Traffic bottleneck control method based on road residual capacity and flow allocation

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Abstract. In order to dissipate traffic congestion and bottleneck quickly, a traffic bottleneck control method based on residual capacity and flow distribution of road section is proposed. According to the standard of adjustable green letter ratio in the limit case of upstream and downstream of the bottleneck section, the capacity that the bottleneck section needs to increase is allocated to the upper and lower reaches for adjustment. According to the weight of the remaining capacity of the section, the capacity that the relevant section of the bottleneck section needs to increase is allocated to the adjacent section. The green time of non-bottleneck related phase is compressed and tested to prevent congestion transfer. The effectiveness of the algorithm is verified by simulation experiment.

1. Introduction
With the increasing number of motor vehicles, it is easy for the road demand capacity to exceed the actual supply capacity in the traffic network[1]. When vehicles cannot be released effectively, it is easy to cause the queue length of vehicles on the road section to be close to or equal to the length of the road, and the queue will be upstream, thus causing the diffusion of congestion[2]. Traffic congestion will significantly increase the travel time of vehicles, cause environmental pollution, bring about a variety of traffic safety problems and so on[3]. Large area traffic jam usually starts from a certain section of traffic jam. Therefore, it is of great significance to study the optimization control of section congestion[4].

2. Related Work
Zhao yingying[5] analyzed the mechanism of bottleneck intersection leading to road network congestion, and put forward three bottleneck control methods according to different traffic conditions: demand control, supply control and coordinated control. Ma dongfang[6] put forward the concept of rolling time occupancy rate, the optimization method of timing parameters and the balanced transition method for the upper and lower reaches of the bottleneck section. Based on the traffic network reserve capacity model, zhu senlai[7] proposed the identification method of potential bottleneck sections in the traffic network, and designed the solution algorithm of reserve capacity model. Sun weili[8] proposed several new unconventional intersection designs for congestion control, including the widely recognized continuous flow intersection design. Sun lingtao[9] proposed the concept of influence rate and share rate between traffic load of bottleneck traffic flow and traffic flow in upstream and downstream sections, and proposed a multi-point linkage bottleneck control method. Wang fujian[10] based on the critical path and the residual capacity of the section, established the allocation method of the total regulation amount of inbound traffic between controllable sections. Zhu haifeng[11]
determined the correlation degree between each road section and the bottleneck road section through vehicle passing data, carried out flow equalization treatment on the potential bottleneck road section, and carried out timing optimization with saturation equalization as the goal.

In this paper, a traffic bottleneck control method based on road flow distribution is proposed, which distributes the capacity according to the residual capacity of the road, and optimizes the upper and lower reaches of the bottleneck section respectively, so as to make the road flow distribution more balanced.

3. Traffic bottleneck control method based on road residual capacity and flow allocation

3.1. Basic structure of bottleneck controlled intersection

The emergence of road network congestion, often from a certain section of congestion began to gradually spread outward. When the queue length of vehicles is close to the length of the road, it is easy to cause the queue upstream, which leads to serious congestion. Figure 1 is the basic structure of adjacent intersections controlled by bottlenecks. If congestion occurs in section m, section m is called bottleneck section, and intersection 2 is called bottleneck intersection.

![Figure 1. Basic structure of adjacent intersections controlled by bottleneck](image)

3.2. Capacity dissipation of bottleneck section upstream and downstream

After the congestion bottleneck is triggered, in order to maximize the capacity of the intersection, the cycle of the congested intersection is generally set as the maximum cycle. At the same time, in order to evacuate the traffic flow of the bottleneck section as soon as possible, it is necessary to increase the green signal ratio of the road exit phase and reduce the green signal ratio of the road entrance phase.

When the phenomenon of queuing upstream occurs, the downstream phase of the bottleneck section is in the state of oversaturation. During the whole queuing process, it can be considered that the phase of the bottleneck section is released by vehicles according to the saturation flow rate. In order to dissipate the queue length of the bottleneck section to the normal queue length within time $T$, the difference between the downstream output capacity and the upstream input capacity of the bottleneck section $\Delta S_i$ should meet:

$$\Delta S_i = \frac{L_{\text{max}} - L_0}{T \cdot l \cdot \varphi}$$

Where, $L_{\text{max}}$ represents the queue length of the section when the bottleneck is triggered; $l$ is the distance between the front and $\varphi$ is the number of lanes.
The downstream output capacity of the bottleneck section $S_{out,m}$ is the saturation flow rate of each output lane $Q_{m,h}$ times the green traffic ratio $\lambda_{m,h}$:

$$S_{out,m} = \sum_{h \in I_{out}^m} (\lambda_{m,h} \cdot Q_{m,h})$$  \hspace{1cm} (2)

Upstream input capacity $S_{in,m}$ of bottleneck section is the smaller value of vehicle arrival rate $q_{z,m}$ of each input lane and saturation flow rate $Q_{z,m}$ of each input lane multiplied by greenletter ratio $\lambda_{z,m}$:

$$S_{in,m} = \min_{h \in I_{in}^m} (q_{z,m} \cdot \lambda_{z,m} \cdot Q_{z,m})$$  \hspace{1cm} (3)

Where, $Q_{m,h}$ represents the saturated flow rate from section $m$ and section $h$; $\lambda_{m,h}$ represents the green letter ratio from section $m$ and section $h$; $q_{z,m}$ represents the vehicle arrival rate from section $z$ and section $m$, and $Q_{z,m}$ represents the saturated flow rate from section $z$ and section $m$. $\lambda_{z,m}$ represents the green ratio from section $z$ to section $m$.

Under the conventional control scheme, there is no queue accumulation in the upstream, and the difference between the downstream output capacity and the upstream input capacity of the bottleneck section is $\Delta S_2$:

$$\Delta S_2 = S_{out,m} - S_{in,m} = \sum_{h \in I_{out}^m} (\lambda_{m,h} \cdot Q_{m,h}) - \min_{z \in I_{in}^m} (q_{z,m} \cdot \lambda_{z,m} \cdot Q_{z,m})$$  \hspace{1cm} (4)

If there is queue accumulation upstream, then:

$$\Delta S_2 = S_{out,m} - S_{in,m} = \sum_{h \in I_{out}^m} (\lambda_{m,h} \cdot Q_{m,h}) - \sum_{z \in I_{in}^m} (\lambda_{z,m} \cdot Q_{z,m})$$  \hspace{1cm} (5)

Therefore, the capacity $\Delta S$ that the bottleneck section needs to increase is:

$$\Delta S = \Delta S_1 - \Delta S_2$$  \hspace{1cm} (6)

Without considering non-bottleneck phase and other sections, according to the maximum compressibility of the upstream capacity of the bottleneck section and the maximum increase of the downstream capacity of the bottleneck section under the limit condition, the capacity that the bottleneck section needs to change is allocated to the upstream and downstream intersection.

The maximum compressible capacity of the upstream capacity of the bottleneck section $\Delta S_{u,max}$ is the capacity of the upstream capacity of the bottleneck related phase multiplied by the green signal ratio corresponding to the relevant phase of the bottleneck. The maximum increase in the downstream capacity of the bottleneck section $\Delta S_{d,max}$ is the capacity of the downstream bottleneck related phase multiplied by the green signal ratio corresponding to the non-bottleneck related phase. According to the standard of adjustable green signal ratio under the limit condition of upstream and downstream, the capacity that the bottleneck section needs to increase is allocated to the upper and lower reaches respectively for adjustment.

$$\Delta S_u = \frac{\Delta S \cdot \Delta S_{u,max}}{\Delta S_{u,max} + \Delta S_{d,max}}$$  \hspace{1cm} (7)

$$\Delta S_d = \frac{\Delta S \cdot \Delta S_{d,max}}{\Delta S_{u,max} + \Delta S_{d,max}}$$  \hspace{1cm} (8)

3.3. Calculation of green traffic ratio regulation in upper and lower reaches of bottleneck section

As shown in the figure 2, assume that the red section is the bottleneck section, the adjacent section is the first-level relevant section, and the adjacent section is the second-level relevant section, and so on. In order to allocate the traffic flow pressure of the bottleneck section to the surrounding section, the residual capacity of the section was defined as follows:
\[ F_i = \frac{\alpha \bar{L}_{i} - L_{i}}{l} \varphi_{i} \]  

(9)

Where, \( \alpha \) represents the safety queuing coefficient; \( \bar{L}_{i} \) represents the actual length of the section; \( L_{i} \) represents the length of the section queue; \( \varphi_{i} \) is the number of lanes.

According to the weight of the residual capacity of the section, the capacity that the downstream of the bottleneck section needs to increase is allocated to the adjacent level-1 relevant section.

\[ \Delta \lambda_{i} = \frac{\Delta S_{i}}{\varphi_{i}Q_{i}} \]  

(10)

According to the phase green signal ratio in the original scheme, the green time compression amount of non-bottleneck related phase is allocated according to the same proportion:

\[ g' = g - \sum_{j \in J_{i+1}} \lambda_{j} \sum \Delta \lambda_{i} \cdot c \]  

(11)

Where, \( g \) represents the green time in the original timing scheme; \( J_{i+1} \) represents non-bottleneck related phase; \( c \) represents the cycle length of the intersection.

In order to ensure that the corresponding sections of non-bottleneck related sections do not have queuing upstream in time, it is necessary to calculate the maximum green letter ratio compression amount of non-bottleneck related sections, and compare it with the theoretical value calculated above, and take the two smaller values as the actual green letter ratio compression amount. The capacity that cannot dissipate downstream of the bottleneck section will be transferred to the upstream of the bottleneck section for dissipation.

Downstream bottleneck related road, after the allocation of capacity to dissipate, it is necessary to calculate whether the queuing upstream will occur in the time, if the queuing upstream does not occur, then the control ends. If there will be queuing upstream, the increased capacity will be needed to make up after crossing the downstream of the section, and the specific method is consistent with the bottleneck section. If a road is adjacent to a number of road sections related to bottlenecks, the amount of adjustment needed for the road sections with high correlation of bottlenecks and small remaining road capacity should be calculated first. At this point, the downstream green traffic ratio adjustment of the bottleneck section has been completed.

The capacity that the upstream of the bottleneck section needs to compress is distributed proportionally according to the remaining capacity of each adjacent bottleneck related section, and the
control mode is consistent with the control of the downstream of the bottleneck section. It should be noted that if the green ratio compression in the upstream section is larger than the actual compression, all directions have been adjusted, indicating that the bottleneck of the section cannot be dissipated to the expected length $L_0$ within time $T$. Therefore, it is necessary to increase the control time of the bottleneck and recalculate.

4. Experimental verification and analysis
In this paper, a road network in Hefei was selected for algorithm verification, and the simulation diagram was drawn in VISSIM traffic simulation software. The road network includes 19 intersections and 29 sections, as shown in figure 4.

In order to fully reflect the influence of the bottleneck control method in this paper, the maximum queue length, average queue length, average delay and average stopping times of the bottleneck intersection were selected for evaluation.

In this paper, under the same simulation conditions, the road network control scheme under normal conditions is taken as the original control algorithm, and the downstream flow is controlled by referring to other bottleneck control methods, which is called the downstream control algorithm. Meanwhile, the traffic bottleneck control algorithm proposed in this paper is adopted for optimization comparison.

Figure 4. Road network structure

Figure 5. Maximum queue length comparison

Figure 5 shows the variation of the maximum queue length of the bottleneck section under the three control algorithms. Table 1 shows the comparison of the maximum queue length, average queue length, average delay and average stopping times at the bottleneck intersection under the three control schemes. As can be seen from figure 5, in terms of the maximum queue length, the control algorithm in this paper is superior to the conventional control algorithm and the downstream control algorithm. As can be seen from table 1, the control algorithm in this paper has a good effect on key traffic indicators.

| Control scheme                  | $L_{max}$/m | $L_{ave}$/m | D/s  | S/time |
|---------------------------------|-------------|-------------|------|--------|
| Conventional control algorithm  | 196.55      | 122.62      | 51.54| 1.36   |
| Downstream control algorithm    | 176.8       | 90.78       | 43.35| 1.19   |
| Control algorithm in this paper | 164.04      | 85.02       | 38.75| 1.05   |

5. Conclusion
This paper proposes a traffic bottleneck control method based on residual capacity and flow allocation. The upstream and downstream control of the bottleneck section, the control of the bottleneck related
section and the control of the non-bottleneck related phase are considered comprehensively, and the validity of the algorithm is verified by experiments.

The study in this paper is based on the case of fixed cycle. The next step is to study the bottleneck control under the case of variable cycle.

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