Journal of Theoretical and Applied Information Technology
10th April 2013. Vol. 50 No.1

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

A DEFORMED CELLULAR AUTOMATON MODEL

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ABSTRACT

In existing Cellular Automaton (CA) model, the cellular width is not related to vehicular velocity. However, in real condition, at road's toll station or intersection, the introduced fixed infrastructure or pedestrians moving into vehicle lane will result in the lane narrowing, so limit the passing speed of vehicle. According to this condition, this paper presents a deformed CA model, and makes a primary study on relationship between cellular deformed volume and actual cellular width, vehicle speed and width. Through simulating, we compare the traveling states of vehicle on single lane under three cases respectively without deformation, with and with unfixed deformation. The simulation shows that the limited speed resulted from cellular deformation has obvious impact on the fluency and smoothness of traffic flow, and there is a boundary between congested and free phases at position of deformed cell, however, with the increase of traffic flow density, the deformed cell appears to have less influence on vehicle advance.

Keywords: *Cellular Automaton Model，Deformed Cell，Vehicle Velocity，Perceptive Width*

1. INTRODUCTION

Cellular Automaton (CA) is a simulative model that variables of time, space and state are all discrete. The most typical CA is NS model[1] that describes the traffic flow of expressway introduced by Nagel and Schreckenberg in 1992. Only using four simply parallel rules, it can simulate some real and complicated traffic phenomenon. After that time, a larger number of researches have been done to modify, improve or set some rules based on the NS model to study specific traffic phenomenon[2-13], for instance, problems of expressway toll station, mixed traffic flow with motor and non-motor vehicle, different driving capability, ramp effect and mixed traffic at intersection, etc. Thereinto, on researching the expressway ramp effect by NS model, Hua et al. [9] studied a case that each cell of accelerating lane was wedged into main road cell. Although this research introduces virtual vehicle, and presents that when the position of a virtual vehicles, which runs into the main lane, is ahead of or parallels to a half of lattice, the following vehicle will be affects, actually, it is just a another way to deal with the case of two lanes in a same space, which is not involving the cellular width. On studying the influence of bicycle on motor vehicle, Jia et al.[10] focuses on interference of friction besides block, which means that bicycle will swing more or less when it moves forward, the automobile driver will feel stress about security from the side of bicycle, so he will take care and decrease the driving speed. Here, though the case of bicycle occupying vehicle lane is taken into account, it is still a problem of sharing lanes of bicycle and vehicle in essence. It describes the behaviors of vehicle traffic flow and bicycle respectively by NS model and EBCA1 model[11], just considering the double restriction from vehicle and bicycle in a sharing lane for vehicle traveling. Zheng[12] studied the mixed traffic flow at intersection and found the difference between motorcycle and automobile. When the green lights, because motorcycle is faster than automobile in startup velocity and rider of motorcycle is urgent to pass the intersection, the lateral expansion effect will be brought by motorcycle, then the driving space of automobile will be compressed, which makes the speed of automobile decrease.[14] On dealing with the expansion and extrusion effects, he also utilized NS and EBCA2[11] model respectively to analyze the behaviors of automobile and motorcycle traffic flow at intersection, and considered the cell-shared as a traveling constraint. About mixed traffic flow with vehicle and pedestrian, Zheng et al. [13] divided a shared road into different sizes of lattices in terms of vehicle, bicycle and pedestrian, and defined the lattice evolution equations respectively, which are restricted by total occupied state of the shared space when they go ahead. For these existing traffic flow CA models, we can find that the width of every cellular lattice is invariable, and the driving speed of vehicle is independent of the cellular width. In

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

fact, at road's toll station or intersection, after some fixed infrastructure was established or pedestrians walked into vehicle lane, the lane is narrowed and results in that vehicular speed is limited. [15]This paper analyzes this real traffic phenomenon, and defines a cell in narrowed width as deformed cell, and the limited speed resulted from deformed cell as deformed limited speed.

The paper is organized as follows. In Section 2, we present the cellular lattice figures for single lane without deformation and with fixed deformation, and for double lanes with unfixed deformation. The relationship between deformed volume and actual cellular width, vehicle velocity and vehicular width are also analyzed qualitatively. Section 3 simulates the traffic flow by NS model according to above three cellular cases, and makes a related comparison and analysis. Finally, Section 4 concludes the paper.

2. A DEFORMED CELLULAR AUTOMATON MODEL

In the existing traffic flow CA models, the width of every cellular lattice is invariable, and the driving speed of vehicle is irrelevant to the cellular width （shown in Figure.1）. But in real condition, the lane's width is variable, and it does impact vehicle driving velocity greatly. One of cases is at road's toll station or ramp channelized area, the lane's width becomes narrowing generally (shown in Figure.2). The other case is at road intersection, pedestrians gradually move into vehicle lane, which makes the lane more and more narrow, and its width will change dynamically (shown in Figure.3). This case is very common in Chinese city.

Figure.1 represents a traffic flow CA model with invariable width for single lane (called Case 1). It shows that the simulated lane consists of cellular lattices with a same size, the width of each cell is uniform and it has no any impact on driving vehicle.

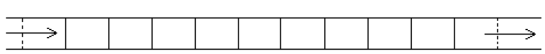

Figure1. Case 1: Existing Traffic Flow CA Model For Single Lane

Figure.2 is a traffic flow CA model with fixed deformation for single lane (called Case 2), and Section AB is a toll station or ramp channelized area. We can find that the fixed infrastructure has occupied quite area of the lane (marked by thick-black line in Fig.2), which leads to vehicle slowing down or even stop. As the infrastructure is immovable, the deformed volume of a cell is fixed. Although there is no definite speed-limited sign, according to real condition, the passing vehicle will take corresponding countermeasures, such as slowing down or driving carefully.

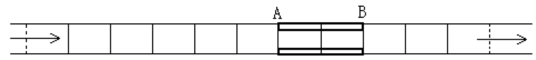

Figure2. Case 2: A Traffic Flow CA Model With Fixed Deformation For Single Lane

Figure.3 is a traffic flow CA model with unfixed deformation for single lane (called Case 3), and lattices a, b, c, d constitute a common area shared by lanes from east to west and south to north. In this figure, the right of way is for the traffic flow in east-west direction, but there are some pedestrians in south-north direction who try to pass the crossroad, and they will step into the vehicle lane, so occupy the lane's width in east-west direction. With pedestrians going forward, more and more cellular width will be occupied, which are presented as 4 semicircles in Fig.3. In this condition, vehicle will decrease its velocity gradually till stop. Comparing with Case 2, the lane's width is variable with pedestrians' movement, resulting in that the passing velocity of vehicle is also variable.

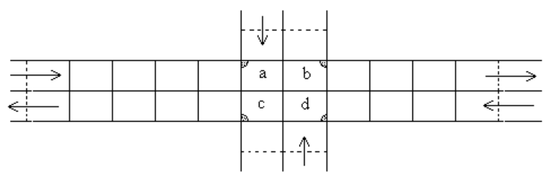

Figure3. Case 3: A Traffic Flow CA Model With Unfixed Deformation For Single Lane

The erect dashed lines in Figure.1, Figure.2 and Figure.3 denote that the length of this section is variable. In order to compare the influence of cellular deformation on traffic flow, here, we only simulate the traffic flow in a single lane, and in Case 3, there is only the traffic flow from west to east, therefore, no vehicle changes into other lanes. In these three cases, we use NS model[12] as the vehicle motion rules, i.e. at each discrete timestep $t \to t+1$, the motion of vehicle i is updated in sequence by the following rules:

(i) Acceleration rule: $v_i \to \min(v_{\max}, v_i + 1)$;

(ii) Deceleration rule: $v_i \to \min(v_i, gap_i)$;

(iii) Randomization rule (with a certain probability p): $v_i \to \max(v_i - 1, 0)$;

(iv) Movement: $x_i \to x_i + v_i$.

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

Here, v_i is the speed of vehicle i, $v_{\max}$ is the permitted maximum speed, x_i denotes the cellular position of vehicle i. gap_i is the number of empty cells in front of the vehicle i, with $gap_i = x_{i-1} - x_i - 1$, vehicle $i-1$ is the leading car of vehicle i. p is a deceleration probability to imitate driver's behaviors of acceleration or deceleration.

For the case of deformed cell, driver will feel a perceptive width in terms of current condition, and then take corresponding countermeasures according to the width apperceived himself. Certainly, the effective area of deformed cell is included in the range of driver's judgment. A primary study shows that the perceptive width w_j^f that driver feels for ahead deformed cell j is related to the current vehicular speed v_i, vehicular width w_c, actual width w_j^r of deformed cell j and factor λ that causes a cell deformed, i.e.:

$$w_j^f = f(\lambda, v_i, w_c, w_j^r) \tag{1}$$

Because function f is characterized by obviously nonlinear and statistic features, here, we only make a qualitative analysis: the higher the vehicular speed v_i, the less the perceptive width w_j^f is, but when v_i decreases to a certain speed, the perceptive width w_j^f will remain the same; the wider the vehicular width w_c, the less the perceptive width w_j^f is ; the actual width w_j^r is directly proportional to the perceptive width w_j^f; in the condition of fixed deformation, factor λ that causes a cell deformed is equal to 1, i.e. $\lambda = 1$, otherwise, $\lambda < 1$.

We also qualitatively study the relationship between countermeasures of driver and the perceptive width: when $w_j^f \le w_c$, it means that driver feels the vehicle can not pass, then he will stop vehicle; when $w_j^f \ge w_s$, driver thinks that the perceptive width is large enough for vehicle passing, then he will drive carefully and do not take the action of brake; when $w_c < w_j^f < w_s$, driver will decelerate the vehicle and pass the deformed cell in a safe speed. The nearest w_j^f is close to w_c, the more driver decelerate. Here, w_s is a safe width, which value can be a standard width of lane, for instance, each lane's width for urban road is 3.5m.

3. SIMULATION AND DISCUSSIONS

3.1 Simulation Assumptions

(1) Length of road section

In above three cases, lengths of road section L are all 1,000 cells. In Case 2, Section AB comprises 2 fixed deformed cells, and the length of its left section is $L_A = 500$ cells, right section $L_B = 498$ cells. In Case 3, the left section of cellular lattice a is $L_A = 500$ cells in length, and the right one of cellular lattice b is $L_B = 498$ cells. Suppose that the serial number of cell farthest to the road's left is 1, and that farthest to the right is L.

(2) Vehicle velocity

The permitted maximum speed for all vehicles is $v_{\max} = 5$ cell/step, each cellular length is 7.5m, and the interval of every timestep is 1s, then the maximum speed $v_{\max} = 5$ cell/step is equivalent to 135 km/h. In Case 2, the limited speeds brought by these 2 deformed cells are the same; in Case 3, the limited speeds produced when pedestrians pass cellular lattice a and b also are the same.

(3) Deceleration probability p

The deceleration probability p has great impact on the smoothness of traffic flow. Since our simulating condition is expressway, its traffic flow is relatively fluent and smooth, so the deceleration probability is quite small. Here, $p = 0.1$.

(4) Boundary condition

In order to compare conveniently, there is only a single lane in one direction in Case 1, 2 and 3. In Case 3, the traffic flow is just from west to east. The simulating boundary condition is periodic, which means that the vehicle leaved off lattice L (i.e. the end of a lattices chain) will be back to lattice 1 (i.e. start of that chain). Thus, in each simulation, once we set the total number of vehicles

Journal of Theoretical and Applied Information Technology
10th April 2013. Vol. 50 No.1

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

N in a lattices chain, the traffic flow density $\rho = \frac{N}{L}$ will be a constant. The density will be increased by 0.5% each time, till the maximum density is 80%. Through changing the traffic flow density, we can investigate the variety of vehicle speed.

The data to be analyzed is those of simulating outputs after 40,000 timesteps, so as to eliminate the influence by initial state.

3.2 Simulation Outputs

Figure.4, Figure.5 and Figure.6 represent the evolution of traffic flow when density is 20% respectively in Case 1, Case 2 and Case 3. In these figures, the horizontal axis denotes a continuous cellular lattices chain, in which the white indicates this cell is available and the black is occupied by vehicle; the longitudinal axis represents the evolving timestep. These three figures only show the traffic flow of one of road's sections, which is a section around No. 500 cell, i.e. a section around the deformed cell.

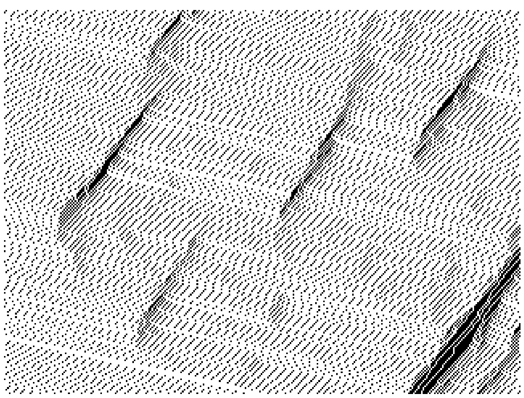

Figure4. Traffic Flow Evolution When Density Is 20% In Case 1

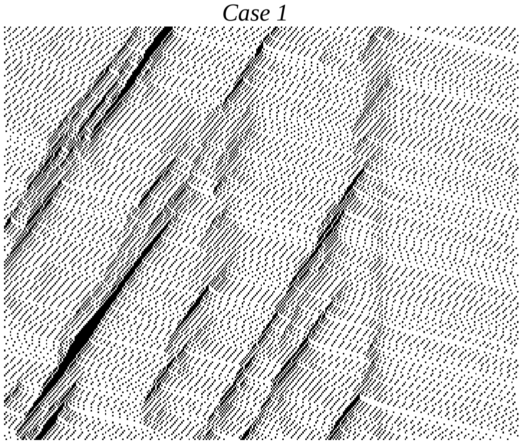

Figure5. Traffic Flow Evolution When Density Is 20% In Case 2

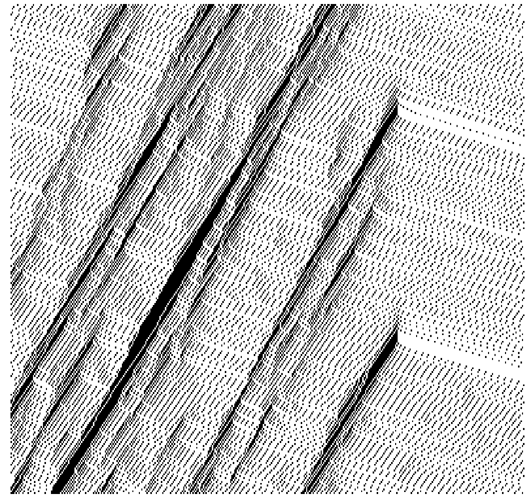

Figure6. Traffic Flow Evolution When Density Is 20% In Case 3

Figure. 7 shows the relationship between traffic flow density and velocity when cells are fixed deformation. This paper present 3 types of simulating data under three fixed deformation cases. They are the deformed limited speeds of 1cell/step (i.e. 27km/h), 2 cell/step (i.e. 54 km/h) and 3 cell/step (i.e. 81 km/h) respectively. For the deformed Section AB, the maximum passing speed for each vehicle is limited by the deformation. In order to clearly show the difference of speeds, we use different colors to distinguish these 3 deformed cases that from left curve (marked with blue) to right one (black) reflect relationship between density and speed respectively with limited speed 1, limited speed 2 and limited speed 3.

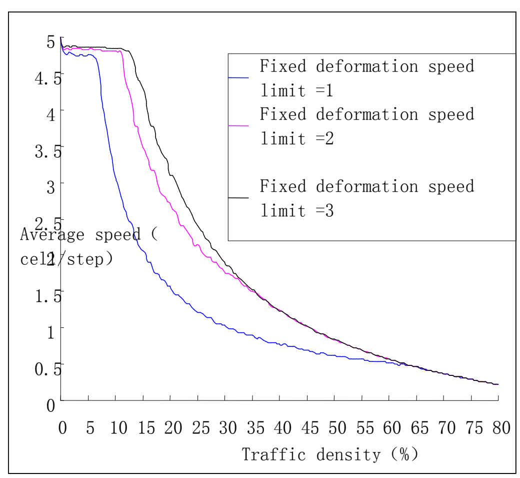

Figure7. Relationship Between Traffic Flow Density And Speed In Case 2

Figure.8 illuminates the traffic flow density and speed in three cases. From left (marked with red) to

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ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

right (blue) represent the curves of density and speed in Case 1, Case 2 and Case 3 in turn. Here, the curve of Case 2 is with deformed limited speed 2. In Case 3, we define 120 timesteps as a cycling period, so the limited speed of 5cell/step is 95 timesteps, 4cell/step is 5, 3cell/step is 5, 2cell/step is 5, 1cell/step is 5 and 0cell/step is 5.

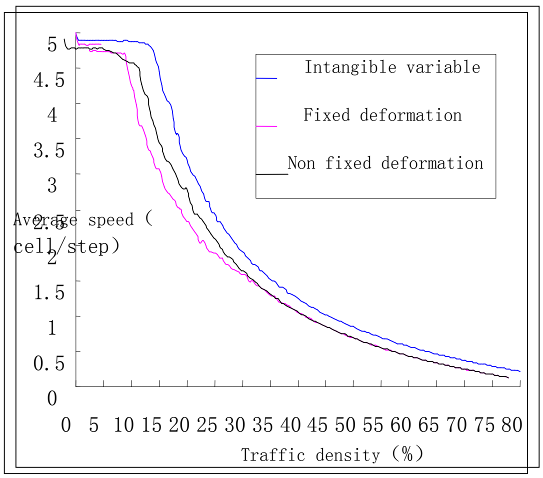

Figure8. Comparison Of Traffic Flow Density And Speed In Three Cases

3.3 Discussions

(1) From Figure.4, 5 and 6, we can find that under the same density, there are phases of traffic congestion to some extent in these three cases. However, the congestion in Case 1 occurs in local, and the congested state also spreads locally, it means that once congestion occurs, it can be evacuated quite quickly, and there is no obvious congestion around No. 500 cell. But the congestion in Case 2 is heavier than that of Case 1, and there is an evident boundary between congested and free phases about No. 500 cell, that is to say, at the position of deformed cell, because the speed is limited to decrease, congestion often takes place, while after deformation, because of the low speed, traffic flow will be free. In Case 3, there is periodic congestion about No. 500 cell, and its spread is overall. In addition, we can find a Threshold Effect that there appears a blank traffic zone.

(2) In Figure.7 we can find that under different fixed deformations, the variety of permitted passing speed has obvious impact on the fluency and smoothness of traffic flow. Under the fixed deformation with limited speed of 1 cell/step, when density is 8%, there is a distinct inflexion for traffic flow speed, decreased from 4.51 cell/step to 3.94 cell/step. With limited speed of 2 cell/step, there is an inflexion when density is 12.5%, which the speed drops from 4.27 cell/step to 3.79 cell/step. However, with limited speed of 3 cell/step, the inflexion appears only when density is 15%, its speed decreased from 4.29 cell/step to 3.94 cell/step. It also exactly reflects that the higher the passing speed in toll station, the better is, for example, to establish an Electronic Toll Collection (ETC) lane, or increase number of toll lanes to decrease traffic flow density. In Figure.7, we also can find that with the increase of density, the fixed deformed cell appears to have less influence on vehicle advance. When the density reaches 63%, there is little impact on the smoothness of traffic flow.

(3) From Figure.8, we can observe that there are influences of both cells with fixed or unfixed deformation on the advance of traffic flow to some extent, but the effect of Case 3 is less than that of Case 2, this is because the limited speed below 2 cell/step only lasts 10s, accounting for 8.33% of a whole period. Moreover, we can find again that when the density reaches 35%, the average speeds for three cases are basically uniform, which shows that the density has become one of main factors influencing the vehicle advance.

4. CONCLUSIONS

In real traffic flow, we find that when the fixed infrastructure is introduced at road's toll station, or pedestrians move into vehicular lane at intersection, the lane is becoming narrow, which limits the passing speed of vehicle. Therefore, this paper presents a deformed CA model based on existing CA traffic flow models, and compares the traveling states of vehicle on single lane under three cases respectively without deformation, with fixed and unfixed deformation. According to the simulating results, we find that the limited speed led by cellular deformation has obvious impact on the fluency and smoothness of traffic flow, and a boundary appears between congested and free phases at position of deformed cell, the expected Threshold Effect also is observed. However, we did not make the quantitative analysis on relationship between density, number of toll lanes and passing speed. In addition, although the relationship between cellular deformed volume and actual cellular width, vehicular speed and width has been discussed preliminarily, since this relationship is characterized by obviously nonlinear and statistic features, it still needs to investigate and study further.

ISSN: 1992-8645 www.jatit.org E-ISSN: 1817-3195

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