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Determination of storage lengths of right-turn lanes at signalized intersections

By Jinghui Wang Lei Yu Hui Xu

ABSTRACT

This paper develops an analytical method of determining storage lengths of right-turn lanes at signalized intersections based on Queuing Theory Principle. The models of the storage length for two cases (Right-Turn-On-Red (RTOR) and No RTOR) are respectively developed, considering two situations: a. overflow: the right-turn vehicles overflow the lane and block the movement of the through-vehicles; and b. blockage: the queued through vehicles block the entrance of right-turn vehicles. The study investigates the effect of saturation ratio on the storage length to explore the influence of saturation ratio on right-turn length, and also provides the critical traffic volume for determination of the storage length. The impacts of saturation ratio and confidence level (the confidence probability of no-overflow or no-blockage) are also taken into account in this study, which has little considered in the existing references. Finally, the recommended storage lengths are obtained by modeling solution and verified through Vissim simulation. It is demonstrated that the obtained results are reasonable.

1. INTRODUCTION

The right-turn lane is an important design element at a signalized intersection. It helps to increase the capacity of intersection by separating right-turn movement from through movement and also by providing an additional channel of flow. The length of right-turn lane is one of the most important factors which affect the efficiency of the intersection. Therefore, the exploration of the length of the right-turn lane becomes a very significant issue and is intensively studied in this paper.

Generally, as shown in Figure 1, the length should be long enough to store all the Vehicles (through- and right-turn vehicles, separately) that arrive during the red phase, into individual lanes. However, the guidelines about the length of the right-turn lane vary in the literature. This paper reviews the current guidelines and practices, discusses the possible factors which affect the lengths of right-turn lanes, develops two models of computing the lengths, and the results can be used for design reference. The analysis is performed for two cases, when right-turn-on-red (RTOR) is permitted and not permitted, and also involves the effect of saturation ratio and confidence level *(confidence level refers to the confidence probability of no-overflow or no-blockage for right-turn lanes)* on the length.

The remainder of this paper is organized as follows: the first section puts forward the purpose of this study; the second section reviews the existing references; and the third section develops two model of determining the lengths of right-turn lanes based on Queuing Theory Principle; the fourth section discusses the recommended lengths of right-turn lanes based on the developed models considering the effect of saturation ratio and costs; and the last section does the comparative analysis of the lengths of right-turn lanes between the RTOR case and with NO-RTOR case, and also verifies the results of the recommended lengths obtained by models using VISSIM simulation.

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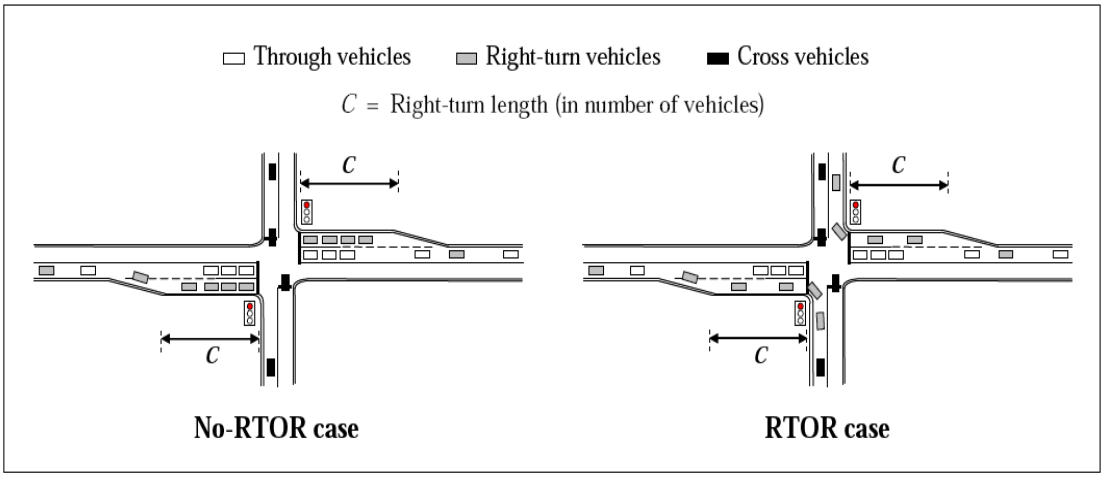

Figure 1 the two cases for discussion

2. STUDY PRPOSE

Most of the existing guidelines or practices for determining the lengths of right-turn lanes are limited and lack specificity. For example, only few literatures take saturation ratio and confidence level into consideration when determining the lengths of right-turn lanes which also affect the lengths. The purpose of this study is to develop an analytical process to determine the lengths of right-turn lanes through Queue Theory Principle, considering both of these two factors.

The process of determining the length is very complicated because of a variety of factors which have an effect on the determining process.

The factors that affect the length of right-turn lanes [1]

- Arrival rates of vehicles: through, right-turn, and cross-traffic, and the vehicle types;
- Arrival sequence of the two types of vehicles (through, and right-turn vehicles);
- Signal phases, cycle time, and timing for each phase (green time/ cycle time ratio);
- Geometry of the intersection including horizontal and vertical alignment;
- Sight distance (particularly when right-turn-on-red (RTOR) is allowed) and gap Acceptance;
- Pedestrian and bicycle activities;
- Right-turn-on-red (RTOR) permitted or not;
- Approach speed;
- Presence of transit vehicles and bus stop locations;
- The saturation ratio of approach driveway (right-turn lane and through lane);
- Confidence level;

Among these, the vehicle arrival rates, arrival sequence of the two types of vehicles, signal phases, RTOR permitted or not, the saturation ratio and confidence level are the most relevant factors which affect the length of the right-turn lane. All of these most relevant factors are considered when developing the models of the length of the right-turn lane and discussing the recommended lengths according to the models. Others are not taken into consideration in this study.

3. LITERATURE REVIEW

The literature review includes two sections: the first section is the research about RTOR, and the second one is “determining the lengths of right-turn lanes at signalized intersections”.

3.1 The literature reviews about RTOR

Most of existing researches about RTOR are focusing on the capacity of intersections and few go deep in the study of the length of right-turn lanes.

Shinya Kikuchi (1), at Virginia Tech, develops the probability models of determining the length and suggests the recommended length according to the models when RTOR is permitted. However, the models in this paper are very complicated and not easily solved because of its infinite series, which also don't take the costs into consideration.

Feng-Bor Lin (2) stated that RTOR could effectively reduce right-turn delays, if the saturation ratio of the cross flow is less than 0.6, and the right-turn delays without RTOR exceed 30 sec per vehicle. Lin was the first person to point out that the need to examine the possibility of the through-vehicles blocking the turn lane; however, his equationtion lacked consideration of vehicle arrival sequence.

Tian and Wu (3) developed an analytical method of modeling the relationship between the length of a right-turn lane and its capacity. They suggested that it is very important to consider vehicle arrival sequence when discussing the length of a right-turn lane.

Tarko (4) also recognized the importance of vehicle arrival sequence and the possibility of blockage of the right-turn vehicles, but just focused on the research of capacity and did not go deep in the analysis of the length.

ITE Handbook (5), in which K equals to 1.5, proposed the recommended length when RTOR is permitted, without giving any explanation about the length but that K is a random arrival factor.

$$\text{storage length} = \frac{\left(1-\frac{g}{C}\right)(\text{volume})(\text{K})(25\ \text{feet})}{(\text{No.of cycles per hour})(\text{No.of lanes})} \tag{1}$$

where storage length in feet; volume in vehicles per hour; and g/C: green time–cycle length ratio.

3.2 The determination of the length for right-turn movement at signalized intersections

Shinya Kikuchi (1), at Virginia Tech, develops the probability models of determining the length and suggests the recommended length according to the models when RTOR is permitted and not, consisting of a combination of input variables, like arrival rates and sequence, green-to-cycle ratio. However, the model in this paper is very complicated and not easily solved because of its infinite series. Besides, this paper has not taken the saturation ratio into consideration when determining the length and the models cannot be widespread used.

FHWA's Signalized Intersection: Informational Guide (6, p.329) suggests that the storage length should be long enough to accommodate the maximum vehicle queue for both right turn- and through lanes under design year conditions. The AASHTO Green Book (7, p.719) suggests, the length of the right-turn (or left-turn lane) should usually be based on one-half to two times the average number of vehicle queues per cycle. Transportation and Land Development, published by ITE (8), presents a look-up chart based on the AASHTO Green Book.

Delaware (9) suggests that the storage length should be sufficient to accommodate the maximum vehicle queue most commonly experienced for both right-turn and left-turn lanes. The recommended length of either left turn or right-turn is 100 ft (30 m) for heavy through traffic and 50 ft (15 m) for light through traffic.

California (10) and Minnesota (11): The analytical method of determining storage lengths for right-turn movement is in the same way as for left-turn movement. The storage length should be based on one-half to two times the average number of vehicles per cycle, as is suggested by AASHTO Green Book (7).

Other states, like Florida (12), Washington (13), and Tennessee (14), also state that the method of determining the length of a right-turn lane is in the same manner as the one for the left-turn movement, and the length should satisfy the maximum vehicles queue expected commonly

Jingyuan Wang and Wei Wang (15) in China suggest the reasonable length for left-turn lanes at signalized intersections with no RTOR and put forward the conception of critical traffic volume which affects the determination of the length, without considering the RTOR case. However, the analytical process can also be used to determine the length of right-turn lanes.

Feng-Bor Lin (2) also develops the model of determining the length through probability theory principle and suggests the recommended length for right-turn movement, considering the straight-through and right-turn volume; however, other factors affecting the length haven't been considered in the model, so have the situation with RTOR.

Gattis (16) reviews the requirements of the length for both right turn- and left-turn lanes, treating left-turn and right-turn equally. Also it is not convictive to make a distinction between RTOR and NO-RTOR case just by giving a random factor K, like ITE Handbook (5) does.

3.3 Conclusion

In conclusion, the available literature can be summarized as follows: (a) the lengths of right-turn lanes when RTOR is permitted has been little studied in detail; and (b) saturation ratio and confidence level have not been studied deeply in the existing references; and (c) some relatively reasonable analytical methods are too complicated to be put in wide use. For these purposes, it is important to develop a simple and useful analytical method for determining the lengths of right-turn lanes in the two cases (RTOR and NO RTOR), also considering saturation ratio and confidence level.

4. MODEL DEVELOPMENT

As mentioned before, both RTOR and NO-RTOR cases should be studied when discussing the lengths of right-turn lanes. For each case, the two situations (overflow and blockage) are considered when developing models. In this section, RTOR and NO-RTOR will be developed respectively through queuing theory under the following assumptions:

1. The arrival pattern conforms to Poisson Distribution, and the headway conforms to negative exponential distribution;
2. The recommended lengths in the models are indicated by the number of vehicles queuing in through and right-turn lanes;
3. The approach with only one through lane and one right-turn lane will be the object of this study, other kinds of approaches with multiple lanes are not studied in this paper;
4. The effect of vehicle type is not considered when developing models;
5. The queuing vehicles during the red phase depart parking line by saturation rate;
6. The right-turn and through movements share the same green phase.

4.1 Parameters Notation

The following notation is used in this paper:

P_{nr} =the probability of n vehicles lining up in the right-turn lanes;

$P(n \le N_r)$ =the probability of no-overflowing (confidence level);

P_{ns} =the probability of n vehicles lining up in the through lanes;

$P(n \le N_s)$ =the probability of no blockage (confidence level);

n =the number of queuing vehicles;

λ_r =the number of right-turn vehicles arriving per cycle;

u_r =the number of departure right-turn vehicles during the green phase without RTOR, so $\frac{\lambda_r}{u_r}$ = saturation ratio of right-turn lane;

u_r' =the number of departure right-turn vehicles per cycle with RTOR;

λ_s =the number of straight-through vehicles arriving per cycle;

u_s =the number of departure through vehicles during the green phase, so $\frac{\lambda_s}{u_s}$ represents saturation ratio of through lane;

C =Cycle length;

g =the duration of green phase for both right-turn and through movements;

q_r =the arrival rate of right-turn vehicles;

q_s =the arrival rate of through vehicles;

q_c =the arrival rates of cross traffic;

S_r =the saturation flow of right-turn lane, HCM2000 assume $S_r = 1550 vph/h$;

S_s =the saturation flow of through lane, HCM2000 assume $S_s = 1650 vph/h$;

x_r and x_r' =the saturation ratio of right-turn lane;

N_r =the maximum queue length of right-turn lane without RTOR;

N_r' =the maximum queue length of right-turn lane with RTOR;

N_s =the maximum queue length of through lane;

N =the recommended length of right-turn lane without RTOR;

N' =the recommended length of right-turn lane with RTOR;

N_c =the number of vehicles that can potentially make a right turn during the red phase;

α =the critical gap for making right turn (s), assumed $\alpha = 6.5s$

α_0 =follow-up time (s), $\alpha_0 = 3.3s$;

4.2 Modeling steps

For RTOR and NO-RTOR, the modeling process is divided into two steps: 1. Develop the model for No-RTOR; 2. Generate the model for RTOR through modifying the model of No-RTOR.

Step 1 Develop the model for No-RTOR

According to the Queuing Theory: the probability of n vehicles lining up in the right-turn lane and through lane is respectively signified as follows:

$$P_{nr} = (1-\frac{\lambda_r}{u_r})(\frac{\lambda_r}{u_r})^n \tag{2}$$

$$P_{ns} = (1-\frac{\lambda_s}{u_s})(\frac{\lambda_s}{u_s})^n \tag{3}$$

When P value is determined, there must be an N value corresponding to it, which represents the maximum queuing length, Based on the alteration of equation (2) and (3), the probabilities of no-overflow and no-blockage have been obtained as follows:

$$\begin{aligned} P(n \le N_r) &= P(n=0) + P(n=1) + \ldots + P(n=N_r) \\ &= (1-\frac{\lambda_r}{u_r}) + (1-\frac{\lambda_r}{u_r})(\frac{\lambda_r}{u_r}) + (1-\frac{\lambda_r}{u_r})(\frac{\lambda_r}{u_r})^2 + \ldots + (1-\frac{\lambda_r}{u_r})(\frac{\lambda_r}{u_r})^{N_r} \\ &= 1-(\frac{\lambda_r}{u_r})^{N_r+1} \end{aligned} \tag{4}$$

$$\begin{aligned} P(n \le N_s) &= P(n=0) + P(n=1) + \ldots + P(n=N_s) \\ &= (1-\frac{\lambda_s}{u_s}) + (1-\frac{\lambda_s}{u_s})(\frac{\lambda_s}{u_s}) + (1-\frac{\lambda_s}{u_s})(\frac{\lambda_s}{u_s})^2 + \ldots + (1-\frac{\lambda_s}{u_s})(\frac{\lambda_s}{u_s})^{N_s} \\ &= 1-(\frac{\lambda_s}{u_s})^{N_s+1} \end{aligned} \tag{5}$$

Through logarithm calculation of equation (4) & (5), we can get the expression of the maximum queuing length (in number of vehicle spaces) for right-turn lane and through lane:

$$N_r = \frac{\ln(1-P(n \le N_r))}{\ln(\frac{\lambda_r}{u_r})} - 1, \frac{\lambda_r}{u_r} < 1.0 \tag{6}$$

$$N_s = \frac{\ln(1-P(n \le N_s))}{\ln(\frac{\lambda_s}{u_s})} - 1, \frac{\lambda_s}{u_s} < 1.0 \tag{7}$$

Considering a combination of the equations as follows, the ultimate models of the maximum length are shown below:

$$\lambda_r = \frac{q_r C}{3600}, \quad u_r = \frac{S_r g}{3600}, \quad \lambda_s = \frac{q_s C}{3600}, \quad u_s = \frac{S_s g}{3600}$$

$$N_r = \frac{\ln(1 - P(n \le N_r))}{\ln(\frac{q_r C}{S_r g})} - 1 \tag{8}$$

$$N_s = \frac{\ln(1 - P(n \le N_s))}{\ln(\frac{q_s C}{S_s g})} - 1 \tag{9}$$

In general, the length of a right-turn lane needs to satisfy not only the line-up demand of right-turn vehicles (no-overflow), but also the demand of through vehicles (no-blockage). In this way, it is necessary to select the larger value between the two maximum queuing lengths as the recommended storage length:

$$N = \max(N_r, N_s) \tag{10}$$

Step 2 Generate the model for RTOR

The theory principle and analytical method in this section are the same as No-RTOR; however, there is something different during the red phase. No vehicles can go through the stop line during the red phase when RTOR is not permitted. In this way, the maximum right-turn queue length (in number of vehicles) when RTOR is permitted may be less than the one when RTOR is not permitted, but the length of the through lane will not be affected. That is to say, the right-turn lane can store not only the vehicles in the physical length, but also the ones that potentially can make a right turn during the red phase.

The number of vehicles that potentially can make right turn during the red phase depends on the cross traffic, gap acceptance, follow-up time and the green phase of cross traffic. It is obtained by modifying the model in HCM's RTOR capacity.

$$N_c = \frac{q_c g}{3600} * \frac{e^{-q_c \alpha/3600}}{1 - e^{-q_c \alpha_0/3600}} \tag{11}$$

Based on the equation (11), the saturation ratio is modified as equation (12) considering the change of the number of right-turn vehicles departing per cycle.

$$x_r^{'} = \frac{\lambda_r}{u_r^{'}} = \frac{\frac{q_r C}{3600}}{\frac{S_r g}{3600} + N_c} = \frac{q_r C}{S_r g \ + 3600 N_c} \tag{12}$$

Due to the modification of saturation ratio, the maximum queue length of the right-turn lane can be modified as follows:

$$N_r^{'} = \frac{\ln(1 - P(n \le N_r^{'}))}{\ln(\frac{q_r C}{S_r g \ + 3600 N_c})} - 1 \tag{13}$$

With the same principle, the larger value between the two maximum queuing lengths would be selected as the recommended length of right-turn lane:

$$N^{'} = \max(N_s, N_r^{'}) \qquad (14)$$

5. RECOMMENDED LENGTHS

In this section, the recommended length will be separately given out for both cases: RTOR and No-RTOR. Also, to probe the effect of various factors on recommended lengths under different conditions, comparative analysis will be performed between the two cases.

5.1 The effect of Saturation ratio on Maximum Queue Length

Saturation ratio is important and needs to be valued before determining the recommended length. It has strong relationships between the maximum queue length and saturation ratio.

According to the models in the prior section, the equation of saturation ratio under the condition of No-RTOR can be indicated as follows:

Saturation ratio of the right-turn lane: $x_r = \dfrac{q_r C}{g S_r}$ (15)

Saturation ratio of the through lane: $x_s = \dfrac{q_s C}{g S_s}$ (16)

Equa (12) is the expression of saturation ratio for RTOR.

According to model (8), (9), (12), (13), (15) and (16), the relationship between maximum queue length and saturation ratio would never change unless P value (confidence level) alters. Therefore, the trend of the maximum queue length changing with saturation ratio will not be altered with the alteration of signal timing, volume and RTOR or NO-RTOR. In this way, it is sufficient and convictive under just only one case to study the relationship between the maximum queue length and saturation ratio.

The probability (P) is assumed to be 95% which is the value most often quoted in the literature. The curve reflecting the trend has been generated as follows (according to eq. (15), assumed that: C=90s, g=45s, RTOR is not permitted):

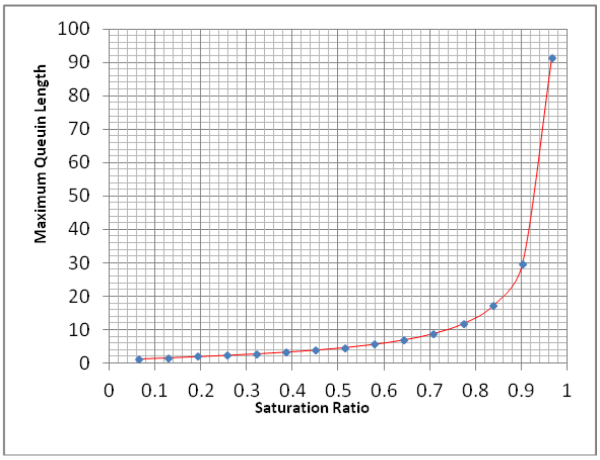

Figure 2 the trend of the maximum queuing length changing with saturation ratio

The maximum queue length increases as saturation ratio ascends for both right turn- and through lanes, especially when $x > 0.85$. Little increase of saturation ratio will cause rapid ascend for the length when $x > 0.85$, which is bound to greatly increase the saturation ratio. Practically, it is unreasonable and uneconomical to greatly increase the recommended length just for satisfying the little grow-up traffic volume. Consequently, it is necessary to make the traffic volume go back to an acceptable level before determining the recommended length when $x > 0.85$. In this way, the exploration of critical traffic volume has its significant sense and $x = 0.85$ becomes the critical point which is used to be the criteria for determining the critical traffic volume. Table 1 shows the results of critical right-turn volume for determining the lengths of right-turn lanes in NO-RTOR case:

Table 1 critical traffic volume

Right-turn lane								
Green Time Interval s	Cycle Length s							
	60	70	80	90	100	110	120	…
10	250	200	200	150	150	150	150	
15	350	300	250	250	200	200	200	
20	450	400	350	300	300	250	250	
25	550	500	450	400	350	300	300	
30	700	600	500	450	400	400	350	
35	800	700	600	550	500	450	400	
40	900	800	700	600	550	500	450	
45	1000	850	750	700	600	550	500	
…	…	…	…	…	…	…	…	…

Apparently, the less green-to-cycle ratio is, the smaller the value of critical volume will be. That's because the saturation ratio will increase with the decreasing of green-to-cycle ratio when traffic volume is a constant. In this way, the volume (the critical volume) when $x = 0.85$ will decrease with the reduction of green-to-cycle ratio. In the same way, the critical volume in RTOR case can also be obtained with the same analytical method, and the result shows that $x = 0.85$ is still the critical point. Therefore, the study of determining the length of right-turn lane cannot be directly performed unless the actual volume is not greater than the critical volume.

5.2 Determining the recommended Lengths

Considering a combination of variables: right-turn flow (50, 100, 150, …, 650), straight-through flow (50, 100, 150, …, 650), RTOR and NO RTOR, cross traffic (400, 800, 1200), green-to-cycle ratio (0.75, 0.5, 0.375), the recommended lengths can be obtained through model-solving.

1. General analysis

Generally, the trends of recommended storage lengths changing with traffic volume are in the similar way, shown in appendix. That is, when traffic volume grows up, the recommended lengths will increase as well. In some cases, however, the recommended lengths are constant when the right-turn volume or through volume grows up. Why does this happen? Apparently, the recommended length is the larger part of the maximum right-turn queue length and the maximum through queue length. When the maximum through queue length is greater than the right-turn queue length, the through volume is the dominant factor that influences the length until the right-turn volume grows up to the extent at which the maximum right-turn queue length exceeds the through volume; on the contrary, the recommended right-turn length is subject to the right-turn volume.

Furthermore, it is distinctive that there are no exact recommended lengths in the table when

C=120s,gr=45s, P=95% and the right-turn volume exceeds 500veh/h and through volume surpasses 550veh/h. It's just because 500veh/h and 550veh/h are respectively the critical right-turn volume and the critical through volume.

2. The effect of green-to-cycle ratio on the storage length

The storage length has a strong relationship with the green-to-cycle ratio, which is shown in table2:

Table 2 The effect of green-to-cycle ratio on the recommended length (should note the unit for all the numbers in all tables, like m, feet…)

Right-turn volume(vphpl)	**green-to-cycle time ratio (g/C)=0.75**(C=60s,gr=45s, P=95%)				**green-to-cycle time ratio (g/C)=0.5**(C=90s,gr=45s, P=95%)				**green-to-cycle time ratio (g/C)=0.375**(C=120s,gr=45s, P=95%)			
	Through traffic volume(vphpl)				**Through traffic volume(vphpl)**				**Through traffic volume(vphpl)**			
	150	**300**	**450**	**600**	**150**	**300**	**450**	**600**	**150**	**300**	**450**	**600**
150	0	1	1	3	0	1	3	8	1	3	8	/
250	0	1	1	3	1	1	3	8	2	3	8	/
350	1	1	1	3	2	2	3	8	4	4	8	/
450	2	2	2	3	4	4	4	8	10	10	10	/
550	3	3	3	3	7	7	7	8	/	/	/	/
650	4	4	4	4	16	16	16	16	/	/	/	/

The recommended length increases as green-to-cycle ratio decreases, especially when right-turn volume is in high level. That's because under the same flow level, the queue length in low green-to-cycle ratio becomes greater than the length in high ratio.

3. The comparative analysis of the recommended length between two cases: RTOR and NO-RTOR

A comparative analysis has been performed in this paper and the result is shown in table 3.

Table 3 the comparison of the recommended lengths for both cases—RTOR and NO RTOR

Right-turn volume (vphpl)	**green-to-cycle time ratio (g/C) = 0.5** (C=90s, gr=45s, P=95%)															
	Through traffic volume 150 (vphpl)				**Through traffic volume 300 (vphpl)**				**Through traffic volume 450 (vphpl)**				**Through traffic volume 600 (vphpl)**			
	NO RTOR	RTOR CROSS TRAFFIC			NO RTOR	RTOR CROSS TRAFFIC			NO RTOR	RTOR CROSS TRAFFIC			NO RTOR	RTOR CROSS TRAFFIC		
		400	**800**	**1200**		**400**	**800**	**1200**		**400**	**800**	**1200**		**400**	**800**	**1200**
150	0	0	0	0	1	1	1	1	3	3	3	3	8	8	8	8
250	1	1	1	1	1	1	1	1	3	3	3	3	8	8	8	8
350	2	1	1	2	2	1	1	2	3	3	3	3	8	8	8	8
450	4	2	2	3	4	2	2	3	4	3	3	3	8	8	8	8
550	7	3	4	5	7	3	4	5	7	3	4	5	8	8	8	8
650	16	4	6	8	16	4	6	8	16	4	6	8	16	8	8	8

Take the typical situation (g/C=0.5) as an example, the recommended length is generally less when RTOR is permitted than RTOR is prohibited, especially when right-turn volume is high. With regard to the case that RTOR is permitted, the recommended length increases with the increase of the cross traffic volume because the number of the vehicles that can potentially make a right turn during the red phase reduces as the cross traffic increases. In some cases, shown in table 3, the recommended lengths remain unchanged when the right-turn volume or cross traffic volume increases. That's because the maximum queue length of the through lane, which is not subject to the cross traffic, is always greater than the right-turn queue length until the right-turn volume is up to the critical point at which the maximum queue length of the right-turn lane is greater.

6. DISSCUSION

The analytical method of determining the storage length has been discussed under the same confidence level. In this section, the effect of confidence level on the lengths is discussed, and then the result of the lengths shown in table 3 is validated with simulation.

6.1 The impact of confidence level on recommended lengths of right-turn lanes

The P value (confidence level) is actually the confidence probabilities of no-overflow and no-blockage, reflecting the level of the restriction for overflow and blockage. The requirement for the recommended storage length will be improved with the rising of the P value. Take the case when green-to-ratio equals to 0.5 as an example, the trend of the maximum queue length changing with saturation ratio under different P values is shown as follows:

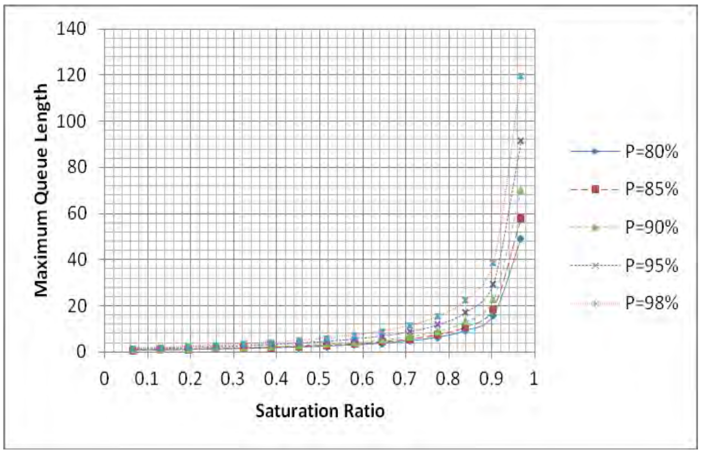

Figure 3 the trend of the maximum queuing length changing with saturation ratio under different P values

As is shown in figure 3, different curves go in the same way, though the length with high P value is larger than the one with low P value. Furthermore, the critical point of the saturation ratio on which the critical volume depends is still located in the place where saturation ratio is 0.85, being unrelated to the P value. In this way, the critical volumes in different P values will be the same as the ones when P equals to 95%. However, the saturation ratio increase greatly as the P value rises up under the same condition of volume and signal timing.

Considering different cases: NO RTOR or RTOR, cross traffic (400, 800, 1200), Right-turn volume (150, 250, 350,450,550,650) and through traffic volume (150, 300, 450, 600), P (80%, 90%, 98%), the recommended lengths of right-turn lanes are obtained in table 4.

It is demonstrated in table 4 that the recommended storage lengths increase when the P value is rising. Particularly, when the P value is larger than 90%, this growth trend seems to become obvious with the increasing of the right-turn volume. For example, when right-turn volume is 550veh/h, the difference of recommended lengths between P=90% and P=80% is significantly smaller comparing with the case between P=90% and P=98%; while this difference is not that big when right-turn volume is less than 550veh/h. Consequently, the impact of confidence level on recommended lengths depends not only on the P value itself but also on right-turn volume.

Table 4 Recommended lengths of right-turn lanes under different P values (NO RTOR)

Right-turn volume (vphpl)	**NO RTOR** **green-to-cycle time ratio (g/C) = 0.5** (C=90s, gr=45s)											
	Through traffic volume 150 (vphpl)			**Through traffic volume 300 (vphpl)**			**Through traffic volume 450 (vphpl)**			**Through traffic volume 600 (vphpl)**		
	P=80%	P=90%	P=98%	P=80%	P=90%	P=98%	P=80%	P=90%	P=98%	P=80%	P=90%	P=98%
150	0	0	1	0	1	2	1	2	5	4	6	11
250	0	1	2	0	1	2	1	2	5	4	6	11
350	1	1	3	1	1	3	1	2	5	4	6	11
450	1	3	6	1	3	6	1	3	6	4	6	11
550	3	5	10	3	5	10	3	5	10	4	6	11
650	8	12	21	8	12	21	8	12	21	8	12	21
Recommended lengths of right-turn lanes under different P values (RTOR) cross traffic=400												
Right-turn volume (vphpl)	**RTOR** **green-to-cycle time ratio (g/C) = 0.5** (C=90s, gr=45s) cross traffic=400 **(vphpl)**											
	Through traffic volume 150 (vphpl)			**Through traffic volume 300 (vphpl)**			**Through traffic volume 450 (vphpl)**			**Through traffic volume 600 (vphpl)**		
	P=80%	P=90%	P=98%	P=80%	P=90%	P=98%	P=80%	P=90%	P=98%	P=80%	P=90%	P=98%
150	0	0	1	0	1	2	1	2	5	4	6	11
250	0	0	1	0	1	2	1	2	5	4	6	11
350	0	1	2	0	1	2	1	2	5	4	6	11
450	0	1	3	0	1	3	1	2	5	4	6	11
550	1	2	4	1	2	4	1	2	5	4	6	11
650	2	3	6	2	3	6	2	3	6	4	6	11
Recommended lengths of right-turn lanes under different P values, cross traffic=800												
Right-turn volume (vphpl)	**RTOR** **green-to-cycle time ratio (g/C) = 0.5** (C=90s, gr=45s) cross traffic=800 **(vphpl)**											
	Through traffic volume 150 (vphpl)			**Through traffic volume 300 (vphpl)**			**Through traffic volume 450 (vphpl)**			**Through traffic volume 600 (vphpl)**		
	P=80%	P=90%	P=98%	P=80%	P=90%	P=98%	P=80%	P=90%	P=98%	P=80%	P=90%	P=98%
150	0	0	1	0	1	2	1	2	5	4	6	11
250	0	0	1	0	1	2	1	2	5	4	6	11
350	0	1	2	0	1	2	1	2	5	4	6	11
450	1	2	4	1	2	4	1	2	5	4	6	11
550	1	3	6	1	3	6	1	3	6	4	6	11
650	3	4	9	3	4	9	3	4	9	4	6	11
Recommended lengths of right-turn lanes under different P values, cross traffic=1200												
Right-turn volume (vphpl)	RTOR green-to-cycle time ratio (g/C) **= 0.5** (C=90s, gr=45s) cross traffic=1200**(vphpl)**											
	Through traffic volume 150 (vphpl)			**Through traffic volume 300 (vphpl)**			**Through traffic volume 450 (vphpl)**			**Through traffic volume 600 (vphpl)**		
	P=80%	P=90%	P=98%	P=80%	P=90%	P=98%	P=80%	P=90%	P=98%	P=80%	P=90%	P=98%

150	0	0	1	0	1	2	1	2	5	4	6	11
250	0	0	2	0	1	2	1	2	5	4	6	11
350	0	1	3	0	1	3	1	2	5	4	6	11
450	1	2	4	1	2	4	1	2	5	4	6	11
550	2	3	7	2	3	7	2	3	7	4	6	11
650	4	6	12	4	6	12	4	6	12	4	6	12

6.2 Verification of the results of the recommended lengths by VISSIM simulation

The approach marked red in the diagram below is the objective approach for study.

Figure 4 the network model of simulation

The recommended storage lengths of the right-turn lane presented in table 3 are validated in this section using VISSIM simulation. Table 3 consists of a combination of input variables: NO RTOR or RTOR, cross traffic (400, 800, 1200), Right-turn volume (150, 250, 350,450,550,650) and through traffic volume (150, 300, 450, 600). VISSIM was run 96 times (3600s for each time with a total of 5760 min simulation time); the number of times when lane overflow and/or lane blockage occurs is observed. The result shows that 85% to 96% of the total times, no overflow and/or no blockage occurred (figure 5). Thus, the recommended lengths in table 3 are reasonable and convictive.

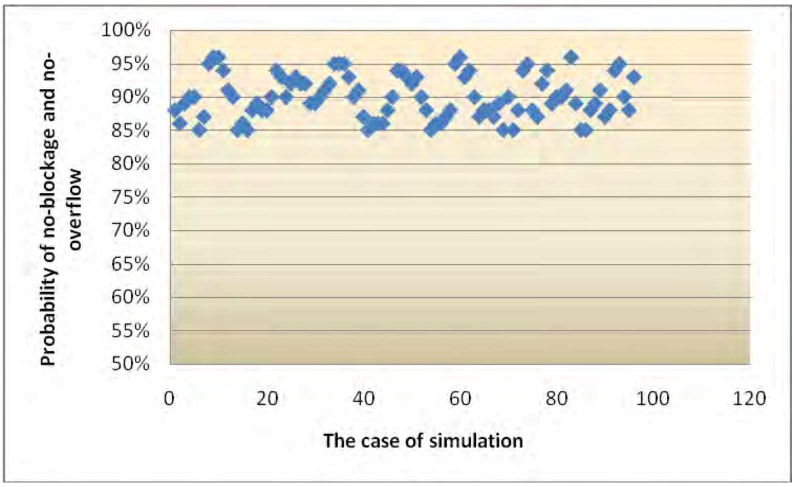

Figure 5 the Result of VISSIM Validation

For studying whether P value affects the accuracy of the recommended lengths, the results in table 4 are also validated using VISSIM simulation. Table 4 consists of a combination of input variables: Right-turn volume (150, 250, 350, 450, 550, 650) and through traffic volume (150, 300, 450, 600), P value (80%, 90%, 98%). VISSIM was run 72 times (3600s for each time with a total of 4320 min simulation time). It is found that 80% to 92% of the times no overflow and/or no blockage occurred, which is located in the acceptable level. Therefore, recommended lengths in this paper are reasonable and the variation of P value has little influence on the accuracy of recommended length model of this study.

7. CONCLUSIONS

In this paper, the study of determining the storage lengths is performed, considering two cases (RTOR and NO RTOR). For each case, two criteria are discussed: overflow and blockage. Two simpler and easier-to-solve models, comparing with the former guidelines, are developed based on Queuing Theory Principle for determining the storage lengths of right-turn lanes. The effects of saturation ratio and confidence level on the storage lengths are also discussed, and the critical points for each case are given out to avoid costing too much in the construction of right-turn lanes just for little traffic volume increasing, which is little studied in existing guidelines. Then the recommended lengths in typical cases are provided, and the effect of primary factors on the length is also discussed. Finally, the comparative analysis under different confidence levels is studied.

There are still some remaining issues expected to be studied in the future research. The impact of pedestrian & bicycle activities and transit vehicles & bus stop locations which have not been taken into consideration for determining the storage length in this paper. Actually, cross traffic flow is not the only traffic stream that right-turn vehicles need to run cross; pedestrian and bicycles may also hold up the normal right-turn movement, especially when the volume is in high level. A transit vehicle has a much longer body than a car, which means the proportion of transit vehicles affects the storage length in actual distance. Furthermore, the bus location approaching an intersection has an effect on the arrangement of the right-turn lane, which may affect the storage length.

The two remaining issues are the main direction for the future research. We are planning to make a deep exploration to examine the effects of pedestrians & bicycles and bus location on the storage length.

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APPENDIX

C=60s, gr=45s, P=95%													
Right-turn Volume Veh/h	Through Traffic Volume veh/h												
	50	100	150	200	250	300	350	400	450	500	550	600	650
50	0	0	0	0	0	1	1	1	1	2	2	3	3
100	0	0	0	0	0	1	1	1	1	2	2	3	3
150	0	0	0	0	0	1	1	1	1	2	2	3	3
200	0	0	0	0	0	1	1	1	1	2	2	3	3
250	0	0	0	0	0	1	1	1	1	2	2	3	3

300	1	1	1	1	1	1	1	1	1	2	2	3	3
350	1	1	1	1	1	1	1	1	1	2	2	3	3
400	1	1	1	1	1	1	1	1	1	2	2	3	3
450	2	2	2	2	2	2	2	2	2	2	2	3	3
500	2	2	2	2	2	2	2	2	2	2	2	3	3
550	3	3	3	3	3	3	3	3	3	3	3	3	3
600	3	3	3	3	3	3	3	3	3	3	3	3	3
650	4	4	4	4	4	4	4	4	4	4	4	4	4
C=90s, gr=45s, P=95%													
Right-turn Volume Veh/h	Through Traffic Volume veh/h												
	50	100	150	200	250	300	350	400	450	500	550	600	650
50	0	0	0	1	1	1	2	3	3	4	6	8	11
100	0	0	0	1	1	1	2	3	3	4	6	8	11
150	0	0	0	1	1	1	2	3	3	4	6	8	11
200	1	1	1	1	1	1	2	3	3	4	6	8	11
250	1	1	1	1	1	1	2	3	3	4	6	8	11
300	2	2	2	2	2	2	2	3	3	4	6	8	11
350	2	2	2	2	2	2	2	3	3	4	6	8	11
400	3	3	3	3	3	3	3	3	3	4	6	8	11
450	4	4	4	4	4	4	4	4	4	4	6	8	11
500	5	5	5	5	5	5	5	5	5	5	6	8	11
550	7	7	7	7	7	7	7	7	7	7	7	8	11
600	10	10	10	10	10	10	10	10	10	10	10	10	11
650	16	16	16	16	16	16	16	16	16	16	16	16	16
C=120s,gr=45s, P=95%													
Right-turn Volume Veh/h	Through Traffic Volume veh/h												
	50	100	150	200	250	300	350	400	450	500	550	600	650
50	0	0	1	1	2	3	4	5	8	13	18	/	/
100	0	0	1	1	2	3	4	5	8	13	18	/	/
150	1	1	1	1	2	3	4	5	8	13	18	/	/
200	1	1	1	1	2	3	4	5	8	13	18	/	/
250	2	2	2	2	2	3	4	5	8	13	18	/	/
300	3	3	3	3	3	3	4	5	8	13	18	/	/
350	4	4	4	4	4	4	4	5	8	13	18	/	/
400	7	7	7	7	7	7	7	7	8	13	18	/	/
450	10	10	10	10	10	10	10	10	10	13	18	/	/
500	18	18	18	18	18	18	18	18	18	18	18	/	/
550	/	/	/	/	/	/	/	/	/	/	/	/	/
600	/	/	/	/	/	/	/	/	/	/	/	/	/
650	/	/	/	/	/	/	/	/	/	/	/	/	/