

CAPACITY AT SIGNALIZED INTERSECTION APPROACH WITH A SHORT RIGHT-TURN LANE

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Zong Tian, Ning Wu, and Mark Vandehey

Abstract

The paper presents the findings of a study on the development of a capacity model for a signalized intersection approach with a short right-turn lane. The model takes into account of the stochastic nature of traffic flow and the effect of queue blockage to the short right-turn lane. The proposed model provides enhancements to the current Highway Capacity Manual methodology where the short-lane issue has not been addressed. The research showed that the capacity of a signalized intersection approach with a short right-turn lane is strongly related to the length of the right-turn lane, the proportion of through or right-turn vehicles, and cycle length. The study also found that CORSIM, the simulation model used in the model validation, yields higher saturation flow rates for the single lane section (i.e., the point where the right-turn lane splits) when a short right-turn lane is present. Such a flow-discharging characteristic is perhaps due to the nature of car-following models. Based on the case tested, the capacity enhancement with a short right-turn lane ranges between 5 to 19 percent compared to the shared-lane situation. Such capacity enhancements are contributed by both the short-lane usage and the increased saturation flow rate from the single-lane section. The proposed model yields capacity enhancement results within 1 percent error compared to the results from CORSIM.

Key Words: *Short Right-Turn Lane, Capacity, Simulation*

Introduction

At signalized intersections, a right-turn lane often exists in the form of a short lane or a right-turn pocket. The methodology to estimate capacity and control delay included in the Highway Capacity Manual (HCM) [1] treats the short right-turn lane as an exclusive lane. Such a treatment neglects the potential effect of queue blockage in situations where short turn lanes are present. Without queue blockages, the approach would operate as if there were an exclusive lane. However, when traffic demand does cause queue blockages to the short-lane section, the capacity of the approach is reduced. The current HCM procedure would overestimate capacity and 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.

Estimating the appropriate length for right turn lanes can be important in situations where it is expensive (due to topographic or right-of-way constraints) to increase the length of existing right turn lanes or construct new right turn lanes. While traffic engineers could use simulation models as an alternative, capacity is usually not a direct output from simulation. The large variations on capacity and delay with a short-lane case often require multiple simulation runs in order to yield a reasonable mean value.

There has been a very limited amount of research conducted on this topic. To our best knowledge, the only available documents where the short-lane issue has been addressed include the German Highway Capacity Manual [2] and the SIDRA [3] software package. The models included in both documents are deterministic models. The stochastic nature of blockage to the short lane does not appear to have been addressed to date. The purpose of this paper is to introduce a capacity estimation model for the short-lane case based on probabilistic and statistical theory. The model takes into account the short-lane effect, and the stochastic nature of queue blockage. The proposed model was validated using the CORSIM [4] microscopic simulation model. Delay estimation under a short right-turn lane situation is not part of this paper, and will be addressed in a separate study.

Proposed Capacity Model

The goal of the research is to develop a mathematical model to estimate the capacity of a signalized intersection approach with a short right-turn lane. 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 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 is usually assumed. In the case of this research, 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 right-turn lane is always blocked at the start of the green interval.

For the purpose of model derivation in this study, 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 would be applied to estimate a lane-based capacity. The effects of right-turn on red are not considered in the model, but will be addressed later in the paper.

The parameters used for model derivation are given below. All the vehicles are assumed to be passenger cars.

C	= cycle length, sec
N	= length of the right-turn pocket, vehicles
v_r, v_t	= right turn and through volumes, veh/hr
g	= length of green interval, sec
s_t	= saturation flow rate for a through lane, veh/hr
s_r	= saturation flow rate for a right-turn lane, veh/hr
s_{sh}	= saturation flow rate for a shared through/right lane, veh/hr
s_N	= saturation flow rate from the single-lane section after the split, veh/hr
t_s	= start-up lost time, sec
t_e	= effective green extension, sec
c	= total approach capacity, veh/hr

- c_1 = capacity when the blockage is due to through vehicles
 c_2 = capacity when the blockage is due to right turn vehicles
 c_N = approach capacity with a short right-turn lane of length N , veh
 p_t = proportion of through traffic, $v_t/(v_t + v_r)$
 p_r = proportion of right-turn traffic, $1 - p_t = v_r/(v_t + v_r)$
 Pr_t = probability of short-lane blockage due to through vehicles
 Pr_r = probability of short-lane blockage due to right-turn vehicles
 $E(x)$ = average number of vehicles in both lanes in the short-lane section when blockage occurs, veh
 $E_r(x)$ = average number of vehicles in the right-turn lane when blocked by through vehicles, veh
 $E_t(x)$ = average number of vehicles in the through lane when blocked by right-turn vehicles, veh

Probability of Blockage

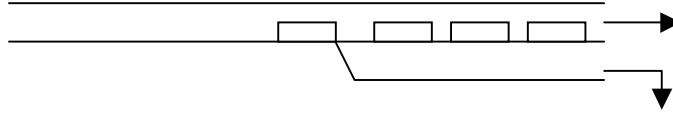
Considering the cases as shown in Figure 1 where the blockage is due to through vehicles. The length of the right-turn lane is N ($N = 3$ in this case). If we assume that a right-turn vehicle following the N^{th} through vehicle can still get into the right-turn lane position (design of the transition section for a right-turn lane normally allows enough space for this to occur), then the blockage due to a through vehicle is equivalent to the $(N+1)^{\text{th}}$ (4^{th} in this case) through vehicle arriving at the intersection.

For the case of $N = 0$ (shared lane case), the probability (Pr_t) of blockage due to through vehicles is simply the proportion of through traffic (p_t). For $N > 0$ this probability can be calculated as follows.

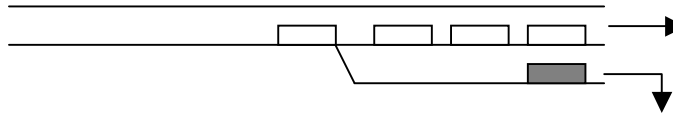
Consider the first $2N + 1$ vehicles after the green interval (no more vehicles are needed to cause the blockage). The number of through vehicles (n_t) then follows a binomial distribution, where the arrival of a through vehicle can be considered as an event of success. The probability density function for n_t is given by *Equation (1)*.

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

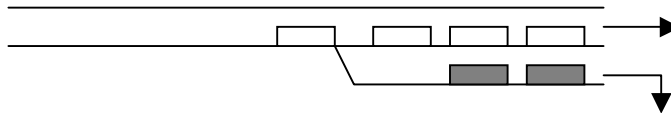
Case 1: No car in the right-turn lane



Case 2: One car in the right-turn lane



Case 3: Two cars in the right-turn lane



Case 4: Three cars in the right-turn lane

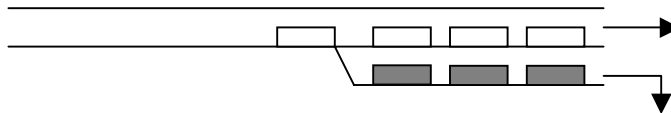


Figure 1 Number of Vehicles in the Right-Turn Lane When Blocked by Through Vehicles

The blockage events due to through vehicles include the cases when n_t is greater than N among $2N + 1$ vehicles. Thus, the probability of blockage due to through vehicles (Pr_t) can be calculated using *Equation (2)*.

$$Pr_t = \sum_{n_t=N+1}^{2N+1} f(n_t) \quad (2)$$

Similarly, the probability density function for the number of right-turn vehicles (n_r) is given by *Equation (3)*.

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

The probability of blockage due to right-turn vehicles is then

$$Pr_r = \sum_{n_r=N+1}^{2N+1} f(n_r) \quad (4)$$

Where $Pr_t + Pr_r = 1$ holds. Figure 2 illustrates the probabilities of blockage based on the proportion of through vehicles and the length of the right-turn lane.

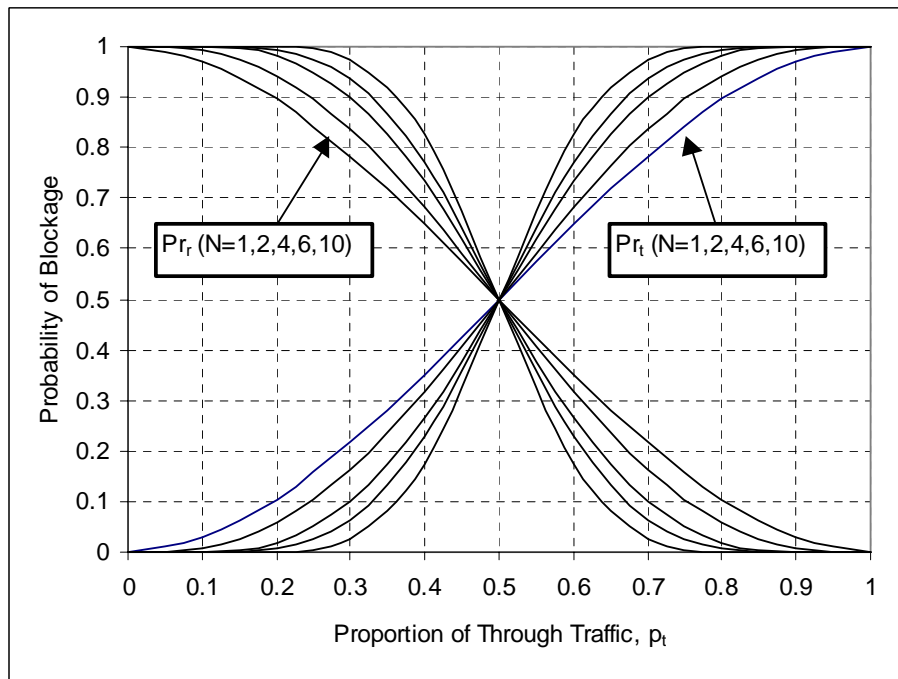


Figure 2 Probability of Blockage by Through and Right-Turn Vehicles

Figure 2 shows that the probability of blockage due to through vehicles (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 the Short Lane

When a blockage occurs due to through vehicles, there might be 0 to N vehicles in the right-turn lane as shown in Figure 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 through vehicles is equivalent to the event that the $(N + 1)^{th}$ arrival is a through vehicle. 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 *Equation (5)*.

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

While the expected value of x for a general negative binomial distribution can be calculated using *Equation (6)*, a slight modification on *Equation (6)* 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 *Equation (7)*.

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

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

where

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

The variance σ^2 (σ is the standard deviation) of x can then be calculated using *Equation (9)*.

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

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

$$E_r(x) = E(x) - (N+1) \quad (10)$$

Figure 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, $E_r(x)$.

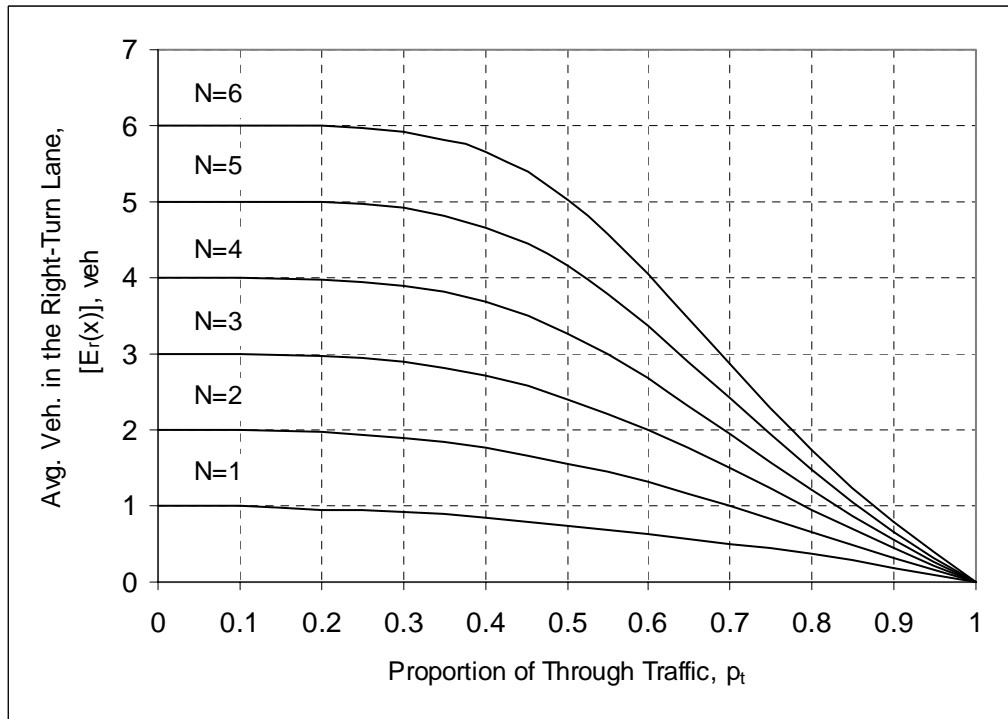


Figure 3 Average Number of Vehicles in the Right-Turn Lane

As can be seen, $E_r(x)$ increases with increases in N , but decreases with increases in p_t . A

non-linear relationship can be observed among these parameters, contrary to the linear relationship as would be obtained using the German deterministic approach [2].

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

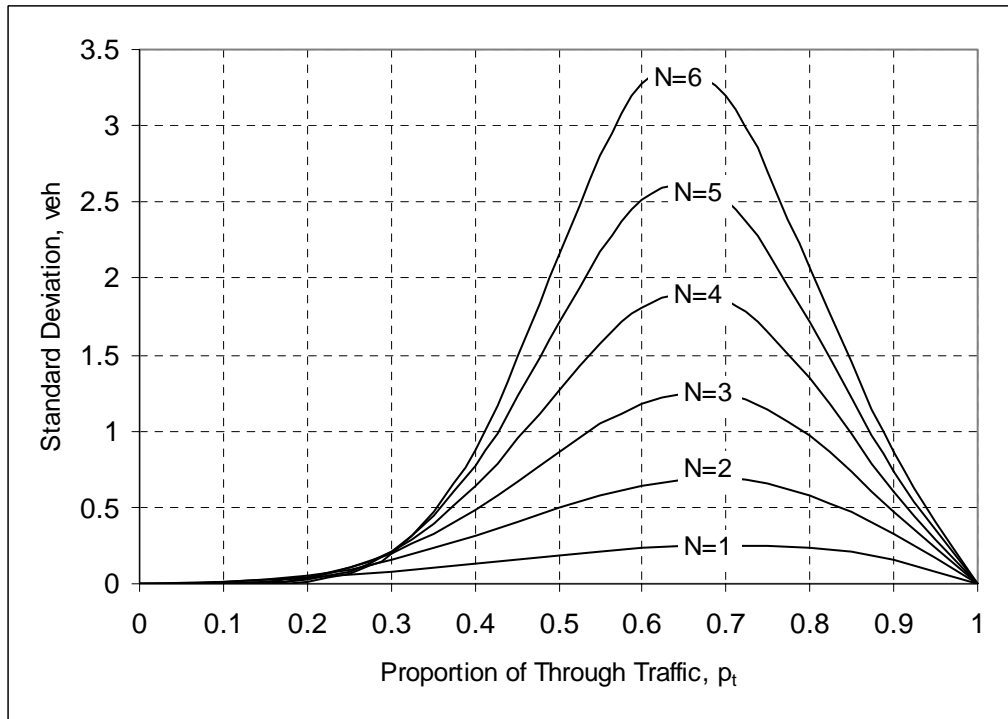


Figure 4 Variations on the Average Number of Vehicles in the Right-Turn Lane

Using the same methodology, the average number of through vehicles in the short-lane section, $E_r(x)$, when blocked by right-turn vehicles can be obtained. 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

(blockage is by through vehicles). The capacity during the first portion of green, c_1' , can be calculated using *Equation (11)*.

$$c_1' = \frac{3600}{C} [E_r(x) + N] = \frac{3600}{C} [E(x) - 1] \quad (11)$$

The length of the first portion of green, which is the time to discharge the queue in the short-lane section, can be calculated using *Equation (12)*.

$$g' = \frac{N}{s_t} 3600 + t_s \quad (12)$$

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 CORSIM simulation model.

The capacity for the second portion of green, c_1'' can be calculated using *Equation (13)*.

$$c_1'' = \frac{I}{C} \left(g - \frac{N}{s_t} 3600 - t_s + t_e \right) s_N \quad (13)$$

If the start-up lost time t_s is equal to the effective green extension t_e , then

$$c_1'' = \frac{I}{C} \left(g - \frac{N}{s_t} 3600 \right) s_N \quad (14)$$

The total capacity can then be obtained by *Equation (15)*.

$$c_1 = c_1' + c_1'' \quad (15)$$

Similarly, the capacity when the blockage is due to right-turn vehicles can be obtained from *Equation (16)*.

$$c_2 = c_2' + c_2'' \quad (16)$$

where

$$c_2' = \frac{3600}{C} [E(x) - 1] \quad (17)$$

$$c_2'' = \frac{1}{C} \left(g - \frac{N}{s_r} 3600 \right) s_N \quad (18)$$

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 to 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 *Equations (19)* and *(20)*. Capacity under such a condition would be close to the separate-lane capacity.

$$c_1 = c_1' = \frac{1}{C} [\min(g s_r, 3600 E_r(x)) + g s_t] \quad (19)$$

$$c_2 = c_2' = \frac{1}{C} [\min(g s_t, 3600 E_t(x)) + g s_r] \quad (20)$$

The approach capacity is then obtained from *Equation (21)*.

$$c_N = Pr_t \times c_1 + Pr_r \times c_2 \quad (21)$$

Effect of Short Right-Turn Lane on Capacity

To illustrate the effect of a short right-turn lane on capacity, the case with a shared through/right lane is selected as the basis for comparison. 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, $g = 55$ sec

cycle length, $C = 90$ sec

saturation flow rate for a through movement, $s_t = 1900$ vph

saturation flow rate for a right-turn movement, $s_r = 1900 \times 0.85 = 1615$ vph

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 following basic capacity equation included in the HCM.

$$c_{sh} = \frac{g}{C} s_{sh} \quad (22)$$

The HCM method uses a right-turn adjustment factor, f_{RT} to calculate the saturation flow rate for a shared lane. It is noted, however that the equation to calculate f_{RT} is changed from the 1997 HCM as shown in *Equation (23)* to the 2000 HCM as shown in *Equation (24)*.

$$f_{RT} = 0.9 - 0.135 p_r \quad (23)$$

$$f_{RT} = 1.0 - 0.135 p_r \quad (24)$$

If we assume 20% right-turn vehicles in the shared lane, the change on f_{RT} calculation would result in the saturation flow rate for a shared lane being increased from 1660 vph (1997 HCM) to 1850 vph (2000 HCM), representing an approximate 12% increase in

capacity. Since no research has been found to justify the improved accuracy for the 2000 HCM method, caution should be used in reporting capacity enhancement results. In this study, capacity enhancements over the shared-lane case are based on the 2000 HCM results.

Figure 5 illustrates the capacity enhancement results based on different N and p_t values. The ideal saturation flow rate for the through movement (1900 vph) was used for s_N to generate the results.

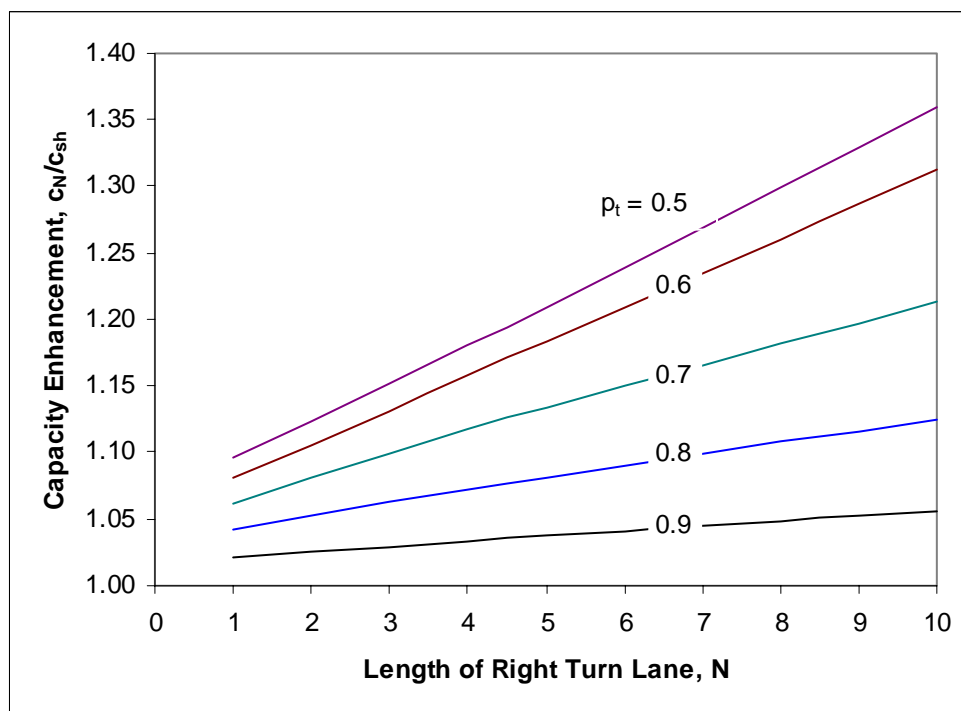


Figure 5 Capacity Enhancements

The results in Figure 5 indicate that the maximum capacity enhancement is achieved when p_t is 0.5, and the capacity enhancement ranges from 10 to 36 percent with N ranging between 1 and 10. Less capacity enhancement results from unbalanced turning movements. For example, with p_t at 0.9, the capacity enhancement ranges from 2 to 6

percent. The capacity equivalent to the separate-lane capacity would be reached when N is approximately 29 vehicles ($55/3600 \times 1900 = 29$).

The effect of cycle length under the short-lane situation is illustrated in Figure 6. A constant g/C ratio is used to develop the results in Figure 6. As can be seen from Figure 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.

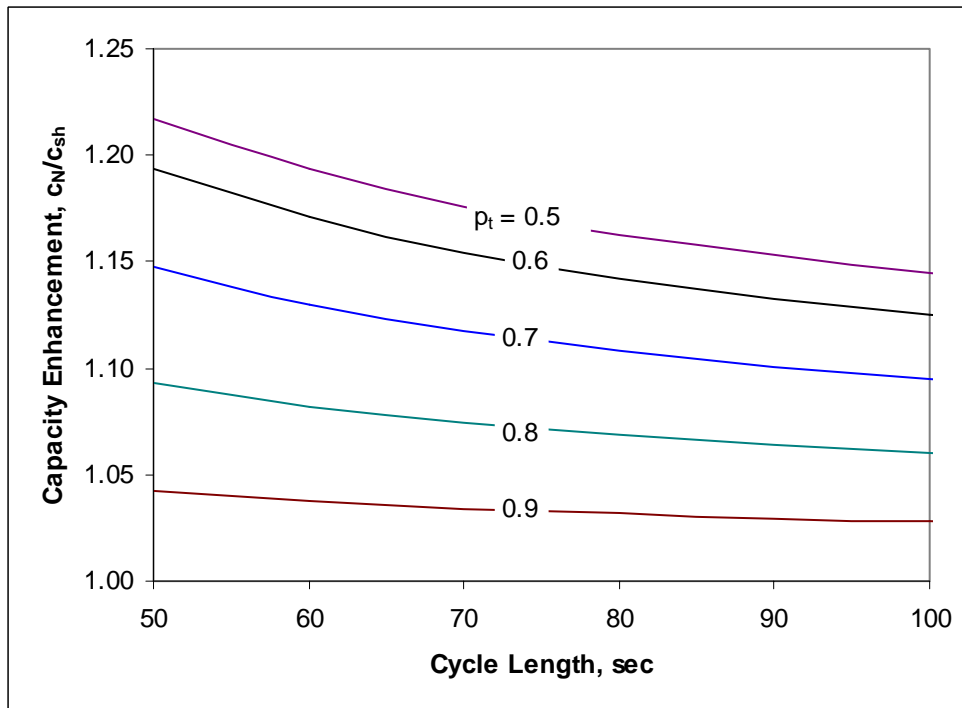


Figure 6 The Effect of Cycle Length on Capacity Enhancement ($N=3$)

Model Validation Using Simulation

Validation of the proposed model was conducted in two steps. The first step was to verify (in a mathematical sense) the accuracy of the proposed model using a simple simulation model developed during this study. The second step was to compare the results with the popular CORSIM traffic simulation model.

The data used for model validation is derived from a real-world case located in Portland, Oregon. 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 per hour (vph) of through traffic and 190 vph 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-sec green interval and a 90-sec cycle length, the volume-to-capacity ratio for the eastbound approach is calculated at 1.05 based on the 2000 HCM method and 1.16 based on the 1997 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 grade and the adjacent property constraints, adding an additional right-turn lane would be very costly, so it was desired 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. Model validation was focused on this eastbound approach.

Step 1: Model Validation on Mathematical Accuracy

The purpose of model validation in this step was to verify that the parameters given by the proposed model were mathematically correct, such as the probability of blockage (Pr_t , Pr_r), the average number of vehicles in the short lane [$E_r(x)$], and the standard deviation (σ). A simple simulation model was developed in this study to perform the test. The simulation model generates 10,000 events of blockage based on the proportions of through and right-turn traffic, and different length of the right-turn pocket. Each blockage event would represent an actual cycle of a signalized intersection.

Table 1 summarizes the results from the simulation model and the proposed model. Table 1 indicates that the results from simulation matched well with the proposed model. For the data used in this case where the proportion of through traffic is 0.84, the majority of blockages are due to through vehicles. The difference in predicting Pr_t and Pr_r is within 0.002. The difference in $E_r(x)$ is within 0.057. Higher errors are observed on $E_r(x)$ where the maximum error is found to be 1.384 (when $N = 7$). The higher error in $E_r(x)$ is mainly due to the limited number of observations as indicated by the small values on Pr_r ,

(blockage by a right-turn vehicle is a rare event). Despite the high errors in $E_r(x)$, the final capacity calculation would be negligibly affected due to the small probability of such an event. High variations on both $E_r(x)$ and $E_l(x)$ are also observed from both simulation and the proposed model.

Table 1 Results from Simulation and Proposed Models

Statistics		Length of Right-Turn Lane, N									
		1	2	3	4	5	6	7	8	9	10
Pr _l	M'	0.931	0.968	0.985	0.993	0.996	0.998	0.999	1.000	1.000	1.000
	S	0.933	0.969	0.986	0.993	0.996	0.998	0.999	1.000	1.000	1.000
	Diff	-0.002	-0.001	-0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Pr _r	M	0.069	0.032	0.015	0.007	0.004	0.002	0.001	0.000	0.000	0.000
	S	0.067	0.031	0.014	0.007	0.004	0.002	0.001	0.000	0.000	0.000
	Diff	0.002	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000
E _r (x)	M	0.294	0.530	0.742	0.942	1.138	1.331	1.522	1.714	1.904	2.095
	S	0.237	0.486	0.705	0.914	1.104	1.327	1.499	1.722	1.896	2.112
	Diff	0.057	0.044	0.037	0.028	0.034	0.004	0.023	-0.008	0.008	-0.017
S.D.	M	0.208	0.495	0.783	1.055	1.313	1.559	1.797	2.031	2.262	2.491
E _r (x)	S	0.425	0.663	0.841	0.982	1.117	1.230	1.309	1.436	1.496	1.578
	Diff	-0.217	-0.168	-0.058	0.073	0.196	0.329	0.388	0.595	0.766	0.813
E _l (x)	M	0.974	1.981	2.989	3.994	4.997	5.998	6.999	7.999	9.000	9.999
	S	0.604	1.466	2.312	3.074	3.974	5.087	5.615	7.667	8.000	9.500
	Diff	0.370	0.415	0.567	0.920	1.023	0.911	1.384	0.332	1.000	0.499
S.D.	M	0.025	0.026	0.019	0.012	0.007	0.004	0.002	0.001	0.001	0.000
E _l (x)	S	0.489	0.691	0.871	1.124	1.026	1.276	1.261	0.577	1.732	0.707
	Diff	-0.464	-0.665	-0.852	-1.112	-1.019	-1.272	-1.259	-0.576	-1.731	0.707

Note: M – Proposed Model, S – Simulation

Step 2: Model Validation Using CORSIM

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 [5,6]. Model validation using CORSIM would provide insight on whether

the proposed model would yield reasonable results for practical applications. To be consistent with the proposed model, no right-turn-on-red is allowed in the simulation.

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 2000 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 [7,8]. Capacities from CORSIM and the 2000 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 from the HCM is obtained using *Equation (25)*. Capacity obtained in such a way would be more practical since it maintains the fixed proportion of the turning movements.

$$c_{ex} = c_T + c_T \frac{v_r}{v_t} \quad (25)$$

where c_{ex} = approach capacity with an exclusive right-turn lane, vph

c_T = single lane capacity for the through movement, vph

For the particular case used in this study, $c_T = g/C \times s_t = 55/90 \times 1900 = 1161$ vph, and $c_{ex} = 1161 + 1161 \times 990/190 = 1384$ vph. The shared lane capacity based on the HCM 2000 is $c_{sh} = g/C \times s_{sh} = 55/90 \times 1859 = 1136$ vph.

The calibrated CORSIM model yielded capacity with a single lane at 1109 vph, and with an exclusive right-turn lane at 1387 vph, which are considered to match closely to the HCM results. Based on the calibrated CORSIM model, simulation runs were conducted for various lengths of a right-turn pocket ($N = 1 \sim 10$). Again, 30 multiple runs were automatically conducted and the average of these runs were obtained for each scenario. Figure 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 shown in Figure 7 indicate that the capacity enhancement appears to be close to a linear relationship. Capacity enhancement ranges between 1.05 (or 5 percent) and 1.19 (or 19 percent). These numbers seem to be much higher than that given by the proposed model, where the capacity enhancement ranges between 1.03 and 1.10. 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 seems unlikely if the traffic stream generated from CORSIM is truly random. The mathematical accuracy of the proposed model has been proven as shown in *Step 1* of the model validation. Another possible source is that CORSIM may have produced higher saturation flow rates from the single-lane section.

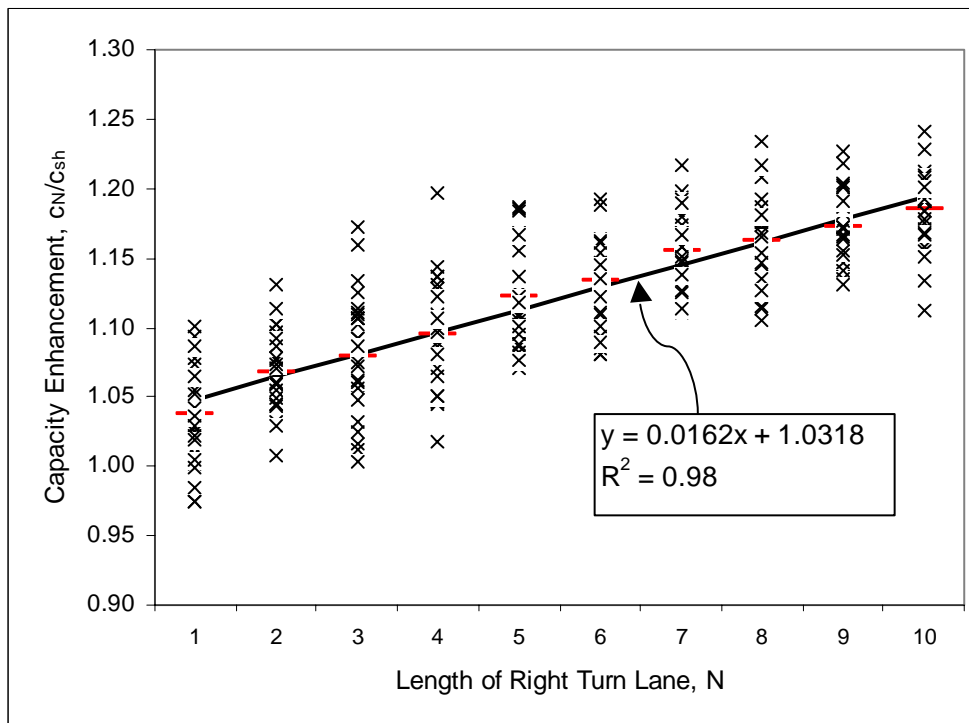


Figure 7 Capacity Enhancements based on CORSIM

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 1134 vph is obtained. Based on the green time (55 sec) and the cycle length (90 sec), the equivalent saturation flow rate for the single-lane through movement, s_t is obtained using *Equation (22)*. In this case, s_t is calculated as 1856 vph.

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 *Equation (26)*.

$$s_N = [c_N - E_r(x, N) \frac{3600}{C} - N \frac{3600}{C}] \frac{C}{(g - N \frac{3600}{s_t})} \quad (26)$$

Equation (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 $[c_N - E_r(x, N) \frac{3600}{C} - N \frac{3600}{C}]$ 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 $g - N \frac{3600}{s_t}$. Figure 8 is a plot of the ratios of s_N to s_t .

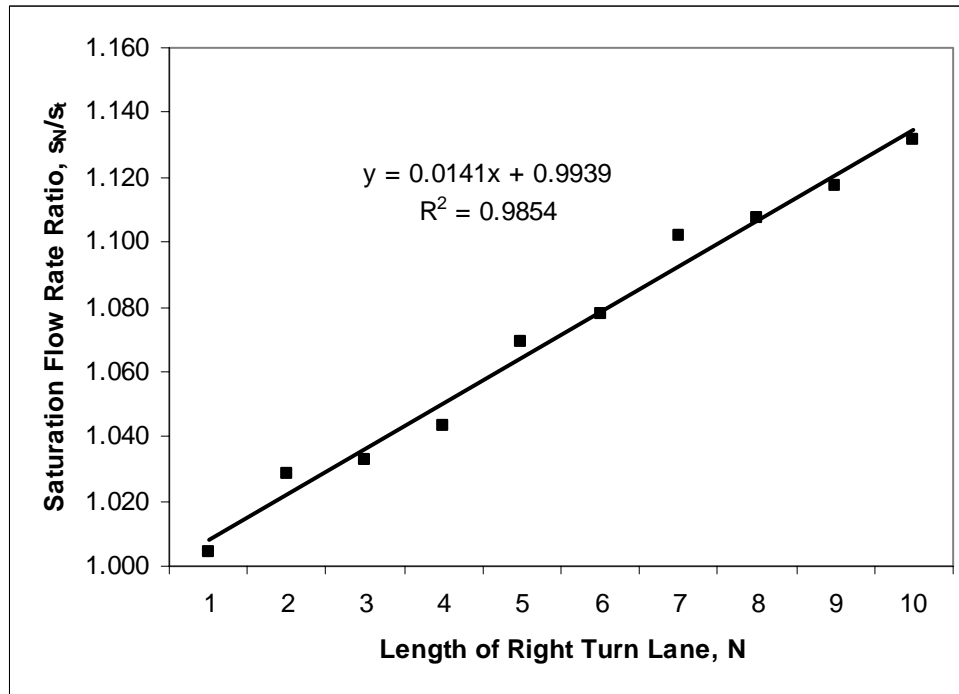


Figure 8 Saturation Flow Rate Ratio Related to Length of Right-Turn Lane

Figure 8 indicates that CORSIM does yield higher saturation flow rates for the single-lane section. The saturation flow rate increases 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 [9], saturation flow rate is a function of speed. Compared to the saturation flow rate at freeways, the lower saturation flow rate at signalized intersections is mainly contributed by the lower speeds. With the presence of a short right-turn lane, large gaps are created whenever a right-turn vehicle enters the right-turn lane. The resulted large gaps allow the following vehicles to accelerate and catch up with the leading vehicles. When discharging flow rate is measured at the stop line, the flow rate from the through lane would not be much less than the saturation flow rate. Thus, an increased saturation flow rate from the single-lane section results. Further validation in the field should be conducted. An important enhancement and understanding of saturation flow rate characteristics would be achieved if field data can verify the finding.

Figure 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 Figure 7.

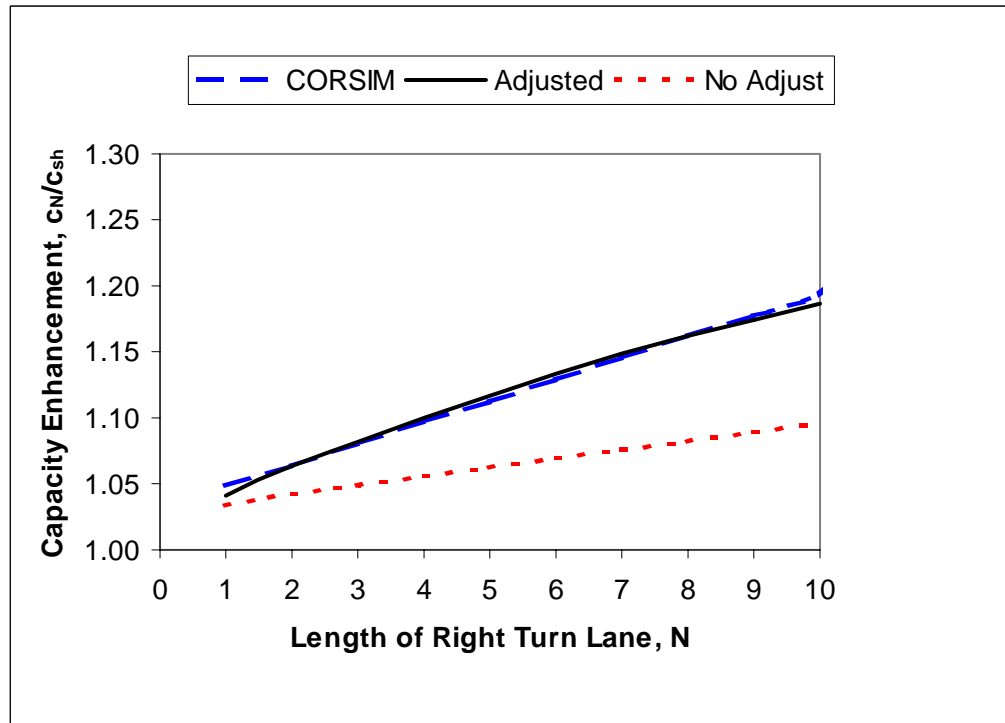


Figure 9 Capacity Enhancement Results from CORSIM and the Proposed Model

It can be seen in Figure 10 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 percent.

Pedestrian and Right-Turn-on-Red

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

Pedestrian Crossing

The impact of pedestrian crossings will be reflected by the calculations of g' as shown in *Equation (12)* and s_N as shown in Figure 8. As pointed out earlier that the underlying assumption of *Equation (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.

$$g' = \max\left[\frac{N}{s_t} 3600 + t_s, \frac{E_r(x)}{s_r} 3600 + t_s\right] \quad (27)$$

Equation (11) should also be adjusted to account for the extra discharging through vehicles beyond N .

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

Right-Turn-on-Red

Right-turn-on-red would affect the capacity result only if the blockage is by a right-turn vehicle, a case 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 [10], 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 right-turn-on-red would not increase the capacity since the number of vehicles discharging during the first portion of 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 of the stochastic nature of queue blockage of the short lane, and the effect of such queue blockage on capacity is specifically addressed from probabilistic point of view. The study resulted in the following conclusions:

- The proposed model proves to be accurate and reliable based on validation using microscopic simulation model. The model accurately estimates the probabilities of blockage, and the average number of vehicles in the short lane. In the case tested using CORSIM, the errors on capacity enhancement are within 1 percent when identical saturation flow rates are used in both models.
- 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.
- 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 percent. The proposed model eliminates the significant effort involved in simulation modeling where multiple runs are necessary to yield a reasonable average value.
- 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 with the right-turn lane increases. Such flow discharging characteristics can be somewhat explained by the car-following theory, but need further study using field data. However, a significant enhancement and understanding of saturation flow characteristics may be achieved if field study does verify the above finding from this study.

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