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Exploring Traffic Congestion on Urban Expressways Considering Drivers' Unreasonable Behavior at Merge/Diverge Sections

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Abstract: Mechanism of traffic congestion generation is more than complicated, due to complex geometric road design and complicated driving behavior at urban expressway in China. We employ Cell transmission model (CTM) to simulate traffic flow spatiotemporal evolution process along the expressway, and reveal the characteristics of traffic congestion occurrence and propagation. Here we apply the variable-length-cell CTM to adapt the complicated road geometry and configuration, and propose the merge section CTM considering drivers' mandatory lane-changing and other unreasonable behavior at on-ramp merge section, and propose the diverge section CTM considering queue length end extending expressway mainline to generate dynamic bottleneck at diverge section. In the new improved CTM model, we introduce merge ratio and diverge ratio to describe the effect of driver behavior at merge and diverge section. We conduct simulation on the real urban expressway in China, results show that merge section and diverge section are the original location of expressway traffic congestion generation, on/off-ramp traffic flow has great effect on expressway mainline operation. When on-ramp traffic volume increases by 40%, merge section delay increases by 35%. And when off-ramp capacity increases by 100 veh/hr, diverge section delay decreases about by 10%, which proves the strong interaction between expressway and adjacent road networks . Our results provide the underlying insights of traffic congestion mechanism in urban expressway in China, which can be used to better understand and manage this issue.

Keywords: Urban expressway; Cell transmission model; Mandatory merge; Merge section; Diverge section

1. Introduction

To alleviate traffic congestion, expressways were built in many Chinese cities, including Beijing, Shanghai, Guangzhou, and Tianjin. Compared with arterial roadway, expressway can provide continuous and rapid movement by grade separation and fully enclosed routes. Due to its key role in the whole road network, expressway traffic congestion has attracted the broad concern of travelers and traffic managers. According to the 2017 annual traffic analysis report of China's major cities, the traffic congestion index of averaged road in Beijing was 1.95 in rush hour, while the expressway reached 2.5. In Jinan, the traffic congestion index of averaged road was 1.95 during rush hour, while the expressway reached 3.0. In order to scientifically formulate an urban expressway

traffic congestion management plan, it is important to deeply reveal and accurately simulate the generation, propagation mechanism of traffic congestion.

Generally, the main features of Chinese urban expressway include:

- Short distance between on/off-ramps, resulting in numerous merging and weaving sections along the expressway mainline. According to the 2017 annual traffic analysis report of China's major cities [1], the average distance between the on/off-ramps of expressways are 850 m, 850 m, and 890m in Beijing, Xiamen, and Dalian, respectively.
- Drivers do not strictly follow the "mainline priority" in the merge/weave sections along the urban expressway. Vehicles from on-ramp often enter expressway after mandatory lane changing, forcing vehicles on mainline to decelerate intensely to avoid collision.
- Strong interaction between expressways and its adjacent road network. On-ramps and off-ramps are directly connected with road network. Due to the short ramp length, traffic flow disturbance and congestion that occurs in the local road network may quickly spread to the expressway mainline, and vice versa.
- Large traffic volume on the expressway. Although the expressway mileage reached about 9.0% of the whole road network in Beijing, the ratio of traffic volume transported by expressway reached about 34.3%.
- Traffic congestion on expressway usually occurs in merge and weaving areas. Unreasonable lane changing behavior, forced changing lane and unreasonable deceleration behavior are the fundamental reasons for traffic congestion on expressways [2,3].

Over the past decades, considerable research have been conducted on expressway congestion issue, which includes traffic flow model, traffic flow simulation and traffic congestion detection. These fruitful research construct the foundation of freeway congestion mechanism analysis. However, these fruits fail to simulate traffic operation on Chinese urban expressway precisely, without considering the particular driving behavior in China.

1) Traffic congestion detection

Traditional traffic detection technologies include video detection and inductive loop detection. In recent years, new detection technologies appeared continuously. Nantes A. et al[4]collected expressway traffic data using Bluetooth device installed in the vehicle and proposed a new traffic state prediction model. Dongre et al[5] used vehicle to vehicle (V2V) and vehicle to infrastructure (V2I) communication to provide traffic information for drivers and traffic control system. Yuan et al [6] proposed an expressway traffic congestion detection and control strategy based on VANET and conducted simulation using TRANSMODELER. Néstor et al [7] started from the idea of big data analysis, and proposed a road network traffic state detection method which combined in-vehicle information with roadside facilities data.

2) Expressway traffic flow model and simulation

Traffic flow model is the basis of traffic congestion mechanism analysis and traffic flow simulation. At present, there are two types of traffic flow model, the macroscopic model and the microscopic model.

- Macroscopic traffic flow model

The earliest macroscopic traffic flow theory is LWR model proposed by Lighthill, Whitham, and Richards, in which traffic flow was regarded as continuous and compressible fluid. Then, several other macroscopic models such as the hydrodynamic and kinematic model were proposed successively [8]. Chen et al. [9] researched on the expressway bottleneck, and proposed a traffic flow collapse probability model based on the distribution of the time headway and space headway, which revealed the inherent complexity and stochastic evolution mechanism of expressway traffic

flow. Scholars et al [10]c onducted simulation on urban roads using cell transmission model (CTM), and revealed traffic congestion evolution mechanism in the road network. The results showed that CTM could accurately predict the occurrence time and spreading range of traffic congestion. Yuan et al [11] combined the Kalman filter and LWR model to estimate the traffic state. Wei et al[12]proposed a large-capacity CTM and applied it to optimize the aviation routes. Shi et al[13]tested hysteresis loops of road detectors using macroscopic fundamental diagram, the results will provide a theoretical basis for predicting traffic state. Yan et al[14]used the non-oscillating center format algorithm to solve the LWR model on non-uniform roads. Yang et al[15]established an improved CTM based on the hysteresis phenomenon and discussed the effect of irregular road geometric features on expressway traffic flow transmission.

- Microscopic traffic flow model

The microscopic traffic model takes the single vehicle as the research object, analyzes the traffic flow characteristics. At present, the main microscopic models include car-following model, lane change model, and cellular automata model. Sun et al[16]researched on road bottlenecks and simulated on-ramp traffic flow based on the car-following theory. Chen and Laval[17]researched on the single bottleneck and proposed a new car-following model based on the stop and go wave data, which revealed the effect of driver behavior on traffic oscillations. Mei et al[18]simulated on-ramp lane-changing behavior, and found that it would take less time to generate congestion on expressways when on-ramp traffic volume increased. Cellular Automaton (CA) is another microscopic traffic model, proposed by Von Neumann in 1940s. Cellular Automaton can simulate the evolution of traffic flow in the discrete time. Some researcher applied CA to analyze traffic congestion formation at merge section.

To sum up, the macroscopic model focuses on traffic flow integrity and dynamic behavior. As a result, macroscopic model has deficiency that it fails to accurately describe the actual traffic flow for some traffic phenomena. For example, it can't simulate the effect of microscopic behavior such as mandatory merges and car-following on traffic congestion. On the other side, although microscopic model can capture drivers' microscopic behavior, it has shortcoming. In the real world, each individual has entirely different driving behavior, therefore, it's almost impossible to construct one model to simulate all different drivers' behavior under different conditions, in addition, calibrating the microscopic model is extremely time-consuming and laborious. So, such a kind of model is needed, which could describe the traffic flow state while considering the drivers' behavior.

The main goal of this research is to reveal the mechanism, and simulate the evolution process of traffic congestion on urban expressway in China. Firstly, Cell Transmission Model (CTM) can simulate the evolution process of traffic flow in spatiotemporal dimension, and adapt to dynamic modeling for traffic flow. Secondly, CTM has obvious superiority in the oversaturated traffic simulation[19]. In addition, accuracy of CTM analysis can meet the requirement of traffic flow analysis and traffic management evaluation. To this end, CTM was selected as the analyzing tool.

Considering the particular features listed above on Chinese urban expressway, CTM is improved in this paper. First, "variable length" cell model was selected to treat expressways complicated geometry and configuration. Then, merge and diverge section CTM modelswere proposed, which can consider the effect of driving behavior such as forced merges and queue spill-out from adjacent road networks. Accordingly, the formula of cellular flow transmission was

deduced, and a new improved CTM was established. In the case study, one elevated expressway in Changsha China was selected, traffic flow was modeled and simulated by using the improved CTMs . Based on the simulation results, the paper revealed the effect of on-ramp traffic flow input on mainline traffic congestion the interaction between the adjacent local street capacity and the expressway diverge section congestion. The research result will provide a theoretical basis for real-time traffic congestion prediction, traffic management control, and traffic guidance on urban expressway.

2. Methodology

2.1. Basic Idea

CTM was originally put forward by Daganzo in 1993[20], then widely used to study the evolution of dynamic traffic flow in the road network[21], its core idea is to divide the road into multiple cells of equal length, and to describe the traffic flow propagation by using the transmission process of vehicle numbers between adjacent cells. Due to the discrete time and space of the CTM model and its simple structure, it is widely used in the process of traffic flow simulation research. However, the traditional CTM has obvious shortcomings when applied to simulate traffic operation on urban expressway in China, which include:

Firstly, the traditional CTM assumes that all the cells have the same length. Because the geometric features of actual urban expressways are complex, and simulated roads may not be exact integer multiples of the uniform cell length, the traditional CTM cannot accurately describe urban roads. To solve this problem, we introduced variable-length-cell in the simulation.

  Secondly, the traditional CTM strictly follows the "mainline priority" operating rule, while there are many common practical phenomena that do not match the rules such as "mandatory merge", unreasonable lane-changing and other unreasonable driving behavior   on Chinese expressway.

Last but not least, the traditional CTM assumes that the terminal cell capacity is infinite, while the expressway off-ramps connectwith local road, off-ramp queue length often extends expressway mainline upstream due to the unmatched capacity of local street.

To this end, considering the situations above, this paper improved the CTM from the following aspects:

- Cell length parameters were introduced to CTM to accurately describe the complex and variable geometric shapes of the expressway.
- The merge section is divided into three cells: the upstream mainline cell, on-ramp cell, and downstream mainline cell. On domestic roads, there is no clear rule that drivers must obey the "mainline vehicle priority," so forced merges and crossing multi-lane merges are general phenomena, which have a great effect on the expressway mainline. Therefore, the merge ratio was introduced to improve the traditional CTM, in which the "forced merge" behavior can be considered in the merge area.
- The diverge section is divided into three cells: the upstream mainline cell, off-ramp cell, and downstream mainline cell. On Chinese expressway, congestion often occurred in expressway diverge section site. Due to the local street remained capacity is limited, off-ramp queue often extend mainline rapidly to congest expressway. In order to describe such traffic operation features, we introduced the capacity parameters for the off-ramp. Compared with the traditional CTM, capacity of the off-ramp cell is no longer infinite; instead, when the off-ramp traffic volume is larger than capacity of the local street, congestion will generate on the off-ramp and spread to the mainline.
- In addition, this study makes the following assumptions:

- There is at most one on-ramp or off-ramp in a single cell.
- There is a single cell including an on-ramp (off-ramp) in the start (end) position of the cell series.
- The basic road section is formed by a single cell without an on-ramp (off-ramp).
- There is same number of traffic lanes in a single cell.

2.2. Improved CTM

The CTM assumes that the volume-density relationship follows the trapezoidal fundamental diagram, illustrated in Figure 1. In the case of low density, free flow velocity is a constant *vf*. In the case of heavy density or traffic congestion, the shock wave speed is also a constant ω and generally satisfies *vf* >ω. The traffic flow transmission relation is shown as equation (1):

$$q = \{v_f k, Q_{max}, \omega(k_{jam} - k)\} \tag{1}$$

Here, q is traffic volume; k is traffic flow density; Q_{max} is the capacity of the road section, namely, the maximum traffic flow rate of the road section; k_{jam} is the congestion density; v_f is the free flow speed; ω is the shock wave speed when congestion occurs; k_A and k_B are the corresponding minimum and maximum density when the traffic volume is maximum in the trapezoidal fundamental diagram .
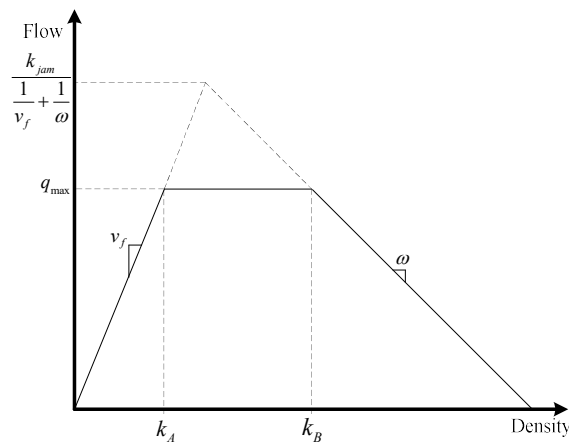

Figure 1. Trapezoidal fundamental diagram

Cell length parameter l_i is introduced in the basic CTM, as shown in Figure 2, L_c is the standardized cell length of traditional CTM,. The length of cells can be inequality in the improved CTM, and must be greater than L_c that the vehicle travels at the free flow speed within unit time. Clearly, we can set L_c according to the simulating time step length.
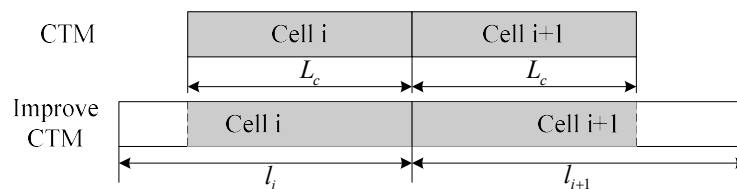

Figure 2. Configuration of the Traditional and Improved CTM

According to the traffic flow transmission relationship among cells in improved CTM, within the unit time step σ, the number of vehicles leaving cell *i* is only related to the length L_c in the latter

shade part in Figure 1. Similarly, the number of vehicles received by downstream cell *i*+1 only includes the number of vehicles within L_c in cell *i*. Therefore, the actual transmission number that flows into cell *i* at time *t* is related to l_i and L_c, as shown in Equation (2)

$$y_{i+1}(t) = \min\{\frac{L_c}{l_i}n_i(t), Q_{i+1}(t), \frac{L_c\omega}{l_{i+1}v_f}[N_{i+1}(t) - n_{i+1}(t)]\} \qquad (2)$$

Here, $n_i(t)$ is the quantity of vehicles in cell *i* at time *t*; $y_i(t)$ is the actual transmission quantity of cell *i* to cell *i*+1; $N_i(t)$ is the max quantity of vehicles in cell *i* at time *t*; $Q_i(t)$ is the max actual transmission quantity cell *i* at time *t*; ω is the shock wave speed; v_f is the free flow speed.

The CTM of the expressway mainly includes three types of cell models: basic segment, merge section, diverge section, as shown in Figure 3.
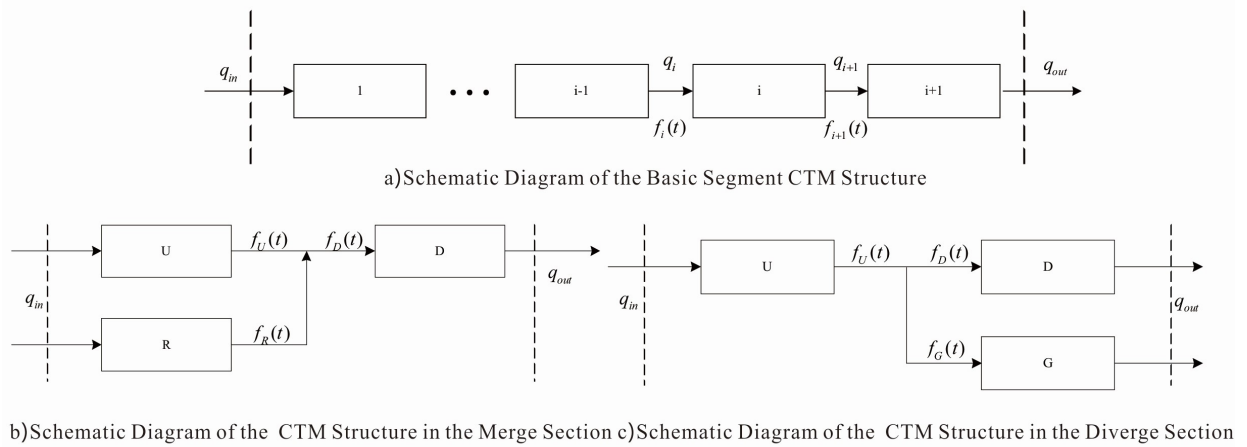

a) Schematic Diagram of the Basic Segment CTM Structure

b) Schematic Diagram of the CTM Structure in the Merge Section c) Schematic Diagram of the CTM Structure in the Diverge Section

Figure 3. Schematic configuration of CTM

2.2.1. Basic road segment cell model

From Figure 3 a), according to the continuous conservation principle of inter-cellular traffic flow in LWR theory, we discretize its time and space, and establish the cell transmission model for the basic road section, as follow:

$$n_i(t) = n_i(t-1) + y_{i-1}(t-1) - y_i(t-1) \qquad (3)$$

$$y_i(t) = \min\{n_{i-1}(t), Q_i(t), \omega/v_f[N_i(t) - n_i(t)]\} \qquad (4)$$

2.2.2. Merge section cell model

Figure 3 b) illustrates the schematic configuration of merge section on the expressway. Merge section contains three cell parts: cell U is expressway mainline upstream, cell R is on-ramp, and cell D is expressway mainline downstream. Within t time interval, traffic flow output of cell U is $f_U(t)$, the receiving flow is $A_U(t)$, the sending flow is $S_U(t)$; while traffic flow output of cell R is $f_R(t)$, the receiving flow is $A_R(t)$, the sending flow is $S_R(t)$; and traffic flow of cell D is $f_D(t)$, the receiving flow is $A_D(t)$, and the sending flow is $S_D(t)$. According to the definition of cell receiving flow and sending flow, the merge area meets the following restrictions:

$$\begin{cases} f_U(t) \le S_U(t) \\ f_R(t) \le S_R(t) \\ f_D(t) = f_U(t) + f_R(t) \le A_D(t) \end{cases} \tag{5}$$

Considering whether the receiving flow of downstream cell D is sufficient or not, there are two cases for merge cell model.

Case 1: When $A_D(t) \ge S_U(t) + S_R(t)$

$$\begin{cases} f_U(t) = S_U(t) \\ f_R(t) = S_R(t) \\ f_D(t) = f_U(t) + f_R(t) \end{cases} \tag{6}$$

Case 2: When $A_D(t) < S_U(t) + S_R(t)$, assume that merge ratio of ramp cell R is $r_R(t)$ denoting the ratio of ramp volume entered mainline to mainline volume downstream, then,

$$\begin{cases} f_U(t) = \min\{S_U(t), A_D(t) - S_U(t), A_D(t)[1 - r_R(t)]\} \\ f_R(t) = \min\{S_R(t), A_D(t) - S_R(t), \; A_D(t)r_R(t)\} \\ f_D(t) = f_U(t) + f_R(t) = A_D(t) \end{cases} \tag{7}$$

In case 2, when traffic volume from expressway mainline and on-ramp are both extremely large, the receiving flow of downstream cell D is insufficient, it cannot accommodate the demand of upstream cell U and ramp cell R. Then merge area will experience congestion, and the transmission of traffic flow is determined by downstream cells. In the traditional CTM model, vehicles entering merge section should obey "mainline priority" rule in which ramp vehicles must give way to mainline vehicles. However, in the real-world vehicles will not obey this "mainline priority" rule. There are numerous forced merges and unreasonable lane-changing in the merge sections, resulting in congestion frequently at merge area. To represent this character, merge ratio $r_R(t)$ is introduced to CTM model. In this paper, merge ratio $r_R(t)$ is set as a certain value, which can express the fact that ramp vehicles do not fully obey the "mainline priority" rule. Equation (3), (6), and (7) constitute the fundamental model of the merge area based on the improved CTM.

2.2.3. Diverge section cell model

Figure 3c illustrates the schematic diagram of diverge section. Upstream mainline cell is U, off-ramp cell is G, traffic flow output of ramp cell G is $f_G(t)$, the receiving flow is $A_G(t)$, the sending flow is $S_G(t)$. Therefore, off-ramp cell and mainline cell in diverge section should meet the following restrictions:

$$\begin{cases} f_U(t) = f_G(t) + f_D(t) \le S_U(t) \\ f_D(t) \le S_D(t) \\ f_G(t) \le S_G(t) \end{cases} \tag{8}$$

Introducing another variable diverge ratio $r_G(t)$ to denote the ratio of off-ramp volume to mainline volume, and off-ramp capacity C_G, then:

$$\begin{cases} f_U(t) = \min\{S_U(t), A_G(t)/r_G(t), A_D(t)/[1-r_G(t)]\} \\ f_G(t) = \min\{A_G(t), f_U(t) \cdot r_G(t), C_{G,i}/r_G(t)\} \\ f_D(t) = f_U(t) \cdot [1-r_G(t)] \end{cases} \tag{9}$$

At normal case, off-ramp capacity C_G, is mostly determined by its connecting local street or local intersection. When traffic demand exceeds capacity on off-ramp, the vehicle in the off-ramp will get stuck in the off-ramp cell, and cause traffic congestion and even spread to the mainline. Formulas (3) and (9) constitute the basic diverge section model, based on the improved CTM.

3. Simulation

3.1. Road General Condition

To accurately describe and analyze the characteristics of urban expressway traffic flow and congestion, the Wanjiali Expressway in Changsha was selected in this study. Wanjiali Expressway is a two-way, six-lane urban elevated expressway. The total length is 16.6km; the speed limit is 80km/h, without traffic signal lamps; and the ramp spacing is non-uniform. Figure 4 shows the general schematic diagram of the Wanjiali Expressway:

Figure 4. Layout of the Wanjiali Expressway

According to the improved CTM, the Wanjiali Expressway is divided into 28 cells from south to north. As shown in Figure 4, it contains the basic segment cell, merge section cell, weaving section cell, diverge section cell and ramp cell. The improved CTM is used to simulate and analyze the expressway traffic flow.
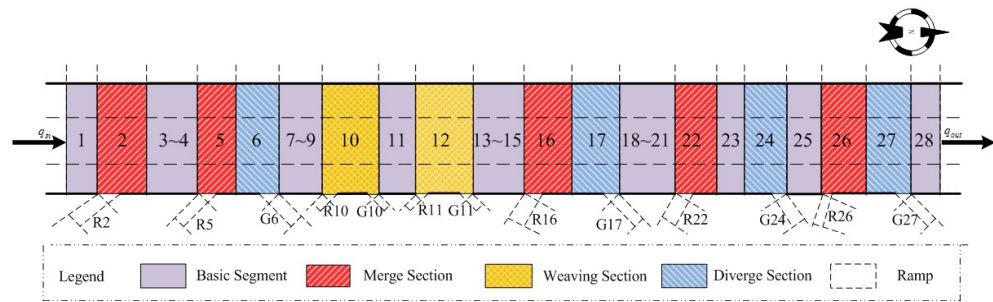
Figure 5. Schematic Diagram of Cell Division

3.2. Parameter Calibration

The core of CTM model calibration is the parameters of the flow-speed model. In this paper, we collected the flow and speed data, and conducted curve regression analysis based on flow-velocity model. The calibration is operated using SPSS software packet. Fitted with the data, the result as follows:
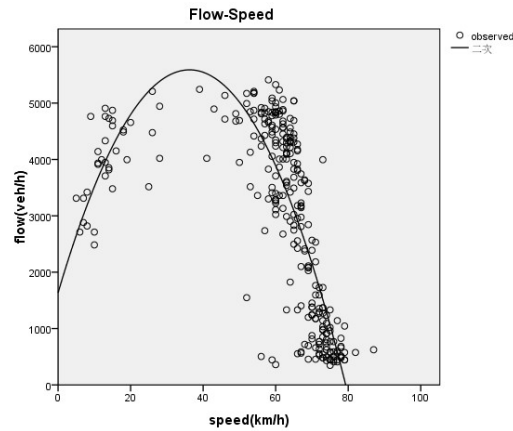

Figure 6. Flow- Speed Data Fitting

Table 1. Result of Flow-speed Regression Analysis by SPSS

	Coefficient				
	Not Standardized Coefficient		Standardized Coefficient	T	Sig.
	B	Standardized error	Beta		
speed	218.310	14.141	2.445	15.438	.000
speed** 2	-3.013	.158	-3.017	-19.053	.000
Constant term	1635.770	282.139		5.798	.000

As shown in Table 1, the significant value 0.000 is within the confidence interval, flow-speed relationship follows a quadratic curve quite well, flow-speed model can be written as:

$$q = -3.013v^2 + 218.310v + 1635.77 \tag{10}$$

When traffic flow is close to zero, speed is close to 80km/h, traffic is free flow, which is consistent with the real world.

After calibration, the main parameters of simulation model are as shown in Table 2:

Table 2. Value of Calibrated Model Parameters

Parameter	Unit	Value
Simulation Time Length, T	hour	24
Time Step interval, σ	second	10
Mainline Capacity, Q_{max}	veh/hr	5400
On-ramp Capacity, Qr_{max}	veh/hr	1200
Free-flow Speed, v_f	km/h	75
Traffic Back Propagation Speed, ω	km/h	25
Jam Density, k_{jam}	veh/(km•ln)	122
On-ramp merge Ratio,r_R	—	0.3
Off-ramp Diverge Ratio,r_G	—	0.1
Off-ramp Capacity local street, C_{Gi} (i=6,10,12,17,24,27)	veh/hr	(1000,1200,1100,800,1200,2000)

4. Simulation Results

4.1. Density/delay Spatiotemporal Distribution

We collected traffic volume data and speed data of the Wanjiali Elevated Expressway, in which, traffic volume detectors include seven on-ramp detectors and three expressway mainline detectors, speed detectors locate on the mainline near on-ramp merge section. Traffic data on Wednesday from 0:00 to 24:00, December 13, 2017 was collected for simulation as workday traffic flow data. Traffic data on Saturday between 0:00 and 24:00, December 16, 2017 was collected for simulation as non-workday traffic flow data. We conducted simulations on workday and non-workday using the improved CTM, and obtained the detailed results which include cell density, delay and the spatiotemporal evolution diagram of the expressway traffic flow, as shown in the following Figure 7:
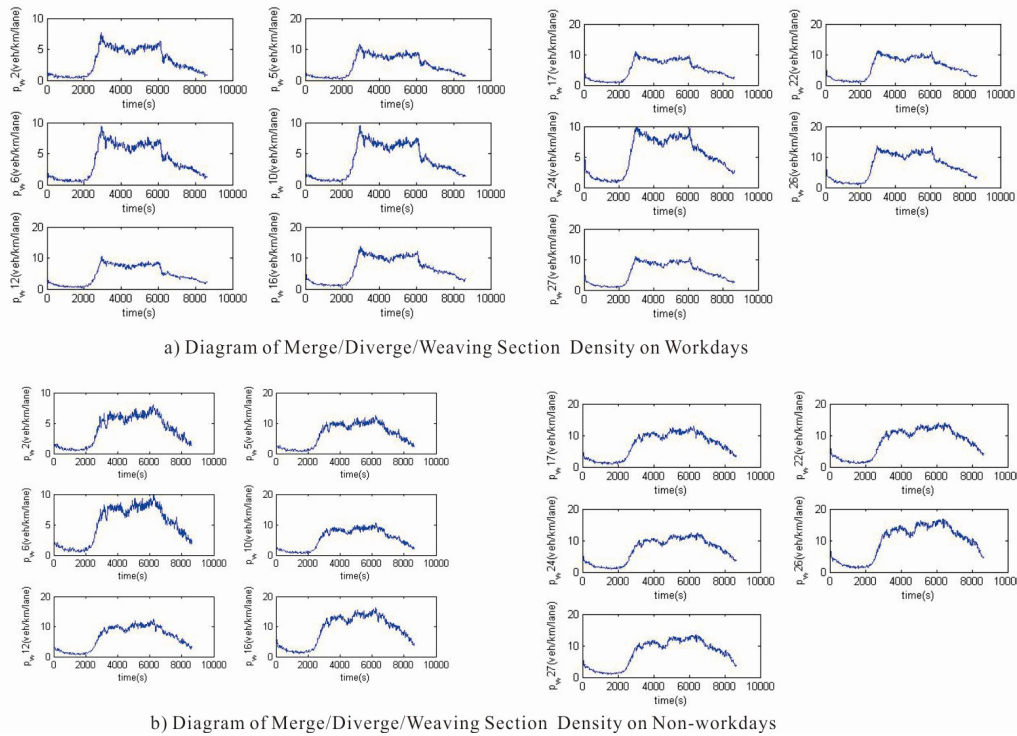
a) Diagram of Merge/Diverge/Weaving Section Density on Workdays

b) Diagram of Merge/Diverge/Weaving Section Density on Non-workdays

Figure 7 Diagram of Merge/Diverge/Weaving Section Density Evolution

Figure 7 mainly shows the density-time evolution at merge section, diverge section and weaving section, in which, Figure 7 a) represents workday, Figure 7 b) represents non-workday. From Figure 7 a), traffic density suddenly rises at around 6:00 A.M. (simulation time 2200s), and reached peak value at 8:00A.M. (simulation time 3000s), and began to decrease gradually at around 19:00P.M. (simulation time 7000s). From Figure 7 b), traffic density suddenly rises at 6:00A.M. and reached peak at 8:30A.M., and gradually decreased at around 21:30 P.M. The simulation results are fully consistent with the real operation on Wanjiali Expressway.

Figure 8 Average density/delay distribution at expressway

Figure 8 represents traffic operating index of all cells in Wanjiali Expressway on workday and non-workday. In the wave curve, apex and peak locate at the merge section, diverge section or weaving section. The average density and delay on non-workdays are larger than workdays. In addition, looking into the diverge section density of the off-ramp, we found that smaller capacity of local street connecting to off-ramp, the larger cell delay in the diverge area.
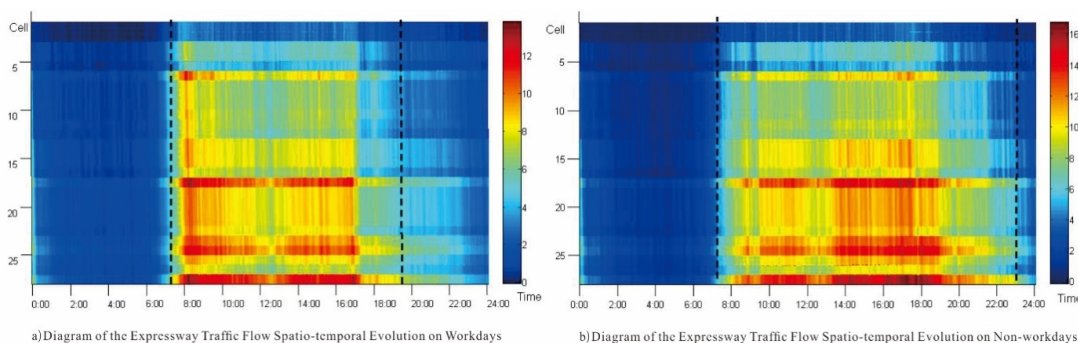
a) Diagram of the Expressway Traffic Flow Spatio-temporal Evolution on Workdays   b) Diagram of the Expressway Traffic Flow Spatio-temporal Evolution on Non-workdays

Figure 9 Diagram of the Expressway Traffic Flow Spatiotemporal Evolution

From Figure 9 a), on workday, the first congestion occurs on the expressway at around 7:30am, congested cells number include 6,16,24 and 26 which represent diverge section and merge section. From Figure 9 b), on non-workday, traffic congestion starts at the diverge section and merge section, the same as workday. Comparing the spatiotemporal evolution graph of workday and non-workday, we can find congestion duration on non-workday is longer than workdays.

4.2. Sensitivity analysis & discussion

This section will discuss the influencing factors of traffic congestion in urban expressway mainlines, as follow.

4.2.1. Effect of on-ramp traffic volume on mainline traffic congestion

There are seven on-ramps along Wanjiali elevated expressway. We will discuss the relation between on-ramp traffic volume and expressway mainline congestion. We collected traffic flow data from 10:00 am to 11:00 am, December 16,2017, then conducted simulation under different on-ramp traffic flow input conditions. To simplify, we define the merge rate r_R as the ratio of the number of on-ramp vehicles to the number of vehicles on mainline of expressway. Four scenarios of different merge rate r_R value were studied, in which r_R = 0.2, 0.3, 0.4, 0.5, respectively.

Traffic delay of Merge area (Cell 5 in Figure 4) and weaving area (Cell 10 in Figure 4) were collected under different merge rate r_R, listed in Figure 10.
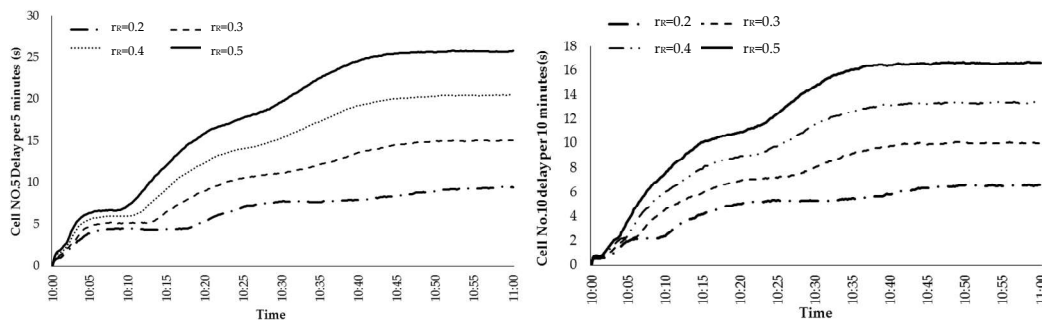

Figure 10 Relation of merge/weave section traffic delay and merge rate r_R

From figure 10, delay of the merge and weaving section increases with merge rate r_R, in addition, the increasing rate of delay decreases gradually. Further analysis can reveal the concrete

effect of on-ramp traffic volume. When merge rate r_R increases from 0.2 to 0.3, delay in the merge area (cell 5) and weaving area (cell 10) increases by 35% and 34% respectively. When merge rate r_R increases from 0.3 to 0.4, delay in the merge area (cell 5) and weaving area (cell 10) increases by 26% and 25%. This phenomenon reveals that when merge rate r_R increases, more vehicles will enter merge/weave section and interact with vehicle of expressway mainline, more disturbance will generate in the traffic flow due to the numerous unreasonable forced merging vehicles from on-ramp, and congestion will generate more frequently.

4.2.1. Effect of off-ramp capacity on mainline traffic congestion

Off-ramp connects Urban expressway mainline to the adjacent local arterial or collector street. Due to the short length of off-ramp, expressway traffic has strong correlation with the local street. Therefore, capacity of the off-ramp C_G is mostly determined by local street. To this end, we conducted simulation under different off-ramp capacity C_G conditions. Six scenarios of different off-ramp capacity were studied, in which C_G = 500,600,700,800,900,1000 veh/hr, respectively. Traffic data was collected from 10:00 to 11:00 am, on December 16, 2017, and applied for simulation. Delay in four diverge cells (No.6,17,24,27) was collected from simulation, which are shown in the following figure:
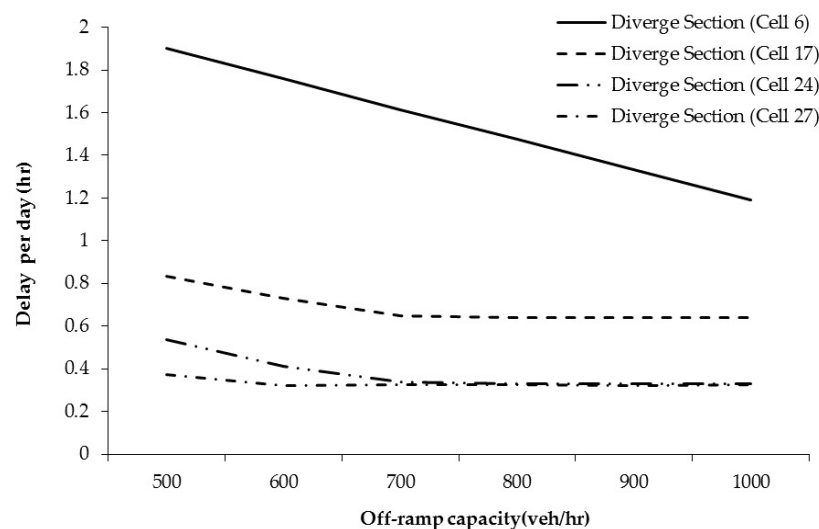

Figure 11 Diverge section delay to off-ramp capacity

Figure 11 indicates that, delay of diverge cell in the expressway mainline decreases with off-ramp capacity C_G increasing. For diverge cell 6, when C_G increases by 100 veh/hr, the delay of cell 6 decreases by about 10%. For cell 17 and cell 24, in the former part, diverge cell delay decreases with C_G increasing. And in the latter part, when C_G reaches 700 veh/hr, delay of the diverge cell is basically unchanged. Similarly, when C_G reaches 600 veh/hr, delay of the diverge cell 27 remains unchanged. To sum up, capacity of local street will determine capacity of off-ramp, which has a strong effect on operating state at expressway mainline. As a result, traffic congestion occurring in the local road network will quickly spread to the expressway mainline, even causing congestion.

5. Conclusions

To analyze the mechanism of traffic congestion generation on the urban expressway in China, Wanjiali Expressway, one representative urban elevated expressway in Changsha Hunan was selected as the study object. Cell transmission model CTM was adopted to model and simulate the expressway traffic operation. Considering the particular characteristics of traffic operating on urban expressway in China, CTM was improved in which cell length is variable, microscopic drivers mandatory merge behavior is integrated to merge cell, limit of local streets capacity is linked to diverge cell. The simulation was conducted on Wanjiali Expressway by the improved CTM. Sensitivity analysis was conducted under different on-ramp volume and off-ramp capacity, results indicate the specific characteristics and mechanism of traffic congestion at urban expressway, which include:

- Most traffic congestion generates originally at merge, diverge and weaving sections, then propagates to the next section upstream.
- Merge section congestion in urban expressway is mostly caused by unreasonable driving behaviors such as mandatory merging and lane-changing from on-ramp. Due to vehicles from on-ramp not obeying the "mainline priority" rule, on-ramp vehicles entering merge section cell occupy the considerable ratio of the mainline capacity (sending flow), and delay of the merge and weaving section increases with merge rate.
- Diverge section congestion is mainly determined by capacity of local street connecting to expressway mainline through off-ramp. Based on the data analysis, delay of diverge cell in the expressway mainline decreases with off-ramp capacity C_G increasing. Due to the unmatched capacity of off-ramp, vehicle queue length often exceeds the off-ramp and extends the mainline upstream. As a result, in the vehicle queue end dynamic bottleneck is generated at the diverge section, which reduces the capacity (receiving flow) of the diverge section cell.

Further researches will aim at the congestion propagating feature on the urban expressway, also, more study examples will be included to extend the methodology. In addition, CTM is a first order macroscopic model. In comparison, second order models can provide more realism, can be applied to this issue in future.

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