Research on the optimal control method of regional road network based on dynamic vehicle distribution

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ABSTRACT

The traffic optimization control of the regional road network often involves two parts: the internal signal optimization control and the boundary flow control. This paper proposes some new methods for the traffic optimization of regional road network. First, the intersections inside the road network are divided to two types of groups by overlapping division method. Then the internal traffic flow characteristics for each type of group are analyzed to determine the vehicle distribution rate on the section. Based on the vehicle distribution rate, the vehicle capacity of the regional road network is calculated indirectly, providing reasonable threshold for boundary intersection flow control. According to previous research, a two-stage fuzzy control scheme is designed for the type-II central intersection, realizing the coordinated control between adjacent intersections and optimizing the operation of traffic flow in the regional road network effectively. Finally, the effectiveness and rationality of each method proposed in this paper are proved by simulation results.

Keywords: Signal optimization control, regional road network, vehicle distribution, coordinated control

1. INTRODUCTION

When optimizing the traffic control of the regional road network, scholars usually start from two aspects. One is to set a reasonable threshold, that is, a maximum of the vehicle capacity of the road network, combining with the vehicle closure control at the boundary intersection[1], to avoid congestion caused by excess vehicles. The other is to implement the providential optimal control plan at each intersection inside the regional road network, so that the vehicles accumulated on the entrance lanes can leave as soon as possible.

Many scholars employ traffic simulation software to simulate the traffic flow and obtain the threshold of the vehicles flowing in the regional road network indirectly[2]. Based on the research results of the vehicle occupancy rate in the section of the regional road network, the vehicle threshold of the regional road network is deduced, which avoids the tedious modelling process and simulation process[3]. In the equation of the optimal control plan of each intersection in the regional road network, the overlapping division method is proposed and the intersections in the regional road network are divided into different control groups: type-I group and type-II group. The coordinated signal control method is adopted to make the adjacent intersections cooperate with each other to promote the efficient operation of traffic flow and avoid congestion. All details will be elaborated in the following sections.

2. METHODS

2.1 The overlapping division method

Under normal circumstances, the impact of the traffic supply from the upstream intersection on the traffic demand at the downstream intersection should be considered fully. As a result, the adjacent intersections should not be completely isolated when dividing the subnets of the regional road network.

As shown in Figure 1, there are five adjacent traffic intersections marked by dots in a blue diamond and they form the control group 1. The red dot represents the central intersection of the group 1 and the blue dots represent its adjacent intersections. Also, there are five adjacent intersections marked by triangles in an orange diamond and they form the control group 2. The pink triangle represents the central intersection of the control group 2 and the green triangles represent its adjacent intersections. Obviously, the intersection marked both by dot and triangle belongs to two different

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control group, causing “overlap” in grouping.

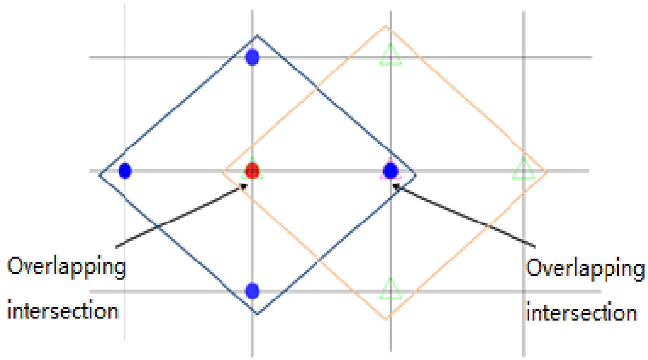

Figure 1. Intersection grouping based on overlapping division method.

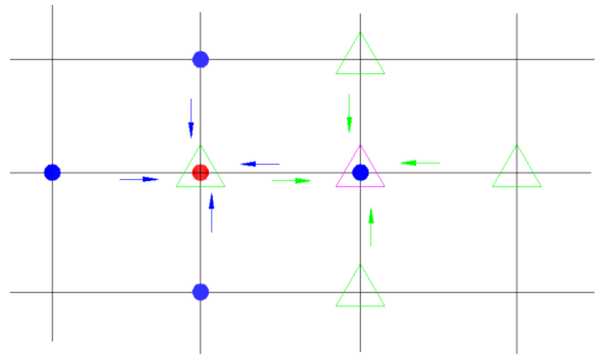

Figure 2. Schematic of traffic flow between adjacent intersections.

The overlapping division method will not isolate each intersection in the geographical distribution completely, but only considers the traffic supply from the upstream intersection to the downstream one, as shown in Figure 2. The vehicle flows represented by blue arrows flow into the central intersection of control group 1 (red dot), while the traffic flows represented by green arrows flow into the central intersection of control group 2 (pink triangle). After adopting the overlapping division method, each intersection in the regional road network belongs to several adjacent control groups at the same time, and the “overlapping” phenomenon appears. However, the traffic flows that need to be considered to optimize the traffic at each intersection are non-overlapping, so the complicated situation of control confusion will not happen. We define the central intersection that performs SEFP control method[4] and its adjacent intersections as type-I group. Its adjacent group is defined as type-II group.

2.2 Vehicle distribution model in regional road network based on overlapping division method

In this paper, the queue length waiting on the segment per signal cycle divided by the segment length is defined as the vehicle distribution rate on this section, which is indicated by η. A reasonable vehicle distribution will help to exert the storage capacity of the regional road network and ensure the smoothing traffic in the regional road network.

2.2.1 The Vehicle Distribution Model in Type-I Group. When determining the vehicle distribution of each enter lane for the central intersection of type-I group, the storage and buffering functions should be utilized fully, so as to improve the utilization rate of road space resources. At the same time, pre-storing an appropriate number of vehicles on the section is also beneficial for these vehicles to pass through the stop line at a saturated flow rate when released, avoiding the waste of time resources.

As shown in Figure 3, at the central intersection *i* of type-I group, the lane length at the entrance 1 is li,1, the queue length released in each signal cycle on this lane is qi,1, and the tail of the queue is located at spot A. The road space to the left side of A can be used to pre-store some vehicles to be released in the next signal cycle. In order to prevent overflow on this section, the allowable queue length should not exceed the entrance position, namely spot C. Equation (1) can be used to calculate the length of the section between B and C, then the range of the vehicle distribution rate η^{i},1 on the section li,1 can be got by means of equation (2).

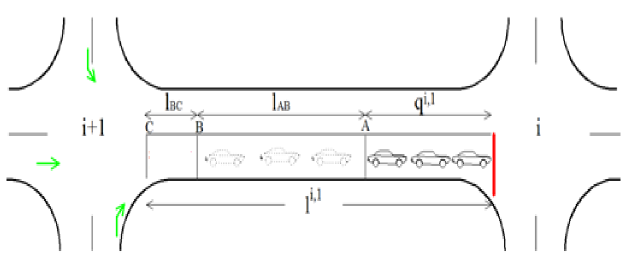

Figure 3. The vehicle distribution on the section of the type-I central Intersection.

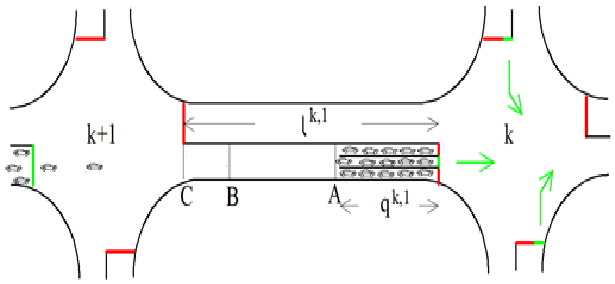

Figure 4. The vehicle distribution on the section of the type-II central Intersection.

$$\text{qi,1}\; q^{i,1} = (g^{i,1} - Ts) \times S \times \rho \tag{1}$$

$$l_{BC} = \frac{(g_{\min} - Ts) \times S \times (n_l^{i+1,1} + n_z^{i+1,2} + n_y^{i+1,4})}{n_z^{i,1} + n_l^{i,1} + n_y^{i,1}} \times \rho \tag{2}$$

$$\frac{q^{i,1}}{l^{i,1}} < \eta^{i,1} < \frac{l^{i,1} - l_{BC}}{l^{i,1}} \tag{3}$$

In equation (2), $g^{i,1}$ is the green time for the first phase at intersection i. T_S is the vehicle delay and T_S=4 second. S is the saturated flow rate. ρ is the density of vehicles in the motorcade. $n_z^{i,1}$, $n_l^{i,1}$ and $n_y^{i,1}$ are the left-lane number, straight-lane number and right-lane number of entrance 1 in intersection i. $g_{\min}$ is the minimum green time and its value in this paper is 15 seconds, l^{BC} is length of the reserved section.

According to equation (3), the vehicle distribution rate on the entrance lane of the central intersection in each type-I group is not a fixed value, but dynamic. In other words, the allowable queue length of vehicles on the section can vary within a certain range, which can utilize the storage and buffering functions of the section flexibly, helping to coordinate the traffic flow operation between adjacent intersections.

2.2.2 The Vehicle Distribution Model in Type-II Group. In Figure 4, according to the phase release sequence of the related three-turn traffic flow[5] at intersection k and that of the SEFP method[4] at the adjacent intersection (k+1), the right-turn vehicles at the west entrance of intersection k will be released last, so the queue waiting there is the longest. Its calculating equation is

$$q_{\max}^{k,1} = q^{k,1} + \frac{(g^{k+1,1} - Ts) \times S \times n_l^{k+1,1} + (g^{k+1,2} - Ts) \times S \times n_z^{k+1,2} + (g^{k+1,4} - Ts) \times S \times n_y^{k+1,4}}{n_l^{k,1} + n_y^{k,2} + n_z^{k,4}} \times \rho \tag{4}$$

where $q_{\max}^{k,1}$ is the maximum queue length at the west entrance of intersection k; $q^{k,1}$ is the average queue length on the entrance lane there. The specific meanings of other parameters are the same as the previous ones.

To prevent overflow on the entrance lane, the tail of the queue should not exceed the spot C shown in Figure 4. The equation for calculating the length of the reserved section is

$$l_{BC} = \frac{(g_z^{k+1,2} - Ts) \times S \times n_z^{k+1,2}}{n_z^{k,1} + n_l^{k,1} + n_y^{k,1}} \times \rho \tag{5}$$

where the numerator shows the number of left-turn vehicles released at the second phase of the intersection (k+1) in each signal cycle, the denominator shows the total number of lanes at the entrance 1 of the central intersection k. The specific meanings of other parameters refer to the previous section.

Combined with equation (4), the queuing length on the section at entrance 1 of the central intersection k should not exceed the reserved area, so inequality (6) should be satisfied. After substituting into equation (5), equation (7) is obtained.

$$q_{\max}^{k,1} < l^{k,1} - l_{BC} \tag{6}$$

$$q^{k,1} < l^{k,1} - l^{BC} - \frac{(g^{k+1,1} - Ts)\times S \times n_l^{k+1,1} + (g^{k+1,2} - Ts)\times S \times n_z^{k+1,2} + (g^{k+1,4} - Ts)\times S \times n_y^{k+1,4}}{n_l^{k,1} + n_y^{k,2} + n_z^{k,4}} \times \rho \tag{7}$$

In order to satisfy the requirement that the related three-turn vehicle flows can pass the stop line at entrance 1 of the central intersection k with the saturated flow rate during the minimum green time, the queue length on the section of entrance 1 should satisfy equation (8).

$$q^{k,1} > (g_{\min} - Ts)\times S \times \rho \tag{8}$$

Considering equation (7) and equation (8) comprehensively, the vehicle distribution rate on the section of the entrance 1 at the central intersection k of type-II group is

$$\frac{(g_{\min} - Ts)\times S \times \rho}{l^{k,1}} < \eta^{k,1} < \frac{l^{k,1} - l^{BC} - \dfrac{(g^{k+1,1} - Ts)\times S \times n_l^{k+1,1} + (g^{k+1,2} - Ts)\times S \times n_z^{k+1,2} + (g^{k+1,4} - Ts)\times S \times n_y^{k+1,4}}{n_l^{k,1} + n_y^{k,2} + n_z^{k,4}} \times \rho}{l^{k,1}} \tag{9}$$

From equation (9), the vehicle distribution rate on the entrance lane of the central intersection in type-II group is also dynamic. It can be adjusted according to the release time and queuing length on the road, which is conducive to assigning the release time of each phase at the central intersection of type-II group flexibly. While satisfying the reasonable range of vehicle distribution on the road, it can also consider the vehicle storage situation on the downstream section fully.

2.3 Vehicle capacity calculation of regional road network based on dynamic vehicle distribution

On the basis of the dynamic vehicle distribution rate on the entrance lane of the central intersection in the type-I and type-II groups, the range of vehicle number suitable for high efficient operation in the regional road network, that is, the size of the vehicle capacity of the regional road network can be obtained indirectly.

As shown in Figure 5. Type-I group includes: (1, 2, 5), (3, 2, 4, 7), (6, 5, 2, 7, 10), (8, 7, 4, 12), (9, 5, 10, 13), (11, 10, 7, 12, 15), (14, 13, 10, 15) and (16, 15, 12). And type-II group includes: (2, 1, 3, 6), (4, 3, 8), (5, 1, 6, 9), (7, 6, 3, 8, 11), (10, 9, 6, 11, 14), (12, 11, 8, 16), (13, 9, 14) and (15, 14, 11, 16). After calculating the vehicle distribution rate on each internal section, multiply it by the length of the corresponding section to obtain the range of vehicle number running in the road network. The calculation equation is shown below.

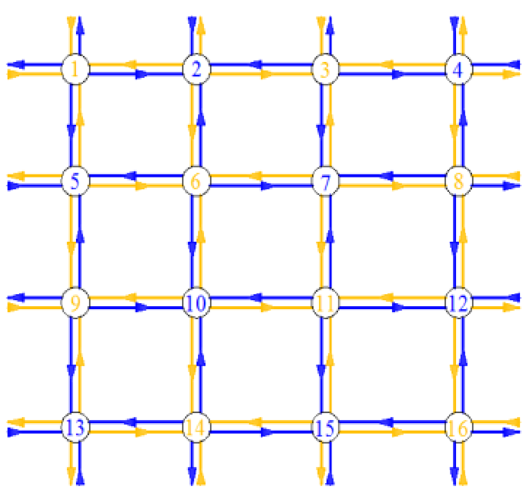

Figure 5. The diagram of regional road network structure.

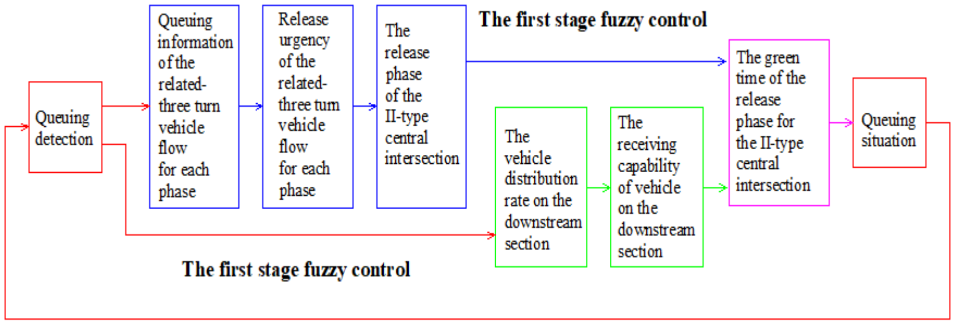

Figure 6. Two-stage fuzzy control structure of the type-II central intersection.

$$Q_{in} = \frac{[\sum_{i=1}^{16}(\sum_{j=1}^{4}\eta^{i,j}\times l^{i,j}) - \sum_{e\in E}(\sum_{f\in F}\eta^{e,f}\times l^{e,f})]}{\rho} \tag{10}$$

where Qin is the number of vehicles, that is, the capacity of the regional road network; i is the number of each intersection in the regional road network; j is the number of each entrance of the intersection; $\eta_{i,j}$ is vehicle distribution rate on the section of entrance j at intersection i; $l_{i,j}$ is the section length of entrance j at intersection i; E is the set of all boundary intersections in the regional road network; F is the set of external sections of the regional road network corresponding to each boundary intersection; ρ is the average distance between two adjacent vehicles in the queue.

According to equation (10), since the vehicle distribution rate on each section is a numerical range, the total number of vehicles that allowed running in the regional road network is also a numerical range. When the vehicle distribution rate on each section takes the minimum value, the total number of vehicles running in the regional road network is the smallest and the traffic is flowing smoothly and steadily. However, the free space on each section is relatively large, which is not conducive to the space storage function of the regional road network. When the vehicle distribution rate on each section takes the maximum value, the total number of vehicles inside the regional road network is the largest. At this time, the vehicles distributed on each road section are more reasonable, and the road network space resources are fully utilized.

2.4 Flow control at boundary intersection based on vehicle capacity of regional road network

The capacity of the regional road network is limited, so the number of vehicles running in the regional road network should be controlled within a certain range. According to overlapping division method, there are two types of boundary intersections, type-I central intersection and type-II central intersection. I-type central intersection adopts the fixed-timing control method. When the vehicles pass the stop line with saturated flow rate, the number of vehicles leaving each entrance per signal cycle is fixed. It is difficult to reduce the number of vehicles running in the regional road network by increasing the number of leaving vehicles. Therefore, we focus on the flow-limiting strategy of "reducing the input" to reduce the number of vehicles entering the regional road network from external sections. Specifically, reduce the number of release lanes where vehicles flowing into the regional road network.

If the number of prohibited lanes at boundary intersection i is N_w^i. When the entrance performs "incomplete" interception control[6] during the release period, the corresponding boundary flow control model is

$$Q_\Delta^{\mathrm{I}} = (g^{i,1} - Ts)\times S\times N_w^i \tag{11}$$

where Q_Δ^I is the reduction of the input traffic flow in each cycle after implementing the "incomplete" interception control at intersection i, $g^{i,1}$ is the green time of the entrance.

At type-II central intersection, the related three-turn vehicle flows are released synchronously, which is conducive to centralized management of the vehicle flow and realize the "increasing output" strategy. When the number of vehicles running in the regional road network exceeds the threshold, switch the current release phase of the type-II central intersection at the boundary to the traffic-output phase quickly, which can expel the excess vehicles from the regional road network in time and achieve “increase output”, relieving the traffic pressure inside the regional road network effectively.

When the number of vehicles in the regional road network exceeds the threshold, the corresponding flow-limit methods are implemented for the two types of boundary intersections at the same time. So that the boundary flow control of “reducing input” and “increasing output” can be realized to help the vehicle number running in the regional road network remain steady, preventing the occurrence of supersaturation.

2.5 Optimal control method for internal intersections

As mentioned previously, there are two types of intersections in the regional road network. In previous studies[4], the fixed-time control plan is adopted at type-I central intersection implementing SEFP method, and it works well. However, type-II central intersection implements the related three-turn vehicle flow release method, as a result, the traffic flow in the section is complex and there are many related parameters[7]. So it is difficult to establish an accurate mathematical model to describe the traffic operation at the type-II central intersection. Moreover, the signal timing scheme calculated by the traffic demand of the I-type central intersection cannot get a consistent cycle with the II-type central intersection. Taking the above factors into consideration, the two-stage fuzzy control method is adopted at the type-II central intersection.

The structure diagram is shown in Figure 6. By burying the ground induction coils at the appropriate positions of the entrance lanes and the downstream section, the queuing information in each phase of the type-II central intersection and the remaining space of the downstream section are obtained, realizing adjusting the release plan dynamically[8]. The first stage fuzzy control is used to determine the release urgency of each phase at the type-II central intersection, and then the phase release time is determined through the second stage fuzzy control.

3. SIMULATION AND RESULT ANALYSIS

3.1 Simulation object and parameter calculation

In order to verify the effectiveness and practicability of the control method proposed in this paper, the regional road network in the central urban area of Mianyang is selected as the simulation object. We employ the traffic simulation software VISSIM to conduct the simulation experiment, and the fuzzy control logic is realized by VAP (vehicle actuated program) module in VISSIM[9]. The regional road network simulation model is built as shown in Figure 7, where red circles and blue triangles are used to mark type-I central intersections and type-II central intersections respectively. The numbers in parentheses represent the internal section numbers in the regional road network. The first digit is the intersection number, and the second digit is the entrance number of the intersection. For example, (1-3) represents the section corresponding to the entrance 3 of intersection 1.

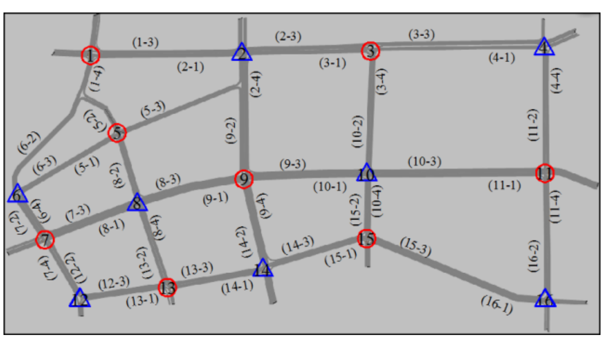

Figure 7. The plan of the regional road network.

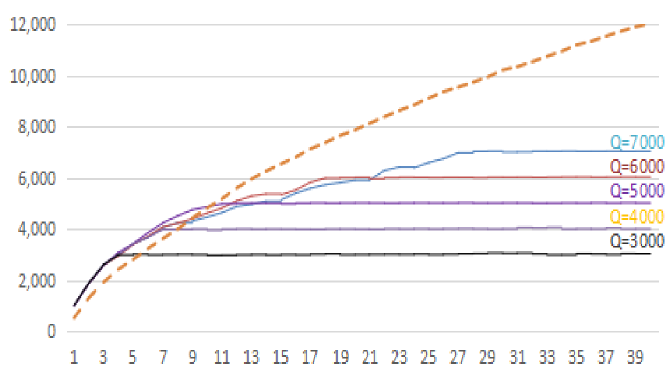

Figure 8. The flow control effect diagram of boundary intersections.

Statistics on each section length and lanes number, then refer to the signal timing method[4]. According to the fuzzy control method mentioned in this paper, the timing scheme of each intersection in the regional road network shown in Figure 7 will be obtained (here take the signal time C=180 seconds, and the yellow light Ty=3 seconds). According to equation (3) and equation (9), the vehicle distribution rate on each section of the regional road network can be gotten.

Combining these parameters and referring to equation (10), the range of vehicles number running in the regional road network is calculated, $Qin \in [2045, 6586]$.

3.2 Simulation of flow control at boundary intersections

According to the flow control method for the two types of boundary intersections in the regional road network mentioned above, "incomplete" interception control should be implemented at the external sections of intersections 1, 7, 11, 13 and 15 when the number of vehicles in the regional road network exceeds the threshold. At the same time, the release phases of intersections 2, 4, 12, 14 and 16 should switch to the traffic-output phases.

Set different threshold Q to detect the flow control effect of boundary intersections. The traffic flow of each lane is 1800 vehicles/hour, and the simulation time is 2 hours. The traffic simulation results are shown in Figure 8, where the horizontal axis is the number of signal cycles, the vertical axis is the number of vehicles running in the regional road network (Q_{in}), and each solid line shows the change of vehicle number in the regional road network in each cycle. In order to compare the influence of the boundary flow control method to common control method, another simulation result without boundary flow control is added, as shown by the dotted line in the figure.

It can be seen from Figure 8 that the number of vehicles inside the regional road network increases with time when no flow-limit measure is implemented. As a result, most of the sections overflowed during the simulation. After the flow control is executed, the boundary flow control will be activated immediately when the detectors located on the section of the regional road network detect the number of vehicles running in the regional road network exceeds the threshold, keeping the vehicle number inside the regional road network within the threshold. Obviously, the boundary flow control method of "reducing input and increasing output" proposed in this paper can maintain the stability of the number of vehicles in the regional road network effectively.

3.3 Evaluation of calculation method for vehicle capacity

According to the calculation method of the vehicle capacity based on dynamic vehicle distribution proposed in this paper, the number of vehicles in the regional road network is 6586. In order to verify the rationality and correctness of this value, the MFD[10] of the regional road network is obtained by simulation method, as shown in Figure 9.

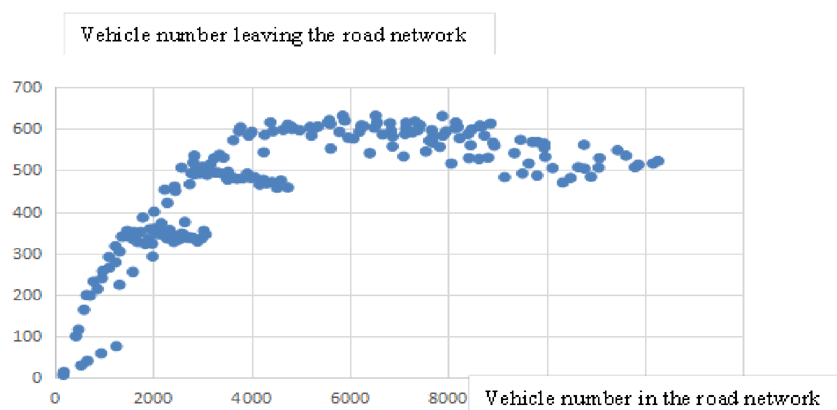

Figure 9. The MFD of the regional road network.

As shown in the MFD of the regional road network, when the vehicle number exceeds 8000, the vehicles that leave the regional road network in each cycle decrease. When the vehicles number maintains between 4,000 and 8,000, the vehicles can leave the road network in each cycle hold at a high level, and the traffic in the regional road network running in an optimal state. By contrast, the maximum value of vehicle capacity in the regional road network calculated based on dynamic vehicle distribution is 65856, just between 4000 and 8000. Consequently, the vehicle capacity calculation method of the regional road network proposed in this paper is the rational and accurate.

3.4 Optimization control effect of the regional road network

We set the capacity threshold of the regional road network to 6586, and load the optimization control method proposed in this paper for simulation. According to the simulation results, the maximum queuing length on each section in the regional road network is counted to determine whether overflow occurs. The simulation results are shown in Table 1.

As shown in Table 1, on the most of sections, the queuing length are controlled within the expected range, but there are still some sections, such as 5-1, the vehicle distribution on it exceeds the theoretical upper limit. However, no vehicle distribution rate bigger than 1 and causes overflow. Because the corresponding vehicle distribution rate showed in Table 1 is calculated when the maximum queuing length appears on the section, the phenomenon that the queuing length exceeds the expected range is occasional. During the simulation process, almost all the queue lengths on the whole sections of the regional road network are maintained within the expected range.

Table 1. The table of the maximum queue lengths and vehicle distribution rates.

Section number	**Maximum queue length (meters)**	**Maximum vehicle distribution rate**	**Theoretical calculated value of vehicle distribution rate**	**Section number**	**Maximum queue length (meters)**	**Maximum vehicle distribution rate**	**Theoretical calculated value of vehicle distribution rate**
1-3	342.5	0.67	0.38-0.88	9-1	267.3	0.74	0.24-0.89
1-4	255.3	0.77	0.25-0.88	9-2	255.5	0.59	0.29-0.91
2-1	474.2	0.93	0.1-0.58	9-3	336.0	0.80	0.28-0.9
2-3	418.9	0.95	0.1-0.4	9-4	248.2	0.92	0.18-0.81
2-4	221.3	0.51	0.1-0.52	10-1	290.9	0.69	0.1-0.4
3-1	354.8	0.81	0.3-0.9	10-2	353.0	0.84	0.1-0.38
3-3	504.6	0.84	0.4-0.9	10.3	504.0	0.79	0.1
3-4	326.7	0.78	0.4-0.88	10-4	187.7	0.94	0.1
4-1	502.3	0.84	0.1-0.58	11-1	376.6	0.59	0.37-0.94
4-4	120.1	0.29	0.1-0.66	11-2	378.3	0.90	0.24-0.87
5-1	372.4	0.98	0.21-0.86	11-4	373.8	0.89	0.24-0.87
5-2	264.6	0.44	0.34-0.9	12-2	126.8	0.58	0.14-0.2
5-3	193.6	0.35	0.32-0.95	12-3	238.7	0.82	0.14-0.4
5-4	169.1	0.74	0.13-0.83	13-1	227.1	0.78	0.27-0.81
6-2	170.3	0.31	0.1-0.6	13-2	221.5	0.74	0.28-0.87
6-3	216.5	0.57	0.1-0.35	13-3	227.5	0.91	0.23-0.84
6-4	171.7	1.01	0.15-0.24	14-1	151.8	0.61	0.1
7-2	146.8	0.86	0.18-0.87	14-2	194.9	0.72	0.15-0.3
7-3	267.6	0.81	0.34-0.88	14-3	261	0.87	0.13-0.27
7-4	203.2	0.92	0.23-0.82	15-1	271.3	0.90	0.16-0.87
8-1	242.4	0.73	0.12-0.36	15-2	140.7	0.70	0.12-0.8
8-2	90.2	0.39	0.1-0.3	15-3	504.7	0.75	0.36-0.93
8-3	199.0	0.55	0.11-0.53	16-1	275.6	0.41	0.1-0.8
8-4	258.2	0.86	0.13--0.25	16-2	299.9	0.71	0.1-0.52

There is one exception. The vehicle distribution rate on Section 6-4 is greater than 1. Through observation, it is found that the length of Section 6-4 is only 170 meters, which is the shortest section in the regional road network. Accordingly, its function of storing vehicles is poor. The maximum value of the queuing length causes the overflow, but this situation does not always exist, and the congestion does not occur at the adjacent intersection 7. Consequently, the traffic operation of the regional road network is not affected, and the regional road network optimization control method proposed in this paper has achieved the expected control effect.

4. CONCLUSIONS

The calculation method of vehicle capacity in regional road network based on vehicle distribution rate is proposed in this paper, avoiding the shortcomings of traditional MFD method effectively, such as long detection time and cumbersome modeling process. Then, on the basis of the signal timing plan for the type-I central intersection in the regional road network, the fuzzy control rules for the traffic signals at the type-II central intersection are employed, realizing the vehicle distributions on the sections conform to a reasonable range and prevent traffic saturation in the regional road network.

The proposed optimization control method of regional road network takes into account the flow control of boundary intersections and the coordinated control of internal intersections. The internal and external cooperation improves the traffic flow operation efficiency of the regional road network greatly and provides a new method for the traffic optimization control of the regional road network.

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