Research on Urban Renewal Area Boundary Control Algorithm Based on Macro Basic Map

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Abstract. With the continuous growth of urban population and rapid economic development, urban renewal has become a solution to many challenges such as outdated urban infrastructure, environmental pollution, and traffic congestion. This article discusses traffic management and control under the background of urban renewal and proposes a boundary control method based on macro basic maps. By conducting field data surveys instead of simulation data, the operational status of the road network can be more accurately reflected. The boundary control quantity is determined based on the control area flow, and the signal adjustment plan for boundary intersections is determined with the queue length of each entrance lane and the shortest green light duration as constraints. Finally, the effectiveness of the proposed method was verified through control effect analysis using SUMO simulation software. This study fills the research gap in boundary control algorithms under the background of urban renewal and provides technical support for improving the overall operational level of the road network in urban renewal areas.

Keywords: Urban renewal; Macro basic diagram; Regional boundary control; Dynamic traffic simulation

1 Introduction

With the continuous growth of urban population and rapid economic development, cities are facing multiple challenges. The lagging infrastructure, environmental pollution, and traffic congestion in old urban areas are becoming increasingly serious, which not only affects the quality of life of citizens but also restricts the sustainable development process of the city. In order to address these issues, many cities have begun urban renewal by means of re planning, renovating, and upgrading urban infrastructure, transportation systems, and public service facilities, in order to enhance the overall functionality and living environment of the city. However, in the process of urban renewal, there are often problems such as road traffic congestion, low intersection service levels, and frequent traffic accidents, which require scientific and effective solutions.

At present, many domestic and foreign scholars have conducted a lot of research on regional traffic organization and management, congestion evacuation, and regional

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coordination and control. In the study of urban traffic congestion management and traffic flow characteristics, early scholars used various algorithms and models for traffic operation analysis and evaluation, such as Analytic Hierarchy Process[1] and Video Detection Method[2]. However, these methods are complex and difficult to operate, and cannot visually display the traffic operation parameters and characteristics of urban renewal areas. The Macro Fundamental Diagram (MFD) is a measurable and objectively existing macro traffic flow model used to describe the relationships between variables such as flow, average density, and average speed in road traffic networks. The model was initially proposed by Daganzo[3] and the existence of MFD at the urban scale was demonstrated through experiments. This discovery provides important practical significance for the analysis and management of regional traffic. Afterwards, domestic and foreign scholars conducted research on regional macro basic maps, fully proving the existence of macro basic maps[4],[5], improving their definition and analyzing their characteristics[6],[7]. The improvement and development of MFD have gained recognition from numerous scholars and experts, and it has been applied to traffic network control. In recent years, many scholars have used VISSIM[8] and SUMO[9] simulation software to simulate regional traffic, draw macro basic maps of the region, and proposed a series of regional boundary control methods. Wang Yawei[8] used simulation data to draw a macro basic map of the area, determined the threshold for the optimal cumulative value of vehicles, established a vehicle conservation equation, integrated the number of vehicles in the control area and peripheral queue vehicles into one model, and used them together as boundary control conditions to keep the total number of vehicles in the road network within an optimal range. This method is collectively referred to as feedback control. However, this type of method is entirely based on simulation data and cannot effectively reflect the real situation of the complex road network in the control area. GUO et al.[10] combined macro basic maps with dynamic user equilibrium route selection behavior and proposed a dynamic user equilibrium boundary control method based on MFD. This method integrates system signal control and traveler behavior into the model framework and mutually constrains each other, ensuring optimal regional system travel while also considering optimal individual travel. The results show that in specific demand scenarios, this method can improve traffic operation efficiency by 10.31%.

However, in the context of urban renewal, transportation demand has undergone significant changes, and relying solely on simulation data is difficult to accurately reflect the actual situation. Therefore, it is necessary to obtain more realistic traffic operation conditions through field data investigation in order to formulate traffic control strategies more effectively. At the same time, we must also note that changes in the control area will have a significant impact on its periphery. Therefore, when formulating control plans, it is necessary to constrain the periphery of the control area to ensure the smooth operation of the entire transportation system and avoid causing larger scale traffic problems due to local adjustments.

In summary, exploring how to scientifically and effectively improve the overall operational level of urban renewal regional road networks is still a major research hotspot in the field of traffic management and control, but there are still many breakthroughs in data, scenarios, and technology. This article proposes a boundary control method based on macroscopic basic graphs. Firstly, replacing simulation data with actual data investigation can better reflect the operational status of the road network. Secondly, the boundary control quantity is determined based on the inflow and outflow of the control area, and the queue length of each entrance lane and the shortest green light duration are used as constraints to ultimately determine the signal adjustment plan for the boundary intersection. This method can effectively compensate for the shortcomings of existing boundary control algorithms in urban renewal scenarios, while also effectively responding to real-time changing traffic conditions, even unexpected increases in traffic volume. Finally, the effectiveness of the proposed method was verified through control effect analysis using SUMO simulation software.

2 Urban Renewal Area Boundary Control Algorithm Based on MFD

2.1 Principles of Macro Basic Diagram

Real time understanding of the dynamic changes in traffic flow in road networks has always been the research foundation for road network structure design and performance optimization. However, in general, road network traffic flow includes characteristic attributes such as time distribution, spatial distribution, composition types, and formation reasons of traffic flow. In actual traffic environments, it is difficult to collect sufficient traffic information to describe and analyze some or all of the characteristic attributes of network traffic flow in real time. The macroscopic basic diagram of the transportation network, as an objective and measurable attribute of the road network, can describe the relationship between the macroscopic traffic parameters of the road network traffic flow, such as the average flow and density of the road network, and indirectly describe the temporal and spatial distribution characteristics of the road network traffic flow. This project will start from the overall structure of the road network, systematically analyze the relationship between traffic flow variables of multiple road sections or regional road networks, and based on this, achieve the macroscopic basic map drawing of the research area.

In this article, we use the Cumulative Vehicle Departure Vehicle Diagram (MFD) to present the overall traffic situation of the road network. MFD can be regarded as a function between the outflow F (D (t)) of the road network and the cumulative number of vehicles N in the road network. According to the principle shown in Figure 1, we understand that MFD presents a continuous unimodal curve, which roughly divides regional traffic flow into free flow, saturated flow, supersaturated flow, and congested state. The left side of the peak indicates that as the cumulative number of vehicles in the road network increases, the number of vehicles exiting the road network also increases; On the right side of the peak, it indicates that as the cumulative number of vehicles in the road network increases, the number of vehicles exiting the road network gradually decreases. Therefore, by fluctuating the traffic flow of the road network within the urban renewal area around the optimal cumulative number of vehicles N*, we can maximize the number of vehicles leaving the regional road network, thereby ensuring that the overall traffic operation efficiency of the urban renewal area road network is in the best state and remains stable.

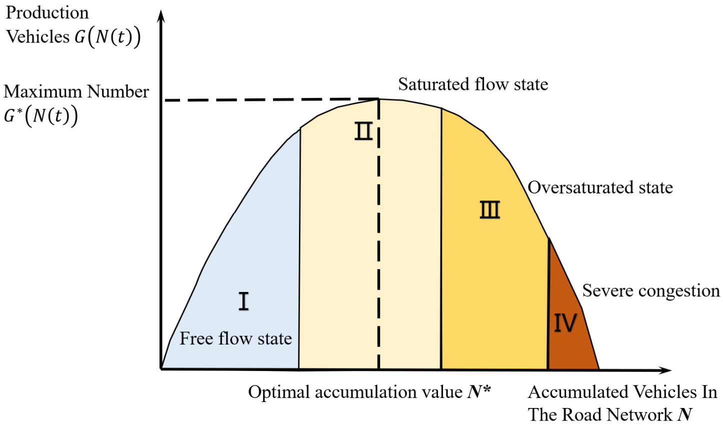

Fig. 1. Regional Macro Basic Map

2.2 Boundary Signal Control Model Based on MFD

Discretize time into equidistant intervals, where *D(t)* represents the number of vehicles operating within the regional road network $d_{in}(t+1)$ at the end of time period t, $d_{out}(t+1)$ represents the number of vehicles entering the control area from outside the control area during period *t+1*, and represents the number of vehicles leaving the control area during period *t+1*. The principle is shown in Figure 3, and the number of vehicles operating on the road network *D(t+1)* in the next cycle time area is obtained from formula (1):

$$D(t+1) = D(t) + d_{in}(t+1) - d_{out}(t+1) \tag{1}$$

Let the number of vehicles leaving the internal area of the road network at time t be *F(D(t))*. According to the properties of the macroscopic basic graph, *F(D(t))* can be approximately fitted as a quadratic function about *D(t)*, represented by formula (2):

$$F(D(t)) = aD^2(t) + bD(t) + c \tag{2}$$

By fitting the macro basic map, the optimal cumulative number of vehicles *D** in the regional road network is obtained based on the peak number of vehicles driven out on the vertical axis, i.e. the maximum number of vehicles driven out. The difference between the number of vehicles obtained at a certain moment and the given optimal cumulative threshold for vehicles is used as a dynamic input, and the incremental value of the optimal number of vehicles considering internal occurrence in the time t+1 region is obtained $\Delta D^*(t+1)$ can be obtained by formula (3).

$$\Delta D^*(t+1) = D(t+1) - D^* \tag{3}$$

Assuming that the number of vehicles entering the control area through the entrance section i outside the control area during the t+1 period is $d_{i,in}(t+1)$, considering the significant differences in service levels at different intersections, the weight of each entrance is determined by the ratio of the number of vehicles entering the control area at a certain boundary entrance to the total number of vehicles entering the control area. Then, the incremental value obtained from formula (4) is used to determine the weight of each entrance $\Delta D^*(t+1)$ is allocated to each entrance section of the boundary, that is, the number of vehicles allocated to entrance section i $\Delta D_{i,in}(t+1)$ is shown in formula (4).

$$\Delta D_{i,in}(t+1)=\Delta D^*\left(t+1\right)\cdot\frac{d_{i,in}\left(t+1\right)}{d_{in}\left(t+1\right)} \tag{4}$$

The number of vehicles $d_{i,in}(t+1)$ entering the road network through the entrance section i during the $t+1$ cycle and the corresponding travel time ΔT can calculate the flow rate $q_{i,in}(t+1)$ of the entrance section entering the control area road network, and obtain a more reasonable green light reduction time for each cycle at the entrance $\Delta Ti,in(t+1)$ size, as shown in formula (5).

$$\Delta T_{i,in}(t+1)=\frac{\Delta D_{i,in}(t+1)}{q_{i,in}\left(t+1\right)} \tag{5}$$

On the basis of the above, in order to avoid the boundary control method causing the queue length of the entrance to be too long, resulting in the overflow of queuing vehicles and affecting the traffic efficiency of other sections outside the control area, and to avoid the reduction of effective green light duration in the direction of the entrance to lead to insufficient pedestrian crossing time, this article proposes two constraint conditions: (1) the queue length constraint on the periphery of the boundary; (2) The shortest green light duration constraint is shown in formulas (6) and (7).

$$T_d=\frac{n_i-(L_i\times R_i)/l}{q_{i,in}\left(t+1\right)} \tag{6}$$

Among them, L_i represents the maximum queue length allowed on the i entrance section, R_i represents the number of lanes on the i entrance section, l represents the average vehicle length, and n_i represents the number of existing queued vehicles on the i entrance section.

$$T_{min}=7+\frac{W}{V}-I_i \tag{7}$$

Among them, W represents the width of the road section, V represents the pedestrian crossing speed, and I_i represents the green light interval time.

In summary, the green light time $T_{i,in}(t+1)$ of the entrance section i entering the area in the next cycle can be subtracted from the green light time $T_{i,in}(t)$ of the previous cycle $\Delta T_{i,in}(t+1)$, and considering the two constraints of peripheral queue length and the shortest green light duration, the effective green light duration that should be adjusted in each system control cycle is finally obtained, as shown in formula (8).

$$T_{i,in}(t+1) = T_{i,in}(t) - \max\left(0, \Delta T_{i,in}(t+1)\right) + \max\left(0, T_d\right) \geq T_{\min} \tag{8}$$

3 Experimental Design and Data Acquisition

This study selects the urban renewal area of Xiaozhai in Xi'an City as the research object, with Xiaozhai West Road and Xiaozhai East Road as the northern boundary, Changming Road as the southern boundary, Cuihua Road as the eastern boundary, and the southern section of Zhuque Street as the western boundary, with a total area of about 2.43 square kilometers. This area is mainly composed of high-grade main roads, with secondary roads interspersed between the main roads for centralized and decentralized transportation. There are a total of 16 intersections in the area, except for the intersection of Changming Road and Chang'an South Road, all others are controlled by signals. Figure 2 illustrates the 13 entry and exit positions of the regional boundary.

In order to obtain actual data support, we organized 60 professional technicians to conduct data surveys on the control area for three consecutive hours during the peak period from 16:00 to 19:00 every day. The survey content includes but is not limited to: controlling the inflow and outflow traffic volume at intersections at the boundary of the area (recorded at intervals of every minute), traffic flow at intersections and sections within the area, inflow and outflow traffic volume at important traffic points, signal timing schemes at each intersection, and the maximum acceptable queue length at each entrance section.

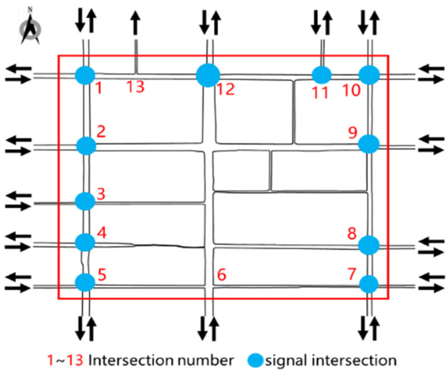

Fig. 2. Schematic diagram of boundary intersection channels

Figure 3 shows the traffic flow characteristics of key intersections 1, 5, 7, and 10, which are located at the four corners of the survey area. Intersection 1 is intersected by two main roads, while intersections 5 and 10 are intersected by a branch road and a main road respectively, and intersection 7 is intersected by two branch roads. Obviously, there are significant differences in the import traffic flow at different intersections due to the different levels of intersecting roads. Therefore, by implementing personalized asymmetric signal control for each intersection based on the original signal control scheme, it is possible to adapt to the flow characteristics of the intersection and maximize the overall operational efficiency of the region.

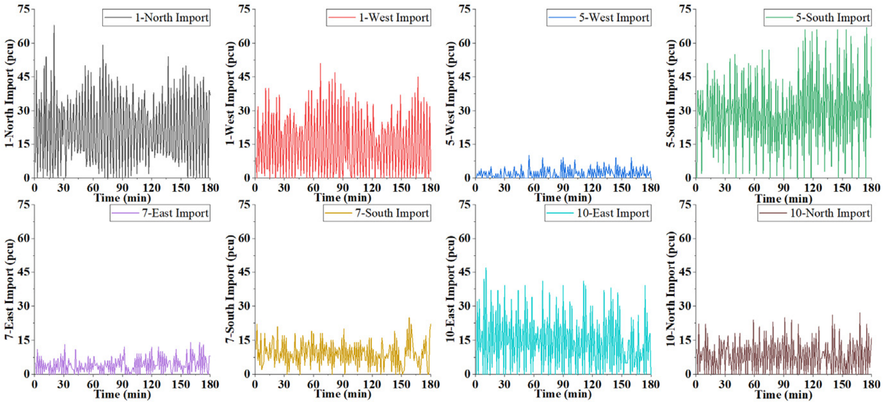

Fig. 3. Traffic flow entering the regional road network from boundary intersections

4 Result Analysis and Simulation Evaluation

4.1 Result Analysis

The real-time traffic obtained through data collection was used to calculate the cumulative number of vehicles within the region, and a macro basic map of the road network in this study area was fitted, as shown in Figure 4.

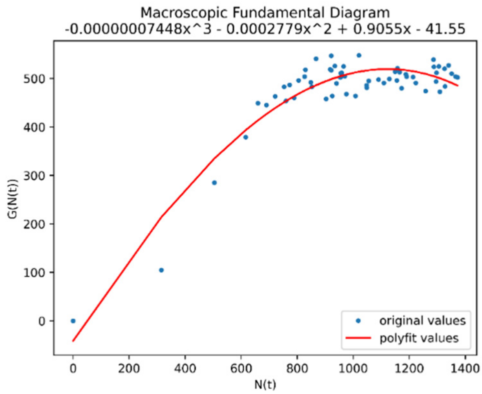

Fig. 4. Macro Basic Figure Fitting Results

Based on the optimal operating vehicle volume obtained from the MFD fitting results in Figure 4, analyze the inlet flow at each intersection, compare and take corresponding flow limiting measures. Specifically, the dynamic analysis of road traffic flow is mainly achieved through real-time acquisition of accumulated vehicle data, and traffic signal adjustments are made to relevant boundary control points. Taking the traffic flow of the road network at the end of the statistical period as an example of 933, calculate the green light time that should be changed within a system control cycle, as shown in Figure 5.

Green light adjustment duration	Entrance section j															
The i-th minute	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	-1
10	-1	0	-1	0	0	0	-1	-2	0	0	0	0	-1	0	0	-1
15	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	-1
20	-1	-1	-1	0	0	0	-1	-2	0	-1	-1	0	-1	0	0	-1
25	0	0	-1	0	0	0	-1	-1	0	0	0	0	-1	0	0	-1
30	-1	0	-1	0	0	0	-1	-1	0	0	0	0	0	0	0	-1
35	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	-1
40	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
45	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	-1
50	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0
55	0	0	0	0	0	0	0	-1	0	0	0	0	0	0	0	0
60	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
65	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
70	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
75	1	0	1	0	0	0	2	2	0	0	1	0	1	0	0	2
80	3	2	2	1	1	0	3	5	0	1	2	1	2	1	1	4
85	3	2	3	0	1	0	3	5	1	1	2	1	2	1	1	5
90	2	1	2	0	1	0	3	5	1	1	1	1	2	1	1	4
95	4	3	2	1	1	0	3	6	1	1	2	1	2	2	1	4
100	2	1	2	0	1	0	3	4	0	1	2	1	1	1	1	4
105	1	1	1	0	1	0	2	3	0	0	1	1	1	0	0	2
110	1	1	1	0	0	0	1	2	0	0	0	0	0	0	0	1
115	1	1	1	0	1	0	2	3	0	1	1	0	1	0	0	3
120	1	1	1	0	1	0	2	3	0	0	1	0	1	0	0	2
125	1	1	1	0	0	0	2	3	0	0	1	1	1	1	0	2
130	1	0	1	0	0	0	2	2	0	0	1	0	0	0	0	2
135	1	1	1	0	0	0	2	2	0	0	0	0	0	0	0	1
140	4	3	3	1	1	1	5	6	1	1	1	1	3	2	1	5
145	3	3	3	1	3	1	8	9	1	2	2	2	4	2	1	6
150	9	6	6	1	3	1	13	3	2	2	3	3	7	3	1	10
155	4	2	3	0	1	1	4	2	1	1	1	1	2	0	1	8
160	2	1	2	0	1	0	4	2	1	2	1	1	1	1	1	4
165	2	1	1	0	1	0	3	3	0	1	1	1	1	1	0	3
170	1	1	1	0	1	0	2	3	0	0	1	1	1	1	0	2
175	1	0	0	0	0	0	0	1	0	0	0	0	0	0	0	1
180	-1	0	-1	0	0	0	-1	-1	0	0	0	0	0	0	0	-2

Note: Negative numbers and zero indicate that the entrance is not regulated, while positive numbers indicate the green light duration of the entrance minus this number.

Fig. 5. Adjustment duration of green light at the entrance of boundary intersections

4.2 Simulation Evaluation

This study uses SUMO simulation and Python programming to simulate traffic signal control in the urban renewal area of Xiaozhai commercial district based on MFD. As an open-source traffic simulation platform, SUMO can simulate traffic flow in complex environments. Through Python programming, it can achieve real-time dynamic signal control simulation of regional boundary intersections. Based on the actual road network investigated, the original scale of the urban renewal affected area was drawn in SUMO software, and the entrance roads of each boundary intersection were numbered and simulated for evaluation, as shown in Figure 6.

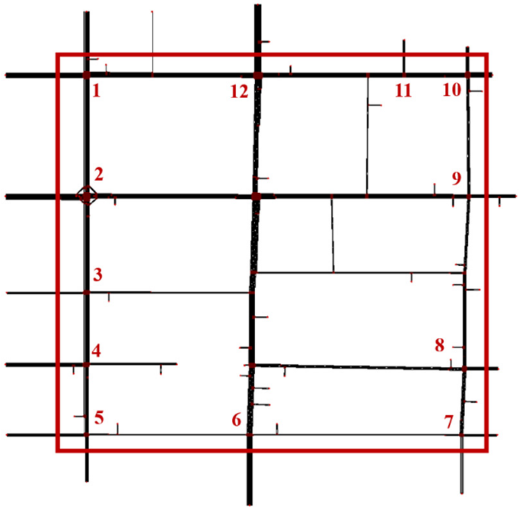

Fig. 6. Schematic diagram of simulated road network

In this study, a comparison was made between the original scheme and the boundary control scheme during the simulation process, and the impact of signal adjustment on the operational efficiency of the road network was analyzed. Within the control area, the average delay of the road network and the average speed of vehicles were selected as evaluation indicators, and the simulation results are shown in Table 1. It can be seen that when boundary control is adopted, the average delay in urban renewal areas is reduced by 13.12%, and the average vehicle speed is increased by 24.71%. The simulation results show that due to the use of boundary control, the number of vehicles entering the area always remains near the optimal cumulative number of vehicles in the road network, improving the operational indicators of the road network and enhancing the overall operational efficiency of the road network.

Table 1. Road network operation indicators before and after the implementation of signal adjustment strategies in the region

	average delay (s)	**Average speed (km/h)**
Before renovation	fifty-four point three three	eleven point two five
After renovation	forty-seven point two one	fourteen point zero three
Improvement level	13.12%	24.71%

When adjusting signals, it is not only necessary to consider the operational efficiency within the control area, but also the queuing factors at boundary controlled intersections. The average queuing length at the entrance section of boundary controlled intersections is shown in Figure 7. As shown in the figure, although the boundary control algorithm has shortened the green light time for vehicles entering the area, the average queue length at the entrance section of the 11 boundary controlled intersections has not changed much. On the contrary, the average queue length at 7 intersections has decreased, indicating that the boundary control algorithm in this area does not affect the traffic operation efficiency outside the control area while optimizing the control area inside.

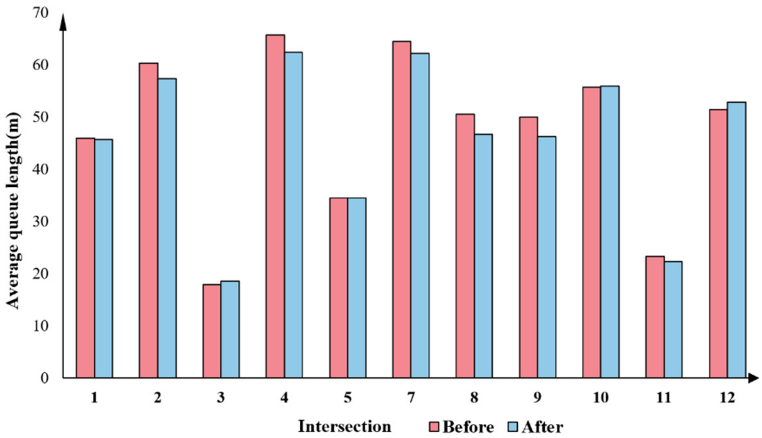

Fig. 7. Comparison of average queue length at the entrance section of boundary controlled intersections

5 Conclusion

This article proposes a regional boundary signal control algorithm based on macro basic maps, which breaks the limitations of traditional boundary control. By using field survey data from urban renewal areas for boundary control simulation, it can effectively alleviate traffic congestion within the region, improve the efficiency of road network traffic operation, and will not have adverse effects on peripheral intersections. The main achievements of this article are as follows:

(1) To alleviate the problem of large-scale traffic congestion in urban renewal areas, a regional boundary signal control algorithm based on improved macro basic maps is proposed. This algorithm utilizes field survey data and is constrained by the shortest green light duration for pedestrians crossing the street and the long queue at the entrance of peripheral boundary intersections. It is suitable for control areas with significant changes in traffic volume after urban renewal, without affecting the entrance of regional boundary intersections, making up for the shortcomings of the original boundary control methods.

(2) A research area simulation model was constructed using SUMO open-source traffic simulation software, and the boundary control algorithm was programmed into

the simulation model using Python programming language. The control area boundary signal control scheme was dynamically changed according to the control algorithm, and various detectors were set up. The applicability and effectiveness of the proposed algorithm in urban renewal areas were successfully verified through evaluation indicators such as regional average operating speed and regional average vehicle delay. It can effectively reduce traffic congestion within the area, improve the average operating speed of the road network by 24.71%, and reduce the average driving delay by 13.12%, ultimately improving the traffic operation level and efficiency of the entire control area.

This article provides a new theory and method for coordinated control of urban renewal areas. Due to the objective existence of the macro basic map characteristics of the regional road network, this method can also be applied to other urban areas, with strong scalability. However, it is still difficult to apply this boundary control method in practical scenarios. It is required that the control area has complete intelligent monitoring equipment for real-time traffic volume statistics and calculation, and the algorithm should be written into the signal and monitoring equipment linkage. The next step will continue to study regional signal coordination control strategies, explore intelligent monitoring equipment and traffic information recognition algorithms, and help improve the traffic efficiency of urban renewal areas.

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