Applied Mechanics and Materials Vols 409-410 (2013) pp 1075-1080 *Online: 2013-09-03*
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doi:10.4028/www.scientific.net/AMM.409-410.1075

Simulating impacts of variable accident sites on freeway weaving section traffic flow in cellular automation model

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Keywords:traffic flow; weaving section; an accident car; cellular automata; variable accident sites

Abstract. As a typical traffic bottleneck, the freeway weaving section is one source of vehicle conflict and an accident-prone area.This paper presents a cellular automaton model to characterize accident-induced traffic behavior around the weaving section, in which different accident sites are considered. The spatial-temporal profiles are presented after the numerical simulation. It is shown that the accident car not only causes a local jam behind the accident car, but also causes vehicles to cluster in the bypass lane. The accident occurring in lane 1 (the left lane) in the weaving section are more inclined to cause traffic jam and the decrease of traffic capacity than in lane 2 (the right lane). Furthermore, the curves of saturated flux of weaving section against different accident sites are given. It is found that the capacity of weaving section will decrease fastest when the accident is located in the downstream of weaving section.

Introduction

With the development of modern society, traffic problem such as congestion and traffic accident have attracted considerable attention from physicists[1,2]. Nowadays CA has become an excellent tool for simulating real traffic flow, because its efficient and fast performance when used in computersimulations.Nagel and Schreckenberg proposed the well-know NaSch model for single-lane traffic flow[3]. Later, various generalizations and extensions of the NS model are proposed to simulate the behavior of traffic flow, such as the Fukui-Ishibashi(FI) model, VDR model, TT model, etc.

A traffic bottleneck is a section of road with a carrying capacity substantially below that characterizing other sections of the same road. It can be classified into permanent and temporary bottleneck. The permanent bottleneck includes on- and off-ramp, weaving section, uphill gradient, tollbooth, etc. The temporary bottleneck includes traffic accident and lane reduction and so on. Among the various types of bottlenecks, many of them have been widely studied by using CA model. Jiang et.al modeled and analyzed the on-ramp and off-ramp road system in cellular automaton. They studied the interaction between the main road and the ramp in detail[4]. Jia et al. adopted some realistic lane-changing rules to depict the merging and diverging behavior and proposed a more suitable CA model to describe the weaving section[5]. Zhu et.al.adopts both symmetric lane changing rules and asymmetric lane changing rules to study two-lane traffic with a blockage induced by an accident car[6]. Nassab et.al investigated the simulation of vehicular dynamics near a partial reduction in a road from two lanes to one lane and some regulation strategy[7]. In this paper, we study the combined effect of permanent and temporary bottleneck on weaving section traffic flow and analyzed the evolution of traffic flow around the weaving section after an accident.

In the weaving section, in order to enter the appropriate lane within a limited time and space, the driver have to change lanes frequently and often are forced to change lanes, which makes weaving section become a traffic bottleneck and accident-prone area. After the accident, due to various reasons, the accident vehicles usually are not cleared away from the scene of accident very soon so that the vehicle has become a temporary bottleneck of the road .Kurata and Nagataniemployed an optimal velocity model to generate a two-lane traffic model in which symmetrical lane-changing rules were adopted to investigate accident-induced traffic congestion[8]. Sheu established a microscopic traffic behavior modeling approach that characterises incident-induced intra-lane and inter lane traffic manoeuvers, which focuses on cases of arterial lane blocking(i.e. incidents on a roadway between two adjacent intersections)[9].

In order to decrease the traffic accident frequency and its adverse impact, it is meaningful to investigate the traffic behavior near weaving section influenced by an accident, which is the combined effect of permanent and temporary bottleneck. However, these issues have seldom investigated in previous researches. Little has been studied about the dynamics of traffic induced by a car accident near the weaving section using CA model. In this article, the physics of congested traffic pattern in freeway weaving section with an accident car is studied using the cellular automaton model.

The remainder of this article is organized as follows. In section 2, the model used for simulation is introduced, including the weaving section model and the accident model. In section 3, the simulation results are analyzed. The conclusion is given in Section 4.

Model

Nagel-Schreckenberg model of single-lane traffic. The simple single-lane stochastic cellular automata model is studied by NaSch et al. In this traffic flow model, the road is divided into L cells, and a vehicle has a length of$l$ cell(s) and the time is discrete. Each cell can be either empty or occupied by a vehicle with a velocity$0,1,2\cdots,v_{max}$, where $v_{max}$is the maximum speed.The underlying dynamics of the NaSch model is governed by the updating rules applied at discrete time steps.Next, we briefly recall the updating rules of the NaSch model. There are four sub-steps:

Step1 acceleration, $v_n \to \min(v_n+1, v_{max})$;

Step2 deceleration, $v_n \to \min(v_n, d_n)$;

Step3 randomization, $v_n \to \min(v_n-1, 0)\ with\ probability\ p$;

Step4 position update, $x_n \to x_n + v_n$;

Here, v_n and x_n denote the velocity and the position of the n_{th} vehicle respectively;$d_n = x_{n-1} - x_n - l$ denotes the number of empty cells in front of the nth vehicle , and l is the length of the vehicle , i.e.the number of cells that is taken up by the vehicle ; p is the randomization probability.

Two-lane cellular automaton model of homogeneous traffic. In order to extend the NaSch model to multi-lane traffic, one has to introduce lane changing rules. Here we consider two lanes traffic and adopt the symmetric lane changing rules proposed by Chowdhury et al[10]. The updating step is divided into two sub-steps: one is sideways movement, i.e., vehicles may change lanes in parallel according to the lane-changing rules; and the other is forward movement, i.e., the speed and position of each vehicle is updated in the current lane following the rules as those in the NaSch single-lane model.

According to the motivation of lane-changing, the lane-changing rules can be classified into two kinds: discretionary and mandatory. Discretionary lane changes are those which are only desired when the driver wishes to move from a slower lane to a fast moving one. The discretionary lane changes on the two-lane main road are modeled by the following symmetric rule, which is denoted as rule 1:

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

Here,d_n, $d_{n,back}$ denote the number of free cells between the nth vehicle and its two neighbor vehicles on the other lane at time t.$d_{n,back} > v_{max}$ is the security criterion and$d_n < \min(v_n + 1, v_{max})$, $d_{n,other} > d_n$is the incentive criterion.

Mandatory lane changes arise due to the vehicle approachingthe entrance which it must pass through to continue the journey. Such behavior is mandatory lane change and the lane-changing rule is described asfollows and it is denoted as rule 2:

$$d_{n,other} \geq l \ and \ d_{n,back} \geq v_{n,back} \quad (2)$$

Here,$v_{n,back}$is the velocity of the vehicle behind on the destination lane. It meansthat the vehicle will change lane as long as the conditions on the desired lane isconvenient for driving and the gap to the following vehicle is large enough.

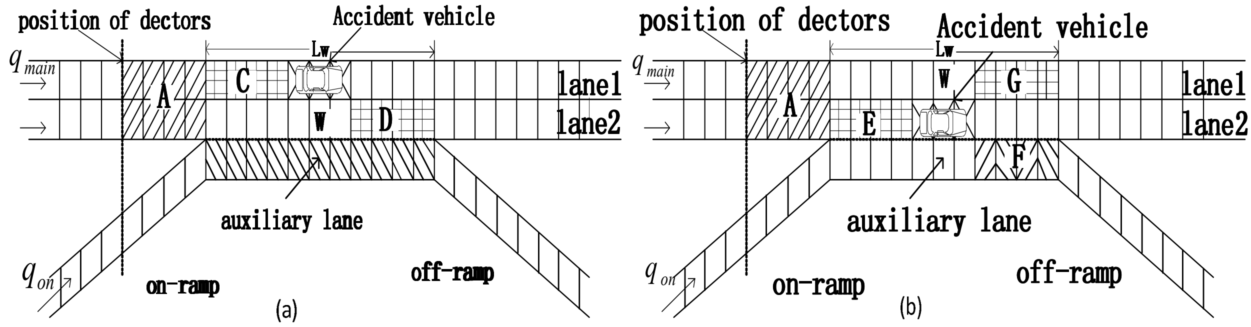

Fig. 1The schematic of an accident in the weaving section, case 1 (a) and case 2 (b)

A weaving section CA model with a blockage due to an accident car. The schematic of the weaving section is shown in Fig. 1. According to Ref.[5], we assume that the exit vehicle on lane1 will first change to lane2 before they drive into the weaving section W. There is a section A with a length of L_A on the main road, and the control measures in section A and W are also similar to Ref.[5].

When a car is broken down or involved in an accident, this car can be considered as a blockage. The accidents are located in the$X_{a\text{th}}$ cells of the road and the scope of this accident is only a length of two cars.As there are two lanes in the main road, we firstly discuss only two kinds of situation: case 1: accident in lane 1; case 2: accident in lane 2.In order to make the conclusion clear, we also study the case that there is no accident in the road, which is called case 0.

When other vehicles behind reach the position occupied by the accident car, they will always stop or change lane to pass through the site. Such change lane behavior is mandatory lane changes and the lane-changing rule is described as rule 2. When the gap between upstream vehicles and accident site is smaller than 75 meters,these vehicles can change to adjacent lane as long as it meets the rule 2. If accident didn't occur in weaving section, it is simply introduced mandatory the lane-changing rules. However, when the accident had occurred in the weaving section, the drive-in and exit vehicle need to adopt some special rules.For case1, the schematic as shown in Figure 1(a), in weaving section, the drive-in vehicle is only allowed to change lane in section D and only the lane-changing from lane 2 to lane 1 is permitted. For case2, the schematic as shown in Figure 1(b), the exit vehicles are only allowed to change lane from the lane 2 to the auxiliary lane in E area, while the drive-in vehicles are only allowed to change lane from the auxiliary lane to lane 2 in section F.

The boundary conditions are adopted as follows. At each timestep, a vehiclecan enter into the two lanes of the main road (on-ramp) with probability q_m (q_{on}), as long as the first v_{max}cells of the lane are not occupied by any vehicles. Andthe position of the new vehicle is min(x_{last}− v_{max}, v_{max}), wherex_{last} denotes theposition of the last vehicle on the lane. The vehicle entering into the main road isset as an exit one with probability p_{off}, which stands for the percentage of the exit vehicle. At the right end of the main road and the off-ramp, the vehicle is removedif its position is larger than the length of the road.

Simulation results and discussion.

In this section, the simulation results are presented. In the simulations, the main road is divided into $2L$ (L = 12000) cells, and the weaving section is at the center of the road. The on-ramp, the auxiliary lane and the off-ramp are joined together as a lane with the length of L. Each cell corresponds to 2.5 m and a vehicle has a length of three cells. One time step corresponds to 1 second. The model parameters v_{max} = 15 and p = 0.3 are used. L_A= 30 and L_W= 100 are chosen if it is not specifically mentioned. Three detectors are installed at the left edge of section A on each lane. They can count the number of vehicles and the velocity of vehicles passing them. Then the flux on the main road J_m(veh/sec/lane), that on the on-ramp J_{on} (veh/sec/lane) and the total flux upstream the weaving section J_{all} (veh/sec) can be obtained. The first 10 000 time steps are discarded to let the transient time die out. The results are obtained in 100 000 time steps.

Spatial-temporal profiles after an accident..First, we examine the spatial-temporal characteristics of weaving section after the accident. We select 300 timesteps (equivalent to 5min) in spatial-temporal diagram, which indicate the vehicle trajectory of weaving section. The 6000_{th}~6100_{th} cells indicate the location of weaving section and we assume the 6050_{th} cell is the accident site in here. In Figure 2, the horizontal axis indicates locations and the vertical axis indicate time steps. Respectively, the vehicles in weaving sectionare divided into 3 types: (1) the vehicles which drive to the right part of the main road, represented by blue spots in the diagrams;(2)the drive-in vehicles, represented by red spots ;(3)the exit vehicles , represented by green spots.

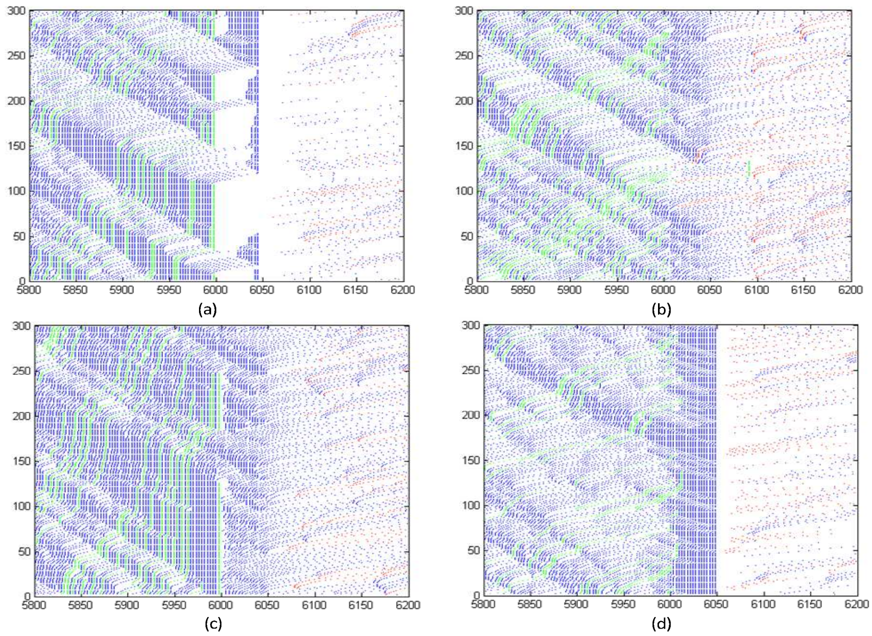

Fig.2. Spatial-temporal profiles in the case ofq_m=0.4, q_{on} =0.2and p_{off}=0.2,the upper diagram indicates case 1 and the lower indicates case 2,(a) and (c) indicate lane 1,(b) and (d) indicate lane 2.

From the figure 2 we can clearly see that the accident causes distinct impact on the weaving section. We focus on analyzing the dynamic characteristics of the weaving section after an accident. From Figure 2 (a) can be seen, there are two main congested area. The first is the right boundary of section A.The second is the right boundary of section C in the weaving section, namely the front of the accident site. This phenomenon is easy to be explained. In lane 1, the exit vehicles (the green spots in Figure 2) must change to lane 2 before reaching the right end of section A. But it is not very easy to change lanes and usually need to wait some suitable chances. Thus the following vehicles (the blue spots in Figure 2),especially the type-1 vehicle ,also have to queue and wait in the lane 1 .Additionally, the car accident in lane 1 make it more difficult for exit vehicle to change lane. Before the accident site, the type-1 vehicles must change to lane 2, but there are three kinds of vehicles in this area and they mutually conflict. As shown in Figure 2(b), there is also a jam area. The lane changing also need to wait, leading to queue and wait, so the second jam area appears. From the above figures, it can be seen that the accident in lane 1 not only have a bad impact on the traffic of lane 1,but also caused a great influence on lane 2, especially on the first half part of weaving area.

After the accident in lane 2, it can be seen from Figure 2(d) that in the first half of weaving area (E area) has dense block and the length of block are basically equal to the length of E section. The reason for this phenomenon is explained as follows. The vehicles in lane 2 must change to lane 1 before arriving at the accident site, but traffic state of lane 1 at this time is also quite crowded. Vehicles must queue up for lane changing, which caused congestion area. From Figure 2(c) we can see, section A and its upstream in lane 1 are quite serious blocked. Because the exit vehicles need to change to lane

2 in section A and vehicles have to wait for space to change lane, which form a more serious congestion in lane 1. The congestion propagates to the upstream, leading directly to the overall congestion upstream weaving area.

The flux of weaving section after an accident . From Fig. 3 (a), one can find that after the accident, the saturation flow of main road has been greatly decreased and the accident exert a great impact on the capacity of weaving area, while have little influence on the on-ramp. This is because, whenq_{on}=0.2, the on-ramp are free flow and the flow are equal with the probability of entering vehicle. Regardless of having accident or not, the interference of weaving area traffic situation on the on-ramp is very small. With the main road vehicle entering probabilityq_m increases the flux of main road is increasing and the flow remained unchanged after reaching saturation. The saturated flow of case 2 is larger than case 1.

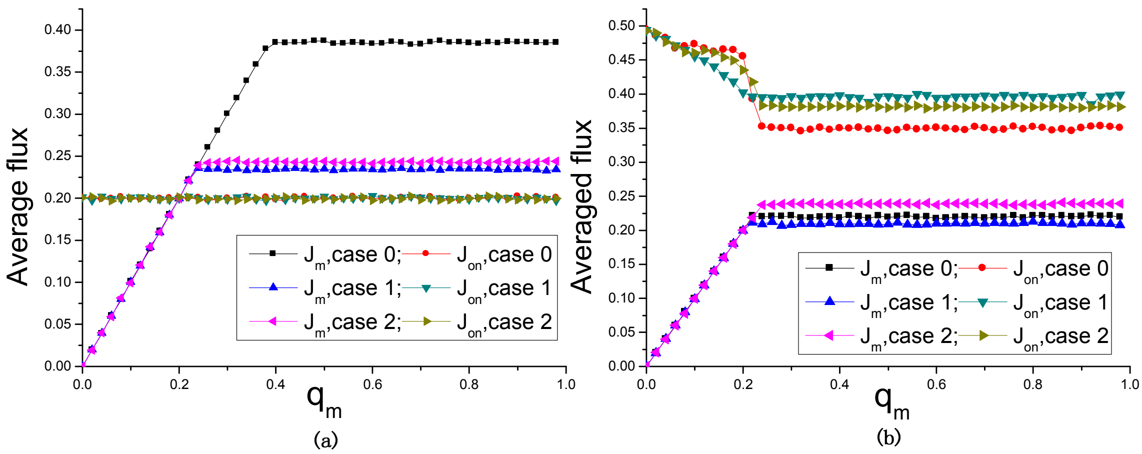

Fig.3. The flux as a function of q_m,(a)q_{on}=0.2;(b)q_{on}=0.5;J_m indicates the flux of main road; J_{on} indicates the flux of on-ramp flux

Figure 3 (b) shows, when the case of q_{on}=0.5, for case 0 (weaving area without accident), on-ramp is congested. Because of mutual interference of main road and on-ramp, saturation flow of main road decreased significantly in contrast withq_{on}=0.2 and on-ramp flow also decreases continuously as the increase ofq_m. For case 1 and case 2, the main road flow change was not obvious in contrast withq_{on}=0.2. At this time, the accident has a positive influence on weaving section to some extent. The two accident cases on-ramp traffic was larger than that at the time of the accident, and in case 2 thesaturated flow is greater than no accidents. Because of the accident, downstream of accident site is in free flow state, making it easier from on-ramp to the main road. To some extent the accident vehicles prevented the congestion propagation, so the main road is rarely influenced by the congestion of on-ramp.As you can see from Figure 4, when q_{on}=0.2, traffic capacity have decreased a lot after the accident. The maximum flow of weaving system of case 2 is larger than case 1.When q_{on}=0.5, the results are analogous.To sum up, in the same conditions, the accident in lane 2 has much worse impact on weaving area, which confirms the conclusion from the flow of view above.

Next, we investigate the impact of different accident sites on weaving section. As we discussed above, the location of weaving section is the 6000_{th}-6100_{th} cells. Additionally, we select 100 cells upstream of weaving section and 100 cells downstream of weaving section here. In the case of q_{on}=0.2， p_{off}=0.2, J_{all}increase as a function q_m until it reach threshold. After the threshold, the flux keep unchanged and become saturated. Then, we record this threshold. From figure 5,one can see that saturated flux in downstream of weaving section are smaller than in upstream of weaving section and saturated flux in upstream of weaving section are smaller than in weaving section. This indicates that when an accident occurred in downstream of weaving section, the capacity of main road decreased. At the same time, the jam caused by this accident also makes it more difficult for vehicles from on-ramp enter into main road. Thus, the capacity of weaving section diminished drastically. However, when the accident occurred in upstream of weaving section, though the capacity of on-ramp

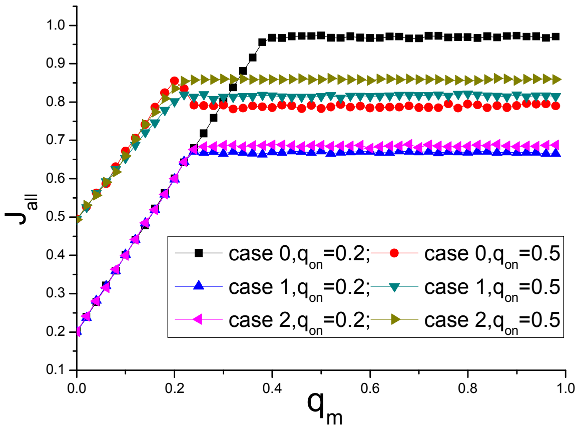

Fig. 4. The flux as a function of q_m , J_{all}indicates the flux of the weaving section

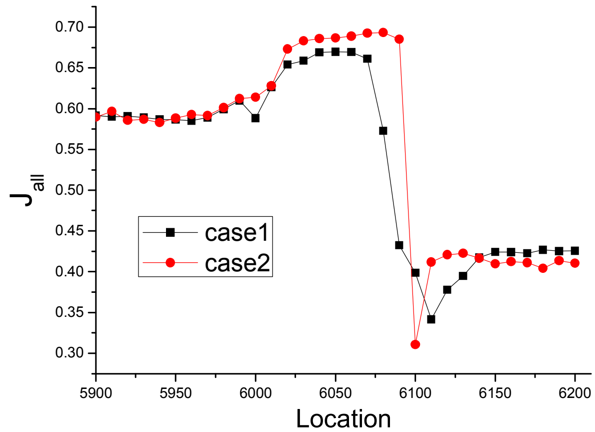

Fig.5. Saturated flux in weaving section when an accident occurred in different sites

diminished slightly, the capacity of main road have a sharp decrease as the accident car hindering and then the capacity of weaving section also become smaller .But it is still larger than downstream accident. As to the accident in weaving section, the traffic jam caused by accident car has a bad impact on main road, which will lead to the decrease of the capacity of main road. But the off-ramp can relieve the congestion caused by accident and thus the capacity of weaving section is much larger than the others.

Conclusions.

After the accident, the road system will show complex dynamic traffic characteristics, especially the accident occurred in the typical road traffic bottleneckweaving section. In this paper, traffic characteristics of freeway weaving section after an accident are studied in cellular automaton model. After the accident, the spatial-temporal diagramand the flux of each road are studied in detail. At the same time, the influence of different accident sites on weaving section also is discussed.

From the space-time diagram we can see the vehicle trajectory, traffic jams after the accident very clearly. Also, accident in different lanes has different impacts on traffic system and accident in one lane can cause certain effect on adjacent lane. From the total flow figure we can see that impact on case 1 the system should be more than case 2. In addition, when the accident occurs in the weaving section downstream, the system capacity decrease most.

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10.4028/www.scientific.net/AMM.409-410

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http://dx.doi.org/10.1016/S0378-4371(96)00314-7