

The Setting Method of Signal Timing Parameters at Over-saturated Intersection

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Abstract—In order to adapt to traffic operation situation of over-saturated signalized intersection, the setting methods of optimal cycle and green split of every phase are studied. Selecting Xinan Rd. and Wuyi Rd. intersection as study object, traffic investigation was carried out. Considering the two factors of the average delay and capacity at over-saturated intersection comprehensively, the optimization method of signal cycle length was proposed. Considering the traffic volume and queue length, setting method of the green splits of every phase was also proposed. Using the measured traffic data, signal timing scheme of the investigated intersection was not only designed, but also compared with the existing situation. The research indicates that, using this method, the average delay will be increased at over-saturated intersection, and the capacity can also be increased. This method is beneficial to reduce vehicles queuing at this kind of intersection.

Keywords—traffic engineering; signal timing; cycle length; green split; over-saturated intersection

I. INTRODUCTION

With the explosive growth of the number of private cars in urban, more and more signal intersections are in a state of over-saturated at peak hours. It means that vehicles in every entrance lane cannot all pass the intersection in a green light of every phase. There are often several queuing vehicles waiting over one signal cycle. This phenomenon is particularly prominent at peak hours. Assuming that all vehicles arriving at stop line are permitted to pass fitly in one cycle and aiming at the minimum average delay, the optimal cycle length can be optimized by the traditional signal timing method. According to the flow ratios of every phase, the green splits of corresponding phase can also be assigned by this method, as HCM's(2000) discussion[1]. Thus, it is needed to discuss that if the traditional method is still applicable to the over-saturated intersection or not. In view of the situation above, it is necessary to study the setting method of signal timing parameters for over-saturated intersection, considering the traffic operation characteristics of this kind of intersection.

To date, both domestic and foreign scholars have studied about this problem. In respect of signal cycle, LI (2013)[2] summarized the research status of signal control at over-saturated intersection. She introduced several objective functions, models, solving algorithms and timing applications of traffic simulation software of signal cycle optimization at this kind of intersection. Simes M. L. et al(2014)[3] constructed the global optimization algorithm of green time and cycle length for fixed timing signal intersection. Using several intersections, the calculation efficiency and accuracy of this algorithm were verified. Taking the maximum volume and minimal average queuing ratio as optimization objective, LI et al. (2013)[4,5] proposed an optimization method of signal cycle at over-saturated intersection, based on Non-dominated sorting genetic algorithm(NSGA-II). Selecting minimal average delay time, maximum capacity and best robustness as object functions, ZHANG et al(2011)[6] constructed the optimization model of signal cycle length. In respect of green split and green time, Roshandeh A. M. (2014)[7] proposed an optimization method of signal timing. Using this method, the green splits of every phase can be adjusted under the premise of keeping signal cycle invariant. The research indicated that, vehicle delays can be reduced by 13% when considering only vehicle delays and by 5% when simultaneously considering vehicle and pedestrian delays. Motawej F. et al. (2011)[8] constructed a discrete timing model for describing the change of queuing length at signal intersections. Based on the dissipative system theory, this model realizes the increasing of green time. According to the difference value of actual traffic volume and the number of queuing vehicles, LIU et al. (2013)[9] assigned the green splits for over-saturated intersection. The method was also verified by case analysis. Based on similar principles, ZHANG et al. (2014)[10] constructed a nonlinear programming model of dynamic signal timing.

It can be found from current research that the optimization models and algorithms of signal timing parameters have been studied emphatically both here and

abroad. These studies focused their attention on reducing the average traveling delay and assigning green time according to the flow ratio rather than the consideration of traffic operation characteristics at over-saturated intersection, such as lower capacity and the phenomenon of queuing waiting. Given this status in literature, in this paper, both capacity and delay are considered comprehensively for optimizing signal cycle length. Both traffic volume and queuing length are also considered to assign green time in every phase. There will be significant theoretical significance and practical application value to be found when setting signal timing parameters and alleviating traffic jams at over-saturated intersection.

II. TRAFFIC INVESTIGATION AND DATA ACQUIRED

A. The Investigation Location

Xinan Rd. and Wuyi Rd. signalized intersection in Dalian is selected as investigation location in this research. As one of the most important traffic nodes in Dalian, the traffic load on this investigation is heavy. Several vehicles cannot pass the intersection in one signal cycle at peak hours. It means that there are queuing vehicles stranded from the last cycle. Thus, this intersection is in the over-saturated state. It is appropriate for this research.

The intersection of Xinan Rd. and Wuyi Rd. is a X type four-way signalized intersection. The Xinan Rd. is from south to north with 8 lanes in two-way. The Wuyi Rd. is from west to east with also 8 lanes in two-way. All the medial lanes of the 4 entrances are left-turn exclusive lane. For outside lanes, only the outside lane of west entrance of Wuyi Rd. is the lane both for straight and right-turn. The others are right-turn exclusive lane. The basic geometric structure and lane function of this intersection are shown in Fig. 1.

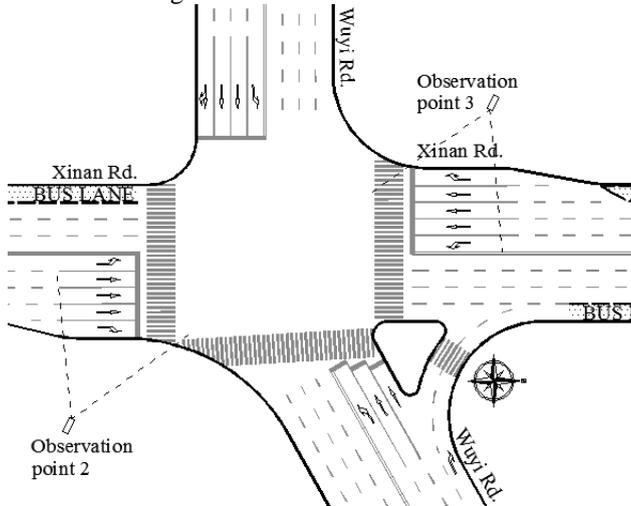


Figure 1. Geometric construction of the investigated intersection

B. The Investigation Time and Method

In order to reflect over-saturated traffic characteristics at this intersection, the investigation should be carried out at peak hour in morning and afternoon. The investigation time interval includes 7:00-9:00 and 16:00-18:00 from Tuesday to Thursday. The method of field investigation is

video observation, and the interior work method is artificial notation.

C. Data Processing and Acquired

After interior artificial data arranging according to the video record get from field work, the traffic volume of every lane and every vehicle type, the number of queuing vehicles in every cycle and the existing signal timing parameters of this intersection can be acquired. These data will be used in the analysis of application effect of the signal timing method. The existing signal cycle length of this intersection is 158s. The timing scheme of every phase is shown in Fig. 2.

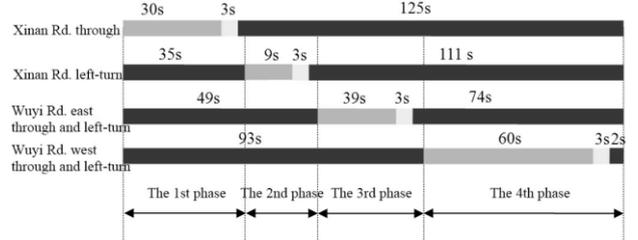


Figure 2. The signal timing scheme of the intersection

Taking one signal cycle as an example, the traffic volumes data on every direction and the number of staid queuing vehicles in this cycle can be acquired. The data after conversion of standard car are listed in TABLE I.

TABLE I. THE NUMBER OF PASSING VOLUME AND QUEUING VEHICLES IN A SIGNAL CYCLE(PCU/CYCLE)

The Entrance	Straight		Left-turn		Right-turn	
	Passing	Queuing	Passing	Queuing	Passing	Queuing
North entrance of Xinan Rd.	31	4	4	1	43	0
West entrance of Wuyi Rd.	61	3	22	2	1	0
South entrance of Xinan Rd.	34	6	4	0	44	0
East entrance of Wuyi Rd.	30	6	16	2	0	0

III. THE OPTIMIZATION METHOD OF SIGNAL CYCLE

After the analysis of the influences of capacity and delay on cycle length, the optimization method of cycle length can be proposed.

A. Capacity

Considering the characteristic of mixed traffic in China, the method of "stop line" proposed by Beijing Municipal Engineering Design Institute[11] should be adopted to calculate the capacity of this intersection. For this method, according to the different functions of lanes, the calculation formulas of capacity are proposed. The capacity of intersection can be acquired by adding the capacities of every lane together. For example, the capacity of straight lane can be calculated by (1). The calculation principles of other lane types are similar to it.

$$N_s = \frac{3600}{C} \cdot \frac{t_g - t_c}{t_s} \quad (1)$$

Where, N_s is the capacity of a straight lane, pcu/h. t_g is the green time of this phase, s. t_c is the lost time of green light in one cycle, s. Its value can be calculated by the method mentioned in literature[11]. t_s is the time interval between two successive vehicles travelling pass the stop line, s. For car flow, it is 2.5s. For heavy truck flow, it is 3.5s.

Taking the investigated intersection as an example, the existing phase and green splits of every phase are unchanged. Several different lengths of signal cycle are selected. According to the method of "stop line", the total capacities and the capacities excepting the right-turn exclusive lanes of different cycle lengths are calculated. The calculation results can be plotted as curves, as Fig .3 shows.

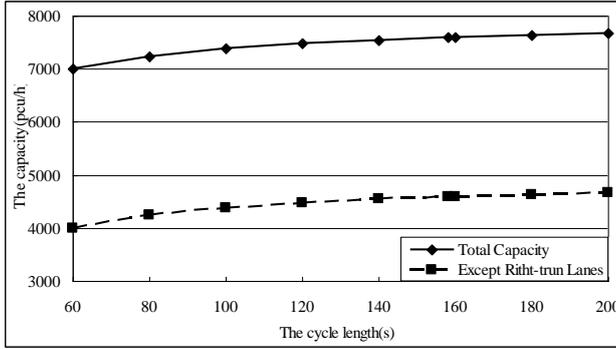


Figure 3. The relationship curve of cycle length and capacity

According to Fig.3, with the increase of cycle length, both the total capacity and capacity excepting the right-turn exclusive lanes of intersection are increased. However, the speed increases more and more slowly.

B. Delay

Delay is an important index for appraising traffic operation state at intersection. Based on delay analysis, aiming at minimum average traveling delay per vehicle, the signal cycle length can be optimized and solved by the traditional optimization method. Thus, it is necessary to analyze vehicle's delay for optimization of cycle length at over-saturated intersection. The delay of one lane of intersection can be calculated by the Webster method, as (2) shows.

$$d_i = \frac{C(1-\lambda_k)^2}{2(1-\lambda_k x_i)} + \frac{x_i^2}{2q_i(1-x_i)} - 0.65 \left[\frac{C}{q_i} \right]^{1/3} x_i^{(2+5\lambda_k)} \quad (2)$$

Where, d_i is the average delay per vehicle for the No.i lane, s. C is the signal cycle length, s. λ_k is the green split in the No.k phase, which is the passing phase for the No.i lane. q_i is the volume ratio at the No.i lane, pcu/s. x_i is the saturation level for No.i lane. It is the ratio of the measured traffic volume to capacity.

Thus, the average delay per vehicle D of the whole intersection should be the weighted average of the average delays at every lane, as (3) shows.

$$D = \frac{\sum_{i=1}^n d_i \cdot q_i}{\sum_{i=1}^n q_i} \quad (3)$$

Still using the intersection case mentioned above, the signal phase and green split are also unchanged. According the different saturation level index, the different traffic volume parameters at every entrance are set respectively. According to the (2) and (3), the relationships between the signal cycle length and average delay of different traffic volume are calculated and plotted in Fig .4.

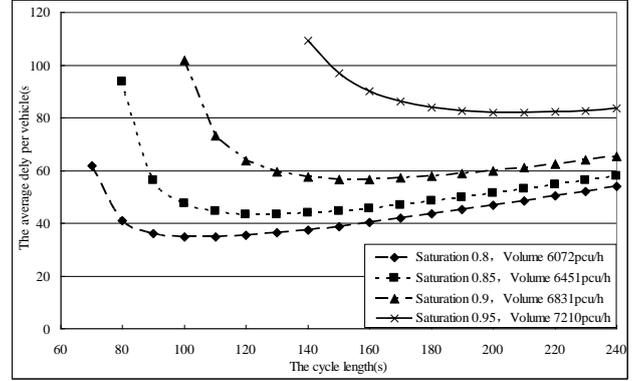


Figure 4. The relationship curves of cycle length and capacity at different traffic volume

It can be found from Fig.4 that, the average delay per vehicle of intersection is related to the cycle length and traffic volume. With the increase of traffic volume of intersection, the average delay is significantly increased. For the same traffic volume, with the increase of signal cycle, the average delay decreases first and then increases. Thus, there is the minimum value of the delay.

C. The Optimization Model of Cycle Length

According to the analysis of capacity and delay of intersection, it can be found that, when the cycle length is more than 180s, the increase of intersection's capacity is not obvious. However, the average delay increases significantly. Thus, the traditional signal timing method believes that, for general intersection, when the signal cycle is long, it is unworthy increasing the capacity at the price of increasing the traveling delay. Therefore, for the traditional signal timing method, the optimal cycle length is optimized, only selecting the minimum average delay of intersection as a single optimization objective.

Considering the characteristics of vehicle stranded and queuing at over-saturated intersection, this study believes that it is necessary to consider the two factors of intersection's capacity and average delay comprehensively to optimize the cycle length. For the general situation in China, the right-turn vehicles are not controlled by signal. Thus, the capacity should be calculated except the right-turn exclusive lane. Therefore, for over-saturated intersection, the selection of the optimal cycle length should make the average travelling delay to be as small as possible, as well as the capacity of straight and left-turn to be as large as possible. So, the objective function as (4) is proposed.

$$\min f = \frac{D}{N'} = \frac{\sum_{i=1}^n d_i \cdot q_i}{N' \cdot \sum_{i=1}^n q_i} \quad (4)$$

Where, f is the ratio of the average delay per vehicle to the capacity of straight and left-turn. N' is the sum capacity of straight and left-turn of intersection.

According to the method above, setting different traffic volume at every entrance of the investigated intersection, the volume ratios of every phase can be calculated. Using the method of search, at the conditions of different traffic volume, the cycle lengths C_0 at the points of minimal D value and f value can be calculated. The calculation parameters of the optimal cycle length are listed in TABLE II.

TABLE II. THE CALCULATION PARAMETERS OF OPTIMAL CYCLE LENGTH

Total Volume (pcu/h)	The Volume Ratio of Every Phase				Sum of Volume Ratio Y	The Optimal Cycle Length C_0 (s)	
	No.1 phase	No.2 phase	No.3 phase	No.4 phase		According to minimal D	According to minimal f
6072	0.138	0.047	0.195	0.289	0.670	106	110
6451	0.150	0.052	0.210	0.311	0.722	126	130
6831	0.161	0.055	0.225	0.335	0.776	156	161
7210	0.172	0.059	0.242	0.358	0.831	207	213

Referring to the traditional formula of optimal cycle length and using the method of regression analysis, the calculation formula of optimal cycle length considering both delay and capacity of intersection can be deduced, as (5).

$$C_0 = \frac{1.5L + 5}{0.958 - 0.954Y} \quad (5)$$

Where, C_0 is the optimal cycle length, s. L is the total lost time of signal, s. Y is the sum of maximum volume ratio of every phase.

IV. THE ARRANGING METHOD OF GREEN SPLIT

For the traditional signal timing method of intersection, the green split is arranged according to the ratio of the volume ratio of every phase. For the over-saturated intersection, there may be several stranded queuing vehicles which can not pass the intersection in one signal cycle. In order to make the number of the stranded queuing vehicles in every phase more balanced, it can be believed that the number of the stranded queuing vehicles in every phase should also be considered besides the volume ratio parameter, when the green split is arranged in over-saturated intersection. Thus, the maximum ratio of the number of passing and queuing vehicles to saturated volume can be defined as x_i , as (6) shows.

$$x_i = \max\left[\left(\frac{q_i + p_i}{S_i}\right), \left(\frac{q_i + p_i}{S_i}\right)'\right] \quad (6)$$

Where, S_i is the saturated volume of the travelling entrance in No. i phase, pcu/h. q_i is the actual passing traffic volume in No. i phase, pcu/h. p_i is the number of stranded queuing vehicles of the travelling entrance in No. i phase, pcu.

Thus, the parameters of effective green times and green split of every phase can be calculated by (7) and (8).

$$g_{ei} = G_e \frac{x_i}{\sum_{i=1}^n x_i} \quad (7)$$

$$\lambda_i = \frac{g_{ei}}{C_0} \quad (8)$$

Where, g_{ei} is the effective green time in No. i phase, s. G_e is the total effective green time, s. it can be calculated by $G_e = C_0 - L$. λ_i is the green split in No. i phase.

V. APPLICATION AND ANALYSIS

A. The Signal Timing Scheme

According to the traffic investigation of intersection, using the traffic volume and the number of stranded queuing vehicles at peak hour every day, the average value of them in 3 days can be calculated. The calculation result of timing parameters is listed in TABLE III.

TABLE III. THE NUMBER OF PASSING VOLUME AND QUEUING VEHICLES IN A PEAK HOUR/PCU

The Entrance	Straight		Left-turn		Right-turn	
	Passing	Queuing	Passing	Queuing	Passing	Queuing
north entrance of Xinan Rd.	792	101	82	9	972	0
west entrance of Wuyi Rd.	1346	79	503	27	22	0
south entrance of Xinan Rd.	742	86	76	11	1012	0
east entrance of Wuyi Rd.	768	102	389	21	971	0

The existing phase remains unchanged. The design saturated volume of a straight lane is selected as 1650pcu/h. The design saturated volume of a left-turn lane or right-turn lane is selected as 1550pcu/h. The sum of maximum saturated volume of every phase can be calculated as $Y=0.788$. According to the investigation, change interval of every phase in this intersection includes yellow light time of 3s and all red time of 2s, as Fig .2 shows. Thus, the total signal lost time in one cycle L is 20s. Therefore, according to (5), the signal optimal cycle length C_0 of this intersection under the condition of the traffic volume above should be 170s.

Considering both the passing traffic volume and the number of queuing vehicles stranded in more than one signal cycle at peak hours, the signal can be timed and designed by the calculation method of green split mentioned above. The acquired signal timing scheme is shown in Fig .5.

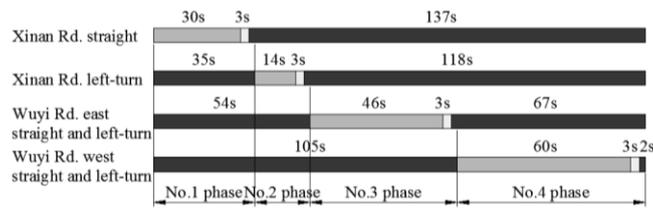


Figure 5. The signal timing designed scheme of the intersection

B. Comparing and Analysis

Comparing the existing signal timing scheme with the designed timing scheme in this paper, it can be found that the existent value and designed value of cycle length are 158s and 170s respectively. The calculated values of green times in every phase considering the number of stranded queuing vehicles in every phase are different from the existing signal timing scheme.

According to the data in TABLE III, the capacities and average travelling delays of two kinds of signal timing scheme can also be compared. Because 3 right-turn exclusive lanes are set in 3 entrances at this intersection and the right-turn vehicles are not controlled by the traffic signal, the capacities of these lanes are not affected by signal cycle length. Thus, only the capacity except right-turn exclusive lanes is compared with each other. After calculating, the capacities except right-turn exclusive lanes at this intersection of existing and designed scheme are 4590pcu/h and 4620pcu/h respectively. The average delays per vehicle of existing and designed scheme are 58.21s and 59.23s respectively. Compared with the existing signal timing scheme, although the average delay per vehicle increases about 1s, the capacity of straight and left-turn at the intersection increases. The number of stranded queuing vehicles is more balanced.

VI. CONCLUSIONS

(1) The optimal cycle length of over-saturated intersection should be optimized and determined after considering the capacity and delay of the intersection comprehensively. Its optimization objective is the minimal ratio of average delay per vehicle to the capacity of straight and left-turn of intersection. The green splits of every phase in this kind of intersection should be arranged according to the ratio of the sum of passing volume and the number of stranded queuing vehicles to the saturated volume.

(2) This signal timing method is applicable to the over-saturated periods of intersection. For general intersections, when the control strategy of segmented pre-timed signal is adopted, this method should be used to design the signal at the over-saturated periods.

(3) Compared with the traditional timing method, when the traffic signal of over-saturated intersection is timed by

this method, both the average delay per vehicle and the capacity of straight and left-turn will be increased.

This research takes a typical intersection as an example to investigate and analyze. Although there will be a certain particularity on data level, signal timing thought is suitable for general over-saturated intersections. The research result still can be referred by similar studies.

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