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Modeling of Tidal Lane Macroscopic Traffic Flow Based on Variable Cell Transfer Model

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Abstract **– The effective measure to alleviate urban tidal traffic problems is to set up tidal lanes. However, most of the tidal lanes are currently set up in a simple form by moving the isolation barriers and manual command. In view of the current situation that the setting of tidal lanes is single and lack of theoretical basis, this paper first proposes the control strategy of dividing sections and opening tidal lanes dynamically. Then, based on the variable cell transmission model, the macroscopic traffic flow model of the tidal lane is established, and the variation of the density and velocity of the traffic flow during the change process is analyzed through the established theoretical model. Finally, the simulation results show that the model can effectively describe the change law of tidal traffic flow, and the vehicle delay before and after the tidal lane is reduced by 23.49%, the model meets the engineering practice requirements.**

Keywords **– Variable Cell Transmission Model, Tidal Lane, Dynamic Control, Macroscopic Traffic Flow Model.**

I. INTRODUCTION

Compared Tidal traffic refers to the serious asymmetry of the two-way traffic flow in the road section, resulting in the misalignment of space resources supply and demand and the drastic decline of traffic efficiency [1]. At present, 20%-40% of roads in large and medium-sized cities in China show such a state [2], and the traffic congestion caused by this severely restricts the efficiency of road network operation. At present, in order to better cope with the traffic congestion pressure caused by the imbalance of two-way traffic flow, setting up the tidal lane is a good solution [3]. However, as the traffic pressure continues to increase, the efficiency of its improvement is gradually declining. As the current setting of the tidal lanes is dominated by manual and fixed-time command and control, with less intelligent and dynamic decision support, it is unable to actively adapt to the current fragile traffic situation. Therefore, this paper proposes a control strategy for dynamic segmentation of tidal lanes.

In order to realize the dynamic segmentation control of variable lanes, it is first necessary to clarify the evolution mechanism of traffic flow state during the process of tidal lane segmentation. The research on the evolution mechanism of traffic flow state mainly relies on the traffic flow state evolution model and dynamic simulation [4]. The cell transfer model (CTM) proposed by Daganzo [5-7] is the most widely used. Later, Hu Xiaojian [8] et al. of Southeast University introduced the parameters of traffic flow density and cell length of cell into CTM model to establish variable element. Cell Transfer Model (VCTM). However, the above two models can not accurately describe the aforementioned dynamic driving strategy of tidal lanes. Therefore, this paper introduces the concept of equivalent lane number, and establishes a macroscopic traffic flow model based on variable cellular transmission model to open tidal lanes, revealing speed and density. The variation law of other parameters has important theoretical guiding significance for realizing dynamic intelligent control of tidal lanes.

II. CELL TRANSFER MODEL (CTM)

The cell transfer model is a discretization approximation of the macrodynamic model LWR [9]. As shown in Fig. 1, the core idea of the CTM model is to divide the entire road segment into n equidistant segments (cells).

The traffic flow in each cell is the same, and the length of each segment is the distance traveled by the vehicle in a unit step δ under free-flow conditions [10].

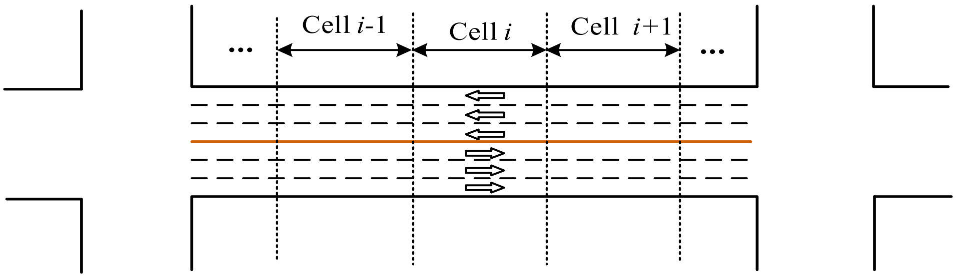

Fig. 1. CTM road section.

$$q = \min\left\{\rho v_{\text{free}}, q_{\max}, \omega(\rho_{\text{jam}} - \rho)\right\}, 0 \le \rho \le \rho_{\text{jam}} \quad (1)$$

Where v_{free} is the free flow velocity; q_{max} is the maximum traffic flow; ω is the reverse propagation velocity of the traffic wave when the traffic is crowded; ρ_{jam} is the blocking density.

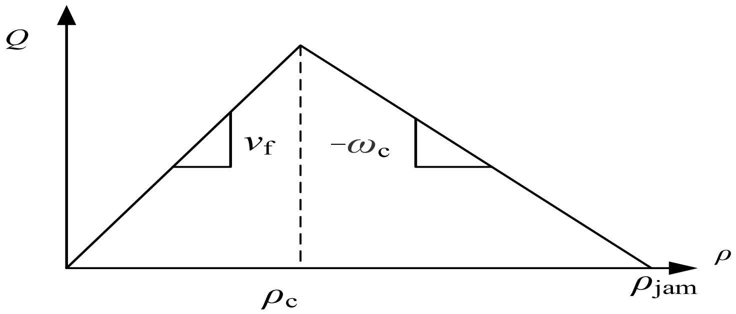

Fig. 2. Density-flow ideal relationship diagram.

As shown in Fig.2, the density-flow relationship diagram assumes that the traffic on the road runs stably at a free-flow speed before the density reaches the critical density ρ_c; when the density reaches the critical value ρ_c, the flow at the maximum reaches the road segment. It is the capacity of the road section; as the density continues to increase, when the maximum value ρ_{jam} is reached, traffic jams occur on the road, and the traffic volume drops to zero. In this process, the traffic flow congestion wave is reversely propagated at a constant value ω_c. In practical applications, the parameters need to be calibrated according to the measured data of the road.

A. *The basic Road Segment Model of the Cell*

Fig. 3 shows a schematic diagram of the basic road segment model of the cell. In the basic road segment model, the two cells are simply handed over without any confluence and shunt ramps. Let cell *i*-1 be the upstream cell of cell *i*, that is, downstream of cell *i* cell *i*-1.

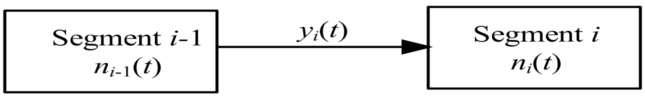

Fig. 3. Basic road segment model of the cell.

The general form of the cellular transmission model is:

$$y_i(t) = q_i(t)\delta = \min\left\{\begin{array}{l} \rho_{i-1}(t) v_{\text{free}}\delta, \\ q_{i,\max}(t)\delta, \\ \omega\left[\rho_{\text{jam}} - \rho_i(t)\right]\delta \end{array}\right\} \quad (2)$$

Where: $y_i(t)$is the inflow of cell i in the t~t+1 period; q_i(t) is the inflow rate of cell i in the t~t+1 period; ρ_i(t) is the cell in period t the vehicle flow density; $q_{i,\max}$(t) is the maximum inflow rate of the cell i in the t~t+1 period; δ is the simulation step size;

According to the relationship between the number of vehicles on the cell and the density:

$$n_i\ (t) = \rho_i\ (t)\ v_{\text{free}}\delta \tag{3}$$

Where: ni(t) is the number of vehicles on cell i in the t~t+1 period; Bring (3) the above formula into (2):

$$y_i(t) = \min\begin{Bmatrix} n_{i-1}(t), \\ Q_i(t), \\ \omega[N_i(t) - n_i(t)] / v_{\text{free}} \end{Bmatrix} \tag{4}$$

Where: $Q_i(t)$ is the maximum inflow on cell i in the t-t+1 period; N_i(t) is the traffic propagation relationship between the neighboring cells with the maximum carrying capacity on cell i in the t~t+1 period:

$$n_i\ (t+1) = n_i\ (t) + y_i\ (t) - y_{i+1}\ (t) \tag{5}$$

III. Variable Cell Transmission Model (VCTM Model)

Although the cell transmission model has good simulation effects on unsaturated traffic flow, saturated traffic flow and supersaturated traffic flow, for urban roads, the road network environment is more complicated than the highway, and the intersection between the intersections, the length of the road is different, and the traffic flow of each road is different. Therefore, the cell transmission model needs to be improved to establish a variable cell transmission model suitable for different road conditions[11].

As shown in Fig. 4 below: The variable cell transmission model establishes cells of different lengths according to the length of different segments. The improved cell transmission model uses the traffic flow density ρi as the state transfer variable instead of the state transfer variable yi in the original model. The established model cell length can be changed at will, but the vehicle must be in a free flow speed in a simulation step. Can pass within the long.

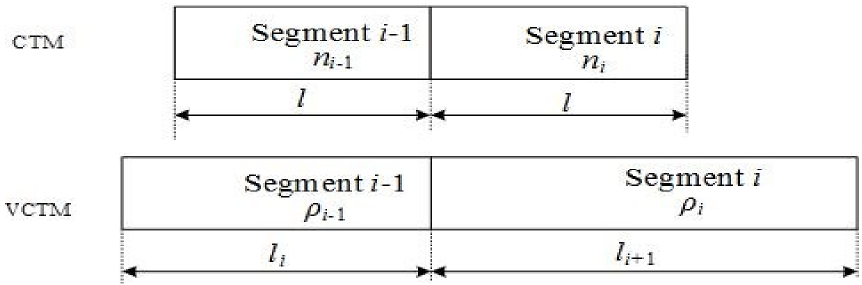

Fig. 4. Cellular transfer model before and after improvement.

The improved cell transfer model satisfies the following equation:

Cell i outflow rate:

$$q_i\ (t) = \rho_i\ (t)\ v_i\ (t)\ \lambda_i \tag{6}$$

Where: λ_i is the number of lanes; Number of vehicles in cell i:

$$n_i\ (t+1) = \rho_i\ (t)\ l_i\ (t)\ \lambda_i \tag{7}$$

Where: l_i is the length of the section of the cell I; Density of cell i:

$$\rho_i(t+1)=\rho_i(t)+\frac{\delta}{l_i\lambda_i}\times\left(q_{i-1}(t)-q_i(t)\right) \tag{8}$$

The speed of the cell i:

$$v_i(t)=\min\left\{v_{\mathrm{sl}}\frac{\rho_c(\rho_{\mathrm{jam}}-\rho_i(t))}{\rho_i(t)(\rho_{\mathrm{jam}}-\rho_c)},v_{\mathrm{sl}}\right\} \tag{9}$$

Where: v_{sl} is the speed limit value of the road segment; ρ_c is the critical density; ρ_{jam} is the blocking density.

IV. Set the Macro Traffic Flow Model of the Tidal Driveway

Setting up a tidal driveway is an effective measure to solve the urban tidal traffic phenomenon. By setting up tidal lanes, you can make full use of the existing road resources to alleviate the traffic congestion caused by the imbalance of two-way traffic flow. However, the current setting of tidal lanes is mostly through the gantry, which is opened every day for a fixed period of time. Relationship, which makes it impossible to cope with sudden and variable traffic conditions. Therefore, this paper deeply studies the change law of traffic flow before and after opening variable lanes, and establishes a traffic flow model for setting up tidal lanes based on the cell transmission model. This model is used to describe the process of traffic flow velocity and density change during the increase and decrease of the lane after the tidal lane is opened, and the state evolution law is revealed, which lays a foundation for the subsequent study of the dynamic control process of the variable lane.

A. *The Opening Process of the Tidal Driveway*

In this paper, the road section that needs to set up the tidal lane is taken as the research object. Firstly, the section of the road segment is divided into 1, 2, ... i by the idea of the cell transmission model, and the direction of the traffic of the tidal lane needs to be determined according to the equilibrium coefficient of the traffic flow branch. A control strategy for each cell segmentation is implemented for the tidal lane. In this process, the process of changing the lane lane properties is as follows:

The first step: closing the initial cell, prohibiting the vehicle from entering the initial cell 1, and waiting for the first lane to be

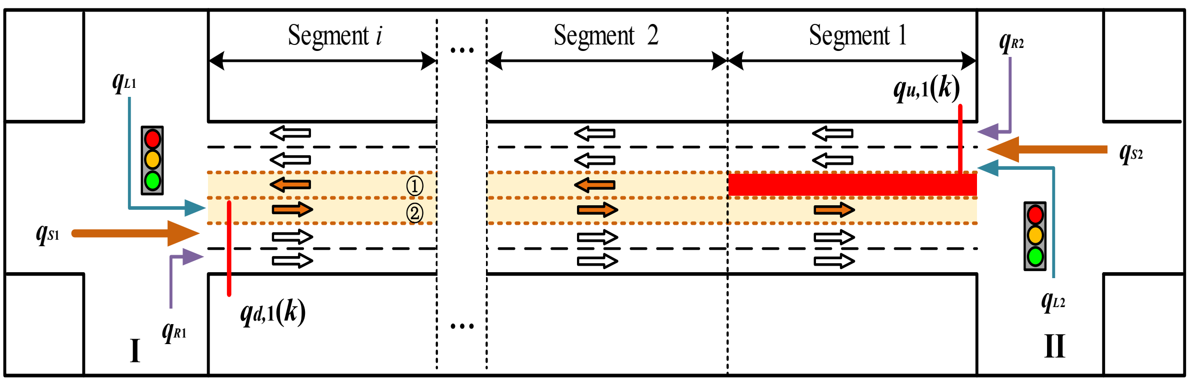

Fig. 5. Opens the first tidal lane.

The second step: closing the cell 2, while allowing the opposite vehicle to enter the cell 1, the cell 1 completes the opening of the tidal lane.

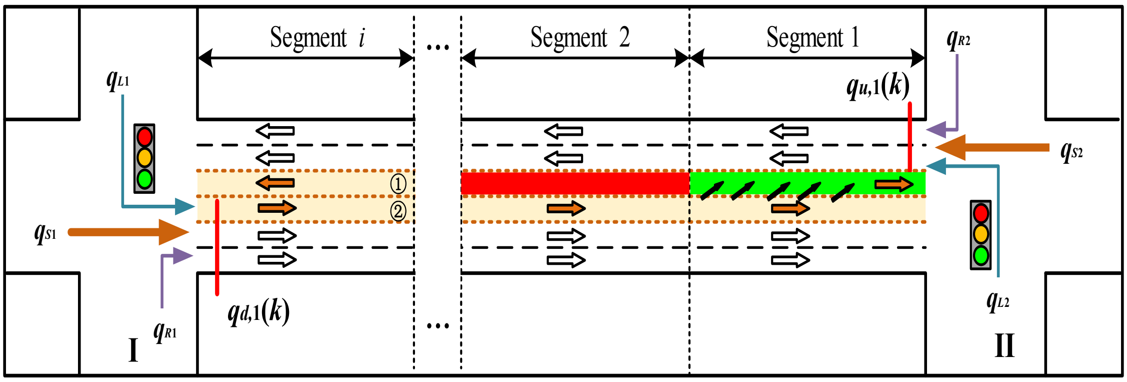

Fig. 6. Opens the second tidal lane.

Step i+1: After waiting for the last segment of cell i to open the tidal lane, the entire section completes the opening of the tidal lane.

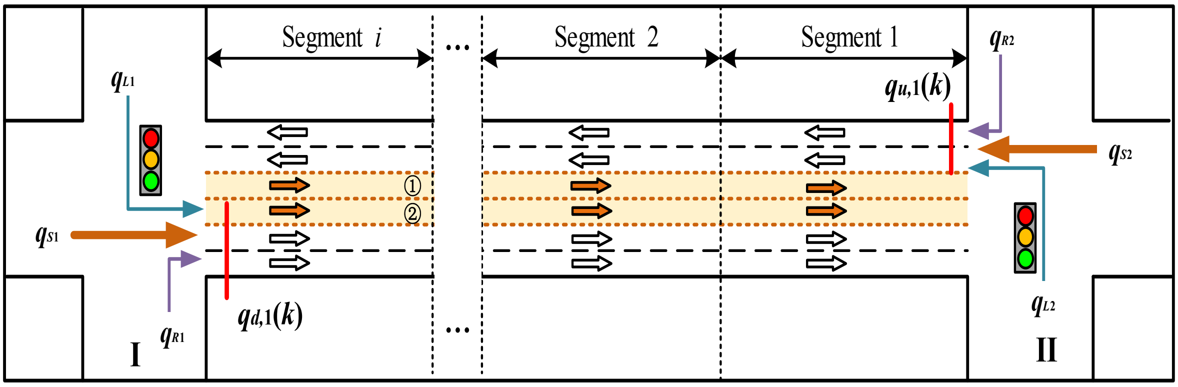

Fig. 7. Opens the last tidal lane.

B. *Model Establishment:*

In the control process as described above, when the tidal lane is closed, the traveling vehicle will gradually drive away, and Di(t) is used to indicate the length of the tidal lane that has been emptied:

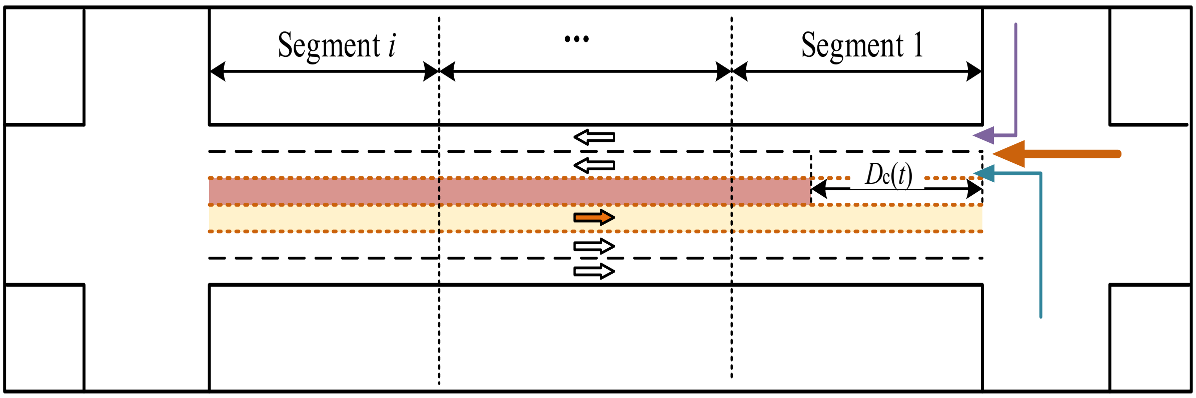

Fig. 8. The length of the road segment is cleared.

Therefore, assuming that the speed of the vehicle in the closed lane is equal to the average speed of all vehicles in the road segment, $D_c(t)$ is calculated by:

$$D_c(t+1) = D_c(t) + \delta \times v_i(t) \qquad D_c(t_0) = 0,\ t \geq t_0, \tag{10}$$

Where: $v_i(t)$ is the speed of the section where the partial lane is closed during the tth time interval;

It should be pointed out that the instantaneous change of the number of lanes will violate the conservation principle of the general density formula. In this process, since the lane is dynamically closed, the concept of the number of equivalent lanes (λ') is proposed to describe the change of lane traffic capacity with time, $\lambda'_i(t)\in[\lambda, \lambda+\Delta\lambda]$, λ represents the number of fixed lanes, and $\Delta\lambda$ represents the number of variable lanes. Therefore, taking the first cell as an example, the number of equivalent lanes on the road segment that opens the reverse variable lane can be described by:

$$\lambda_1^{'}(t+1)=\begin{cases}\lambda+\dfrac{\Delta\lambda\times D_c(t+1)}{l_1} & D_c(t+1)<l_1\\ \lambda+\Delta\lambda & D_c(t+1)>l_1\end{cases} \tag{11}$$

Simplify the above formula:

$$\lambda_1^{'}(t+1)=\max\left(\lambda,\lambda+\frac{\Delta\lambda\times D_c(t+1)}{\Delta l}\right) \tag{12}$$

The general formula that extends to other cells is expressed as follows:

$$\lambda_i^{'}(k+1)=\min\left(\begin{matrix}\lambda+\Delta\lambda,\\ \max\left(\begin{matrix}\lambda,\\ \lambda+\dfrac{\Delta\lambda\times(D_c(k+1)-\sum_{n=1}^{n=i-1}l_n}{l_i}\end{matrix}\right)\end{matrix}\right) \tag{13}$$

The expression indicates the length of the lane that has been cleared on the corresponding road segment i. It is only applicable to the case where the lane is partially empty and the other part still has a car; if the lane is completely cleared, the number of equivalent lanes is equal to λ, and if the lane is occupied, Then the number of equivalent lanes is equal to λ'. According to the change formula of the number of lanes, the road capacity can be obtained, and the density formula is derived as follows: the first part of equation (14) is multiplied by $(\lambda'_i(t)/\lambda'_i(t+1))$, the second part considers the number of lanes changes, expressed as follows:

$$\rho_i(t+1)=\frac{\lambda_i^{'}(t)}{\lambda_i^{'}(t+1)}\rho_i(t)+\frac{\delta}{l_i\lambda_i^{'}(t)}\times\left(q_{i-1}(t)-q_i(t)\right) \tag{14}$$

The speed formula does not depend on changes in the number of lanes, but only on traffic flow and capacity. Therefore, formulas (6), (7), (9), (13), and (14) together constitute a macroscopic traffic flow model for tidal lanes.

C. *Evaluation Indicators*

In this paper, the delay of the link is selected as the evaluation index. The delay is defined as the additional transit time that is added to the upstream cell without entering the downstream cell within a simulation step. The specific calculation formula is as follows:

$$d_i=\delta\times\sum_{t=1}(n_i(t)-q_{i+1}(t)\times\delta) \tag{15}$$

V. Simulation Evaluation

A. *Simulation Analysis*

In order to verify the validity of the model, this paper constructs a section of urban road as the research object to simulate the model. The structure of the road segment is shown in the following figure. The length of the simulated road section is 2.5km, two lanes of six lanes, $\lambda = 2$, $\Delta\lambda = 1$. There is no interference between the entrance and exit ramps in the middle of the road section, and bottleneck control is performed on the cell 6 to induce traffic congestion.

Fig. 9. Road structure diagram.

Firstly, using MATLAB to simulate the model proposed in this paper, the simulation parameters are set as follows: The simulation program divides the road segment into 6 cells, in which the first and last virtual cells are input cells and receiving cells respectively, and the input cells are infinitely large. The capacity of the receiving cell is infinite, and the length of each cell is shown in the following table:

Table 1. Cell length.

Segment	1	2	3	4	5	6
length /m	430	387	344	387	516	436

The simulation time is 3600s, the simulation time step is 20s, the free-flow speed is 54km/h, the back-propagation speed of traffic waves is 32.4 km/h when congestion occurs, and the saturated flow rate of cars is 1800 vehicles/h. Run the simulation program and output the simulation results as shown below:

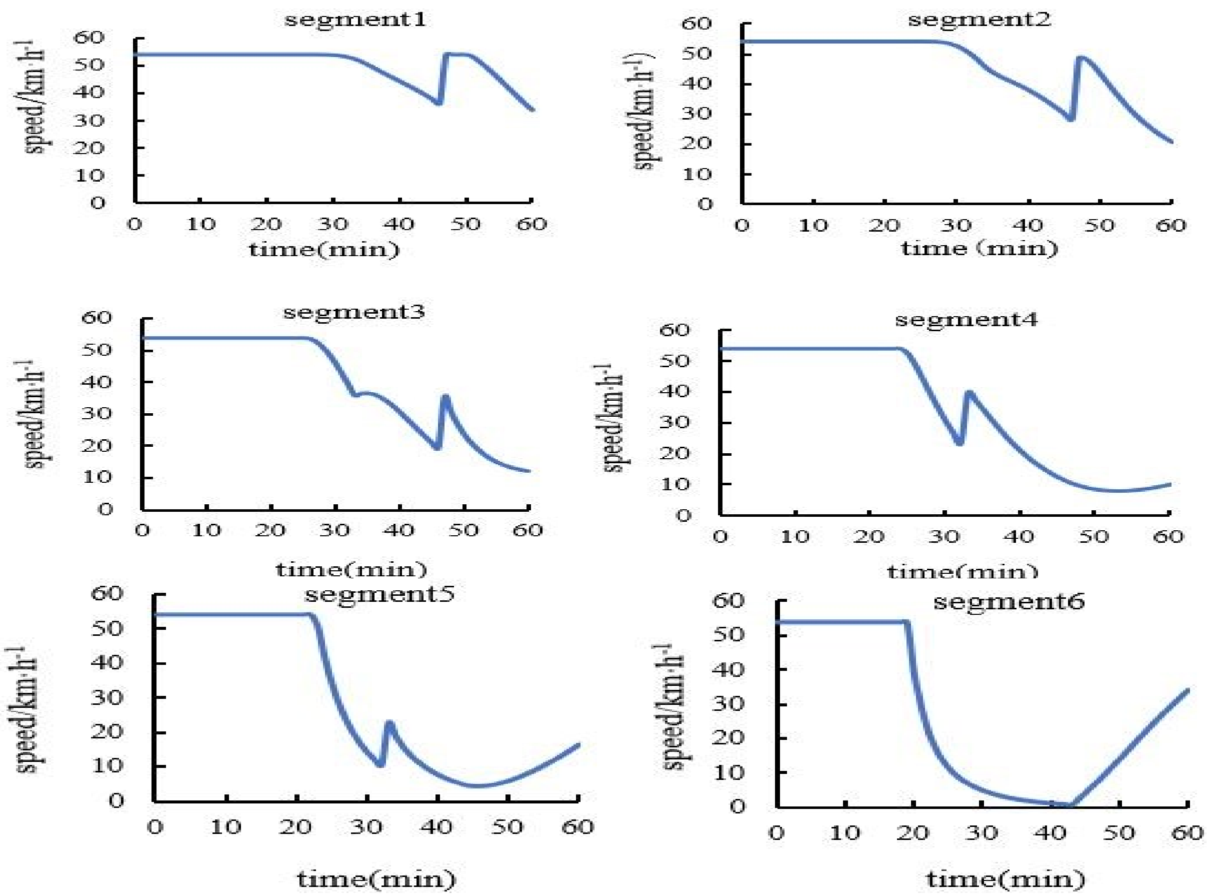

Fig. 10. Speed change law.

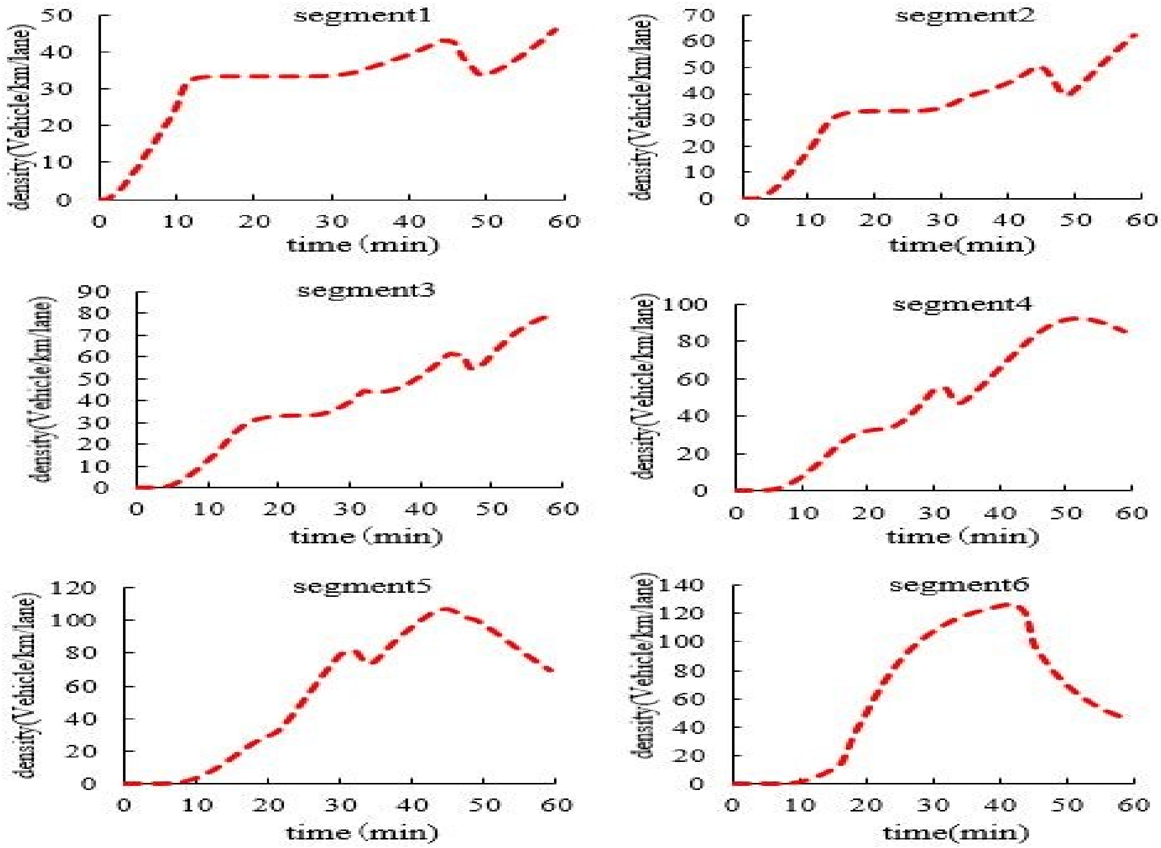

Fig. 11. Density change law.

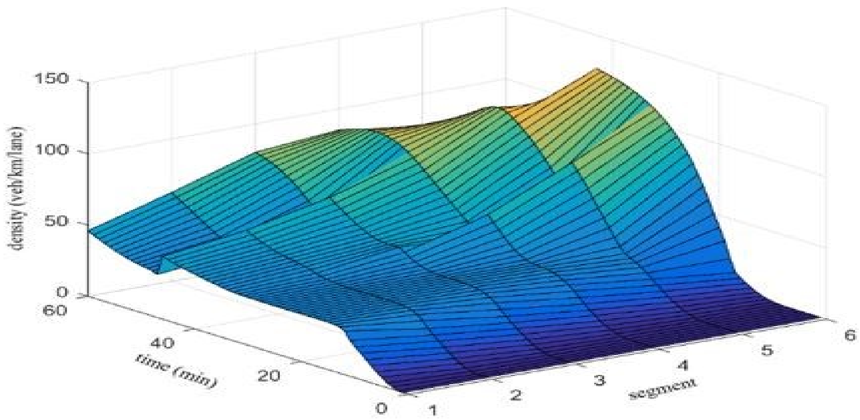

Fig. 12. Three-dimensional density map of the cell.

Based on a comprehensive analysis of the above figure, the model can accurately describe the road traffic congestion and the process of gradually dissipating the congestion after the tide is started. When the simulation is carried out for 20 minutes, the road section gradually increases due to the increasing density of traffic volume, and the density reaches the maximum at 30 minutes. At this time, the road flow rate and speed are close to zero, and the congestion gradually propagates upstream. With the opening of the tidal lane, the density begins to decrease, the congestion gradually dissipates, and the operational status of the road traffic flow reaches normal.

B. *Simulation Evaluation*

In order to verify the validity of the model, this paper compares and analyzes the evaluation indicators of the average delay for the two conditions of the tidal lane (solution 1) and the traditional tidal lane opening method (solution 2). The evaluation results are shown in the following table.:

Table 2. Average delay comparison.

segment	1	2	3	4	5	6	average value
Option 1 average delay /s	23.47	24.69	26.36	27.56	31.78	34.12	28
Option 2 average delay /s	18.52	19.69	20.36	20.18	23.41	24.78	20.32
Benefit improvement	21.09%	20.25%	22.76%	26.78%	26.34%	27.37%	23.49%

The comparison of the delay results is shown in the above table. It can be seen from the table that the dynamic tidal lane can effectively reduce the average delay and improve the traffic efficiency of the tidal lane. Moreover, the efficiency improvement is more obvious in areas with severe congestion.

VI. Conclusion

This paper breaks through the traditional tidal lane control method, and innovatively proposes a dynamic control strategy for segmentation and segmentation of tidal lanes. The concept of equivalent lane number is proposed, and a dynamic tidal wave is established based on the improved cellular transmission model. The macroscopic traffic flow model of the lane describes the variation of density and velocity during the process of changing the traffic flow before and after the tidal lane. Finally, the model is programmed with MATLAB software. The output simulation results show that the dynamic opening of the tidal lane can fully exploit the potential road resources, enhance the function of the tidal lane, and alleviate the traffic pressure brought by the tidal traffic facing the city.

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