Traffic Signal Self-Organizing Control With Road Capacity Constraints

Guangcheng Long, Anlin Wang, and Tao Jiang

***Abstract*— This paper aims at the problem of intersection traffic oversaturation and the spillover of queuing vehicles caused by random fluctuations of traffic flow. A self-organizing control model with road capacity constraints and taking minimum expected traffic flow delay as the goal is established to realize real-time adaptive control of traffic signal phase duration. Taking the local intersection and its adjacent intersections as the basic unit of traffic signal control, defining the constraints of road space in queuing state and the equations of traffic signal control basic unit are established. According to the equations, an online method for solving the optimal phase duration of traffic signal is established to efficiently allocate intersection space resources, by which a rule-based real-time traffic signal control model is established. Through the interaction between adjacent intersections, the traffic inflow rate of oversaturated phase is automatically restricted to alleviate the queuing spillover problem. Computer simulation shows that the control effect is significantly better than that of SCATS under the same boundary inflow conditions. Compared with the traditional centralized coordinated control, the rule-based real-time traffic signal control model can better adapt to the fluctuation of traffic flow and effectively relief the problem of vehicle queuing spillover caused by fluctuations of traffic flow.**

***Index Terms*— Traffic signal adaptive control, self-organizing control, traffic lights control, traffic oversaturation.**

I. Introduction

With continuous growth of urban vehicles, the problem of traffic oversaturation at intersections and queuing vehicles spillover is becoming more and more serious. Improving the traffic signal control efficiency is the most simple and economical way to alleviate the problem. Aiming at the problem of traffic oversaturation, traffic signal control mainly solves the problem from two aspects: 1) optimize traffic signal to improve the traffic flow efficiency; 2) limit the length of queuing vehicles to avoid blocking upstream intersections. However, the problem of urban traffic signal control is very complicated because of the random characteristics of traffic flow, the open characteristics of road environment, the high dimension of system variables and the nonlinear characteristics of the system. Traffic signal control under complex and unstable traffic conditions is a long-term scientific and engineering problem.

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Traditional centrally coordinated traffic signal control system optimizes all intersection traffic signal parameters at the same time, which is known as a NP-Complete problem [1]. Generally, the model is complex and the calculation cost is high, which makes it difficult to realize the real-time control of traffic signal in a large area and lacks the adaptability to the changes of traffic flow. To improve traffic flow efficiency, traffic signal real time control is an effective way [2], [3]. Reference [4] established a traffic signal distributed control model based on the BackPressure scheme. According to the traffic state at the initial moment of each traffic signal cycle, each phase duration is allocated in real time. The simulation showed that it could effectively improve traffic efficiency and relieve traffic congestion. Reference [5] established a model of releasing digital infochemicals (DIs) from vehicles on travel paths by analogy with ant colony algorithm. The traffic signal control agent allocates the green signal ratio of each phase according to the proportion of accumulated digital infochemicals in each direction at the local intersection. Reference [6] established traffic signal self-organizing control rules using secondary extension. Based on actuated traffic signal control logic, the model is not constrained by traffic signal cycle length which can greatly reduce the green light time loss. Reference [7] established the phase-switching rules with the goal of reducing traffic delay. Real-time control of phase duration is realized through multi-agent distributed architecture. According to recent studies, traffic signal self-organizing control is an effective method to improve the flexibility and adaptability of traffic signal control. The self-organizing control is based on the expression of the microscopic model [8]–[10] of the system, which can describe the complex characteristics of the system from bottom to top. It improves the system performance by on-line iteration. The self-organizing control is similar to the learn control, for it can reduce the uncertainties pertaining to the effective control of the system through subsequent observations of inputs and outputs as the process evolves. Compared with the widely used learning control [11]–[13], the self-organizing is locally model-based and always on-line, by which the computing costs can be greatly reduced. The traffic signal self-organizing control method seems to be a very promising control method, especially when the traffic demand is random and systematic.

Due to the unsteady random characteristics (volatility) of urban traffic flow and the limitation of road traffic capacity, phase saturation will oscillate constantly and phase oversaturation is almost inevitable. Traffic oversaturation for a short period of time is usually allowed and the queuing vehicles accumulated in oversaturation time can be released in a number of traffic signal cycles in the future. However, when the adjacent intersections are close and road capacities are relatively small, the spillover of queuing vehicles needs to be considered. Limiting the queuing length of vehicles and preventing the spillover of queuing vehicles is the primary goal of traffic signal control under the condition of traffic saturation [14], [15]. To solve the traffic signal control problem under traffic oversaturation, [16] established an approximate optimal feedback control model under constraint of the maximum queue length. Reference [17] established a stochastic programming model and simplified the traffic signal control model into two steps. In the first step, the constraints of the green signal ratio of each phase are determined according to the prior data. In the second step, the green signal ratio parameters of each phase are solved with the goal of minimum delay. This model only optimizes two consecutive traffic signal cycles, greatly simplifies the complexity of the traffic signal control model and improves the adaptability of the traffic signal control model. Reference [18] established a model-based real-time control model by optimizing the green signal ratio parameters of traffic signals through artificial bee colony algorithm. The model includes the queue spillover detection process and when there is a risk of queue spillover, the current traffic signal cycle is terminated in advance. This model increases the detection process of queuing vehicles spillover, which can alleviate the problem of traffic oversaturation and spillover of queuing to a certain extent. Reference [19] reduces the risk of queuing spillover by optimizing the offset parameters. Traffic signal control under traffic oversaturation can be modeled as a traffic signal control problem with road capacity constraints (vehicle queuing length constraints).

Traffic signal control is the optimal allocation process of space resources at intersections. When traffic demand exceeds the service capacity of the traffic signal phase, traffic oversaturation occurs. Queuing spillover occurs when the vehicle queuing length exceeds the road space constraint. The traditional off-line optimized traffic signal control method is difficult to configure traffic signals timely and efficiently. Under the condition of high traffic flow, it is easy to cause traffic oversaturation at some intersections due to the fluctuation of traffic flow. To the problem of traffic control and traffic oversaturation, this paper proposes a self-organizing control model with road capacity constraints. The self-organizing control model calculates the optimal green light duration of current phase in real time to efficiently allocate space resources of the local intersection. When there is a risk of queuing vehicles spillover at the local intersection, the feedback control function is spontaneously established between adjacent intersections to limit the vehicle outflow rate of the upstream intersections. The vehicle arriving rate of oversaturation phase is reduced and queuing spillover problem is alleviated.

The rest of this paper is organized as follows. Section 2 discusses the definition of real-time phase saturation and traffic signal real-time control. In section 3, the equations of traffic signal control are introduced and the relationship of traffic signals between adjacent intersections is described. Then we define the constraint of road capacity in queuing state. Section 4 introduces the construction of traffic signal self-organizing control rules and the realization of self-organizing control. In section 5, the calculation process of traffic signal phase duration based on self-organizing control rules and the stability conditions of self-organizing control are introduced. Section 6 is computer simulation. By comparing with SCATS (Sydney Coordinated Adaptive Traffic System), the effectiveness of the proposed self-organizing control is been proved. Finally, section 7 discusses conclusions and the future work.

II. Traffic Signal Real-Time Control

A. Traffic Signal Phase Saturation

Traffic signal is composed of phase green time and phase interval time. Traffic signal is described as (1):

$$T = \sum_{i\in\gamma} (\tau_i + g_i), \quad g_i \in \left[g_i^{\min}, g_i^{\max}\right] \tag{1}$$

T is the cycle duration of the traffic signal; γ is the phases set; g_i is the green light duration of phase i; $g_i^{\min}$ is phase i permitted minimum green light duration and $g_i^{\max}$ is the permitted maximum green light duration; τ_i is the interval between the green light of the previous phase turned off and the green light of phase i turned on, which is usually a constant.

Phase traffic saturation is used to represent the matching condition between phase service capacity and traffic demand. Traditional traffic signal phase saturation definition is:

$$x_i = \frac{q_i}{C_i} = \frac{q_i}{S_i} * \frac{T}{g_i^e} = \frac{y_i}{\lambda_i}, \quad i \in \gamma \tag{2}$$

q_i is the average traffic flow rate of phase i, C_i is the service capacity of phase i, g_i^e is the effective green light duration of phase i, S_i is saturation flow rate of phase i, y_i is flow ratio of phase i, λ_i is the green signal ratio of phase i. The unit of q_i, S_i and C_i is pcu/h (pcu, Passenger Car Unit). If $x_i > 1$, traffic at the intersection is over saturated. In oversaturated state, the number of vehicles queuing in the oversaturated phase continues to increase over time. If the number of queuing vehicles cannot be restrained in time, the queuing vehicles will be spillover, which will lead to the upstream intersection jam, or even lead to traffic paralysis.

Formula (2) is a statistical average model. Phase saturation is calculated according to traffic signal cycle, green signal ratio and average traffic flow, which cannot accurately express the real-time phase saturation state. Traffic flow is constantly changing and phase saturation is related to time. To describe intersection traffic state more accurately and timely, we define the real-time saturation of the current phase:

$$x(t) = \frac{N + \int_{t_{i-1}}^{t} q^{\text{in}}(t)dt}{S * g^e(t)}, \quad t \in [t_{i-1}, t_i] \tag{3}$$

N is the number of queuing vehicles at t_{i-1}; t_{i-1} is the initial moment of current phase; t_i is the end moment of current phase; S is the saturation flow rate; $\mathrm{g^e}(t)$ is the effective green light time from t_{i-1} to t; $q^{\text{in}}(t)$ is the arriving flow rate and the unit is pcu/s. The intersection is only in a certain traffic signal phase at any time and (3) can calculate real-time saturation of the current phase. If $x(t) > 1$, the current phase is oversaturated and the green light needs to be extended.

B. Traffic Signal Real-Time Control

Due to the open and unsteady random characteristics of urban traffic flow, the traffic flow rate in each direction of the intersection is constantly changing. Traffic signals need to dynamically allocate the optimal g_i value according to current traffic states to minimize the delay time of traffic flow.

From the perspective of system control, the urban traffic signal control can be regarded as a high-dimensional optimal control system by taking traffic signal as control input parameters, phase saturations as output variables, the number of vehicles queuing at intersections as system states and the overall delay of traffic flow as performance evaluation. Traffic signals at all intersections of the road network are controlled according to the states of traffic flow and phase saturations are controlled at reasonable values to minimize the overall vehicle delay of the road network. Low phase saturation leads to a waste of green time and increasing traffic delay. High phase saturation, due to the fluctuation of traffic flow, is easy to occur traffic oversaturation, leading to the accumulation of queuing vehicles.

Due to the fluctuation of traffic flow and road capacity limit, intersection phase oversaturation is almost inevitable. Short periods of phase oversaturation can be allowed, but queuing spillover and blocking upstream intersections are absolutely not allowed. Therefore, the urban traffic signal control problem can be modeled as the stochastic system optimal control problem under state (vehicle queuing length) constraints.

According to stochastic system control theories, a traffic signal self-organization control model is proposed in this paper. Based on multi-agent architecture, the current phase green time of the local intersection is calculated in real time and the intersection space is efficiently configured to avoid traffic oversaturation. Under self-organizing control, the traffic signal control decision spaces between adjacent intersections are correlated with each other. When there is a queuing spillover risk at local intersection, through the interaction between adjacent intersections, the arriving traffic flow from upstream intersections is automatically restricted and a part of the traffic flow is placed at the upstream intersections, so as to alleviate the queuing spillover problem.

III. URBAN TRAFFIC FLOW MODEL

A. Traffic Signal Control Equations

Taking an intersection in the road network as the research object, due to the isolation effect of the intersection channelization, the traffic flow in each direction of the intersection is independent in time and space. According to the continuous traffic flow model, changes of queuing vehicles can be expressed as (4):

$$\frac{dQ_j(t)}{dt} = q_j^{\text{in}}(t) - q_j^{\text{out}}(t), \quad j \in \beta \tag{4}$$

$$q_j^{\text{in}}(t) - = \sum_{i \in \phi_j} q_{ij}^{\text{in}}(t) + A_j(t) \tag{5}$$

$$q_j^{\text{out}}(t) = \begin{cases} 0 & \text{(red)} \\ S_j & (\text{green}, Q_j(t) > 0) \\ q_j^{\text{in}}(t) & (\text{green}, Q_j(t) = 0) \end{cases} \tag{6}$$

$Q_j(t)$ is the number of queuing vehicles in direction $j(Q_j(t) \geq 0)$; $q_j^{\text{in}}(t)$ is arriving vehicle flow rate in direction j; $q_j^{\text{out}}(t)$ is the departing vehicle flow in direction j; ϕ_j is the set of traffic flows entering direction j from the adjacent intersections; β is the set of traffic flows at the current intersection; $q_{ij}^{\text{in}}(t)$ is the traffic flow rate from the adjacent intersection i arriving the direction j at the current intersection; $A_j(t)$ is the flow rate of vehicles entering from (or departing to) the external environment; S_j is the saturation flow rate of direction j; red indicates that the current traffic signal status is red; green indicates that the current traffic signal status is green. To build (6), we make the following assumption: the effective green light time is approximately treated as the display green light time. The phase loss time is approximately equal to the phase interval time and the phase interval time is treated as red light time. In the green light time, when there are queuing vehicles, the traffic flow departing flow rate is the saturated flow rate; when there are no queuing vehicles, the departing flow rate is equal to the arriving flow rate.

There will be traffic flow delay when there are vehicles queuing to pass. $w_j(t)$ represents the delay time of traffic flow in direction j and $W(t)$ represents the delay time of the overall traffic flow at the intersection. The relationship between the number of queuing vehicles and the delay time is:

$$\frac{dw_j(t)}{dt} = Q_j(t) \tag{7}$$

$$\frac{dW(t)}{dt} = \sum_{j \in \beta} Q_j(t) \tag{8}$$

The unit of S_j, $q_j^{\text{in}}(t)$, $q_j^{\text{out}}(t)$, $A_j(t)$ and $q_{ij}^{\text{in}}(t)$ is pcu/s; the unit of $Q_j(t)$ is pcu.

Diffusion phenomenon [20]–[22] occurs in the process of a platoon of vehicles travel from the upstream intersection to the downstream intersection. Pacey platoon diffusion model [21] indicates that on urban road, the travel time of vehicles travel from upstream section to downstream section conforms to normal distribution. According to (4) and Pacey platoon diffusion model:

$$\begin{aligned} E\{Q_j(t)\} &= N_j(t_0) + E\{\int_{t_0}^{t} (q_j^{\text{in}}(t) - q_j^{\text{out}}(t))dt\} \\ &= N_j(t_0) + \mathrm{E}\{\sum_{i \in \phi_j} \int_{t_0}^{t} \alpha_{ij} d_{ij}(t) q_{ij}^{\text{out}}(t)dt\} \\ &\quad + \mathrm{E}\{\int_{t_0}^{t} A_j(t)dt\} - \mathrm{E}\{\int_{t_0}^{t} q_j^{\text{out}}(t)dt\} \end{aligned} \tag{9}$$

$E\{Q_j(t)\}$ represents the mathematical expectation of queuing vehicles at t; $N_j(t_0)$ is the number of queuing vehicles at t_0; $d_{ij}(t)$ is the normal distribution probability density function of travel time from the upstream intersection i to the current intersection in direction j; $q_{ij}^{\text{out}}(t)$ is the departing traffic flow rate from the adjacent intersection i to the j direction at current intersection; α_{ij} is the proportion of $q_{ij}^{\text{out}}(t)$ flow to j direction at the current intersection. $d_{ij}(t)$ is obtained according to Pacey platoon diffusion model and actual traffic statistical values. If $q_{ij}^{\text{out}}(t)$ and $N_j(t_0)$ are given, (9) can be used to forecast traffic demand.

B. Road Capacity Constraints Definition in Queuing State

Generally, traffic signal control only considers traffic capacity of the intersection. However, the road capacity in queuing state should also be considered in order to prevent vehicle queuing spillover under fluctuation traffic conditions. Defining road capacity constraint in queuing state:

$$V_j = n_j * \frac{L_j}{\overline{l} + \overline{d}} \tag{10}$$

V_j is the road capacity constrain in queuing sate in direction j at the current intersection and the unit is pcu; n_j is the number of lanes in direction j; L_j is the distance between the current intersection and the upstream intersection in direction j, the unit is m; $\overline{l}$ is the average length of Passenger Car Unit; $\overline{d}$ is the average distance between vehicles in queuing state. $\overline{l} + \overline{d}$ is the average road occupancy length of Passenger Car Unit in queuing state and the unit is m/pcu; When $Q_j(t) > V_j$, the queuing vehicles spillover occurs, which is not allowed. The constraints of road capacity in queuing state at current intersection can be expressed as:

$$Q_j(t) \in \left[0, V_j\right], \quad j \in \beta \tag{11}$$

IV. TRAFFIC SIGNAL SELF-ORGANIZING CONTROL

In order to achieve more accurate and efficient control of urban traffic signal, a self-organizing traffic signal control model based on distributed architecture is proposed in this paper. The traffic signal control problem is modeled as an optimal control problem under constraints of road capacity. According to the traffic flow model, the traffic signal control state equations of local intersection are established. The control time is discrete by the traffic signal phase and the optimal green light duration of current phase is solved online in real time with the goal of minimizing traffic flow delay. In this way, intersection space resources can be efficiently allocated to alleviate the problem of traffic oversaturation. When there is a risk of vehicle queuing spillover at local intersection, the traffic signal control equation constraints of the adjacent intersections will be change. Through the interaction between adjacent intersections, the departing traffic flow of upstream intersections will be automatically reduced, the arriving traffic flow of local intersections will be reduced and the problem of vehicles queuing spillover will be alleviated.

A. Equations of Traffic Signal Control Basic Unit

The local intersection and its adjacent (directly connected) intersections are taken as the traffic signal control basic unit. The entire road network is broken down into a combination of basic units. The intersection is modeled as a traffic signal control agent and the following assumptions are made:

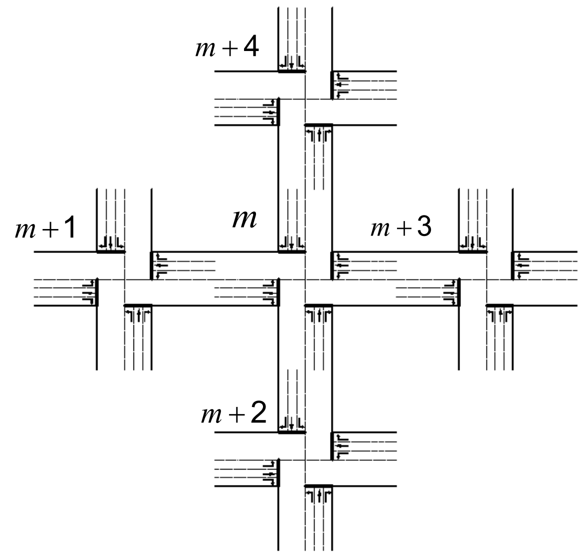

Fig. 1. Basic unit of traffic signal self-organizing control.

1) Sensors are installed in each lane at intersections which can detect the number of queuing vehicles and the traffic flow rate of each lane in real time; 2) adjacent intersections can communicate with each other to obtain traffic flow departing rates and queuing vehicles states information at adjacent intersections.

Taking a standard cross intersection as an example, as shown in Fig. 1, intersection m and its four adjacent intersections $m1$-$m4$ constitute the basic unit of traffic signal control. Based on the assumption that intersection m can communicate with adjacent intersections $m1$-$m4$, the state equations of queuing vehicles at intersection m can be established, as shown in (12):

$$\begin{aligned} &\dot{\boldsymbol{Q}}(t) = f(\boldsymbol{Q}(t), \boldsymbol{u}(t), \boldsymbol{\xi}(t), t); \\ &\boldsymbol{Q}(t_0) = \boldsymbol{Q}_0, \quad \boldsymbol{u}(t) \in \Omega_{\boldsymbol{u}}, \ \boldsymbol{Q}(t) \in \Omega_{\boldsymbol{Q}}, \ t \in [t_0, t_n] \end{aligned} \tag{12}$$

$\boldsymbol{Q}(t)$ is the l-dimensional vector, each component represents the states of the traffic flow in corresponding direction and l is the number of traffic flow directions. $\boldsymbol{u}(t)$ is the z-dimensional traffic signal vector and each component represents the status of the corresponding traffic signal phase. There are only two signal status: red and green. Red stands for red light (phase interval time is regarded as red light), green stands for green light and z is the number of traffic signal phases. $\Omega_{\boldsymbol{u}}$ is the set of admissible traffic signal parameters; $\Omega_{\boldsymbol{Q}}$ is the set of admissible vehicle queuing states; $\boldsymbol{\xi}(t)$ is the l-dimensional random vector, representing the random characteristics of traffic flow; t_0 is the control start moment and t_n is the control end moment. Each equation of (12) is established according to (4) $\sim$ (6) and $l \geq z$.

The goal of traffic signal control is to minimize the delay of traffic flow. Taking the mathematical expectation delay of traffic flow at the intersection as performance evaluation, the performance evaluation of intersection m can be established as shown in (13):

$$\begin{aligned} I(\boldsymbol{u}(t)) &= E\{J(\boldsymbol{u}(t))\} \\ &= E\{(t_n - t_0)^{-1} \int_{t_0}^{t_n} g(\boldsymbol{Q}(t), \boldsymbol{u}(t), t)dt\} \end{aligned} \tag{13}$$

$J(\boldsymbol{u}(t))$ is the evaluation function of traffic flow delay:

$$g\left(\boldsymbol{Q}\left(t\right),\boldsymbol{u}\left(t\right),t\right)=\frac{dW(t)}{dt}=\sum_{i\in\beta}Q_i\left(t\right) \tag{14}$$

Assume that $\boldsymbol{u}^*(t)$ is the optimal traffic signal vector under the evaluation condition of (13), namely:

$$\boldsymbol{u}^*(t)=\{\boldsymbol{u}(t)|\min I(\boldsymbol{u}(t))=I_{\min}\}$$

For the unsteady random characteristics of traffic flow, *if* t_n-t_0 is a long period of time, $\boldsymbol{u}^*(t)$ can hardly be obtained by off-line solution.

B. Self-Organizing Control Based on Phase Duration

The traffic signal is constantly circulating and the control period $t\in[t_0,t_n]$ is divided into continuous segments according to $\Delta T_i=t_i-t_{i-1}=g_k+\tau_k$, $(i=1,2,3,\ldots)$, $k\in\gamma$. According to the characteristics of traffic signal, at any moment t, the traffic signal is only in a certain phase (the τ_k time is classified as phase k). Without losing generality, we assume that $t_n\to\infty$.

When $t_{i-1}\leq t\leq t_i$, traffic signal is in phase k. For the z-dimension traffic signal state vector $\boldsymbol{u}(t)$, only the k component is green (except τ_k) and the rest components are red. With traffic signal circulating, the traffic signal control time is discretized into n segments and each segment is only in a certain phase state of the traffic signal.

Define the evaluation function of time segment i:

$$j\left(i\right)=\int_{t_{i-1}}^{t_i}g(\boldsymbol{Q}(t),\boldsymbol{u}(t),t)dt/\Delta T_i,\quad \Delta T_i=t_i-t_{i-1} \tag{15}$$

Equation (15) is the sub-control target of (13) and (13) can be minimized by on-line sequentially improving (15). It is assumed that the minimum value of $\mathrm{E}\{j(i)\}$ and the corresponding traffic signal vector $\boldsymbol{u}(t)=\boldsymbol{c}_i^*$ can be obtained by an appropriate global search algorithm in each t_i-t_{i-1} time period, namely:

$$\boldsymbol{c}_i^*=\{\boldsymbol{u}(t)|\min E\{j(i)\}=j_{\min}(i)\} \tag{16}$$

$\boldsymbol{c}_i^*$ is the optimal traffic signal vector of t_i-t_{i-1} time period. $\boldsymbol{c}_i^*$ is determined by the phase k green light duration. By (16), we can get the optimal phase duration of phase k.

With continuously iterating, it is easy to prove:

$$\boldsymbol{c}_i^*=\boldsymbol{u}^*(t)\quad(i=1,2,\ldots,)$$

The cumulative evaluation function of h iterations can be expressed as:

$$V(h)=\frac{\sum_{i=1}^{h}\Delta T_i*E\{j(i)\}}{\sum_{i=1}^{h}\Delta T_i} \tag{17}$$

Taking $\boldsymbol{c}_i^*$ as the traffic signal and iterating successively:

$$\begin{aligned}V(h)&=\frac{\sum_{i=1}^{h}\Delta T_i*j_{\min}(i)}{\sum_{i=1}^{h}\Delta T_i}\\&=(t_h-t_0)^{-1}E\left\{\int_{t_0}^{t_h}g(\boldsymbol{x}(t),\boldsymbol{u}^*(t),t)dt\right\}\end{aligned} \tag{18}$$

Iterating over time step:

$$\lim_{h\to\infty}V(h)=I(\boldsymbol{u}^*(t))\to I_{\min} \tag{19}$$

It is can be seen that if $\boldsymbol{c}_i^*$ is successively solved and be used as traffic signal in the time period of t_i-t_{i-1} at intersection m, with evolution of the system, the cumulative performance evaluation function $V(h)$ tends to be continuously approaching the optimal value $I_{\min}$.

C. Self-Organizing Control Rules

Assuming the set of urban road network intersections is Φ, the traffic signal control evaluation function can be expressed as:

$$p(t)=\sum_{s\in\Phi}I_s(\boldsymbol{u}_s(t)),\quad t\in[t_0,t_n]\,\boldsymbol{u}_s(t)\in\boldsymbol{\Omega}_{\boldsymbol{u},s} \tag{20}$$

$I_s(\boldsymbol{u}_s(t))$ is the performance evaluation of intersection s, $\boldsymbol{u}_s(t)$ is the vector of traffic signal at intersection s; $\boldsymbol{\Omega}_{\boldsymbol{u},s}$ is the set of allowable traffic signal parameters at intersection s. The goal of traffic signal control is to minimize the road network overall evaluation index $p(t)$.

Any intersection s in the road network and its adjacent intersections constitute a traffic signal control basic unit similar to Fig. 1. The control equations of basic unit with the minimum expected traffic delay as goal can be established. In the period t_i-t_{i-1}, the optimal control parameter $\boldsymbol{c}_i^*$ is taken as the traffic signal. With the system evolution, the cumulative performance evaluation of intersection s tends to be continuously approaching the optimal value:

$$\lim_{i\to\infty}V_s(i)\to I_{s,\min} \tag{21}$$

$V_s(i)$ is cumulative evaluation function of intersection s after i iterations and $I_{s,\min}$ is the mathematical expected optimal performance evaluation value of intersection s. All intersections in the road network establish the same self-organizing control model as intersection s. With the evolution of the system, the overall evaluation index of the road network tends to be improved continuously:

$$p(t)=\sum_{s\in\Phi}V_s(i) \tag{22}$$

The traffic signal control agent at each intersection takes the minimum traffic delay rate as goal and continuously solves the optimal phase duration. All intersections use the same self-organizing control rules and the overall system performance tends to be continuously improved over time. A system can be described as self-organizing when local elements interact with each other in order to achieve dynamically a global function or behavior.

V. Real-Time Control Based on Self-Organizing Control Rules

By the method of self-organizing control, the multi-step optimal control problem is transformed into continuous observation - decision one-step optimal control problem. By greatly simplifying the model complexity, self-organizing control can realize the urban traffic signal control in real time. By real-time solving the optimal green duration of current phase,

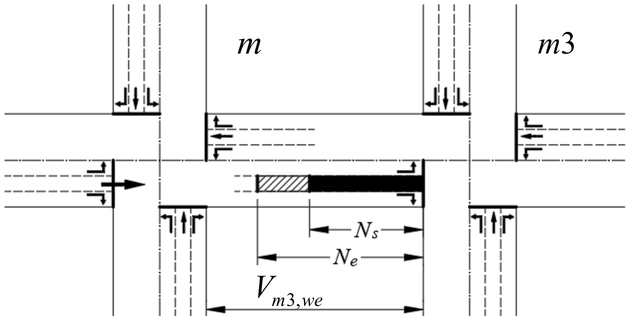

Fig. 2. Road capacity constraints in queuing state.

space resources of intersections can be efficiently allocated to improve traffic efficiency and alleviate the traffic oversaturation problem.

A. Road Capacity Constraints in Queuing State Calculation

As is shown in Fig. 1, intersection m and its adjacent intersections $m1 \sim m4$ constitute the traffic signal control basic unit. The states of traffic signals and the states of traffic flow at the intersection $m1 \sim m4$ constitute the decision-making environment of traffic signal control at intersection m. In the process of traffic signal control at intersection m, it is necessary not only to allocate space resources at local intersection efficiently, but also to consider the impact on adjacent intersections to avoid the queuing vehicles spillover at adjacent intersections. To avoid queuing spillover at adjacent intersections, road capacity constraints in queuing state should be satisfied. Whether queuing spillover risk exists at adjacent intersections can be determined according to (9) and (10).

As is shown in Fig. 2, the road capacity in queuing state of intersection $m3$ in direct from west to east is defined as $V_{m3,we}$, and its value is calculated according to (10). In the direction of traffic flow from west to east, $m3$ is the downstream intersection of intersection m. Part of the traffic flow at intersection m flows to the west-east lane at intersection $m3$. The traffic signal control at intersection m needs to meet the road capacity constraints.

Taking the phase control of west-east traffic flow at intersection m as an example. Assume that the current phase is k, the phase initial moment is t_{i-1} and the phase end moment is t_i. Under green light state, the traffic flow at intersection m flows from west to east through the stop line to intersection $m3$, which will change $Q_{m3,we}(t)$ the states of queuing vehicles at intersection $m3$ in direction from west to east. Based on the communication between intersection m and intersection $m3$, the queuing state information and traffic signal state information at intersection $m3$ can be obtained. $\mathrm{Q}_{m3,we}(t_{i-1}) = N_s(N_s < V_{m3,we})$, according to (9):

$$N_e = \max\{\mathrm{E}\{\mathrm{Q}_{m3,we}(t)\}, \quad t \in \left[t_{i-1}, t_i\right] \tag{23}$$

N_e is the mathematical expectation maximum number of queuing vehicles at intersection $m3$ in direction from west to east. If $N_e > V_{m3,we}$, then the traffic flow in from west to east direction at intersection $m3$ has the risk of queuing spillover. Based on $V_{m3,we}$ constraint:

$$\begin{aligned} t_e &= \{t | E\{Q_{m3,we}(t)\} - V_{m3,we} = 0\} \\ \Delta T_i &= t_i - t_{i-1} = g_k + \tau_k \le t_e - t_{i-1} \end{aligned} \tag{24}$$

t_e is the estimated moment when the west to east traffic flow at intersection $m3$ spillover and ΔT_i is the allowable duration of phase k. Equation (24) requires that the current phase k at the intersection m must be ended before t_e, otherwise a spillover of queuing vehicles will occur. If $N_e \le V_{m3,we}$, there is no queuing spillover risk for the traffic flow in direction from west to east at intersection $m3$. Traffic signal control at intersection m does not have the problem of spillover risk and the optimal phase duration can be selected according to the self-organizing control rules under the constraint $g_k \in \left[g_k^{\min}, g_k^{\max}\right]$, $g_k^{\min}$ is phase k permitted minimum green light duration and $g_k^{\max}$ is the permitted maximum green light duration.

When queuing vehicles pile up at downstream intersections and there is a risk of spillover, the decision space of phase duration at upstream intersections will be compressed to make the phase end in advance. In this case, a part of the traffic flow will be temporarily placed at the upstream intersection, reducing the vehicle inflow of the over-saturated phase at the downstream intersection, so as to restrict the queuing vehicles length. When there is a risk of spillover of queuing vehicles, the traffic signals between local intersection and its adjacent intersections spontaneously establish feedback control functions. The effect of feedback control is to compress the relevant phase durations (green split) of the upstream intersection, temporarily place a part of the traffic flow at the upstream intersection and reduce the inflow of the over-saturated phase traffic flow. Through the coordination control and interaction of traffic signals between adjacent intersections, the problem of intersection traffic oversaturation and spillover of queuing vehicles can be effectively alleviated.

B. Constraint of Basic Green Light Duration

The duration of green light g_b when the queuing vehicles have just been released, is taken as the constraint of basic green duration, namely:

$$\begin{aligned} t_b &= \{t | E\{Q_k(t) = 0\}\} \\ \tau_k + g_b &= t_b - t_{i-1} \end{aligned} \tag{25}$$

$Q_k(t)$ is the number of queuing vehicles of the current phase; t_b is the expected moment when the queuing vehicles of the current phase just have been released and t_{i-1} is the initial moment of the phase. If current phase is ended at t_b, the expected phase traffic saturation is 1. The phase green light time length should be greater than or equal to the basic green duration g_b. Otherwise, the green duration cannot release the all queuing vehicles accumulated in the previous traffic signal cycle, that is phase traffic oversaturation. Taking the basic phase duration as constraint, the green light duration g_k of the current phase should meet the following requirements:

$$\begin{cases} g_k \ge g_b \\ g_k \in \left[\mathrm{g}_k^{\min}, g_k^{\max}\right] \end{cases} \tag{26}$$

If $g_b > g_k^{\max}$, the set of (26) is empty, let $g_k = g_k^{\max}$. The current phase is over saturated and the queuing vehicles are released under the permitted maximum green light time length.

C. Solving the Optimal Phase Duration

$t \in [t_{i-1}, t_i]$, $E\{Q_j\ (t)\}$ is predicted by (9). The phase duration of traffic signal is relatively short, letting $E\{A_j(t) = 0\}$. $q_{ij}^{\text{out}}(t)$ can be predicted by the adjacent intersection. t_{i-1} is the initial moment of phase k and $N_j\ (t_{i-1})$ the number of vehicles queuing in each direction at the initial phase moment can be obtained by the detector of each lane. The equation only has one parameter (current phase green light duration) and the solution space is small, so the optimal control signal vector $\boldsymbol{c}_i^*$ can be solved in real time.

The local intersection traffic signal controller solves the optimal traffic signal vector $\boldsymbol{u}(t) = \boldsymbol{c}_i^*$ in real time in each sub-control time period $t_i - t_{i-1}$. Taking the intersection m as an example, $t_i - t_{i-1} = \mathrm{g}_k + \tau_k$, the traffic signal is in phase k, $\boldsymbol{u}(t)$ is a z-dimension vector; τ_k is a constant number. Only the green state duration of component k needs to be calculated and the remaining $z-1$ component states are red which are no need to be calculated. That is, according to (15), under the constraints of (24) and (26), the optimal green light duration of phase k can be solved to meet the condition of (16).

D. Stability Conditions

The definition of traffic signal control stability is that the number of queuing vehicles is less than infinity [4]. $g_i^{\min}$ is the phase i permitted minimum green light duration to ensure vehicles crossing the intersection safely. It is determined by the intersection geometric parameters and traffic flow characteristics. In order to ensure the stability of traffic signal control, there are certain requirements for the value of $g_i^{\max}$. According to the steady-state traffic flow theory, the requirements for the stability of traffic signal control are:

$$g_i^{\max} \geq \overline{T}\,\overline{q_i}/S_i, \quad i \in \gamma \tag{27}$$

$$\sum_{i\in\gamma} \frac{\overline{q_i}}{S_i} \leq 1 - \frac{\sum\limits_{i\in\gamma} \tau_i}{\sum\limits_{i\in\gamma} (\tau_i + g_i^{\max})} \tag{28}$$

$\overline{T}$ is the average cycle length of traffic signal, $\overline{q_i}$ is the average traffic flow rate of phase i, S_i is the saturated traffic flow rate of phase i. It is easy to prove that the self-organizing control of traffic signals is stable under the condition that (27) and (28) are satisfied and the proof process is similar to that in literature [4] and [7].

VI. Computer Simulation

Fig. 3 shows a part of road network near National Convention and Exhibition Center in Shanghai, China. The road network contains 20 intersections and the traffic signal control system used here is SCATS (Sydney Coordinated Adaptive Traffic System). SCATS is one of the most widely used traffic signal control systems in the world. However, due to the complexity of urban traffic, the stacking of queuing vehicles (oversaturation) at intersections still frequently occurs during morning and evening traffic flow peak hours. In the SCATS system, a flow detector is installed at stop line of each lane at each intersection, which can collect the information of incoming vehicle flow. The red circle is the road network boundary and the incoming traffic flow on the road network boundary is obtained by the traffic flow detector at the stop line of the boundary intersection. The intersection number is marked as shown in the figure.

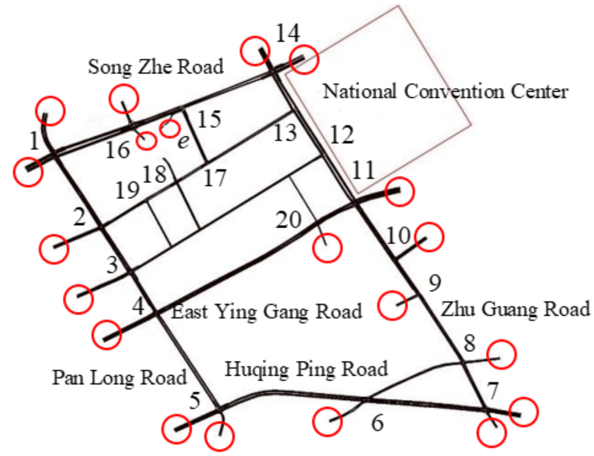

Fig. 3. Road network model.

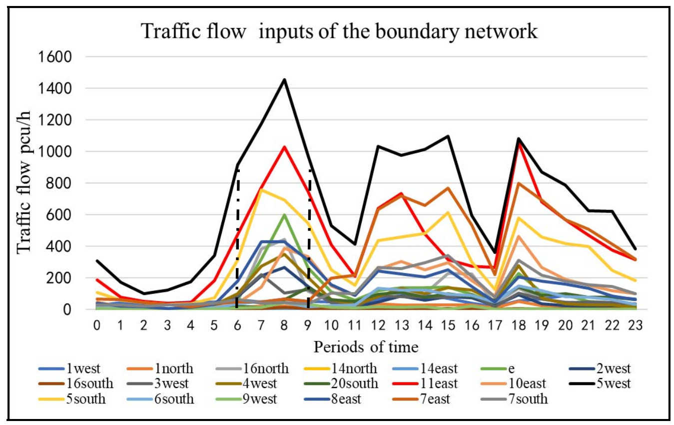

Fig. 4. Traffic flow inputs of the boundary network.

Fig. 4 shows the input flows of the boundary road network on a working day (24 hours) in October 2019. The data is read from the database of SCATS system and sorted out in 3600s (from midnight to 1:00 is time period 0 and from 1am to 2 am is time period 1, and so on). According to the figure, the traffic flow in the morning peak hours (period 6∼9) is higher than other periods and the traffic flow has a large fluctuation.

We verify the effect of traffic signal self-organizing control in the morning rush hours (period 6∼9). On the PTV VISSM software platform, the road network model as shown in Fig. 3 is established. The boundary road network traffic inflow takes 3600s as a period and the inputs (according to Poisson distribution) of road network traffic flow are set according to the data in Fig. 4. The distribution proportion of traffic flow in each section is set according to the statistical value of the historical detection data of the road network. The SCATS system signal schemes (historical data) and the traffic signal self-organizing control model are respectively used to control the traffic signals at the 20 intersections in Fig. 3. The traffic signal schemes of SACTS system are read from the historical data of the corresponding period on the working day and loaded to the corresponding intersection through the software interface. The self-organizing control model calculates and configures the local intersection traffic signals in real time according to the self-organizing control rules. Using the above method, the performance of the self-organizing control model is evaluated based on actual historical traffic flow data and actual historical SCATS traffic signal schemes. In the self-organizing control model, $g_{\min} = 18$ s and $g_{\max} = 87$ s are uniformly set at all intersections. In order to evaluate performances of the two traffic control methods, three evaluation indexes are defined:

1) Average vehicle delay. Its physical meaning is the average delay time of vehicles crossing an intersection, the unit is s/pcu, and the calculation method is:

$\frac{\sum d_i}{n}$, n is the number of vehicles crossed the intersection (unit is pcu). d_i is the delay time of vehicle number i (unit is s) and the value of d_i is obtained through the VISSIM evaluation module.

2) Average queuing length. Its physical meaning is the average queuing length of traffic flow in all directions at the intersection (unit is m) and its calculation method is as follow: $s^{-1}\sum_{k=1}^{s}\left(v^{-1}\sum_{i=1}^{v} l_{i,k}\right)$, v is the number of traffic flow directions at the current intersection, $l_{i,k}$ is the queuing length of vehicles obtained from the kth sampling of traffic flow i and its value is obtained through the VISSIM evaluation module. s is the sampling number. In this paper, 1s is the sampling interval and 3600 s is a time period, that is s=3600.

3) The maximum queuing length. Its physical meaning is the maximum queuing length of vehicles at the intersection within a period of time. Its calculation method is as follow:

$\max l_{i,k}$, $l_{i,k}$ is the queuing length obtained from the kth sampling of traffic flow i at the intersection and its value is obtained through the VISSIM evaluation module. In this paper, 1s is taken as the adoption interval and 3600 s is a time period.

The average vehicle delay reflects the smoothness of vehicles passing the intersection. The average queuing length of vehicles reflects the congestion situation at the intersection. The maximum queuing length represents the risk of vehicle queuing spillover and reflects the stability of traffic signal control to some extent. The three indexes can be used to evaluate the performance of traffic signal control.

The comparison data of SCATS and self-organizing control from time period 6 to 9 (from 6:00 am to 10:00 am) are studied. Taking the time periods as horizontal axis, the average vehicle delay, the average queuing length and the maximum queuing length of the road network are as shown in Fig. 5~Fig. 7.

According to Fig. 5~Fig. 7 the performance of self-organizing control method is better than that of SCATS system. In order to explain the above results, the difference between self-organizing control and SCATS control is analyzed from the micro point of view at an intersection. Taking intersection No.5 as an example, the traffic signal phases of intersection No.5 are shown in Fig. 8. Taking time period as the horizontal axis, self-organizing control scheme and SCATS control scheme are plotted respectively. The mean duration of phases A, B, C and cycle T in each time period are shown in Fig. 9 and Fig. 10.

By comparing Fig. 9 and Fig. 10, the mean phase durations of self-organizing control are much smaller under the same

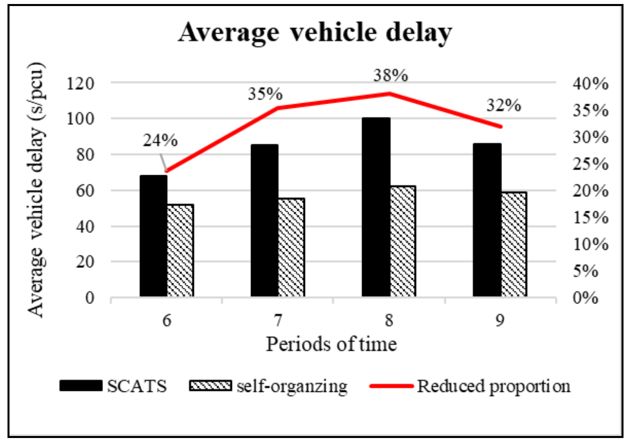

Fig. 5. Average vehicle delay of all intersects.

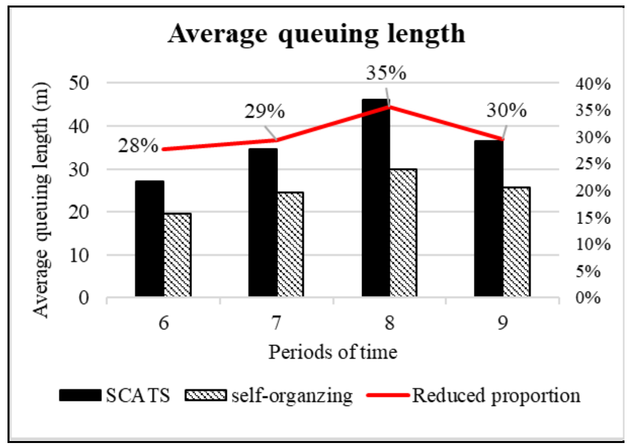

Fig. 6. Average queuing length of all intersections.

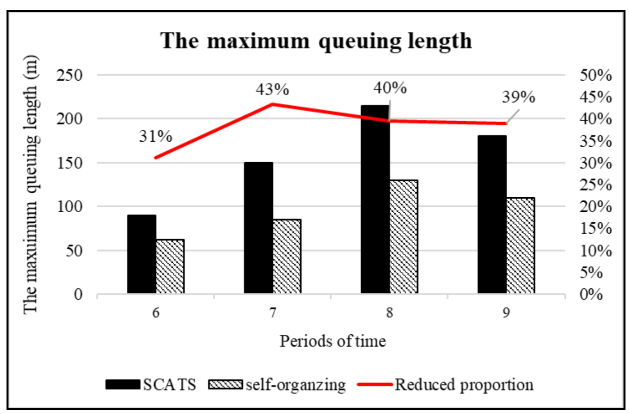

Fig. 7. The maximum queuing length of all intersections.

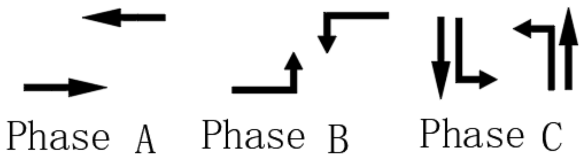

Fig. 8. Traffic signal phases of intersection No. 5.

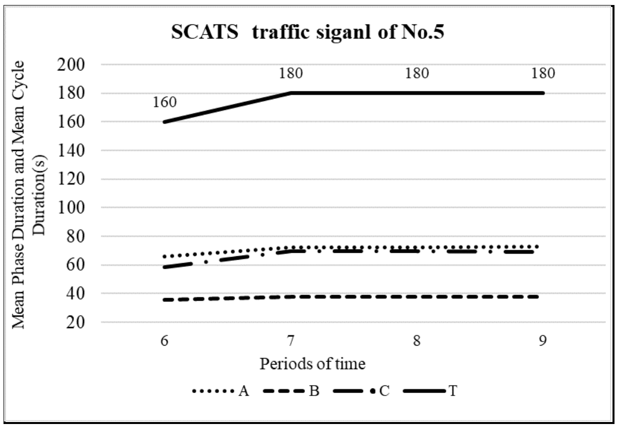

Fig. 9. Mean phase and mean cycle duration of SCATS.

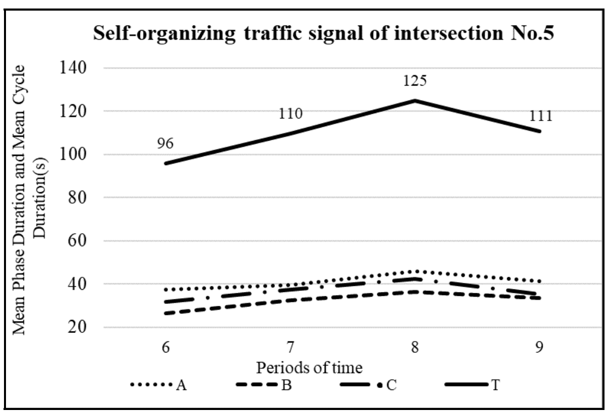

Fig. 10. Mean phase and mean cycle duration of self-organizing control.

vehicle inflow conditions. It can be seen that under SCATS system, the phase durations are much larger than needed, the phase saturations are lower than reasonable value and there is a certain amount of green time waste. When the traffic flow increases or the traffic is oversaturated, the traditional method is to increase the traffic signal cycle length. However, increasing the traffic signal cycle length is often not significant effective. Because increasing the length of traffic signal cycle cannot significantly improve the service capability of each traffic signal phase. If the traffic signal is not configured efficiently, increasing the traffic signal cycle may lead to an increase in green light time waste and will aggravate the traffic oversaturation.

SCTAS is a representative of traditional centralized coordinated control system. In order to achieve regional coordinated control, the control sub-area adopts common traffic signal cycle duration T, which is determined by the traffic flow at key intersections. Based on common cycle duration T, the green signal ratios and phase offsets at each intersection are optimized. Due to the constraint of common cycle duration T, there is a large amount of green time waste at some intersections with small traffic flows. In addition, when the states of traffic flow change rapidly, such as in the morning and evening rush hours, a large number of vehicles rapidly enter the road network, the flow imbalance between intersections intensifies and the fluctuations of traffic flow increase. In the traditional centralized coordinated control model, the phase green signal ratio of each intersection is difficult to adjust timely with the fluctuation of traffic flow and the green signal ratio deviates greatly from the actual demand. When the traffic flow at the intersection is small and the space resources are abundant, the waste of space resources at the intersection caused by the mismatching between the traffic signal and the traffic demand can be allowed. However, when the traffic flow at the intersection is large and the space resources are tight, the traffic signal needs to efficiently allocate the space resources at the intersection according to the traffic demand to avoid space resources waste. Otherwise, it is prone to traffic saturation and queuing spillover.

Through traffic flow local scope prediction and on-line optimizing, the self-organizing control model dynamically adjust current phase duration according to the changes of traffic flow. When there is a queuing spillover risk, through the interaction between adjacent intersections, some vehicles are temporarily stored at the upstream intersections to reduce the inflow rate of downstream intersections, which can alleviate the queuing spillover problem. The self-organizing control model can efficiently allocate space resources of intersections in real-time. Intersection traffic oversaturation and queuing spillover problem caused by traffic flow fluctuation can be effectively relief.

VII. Conclusions and Future Work

To the problem of intersection traffic oversaturation and spillover of queuing vehicles caused by random fluctuations of traffic flow, a traffic signal self-organizing control model is established. The key to solve the problem is to efficiently allocate the space resources of intersections and restrain the number of queuing vehicles to avoid spillover. Based on the traffic flow continuous model and traffic platoon dispersion model, the local intersection traffic signal control sate equations are established. Road capacity constraints in queuing state is defined to constrain traffic signal real-time decision spaces. Assume that adjacent intersections can communicate with each other, the optimal phase duration is solved in real time at local intersection to realize efficient allocation of intersection space resources. Through interactions between adjacent intersections, global optimization is been achieving with the system evolves. Simulation comparison based on actual traffic data proves that the proposed traffic signal self-organizing control model performs better than SCATS.

In the future, we will further study the traffic flow prediction model. Due to the randomness and openness of urban traffic flow, the proportion of traffic flow in each direction of the intersection is constantly changing. We will study the correction method of the traffic flow prediction model and the adaptive learning of parameters, so as to improve the performance of traffic signal control.

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