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Traffic Guidance Self-Organization Method for Neighbor Weaving Segments Based on Self-Organized Critical State

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ABSTRACT Traffic congestion is usually caused by the frequent lane changing behaviour of vehicles in the weaving segments, especially in several adjacent weaving segments. In order to solve the problem of weaving congestion, this paper proposes a traffic guidance method based on self-organizing critical state, and designed a Nash equilibrium optimization scheme based on average traffic delay. Then VISSIM software carries on the simulation verification to the actual neighbor weaving segments. First, it validates the induced traffic organization method, keeps each information input consistent, and only changes the induced distance. Through the daily average traffic volume (4092 pcu / h), the traffic volume in the early peak period (5340 pcu / h), the traffic volume in the late peak period (4596 pcu / h) and annual average traffic volume (3276 pcu/h) of the two near neighbor weaving segments in Chongqing. The results show that the optimal lane change constraint distance is 60% of the length of weaving segment, and the corresponding average traffic delays are reduced by 57%, 73%, 63% and 72% respectively. Through the simulation and optimization of the whole day traffic operation, the average delay reduction rate is as high as 84%. The effectiveness of the proposed method is demonstrated by integrating other output file evaluation indexes, which can be used as a reference for future research on self-organizing criticality optimization method of neighbor weaving segments.

INDEX TERMS Traffic engineering, neighbor weaving segments, equilibrium theory, traffic safety.

I. INTRODUCTION

As an important part of the road system, weaving area affects the traffic efficiency due to the turbulence of traffic flow, which makes it the bottleneck of road traffic [1]. In the neighbor weaving segments, the mixed traffic is particularly serious. Therefore, it is necessary to study the optimal organization of neighbor weaving segments

Literature [2] proposed that the weaving area is a section with high traffic accidents. To improve the traffic safety environment, the author constructs a traffic accident description model based on cellular automata. Proposed a control method based on the relationship between traffic factors (such as flow, speed and density) and the probability of accidents. Literature [3] proposed a cellular automaton model, in which three different lane-changing rules were considered to match the driving behavior when the lanes are allocated. Using the average vehicular travel time and the average velocity as the indicators, the operational performance of various lane allocation schemes was compared under different traffic and geometric conditions. Literature [4] based on the validated driver behavior parameters, a microsimulation network was built for a congested weaving segment, and several RM strategies were implemented. Literature [5] proposed a lane change prompt procedure for vehicles in the weaving area. The purpose is to promote the reasonable distribution of vehicles in weaving area and reduce traffic congestion. The evaluation results show that the program can effectively reduce traffic congestion. Literature [6] use Erlang distribution to define headway distribution of vehicles, use gap acceptance theory

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model to deduce basic capacity model of entrance and exit weaving area. Combined the modified capacity model and reduction coefficient model to establish the on ramp empirical capacity model. Literature [7] proposed the segmentation model and improved regression model for weaving speed prediction, and used genetic algorithm to calibrate the parameters of segmentation model and improved regression model respectively. Literature [8] proposed an effective multi-level hybrid model, which takes into account the location distribution of lane change and vehicle automatic response time under different penetration rates. The experimental results show that this method can effectively reduce the headway and clearance required for lane change, thus improving the traffic capacity. Literature [9] used multiple logistic regression method to analyze the factors of traffic accidents caused by weaving areas. According to the analysis results, the traffic density and weaving ratio have the greatest impact on traffic accidents. When the weaving ratio $\geq$41% or the traffic density $\geq$31 vehicles / 100m, the probability of traffic accidents is the highest. Literature [10] found that the weaving behavior of different vehicle types is different in the expressway weaving area. When merging and diverging, some traffic flow shows collective lane changing behavior. And proposed a random utility formula to calibrate the parameters of lane changing behavior.

Literature [11] put forward a coordination decision algorithm based on FLC to find the optimal coordination scheme without interrupting the normal operation of the expressway. After adopting the local coordinated control strategy proposed in this paper, the system efficiency of freeway ramp has been significantly improved. Literature [12] verifies the behavioral theory and proposes an extension for diverges or weaving segments. The findings provide greater insight into driver behaviors during the transition process and the resulting impact on capacity, which can provide better implications for freeway design and operation. Literature [13] proposed a ramp coordination control strategy considering fairness, which aims to reduce the imbalance of time consumption between different ramps, and comprehensively considered the principles of ramp operation efficiency and fairness. The double objective function is adopted to measure the efficiency by the total travel time and the fairness by the Gini coefficient. The feasibility of the method is verified by comparing the proposed control strategy with the coordinated ramp control strategy by using the micro simulation software. Literature [14] studies the simulation of traffic flow optimization control in weaving section, analyzes the impact of actual traffic capacity on traffic time under different traffic organization schemes, and the results show that the road traffic efficiency is effectively improved. Literature [15] proposed a lane unit combination design scheme based on vehicle operation and road characteristics, and determined the best optimization scheme with the traffic conflict rate as the evaluation index, but did not consider the traffic composition and lane combination scheme. Literature [16] studied the main line decentralized lane change and speed guidance adaptive control method of urban expressway and adjacent intersection, and proposed the main line decentralized lane change adaptive control method for high saturation on ramp and adjacent intersection. Literature [17] proposed a new lane signal control method to regulate the weaving traffic flow of urban arterial weaving areas. Based on this method, the capacity calculation model of weaving section is established to derive the optimal lane signal control scheme. Literature [18] put forward a control method which is suitable for both single ramp control and coordinated control for expressway ramp and trunk line problems. The control method is based on a new nonlinear adaptive control scheme, which is used to estimate unknown system variables.

To sum up, the research on the optimal control scheme of single weaving section has been quite in-depth, but the above research results do not consider the mutual interference between weaving sections. When vehicles continuously pass through multiple adjacent weaving sections, multiple parallel shunting will be formed, resulting in traffic chaos. Therefore, in this paper, a traffic guidance method under self-organized critical state is proposed to guide vehicles to change lanes ahead of time, use the equilibrium organization method to optimize the lane change guidance distance. In this paper, travel time, traffic delay and traffic density are selected as the output indicators to verify the effectiveness of the proposed method. Travel time is the time taken by a vehicle from entering the weaving section to leaving the weaving section. Traffic delay refers to the time lost due to the interference of other vehicles or the obstruction of traffic control facilities. Traffic density refers to the number of vehicles per unit length of a lane at a given moment.

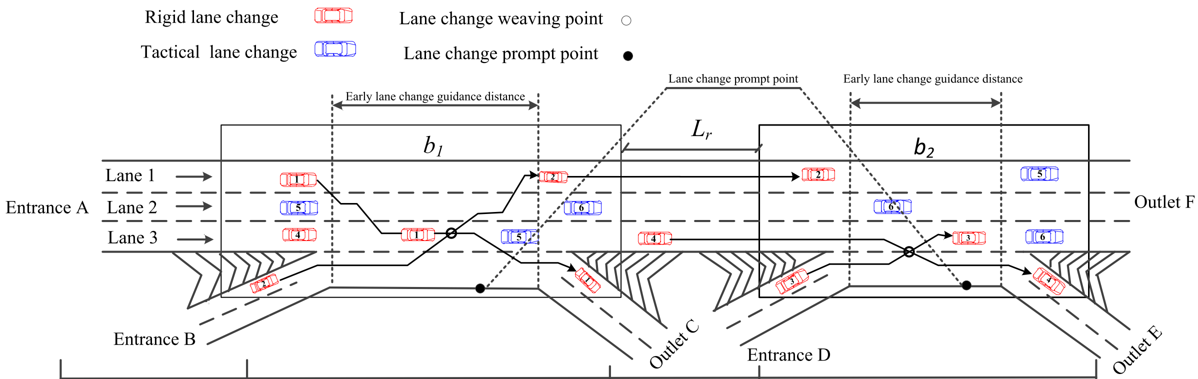
II. ANALYSIS OF STRUCTURE AND OPERATION CHARACTERISTICS OF NEIGHBOR WEAVING SEGMENTS

A. STRUCTURAL CHARACTERISTICS AND TRAFFIC OPERATION CHARACTERISTICS OF NEIGHBOR WEAVING SEGMENTS

Due to the increase of traffic volume between neighbor weaving segments, the traffic flow is disturbed and disordered, so the traffic capacity continues to decline. Neighbor weaving segments are to analyze the weaving segments which its spacing is lower than the design standard and affects each other as a whole, so as to study the correlation degree between adjacent weaving sections and the operation characteristics of traffic flow.

The geometric structure of the neighbor weaving segments is shown in Figure 1,where b_1, b_2 represent weaving segment 1 and 2, respectively. L is the length of weaving segment, L_r and L_{min} is the distance between neighbor weaving segments, L_{max} is the length limit of weaving segment, and Z is the influence range of weaving segment on upstream and downstream.

According to the geometric characteristics of the neighbor weaving segments, the weaving segment in the middle of the neighbor weaving segments are not only affected by the



Unit（m）	Lmax≥L≥Lmin	Lr≤Z	Lmax≥L≥Lmin
Type	Weaving section	Distributary influence area	Weaving section
Analysis method	Joint analysis	Joint analysis	Joint analysis

FIGURE 1. Structural characteristics and traffic operation characteristics of neighbor weaving segments.

upstream weaving segment diversion, but also by the downstream weaving segment confluence. Therefore, it is the key to improve the traffic operation efficiency of the weaving area by analyze the neighbor weaving segments as a whole.

The frequently lane changing and changeable road conditions in the neighbor weaving segments make the traffic operation more complex. The neighbor weaving segment shown in Figure 1 is composed of two consecutive weaving areas, whose traffic operation characteristics mainly include rigid lane changing characteristics, uneven distribution of traffic flow and influence continuity.

The lane change behavior of vehicles in the neighbor weaving segments can be divided into rigid demand lane change and tactical lane change. Rigid lane changing must be completed within a certain range, and deadlock will occur when there is a conflict between forced lane changing of multiple vehicles. As the running track of red marked vehicles shown in the rigid lane changing in Figure 1, which will induce traffic congestion and reduce the overall traffic efficiency. Tactical lane changing is usually the lane changing measures taken by drivers to obtain better driving conditions.

The distribution of traffic flow in each weaving area will be uneven because of the different capacity of each neighbor weaving segments, which is easy to cause traffic bottleneck. When a large number of rigid lane changes occur locally, the actual capacity of exit C will increase, which will lead to unbalanced surge of neighbor weaving segments. In Figure 1, the incoming vehicles of weaving segment 2 are composed of the outgoing vehicles of weaving segment 1 and the incoming vehicles of entrance D, but most of them come from the main road. Therefore, the number of incoming vehicles of the main road will affect the traffic capacity of weaving segment 2. Generally, due to the confusion of a certain weaving segment, the upstream weaving segment will be blocked, and the vehicle arrival rate of the downstream weaving segment will be reduced, so that fewer vehicles or no vehicles will cross the downstream weaving area makes the traffic between weaving areas unbalanced and blocked.

B. SELF ORGANIZATION OF NEIGHBOR WEAVING SEGMENTS

In the system of neighbor weaving segments, there is no signal light and other self-organization phenomenon of traffic control measures is obvious. It usually requires tacit cooperation between vehicles and consciously abide by traffic rules to reflect the role of self-organization. Especially in the complex weaving section, self-organizing behavior is particularly important. When the vehicle passes through the neighbor weaving segments, the self-organization phenomenon will be shown as that the vehicles at the ramp will actively avoid the vehicles on the main road to prevent collision. As shown in Figure 2, vehicle No. 4 will actively avoid the vehicles on the main line, and will only drive into the main line after finding the intersection gap between No. 2 and No.3 vehicles, thus forming a self-organization phenomenon.

In the neighbor weaving segments, after the target exit is determined, the vehicle will actively change the lane near the exit side. If the driver knows the congestion, he will change the route, change the lane close to the exit side in advance and choose a reasonable route to leave the ramp. As shown in Figure 2, No.0 vehicle will consider the driving comfort before choosing lane change to leave the weaving area, and select the lane close to the off ramp in advance to reduce the interference of other vehicles during lane changing. When it starts to change lanes, it will give priority to estimate the lane change conditions according to the traffic conditions, and select the optimal lane change distance and time. When it misses the best choice, because its lane change is rigid,

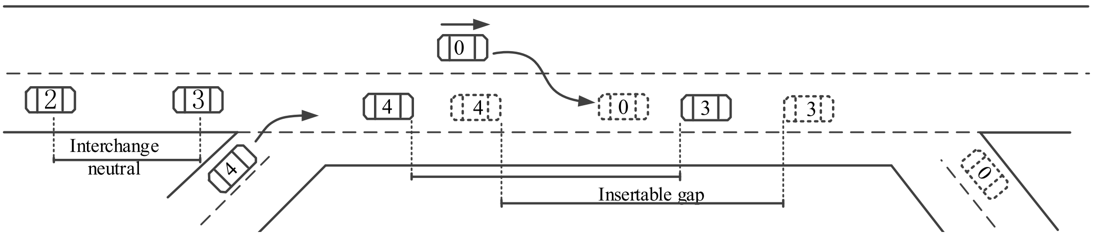


FIGURE 2. Self-organization of neighbor weaving segments.

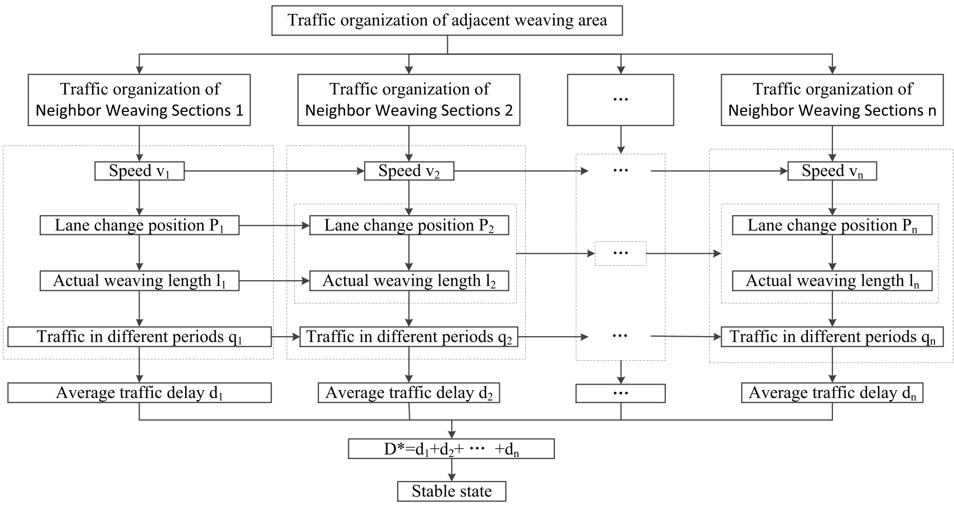


FIGURE 3. Optimizing Scheme of neighbor weaving segments.

the demand will be forced to stop at the exit and wait for other through vehicles to pass, and then change lanes to enter the ramp to leave. This kind of spontaneous avoidance and optimal choice is the self-organization of traffic flow, and finally achieve the traffic self-organization of the neighbor weaving segments.

III. OPTIMAL CONTROL SCHEME OF NEIGHBOR WEAVING SEGMENTS

A. MEASURES TO OPTIMIZE THE ORGANIZATION OF NEIGHBOR WEAVING SEGMENTS

The organization optimization method of neighbor weaving segments is based on self-organizing criticality, which can induce vehicles before self-organization and destroy their self-organized criticality. According to the spatial structure and vehicle operation characteristics of the neighbor weaving segments, the corresponding disturbance mode is proposed: lane change guidance mode in advance. Finally, taking the average traffic delay as the evaluation index, the best disturbance method is selected by using Nash equilibrium model.

The key to the vehicle operation in the neighbor weaving segments is the lane change of weaving vehicles. In order to avoid the highly disordered state of limited length weaving sections, it is necessary to ensure the minimum interference to vehicles in different time and space states. Figure 3 shows a traffic congestion scheme from the two dimensions of time and space. In terms of the traffic volume in different periods, it can disperse the traffic congestion in the weaving area and balance the traffic flow distribution from the perspective of traffic volume. Considering the impact of the actual weaving length on traffic congestion in space, the traffic flow distribution is balanced in space. In order to determine the optimal lane change guidance distance, the average traffic delay is selected as the evaluation index, and the equilibrium theory is used to guide the traffic flow in the neighbor weaving segments so that the traffic flow in the weaving area can reach a stable state, and finally achieve the goal of minimum average traffic delay.

Under the condition of traffic flow self-organization, each weaving section operates in different self-organization forms, which is affected by vehicle speed, lane change position, weaving length and traffic flow. Therefore, the early lane change guidance mode in each weaving section will have different impact on the traffic organization in the neighbor weaving segments. The sum of average traffic delays in each weaving section is selected as the evaluation index to judge whether the early lane change guidance distance is It is the best guidance distance.

B. TRAFFIC DEMAND CHARACTERIZATION IN NEIGHBOR WEAVING SEGMENTS

$G = (W, M)$ is a method for organizing the neighbor weaving segments, where W is the set of all paths in the neighbor weaving segments, M is the number of weaving segments in the neighbor weaving segments, w' is a specific driving path, and $Q_{w'}$ is the demand of specific path w'. Considering the randomness of traffic demand change, normal distribution is used to describe the randomness of demand [19]. The lower and upper limits of demand between records are $q_{\min}$ and $q_{\max}$ respectively. Further, it is assumed that demand is a normal variable on the $[q_{\min}, q_{\max}]$ interval, and its probability density function is:

$$f_{Q_{w'}}(x)=\begin{cases} \frac{1}{\gamma\sqrt{2\pi}\sigma_{w'}}\exp\left[-\frac{(x-\overline{\mu})}{2\sigma_{w'}{}^2}\right], & q_{min}\leq x\leq q_{\max} \\ 0, & x<q_{min}, x>q_{\max} \end{cases} \tag{1}$$

where $\bar{\mu}$ is the demand mean value of the normal distribution corresponding to the tail normal distribution; σ_w is the standard deviation of the normal distribution; γ is the standardized coefficient to ensure that the cumulative probability in the interval is 1; see formula (2) for the value of γ.

$$\gamma = \Phi\left[\frac{q_{max}-\bar{\mu}}{\sigma_{w'}}\right] - \Phi\left[\frac{q_{min}-\bar{\mu}}{\sigma_{w'}}\right] \tag{2}$$

C. NASH EQUILIBRIUM OPTIMIZATION MODEL BASED ON AVERAGE TRAFFIC DELAY

Section delay is usually described by road impedance. According to the impedance function model of American highway administration, the section travel time is described as:

$$t_{ij}(x_{ij}, y_{ij}) = t'_{ij}\left[1+\alpha\left(\frac{x_{ij}}{c_{ij}+y_{ij}}\right)^{\beta}\right] \tag{3}$$

In the formula, t'_{ij} is the free flow travel time of weaving segment 1; x_{ij} is the flow of segment i adopting the j^{th} lane change mode; y_{ij} is the capacity increase of weaving segment i adopting the j^{th} lane change mode; c_{ij} is the actual traffic capacity of weaving segment i; α and β are BPR function parameters. From the aspect of the operation efficiency of the road network system, the smaller the road impedance in the neighbor weaving segments is, the higher the road operation efficiency is, so the minimum expected impedance is used to describe:

$$\min \mathrm{E}\left\{\sum_{i=1}^{m}\left(x_{ij}(Y,Q)t_{ij}\left(x_{ij}(Y,Q),y_{ij}\right)\right)\right\} \tag{4}$$

where m is the number of weaving sections in the neighbor weaving segments; j = 1, 2, 3, ..., n; $Y = (yij)_{m\times n}$ is the capacity increase vector of the j^{th} lane change mode in the weaving area i; $Q=(q_{ij})_{m\times n}$ is the traffic demand vector of the j^{th} lane change mode in the weaving area i. In order to ensure the stability of traffic organization and the probability of traffic organization reaching a certain level, the reliability index is expressed as follows:

$$\max P_r\{R(X(Y,Q)Y)\} \leq \lambda \tag{5}$$

$$R(X(Y,Q)Y) = \frac{\sum_{i=1}^{m} X_{ij}l_i}{\sum_{i=1}^{m}(c_i+y_{ij})l_i} \tag{6}$$

where p_r is the probability; λ is a specified threshold value of saturation; $R(\cdot)$ is the road network saturation; l_i is the length of the first weaving segment. Considering the traffic organization and reliability of neighbor weaving segments, the following models can be obtained:

$$\min\ Z_1 = \mathrm{E}\left\{\sum_{i=1}^{m} x_{ij}(Y,Q)t_{ij}(x_{ij}(Y,Q),y_{ij})\right\} \tag{7}$$

$$s.t.\ \begin{cases} 0\leq y_{ij}\leq y_{ij}^{\max}, & \forall i\in m \\ \sum_k f_k^{w'} = Q_{w'}, & \forall w'\in w \\ f_k^{w'}\geq 0, & \forall i\in m, k\in R_{w'} \end{cases} \tag{8}$$

Nash equilibrium optimization model based on average traffic delay can be expressed as Literature [20]:

$$D = \left(d_{ij}\right)_{m\times n} = \begin{bmatrix} d_{11} & d_{12} & \cdots & d_{1n} \\ d_{21} & d_{22} & \cdots & d_{2n} \\ \vdots & \vdots & & \vdots \\ d_{m1} & d_{m2} & \cdots & d_{mn} \end{bmatrix} \tag{9}$$

Matrix D is a matrix of $m\times n$ order, which indicates that there are m weaving segments in the neighbor weaving segments and n ways to change lanes in advance. d_{ij} is the average traffic delay generated by the first weaving segment in the neighbor weaving segments whose lane change induction distance is j% of the length of the weaving area. According to formula (3) above, $d_{ij} = t_{ij} - t'_{ij}$ $(j = 1, 2, 3 \ldots n)$, $\sum_{i=1}^{m} d_{ij}$ is the delay value of all neighbor weaving segments when the early lane change guidance distance is j% of the length of weaving segment. The optimal equilibrium distribution in the neighbor weaving system should ensure the minimum average traffic delay, which can be expressed as:

$$D^* = \min\left[\sum_{i=1}^{m} d_{i1}, \sum_{i=1}^{m} d_{i2}, \cdots, \sum_{i=1}^{m} d_{in}\right] \tag{10}$$

D^* indicates that when the early lane change guidance distance of each weaving segment is j% of the length of the weaving segment, the cumulative average traffic delay of each neighbor weaving segments is the smallest, and the neighbor weaving segment reaches a better stable state.

IV. AN EXAMPLE ANALYSIS OF NEIGHBOR WEAVING SEGMENTS

A. CURRENT SITUATION AND BASIC PROPERTIES OF WEAVING SECTION

Taking the neighbor weaving segments near the Sigongli interchange in Nan'an District of Chongqing as an example. The Haixia road is located in the east-west direction of the Sigongli interchange, forming a three-dimensional intersection with Jiangnan Avenue, and realizing interchange through the Sigongli interchange. The interweaving mode and physical structure are shown in Figure 4.

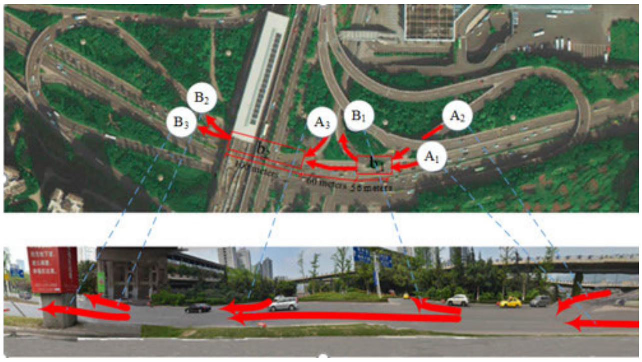


FIGURE 4. Road structure and operation chart of neighbor weaving segments in haixia road.

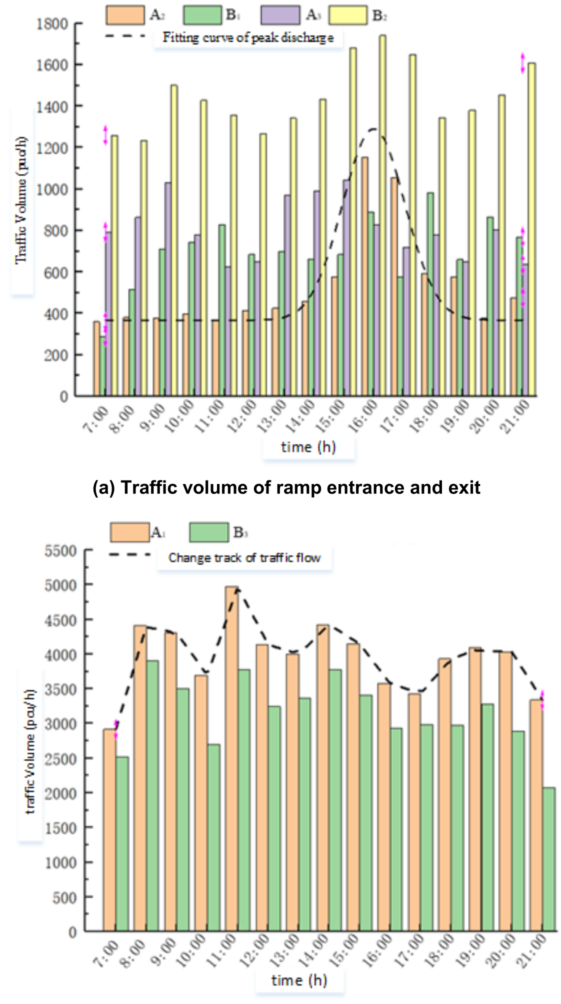
As shown in Figure 4, the neighbor weaving segments of Haixia road includes three entrances A_1, A_2 and A_3, and three exits B_1, B_2 and B_3, A_1 is the main line entrances and B_3 is the main exits. A_1 and A_2 on ramps are 3-lanes and 2-lanes respectively. After passing through the 4-lane weaving section 1 with the weaving length of 56 meters, they are diverted to ramp B_1 and the next weaving area entrance, which are 2 lanes and 4 lanes respectively. Ramp A_3 is a two lane interleave with the exit of the upstream weaving section. After passing through the 4-lane section 2 with a length of 100m, ramp A_3 is diverted to ramp B_2 and ramp B_3, which are two lanes and three lanes respectively.

The method of data collection is manual survey and counting. Through the investigation of the traffic data of each entrance road and exit road from 7:00 a.m. to 9:00 p.m., the 5-minute interval is taken as the basic counting unit. Finally, according to the traffic flow data of each entrance and exit road, the ramp traffic volume of the neighbor weaving segments ramp and the main line entrance and exit traffic volume are formed as shown in Figure 5.

And through the traffic data investigation, the main traffic flow of each period is obtained as daily average traffic volume (4092pcu/h), early peak traffic volume (5340pcu/h), late peak traffic volume (4596pcu/h) and annual average traffic volume (3276pcu/h).

Through field investigation and interview, it is found that the neighbor weaving segments cannot meet the road traffic demand well in peak hours. With the increase of traffic volume in weaving section 1 and the increasing number of vehicles leaving weaving section 2, weaving section 2 has obvious traffic congestion problem, while the traffic operation of weaving section 1 on the upstream will be affected. The causes of such problems are as follows:

(1) The vehicles leaving the ramp in weaving section 1 do not change lanes in time and leave the ramp, resulting in queuing phenomenon of lane changing. Then the vehicles are piled up in weaving section 1 and upstream, and



(a) Traffic volume of ramp entrance and exit

(b) Traffic volume of main line entrance and exit

FIGURE 5. Traffic volume histogram of neighbor weaving segments.

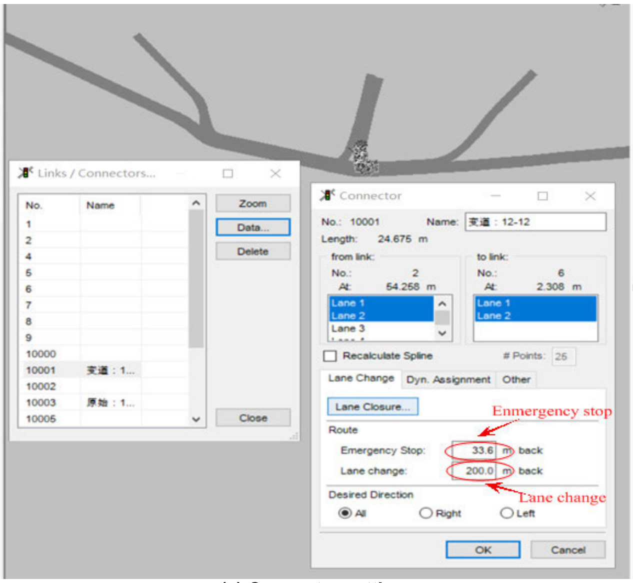
do not lead to the downstream weaving area in time, resulting in road congestion;

(2) Although vehicles have passed through weaving section 1, vehicles leaving the ramp in weaving section 2 do not change lanes in time. If they leave the ramp, they will still cause vehicle accumulation and traffic congestion, which can spread to the upstream weaving area or even a larger area in peak period.

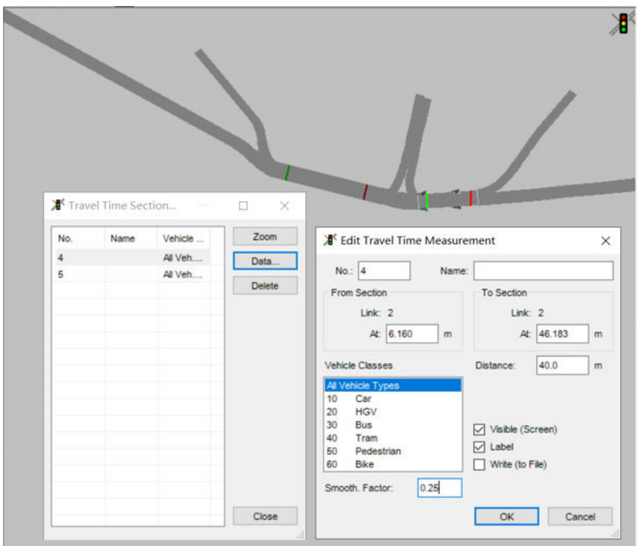
B. ANALYSIS OF SIMULATION RESULTS

1) COMPARATIVE ANALYSIS OF TRAFFIC GUIDANCE METHODS

Based on the actual investigation data of the weaving area near the Haixia Road, the simulation software (VISSIM 4.3) draw simulation road network for simulation experiment, set detectors in each weaving section to obtain average traffic delay data, set simulation parameters in combination with the actual investigation data of the experimental section. Setting the speed of the main line as 60km/h, the maximum speed of the auxiliary road and the up and down ramps as 50km/h, the ratio of bus and car as 3:7 and the simulation time as 3600s. The early lane change guidance is implemented according to the lane change function in the VISSIM connector attribute, as shown in Figure 6.



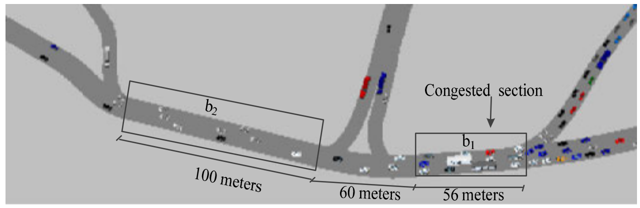
(a) Connector settings



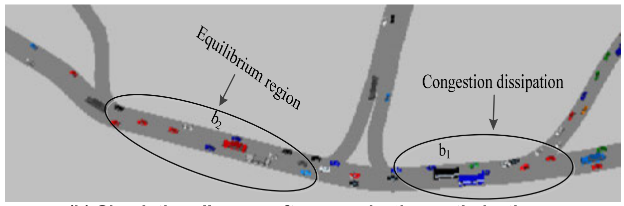
（b）Data monitoring point setting

FIGURE 6. Basic property settings.

Lane change in Figure 6(a) refers to the distance at which the vehicle begins to try to change lanes. Emergency stop refers to the last position where vehicles can change lanes. If the traffic flow is too large to change the lane, but the driving path determines that it must change the lane, it will stop at this position and wait for the chance to change the lane. The distance of emergency stop point in VISSIM is used to replace the distance of lane change guidance in advance. The simulation initial value is the default value of the early lane change guidance distance, as shown in the identification part of Figure 5, and then it changes in turn in an increment of 10% of the length of the weaving segment. That is to say, there are nine ways of lane change. According to the current situation of the road and formula (9), m = 2, n = 9, and $D = (d_{ij})_{2\times 9}$ can be obtained, and $D^* = \min(d_{11} + d_{21}, d_{12} + d_{22}, \ldots, d_{19} + d_{29})$ can be obtained from formula (10). Through 40 simulations, the comparison results of traffic optimization are shown in Figure 7.



(a) Simulation of the current situation of neighbor weaving segments



(b) Simulation diagram after organization optimization

FIGURE 7. Comparison of simulation between optimization and unoptimized of neighbor weaving sections.

From Figure 7(a), it can be seen that before optimization, the congestion in weaving area 1 is heavy, which leads to the reduction of vehicle traffic volume and road utilization in weaving area 2. From Figure 7(b), it can be seen that the traffic flow distribution after optimization is more uniform and the congestion in weaving area 1 is relieved. A total of 80 groups of data are obtained through simulation, shown in Table 1 for the change of average traffic delay in the optimization process.

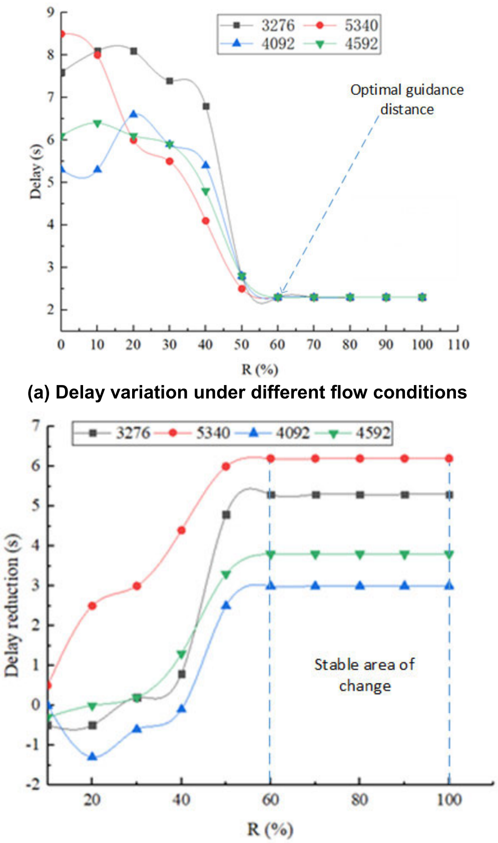
R is the percentage of advance lane change distance in the length of weaving segment. It can be seen from Table 1 that in the process of equalization, each weaving segment does not reduce or increase delay at the same time, but restricts each other to reach the final equilibrium point. The sum of the average delay of each weaving segment is taken as the road evaluation index, and the balanced optimization results under different traffic flows are shown in Figure 8.

In the same weaving section, with the increase of traffic volume, the degree of constraint is more and more great, the probability of random lane change of vehicles is gradually reduced, and the lane change interference between vehicles is also reduced, so the traffic delay is low. Before the optimization of traffic guidance distance, the effect of different traffic guidance distance under different traffic flow conditions will be different. Figure 8 selects four representative groups of flow data (4092pcu/h, 5340pcu/h, 3276pcu/h, 4596pcu/h) in the neighbor weaving segments for simulation. When R = 60%, the interference degree between vehicles reaches the minimum, and the average traffic delay in the neighbor weaving segments is minimized. Even when the lane change guidance distance continues to increase, the

TABLE 1. Average traffic delay under different traffic flows.

R	d_{1j}^{3276}	d_{2j}^{3276}	d_{1j}^{5340}	d_{2j}^{5340}	d_{1j}^{4092}	d_{2j}^{4092}	d_{1j}^{4596}	d_{2j}^{4596}
0.00	3.60	4.00	4.60	3.90	2.80	2.50	3.00	3.10
10.00	3.60	4.50	4.40	3.60	2.80	2.50	2.90	3.50
20.00	3.60	4.50	3.00	3.00	3.10	3.50	2.90	3.20
30.00	3.60	3.80	2.90	2.60	3.00	2.90	2.80	3.10
40.00	3.50	3.30	2.50	1.60	2.90	2.50	2.60	2.20
50.00	1.90	0.90	2.00	0.50	2.00	0.80	2.00	0.80
60.00	1.70	0.60	2.00	0.30	1.90	0.40	1.90	0.40
70.00	1.70	0.60	2.00	0.30	1.90	0.40	1.90	0.40
80.00	1.70	0.60	2.00	0.30	1.90	0.40	1.90	0.40
90.00	1.70	0.60	2.00	0.30	1.90	0.40	1.90	0.40

Note: the unit of average traffic delay reduction is s. when R is equal to 0, there is no simulation data optimized. d_{mj}^{a} , where a represents the traffic flow during the simulation, m is the number of weaving sections in the neighbor weaving segments, j is the capacity increase vector of the j[th] lane change mode.



(a) Delay variation under different flow conditions

(b) Delay reduction under different flow conditions

FIGURE 8. Analysis of simulation results under different flow conditions.

interference degree between vehicles is always kept at the minimum, so the average delay in the neighbor weaving segments remains the minimum. The experimental results verify the effectiveness of the optimization method, and give the optimal early lane change guidance distance in the neighbor weaving segments.

In Table 2, d and d' respectively represent the delay values before and after optimization. For the optimization simulation

TABLE 2. Optimized data analysis and comparison table.

flow (pcu/h)	d_1	d_1'	d_2	d_2'	Delay reduction (s)	Reduction rate (%)
3276	3.60	1.70	4.00	0.60	5.30	0.72
5340	4.60	2.00	3.90	0.30	6.20	0.73
4092	2.80	1.90	2.50	0.40	3.00	0.57
4596	3.00	1.90	3.10	0.40	3.80	0.63

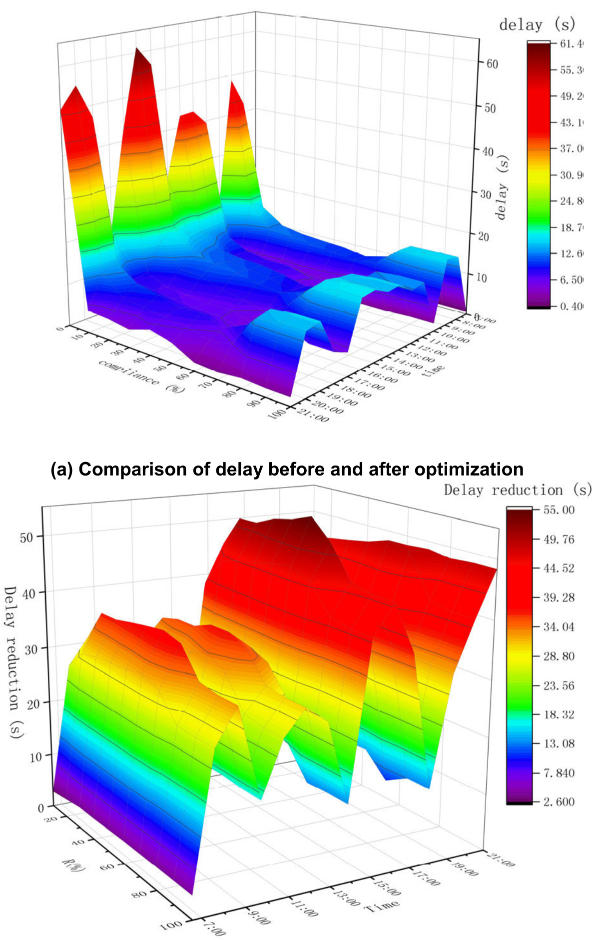
of annual traffic volume (3276pcu/h), the delay is reduced from 7.6 seconds to 2.3 seconds, which is 72%; for the optimization simulation of early peak traffic volume (5340pcu/h), the delay is reduced from 8.5 seconds to 2.3 seconds, which is 73%; for the optimization simulation of daily average traffic volume (4092pcu/h), the delay is reduced from 5.3 seconds to 2.3 seconds, which is 57%; for the optimization simulation of late peak traffic volume (4596pcu/h), the delay is reduced from 6.1 seconds to 2.3 seconds, which is 63%. Based on the optimal early lane change guidance distance, the traffic flow in each period of the day in the experimental section is simulated, and the average traffic delay between 7:00 and 21:00 in the neighbor weaving sections of Haixia road is compared by simulation. The comparison before and after optimization is shown in Figure 9.

Figure 9(a) shows that the change of average traffic delay in neighbor weaving sections. R represents the percentage of advance lane change distance to the length of weaving section. When R = 0, it is the current situation simulation of adjacent weaving area. With the passage of time, the peak time is 9:00 a.m. and 5:00 p.m., and the maximum delay reaches 61.3 seconds. When the induced disturbance is applied to the neighbor weaving sections, the average traffic delay decreases gradually, until the lane change distance is 60% of that in the neighbor weaving sections, the average traffic delay decreases to the minimum, increases after 70% and reaches stability at 90%. Figure 9 (b) shows that due to the small traffic volume at 7:00 a.m., the delay itself is small.

TABLE 3. Comparison of average traffic delay reduction.

Compliance (%)	10.0	20.0	30.0	40.0	50.0	60.0	70.0	80.0	90.0	100
7:00	3.3	3.5	3.5	3.5	3.8	3.7	3.8	3.7	4.0	4.0
8:00	1.4	5.0	8.5	14.0	14.8	22.0	23.9	26.8	30.0	32.2
9:00	0.3	9.4	12	17	15.2	27.9	30.3	34.1	37.0	38.8
10:00	11.6	13.1	13.3	14.5	15.2	15.6	15.8	16.1	16.0	17.3
11:00	-0.2	5.8	7.9	10.7	12.9	23.7	25.4	28.6	32.7	34.0
12:00	3.8	6.7	8.6	11.8	16.3	24.1	28.4	34.3	36.6	37.1
13:00	0.8	1.0	6.3	11.7	13.4	22.0	24.9	28.5	31.2	34.2
14:00	-19.7	-15.0	-6.4	-3.7	-1.0	6.3	8.6	11.6	15.6	19.3
15:00	4.5	8.0	12.2	16.3	22.1	31.6	37.1	40.9	43.5	46.9
16:00	6.3	11.7	17.1	24.5	27.2	35.7	43	47.3	52.4	55.0
17:00	8.5	14.4	19.4	24.0	24.7	32.3	32.5	38.5	37.0	38.0
18:00	-3.0	5.0	7.0	4.8	12.1	12.4	12.6	13.7	13.5	14.4
19:00	1.3	4.2	8.4	10.5	12.8	25.7	25.7	35.3	38.1	40.3
20:00	9.4	10.9	17.0	15.1	23.9	30.9	41.9	45.3	49.1	49.6
21:00	16.0	27.8	26.0	32.2	44.3	44.9	46.3	47.0	48.1	48.4

Note: the unit of average traffic delay reduction is s.



(b) Delay reduction before and after optimization

FIGURE 9. Analysis of simulation results on average delay change.

Under the condition of induced lane change disturbance, the average traffic delay is relatively small and low. With the increase of vehicles, the delay in the adjacent weaving area increases continuously, and the optimization effect of lane change disturbance is more obvious. It can be seen from Figure 9 (b) that at 4 pm, when the lane change guidance distance is 60% of the length of the weaving section, the traffic self-organizing disturbance method proposed in this paper achieves the best effect and the maximum delay reduction.

2) COMPARATIVE ANALYSIS OF TRAFFIC GUIDANCE COMPLIANCE

The decision points are set according to different connectors to realize compliance simulation. The dialog box of induced compliance setting is shown in Figure 10.

In the previous paper, the guidance compliance of early lane change is 100%, without considering the factor of induction compliance. Based on the above optimal simulation research, the induced lane change distance is 60% of the length of the weaving segment. In order to further verify the influence of the interference intensity on neighbor weaving segments, the induced compliance is simulated from 10% to 100%. The total delay of neighbor weaving segments is taken as the output result, as shown in Figure 11.

It can be seen from Figure 11 that when the lane change guidance distance is 60% of the length of the weaving section, with the increase of guidance compliance, the average traffic delay in the neighbor weaving segments will be reduced. The calculated delay reduction under different induction compliance in each period is shown in Table 3.

It can be seen from table 3 that the delay of neighbor weaving segments is different when the induced compliance rate is different, and with the increase of compliance rate, the delay reduction increases gradually. From the point of average traffic delay, the induced compliance degree has a certain influence on the effectiveness of the self-organizing mode of adjacent weaving sections.

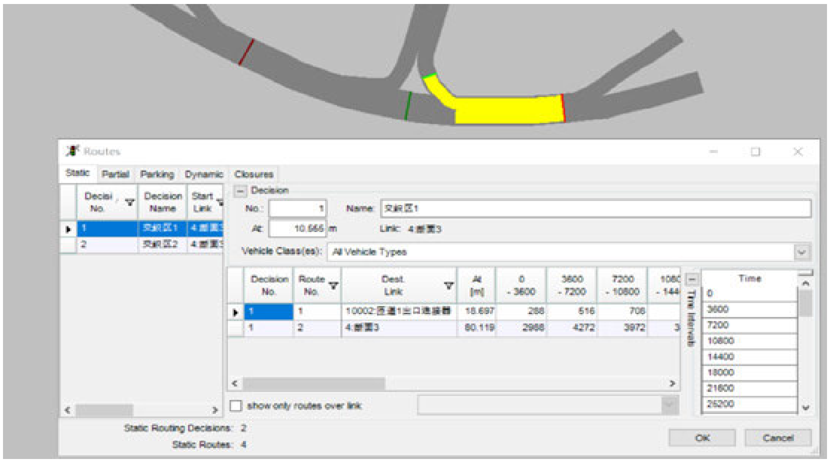


FIGURE 10. Induction compliance setting dialog box.

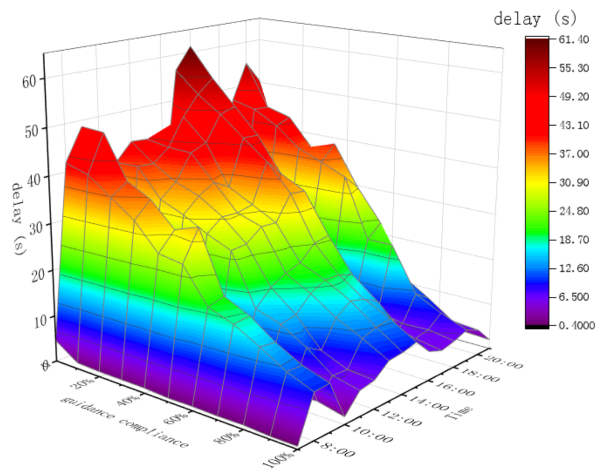
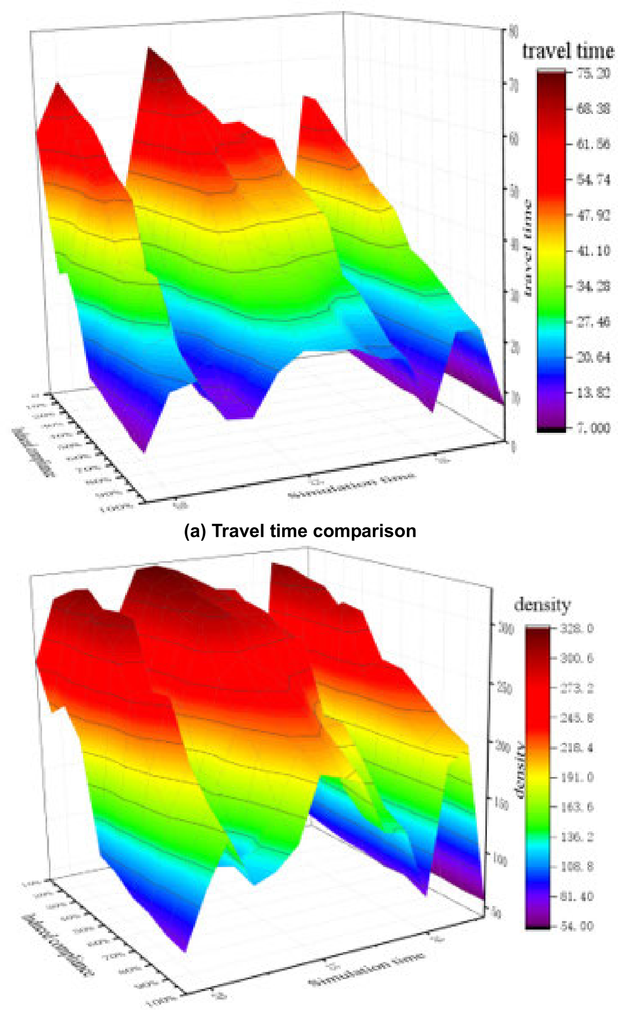


FIGURE 11. Comparison of delays under different degrees of induced compliance.



(a) Travel time comparison

(b) Travel density comparison

FIGURE 12. Travel time and density variation of neighbor weaving segments.

Considering the stability of traffic organization in the process of disturbance, taking one hour as the simulation interval, the travel time and traffic density are selected as the simulation output to reflect the traffic stability of the neighbor weaving segments under different guidance compliance degrees, and the evaluation index data results are obtained as shown in Figure 12.

Figure 12(a) shows that when the guidance compliance degree is zero (when there is no disturbance in the neighbor weaving segments), the travel time in the neighbor weaving segments presents a staggered change of peak and normal peak with the increase of simulation time, and it has a wide range of fluctuations. With the increase of guidance compliance, the travel time decreases significantly. With the increase of guidance compliance, the traffic organization in weaving section is more and more orderly, and the travel time is also reduced. Compared with the guidance compliance degree of 0, when the guidance compliance degree is 100%, the travel time in peak period reaches the minimum at 9:00 a.m., which is 54.8 seconds lower than that when the guidance compliance degree is 0. In the normal peak period, the minimum travel time reduction is 10:00 a.m., 17.3 seconds, and the change is more balanced. From the perspective of travel time, this method can also improve the operation efficiency of the adjacent weaving section. As shown in Figure 12(b) that in different periods of the day, the traffic density of the neighbor weaving segments presents the trend of alternating flat peak and peak. In the same period, with the enhancement of disturbance intensity, the density gradually decreases and reaches the lowest value of 54 pcu/h.

The definition of the service level of the neighbor weaving segments is referred to the standard of road service level (JTG b01-2014). In Table 4, the level of service of the neighbor weaving segments is classified according to the traffic density on the road.

TABLE 4. The los standard of the weaving segment.

level of service	Traffic density, pcu / km/ Lane
Level 1	≤7.0
Level 2	7.0—18.0
Level 3	18.0—25.0
Level 4	25.0—40.0
Level 5	≥40.0

The stability of Los is reflected by analyzing the matching degree between the density in the neighbor weaving segments, and the level of service of the section. The probability distribution of the level of service in the neighbor weaving segments at different levels is obtained as shown in Figure 13.

As shown in Figure 13 that different induced compliance degrees have different effects on the self-organized criticality disturbance of the neighbor weaving segments. The original service level of the neighbor weaving segments is basically maintained in the fifth level, which is in the constraint state. With the increase of induced compliance, the service level gradually increased to the fourth level, even to the third level, and finally maintained at the third level and the fourth level. It can be seen that the higher the degree of induced compliance, the more orderly the self-organization in the neighbor weaving segments, and the lower the average traffic delay.

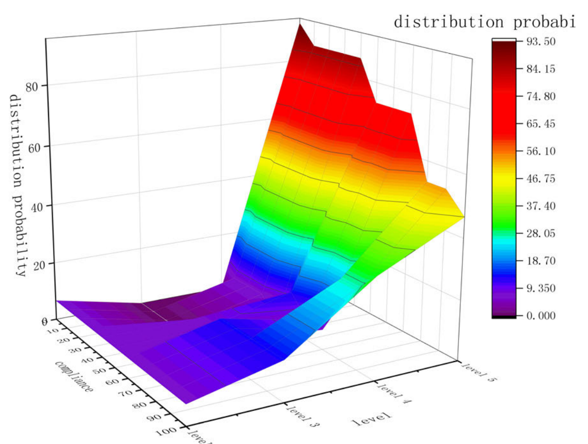


FIGURE 13. Comparison chart of probability distribution of service level.

3) SUMMARY OF SIMULATION EXPERIMENT

In this section, the average traffic delay is selected to evaluate the quality of traffic operation. The simulation results show that the optimization effect of disturbance induced by lane change in advance is obvious, and through the average traffic delay, the optimal disturbance mode is determined to be 60% of the length of the weaving segments. At this time, the average traffic delay is reduced by about 84%. With the increase of disturbance intensity, the lower the average traffic delay and the higher the operation efficiency. Compared with the current situation of the survey, this optimization method has better performance in terms of per capita delay, travel time, traffic density, etc., and can improve the overall operation efficiency of the neighbor weaving segments to a certain extent.

V. CONCLUSION

Based on the traffic characteristics of continuous weaving sections and Nash equilibrium theory, an optimization method of neighbor weaving segments organization based on equilibrium principle is proposed. By using VISSIM software, the paper simulates the vehicle operation condition of the weaving area before and after the optimization of the section near the Sigongli interchange in Nan'an District of Chongqing, and selects the average traffic delay to evaluate the traffic operation quality, and obtains the following conclusions:

(1) When the early lane change guidance distance is 60% of the length of the weaving segment, the average traffic delay of the neighbor weaving segments is the lowest. Four groups of representative data (5340 pcu / h, 3276 pcu / h, 4092 pcu / h, 4596 pcu / h) are selected for simulation. The optimization results show that the average traffic delay is reduced by 73%, 72%, 57%, 63% respectively.

(2) Based on the optimal early lane change guidance distance, different guidance compliance degrees are simulated. The results show that the higher the guidance compliance, the more orderly the self-organization in the adjacent weaving area, and the lower the average traffic delay.

(3) It provides a new idea for the traffic organization optimization of the neighbor weaving segments. Through the simulation experiment, the feasibility and effectiveness of the organization optimization method are verified, which provides a theoretical basis for the optimization of traffic signs and markings.

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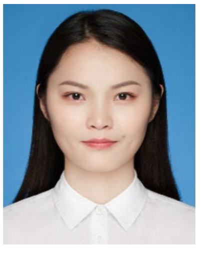

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