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Research Article

Regional Boundary Control of Traffic Network Based on MFD and FR-PID

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In recent years, urban traffic congestion has become more serious and the capacity of roads has declined, resulting in frequent traffic accidents. In order to effectively alleviate the traffic congestion of the regional road network, aiming at the problem of lack of accurate OD data of the road network, a regional boundary control method of the traffic network based on fuzzy RBF neural network PID (FR-PID) is proposed by combining the theory of macroscopic fundamental diagram (MFD). Firstly, based on the traffic survey, the simulation model of the study area is built, and the basic data such as the traffic flow and the time occupation rate of each road section are obtained. Secondly, the simulation data are used to test the existence of MFD in the road network, and the controlled area is defined. Then, the vehicle change model of the road network area is established. Then, in view of the problem of poor adaptive ability of traditional PID control, the FR-PID control structure is designed. Finally, an example is verified by VISSIM software. In the simulation, different control methods are used for comparison and verification, and the simulation results are analyzed. The results show that the control effect of the proposed method is better than that of the traditional method, and the regional average accumulative vehicle number, regional average completed volume, regional accumulative delays, and total vehicle travel time are optimized by 28.21%, 41.19%, 27.06%, and 32.73%, respectively. The research results can provide reference for the management of urban congestion, thereby reducing the number of traffic accidents and improving urban traffic safety.

1. Introduction

The current traffic congestion is no longer limited to road section or node congestion but has evolved into regional congestion. In megacities with dense populations and road networks, congestion has not only occurred on a single road section. Especially, during the commuting peak period, excessive traffic flow in a small area of the road network often occurs in the core area of the city, causing congestion in most sections of the road network at the same time, resulting in regional congestion. Traffic accidents caused by congestion are also increasing. Traditional control measures oriented to nodes or local road sections are hardly effective. For this reason, scholars analyse the internal characteristics of road networks based on existing road network facilities and implement reasonable control measures for traffic flow within the network in order to explore the potential of road networks, alleviate traffic congestion, and improve operational efficiency. Reasonable control of traffic congestion is conducive to the balanced distribution of traffic flow on the road network, is conducive to alleviating urban traffic congestion, reducing urban traffic pollution [1], and plays an important role in promoting the sustainable development of traffic. Therefore, how to implement control measures efficiently so as to alleviate regional traffic congestion is now a hot research topic.

In terms of MFD, with the development of Internet technology in the field of transportation, scholars have carried out continuous research. After proposing the concept of MFD, in 2009, Daganzo and Geroliminis [2] demonstrated the existence of an MFD curve between the average density of the road network and the average traffic flow by using traffic simulation data in Nairobi, Kenya. Daganzo [3] studied several different forms of urban road traffic networks and found that MFD exists in all of these networks, but the shape of MFD sometimes appears more significantly discrete and showed that this phenomenon is caused by uneven and discontinuous traffic congestion in the traffic network. Using road network simulation data, Xu et al. [4] found that MFD can directly reflect the effect of road network control strategies, and bus lanes as well as lane bans can affect the MFD of road networks to some extent. Haddad and Geroliminis [5] analyzed the stability of urban traffic control in two regions and obtained the boundaries of stable and unstable regions in these two cities by MFD, and based on Based on this, a state feedback control strategy was derived. Shi [6] divided the traffic operation state of the road network into four classes according to MFD and used the commonly used average speed as the traffic state evaluation index, and based on which, the traffic operation state evaluation model of the road network was constructed. Jin et al. [7] studied traffic fundamental diagram in combination with traffic congestion and found that the traffic state within the hypercongestion is not homogeneous. Wu et al. [8] studied the evaluation of boundary control and judged the advantages and disadvantages of control strategies using the changes of MFD of the road network. Based on MFD theory, Keyvan-Ekbatani et al. [9] proposed a feedback gating control strategy for the initial congested core area of the urban road network, which was verified to be effective in relieving congestion, with a significant increase in the average vehicle speed and significant improvement in delay in the controlled area within the control range. Geroliminis and Sun [10] found that the factors affecting the MFD end up influencing the morphology and dispersion of the MFD by affecting the spatial distribution of road network density.

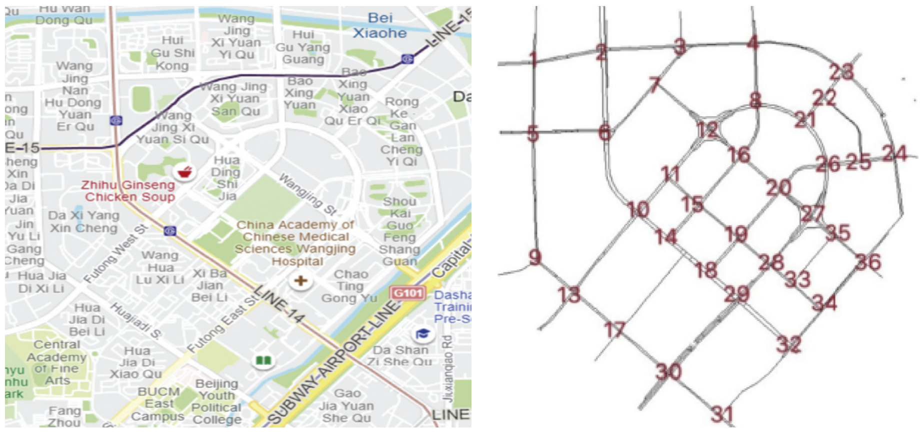
In terms of urban road network control methods, a large number of models have been used in the field of traffic control and safety analysis, such as using Bayesian network models [11, 12] to characterize the randomness of traffic conditions and congestion, and traffic safety analysis, and using cellular automata model [13] to analyse road network traffic density, vehicle speed, and running time. Chen et al. [14] achieved accurate detection of ship behaviour under video detection through an improved YOLO model. This method can also be applied in the field of transportation to realize the tracking of vehicle trajectory [15] and obtain complete traffic data. The traditional microscopic control methods are no longer applicable to regional congestion, and setting up corresponding macroscopic control measures based on the macroscopic fundamental characteristics of the road network from a macroscopic perspective is one of the most promising and rapidly developing research directions nowadays. Haddad and Shraiber [16] designed a perimeter controller (R-PI controller) for a single subzone based on MFD theory, which can maintain the controlled subzone in efficient operation benefit for a certain time interval. Hajiahmadi et al. [17] proposed a cooperative control method for multiple subzones based on MFD, introduced two types of controllers, peripheral controller and switching signal timing schedule controller, and by developing a hierarchical control strategy to achieve traffic flow transfer in congested subareas. Zhang et al. [18] designed a boundary feedback controller for coordinated control of multiple subzones of the road network, which can improve the overall average flow of the road network by about 11% and has a significant effect on relieving largescale traffic congestion. Kouvelas et al. [19] used a nonlinear model to describe a time varying multiarea system and developed a scheme for PI controller-based boundary control of heterogeneous traffic networks, which enables better traffic flow distribution on the road network, thus preventing network performance degradation and improving total road network delay.

In summary, when the road network traffic is controlled based on MFD theory, the control strategy is mainly oriented to the boundary control of a single subzone and multiple subzones. When controlling for multiple subareas, it is necessary to ensure that the traffic state of each subarea is approximate and that a compact and more complete MFD exists, which is a difficult premise to ensure. When boundary control is performed for a single subzone, the upstream sections of the boundary intersections are often ignored, often resulting in excessively long vehicle queue lengths and making the traffic congestion wider. Moreover, most mathematical models are built ignoring the stability of the controller itself, which has certain limitations.

Therefore, we select congestion-prone urban road network areas to make its protection authority prior to other surrounding areas. The road sections that meet this condition will be given priority in the area boundary control. Compared with other road sections, less traffic flow will be allocated and vehicles will be induced to other road sections to prevent congestion in the road sections. In this paper, we proposed a traffic road network area boundary control method based on MFD and FR-PID.

2. Materials and Methods

2.1. Road Network Construction. A part of Wangjing area in Beijing is selected as the study road network area, as shown in Figure 1(a). The area includes a variety of commercial, office, educational, medical, and residential areas within the area, and the road network structure is complex and large in scale, which generates congestion during the morning and evening peak hours and is suitable for the study of this paper. The basic information such as length, number of lanes, and lane function of each road section of the road network in the study area is obtained through Baidu maps and actual research. The intersections in the study area are shown in Figure 1(b), where intersections 14, 18, and 22 are non-signal-controlled intersections and the rest of the intersections are signal-controlled intersections. The simulated road network is drawn using VISSIM, and the signal timing of each intersection, the conflict area of each intersection, and the data collector are set according to the field survey and the results of the survey and research by Wang [20] and Dong [21], etc.



(a) (b)

Figure 1: Wangjing area map: (a) area road map; (b) area road network map.

2.2. MFD Existence Test

2.2.1. MFD Theory. MFD is the most popular macrolevel traffic theory nowadays, which is an inherent property of the road network and is used to depict the changes of the traffic operation condition of the road network. It is a reproducible and stable functional relationship between macro traffic variables of the road network, and the relationship curve fitted can reflect the operation state of the traffic flow of the whole traffic network from the macrolevel.

According to the MFD theory, the relevant parameters are calculated as follows:

$$\begin{cases} n = \sum_i k_i l_i, \\ q^w = \dfrac{\sum_i q_i l_i}{\sum_i l_i}, \\ k^w = \dfrac{\sum_i k_i l_i}{\sum_i l_i}, \\ o^w = k^w s = \dfrac{\sum_i o_i l_i}{\sum_i l_i}, \end{cases} \tag{1}$$

where n is the accumulative number of vehicles in the road network; q^w is the weighted traffic volume within the road network, k^w is the weighted density, and o^w is the weighted time occupancy; i is the section number in the road network; $o_i$is the time occupancy, k_i is density, and q_i is the flow of road segment; l_i is the length of road segment; s is the average length of the vehicle.

In the selection of MFD model variables, experts and scholars believe that different variables can be selected as horizontal and vertical coordinates for constructing MFD models, and the main selection methods can be summarized as the direct method and indirect method. In order to implement the boundary control more intuitively, this paper chooses the indirect method to construct the MFD model, and the horizontal coordinate is selected as the accumulative number of vehicles on the road network, and the vertical coordinate is selected as the completed traffic volume on the road network. The third-order function of the accumulated vehicle count of the road network is used to represent the curve, and the traffic dynamics of the road network is described by the MFD curve [22]. Its mathematical equation is shown in

$$G(n(t)) = a \times n^3(t) + b \times n^2(t) + c \times n(t) + d, \tag{2}$$

where $G(n(t))$ is the road network completed traffic volume (veh/h); $n(t)$ is the accumulative number of vehicles in the road network (veh); a, b, c, d are curve fitting parameters.

2.2.2. MFD Existence Verification in Road Network Area. Firstly, the characteristic parameters of MFD are calculated: the number of vehicles within the road network and the completed volume of the road network. In this paper, the road network completed volume is defined as the completed volume within the sampling time period with the starting and ending points being inside and outside the study road network, respectively. By the data collector set at the boundary of the simulated road network, the number of vehicles passing the detection point within 90s for each road section can be obtained. For the case of the road section input flow in this paper, the number of vehicles inside the road network needs to be calculated by the time occupancy obtained by each data collection point within the sampling time period (90s) [23], which is calculated as shown in

$$o = c \times k, \tag{3}$$

$$N = k \cdot l, \tag{4}$$

where o is the time occupancy of each road segment during the sampling period; c is the sum of vehicle length and detector length; k is the density of each road segment during the sampling period; N is the number of vehicles in each road segment during the collection period; l is the length of the corresponding road section.

Through the above calculation, the scatter plot of the relationship between the accumulative number of vehicles and the completed volume was obtained as Figure 2, and the cubic fitting function was formed through MATLAB, and the parameter value and fitting degree in the function are determined. Combined with Figure 2, it can be seen that the simulated road network exists MFD but the goodness of fit is only 0.4598, and the shape and dispersion of MFD does not reach the ideal state. The study [20] showed that the occurrence of this phenomenon is related to the uneven distribution of traffic density in the road network and the unsuitable size of the road network, and different influencing factors finally affect the shape and dispersion of the MFD by affecting the spatial distribution of the road network density [24].

Due to the large range of the selected area, the distribution of the road network and traffic flow in the area is complicated, which is not conducive to the formation of stable MFD. Therefore, the subareas are divided according to the similarity of the regional road network density. To ensure that the controlled area has a clear and stable MFD, the NCut algorithm is used to divide the subzone of the road network [24], and the road sections with close density sizes are divided into a subzone, and the results of the division are shown in Figure 3. The MFD of each subzone is formed by the accumulative number of vehicles in the region and the completed volume, as shown in Figure 4.

As shown in Figure 4, the four subregions all form a relatively stable MFD, which indicates that the density difference of each subregion is small, and the subregion has "homogeneity." After fitting the MFD curve with MATLAB, the fitting degrees are 0.7276, 0.7597, 0.732, and 0.7221, respectively, which shows that the divided subregions have formed MFDs with higher fit.

Since this paper aims at single subregion control, it is necessary to select the area with clear boundary, congestion prone, and clear and compact MFD as the controlled area on the basis of division. Compared with other areas, the road network boundary of subregion 4 is clearer, and it is located in the core area of the modified area, which is more prone to congestion. Therefore, in the following research, subregion 4 is taken as the central controlled area, and other subregions are taken as the peripheral areas.

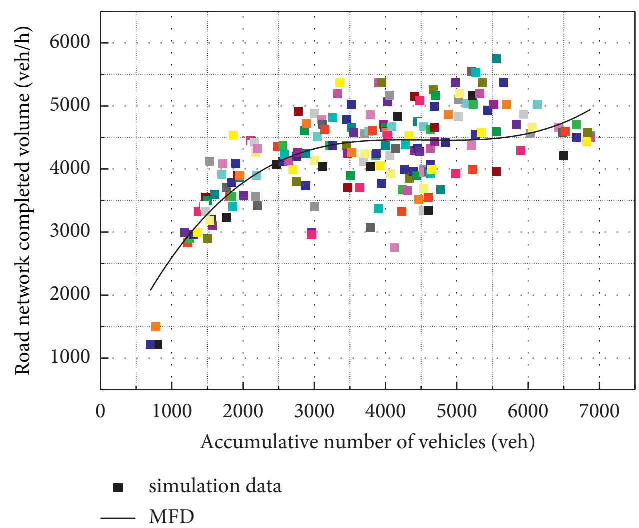


Figure 2: Simulation road network MFD.

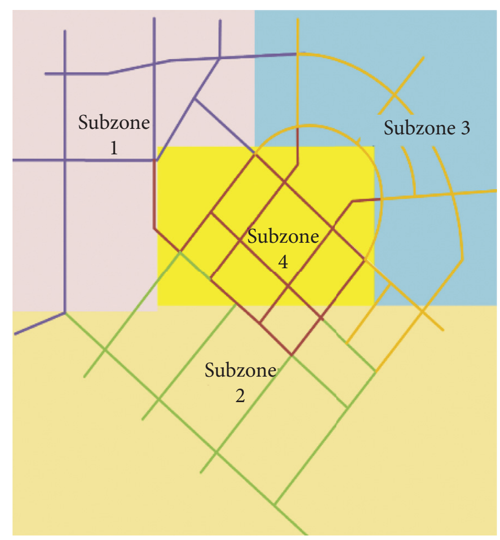


Figure 3: Road network subzone division results.

2.3. Regional Boundary Control Model Based on FR-PID

2.3.1. Principle of Boundary Control. Boundary control is to control the traffic flow into the controlled area through signal timing, so as to achieve the control goal. As shown in Figure 5, it is the schematic diagram of boundary control principle [25].

As shown in Figure 5, the total transfer of traffic flow is divided into two parts, one is the traffic flow entering the controlled area, and the other is the traffic flow q_j driving out of the peripheral area. Among them, the traffic flow entering the controlled area is divided into two parts, one part is D_i, which is mainly composed of the traffic demand generated within the area and the traffic flow entering through the unsignalized intersection, which is not controllable; the other part is q_{in}, which is the traffic flow entering the area at the signalized intersection. Specifically, the q_{ji} that should be driven into the controlled area is obtained through boundary control, and then the actual amount of driving q_{in} is obtained through a specific signal timing scheme to achieve the boundary control goal. And the traffic flow q_j leaves the outer area, part of the q_{ji} is obtained by boundary control, and the other part will bypass the controlled area by means of traffic guidance. At the same time, the traffic information of two areas is collected in each control cycle, and the boundary control is adjusted and changed through data analysis to form a feedback closed-loop control.

For a single subregion in the controlled area, the MFD is shown in Figure 6. According to the accumulative number of vehicles in the area, the traffic state is divided into four states: free flow, stable flow, unstable flow, and forced flow. In this paper, the boundary flow control is used to adjust the flow in

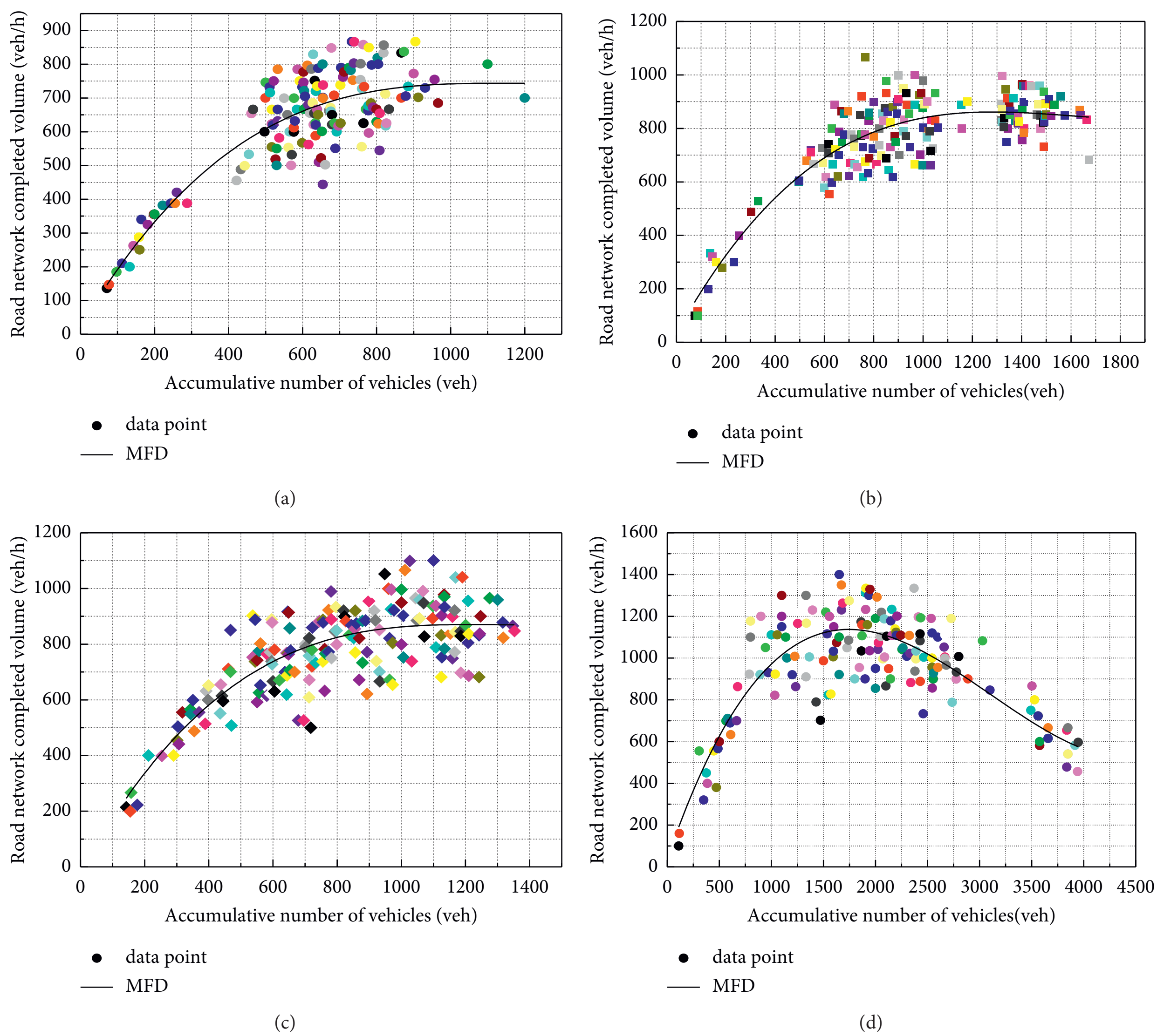


FIGURE 4: MFD of each subregion: (a) subregion 1; (b) subregion 2; (c) subregion 3; (d) subregion 4.

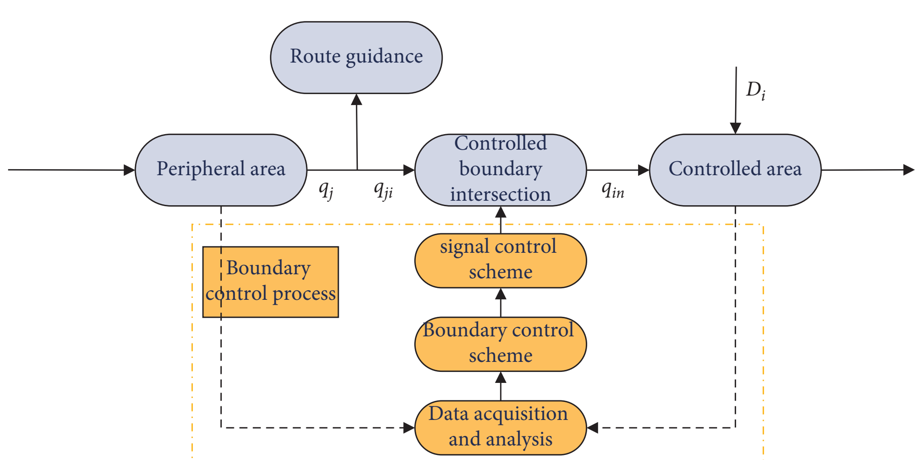


FIGURE 5: Schematic diagram of the boundary control principle.

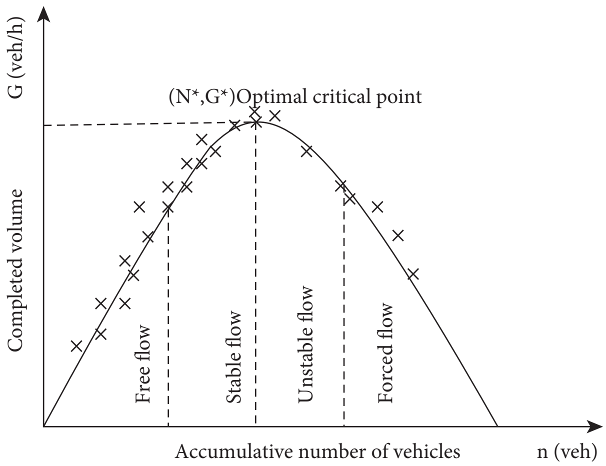


Figure 6: Subzone MFD.

the region, so that the accumulative number of vehicles n of the regional road network is always maintained near the critical traffic volume N^*. The accumulative number of vehicles n_i in the controlled area i after traffic control should meet the following requirements:

$$N_i^* - \varepsilon_i \le n_i \le N_i^* + \varepsilon_i, \quad (5)$$

where N_i^* is the critical accumulative number of vehicles in area i; ε_i is the fluctuation range of traffic control, normally, 1%–3% of N_i^* is used, and 2% is used in this paper.

2.3.2. Vehicle Change Model of the Road Network Area. In a period of time, the inflow and outflow of vehicles, and the increase and decrease of traffic inside the area are always balanced for the road network, as shown in Figure 7, the controlled area is represented by i, and the other subregions are represented by j.

References [23, 26, 27] put forward two hypotheses: (1) boundary control does not change the shape of the region's MFD; (2) define the regional completed volume $G(n(t))$ as the completed volume when the starting and ending points are inside and outside the area, respectively. The construction of the regional vehicle change model is shown in

$$Vn_i(k+1) = Vn_i(k) \times e^{-G_i\prime(N^*)T} + \frac{1 - e^{-G_i'(N^*)T}}{G_i'(N^*)} V\mu_{ji}(k) \times q_{ji}(k) + \omega(k), \quad (6)$$

$$Vn_i(k+1) = \varphi Vn_i(k) + \psi V\mu_{ji}(k) \cdot q_{ji}(k) + \omega(k), \quad (7)$$

where $\varphi = e^{-G_i'(N^*)T}$, $\psi = 1 - e^{-G_i\prime(N^*)T}/G_i'(N^*)$; $n_i(k)$ is the accumulative number of vehicles (veh) in area i at time k; $\mu_{ji}(k)$ is the boundary control rate of traffic flow from peripheral area j to area i at time k, and satisfies $\mu_{ji}(k) \in (0,1]$; $q_{ji}(k)$ is the transfer flow from the peripheral region j to the region i at time k; $\omega(k)$ is the amount of interference at time k.

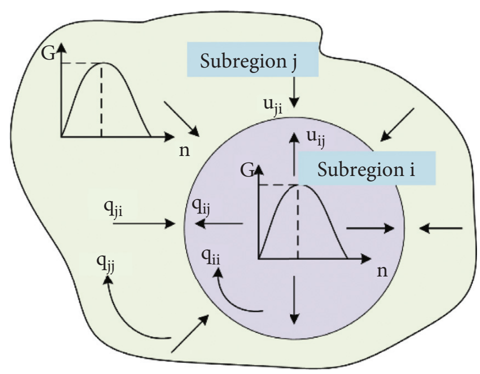


Figure 7: Schematic diagram of traffic flow in the road network area.

2.3.3. Boundary Control Method Based on FR-PID. According to the boundary control principle, the control goal is to make the accumulative number of vehicles in the road network fluctuate around the critical value N^* during the control process, so as to maximize the regional completed volume. Conventional PID control is a widely used and mature control method, and this algorithm is relatively simple and easy to use and has strong adaptability, but not enough self-adaptability. Based on this, this paper selects PID controller as the basis of the control system and uses the fuzzy neural network to output the K_p, K_i, and K_d of PID controller.

Figure 8 shows the structure diagram of boundary control based on FR-PID. The control module is FR-PID controller, and the controlled object is the regional vehicle change model generated in Section 2.3.2. Fuzzy neural network control will directly affect the selection of K_p, K_i, and K_d, so that PID parameters can be automatically adjusted with the change of control object.

2.3.4. Design of Regional Boundary Control Based on MFD. The specific design content includes the design of fuzzy PID controller and the training of the neural network. The design of fuzzy PID controller includes the determination of fuzzy language variable and membership function and the determination of fuzzy control rules. The specific settings are as follows:

(1) Determination of fuzzy language variables and membership functions

The fuzzy sets of 5 parameters of input and output are equally divided into 7 grades. Through simulation experiments, the boundary point of stable flow and unstable flow in the controlled area is determined to be 1870, with 98% threshold as the control target, $N^* = 1833$. The center range of stable flow and unstable flow is about $[0.80N^*, 1.20N^*]$, then the basic domain of deviation and variation rate between the expected number of running vehicles and the actual number of running vehicles is $[-0.20N^*, 0.20N^*]$.

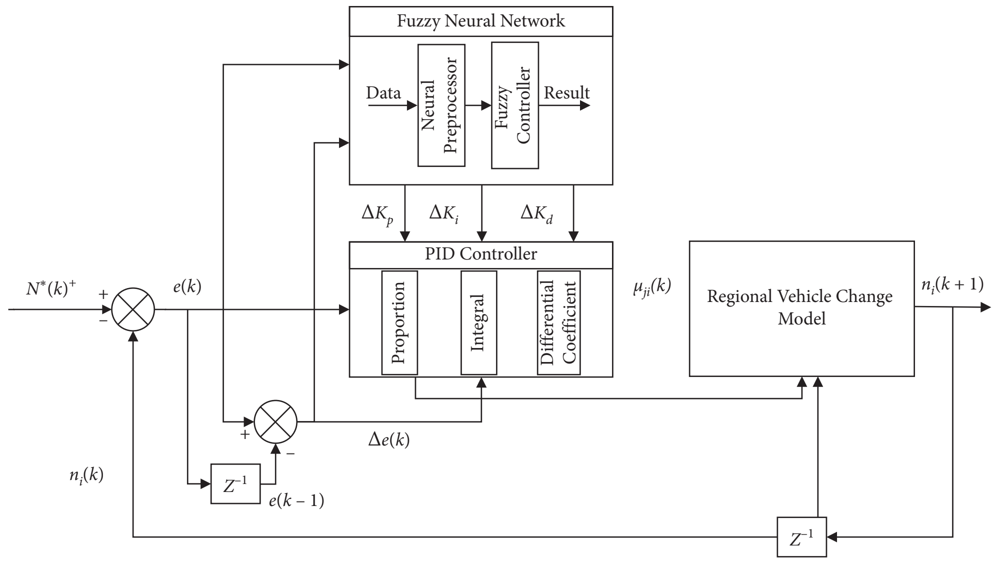


FIGURE 8: Area boundary control structure.

At the same time, through the analysis of simulation experiment, the basic domain of three output variables ΔK_p, ΔK_i, and ΔK_d is taken as $[-0.08, 0.08]$, $[-0.004, 0.004]$, and $[-0.002, 0.002]$. Their corresponding fuzzy domain is $\{-6, -5, -4, -3, -2, -1, 0, 1, 2, 3, 4, 5, 6\}$, and the fuzzy language set is set to {NB, NM, NS, ZO, PS, PM, PB}. The quantization factors of each variable are $K_e = K_{\Delta e} = 1.6043 \times 10^{-2}$, $K_{\Delta Kp} = 1.3333 \times 10^{-2}$, $K_{\Delta Ki} = 6.6667 \times 10^{-4}$, and $K_{\Delta K\ d} = 3.3333 \times 10^{-4}$. The control rules of the three PID control parameters are directly determined by the existing experience.

(2) Determination of fuzzy control rules

Fuzzy control rules are the core of fuzzy control, mainly based on qualitative analysis to design and control, such as expert experience and operator control. According to the existing experience, the relationship between input and output is sorted out, and the following requirements should be met:

When $e(k)$ is small, it is necessary to keep the system stable and overcome the residual error, increase $\triangle K_i$, and decrease $\triangle K_p$; at the same time, in order to prevent system vibration, when $\triangle e(k)$ is large, select smaller $\triangle K_d$, and when $\triangle e(k)$ is small, select larger $\triangle K_d$.

When $e(k)$ is larger, the larger $\triangle K_p$ is selected to strengthen the proportional effect, so as to accelerate the response speed of the system; at the same time, in order to improve the stability of the control system, a smaller $\triangle K_i$ is selected to reduce the integral effect.

When $e(k)$ is in medium size, $\triangle K_p$ can be reduced appropriately, and $\triangle K_i$ and $\triangle K_d$ can be selected appropriately to prevent excessive overshoot of the system.

(3) Training of the neural network

The training process of the neural network is to select 225 samples from the control surface of PID three parameters for training. After many trainings in MATLAB, the obtained network model contains fuzzy control rules. After the training, the trained neural network is generated corresponding to the simulation module in MATLAB.

3. Empirical Analysis

3.1. Parameter Calibration. According to the MFD curve of the controlled area obtained in Section 2.2, it is easy to find that the fitting function is mainly based on the simulation data whose size is in the middle part, and the remaining data are discarded. In order to analyse the control effect more specifically, according to the simulation data, the MFD of upper, middle, and lower lines in the controlled area is, respectively, fitted, and the result shown in Figure 9 is obtained.

The simulation data points are basically within the envelope of the upper and lower lines. According to the MFD curve of each subregion in Figure 10, the required parameters can be obtained. In order to compare and evaluate the final simulation results, the control target range of the accumulative number n of vehicles in the area is calculated according to formula (5), and the maximum and minimum values of the control ranges of the three MFD curves are taken to determine the overall control target range, as shown in Table 1.

3.2. Simulation Result Analysis. In order to better compare the control effects, this article simulates in three scenarios: traditional timing signal control (Traditional), fuzzy PID control (F-PID), and fuzzy RBF neural network PID control (FR-PID). Carry out simulation evaluation on parameters such as the accumulative number of vehicles in the road network area, the completed volume in the road network area, delays, and travel time, and analyse the effects of various control schemes. The details are as follows.

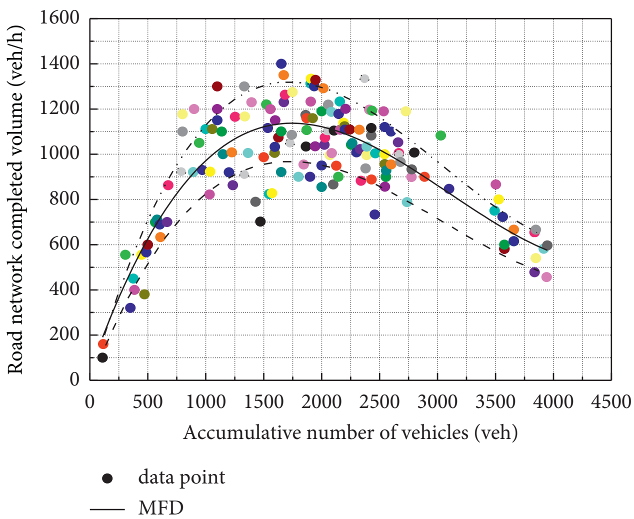


Figure 9: MFD fitting diagram of controlled area.

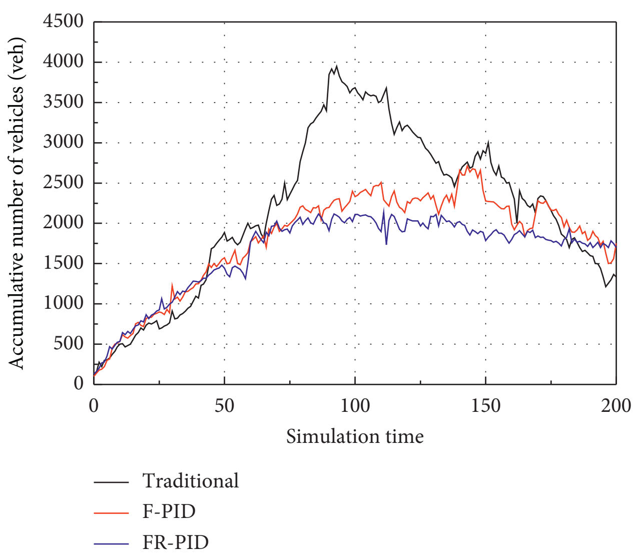


Figure 10: Accumulative number of vehicles.

Table 1: Boundary control target range.

Controlled area	G^*	N^*	Range of control target n
MFD upper line	1274	1868	[1831, 1907]
MFD middle line	1166	1833	[1797, 1870] [1783, 1856]
MFD lower line	954	1819	[1783, 1907]

3.2.1. Analysis of the Accumulative Number of Vehicles in the Area. The simulation result of the accumulative number of vehicles in the area is shown in Figure 10. At the 70th sampling moment, boundary control began to be adopted, and the accumulative number of vehicles in the three scenarios began to differ. In the traditional scenario, the accumulative number of vehicles in the area increases sharply, causing serious traffic congestion. It is not until the later input flow decreases that the traffic conditions in the area alleviate. The fluctuations of the FR-PID and F-PID scenarios are smaller than those of the traditional scenario. The accumulative number of vehicles in the two scenarios is always maintained at a low level, which can increase the stability of the road network area. Among them, the scene FR-PID optimization effect is more obvious.

In the boundary control phase, starting from the 70th sampling time, the average accumulative number of vehicles in the area is compared and analyzed. The average accumulative number of vehicles in the area under the three scenarios of traditional, F-PID, and FR-PID is 2685.450, 2007.104, and 1927.768, respectively. The control effect of FR-PID is optimized by 28.21% compared with the traditional scene, and it is increased by 2.95% compared with F-PID control. The FR-PID control effect is the best.

3.2.2. Completed Volume Analysis in the Road Network Area. The simulation result of the completed volume in the road network area is shown in Figure 11. The size of the completed volume reflects the operational benefits of the road network, and the degree of fluctuation reflects the stability of the traffic flow.

From about the 70th sampling moment, the boundary controller also began to work. There were obvious differences between the three scenarios. The completed volume under the traditional scenario began to decrease, and the latter two scenarios tended to be more stable. As in the case of the accumulative number of vehicles in the area, the fluctuation range of FR-PID and F-PID is smaller, and the area completed volume of the two is maintained near the maximum completed volume for a long time. This shows that boundary control can greatly reduce the occurrence of congestion, improve the operation efficiency of the road network, and ensure the stability of the road network operation, and the FR-PID optimization effect is the most significant.

In order to compare the control effect more clearly and intuitively, this paper selects the average number of completed vehicles in the area as an evaluation index to obtain the accumulative number of completed vehicles in the simulation period, as shown in Figure 12. After implementing boundary control in the controlled area, the efficiency of the area's operation has been effectively improved. Compared with the traditional scenario, the average completed volume of FR-PID in the control period has increased by 41.19%; compared with the F-PID scenario, the average completed volume of FR-PID in the control period has increased by 11.79%. The accumulative completed volume of regional vehicles during the simulation period increased by 5.56%.

3.2.3. Analysis of Regional Accumulative Delays and Total Vehicle Travel Time. Figure 13 and Table 2 show the regional accumulative delays and total regional vehicle travel time obtained under the three control modes. Compared with the traditional scenario, the two indicators in the FR-PID scenario are optimized by 27.06% and 32.73%, respectively. Compared with the F-PID scenario, the FR-PID scenario is increased by 4.08% and 5.04%, respectively.

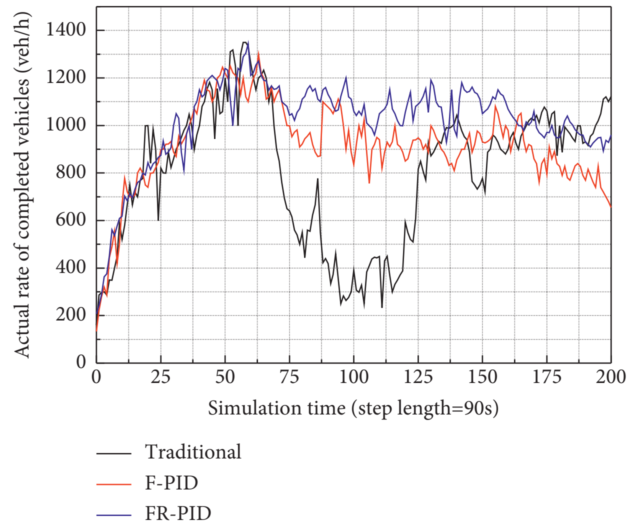


Figure 11: Actual situation.

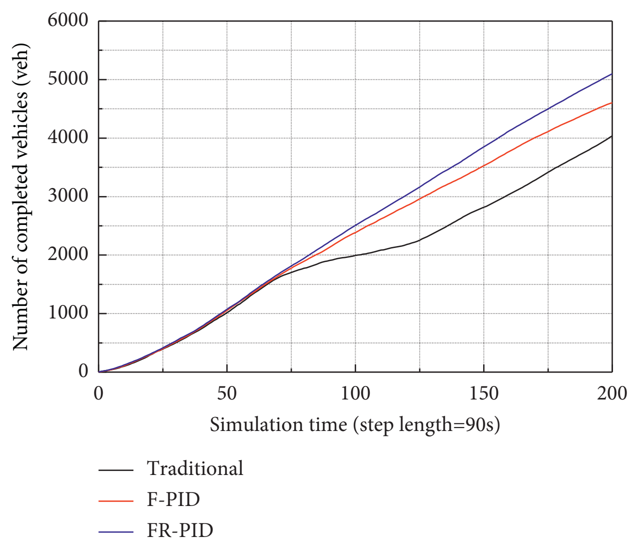


Figure 12: Accumulative completed volume in the controlled area.

3.2.4. Analysis of the Traffic Status of the Regional Road Network. The simulation results show that most of the traffic flow in the FR-PID scenario is concentrated in the stable traffic flow stage, which is basically at the maximum operating benefit of the road network. Although F-PID has also been significantly improved, it is not as good as the control effect of FR-PID.

At the same time, the traffic state of the macro road network before and after the peak hour control is selected for comparison, as shown in Figure 14. It can be seen from the whole that the distribution of the traffic status in each area before the control is unbalanced. Subzone 1 is in the free flow stage, subzone 2 is in the unsteady flow stage, subzone 3 is in the steady flow stage, and subzone 4 is in the forced flow stage. After implementing boundary control, FR-PID effectively diverts the traffic flow in the controlled area, so that the overall traffic conditions in the controlled area have been improved.

In summary, the simulation verification of multiple evaluation indicators shows that when the traffic state of the controlled area tends to be unstable, the boundary control measures proposed in this paper can be adopted to make all the traffic indicators in the controlled area have significant improvement, alleviating traffic congestion, while ensuring higher road network operating efficiency. It also greatly reduces the problems of excessive parking times and long queue lengths at border intersections caused by border control. While achieving the control goal, it also has a relatively low impact on the road network outside the boundary, which is an efficient and desirable boundary control method.

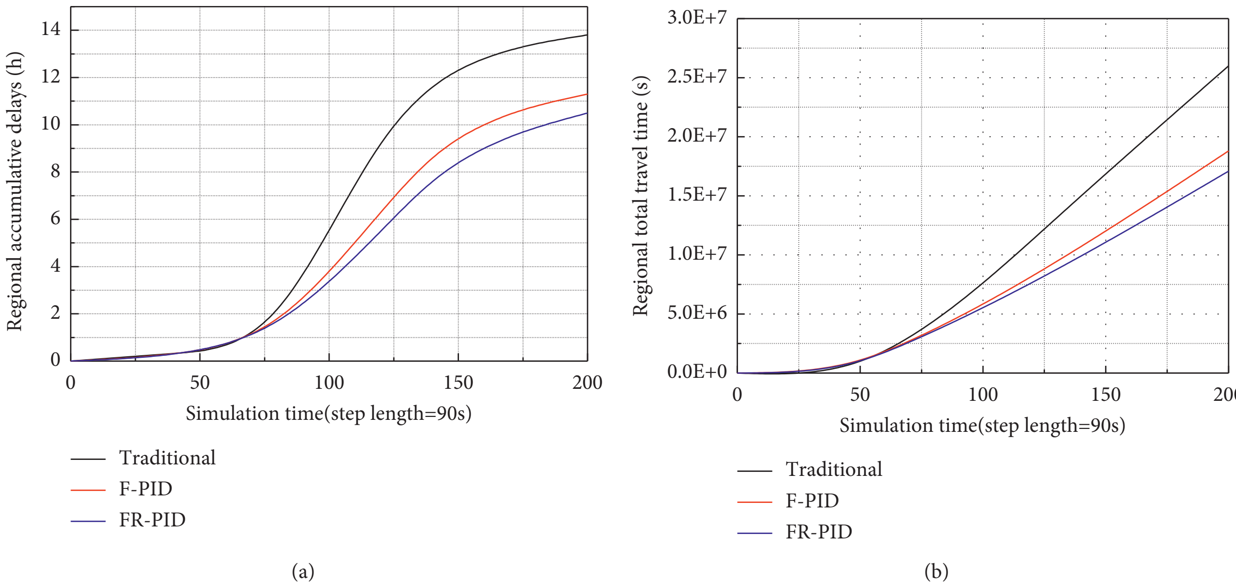


Figure 13: Accumulative delay and travel time of controlled area: (a) accumulative delay; (b) travel time.

Table 2: Comparative analysis of regional accumulative delays and travel time.

Control method	Traditional	F-PID	FR-PID	F-PID optimization ratio	FR-PID optimization ratio
Regional accumulative delays (h)	14.233	11.019	10.382	−22.58%	−27.06%
Total vehicle travel time (s)	$2.632 \times 107\pi$	1.880×107	1.749×107	−27.69%	−32.73%

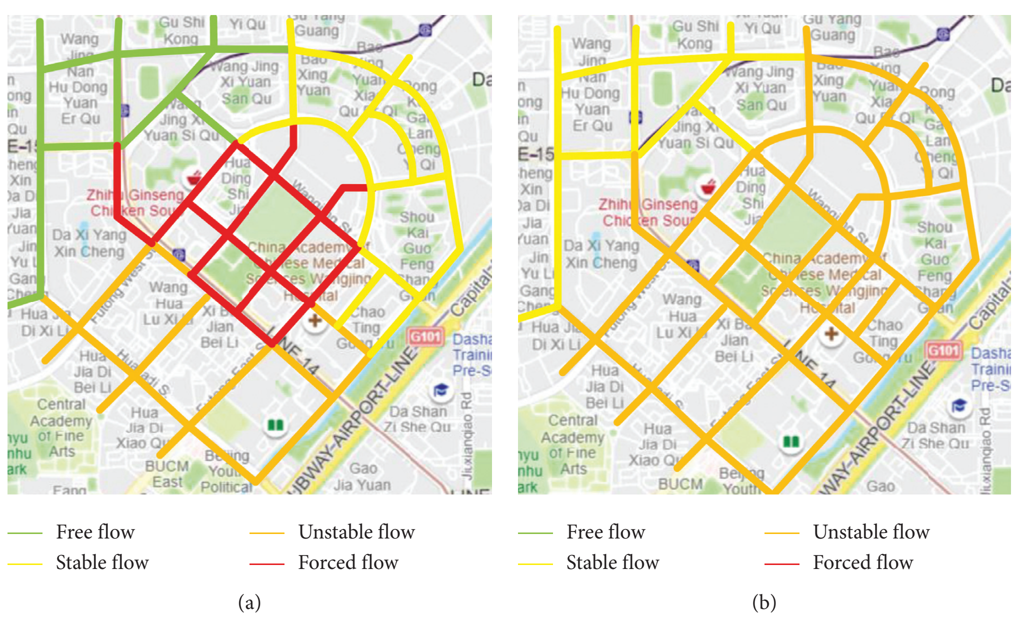


Figure 14: Comparison of traffic conditions before and after control: (a) before control; (b) after control.

4. Conclusions

This paper proposes a road network boundary control method combined with FR-PID on the basis of MFD theory and selects the actual road network for verification, which proves that the proposed FR-PID method has better control effect compared with the traditional method. The specific conclusions are as follows.

Aiming at the urban road network area prone to traffic congestion, the paper proposes a boundary control method that uses MFD to control the road network boundary and adjusts the parameters of the PID controller through the fuzzy RBF neural network.

The paper selects two indicators of accumulative vehicle number and completed volume in the area, obtains the MFD of the road network and analyzes the problems existing in the road network MFD, and puts forward the premise of applying MFD theory to boundary control. To maintain the accumulative number of vehicles in the area near the optimal critical value as the boundary control goal, a fuzzy RBF neural network PID control method is proposed.

The actual road network is selected to realize the empirical analysis of regional boundary control through Vissim simulation. The paper analyzes and evaluates multiple traffic indicators of the controlled area under three simulation scenarios of traditional timing signal, fuzzy PID, and fuzzy neural network PID control. The results show that the proposed boundary control method can significantly improve traffic conditions and increase the efficiency of road network operation.

Data Availability

The data used to support the findings of this study are not made available because of data ownership issues.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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