World Academy of Science, Engineering and Technology
International Journal of Mathematical and Computational Sciences
Vol:7, No:8, 2013

A DMB-TCA Simulation Method for On-Road Traffic Travel Demand Impact Analysis

Zundong Zhang, Limin Jia, Zhao Tian, and Yanfang Yang

Abstract—Travel Demands influence micro-level traffic behavior, furthermore traffic states. In order to evaluate the effect of travel demands on traffic states, this paper introduces the Demand-Motivation-Behaviors (DMB) micro traffic behavior analysis model which denotes that vehicles behaviors are determines by motivations that relies on traffic demands from the perspective of behavior science. For vehicles, there are two kinds of travel demands: reaching travel destinations from orientations and meeting expectations of travel speed. To satisfy travel demands, the micro traffic behaviors are delivered such as car following behavior, optional and mandatory lane changing behaviors. Especially, mandatory lane changing behaviors depending on travel demands take strong impact on traffic states. In this paper, we define the DMB-based cellular automate traffic simulation model to evaluate the effect of travel demands on traffic states under the different δ values that reflect the ratio of mandatory lane-change vehicles.

Keywords—Demand-Motivation-Behavior, Mandatory Lane Changing, Traffic Cellular Automata.

I. Introduction

WITH the development of cities especially in developing countries, traffic congestion is becoming more common in urban traffic systems. It is a hot research point that to analysis the reason of forming congestion phenomenon. From the perspective of system science, congestion is emerging from various kinds of traffic factors, such as travel demands, infrastructures, traffic signal etc. Travel demands have strong effect on traffic states. To analysis the effect is important to understanding the congestion forming process.

Micro traffic models are aiming vehicles behaviors through defining car-following and lane-changing rules. This paper points out that the driving behaviors is decided by drivers motivations and motivations come from travel demands of drivers, which is based on the demand-motivation-behavior reacting procedure of human beings integrated with processes of vehicle motion on roads. We introduce the DMB micro traffic behavior analysis model to explain the forming process of the driving behaviors.

Car-following behaviors and lane-changing behaviors are two elementary class behaviors of vehicles. Lane-change can be divided into optional lane change and mandatory lane change. As stated above, travel demands include two aspects: one is to reach travel destinations, another is to satisfy the expectation of travel speed on roads. The motivations satisfying the first demands can cause mandatory lane-changing behaviors. The latter causes optional behaviors. Therefore, we can analyze the effect of travel demands on traffic states through mandatory lane-changing behaviors.

Z. Zhang is with Beihang University, Beijing, China, 100191; and State Key Lab of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing, China 100044. (Corresponding author to provide email: zhangzundong@gmail.com)

L. Jia, Z. Tian and Y. Yang are with State Key Lab of Rail Traffic Control and Safety, Beijing Jiaotong University, Beijing, China 100044.

We construct the DMB-based cellular automata traffic simulation with Matlab and complete simulation experiments with different kinds of travel demands and mandatory lane change ratios. The simulated results show that the traffic state decreases with mandatory lane change ratio increasing caused by traffic demands.

II. Micro Traffic Cellular Automata Models

As for traffic system modeling approaches, cellular automata on models (CA) is especially popular because of its simple structure and discrete spatial and temporal variables, which makes it easy to simulate the dynamical processes of a huge number of interacting vehicles. After introduced firstly by John von Neumann, CA has got a rapid and great development in traffic systems.

Wolframs CA 184 can be viewed as a 1D traffic model, but too simple [1]. In 1986, Cremer and Ludwig formally used CA to traffic system modeling [2]. The first full-meaningful traffic CA called NS model [3] was introduced by Nagel in 1992. Based on NS model, many CA models was put out with some improvements, such as the speed-based NS extension model[4], TT model[5], BJH model[6], the extension models considering former cars speed [7], FI model [8] etc. All these models focus on modeling the micro car following behavior of vehicles.

Since almost all major highways have two lanes or more, several researchers have constructed multi-lane models for highway traffic. The first work in this area was done by Rickert et al. [11], who designed a working model based on the NaSch model. They noticed that checking for extra space when switching lanes ('look-back') is an important feature of their model in order to get the realistic behavior of laminar to start-stop traffic flow. Cremer and co-workers implemented cellular automata lane changing rules which decided to apply the rules or not according to if a slower car existed ahead in the source lane and are there enough untaken cells of the target lane. Nagatani has formulated an oversimplified model for two-lane traffic in 1993 [9], and has extended it with adding random parameters [10]. Wagner et al. [12] design a two-lane simulation which accounts for a faster left lane which is to be used for passing. Using simple rules, they are able to obtain the realistic behavior that at higher overall densities, the left lane has a higher density than the right one. They remark that this correct macroscopic behavior is fairly easy to obtain using a CA model, and cite some failed attempts to simulate multi-lane traffic using other types of models. Knospe et al. [14] study heterogeneous two-lane traffic and find that even at low densities, a very small amount of slower cars effectively cause both lanes to slow significantly. Also, they note that a system with mostly slow cars and a small percentage of fast cars is almost identical to a system with all slow cars. Finally, Nagel et al. [13] summarize the existing lane-changing CA models and propose a general scheme according to which realistic lane-changing rules can be developed.

As stated above, the existing works focus on the car-following rule set and the lane-changing rule set of traffic CA models. Besides, CAs should have the ability of observing the emerging traffic states under different traffic travel demands. On micro level, traffic travel demands are satisfied through car-following behaviors and lane-changing behaviors. The lane-changing behaviors can be divided into two kinds: the optional and the mandatory. The differences between them include two aspects: the motivation and the procedure after the lane-changing conditions are not met. The difference of motivations reflects the difference of traffic travel demands. The motivation of optional lane-changing behaviors is to satisfy the demands of driving faster. The motivation of mandatory lane-changing behaviors is to satisfy the demands of reaching destinations. When lane-changing conditions mismatched, the optional lane-changing behaviors would be abandoned. On the contrary, the mandatory lane-change would slow down the car and/or give an avoiding signal to cars in the target lane.

III. The DMB-Based Micro Traffic Analysis Model

According to the process from demands determining motivations to driving behaviors forming, the Demand-Motivation-Behavior micro traffic behavior analysis model describes the relationships between micro traffic behaviors and traffic travel demands.

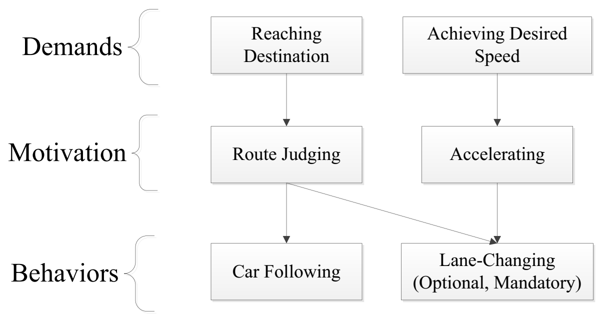

Fig. 1: The Structure of the DMB model

The demands of vehicles on roads include two parts: reaching travel destinations and achieving desired speed. The first is one of the elementary needs of traffic activities. The second reflects another kind of the elementary needs of travel speed during a trip.

As traffic demands generated, the corresponding traffic motivations is determined. Similar to the classes of traffic demands, micro traffic motivations can also be stated in two kinds: route judging and accelerating. The first kind of traffic motivations, aiming to satisfy the demand of reaching traffic destinations, causes car-following behaviors and (optional and mandatory) lane-changing behaviors. The second is to satisfy the demand of achieving desired speed that causes optional lane-changing behaviors. Traffic motivation as the core of DM-B model connects traffic demands and micro traffic behaviors.

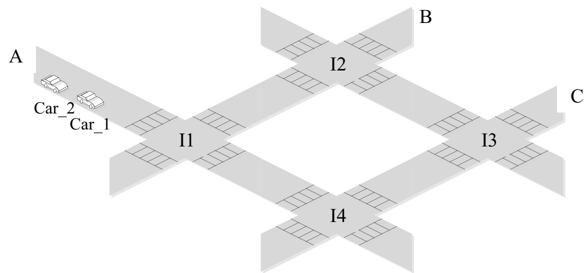

Fig. 2: A Simple Example for Route Judge (I1-I4 are intersections. A, B and C represent the traffic orientations and/or destinations. Car_1 and Car_2 are set to departure from A on the straight lane, whose destinations are B and C respectively.)

In the example, the traffic travel demand of Car_1 is from A to B. Its motivation determines the car should turn left at I1 which causes a mandatory lane-changing behavior. Car_2 with C as its traffic destination can turn left or go straight through at I1 which causes an optional lane-changing behavior.

The example simply explains how one kind of traffic demands of a car determines its micro behaviors. During a trip, a driver decides to change lane or not according to the expectation of speed, the neighboring cars speed and position, the drivers personalities, etc. This kind of traffic demands can cause an optional lane-changing behavior only.

Traffic demands have a significant impact on macro traffic state by taking an effect on micro vehicles traffic behavior.

IV. The DMB-Based Traffic CA Simulation Model

A. *The Structure of DMB-TCA*

The traffic models, aiming to investigate how micro traffic variables affect the macro traffic state, should firstly define corresponding parameters, such as the basic information of urban road sections, types of lane, bus station information, characteristics of drivers behaviors, types of vehicle, rules of departure, signal timing, etc. Secondly, the model should determine the micro state update rules including car following rules, lane-changing rules with different types of vehicle as well as drivers decision-making process.

From a functional perspective, the traffic flow simulation model based on cellular automata consists of the cell space, the vehicle space, the departing rules and control information module, the state updating module and the result display module, as shown in the figure. The updating module is the core of the traffic flow simulation model which is responsible for updating each vehicles state and ultimately implementing the whole cellular space updated.

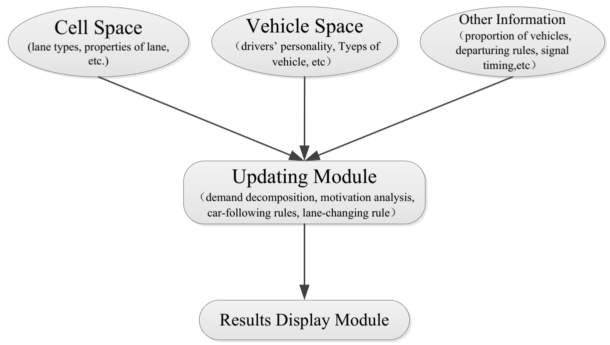

Fig. 3: Basic Structure of the Traffic Flow Simulation Model Based on Cellular Automata

The basic mechanisms of the updating module are shown in the following figure. The mechanisms contain two parts contents: one is that a new vehicle is added to the cell area which is determined by the departure density and the proportion of the type of vehicles; the other one is that existing vehicles in the cell area update their own states. For each vehicle, firstly, the demands ought to be determined. Secondly the motivation should be analyzed according to the demands. Finally, the motivation brings about the behaviors causing updating states. The demands can be presented in two aspects: the route selection determined by traffic travel demands and the expectations to better driving state (higher speed). The motivation is formed to meet the demands through analyzing traffic demands. The motivation also could be divided into two kinds: to reach travel destinations and to get better driving state. Motivation is the reason or reasons for engaging in a particular behavior. Micro traffic behaviors include two classes: the car-following behavior and the lane-changing behavior. The behaviors cause the individual vehicle state updated, eventually the macro-traffic state changed.

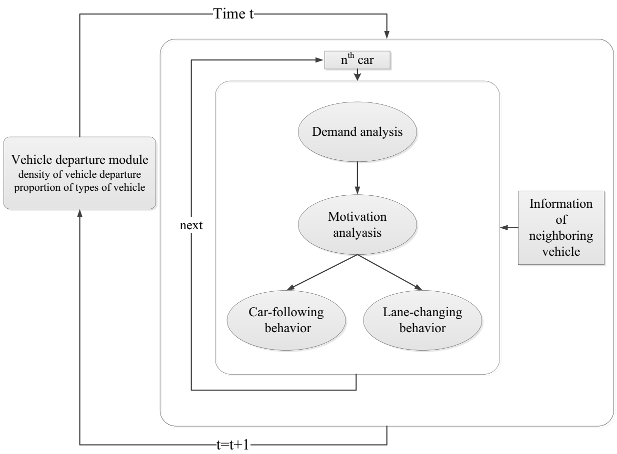

Fig. 4: Rules for Updating State

The figure below illustrates the process from the traffic motivation analyzing to the vehicle state updating, which describes the difference between the mandatory lane-changing behavior and the optional lane-changing behavior. The optional lane-changing behavior meets the needs to improve travel speed and the mandatory lane-changing behavior aims to meet the demand of reaching travel goals. If the lane changing condition is not satisfied, the vehicle with the optional lane-changing behavior would give up changing the lane and continue the following behavior. But the vehicle with the mandatory lane-changing behavior would decelerate to wait or send the avoiding signal to the vehicle behind in the target lane, until completing lanes change.

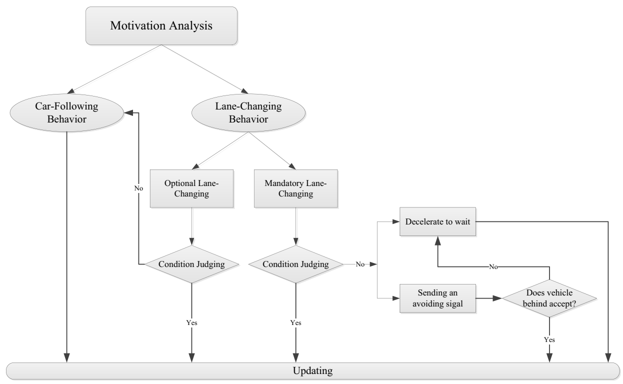

Fig. 5: The State-Updating Process

B. DMB-TCA

According to the basic idea of DMB model, this paper establishes traffic flow cellular automata based on "demand-motivation-behavior" model (DMB-TCA), which is defined as a tuple below.

$$DMB-TCA = \{\mathcal{A}(\Delta x, LN, LL, T, \Delta t), R_{traveldemands}, \mathbb{F}, \Phi, f_{init} \in \mathbb{F}\}$$

Where, $\mathcal{A}$ is the domain, made of spatial cells of size Δx, lane numbers LN and spanning a region of lane length LL, while the quantity Δt is the time step and $T/\Delta t$ is the number of iterations during which $DMB-TCA$ will be run. Therefore, processes with time scales between Δt and T can be represented and spatial scales ranging from $LN \times \Delta x$ to $LN \times LL$ can be resolved. The state of the $DMB-TCA$ is described by an element of $\mathbb{F}$ (space of states) and it evolves according to the update rule $\Phi : \mathbb{F} \to \mathbb{F}$ that mainly includes the car-following rule set and the lane-changing rule set (note that formally both $\mathbb{F}$ and Φ depend on the discretizations $(\Delta x, \Delta t)$.

$R_{traveldemands}$ represents the proportion of the travel demands. $R = \{(r_l^i : r_s^i : r_r^i)|i \in [1, LN]\}$ means the proportion of travel demands, in which $(r_l^i : r_s^i : r_r^i)$ defines the ratio of left-turning vehicles, straight-going vehicles and the right-turning vehicles in the lane i. So the proportion of vehicles with mandatory lane-changing behavior can be calculated by the following formula.

$$\delta^i = \begin{cases} \frac{r_s^i + r_r^i}{r_l^i + r_s^i + r_r^i}, & \text{the lane } i \text{ is the left turning lane} \\ \frac{r_l^i + r_r^i}{r_l^i + r_s^i + r_r^i}, & \text{the lane } i \text{ is the straight going lane} \\ \frac{r_l^i + r_s^i}{r_l^i + r_s^i + r_r^i}, & \text{the lane } i \text{ is the right turning lane} \end{cases}$$

The total proportion of the mandatory lane-changing can be calculated by the following formula.

$$\delta = \sum_{i=1}^{LN} (q^i \times \delta^i) / \sum q^i$$

where: q^i is the number of vehicles entered the cell area at the lane i.

C. Car-Following Rules and Lane-Changing Rules

The traditional car-following rules and lane-changing rules will be used. The relevant parameters include velocity, randomization probability, the minimum safety distance, the probability that the car behind give way for the changing car in the target lane and so on.

1) The Car-Following Rule Set: The car-following rule set is defined as following based on NaSch model.

(1) Acceleration: $v_n(t+1) \to \min(v_n(t)+1, v_{\max})$
(2) Slowing down:$v_n(t+1) \to \min(v_n(t+1), d_n)$
(3) Randomization (with probability p):
$v_n(t+1) \to \max(v_n(t+1)-1, 0)$
(4) Car motion:$x_n(t+1) \to x_n(t) + v_n(t+1)$

$v_n(t)$ is the velocity of the car n at the time t. $d_n = x_{n+1} - x_n - l_{n+1}$ means the number of the cells between the car n and the car $n+1$ ahead. The length of the car $n+1$, recorded as l_{n+1} , means the number of the cells which the car $n+1$ taken. The randomization probability is q. The maximum speed is v_{max}.

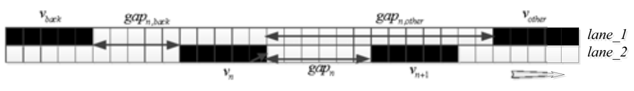

Fig. 6: Declaration of the Lane-Changing Process

2) The Lane-Changing Rule Set: The constraint conditions of the optional lane-changing behavior are following.

(1) $gap_n < \min\{v_n + 1, v_{\max}\}$
(2) $gap_{n,other} > gap_n$
(3) $gap_{n,back} \geq v_{back} + 1$

gap_n is the numbers of the cells between the car n and the car $n+1$ in the same lane; $gap_{n,other}$, the can n and the car ahead in the target lane; $gap_{n,back}$, the car n and the car behind in the target lane. Especially, $gap_{n,other}$ and $gap_{n,back}$ can be negative when the car n and the car ahead or behind in the target lane has overlaps. The condition (1) means that the car n cannot get accelerated in the lane. The condition (2) indicates the driving condition in the target lane is better than the source lane. The condition (3) is set for safety which can avoid the crash between the car n and the car behind in the target lane after lane change.

The car n will change the lane when the above three conditions satisfied. The lane-changing rules are following:

(1) Acceleration:$v_n(t+1) \to \min(v_n(t)+1, v_{\max})$
(2) Slowing down:$v_n(t+1) \to \min(v_n(t+1), gap_{n,other})$
(3) Randomization (with probability p):
$v_n(t+1) \to \max(v_n(t+1)-1, 0)$
(4) Location update:$x_n(t+1) \to x_n(t) + v_n(t+1)$
(5) Lane update

The constraint condition of the mandatory lane-changing only concludes the condition (3) of the optional lane-changing. The mandatory lane-changing rules are same as the optional lane-changing rules. When the constraint conditions of the mandatory lane-changing unsatisfied, the car gives an avoiding signal to the car behind in the target lane. The car behind in the target lane accepts the requirement with the probability p. After the car behind accepted, the car changes lane without considering the safe distance. If the car behind in the target lane rejected, the car n decelerates before the deadline until completing lane change.

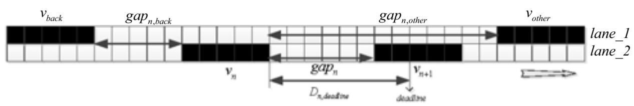

Fig. 7: Declaration of the Mandatory Lane-Changing Process

The mandatory lane-changing rules are following if the condition (3) is not met.

1) The car gives an avoiding signal to the car behind in the target lane. The car behind in the target lane accepts with the probability p. Only if the condition $gap_{n,back} \geq 0$ and $gap_{n,other} \geq l_n$ are met, the car n can change lane without considering the lane-change constraint condition (3).
2) Slowing down:
$v_n(t+1) \to \min(v_n(t), gap_{n,other}, D_{n,deadline})$
3) Randomization (with probability p):
$v_n(t+1) \to \max(v_n(t+1)-1, 0)$
4) Location update:$x_n(t+1) \to x_n(t) + v_n(t+1)$
5) Lane update

$D_{n,deadline}$means the number of the cells between the car n and the deadline. The deadline is the maximum position until which the car n must complete the lane-change.

V. Simulation Experiments And Result Analysis

A. Simulation Experiments

The impact of traffic demands on the traffic flow state is investigated in this paper. At the microscopic level, the traffic demand is reflected in the proportion of mandatory lane change. We adjust the proportion of traffic demands in the system to change the proportion of mandatory lane change. Consequently, the traffic flow characteristics would change. In the experiments, we set a three-lane system, in which each cell length equals $1.5m$, a car occupies 5 cells. The simulating parameters are set as follows: lane length $LL = 300$(cells), maximum velocity $v_{max} = 15$(cells per Δt), total time $T = 2000$ and each step time $\Delta t = 1s$.

B. Result Analysis

Four experiments are compared in this paper. The experimental results are shown as following. Figure 8 shows the comparison among the different traffic demand, where the proportion of mandatory lane change δ values: 0.1, 0.3, 0.5 and 0.7.

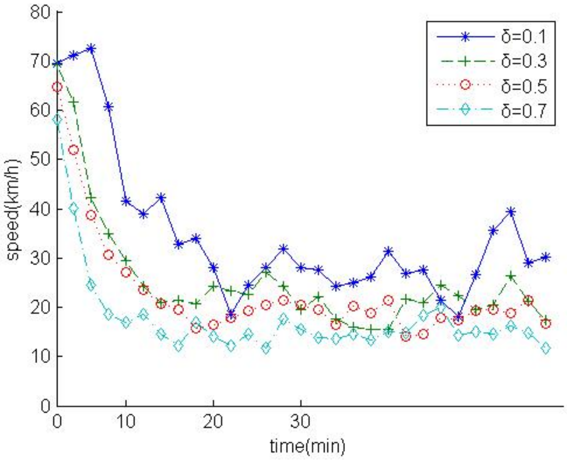

Fig. 8: Comparison of Speed

We conclude that the greater the proportion of mandatory lane change δ values, the faster the velocity declines. Moreover, the mean velocity will be at a lower level. As shown in figure 9, with δ values becoming greater, the more the number of stops is.

In Figure 11, the traffic state becomes worse with the δ value increasing. As seen in Table 1, the traffic travel demand has a significant impact on traffic state reflected by a series of traffic variables, i.e. capacity, delay and number of stops.

TABLE I: Comparison Of Flux, Delay And Times Of Stop

	Actual Flux(veh/h)	Average Delay(s)	Ave. Number of Stops
δ=0.1	1108	98.19	6.7
δ=0.3	948	139.54	11.8
δ=0.5	862	152.16	13.6
δ=0.7	744	211.28	17.6

Experimental results show that the effect of demand on the traffic state variables, such as traffic flow, velocity, density, etc. is significant. The proportion of mandatory lane change δ can be calculated by defining the traffic travel demand proportion. Through the experiments, we find out the strong relation between the travel demand and the traffic state.

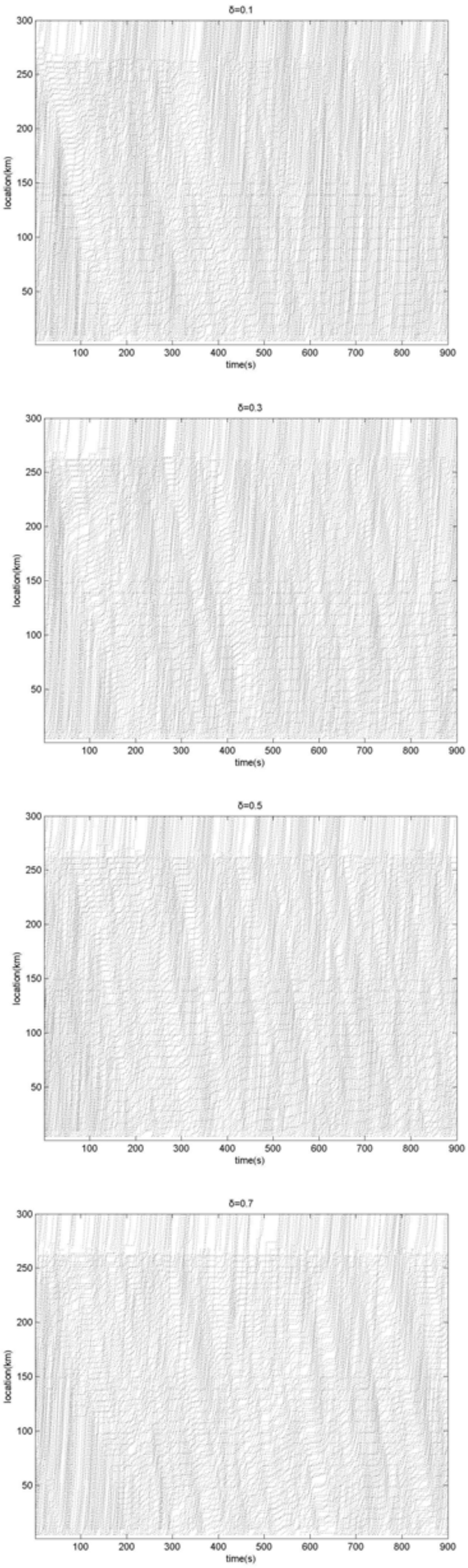

Fig. 9: Time-Location Relationships

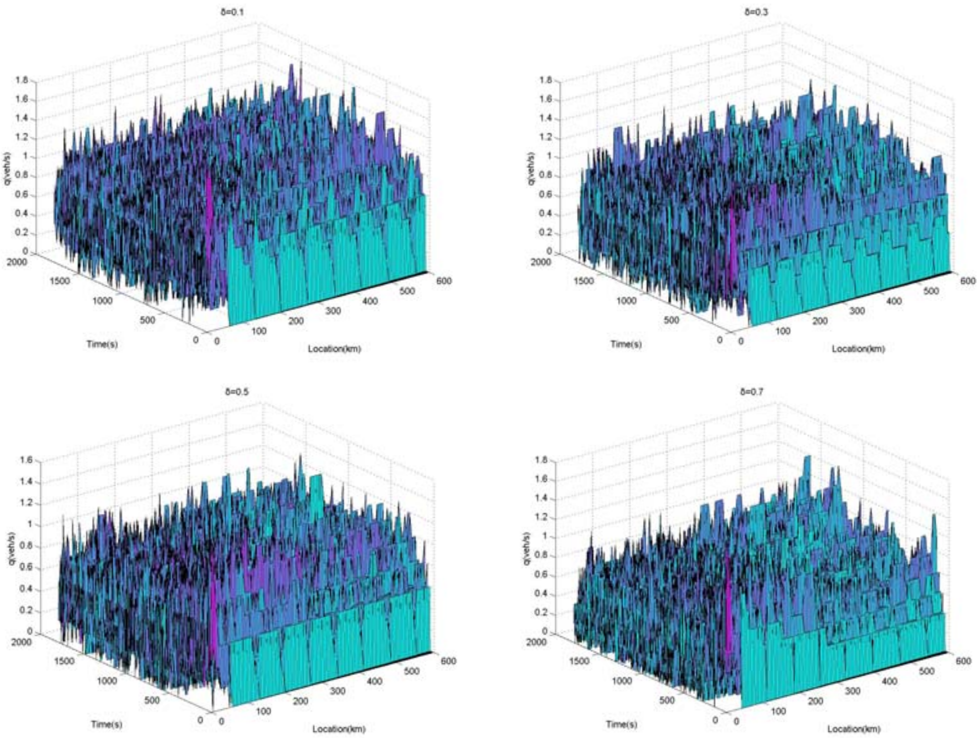

Fig. 10: Flux-Time-Location Relationships

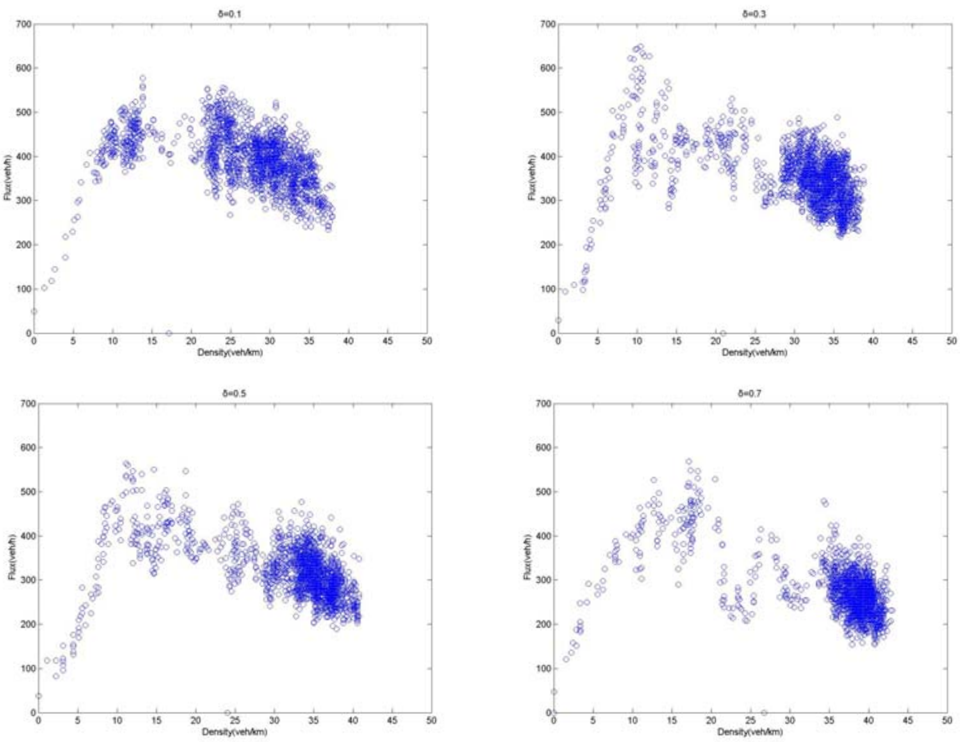

Fig. 11: Flux-Density Relationships

VI. Conclusion

A demand-motivation-behavior (DMB) model based cellular automata is presented in this paper which aims to investigate the impact of the traffic travel demand on the traffic state. The proposed model explains the relationship between travel demand and traffic behavior by comparing the macro traffic state with different micro traffic demands. The traffic travel proportion, car-following model, lane-changing model and mandatory lane-changing proportion δ are described in the proposed model. The paper designs four groups of simulation experiments with different values of δ. The parameter δ reveals the change of the traffic demand proportion. Experiments show that the travel demand takes an effect on the macro traffic state significantly. With the value of δ increasing, the macro traffic state becomes worse.

References

[1] S. Wolfram, *Theory and applications of cellular automata*. Singapore:World Scientific, 1986.
[2] M.Cremer, J.Ludwig, "A fast simulation model for traffic flow on the basis of boolean operations", *Mathematics and Computers in Simulation*, vol. 28, no. 4, pp. 297 C 303, 1986.
[3] K. Nagel and M. Scheckenberg, "A Cellular Automaton Model for Freeway Traffic", *J Phys I France*, vol. 2, pp.2221-2229,1992.
[4] R. Barlovic and L. Santen, "Metastable States in Cellular Automata for Traffic Flow", *Eur Phys J B*, vol.5, no. 3, pp.793-800, 1998.
[5] M. Takayasu and H. Takayasu, "1/f Noise in a Traffic Model", *Factral*, vol.1, no. 5, pp.860-866, 1993.
[6] S.C. Benjamin, N.F. Johnson and P.M. Hui, "Cellular automata models of traffic flow along a highway containing a junction", *J. Phys A*, vol.29, p.3119, 1996.
[7] D. E. Wolf, "Cellular Automata for Traffic Simulations", *Phys A*, vol. 263, pp.438-451, 1999.
[8] M. Fukui and Y. Ishibashi, "Traffic Flow in 1D Cellular Automata Model Including CarsMoving with High Speed", *Japan: J Phys Soc*, vol.65, no.1, pp.868-870,1996.
[9] T. Nagatani, "Self-organization and phase transition in traffic-flow model of a two-lane roadway", *J. Phys. A: Math. Gen.*, vol. 26, p. L781, 1993.
[10] T. Nagatani, "Dynamical jamming transition induced by a car accident in traffic-flow model of a two-lane roadway," *Physica A: Statistical Mechanics and its Applications*, vol. 202, no. 3-4, pp. 449 C 458, 1994.
[11] M. Rickert, K. Nagel, M. Schreckenberg and A. Latour, "Two lane traffic simulations using cellular automata," *Physica A: Statistical Mechanics and its Applications*, vol. 231, no. 4, pp. 534 C 550, 1996.
[12] P. Wagner, K. Nagel, and D. E. Wolf, "Realistic multi-lane traffic rules for cellular automata," *Physica A: Statistical Mechanics and its Applications*, vol. 234, no. 3, pp. 687 C 698, 1997.
[13] K. Nagel, D. E. Wolf, P. Wagner and P. Simon, "Two-lane traffic rules for cellular automata: A systematic approach," *Pys Rev E*, vol. 58, pp. 1425C1437, 1998.
[14] W. Knospe, L. Santen, A. Schadschneider and M. Schreckenberg, "A realistic two-lane traffic model for highway traffic," *Journal of Physics A: Mathematical and General*, vol. 35, no. 15, p. 3369, 2002.

Zundong Zhang received the Ph.D degree in system engineering from Beijing Jiaotong University, Beijing, China, in 2010. He is currently a postdoctoral researcher at Beihang University, Beijing, China, since 2011. His research interests include complex system modeling and simulating, dynamics of complex systems, intelligent transportation systems and cellular automata.

Limin Jia received his PhD degree in China Academy of Railway Sciences. He is currently a Professor with State Key Lab of Rail Traffic Control and Safety and the Traffic and Transportation School, Beijing Jiaotong University, Beijing, China. His research interests are related to complex systems, computational intelligence, cybernetics and information fusion and aggregation.

Yanfang Yang received the M.S. degree, in 2009, in computational mathematics from Beijing Jiaotong University, Beijing China, where she is currently working toward the PhD degree in safety science and engineering. Her research interests include mathematical analysis, dynamics modeling of complex systems, urban traffic system modeling and cellular automata.

Zhao Tian received the M.S. degree in computer science from Zhengzhou University in 2011. He is currently working toward the PhD degree in safety technology and engineering from Beijing Jiaotong University, Beijing, China. His research interests include machine learning, fuzzy theory, petri nets, intelligent transportation systems and urban road traffic network modeling.