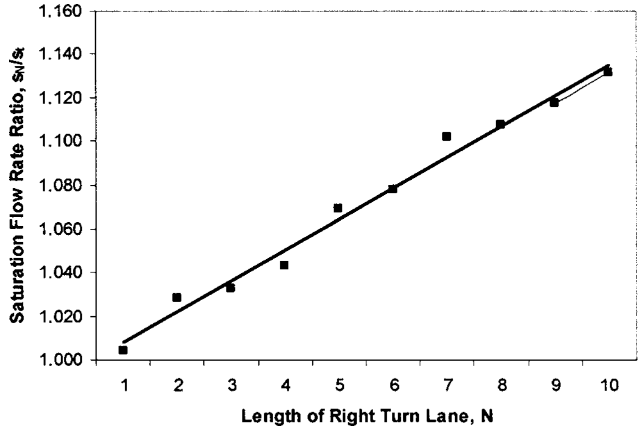

Fig. 8. Saturation flow rate ratio related to length of right-turn lane

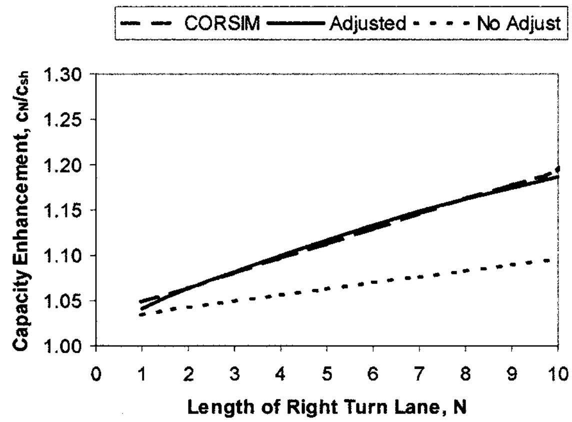

Fig. 9. Capacity enhancement results from *CORSIM* and proposed model

higher saturation flow rates exist on freeways than at signalized intersections. With the presence of a short right-turn lane, large gaps are created whenever a right-turn vehicle enters the right-turn lane. The resulting large gaps allow the following vehicles to accelerate and catch up with the leading vehicles, thus resulting in an increased saturation flow rate from the single-lane section. However, further validation on such a flow discharging characteristic should be conducted in the field.

With the adjusted saturation flow rate, s_N, based on the *CORSIM* results, the capacity enhancement is recomputed using the proposed model. Fig. 9 illustrates the final model validation results. Capacity enhancement results from both the proposed model and *CORSIM* are plotted. Two results from the proposed model are shown in the figure. One is without adjustment on the saturation flow rate for the single-lane section, where s_N is taken as s_t, and the other is with adjustment, where s_N is determined based on the regression results from Fig. 7.

It can be seen in Fig. 9 that when the values of s_N from *CORSIM* are used in the proposed model, capacity enhancement results from the proposed model match closely with that given by *CORSIM*. The errors between the two models are within 1%.

Pedestrian Crossing and Right Turn on Red

The proposed capacity estimation model in this study does not specifically consider the impact of pedestrian crossing and the vehicles making right turn on red. These two issues are briefly addressed below.

Pedestrian Crossing

The existence of pedestrian crossings will result in conflicts between pedestrians and right-turn vehicles, thus affecting the saturation flow rate for the right turn vehicles. The impact of pedestrian crossings will be reflected by the calculation of g' as shown in Eq. (12) and s_N as shown in Fig. 8. As pointed out earlier, the underlying assumption of Eq. (12) is that the queue on the right-turn lane is discharged no later than that in the through lane. As long as this condition holds when pedestrian crossings are present, the proposed capacity model remains valid. However, if the level of pedestrian crossing eventually affects the right turn movement and results in longer time to discharge the queue in the right-turn lane, g' should then be calculated using the following equation:

$$g' = \max\left[\frac{N}{s_t}3{,}600 + t_s, \frac{E_r(x)}{s_r}3{,}600 + t_s\right] \tag{27}$$

Eq. (11) should also be adjusted to account for the additional through vehicles discharged beyond N.

The calculation of s_N may no longer follow the relationship as shown in Fig. 8. A conservative capacity estimation would be to use s_t in the model.

Right Turn on Red

Right-turn vehicles making turns on red (right turn on red) would have some effects on the calculations of the probability of blockages. However, right turn on red would affect the model result only if the blockage is by right-turn vehicles, a case most likely to occur when the proportion of right-turn volume is relatively high. The number of vehicles making right turn on red can be estimated using the model proposed by Tarko (2001), however, the capacity model for the short-lane case would become more complicated, which is beyond the scope of this study.

When the blockage is by a through vehicle, vehicles making a right turn on red would not increase the capacity since the number of vehicles discharging during the first portion of the green interval remains the same.

Summary and Conclusions

The paper introduces a capacity estimation model under the conditions where the approach at a signalized intersection has a short right-turn lane. The model takes into account the probabilistic nature of queue blockage of the short lane, and the effect of such queue blockage on capacity is specifically modeled from a probabilistic point of view. The study resulted in the following conclusions:

1. The proposed model proves to be accurate and reliable based on validation using the *CORSIM* microscopic simulation model. In the case tested using *CORSIM*, the errors on capacity enhancement are within 1% when identical saturation flow rates are used in both models.
2. The proposed model provides an enhancement to the current HCM capacity estimation methodology for signalized intersections. The current HCM methodology treats the short right-turn lane case as if having an infinite length, which for

many situations significantly overestimates capacity for the approach.

3. Results from both the proposed model and simulation indicate that large variations exist on the capacity values under the short-lane situation. The variation reaches the maximum when the proportion of through traffic is between 60 and 80%. The proposed model eliminates the significant effort involved in simulation modeling where multiple runs are necessary to yield a good estimate.
4. An important parameter involved in the proposed model is the saturation flow rate from the single-lane section of an approach with a short right-turn lane. Results from the *CORSIM* model indicate that the saturation flow rate increases when the right-turn lane increases. Such a flow discharging characteristic can be somewhat explained by the car-following theory, but needs further validation in the field. However, a significant enhancement and understanding of saturation flow characteristics may be achieved if field study does verify this finding from this study.
5. While the proposed probabilistic modeling approach provides a good starting point to address the complexity of the short-lane issue, further enhancements to the current model are necessary to make the model practically feasible. Such areas have been identified and discussed in the paper, including the effect of right turn on red, pedestrians, and consideration of mixed vehicle types.

Notation

The following symbols are used in this paper:

C = cycle length (s);
c = total approach capacity (vehicles/h);
c_N = approach capacity with short right-turn lane of length N vehicles (vehicles/h);
c_1 = capacity when blockage is due to through vehicles (vehicles/h);
c_2 = capacity when blockage is due to right turn vehicles (vehicles/h);
$E(x)$ = average number of vehicles in both lanes in short-lane section when blockage occurs (vehicles);
$E_r(x)$ = average number of vehicles in the right-turn lane when blocked by through vehicles (vehicles);
$E_t(x)$ = average number of vehicles in through lane when blocked by right-turn vehicles (vehicles);
g = length of green interval (s);
N = length of the right-turn pocket (vehicles);
Pr_r = probability of short-lane blockage due to right-turn vehicles;
Pr_t = probability of short-lane blockage due to through vehicles;
p_r = proportion of right-turn traffic, $1-p_t=v_r/(v_t+v_r)$;
p_t = proportion of through traffic, $v_t/(v_t+v_r)$;
s_N = saturation flow rate from single-lane section after split (vehicles/h);
s_r = saturation flow rate for right-turn lane (vehicles/h);
s_{sh} = saturation flow rate for shared through/right lane (vehicles/h);
s_t = saturation flow rate for through lane (vehicles/h);
t_e = effective green extension (s);
t_s = startup lost time (s); and
v_r, v_t = right turn and through volumes (vehicles/h).

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