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Mechanism Analysis and Optimization of Signalized Intersection Coordinated Control under Oversaturated Status

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Abstract

How to relieve the congestion of intersection is a long-standing problem. The problem gets even more difficult when intersection is under oversaturated conditions. For the purpose of improving traffic signal control at oversaturated intersection and avoiding the deadlock of intersection, a coordination control model under oversaturated condition is established by using the traffic shockwave theory, which is based on the research of queue spillback types and shockwave profile of traffic flow in intersection, this control model constraints the form of queue spillback into particular type, and keeps the capacity matching between upstream and downstream intersections at the same time. The calculation method of the coordination control model is presented as well. At last, a simulation experiment is conducted to test the effectiveness of this model. The simulation results prove the effectiveness of this model, it shows that the coordination control scheme based on this model can reduce the average delay of vehicles by 24.6%, and decrease the risk of intersection deadlock by 30%, this strategy can also improve the tolerance and reliability of intersection significantly under oversaturated condition.

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Keywords: traffic signal coordinated control; reliability optimization; queue spillback; signal offset;

1. Introduction

Traffic congestion is continuing to grow in urban areas of China, more and more signalized intersections are operated under oversaturated conditions. Sometimes, spillback occurs when a queue from downstream intersection occupies all the space on the link and prevents vehicles from entering the upstream link on green and causing De-facto red to the movement on green, once the congestion occurs at one intersection or the link between two intersections, it will spread to neighboring interconnected intersections or links rapidly, which will make the service level of whole traffic network reduce sharply, and may cause deadlock of intersections at last,

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so the research of finding efficient ways to relieve congestion of intersection under oversaturated conditions and avoiding deadlock of intersection is very important. As the generated signal timing plan should fit the characters of oversaturated intersection, the mechanism analysis and implementation framework of traffic control under oversaturated status are necessary to optimize signal timing plans.

Some signal time optimization software adopt the control of spillback as one of the objectives in the optimization algorithms, SYNCHRO6 and GHASSAN both optimize their algorithms by take into consideration the spillback of queue and the waste of green time in signalized intersections, however, they don’t take into account the risk of intersection deadlock under oversaturated status. It has long been recognized that vehicular queue length is crucial to signal performance measures in terms of vehicle delay and stops. Over the years, many researchers have dedicated themselves to the topic of queue estimation, one of the important queue estimation models by Lighthill and Whitham (1955) for uninterrupted flow; and later expanded by Michalopoulos and Stephanopoulos (1981) to signalized intersections. Henry X. Liu and Xinkai Wu (2009) proposed a method to estimate real-time queue length for congested signalized intersections using loop detector data. Xinkai Wu and Henry X. Liu (2010) proposed the identification of oversaturated intersections using high-resolution traffic signal data. Based on the theory of shockwaves, the process of vehicles queuing and dispersing at intersections and variety of traffic flow between intersections are studied by Wang Dian-hai and Jing Chun-guang (2002), they researched the traffic platoon-interval in artery of the city and the effect of signal coordinate with considering the direction and speed of traffic wave spread, relevant mathematics models are founded in their paper. Fan Hong-zhe (2007) created a real-time queuing model and Grenberg model which is suitable for describe high-density traffic flow is used to modify it.

Traditional objectives of signal control usually focus on the green wave theory. Following the design principle of maximum green wave bandwidth and making use of the time-space diagram for arterial road coordinate control, many problems existed in classical algebraic method such as the determination of value range of ideal intersection distance, the calculation of green wave bandwidth, the selection of optimal intersection distance and the value of signal offsets were deeply analyzed through some practical examples by Lu Kai, Xu Jian-min and Ye Rui-min (2009). Ma Nan, Shao Chun-fu and Zhao Yi (2010) provided quantitative analyses from several aspects of signal timing related to bandwidth optimization, including the influence of signal phasing sequence, the impact of intersection spacing, and the impact of number of signals in a system. Ji Li-na and Song Qing-hua (2011) compared bidirectional green wave design under symmetric and asymmetric signal modes, designed connecting phase specially according to the demand of green wave coordinate control, and considered the driving speed on road and queue length when vehicles come across intersection in the process of phase difference computation. Based on the design principle of minimum arterial road delay time and maximum link travel speed, an urban roads traffic signal control method of bi-level programming model was established by Xu Jian-min and Chen Si-yi (2010) which using intelligent optimization algorithms and group decision making theory.

Some researchers try to use artificial intelligence technology to optimize the traffic control system. An adaptive fuzzy controller is developed for urban traffic signal control by Fan Xiao-ping and Li Yan (2005), the controller gives the real-time signal timing at an intersection, and calculates the average losses of vehicles waited in red phase and the average profits of vehicles cleared in green phase respectively according to the current traffic conditions. Gao Hai-jun, Yu Guo-jun and Li Zhen-long (2004) studied the urban traffic signal control by using agent technology, the agent-based urban traffic signal control system is capable of responding to traffic condition in real-time. The artificial intelligence model is suitable for theoretical analysis but very hard to use in practical application.

Almost all the researchers don’t take into account the risk of intersection deadlock under oversaturated status. However, under oversaturated status, the traditional objectives cannot be easily applied. The signal timing optimization objectives and control structure of under-saturated intersection may not work well under oversaturated status in practice. In this paper, the mechanism and implementation framework of traffic signal control for over-saturated intersections have been analyzed in accordance with shockwave profile of traffic flow in
intersection. Several implementation suggestions have also been discussed. The model of reliability interval optimization is established. The simulation results prove the effectiveness of this model, it shows that the coordination control scheme based on this model can reduce the queue spillback significantly, the study also find that the coordination control scheme can improve the capacity of the network under the impact of oversaturated traffic flow and enhance the reliability of the road network.

2. Classification of queue spillback types

In order to find the control strategy of queue overflow under oversaturated status, the types of queue spillback should be discussed based on the generative process of queue overflow. Based on the difference of traffic signal status when queue spillback occurs, queue spillback can be divided into two types: the first one is own-green queue spillback and the second type is conflict-green queue spillback.

2.1 own-green queue spillback

Illustrated as Fig. 1, own-green queue spillback means spillback occurs when a queue from downstream intersection occupies all the space on the link and prevents vehicles from entering the upstream link on green, but the queue spillback will discharge completely before the end of green time signal. This type of spillback won’t lead to either congestion or waste of green time of the upstream intersection. A number of signalized treatments can reduce the frequency of spillback occurrence such as negative offsets, dynamic offset adjustment and flared green times. For closely-spaced intersections, operating them as one intersection can also be an effective strategy to reduce this type of spillback.

![Fig.1 own-green queue spillback](image_url)

2.2 conflict-green queue spillback
As shown in Fig. 2, sometimes the queue spillback can’t completely dissipate before the end of green time signal in upstream intersection, the residual queues will block the movements of traffic flow from side streets, and even cause the lock-out situation. At this time, the traffic jam can’t be solved by optimize the control strategy of isolated intersection, we can only relieve the residual queues by coordination control of the upstream and downstream intersections.

3. Reliability optimization of coordinated control for oversaturated signalized intersection

3.1 shockwave profile of traffic flow on links

The analysis following is based on the identification of traffic state changes and the associated shockwaves presented in a cycle. As indicated in Fig.3, assuming the length of residual queue from past cycles is $q$. At the beginning of the effective green on upstream intersection, vehicles from the upstream intersection are forced to stop in point A which creates a queuing shockwave ($w_2$) propagating backward from the rear of the queue. At the beginning of the effective green on downstream intersection, vehicles begin to discharge at the saturation flow rate (assume there is no blockage downstream) forming the discharge shockwave ($w_1$), which propagating upstream from the stop-line. The discharge shockwave $w_1$ usually has higher speed than $w_2$, so the two waves will meet some time after the start of the green, which is the time that the maximum queue length is reached (indicated as point B in Fig.3). The shockwave motion described above will repeat from cycle to cycle.
When the traffic flow from upstream exceeds the capacity of downstream intersection, the queue at the downstream intersection will increase continually and lead to conflict-green queue spillback at last. Then the congestion begins to spread to its neighboring interconnected intersections or links. In order to reduce the risk of congestion under oversaturated conditions, we assume that the effective green time of the upstream and downstream intersections are equal to each other, so the capacity of them are equal too.

### 3.2.1 Shockwave analysis

The traditional Lighthill–Whitham–Richards (LWR) traffic flow model hypothesizes that flow is a function of density at any point of the road. A shockwave is defined as “the motion (or propagation) of an abrupt change in concentration” (Stephanopoulos, Michalopoulos, 1979). Traffic shockwave theory is derived from LWR model when applying the method of characteristics to analytically solve the partial differential equation in the model. Basically, when characteristic curves (along which, the density is constant) interact, a shockwave is formed and wave velocity can be determined by following equation:

\[
w = \frac{\Delta q}{\Delta k} = \frac{q_2 - q_1}{k_2 - k_1} = \frac{k_2 u_2 - k_1 u_1}{k_2 - k_1}
\]

where \(q_1, k_1\) are the flow and density of the upstream traffic and \(q_2, k_2\) are the flow and density of the downstream traffic. YANG Shao-hui et.al found that Grenberg model was fit for describing traffic flow under high density condition. Grenberg model can be described by the following equation:

\[
u = u_m \ln \left( \frac{k_j}{k} \right)
\]

where \(u_m\) is the saturation flow speed, \(k_j\) is the jammed flow density. Vehicles begin to discharge at the saturation flow rate start from stop line when it turns green, suppose their speed was \(u_m\) and density was \(k_m\). Also, we assume the average speed on the road is \(u\), and density is \(k\).

At signalized intersections under oversaturated status, multiple shock waves are generated due to the stop-and-go traffic caused by signal changes and residual queue. At the beginning of the effective green, vehicles begin to discharge at saturation flow rate (assume there is no congestion downstream) forming the shock wave which is defined as discharge shockwave \(w_1\) in Fig. 3 at the stop line moving upstream with speed:

\[
w_1 = \frac{k_m u_m - 0}{k_m - k_j} = \frac{k_m u_m}{k_m - k_j}
\]

In the red interval, vehicles are forced to stop, which creates different flow and density conditions between the arrival and the stopped traffic. Such interruption of traffic flow, as indicated in Fig.3, forms a queuing shockwave \(w_2\) moving upstream of the intersection with velocity:

\[
w_2 = \frac{k u_m \ln \left( \frac{k_j}{k} \right)}{k - k_j}
\]

Because \(k_m\) and \(k\) are both less than \(k_j\), so \(w_1\) and \(w_2\) are negative and that means the shockwave’s direction is opposite to the movement of traffic flow.

### 2.3.2 Solution of the reliability interval model
Suppose that the upstream intersection turns green firstly and the two intersections have the same cycle length and green split, the queue accumulation and discharge process under different signal offset are indicated from Fig.4a-d.

Fig.4 Solution of model

Where $\Delta T$ is offset between two intersections; $q$ is residue queue at downstream intersection, $0 \leq q \leq L + d; L$ is the distance between two intersections; $d$ is width of upstream intersection; $g_I$ is effective green time of the main street; $T_i$ is the time that discharge shockwave arrives at upstream intersection’s stop line.

On the moment that intersection comes to saturated, there are some residue cars on this section of road when the green is end. However, though adjusting offset, it can make upstream vehicles got the tail of the queue just at the time that discharge wave arrives there. So this offset can avoid wasting of green time at the downstream intersection, meanwhile, it can reduce queue at the highest degree. These process is shown as Fig.4(a). At this time, if we decrease the offset, when upstream vehicles arrive at the tail, the queue has already discharged, so to some extent, some green time ($t'$ in the Fig.4 b) will be waste. On the other hand, if we increase the offset, some vehicles will add to the tail of the queue (Fig.4 c). But under oversaturated condition, there exist a queue can take full advantage of the spaces of the road. Therefore, to make full use of the effective through time of the downstream intersection, there must be some constraints:

$$t_A \leq t_B$$

(5)

So:

$$\Delta T \geq \frac{L + d - q}{u} - \frac{q}{w_1}$$

(6)
When the intersection saturation is high, because of residue vehicles, spillback couldn’t be avoided, so we will try our best to constrain the spillback as own-green queue spillback. Under the worst condition (the queue arrives at upstream intersection), when the upstream intersection turns red, as long as the discharge shockwave can get to the stop line of the upstream intersection, the conflict flow can turn into the main street following the discharge shockwave, so deadlock can be avoided. Fig.4 (d) illustrates this situation. The constraint equation is:

$$T_i \leq g_i$$ \hspace{1cm} (7)

So

$$\Delta T \leq g_i + \frac{L + d}{w_1}$$ \hspace{1cm} (8)

The reliability interval of $\Delta T$ can be shown by the following set:

$$\Delta T \in \left[ \frac{L + d - q}{u}, g_i + \frac{L + d}{w_1} \right]$$ \hspace{1cm} (9)

To ensure that $\Delta T$ is existed, the effective green time $g_i$ must be larger than a minimum value, which can be calculated by the following equation:

$$g_i + \frac{L + d}{w_1} \geq \frac{L + d - q}{u} \frac{q}{w_1} \geq 0$$ \hspace{1cm} (10)

To ensure the reliability, we assume that $q = L + d$, which means the queue length is the maximum value, then the minimum value of $g_i$ can be calculated by the following equation:

$$g_{i min} = -\frac{2(L + d)}{w_1}$$ \hspace{1cm} (11)

From the above description, we found that the reliability interval is changing according to the initial queue ($q$). To simplify the calculating, let initial queue is $\frac{L + d}{2}$, then calculate the reliability interval and take the mid-value as the offset.

$$\Delta T' = \frac{g_i}{2} + \frac{L + d}{4u} + \frac{L + d}{4w_1}$$ \hspace{1cm} (12)

4. Simulation test

The following is an experiment to test the effectiveness of this control strategy, in which the simulation software VISSIM 5.4 is used. The simulation model and simulation scene in VISSIM 5.4 are illustrated in Fig. 4.
4.1 Basic conditions and assumptions

In this simulation model, the distance between two intersections is 400m. The width of the upstream intersection is 30m. The average speed on this section is 45km/h and the speed of saturated flow is 52 km/h. The congestion density is set as 130veh/km. The proportion of different flow (left, though, right) is 2:18:2 at upstream intersection. The flow of crossing road is 500veh/h whose proportion is 2:3:1. These intersections are all use two-phase signal control and cycle length is set as 120s; the minimum green time $g_{i \text{min}}$ is 90s; the simulation time is 3600s.

4.2 Simulation process

In order to find out the best offset under different saturation level, we conduct four groups of experiments, in which the traffic volume from upstream intersection range from 1600veh/h to 2200veh/h (as shown in Fig. 5), during each experiment, we adjust the offset ($\Delta T$) between two intersections from 0s to 120s. As illustrated in Fig. 5, the average delay of vehicles is changed along with offsets when traffic volume is fixed, the optimum offsets ($\Delta T_1$) at different traffic volume are recorded in Tab 1, and Tab. 2 shows the simulation results under oversaturated condition.

![Fig. 5 The relationship between offset and delay under different traffic volumes](image)

The details of the simulation results when traffic volume is 2200veh/h are also listed in Tab. 2. The offset calculated by equation (12) is 47s, and the offsets which cause the maximum delay and minimum delay are 78s and 42s. A speed detector is set at 1m apart from the stop line of upstream intersection to detect the velocity under these three offsets during the green tail. If the velocity is under 5km/h, the car would be regard as in a queue and the intersection would have great probability to be deadlock. Tab. 2 gives the times that the velocity is under 5km/h in simulation.

<table>
<thead>
<tr>
<th>Upstream flow Q (veh/h)</th>
<th>$\Delta T$ (s)</th>
<th>$\Delta T_1$ (s)</th>
<th>Relative error of $\Delta T$ (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>2200</td>
<td>47</td>
<td>42</td>
<td>11.9%</td>
</tr>
<tr>
<td>2000</td>
<td>39</td>
<td>36</td>
<td>8.3%</td>
</tr>
</tbody>
</table>
### 4.3 Analysis of the simulation results

From Fig. 5, we can draw a conclusion that the average traffic delay of vehicles is changed along with the offset between two intersections, and there will be a best offset under which the average traffic delay is least, it means this offset is an optimal value. As shown in Tab. 1, the offset $\Delta T'$ which calculated by equation (12) is very nearly to the actually optimal offset $\Delta T^*$ (the mean relatively deviation is only 11.2%). Especially, the results in Tab. 2 demonstrates that when saturated flow is 2200veh/h, the control method proposed above can reduce the mean delay of vehicles from 34.9s to 26.3s (reduced by 24.6%), and it will also reduce the risk of intersection deadlock by 30% at the same time.

### 5. Summary

In this research, we propose the definition of different types of queue spillback and shockwave profile of traffic flow on links. Aimed at reducing the risk of intersection deadlock under oversaturated situation, the model to calculate the reliability interval of signal offset which can constrain the spillback of traffic flow into particular form has been put forward. Finally, a simulation experiment is conducted to test the effectiveness of this control strategy, the test results show that this method can reduce average traffic delay of vehicles significantly and protect intersections from deadlock effectively.

But we should note that, although the algorithms is effective enough in the simulation test, but maybe it’s not easily to use in practical application, especially when used for an arterial, or a network of intersections.

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### References


