The Effect of Lane-Changing Time on the Dynamics of Traffic Flow

Xin-Gang Li[1], Bin Jia[1], and Rui Jiang[2]

[1] School of Traffic and Transportation, Beijing Jiaotong University, Beijing, 100044, P.R. China
lsinban@gmail.com, bjia@bjtu.edu.cn
[2] School of Engineering Science, University of Science and Technology of China, Hefei, 230026, P.R. China
rjiang@ustc.edu.cn

Abstract. In this paper, the lane-changing time is considered in the cellular automata models for traffic flow. The lower the velocity of a vehicle, the longer the lane-changing time. The simulations are carried out in the two-lane system and the on-ramp system. When the lane-changing time is taken into account, the maximum flux per lane is reduced in the two-lane system compared with the original two-lane model, and it is even lower than that of single-lane road when a lane-changing takes longer time; the capacity drop can be reproduced in the on-ramp system.

Keywords: lane-changing time; cellular automata; traffic flow.

1 Introduction

In recent years, modelling the dynamics of traffic flow has attracted much attention of researchers from the field of physics. Many theoretical models have been proposed to explore the evolution mechanism of traffic flow [1,2,3,4,5]. Among those models, cellular automaton (CA) is an excellent tool for simulating real traffic flow, because its efficient and fast performance when used in computer simulations. In 1992, Nagel and Schreckenberg proposed the well-known Nagel-Schareckenberg (NaSch) model [6]. Although it is very simple, the NaSch model can reproduce some real traffic phenomena, such as the occurrence of phantom traffic jams and the realistic flow-density relation (fundamental diagram). The NaSch model is a minimal model in the sense that any further simplification of the model leads to unrealistic behavior. Later, several extensions of the NaSch model are proposed [7,8,9,10].

Due to the road consists of multi-lane in real traffic, the single lane NaSch model can not simulate realistic traffic, especially when the system is inhomogeneous. As a result, the two-lane models are proposed by introducing the additional lane-changing rules. Lots of lane-changing rules, which consist of symmetric and asymmetric ones, have been implemented to simulate the realistic lane-changing behaviors [11,12,13,14,15,16,17,18,19]. In our previous work, the

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honk effect [17,18] and the aggressive lane-changing behavior [19] were investigated and more realistic results had been obtained.

The traffic dynamics around bottlenecks, where lane-changing behaviors frequently happen, have been widely studied with CA models [20,21,22,23,24,25]. The bottlenecks include on-ramps, off-ramps, lane closings, uphill gradients, narrow road sections, etc. The lane-changing rules are used to model the vehicle entering, preparing to exit or exiting the main road.

A lane change can be described in three parts [26]. First, the head portion is the time and distance required for a vehicle to move from a straight-ahead path to the first intercept of the lane line. The actual lane change is begun when a vehicle first encroaches on the lane line between the original and destination lane. Secondly, the maneuver is ended once the vehicle has completely crossed that line. Finally, the tail portion of the maneuver is the time and distance required for a vehicle to return to a straight-ahead path in the destination lane after crossing the lane line. It is obvious that time is needed during lane-changing and the vehicle takes up two lanes in the range from the point its head reaching the lane line to the point its end leaving the lane line. The lane-changing time for high speed vehicle can be shorter in comparison to the vehicle with low speed. But in most of the present models, a lane-changing usually completes within one time step, no matter how much the speed the vehicle has.

In order to model the realistic driving behavior in lane-changing, Sasoh proposed a model [27], in which a lane-changing needs 2 seconds; Toledo and Zohar presented a model [28], in which the lane-changing time depends on subject speed relative to neighboring vehicles. In those models, the lane-changing can be cancelled in the duration over which the vehicle would complete the lane change maneuver, if the traffic condition on the original lane becomes better. But the influence of the lane-changing vehicle on the following vehicles on the original lane and the destination lane are not considered.

In this paper, the lane-changing time, which depends on the vehicle's current velocity, is introduced into the CA models for traffic flow. We assume that a lane-changing vehicle takes up the two lanes, i.e., the original lane and the destination lane. So the occupancy of the road will become high when a lane-changing happens. The two-lane system and the on-ramp system are taken as two typical examples to study the effect of lane-changing time on the dynamics of traffic flow. More realistic results are obtained.

This paper is organized as follows: In the following Section, the two-lane system and the on-ramp system are introduced. In Section 3, simulation results are analyzed in detail. The conclusion is given in Section 4.

2 Model

Before introducing the two-lane system and the on-ramp system, we briefly recall the definition of the NaSch model [6], which is used to model the forward motion of vehicle. The NaSch model is a discrete model for traffic flow. The road is divided into L cells, which can be either empty or occupied by a vehicle with a velocity $v = 0, 1, ..., v_{\max}$. The vehicles which are numbered $1, 2, 3, ..., N$ move from the left to the right on a lane with periodic boundary conditions. At each discrete time step $t \to t+1$, the system update is performed in parallel according to the following four rules: (i) acceleration: $v_n(t+1/3) \to \min(v_n(t)+1, v_{\max})$; (ii) deceleration: $v_n(t+2/3) \to \min(v_n(t+1/3), d_n)$; (iii) randomization: $v_n(t+1) \to \max(v_n(t+2/3)-1, 0)$ with probability p; (iv) position update: $x_n(t+1) \to x_n(t) + v_n(t+1)$. Here v_n and x_n denote the velocity and position of the vehicle n respectively; v_{max} is the maximum velocity and $d_n = x_{n+1} - x_n - 1$ denotes the number of empty cells in front of the vehicle n; p is the randomization probability.

2.1 Two-Lane System

The velocity and the position are updated according to the NaSch model. As to the two-lane system, one has to introduce lane-changing rules, which control the parallel motion of vehicles. In two-lane models the update step is usually divided into two sub-steps: In the first sub-step, vehicles may change lanes in parallel according to lane changing rules and in the second sub-step the lanes are considered as independent single-lane NaSch models.

The lane-changing rules can be symmetric or asymmetric with respect to the lanes and to the vehicles. In this paper, we just investigate the symmetric two-lane model. Chowdhury et al. [12] have assumed a symmetric rule set where vehicles change lanes if the following criteria are fulfilled [hereafter referred to as symmetric two-lane cellular automata (STCA) model]:

$$d_n < \min(v_n + 1, v_{max}) \text{ and } d_{n,other} > d_n \text{ and } d_{n,back} > d_{safe}. \tag{1}$$

Here $d_{n,other}, d_{n,back}$ denote the number of free cells between the nth vehicle and its two neighbor vehicles on the other lane at time t, respectively. If there is a vehicle on the destination lane driving side by side with vehicle n, $d_{n,back}$=-1. d_{safe} is a safe distance and equals to the maxspeed of the following vehicle on the destination lane.

2.2 On-Ramp System

The on-ramp system with accelerating lane has been well studied by using CA model in our previous work[22]. The schematic of the on-ramp system is shown in Fig.1. One can see that the road is divided into four sections: region A (main road upstream the point M), B (on-ramp upstream the point M), C (main road downstream the point N) and D (the accelerating section). The NaSch model is used to modelling the movement of vehicle. In section D, the road has two lanes. The vehicle on the right lane must change to the left lane before it reach the end of section D, and the vehicle on the left lane are not allowed to change to the right lane. If the condition

$$d_{n,other} > 1 \text{ and } d_{n,back} > v_{ob} \tag{2}$$

is met, the lane-changing is performed by vehicle n [hereafter referred to as on-ramp with accelerating lane (OAL) model]. Here $d_{n,other}$ and $d_{n,back}$ have the

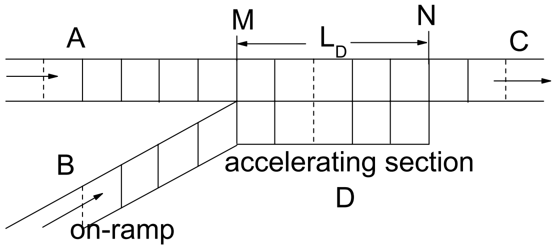

Fig. 1. Schematic illustration of the on-ramp system

same mean as that in the two-lane system. v_{ob} is the velocity of the following vehicle on the destination lane. Condition $d_{n,other} > 1$ means "I can move on the destination lane at next time step"; and condition $d_{n,back} > v_{ob}$ is a safety criterion.

2.3 Lane-Changing Time

The lane-changing time depends on the current velocity. In this paper, $v_{\max}$=5 is selected. We assume that the vehicle with velocity 0, 1, 2, 3, 4 and 5 takes $3t_0$, $3t_0$, $2t_0$, $2t_0$, $1t_0$ and $1t_0$ time step(s), respectively, to perform a lane change. During a vehicle changing lane, it takes up the two lanes, i.e., the current lane and the destination lane. Now, d_n of the lane-changing vehicle is calculated by $d_n = \min(d_n^l, d_n^r)$, d_n^l (d_n^r) is the number of empty cells in front of vehicle n on left (right) lane. When the gaps $d_{n,other}$ and $d_{n,back}$ are calculated, one should take the lane-changing vehicle into account. As to the vehicle just driving behind the lane-changing vehicle, it does not change lane for $d_n = d_{n,other}$. When a vehicle is changing lane, it will return to the original lane if the traffic condition on the original lane becomes better. The two-lane system considering lane-changing time is referred as STCA-LT model, and the on-ramp system considering lane-changing time is referred as OAL-LT model.

2.4 Boundary Condition

In the two-lane system, periodic boundary condition is used. While in the on-ramp system, open boundary condition is adopted. We assume that the first cell on section A and B correspond to x=1, and the entrance regions of road A and B include $v_{\max}$ cells, i.e., the vehicles can enter road A and B from the cells $1, 2, \ldots, v_{\max}$. In one time step, when the update of the vehicles on the road is completed, we check the positions of the last vehicles on road A and B and that of the first vehicle on road C, which are denoted as x_A^{last},x_B^{last} and x_C^{first}, respectively. If $x_A^{last}(x_B^{last})> v_{\max}$, a vehicle with velocity $v_{\max}$ is injected with probability $\alpha_A(\alpha_B)$ at the cell $\min[x_A^{last}(x_B^{last})-v_{\max},v_{\max}]$. Near the exit of road C, the leading vehicle is removed if x_C^{first} is larger than the length of lane C and the following vehicle becomes the new leading vehicle and it moves without any hindrance.

3 Simulations and Discussions

In the simulation, the randomization parameter $p = 0.3$ is used. Each cell corresponds to 7.5m and a vehicle has a length of one cell. One time step corresponds to 1 s.

3.1 Two-Lane System

The two-lane road is divided into 2×2000 cells. Here only the homogenous system with one type of vehicle is considered. In Fig.2, we show the fundamental diagrams. One can see that the flux per lane in the intermediate density range is improved in the STCA model compared to that of a single lane road. As to the STCA-LT model, the flux in the intermediate density range is also enhanced but smaller than that of the STCA model when t_0=1. However, the flux is depreased when t_0=2 compared to that of the single lane road. This indicates that in the homogenous system lane-changing can not improve the flux per lane if a vehicle takes longer time to complete a lane change.

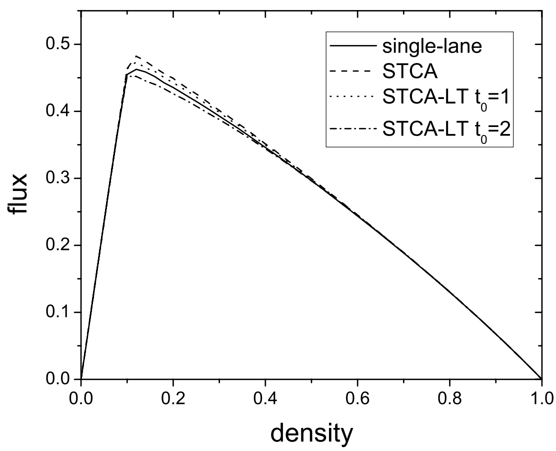

Fig. 2. Fundamental diagrams for the STCA model, the STCA-LT model and the single-lane NaSch model

The lane-changing frequency in the two models are shown in Fig.3. Here the number of lane changes that happen at $v = 0, 1$, $v = 2, 3$ and $v = 4, 5$ are counted seperatedly. The lane-changing frequency is defined as the number of lane changes per time step per vehicle. One can see that as density increasing, the lane-changing frequency first increases then decreases in all cases. In the free flow density range, all the vehicles can drive with free flow speed. There is no vehicle with $v < 4$. So lane-changing frequency with $v < 4$ is 0. As the density increases to the congested flow density range, jams will appear on the road. Vehicles with low speed may change lane to obtain good traffic condition. When the density is

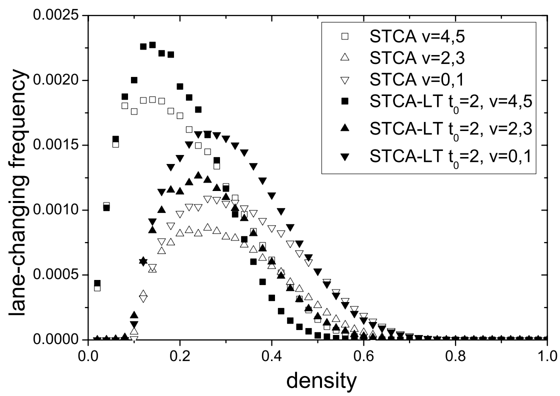

Fig. 3. Lane-changing frequency of the vehicles with different velocity in the two models

not large, the lane-changing with v=4,5 takes the highest proportion. But when the density is large, the lane-changing with v=0,1 takes the highest proportion. When the density is larger than 0.7, lane-changing rarely happens. Compared the results of the STCA model with that of the STCA-LT model, one can see that, the lane-changing frequency of the latter is higher than that of the former in the intermediate density range. The longer the lane-changing time, the higher the frequency. Because the vehicle will take up the two lanes in the duration over which it performs lane-changing, the occupancy of the two-lane road becomes higher as lane-changing time growing. The traffic condition becomes worse and more vehicles are willing to change lane to improve the driving condition. As we can see in Fig.2, the maximum flux of the STCA-LT model is lower than the of the STCA model. So high lane-changing frequency does not bring high flux when the lane-changing time is considered.

We argue that in the homogenous two-lane road system, the traffic condition can not be improved but wrosened by lane-changing if the lane-changing time is too longer.

3.2 On-Ramp System

In the simulations, section C is divided into 1000 cells; section D into L_D=20 cells and sections A and B into 2000 cells. The first 50,000 time steps are discarded to let the transient time die out. The flux is obtained by counting the vehicles that pass a virtual detector in 50,000 time steps. The flux on roads A, B and C are q_A, q_B and q_C, respectively.

In Fig.4, the phase diagram in (α_A, α_B) space of the two models is shown. Similiar to the results in Ref.[22], one can see that the phase diagram is categorized into four regions. In region I, the traffic flows on both roads A and B are free flow; in region II, the traffic is free on road A and it is congested on road B; in region III, the traffic is congested on road A and is free on road B; and in region IV, the traffic flows are congested on both roads A and B.

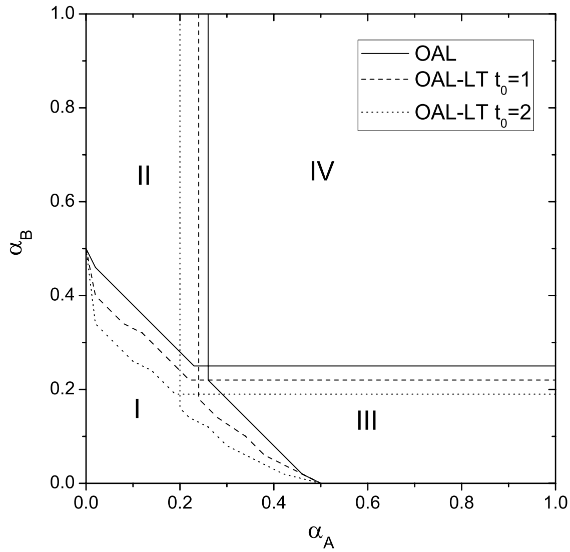

Fig. 4. The phase diagrams in (α_A, α_B) space of the OAL model and the OAL-LT model. Here L_D=20.

Compared with the results of the OAL model, one can see that region I shrinks and region IV enlarges in the OAL-LT model. As t_0 becomes large, regions I and IV also change with the same trend. This indicates that longer lane-changing time deteriorates the traffic condition on both the main road and the on-ramp.

Next, the capacity of the on-ramp system is investigated. Since $q_C = q_A + q_B$, the saturated flux q_C^s on road C is deemed as the capacity of the on-ramp system. Fig.5 shows q_C as a function of α_A with different α_B. One can see that q_C first increases as α_A growing then the saturated flux q_C^s is reached. When there is no vehicles from on-ramp lane α_B=0, the on-ramp system is degenerated into the single-lane system. $q_{\max}$ is the maximum flux of the single-lane system. When there are vehicles from on-ramp lane α_B >0, the saturated flux q_C^s equals to the value of $q_{\max}$ in the OAL model, while q_C^s is lower than $q_{\max}$ in the OAL-LT model. Thus the capacity of the on-ramp system is not reduced in the OAL model, while it drops to lower values in the OAL-LT model. We know that the capacity drop usually happens in real traffic, so we believe that the lane-changing time is a factor for capacity drop. Fig.5 also shows that as t_0 increasing, the capacity drops to smaller values.

Lastly, the impact of the on-ramp on the main road is studied. We choose α_A=0.5, and the flux of road C q_C as a function of α_B is shown in Fig.6. One can see that in the OAL model, q_C does not change as α_B increasing. This is consistent with the above result that the capacity is not reduced in the OAL model. However, q_C will first decrease then become constant in the OAL-LT model. As α_B increasing, the number of vehicles changing from the on-ramp to the main road becomes larger, thus more disturbances are brought to the

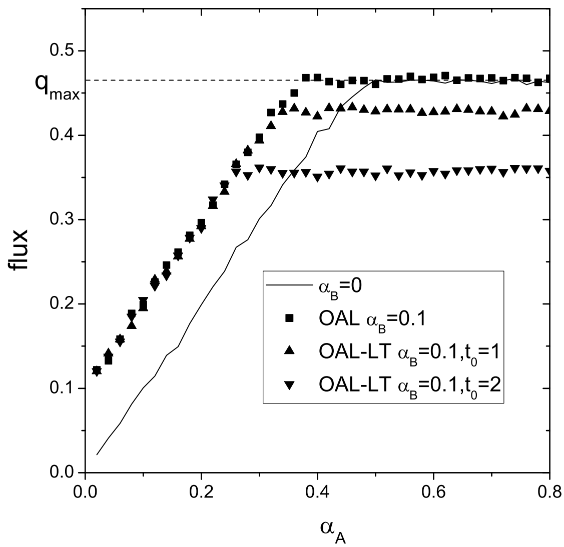

Fig. 5. q_C as a function of α_A. L_D=20.

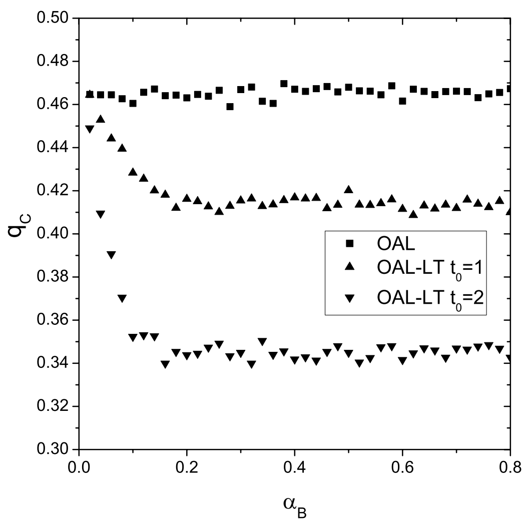

Fig. 6. q_C as a function of α_B. The parameters are α_A=0.5 and L_D=20.

traffic on the main road and q_C decreases. When α_B is larger than the critical value, the traffic flow on both the main road and the on-ramp are saturated, and the number of vehicles changing from the on-ramp to the main road becomes constant. So q_C does not change when α_B is larger.

4 Conclusion

In this paper, the lane-changing time is taken into account in the CA models for traffic flow. A vehicle with low speed will need more time to complete a lane change. Thus we assume that the lane changing time is related to the velocity of the vehicle.

In the two-lane system, with longer lane changing time the maximum flux per lane is depressed, but the lane-changing frequency is improved.

In the on-ramp system, the traffic conditions on both the main road and the on-ramp are deteriorated and the capacity drop can be simulated when lane-changing time is considered.

Finally, we should mention that only the simulation results are presented here. The empirical data need to be collected to verify our model and this will be done in our future work.

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