Research on Intersection Signal Timing Optimization Based on Eliminating Secondary Queuing Time

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Abstract. This paper takes Guanzhou Tunnel Intersection in Guangzhou Higher Education Mega Center as an example, first uses PARAMICS to simulate the traffic condition, then uses Webster method to optimize the intersection, besides, a simplified signal optimization method based on reducing the number of secondary stops is proposed. Finally, intersection evaluation indicators are compared and analyzed.

1. Introduction

As an important part of the urban traffic management system, traffic signal control is an important topic in the field of traffic engineering research. The intersection is the throat of the urban road traffic network, and its traffic efficiency directly determines the operational status of the network[1]. The computer-based urban traffic signal control systems have been rapidly developed and applied in many large cities. These systems have played a specific role in reducing traffic delays, parking, and maintaining traffic safety at intersections. However, the cost of these systems is very high, and they could be extremely complicated. Besides they sometimes are not suitable for small cities and suburbs of big cities. It can be said that the role of urban traffic control system is still far from being fully utilized. There are two ways to improve the efficiency of transportation systems: one is to increase the supply of the systems[2]. Recently, the traffic efficiency of the entire road network and the capacity of intersections have been improved through the optimization of traffic signal timing, and it has gradually become the main means to solve the traffic congestion of urban roads and has been proven to be an effective strategy[3-4]. Signal timing can be divided into two types: dynamic timing and static timing. Although it is a good choice to use the signal timing based on dynamic detection to optimize intersection, with the existing actual traffic control equipment, the signal timing dynamic adjustment often depends on the collection of the current number of queuing vehicles and proportionally allocates the green time, which can not better cope with the demand of the intersection under the supersaturated traffic flow[5]. Actually, if a static timing plan with good adaptability can be established, the length of the green light time, the signal period, and the start and stop time of the green light in each direction are relatively fixed in one or a series of directions are determined beforehand, the demand of the optimization of the intersections could be met. Webster signal timing method based on signal delay minimization is a classic static timing method. In the process of optimization, it could be observed that in the delay of the intersection, a large part of the delay is caused by more than one times of queuing of some vehicles. Some green time of phases is wasted, resulting in serious vehicle delays and traffic congestion. From this point, it is also a good plan to eliminate these redundant queues of these vehicles with proper signal timing.
Traffic simulation is an important tool for control and management of urban traffic systems [6]. In order to verify the effectiveness of these static timing method, this article took Guanzhou Tunnel Intersection in Guangzhou Higher Education Mega Center as an example.

2. Condition of the intersection
Traffic congestion has become a serious problem [7]. Guanzhou tunnel intersection of Guangzhou Higher Education Mega Center is no exception. It is located at the convergence of the Central North Street and the Middle Ring East Road in Panyu District, Guangzhou City, Guangdong Province, China. It is also connected to the Quiet Street. There are Sun Yat-Sen University in the northeast of the intersection, Xinghai Conservatory of Music in the southwest, and the Higher Education Mega Center North subway station.

The number of exit lanes of the East Middle Ring Road of the Higher Education Mega Center is five, including one left-turn lane, two straight lanes, and two right-turn lanes. The number of entrance lanes of the East Middle Ring Road is three. The number of entrance and exit lanes of the West Middle Ring Road is three. And there is another right-turn lane at the exit of the West Middle Ring Road. The number of entrance and exit lanes of Central North Street is two. And there is another right-turn lane at the exit of the Central North Street. There are two one-direction double lanes in the Guanzhou tunnel. The width of these lanes is set to 3.5m. Simulate the intersection with PARAMICS, and the result is shown in Figure 1.

![Figure 1. Simulation with PARAMICS](image)

The phase scheme of the intersection adopts four phases. Phase I is the time when going straight ahead, turning left and right at the East Middle Ring Road are permitted. During this period, the rest lights are red. This green light lasts 27s. The second phase II is the time when going straight at the West Middle Ring Road, turning right at East Middle Ring Road are permitted. This green light lasts 25s; the third phase III is the time when turning left at the Central North Street and turning right at East Middle Ring Road are permitted. The green light is for 27s. In order to ensure the passage of pedestrians, the fourth phase IV, a full red light is set, which lasts 17s.

The traffic volume survey of the intersection is complicated. According to the traffic flow characteristics of the intersection, the artificial observation method is used to observe the traffic volume at 17:30-18:30. The results of the survey are shown in Table 1.
Table 1. Survey results.

| Entrance                | Traffic flow/(pcu/h) |
|-------------------------|----------------------|
| Middle Ring East Road   |                      |
| Straight                | 179                  |
| Left                    | 169                  |
| Right                   | 1043                 |
| Middle Ring West Road   |                      |
| Straight                | 212                  |
| Left                    | 0                    |
| Right                   | 88                   |
| Central North Street    |                      |
| Straight                | 0                    |
| Left                    | 205                  |
| Right                   | 102                  |

Use the traffic flow above and set every road as a traffic zone to build OD matrix. Stimulate the traffic situation with the OD matrix on PARAMICS.

3. Signal timing optimization

This section is optimized with two optimization methods, the one is Webster method, it is a classical signal timing method, and another is a simple queuing optimization method based on the elimination of secondary queuing.

3.1. Webster method.

The classic Webster signal theory is based on the minimization of delay at the intersection. The kernel is the calculation of vehicle delay and optimal signal period. And the optimal signal period is based on the calculation of delays. Webster method is a commonly used calculation in traffic signal control.

If there are n signal phases, the total delay should be:

$$D = \sum_{i=1}^{n} q_i d_i$$  \hspace{1cm} (1)

where: $d_i$ ----the delay of i th phase.
$q_i$ ----arrival rate of i th phase.

The signal period length optimization can be summarized as:

$$MinD = \sum_{i=1}^{n} q_i d_i$$ \hspace{1cm} (2)

By the partial derivation of length of the cycle signal period length, use the equivalent substitution and approximation calculation, the following optimal signal period calculation formula is finally obtained:

$$C_0 = \frac{1.5L + 5}{1 - Y}$$ \hspace{1cm} (3)

where: $C_0$ ----the optimal signal period length(s);
$L$ ----total loss time(s);
$Y$ ----Traffic flow ratio of the intersection;

The total loss time:

$$L = nl + AR$$ \hspace{1cm} (4)

where: $l$ ----the loss time in one phase;
n ----the number of phases;
$AR$ ----all red light time in the period.

Traffic flow ratio of the intersection $Y$ is the sum of the traffic flow ratios of the critical lanes of each phase signal $y_i$, that is:
\[ Y = \sum_{i=1}^{n} y_i. \]  

By the above principle, optimize the signal timing of the intersection of Guanzhou Tunnel. Drive the lane leading to the Guanzhou Tunnel. Let the loss time of every phase be 5s, the time of yellow light be 3s.

- Phase I: Green 32s  Yellow 3s;
- Phase II: Green 29s  Yellow 3s;
- Phase III: Green 46s  Yellow 3s;
- Phase IV: Full right time 17s.

It is worth noting that Webster method is based on the even arrival to the downstream, but actually this does not usually happen, so the effect of Webster method is not satisfactory.

3.2. Queuing optimization method.

There is often such a phenomenon at the intersection of urban main roads and non-main roads: There are many cars that are parking on the traffic direction of the red light, but there are few vehicles passing on the green light traffic direction, causing serious waste[8]. During the simulation process, it is observed that during the green time of certain phase, the arrival rate of the vehicles in the phase lane is low, there are few vehicles passing through, and in this time, there are too many queued vehicles in other lanes, causing a secondary queuing phenomenon in other lanes. In the active priority signal control theory, when the phase green light signal is about to end, but a bus arrives at this time and can not pass, the green light extension strategy can be adopted. Based on this idea, the green time of the phase in which the secondary queuing occurs can be extended to assure that these vehicles have enough time to pass.

For example, in the simulation, during the green time of phase II, the number of arriving vehicles is small. So it can be judged that this green time is not fully utilized. At the same time, lots of secondary queuing occurs at other intersections. So it is necessary to extend the green time of phases when these vehicles at these intersections are allowed to pass to eliminate these secondary queuing. So, it is useful to shorten the green time of phase II in order to shorten the whole period.

Most cars that pass the intersection would follow closely behind the cars in front. To find the most effective period length, firstly the green time of every phase is shortened to 10s. In this way, some secondary queuing occurs at the Central North Street. The average number of vehicles that had to queue for more than one time per lane is four. So the extension of the green time of the phase when passing right are allocated to the Central North Street. The extended green time is calculated by:

\[ G = G + t_s * n \]  

where:
- \( G \) --- green time(s);
- \( t_s \) --- saturated time headway (s);
- \( n \) --- the average number of vehicles the queue for more than one time per lane.

The simulation is performed using the updated green time, and if the secondary queuing vehicle appears in other lanes in the green time of each phase, the green light time of these phases when these lanes are allocated passing right is extended. Simulate and optimize until secondary queuing does not occur in any lane. The optimization process is shown in table 2:

| Time | Phase I | Phase II | Phase III | The number of vehicles that experience secondary queuing |
|------|---------|----------|-----------|--------------------------------------------------------|
| 1    | 10s     | 10s      | 10s       | phase III                                             |
| 2    | 10s     | 10s      | 12s       | phase II                                              |
| 3    | 10s     | 10s      | 14s       | phase I                                               |
| 4    | 12s     | 10s      | 14s       | none                                                  |

The signal timing when secondary queuing does not occur on any lane is used as the final optimized scheme.
4. Data analysis

Use Plan A to indicate the optimized timing by queuing optimization method above, in this plan, full red time is not be changed; Besides, on the basis of ensuring that pedestrians have enough time to pass the street, set full red time to 12s, then use Plan B to indicate it. To clarify the effect of the plan that full red time are set to 0s, Plan C is set.

Take average delay, total parking time, average speed and parking rate to evaluate the effect of the intersection. The data is as Figure 2.

![Figure 2. Data comparison](image)

Although the percentage of parked vehicles on each road of Plan A has increased, the parking time of each vehicle has been greatly reduced due to the compression of signal period, which has been reduced from the original 27886s to 15104s; the average vehicle speed has increased from 14.6km/h to 15.2 km/h. This solution optimizes entire intersection network system.

On the basis of Plan A, Plan B shortens the full red time. The average parking time only increased 0.9s, but the average speed increased from 15.2km/h to 16.4km/h. As the full red time is shortened, the percentage of parked vehicles on each road is also greatly reduced.

In the plan of Webster method, compared with the original plan, the green time is extended, the full red time is not changed. Compared with the original scheme, the average speed is reduced from 14.6km/h to 13.2km/h; the total parking time is greatly increased from 27886s to 37531s.

Plan C has reduced the percentage of parked vehicles on each road. The average speed of each vehicle has increased to 18.8km/h, the total parking time has been greatly reduced to 9537s, and the average delay has been greatly reduced. However, this scheme is not realistic, because the full red time is reserved for pedestrians. If the red time is reduced to zero, then pedestrians need to a bridge or pass the tunnel, which requires a lot of cost.

5. Conclusion

The simplified queuing optimization method is well adaptable in reducing the delay of the intersection, and is superior to the traditional Webster method. In the optimization of the signal intersection of Guangzhou University City, the method significantly reduces the average delay, parking time, and significantly improves the average speed of the traffic. However, the model does not consider the microscopic of the vehicle queue, nor does it consider the mutual influence inside the traffic flow, so it till has certain deficiencies.
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