Emergency Vehicle Priority Control Method Combining Dynamic Lane Control and Phase Control in Cooperative Vehicle Infrastructure

Lili Zhang[1], Kang Yang[1], Ke Zhang[1], Wei Wei[1], Hongxin Tan[2]*

[1] Beijing Institute of Petrochemical Technology, China
[2] Science and Technology on Complex Aviation Systems Simulation Laboratory, China
zhanglili@bipt.edu.cn, yangk19990915@163.com, zhangke_bipt@163.com, weiwei@bipt.edu.cn, zll_txx@163.com

Abstract

Although the road traffic safety laws in various countries stipulate that emergency vehicles are exempt from route restrictions and traffic signals when performing emergency tasks, the severe traffic congestion issues in almost all major cities need to be considered. The frequent occurrence of these problems hinders the passage of emergency vehicles, and the key factor behind this obstruction is often due to the inherent flaws of traditional passive traffic control theories. In order to solve this problem, this paper innovatively constructs a high-dimensional and multi-variable flexible traffic control model. This model has four variables, which can greatly enhance the flexibility and capability of intersection control. On the basis of this model, an emergency vehicle priority control method combining dynamic lane control and dynamic phase control is designed. Comprehensive experimental results demonstrate that the proposed method in this paper can effectively ensure the fast and priority passage of emergency vehicles even in the presence of traffic congestion at intersections.

Keywords: Priority for emergency vehicles, Dynamic lane control, Dynamic phase control, Undersaturated, Oversaturateds

1 Introduction

Emergency needs generally include four stages from generation to proper disposal: pre-warning, incident response, in-incident disposal and post-event recovery, as shown in Figure 1. The final link is emergency response. As an important carrier of emergency response, emergency rescue vehicles undertake the important tasks of personnel and equipment transportation and rapid arrival at the scene [1-2].

However, the priority of emergency vehicles is difficult to guarantee because of the frequent urban traffic congestion. Take Beijing as an example, most emergency rescue vehicles still need to rely on traffic participants to consciously give way, as shown in Figure 2.

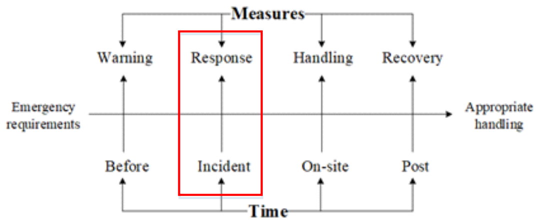


Figure 1. Process of emergency response to demands

(a) Difficulties in ensuring emergency response time

(b) Active yielding by traffic participants

Figure 2. Current status of emergency vehicle passage

In recent years, with the vigorous development of technologies such as vehicle-infrastructure cooperation, major cities both domestically and internationally, led by Beijing, have begun large-scale construction of intelligent transportation infrastructure, laying the preliminary foundation for theoretical research and technological practices in the field of intelligent transportation under the context of vehicle-infrastructure cooperation [3]. As

*Corresponding Author: Hongxin Tan; E-mail: zll_txx@163.com
DOI: https://doi.org/10.70003/160792642025012601002

a typical application scenario of vehicle-infrastructure cooperation technology, emergency vehicle priority passage based on vehicle-infrastructure cooperative traffic control has become a research hotspot. It utilizes onboard equipment to real-time transmit information about the location and speed of emergency vehicles to intersections. By integrating the vehicle information with road traffic flow perception at intersections, it can effectively achieve the priority passage of emergency vehicles.

This paper focuses on the vehicle-infrastructure cooperation environment and starts from the demand for priority passage of emergency rescue vehicles under congested conditions. Taking the broad concept of active traffic control as the core, a dynamic lane control and phase control fusion-based emergency vehicle priority control model is established within the vehicle-infrastructure cooperation environment. A bi-level optimization method is designed, and an independently developed emergency management traffic simulation software is used to verify the proposed method through examples.

The most important innovation of this paper is to construct a control model of four variables (green light, phase, phase sequence, lane), which increases the number of components of the control scheme several times, that is, the flexibility of traffic control is very high. For emergency vehicles, their traffic needs come first, breaking the fixed combination of control schemes and even the attributes of the lane, such as the lane changing from left to straight, the reason for this is that life comes first. Specific contributions are as follows:

The main contributions of this paper can be summarized as follows:

(1) A new high-dimensional variable traffic control model is proposed, which can both adapt to traffic demands and actively modify traffic demands. It possesses a high degree of flexibility.

(2) A priority control method for emergency vehicles is designed by integrating dynamic lane control and dynamic phase control. This method ensures that even in congested traffic conditions, emergency vehicles still have a very high level of travel efficiency.

(3) An innovative concept of virtual phase is introduced in dynamic phase control, providing an effective solution for the passage requirements of special vehicles such as emergency vehicles.

The organization of this paper is as follows: Chapter 2 reviews related work. Chapter 3 describes the control model that integrates dynamic lane control and phase control. Chapter 4 designs a bi-level optimization method with dynamic lane control at the upper level and dynamic phase and virtual phase control at the lower level. Chapter 5 presents simulation results. Chapter 6 provides a summary of the article.

2 Related Works

Early emergency vehicle priority control vehicle-infrastructure collaboration was built using technologies such as GPS (Global Positioning System) and RFID (Radio Frequency Identification).

Thompson et al. [4] developed a signal priority system that provides priority to emergency vehicles. The system receives information about the speed, location, and movement direction of emergency vehicles through onboard GPS and calculates the time for emergency vehicles to reach intersections to achieve priority passage at signalized intersections. Van et al. [5] used RFID technology to construct a vehicle-infrastructure interactive environment and achieved priority control of emergency vehicles. They also analyzed the scalability of this technology using onboard GPS data. Jiang et al. [6], based on the transportation security during the Beijing Olympics, installed wireless radio frequency identification devices on signal controllers and transmission devices on buses, Olympic VIP vehicles, and special police vehicles to realize a primary vehicle-infrastructure cooperative condition and propose priority control strategies for buses and special vehicles. Yang et al. [7] implemented a simple vehicle-infrastructure cooperative environment using RFID technology and proposed an emergency vehicle priority control strategy based on fuzzy control. The primary vehicle-infrastructure cooperation is essentially a triggering-based approach to prioritize emergency vehicles, while advanced vehicle-infrastructure cooperation achieves data interaction between onboard and roadside devices, and emergency vehicle priority is a typical application scenario in advanced vehicle-infrastructure cooperation. Unibaso et al. [8] proposed an emergency vehicle priority control method based on the European Vehicle Communication System, which uses Cooperative Awareness Messages (CAM) to broadcast real-time emergency vehicle information to surrounding vehicles to respond to priority control needs. He et al. [9] combined emergency vehicle priority with bus priority and proposed a heuristic control algorithm in the vehicle-infrastructure cooperative environment, especially addressing the problem of conflicts among multiple priority requests at a single intersection. Agrawall et al. [10] studied emergency vehicle priority control in a Vehicle-to-Vehicle (V2V) environment. They optimized the lane-level dynamic model of emergency vehicles, considered the setting of road sections with different traffic conditions, and proposed fixed-lane priority control strategies and optimal lane control strategies. Simulation results showed that the optimal lane control strategy outperformed the fixed-lane priority control strategy in complex traffic environments, while the fixed-lane strategy performed better in good traffic conditions. Humayun et al. [11] used virtual optimal lanes to set priority sequences for vehicle passage through V2V communication. When an emergency vehicle enters the traffic flow, social vehicles yield to ensure its priority passage. Noori [12] and Asaduzzaman [13] based their research on V2I technology. The former studied the impact of signal state changes on green light phases under emergency vehicle priority conditions and developed an emergency vehicle priority control method in the vehicle-infrastructure cooperative environment. The latter considered single or multiple emergency vehicle passage requests and designed a TSP (Traveling

Salesman Problem) priority control method. Ajayi et al. [14] achieved interconnection and information collection among emergency vehicles, social vehicles, and roadside facilities using IoT technology, further realizing priority control. Karmakar et al. [15] used RF data from a large number of social vehicles and the vehicle-infrastructure cooperative conditions for emergency vehicles to determine the priority level of emergency vehicles based on event types and severity. They also designed necessary signal intervention control schemes, considering the impact of surrounding roads and intersections on the travel path of emergency vehicles. Rosayyan et al. [16] designed an emergency service electronic fence based on onboard navigation and roadside facilities. The electronic fence separates social vehicles from emergency vehicles to prioritize the passage of emergency vehicles. Wang et al. [17] designed an emergency vehicle priority control system based on the vehicle-infrastructure cooperative environment. They proposed a dynamic signal priority control strategy and conducted practical application tests in Taicang, Jiangsu Province. Long et al. [18] obtained real-time information about signal status at intersections, queue lengths in various directions, emergency vehicle position, and speed in the vehicle-infrastructure cooperative environment. They designed an emergency vehicle priority control method. Huang et al. [19] established a two-phase entity scheme network modeling method for emergency vehicle priority control using Time Petri Nets and used reachability graphs to analyze the liveness and reversibility of the model. Building on this, Pei et al. [20] designed a four-phase entity scheme priority control method and also verified the liveness and reversibility of the model. Li et al. [21] considered the impact of V2X (Vehicle-to-Everything) communication delay on the response to emergency vehicle priority requests and proposed an emergency vehicle priority control method based on compensation distance. Cao et al. [22], considering emergency vehicle performance, proposed an emergency-centered vehicle-infrastructure cooperative intelligent emergency traffic system to ensure rapid passage of emergency vehicles and reduce the impact on social traffic. Mu et al. [23] and Xu [24] both focused on transition control at intersections after the prioritized passage of emergency vehicles.

In summary, these papers have been studied within the framework of traditional intersection control theory, and their lack of flexibility is due to the inherent shortcomings of traditional traffic control, which only have three variables {green light, period, and phase}. Even if lane control is applied, lanes are not considered as variables in the control model, which further limits the flexibility of control.

3 Construction of Urban Road Intersection Active Control Model

Traditional traffic control achieves priority control of emergency vehicles by constructing a model that includes three variables: {cycle, green signal ratio, and phase}. However, these models generally lack flexibility, which is reflected in the inability to quickly change traffic flow based on the actual needs of emergency vehicle traffic. For this purpose, we have designed a traffic control model with four variables (green light, phase, phase sequence, and lane), which can solve the problem of insufficient flexibility.

In order to ensure safety and reduce conflicts, considering the development of cooperative vehicle-infrastructure systems (CVIS), the means of traffic control have been enriched and expanded. Therefore, it is proposed to integrate intersections and connecting road segments into a unified model, forming a flexible traffic control model, as shown in Figure 3.

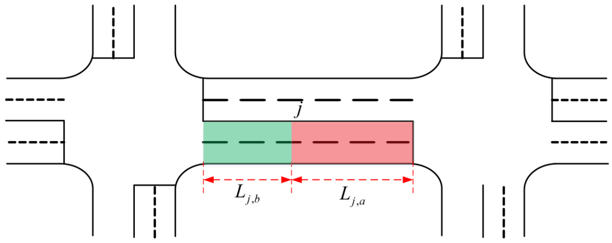


Figure 3. Traffic control model of intersection

3.1 Intersection Store-and-forward Model

The intersection consists of an internal conflict area and upstream and downstream connecting sections, as shown in Figure 4. Where j represents the connecting section of two intersections, which is divided into two parts: speed control zone j,b and speed control zone j,a . The length of the road section in the speed control zone is $L_{j,a}$, and the length of the road section in the speed control zone is $L_{j,b}$.

The equation of state of the connecting part j,a of the section j between the two intersections is formula (1).

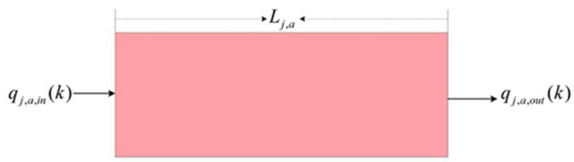


Figure 4. Storage and forwarding model of intersection

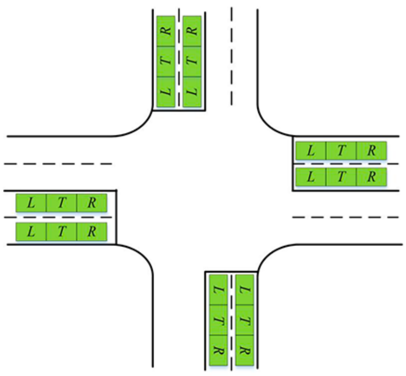
$$n_{j,a}(k+1) = n_{j,a}(k) + q_{j,a,in}(k) - q_{j,a,out}(k) \quad \textbf{(1)}$$

In the formula, it represents the number of vehicles on section j,a within the sampling period k+1, which is equal to the sum of the difference between the number of vehicles on section j and a within the sampling period k and the number of vehicles flowing upstream to j,a, as well as the number of vehicles flowing out of j,a . $n_{j,a}(k)$ is the number of vehicles in period k on road j,a , $q_{j,a,in}(k)$ is the number of vehicles in period k entering the road j,a, $q_{j,a,out}(k)$ is the number of vehicles in period k leaving the road j,a .

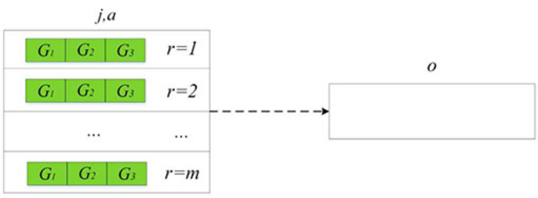
3.2 Lane Control

To accurately characterize the dynamic characteristics of lane properties, the paper first proposes the concept of "lane genes". Then the turning properties of the lane change into a control variable. As shown in Figure 5(a), the turning properties of the lane include left turn, straight turn, and right turn, which are described as L, T, and R.

Further, the smallest unit of traffic scheduling at the intersection is composed of the turning attribute of the entrance lane of the intersection and the downstream link. As shown in Figure 5(b), j,a is the upstream road, o is the downstream road. $F_{j,a}(k)=\{f_r^{(j,a)}(k)\}_{r=1,2,...m}$ is the lane gene expression combination in the period k, where $f_r^{(j,a)}(k)$ represents the gene expression of the lane r, $f_r^{(j,a)}(k)=\{G_u^{(j,a\to r)}(k)\}_{u=1,2,3}$, where $G_u^{(j,a\to r)}(k)$ is the gene of the lane r and $G_u^{(j,a\to r)}(k)=\begin{cases}0, if\ Gene\ doesn't\ be\ express\\ 1,\ Gene\ is\ express\end{cases}$. A lane consists of three genes: G_1, G_2, and G_3. $G_1\to L$ means the first gene map is turned left, $G_2\to T$ means the second gene map goes straight, $G_3\to R$ means the third gene map is turned right.



(a) Intersection lane genome



(b) Lane gene of road j,a and linkage of downstream road

Figure 5. Intersection lane genome

$$\Gamma_{j,a}(k)=\{\varpi_{j,a,o}(k)\}_{o=1,2,...,\omega_{j,a}(k)} \tag{2}$$

Formula (2), $\Gamma_{j,a}(k)$ is the set of spatial variables. $\varpi_{j,a,o}(k)$ is the control variable, which is a function of the number of lanes, as shown in formula (3). $\omega_{j,a}(k)=\sum_{u=1}^{3}G_{F_{j,a}(k)[\cup](u)}$, $\omega_{j,a}(k)$ is the number of connections from road j,a to road o. $F_{j,a}(k)[\cup]=f_{r=1}^{(j,a)}(k)\cup f_{r=2}^{(j,a)}(k)\cup\ldots\cup f_{r=m}^{(j,a)}(k)$, $G_{F_{j,a}(k)[\cup](1)}$ is the first gene in the lane set gene expression, $G_{F_{j,a}(k)[\cup](2)}$ is the second gene in the lane set gene expression, and $G_{F_{j,a}(k)[\cup](3)}$ is the third gene in the lane set gene expression.

$$\begin{cases}\varpi_{j,a,o}(k)=\dfrac{\omega_o^{j,a}(k)}{m}\\ \omega_o^{j,a}(k)=\{\sum_{i=1}^{m}G_{i,u}^{j,a\to o}\}_{u=1,2,3}\end{cases} \tag{3}$$
$$s.t.$$
$$0<\varpi_{j,a,o}(k)\le 1$$

Where, $\varpi_o^{j,a}(k)$ is the number of identical genes after lane gene expression.

From formula (1) and formula (2), the formula (4) can be obtained:

$$n_{j,a}(k+1)=n_{j,a}(k)+q_{j,a,in}(k)-\sum_{o=0}^{\min\{\omega_{j,a}(k),\omega_{j,a}^{Xx}(k)\}}\varpi_{j,a,o}(k)\cdot S_{j,a}\cdot g_{j,a,o}(k) \tag{4}$$

Formula (4), $S_{j,a}$ is the capacity of the road section, $g_{j,a,o}(k)$ is the green light time of the phase of the road section j,a in the sampling period k, and $g_{j,a,o}(k)\ge g_{j,a,o,\min}$. $g_{j,a,o}(k)$ is obtained from the following solution space.

3.3 Speed Control

To realize the study of discrete state and speed control of urban road traffic flow, the basic road traffic flow operation condition is described, as shown in Figure 6.

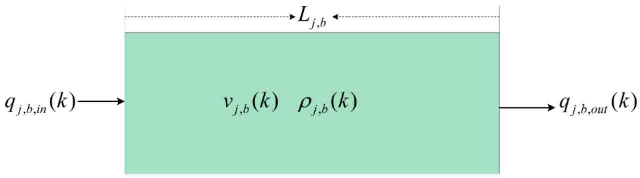


Figure 6. Speed control model

It is described as the current traffic flow density of road J is equal to the sum of the traffic flow density of road J and the change in traffic flow density of the road j,b in the previous time interval.

$$\rho_{j,b}(k+1)=\rho_{j,b}(k)+\frac{T}{L_{j,b}\cdot\lambda_{j,b}}[q_{j,b,in}(k)-q_{j,b,out}(k)] \tag{5}$$

Where the road j,b is used as an example. $q_{j,b,in}(k)$ is the input flow of road j,b in the period k. $q_{j,b,out}(k)$ is the output flow of road j,b in the period k. $v_{j,b}(k)$ is the average speed of traffic flow on the road j,b in the period k. Q is the traffic flow density of the road j,b in the period k. $L_{j,b}$ is the length of the road j,b.

The relationship between dynamic velocity and density parameter and expected velocity of the road j,b is constructed to describe the physical characteristics of traffic flow of road j,b according to formula 5. In the model, the dynamic velocity value in the $k+1$ sampling interval is equal to the deviation between the average vehicle velocity in the k sampling interval and the expected driver velocity $V[\rho_{j,b}(k)]$:

$$v_{j,b}(k+1) = v_{j,b}(k) + \frac{T}{\tau}\{V[\rho_{j,b}(k)] - v_{j,b}(k)\} \tag{6}$$

Where τ,υ is the model parameter, and the expected velocity is:

$$V[\rho_{j,b}(k)] = v_{j,b,free} \cdot \exp[-\frac{1}{\alpha_{j,b}}(\frac{\rho_{j,b}(k)}{\rho_{j,b,crit}})^{\alpha_{j,b}}] \tag{7}$$

Where, $v_{j,b,free}$ is the free flow velocity of road j,b , $\alpha_{j,b}$ is the model parameter, and $\rho_{j,b,crit}$ is the critical density of road j,b .

3.3 Active Control Model of Intersection

The active traffic control model of the intersection is composed of the temporal and spatial resource dynamic allocation model and the speed control model.

Firstly, the store and forward form of the active traffic control model at intersections is as follows.

$$\begin{cases} q_{j,b,out}(k) = q_{j,b,in}(k) - L_{j,b} \cdot \rho_{j,b}(k) \\ n_{j,a}(k+1) = n_{j,a}(k) + q_{j,a,in}(k) - q_{j,a,out}(k) \end{cases} \tag{8}$$

where set $q_{j,b,out}(k) = q_{j,b,in}(k)$, formula 1 is transformed into:

$$n_{j,a}(k+1) = n_{j,a}(k) + q_{j,b,in}(k) - L_{j,b} \cdot \rho_{j,b}(k) - q_{j,a,out}(k) \tag{9}$$

The complete form of the active traffic control model at the intersection is obtained from formula (4) and formula (5):

$$n_{j,a}(k+1) = n_{j,a}(k) - V(k) - G(k) \tag{10}$$

Make:

$$\begin{cases} V(k) = L_{j,b} \cdot \rho_{j,b}(k) \\ G(k) = q_{j,a,in}(k) - \sum_{o=0}^{\min\{n_{j,a}(k),\, n_{j,a}^{\mathrm{Xx}}(k)\}} \varpi_{j,a,o}(k) \cdot S_{j,a} \cdot g_{j,a,o}(k) \end{cases} \tag{11}$$

Put $v(k) = v_{crit} \cdot \ln(\frac{\rho_{jam}}{\rho(k)})$ into $V(k)$ to get $V(k) = L_{j,b} \cdot \exp[-\frac{v_{j,b}(k)}{v_{j,b,crit}}]$. Put it into formula (11) to get:

$$\begin{cases} V(k) = L_{j,b} \cdot \exp[-\frac{v_{j,b}(k)}{v_{j,b,crit}}] \\ G(k) = q_{j,a,in}(k) - \sum_{o=0}^{\min\{n_{j,a}(k),\, n_{j,a}^{\mathrm{Xx}}(k)\}} \varpi_{j,a,o}(k) \cdot S_{j,a} \cdot g_{j,a,o}(k) \end{cases} \tag{12}$$

4 Design of Emergency Vehicle Priority Control Algorithm

4.1 Objective Function Set

The mixed scene characteristics of the intersection determine the difference of the control objective function. Considering the unity of objective function design, the lower control objective of the two-layer optimization method:

$$\begin{gathered} \min(\alpha J_{TTS} + \beta J_{STS}) \\ s.t.\ \alpha + \beta = 1 \end{gathered} \tag{13}$$

where J_{TTS} represents the travel time of all vehicles at the intersection; J_{STS} represents the travel time of a special vehicle.

The choice of weight coefficient is determined by the scene of the intersection. Here are a few examples:

(1) When the scene at the intersection is a common scene, $\alpha = 1$, $\beta = 0$ is to minimize the total travel time of vehicles passing at the intersection as the objective function.

(2) When the scene at the intersection is a special scene of emergency vehicles, $\alpha = 0$, $\beta = 1$ is to minimize the travel time for emergency vehicles to pass through the intersection as the objective function.

The upper-level control is dynamic lane control, taking into account the time continuity and uniformity characteristics of the upper-level control objective function. Let the upper-level control objective function be:

$$\max_{t \to \Delta} J_s(t) \tag{14}$$

Make:

$$\begin{cases} \lim_{t \to \tau} \| J_s(t) | - \overline{J_s} | = \varepsilon \\ \lim_{t \to \pi} \| J_s(t) | - \overline{J_s} | = \varepsilon \end{cases}$$
$$s.t.\ t \to \tau \to \pi$$

Among them, $\begin{cases} \max_{t \to \pi} J_s(t) \\ \lim_{t \to \pi} \| J_s(t) | - \overline{J_s} | = \varepsilon \end{cases}$ represents the objective function of the upper-level control; $t \to \tau \to \pi$ represents the determination of startup sequence and consideration of time continuity in the bi-level optimization, $\overline{J_s} = 0$ represents the critical value of the capacity coefficient; $\varepsilon \to 0$ is the minimum.

4.2 The Proactive Control Method for Prioritized Passage of Emergency Vehicles

When the demand for prioritized passage of emergency rescue vehicles arises, a bi-level optimization algorithm is designed. The upper level is based on reinforcement learning for dynamic lane control, and the lower level utilizes model predictive control for dynamic phase and virtual phase control. As shown in Figure 7, the combination of speed control and dynamic phase and its extended control methods form the internal and external control areas of the intersection with boundary characteristics. They are called speed control zones and lane control zones. It determines whether to start speed control by judging the change of J_S . It can achieve the purpose of reducing the number of vehicles in the control area by suppressing the input flow.

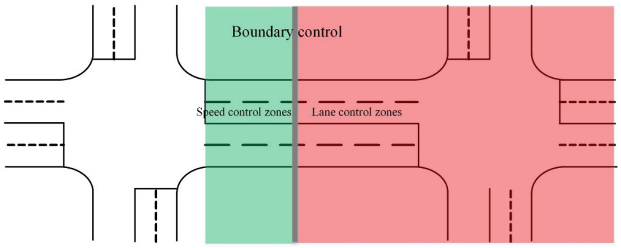


Figure 7. Bi-level optimization algorithm

Two-level optimization 1 uses a two-level programming algorithm. The basis of the upper-level planning is the speed control of the speed-control area in Figure 7. When the J_S control area reaches the critical value, it means that the traffic capacity has reached the limit. At this time, formula (15) is used as the objective function of the upper-level planning:

$$J_{up}(t) = \max_{t\to\Delta} J_s(t) = \max_{t\to\Delta}(J_M(t) - J_N(t)) \quad \textbf{(15)}$$

The specific form of upper-level planning constraints and capacity coefficient J_S:

$$\begin{cases} J_M = \dfrac{\sum_{j=1}^{n} S_{j,a}\cdot g_{j,a,o}(k)}{\sum_{j=1}^{n}\left(S_{j,a}\cdot g_{j,a,o}(k) + \dfrac{\Delta n_{j,a}(k)}{n_{j,a}}\right)} \\ J_N = \dfrac{\sum_{i=1}^{n} \dfrac{\Delta n_{j,a}(k)}{n_{j,a}}}{\sum_{j=1}^{n}\left(S_{j,a}\cdot g_{j,a,o}(k) + \dfrac{\Delta n_{j,a}(k)}{n_{j,a}}\right)} \\ \Delta n_{j,a}(k) = n_{j,a}(k+1) - n_{j,a}(k) = -V(k) - G(k) \\ \lim_{t\to\tau} \| J_s(k) | - \overline{J_s} | = \varepsilon \end{cases} \quad \textbf{(16)}$$

The objective function and constraint conditions of the lower-level planning adopt formula 15. The lower-level planning solution of the two-level optimization 1 uses a combination of dynamic phase and virtual phase control algorithm.

4.2.1 Lower Level: Dynamic Phase and Virtual Phase Control

Considering the uniqueness of scenarios involving emergency vehicles, a dynamic phase and virtual phase control algorithm is employed for dynamic phase control. In this approach, the length of the control chain in the dynamic phase control algorithm is extended, with the last phase in the predictive control chain defined as the virtual phase. The virtual phase is used to address specific control requirements in special scenarios. Its definition does not specify a particular phase type, but allows for the selection of the optimal phase from the set of phases at the intersection when a special emergency scenario demands it. Figure 8 illustrates the tree-like evolution process of dynamic phase and virtual phase control. VP1 represents the control for a specific scenario, where the virtual phase is activated and the best phase from the intersection's phase set is selected to address the situation.

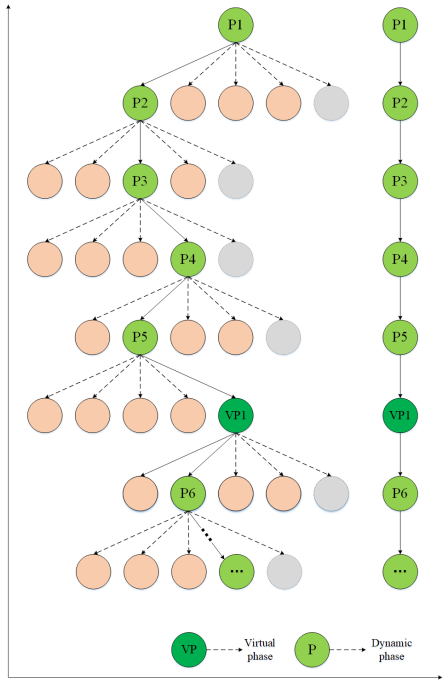


Figure 8. Treelike evolution process of dynamic phase and virtual phase

As shown in Figure 9, the specific process of the dynamic phase and virtual phase control algorithm is as follows:

Input: Traffic volume and queue length at the intersection during the execution of a certain phase within a sampling period k .

Output: Interval time, phase, green light duration.

(1) When a special scenario occurs, activate the virtual phase.

(2) Search in the solution space for n candidate phases that match the currently executed phase as the next steps to be executed.

(3) For each candidate phase, select m consecutive phases as the control chain.

(4) Use the target function $\begin{matrix} J = \min(\alpha J_{TTS} + \beta J_{STS}) \\ s.t.\ \alpha + \beta = 1 \end{matrix}$ as the optimization objective, adjust the weight values, and modify the form of the objective function. Employ a Genetic Algorithm as the optimization method to carry out the optimization process for the n control chains.

(5) Sort the obtained objective function values J of the n control chains and select the first phase of the control chain with the smallest J as the next executed phase of the current phase.

(6) Use the obtained interval time, phase, and green light duration as the output for actual traffic signal control.

Through the above process, the dynamic phase and virtual phase control algorithm can select the optimal phase from the set of phases at the intersection based on the requirements of special scenarios. It can determine the corresponding interval time and green light duration, thereby achieving prioritized passage control for emergency rescue vehicles.

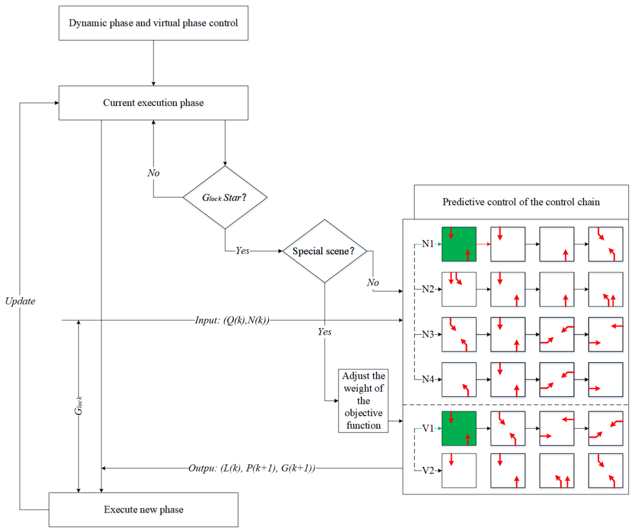


Figure 9. Dynamic phase and virtual phase control

Dynamic phase and virtual phase control algorithm is shown in Algorithm 1:

Algorithm 1. Dynamic phase and virtual phase control algorithm

Step 1: Execute the current phase and green light duration. When entering G_{lock}^{i} , output the traffic flow and queue status of each road segment at the current intersection.

Step 2: Determine if it is a special scenario. If it is, determine the type of scenario and adjust the weight values to change the form of the objective function. Proceed to Step 4. Otherwise, proceed to Step 3.

Step 3: Start phase control chain prediction. Select the compatible control chain group for the currently executed phase from the set of phase control chain schemes. Use the traffic flow and queue status from Step 1 as input, with Jmin as the objective function, and use the Genetic Algorithm as the optimization algorithm. Execute all schemes in the compatible phase control chain group and rank the results. Output the first phase, green light duration, and interval time from the top-ranked compatible phase control chain scheme. This process uses asynchronous multi-threaded computation, with a computation time of G_{lock}^{i} .

Step 4: Start phase control chain prediction and activate the virtual phase. Select the matching and compatible control chain group for the current scenario from the set of required phase control chain schemes. Use the traffic flow and queue status from Step 1 as input, with Jmin as the objective function, and use the Genetic Algorithm as the optimization algorithm. Execute all schemes in the compatible phase control chain group and rank the results. Output the first phase, green light duration, and interval time from the top-ranked compatible phase control chain scheme. This process uses asynchronous multi-threaded computation.

Step 5:Output the calculated (interval time, phase, green light duration) from Step 3 or Step 4 to the main process. After the current phase's B ends, execute the calculated (interval time, phase, green light duration).

4.2.2 Upper Layer: Dynamic Lane Control

Dynamic Lane Control adopts a reinforcement learning-based approach. In this approach, both the upper-level and lower-level objective functions need to comply with the requirements of the objective function set mentioned in the preceding context. Additionally, the initiation timing of lane control is determined by constraint

$$\begin{cases} \lim\limits_{t\to\tau} \| J_s(t) | - \overline{J_s} | = \varepsilon \\ \lim\limits_{t\to\pi} \| J_s(t) | - \overline{J_s} | = \varepsilon \end{cases} .$$

$$s.t.\ t \to \tau \to \pi$$

The specific algorithm flow is as follows:

(1) State Space:The state matrix of the maximum queue length of all entrance phases obtained during continuous n periods when T_S has $J_S < 0$. The maximum queue length of all entrance phases of the intersection during continuous n periods of T_S is denoted as $s_t = [N(k), N(k+1), ..., N(n)]$, which represents the state of the intersection within the sampling period k.

(2) Action Space: The set of lane gene expressions for all entrance sections of the intersection is used as the action space. After observing a state, an action must be selected from the current available action set, which means selecting a set of gene expressions from the intersection's lane gene expression set. The principle for selecting actions is to minimize the mean square deviation between the gene expression in the previous state and the gene expression after the current selection at the conflict points inside the intersection, while also aiming to increase the traffic capacity by increasing the judgment phase J_S .

(3) Reward Function:

$$r = \begin{cases} 0 & |[J_s(k+1)]^2 - [J_s(k)]^2| < 0 \\ 1 & |[J_s(k+1)]^2 - [J_s(k)]^2| \geq 0 \end{cases}$$

As shown in Figure 10, the final process

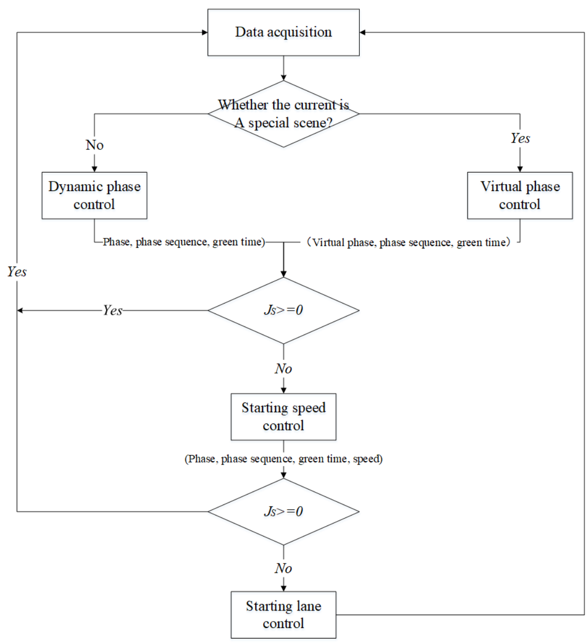


Figure 10. Combining dynamic lane control and dynamic phase control

The overall algorithm is shown in Algorithm 2:

Algorithm 2. Combining dynamic lane control and dynamic phase control algorithm

Stage 1: Start
Step 1.1: Obtain traffic scene data and identify.
Step 1.3: Proceed to Stage 2.
Stage 2: Phase Control
Step 2.1: Determine if the traffic scene identified in Step 1.2 is an emergency scenario. If it is, implement dynamic phase control and virtual phase control at the current intersection. This involves activating the virtual phase and selecting the optimal phase from the phase set suitable for the scene. The virtual phase can be a continuation of the current phase or any phase in the phase set. The determination of the optimal phase is based on the optimization of the objective function corresponding to the scene. Output {virtual phase, phase sequence, green light duration}. If it is not an emergency scenario, proceed to Step 2.2.
Step 2.2: Implement dynamic phase control. Output {phase, phase sequence, green light duration}.
Step 2.3: Proceed to Stage 3.
Stage 3: Implement Dynamic Lane Control
Step 3.1: If the pass-through capacity coefficient J_S is zero and there are continuous n sampling periods with $J_S = 0$, implement lane control. Update the intersection's lane properties, phase set, and control chain. Output {phase/virtual phase, phase sequence, green light duration, speed, lane}. Return to Stage 1.

5 Experiment and Analysis

5.1 Simulation Environment Setup

We use the self-developed OSP simulation platform to perform example verification of the designed proactive control method for emergency rescue vehicles, as shown in Figure 11. We establish a moderately-sized simulated road network where the traffic conditions can be simulated as either "under-saturated" or "over-saturated". The generation of emergency demands is random, while the location of the emergency rescue center remains fixed, allowing us to realistically simulate the traffic conditions of emergency rescue vehicles after the occurrence of emergency demands. The specific parameters of the simulation are shown in Table 1.

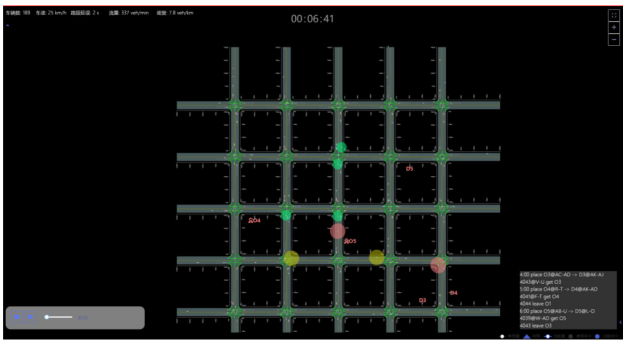


Figure 11. Simulation example of priority control for emergency rescue vehicles

Table 1. Detailed simulation parameter settings

Parameter	Content
Road	The road network is 5*5 intersections; the length of the intersection connecting section is 470m-490m; the section uses two-way 4 lanes, and the channelization is set at 30 meters at the entrance of the intersection. The width is 3.5m.
Vehicle	The speed distribution is [20km/h, 60km/h], and the ratio of vehicle types is 1: 99 (large cars: small cars), the ratio of buses to emergency vehicles is 99:1 in the large car.
Flow	Initial: The flow of stage 1 is 1000v/h; the flow of stage 2 is 500v/h; the flow of stage 3 is 1000v/h. The flow of stage 4 is 500v/h. Every 3600s multiply the flow of each stage by the coefficient of change x, 0.5 < x < 2.
Intersection and signal control	All intersections are controlled by 4-stage signal lights. The stages are stage1: north-south straight; stage2: north-south left; stage3: east-west straight. Stage4: turn left from east to west; straight-right vehicles and straight-going vehicles are released at the same time; the signal control period is 120s; the interval time is 3s for yellow light and 2s for all red; Tstage1 is 35s, Tstage2 is 15s, Tstage3 is 35s, and Tstage4 is 15s.
Scenarios	Undersaturation emergency vehicles, and oversaturation emergency vehicles
Data collection	Collect the road section number, lane number, whole road section density, flow, and vehicle speed. The acquisition interval is 600s.
Evaluation parameters	The average number of stops and average delay time.

Further explanation for the experiment:

In order to ensure the validity of the comparison, it is necessary to compare the proposed method with traditional emergency vehicle control [6] in both under-saturated and over-saturated traffic scenarios.

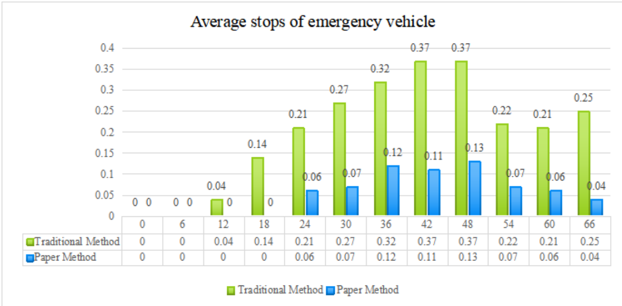
In the simulation, the detection points are used to replace the commonly used RFID detectors in practice, and the detection points are respectively arranged at positions about 150m away from the parking line.

All emergency vehicles appearing are subject to emergency priority control.

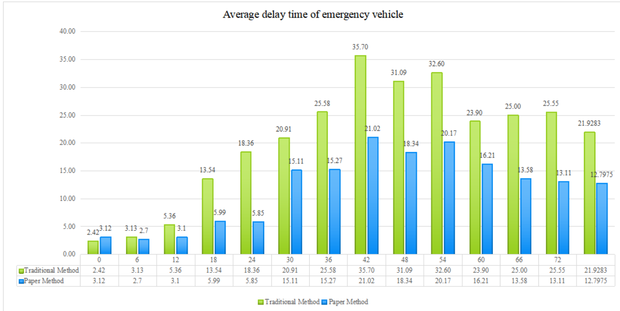
In the simulation, the objective function parameters α and β are selected as: {undersaturated emergency, oversaturated emergency}. $\alpha = 0, \beta = 1$, indicating that the objective function is to minimize the travel time for emergency vehicles passing through the intersection (this choice of objective function parameters is made to align with traditional control methods for comparison purposes).

5.2 Simulation Result Analysis

Figure 12 represents the number of emergency vehicle stops and average delay time when passing through the intersection under undersaturated and oversaturated conditions (Explanation: After the simulation runs for 3600s, the traffic state begins to enter a saturated state.). From the graph, it can be observed that in the under-saturated and emergency vehicle passage scenario, the proposed method shows similar control effects compared to the traditional control method. However, in the over-saturated and emergency vehicle passage scenario, the proposed method demonstrates better control effects than the traditional control method.



(a) Average stops of emergency vehicle



(b) Average delay time of emergency vehicle

Figure 12. The contrast of control effect of emergency scenarios

As shown in Table 2, during the simulation period of 7200s, the traffic flow in the road network alternates between under-saturated and over-saturated traffic conditions. In such cases, it is very challenging to ensure the timeliness of emergency vehicles passing through the road network. However, by comparing the results, it is found that when using the method proposed in this paper compared to the traditional control method, the average delay time for emergency vehicles is reduced by 40.47% and the number of stops is reduced by 73.33%. This fully demonstrates the effectiveness of the method proposed in the paper.

Table 2. Comparison of simulation results of control methods

Experimental scene	Method	Evaluation parameters	Results	Improve
Undersaturated emergency, Oversaturated emergency	Traditional method	Average stops	21.5	—
	Paper method	Average delay time	12.8	40.47%
	Traditional method	Average stops	0.18	—
	Paper method	Average delay time	0.048	73.33%

6 Conclusion

This paper thoroughly considers the actual needs of prioritizing emergency vehicle passage and addresses the issues with traditional passive traffic control methods. It introduces an innovative approach by utilizing the concept of generalized active traffic control, which elevates the dimension of traffic control variables from three dimensions (cycle, green signal ratio, phase) to four dimensions (green light, phase, phase sequence, lane). This establishes a high-dimensional and multi-variable flexible urban road traffic control model, significantly enhancing the flexibility and capability of intersection control. Based on this model, a control method prioritizing emergency vehicles is designed by integrating dynamic lane control and dynamic phase control. Utilizing a self-developed online traffic simulation platform, simulation experiments are conducted on a moderately sized complex traffic network consisting of 5x5 intersections. The proposed control method is compared with traditional methods in both under-saturated and over-saturated scenarios. The results demonstrate that the proposed method outperforms traditional methods in terms of average delay time and average number of stops for emergency vehicles in the over-saturated scenario, confirming the feasibility and effectiveness of the proposed method. This research is significant in improving intersection capacity and optimizing emergency vehicle passage.

Acknowledgement

This work is supported by General Project of Science and Technology Plan of Beijing Municipal Education Commission (No. KM202210017006), the Beijing Science and Technology Association 2021-2023 Young Talent Promotion Project (BYESS2021164), Beijing Digital Education Research Project (BDEC2022619048), Ningxia Natural Science Foundation General Project (2022AAC03757, 2023AAC03889), Beijing Higher Education Association Project (MS2022144), Ministry of Education Industry-School Cooperative Education Project (220607039172210, 22107153134955). R&D Program of Beijing Municipal Education Commission (KM202410017006). The referees' valuable suggestions are greatly appreciated.

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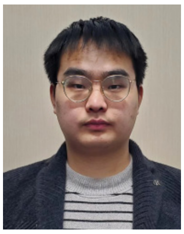
Biographies

Lili Zhang, associate professor of the College of Information Engineering, Beijing Institute of Petrochemical Technology. His research interests include intelligent traffic signal control and traffic simulation, internet of Vehicles and artificial intelligence.

Kang Yang, postgraduate of the College of Information Engineering, Beijing Institute of Petrochemical Technology. His research interests include artificial intelligence, computer vision and image recognition.



Ke Zhang, postgraduate of the College of Information Engineering, Beijing Institute of Petrochemical Technology. His research interests include artificial intelligence, computer vision and image recognition.

Wei Wei, research assistant of the College of Information Engineering, Beijing Institute of Petrochemical Technology. Her research interests include Artificial intelligence, machine learning, emotion recognition.

Hongxin Tan, research assistant of Science and Technology on Complex Aviation Systems Simulation Laboratory. Her research interests include vehicle intelligence, artificial intelligence and logistics protection .