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# Research of vehicle flow based on cellular automaton in different safety parameters

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ABSTRACT

In this paper, the cellular automaton model is put forward to evaluate the effect of the different drivers' psychology in the two-lane highway. Each value of safety parameter $\beta_j^i$, used to reflect the $j$th vehicle driver's psychology in the $i$th lane, represents his or her cautious or risky preference. Assuming that $\beta_j^i$ follows normal distribution, whose mathematical expectation is $\beta$, we generate a stochastic safety coefficient for each driver in the simulation area. Based on different values of $\beta$, the vehicle flow and density are contrasted under some different traffic rules such as driving on the right, free overtaking and non-overtaking with low speed limitation. Through the cellular automaton simulation, the results demonstrate that safety parameter has less influence on the traffic flow under the lightest and heaviest traffic. Meanwhile, non-overtaking with the lowest speed limitation can increase the traffic flow in the light traffic. Free overtaking can improve the usage of the highway. With the increase of vehicle, non-overtaking with the lowest speed limitation will be of benefit to improving the traffic flow.



## 1. Introduction

With the rapid development of society, the traffic safety has aroused people's wide concern. In recent years, the research of traffic flow has been a hot topic (Luna-Benoso et al., 2013; Xiong, 2010; Guan et al., 2008).

Traffic safety on the highway is influenced by various factors. These come from drivers, vehicle performance, environment, traffic flow and so on. In order to make vehicle driving safe and ordered, many researchers have developed some traffic flow models to analyze the rules of driving on the right or the left (Alhajyaseen et al., 2012; Oza, 1999; Qu et al., 2014). According to some experts, the traffic flow models can be divided into three categories (Gong et al., 2002; Hoogendoorn and Knoop, 2013; Liu et al., 2005).

- A macroscopic fluid model: From macro perspective, it describes the traffic state in the form of fluid.
- A car-following model: On the micro level, it describes a single vehicle movement behavior.
- A cellular automaton: On the micro level, it sets up a custom rules to describe the behavior of vehicle.

The traditional macroscopic fluid model studies the average collective behavior of vehicles from the view of fluid mechanics. It is composed of the continuity equation of vehicle conservation and the relation between speed and density. The former is a nonlinear partial differential equation, while the latter can be expressed as a heuristic equation used to close continuity (Gan et al., 2007). Because its several parameters need lots of experimental data to figure out, the usage is limited. Car-following model is one of the basic microscopic traffic flow models. It is a simulation model of vehicular traffic and describes the one-by-one following process of vehicles on the same lane. As a common traffic phenomenon, the following behavior is important. In consequence, car-following model has been paid great attention to. Compared with other traffic flow models, it embodies the human factors and reflects the real traffic situation in a better way. In general,car-following model is mainly expressed as nonlinear partial differential equations and has a variety of parameters confirmed by lots of experimental data. Especially, it is necessary to redefine the parameters and equations with large and complex calculation under different traffic rules. In recent years, to improve car-following model is still a hot topic in the traffic field (Peng and Cheng, 2013; Tang et al., 2011; Yang et al., 2013).

A cellular automaton (CA) is a collection of cells arranged in a grid, such that each cell changes state as a function of time according to a defined set of rules that includes the states of neighboring cells. It is a discrete model widely used in many fields such as computability theory, mathematics, physics, complexity science, theoretical biology and microstructure modeling, especially in traffic simulation (Barlovic, 2003; Rawat et al., 2012; Zia and Ahmad, 2013). Due to its algorithm being simple and flexible, this model

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is easy to be simulated on the computer. At the earliest, the concept was put forward by Stanislaw Ulam and John Von Neumann in the 1940s. In 1986, it was applied to the study of vehicle traffic by Cremer and Ludwig (1986). The most primitive CA traffic flow model was named by Wolfram (1983). In 1992, Nagel and NaSch Schreckenberg put forward the one-dimensional CA model (Nagel and Schreckenberg, 1992). In the same year, Biham et al. came up with the two-dimension and determined its research on the basis of traffic flow (Biham et al., 1992). In 2012, based on symmetric two-lane Nagel–Schreckenberg (STNS) model, Zhang et al. established a CA model of variable speed limit section in freeway with access to real-time traffic information of intelligent transportation system (Zhang et al., 2012). But their drawback lacked the right or the left rules. Sun et al. applied CA theory to model complex traffic behavior in microscopic simulation, however, they had no consideration of overtaking under the different traffic rules (Sun et al., 2005). Based on drivers' psychological characters, Hua et al. studied the city double lanes CA traffic flow model, but their work lacked the corresponding different rules (Hua et al., 2011).

In terms of the advantages and disadvantages of the above researches, we come up with the CA model in a safety parameter, which reflects a driver's psychology correspondingly. Different traffic rules such as driving on the right, free overtaking and the minimum speed without overtaking are also put forward in this paper. Considering the mean of the safety parameters, we find the relationship between traffic flow and density under the different rules. Meanwhile, some relationships with the same mean are also obtained by simulating the CA model. Because of sufficient consideration of the drivers' influencing factors such as safety coefficient, accelerated and decelerated probability and lane-changing probability, the model is better to meet the actual circumstances in highway driving. The results of the simulation are more credible.

## 2. Two-way traffic flow under different traffic rules

A highway with two or more lanes is usually two-way. On the highway the limited speed of vehicle is higher than that of the ordinary driving road. Generally, there are some free-driving and overtaking vehicles under the keep-right-except-to-pass rule. To obverse the dynamic process of traffic flow, we choose the two-lane road to simulate the process of free-driving and overtaking. Meanwhile, there are some assumptions to make readers understand clearly.

- In the simulation area, the highway conditions are the same and there are no traffic accident.
- The limited deceleration/acceleration of vehicles is not considered for simplifying the simulation process.
- Every driver follows the speed limitations of highway traffic rule.
- The speed of a vehicle is not affected by the sinuate road.

### *2.1. Section vehicles generation and their initial velocity in CA*

We regard the lanes as two one-dimensional-discrete-grid chains whose length is $L$. One grid is empty or occupied by a vehicle at the moment $t$, and it is also described one cellular. Based on driving on the right, we define the right lane as the main driving one, and the left as the overtaking lane. Meanwhile, we assume the moving vehicles are standard. To reflect the highway traffic condition more accurately, the length of each cell can be assumed 2.5 m and three-cell length stands for the one of a vehicle. In fact, the average length of a vehicle is 5 m. On the highway, it is impossible to display the conjoint situation of two vehicles. So we add a cell to form a minimum safety distance between two adjacent vehicles in the process of simulation.

In this paper, we study the traffic flow changes under the different congestion extent. The traffic flow is the number of the vehicles passing through a section of the simulation area in a period of time. And the congestion is determined by the vehicle density. When simulation starts, giving the vehicle density $\rho$, we can obtain the vehicle generation rules as follows.

**Step 1.** In the simulation area, from the first cell in the rightmost lane, generate the random number $\lambda$ respectively, and $\lambda \in (0,1)$;
**Step 2.** If $\lambda < \rho$, the corresponding cell will generate one vehicle and the following two cells filled up by this vehicle;
**Step 3.** Continue to find the next blank cell and regenerate the random number $\lambda$; repeat the second step and stop in the leftmost lane of the simulation area;
**Step 4.** If the last but two cell cannot meet $\lambda < \rho$, the last two cells will not generate a vehicle.

In order to obtain the changes of vehicle flow under the different congestion, it is required to maintain the same congestion extent in every process of the simulation. We assume the road tends to infinity. It can be regarded as the unimpeded road in front of simulation area from which the vehicle drive away. Then the congestion traffic will become smoother with the change of time. However, the infinite road is difficult to come true in computer. We can joint two ends into a circle in simulation area. After determining the length of the simulation area, the concrete implement method is that the rightmost vehicles driving away from the simulation area enter the leftmost lane. In order to obtain the reasonable result under the different congestion, we regard the rightmost simulation area as a section of the traffic flow.

According to the-keep-right-except-to-pass rule, the number of vehicles on the main lane is higher than that on the overtaking lane. We define the vehicle density $\rho$ in the unit cell as follows.

$$\rho = \frac{\rho_l + \rho_r}{2} \tag{1}$$

Here,$\rho_r$ is the vehicle number on the main lane and $\rho_l$ on the overtaking lane in the unit cell.

In addition, the generation vehicles should be given a certain speed without random. The initialization of the vehicles plays an important part in affecting the simulation accuracy in the cellular automata theory. Many data and related theoretical researches have proved that the section speed $S$ is a random variable and generally follows normal distribution (Liu et al., 1995).

The generation section vehicle should meet the rule of the speed limit of a highway. As to the regulation in China, the maximum speed of the smooth traffic is 120 km h$^{-1}$ and the minimum 60 km h$^{-1}$. In the cellular automata, we change them into the simulation cells according to the following formula.

$$V = \frac{S \div 3.6}{2.5} \tag{2}$$

Considering the values from the process of cell automata simulation being integers, we adjust the maximum and minimum speed. In this paper, let the maximum to be 117km h$^{-1}$ and the minimum 63km h$^{-1}$. From Eq. (2), we can figure out the maximum $V_{max} = 13$ and the minimum $V_{min} = 7$. So the initial velocity follows normal distribution on the mean of 10. Under the different traffic conditions, the driving speed range is $[0, 13]$.

### *2.2. Traffic flow model based on safety driving*

Let $X_j^i(t)$ mark the rightmost location of the $j$th vehicle in the $i$th ($i = R$ or $L$) lane at the moment $t$ in the simulation area. When the $j$th vehicle is in the right lane, $i$ equals $R$. And $i = L$ denotes the left.

$D_j^i(t)$ signifies the distance between the $j$th vehicle and its front one, nearest to it in the same lane. So $D_j^i(t)$ can be expressed as follows.

$$D_j^i(t) = X_j^i(t) - X_{j-1}^i(t) - 3 \tag{3}$$

Here, three cellular units are described a vehicle length.

Similarly, Let $X_{j-1}^k(t)$ ($k = L$ or $R, k \neq i$) mark the location of the nearest vehicle in front of the $j$th one in the adjacent lane (the $k$th lane) at the moment $t$. $B_{j-1}^k(t)$ signifies the distance between $X_j^i(t)$ and $X_{j-1}^k(t)$. it can be expressed as

$$B_{j-1}^k(t) = X_j^i(t) - X_{j-1}^k(t) - 3 \tag{4}$$

For example, if $i = R$ and $k = L$, The vehicle locations and distances are depicted in Fig. 1.

*2.2.1. Deterministic deceleration*

On the highway, a driver usually makes a decision to decelerate according to the front vehicle distance and speed. In addition, the driver's psychology is an important factor to affect deceleration. A cautious driver will decelerate as long as the distance is shorter than the safety one he judges. However, an adventurous driver often judges the speed of the front vehicle when the distance is shorter. If the speed is quite fast, he will not decelerate. Certainly, the sense of vehicle safety is important to every driver. These influenced factors include the speed, the road feeling, braking distance, the quality of tire, wear-resisting property, security configuration, aging degree serviceability rate etc. (Zhao, 2006). In order to describe the driver's psychology of the $j$th vehicle in the $i$th ($i = R$ or $L$) lane, we introduce $\beta_j^i$ ($\beta_j^i \in [0,1]$) as a parameter to express his venturesome level and $V_{j-1}^i(t)$ to note the speed of his nearest front vehicle. $\beta_j^i V_{j-1}^i(t)$ is the estimated speed judged by this driver. Clearly, the larger $\beta_j^i$ is, the more adventurous the driver is.

Different drivers have different safety psychology because of different influenced factors. So the safety parameters have different values. These parameters are assumed to follow the normal distribution.

$$F_{\beta_j^i}(x) = P(\beta_j^i \leqslant x) = \frac{1}{\sqrt{2\pi}\sigma}\int_{-\infty}^{x} e^{-\frac{(t-\beta)^2}{2\sigma^2}}dt \tag{5}$$

Here, $\beta$ is the mathematical expectation of $\beta_j^i$ and $\sigma^2$ the variance, respectively.

In order to avoid the vehicle collision, the driver's deterministic deceleration should be carried out when the following inequality is correct.

$$V_j^i(t) > D_j^i(t) + \beta_j^i V_{j-1}^i(t) \tag{6}$$

Let

$$V_j^i(t) = D_j^i(t) + \beta_j^i V_{j-1}^i(t) \tag{7}$$

Clearly, when $\beta_j^i = 0$, Eq. (7) is the classical NaSch model in the deceleration rules (Schneider, 2002). In fact, $\beta_j^i = 0$ is not the safest driving. In this condition, due to leaving out of consideration the front vehicle speed, that a driver suddenly slows down not only hurts the vehicle performance, but also easily causes the rear-ending. Thus, to ensure the safety of deterministic deceleration, the value of $\beta_j^i$ should be more than 0 and close to 0.

*2.2.2. Safe deceleration*

Let $T$ be the safe time in vehicle flow. It refers to the minimum for any driver safely braking when the front vehicle suddenly stop. $T$ can be determined as follows.

$$T = t_1 + t_2 + t_3 \tag{8}$$

Here, $t_1$ is the time of reaction by the rear-following driver. $t_2$ is the brake lag time from a driver pressing on the brake to having an effect. $t_3$ is the time of brake from start to end. Under common conditions, $t_1$ depends on the driver psychology and physiology. $t_2$ depends on operating experience and vehicle performance, and $t_3$ relies on vehicle performance, lane condition and meteorological conditions (Ma and Yan, 1997). With the reference to the regulation on American Association of State Highway Officials, usually $t_1$ is 0.8 s, $t_2$ is 0.7 s, and $t_3$ is 1–1.5 s. Then the total $T$ is 2.5–3.0 s. It needs to modify $t_1$ and $t_3$ under the special lanes and meteorological conditions. We select the safest interval to guarantee that the driver can safely brake in different situations.

When the following inequality (Eq. (9)) is correct, based on kinematics, the $j$th vehicle needs to decelerate.

$$TV_j^i(t) \geqslant D_j^i(t) + T\beta_j^i V_{j-1}^i(t) \tag{9}$$

Because the rear-following vehicle is faster, to avoid collision, it must slow down. In the end, it should decelerate to the same speed of the front vehicle and keep a safety distance. In this paper, we assume that the rear-following vehicle is uniformly deceleration. Let $\alpha(\alpha < T)$ be the deceleration duration of the rear-following vehicle, we can obtain the following equations.

$$V_j^i(t) - g\alpha = V_{j-1}^i(t),$$

$$(t_1 + t_2 + \alpha)V_j^i(t) - \frac{1}{2}g\alpha^2 = D_j^i(t) + (t_1 + t_2 + \alpha)V_{j-1}^i(t) - TV_{j-1}^i(t) \tag{10}$$

Here, $t_1 + t_2 = 1.5$ s. Then

$$g = \frac{\left(V_j^i(t) - V_{j-1}^i(t)\right)^2}{2(D_j^i(t) - TV_{j-1}^i(t) - 1.5(V_j^i(t) - V_{j-1}^i(t)))} \tag{11}$$

$g$ is an acceleration generated from the process of deceleration. It should be a positive integer. We use $g'$ to describe it as follows.

$$g' = \begin{cases} g, & g \text{ is an integer;} \\ [g+1], & g \text{ is a decimal.} \end{cases}$$

Here, $[\cdot]$ is the integral function. Therefore,

$$V_j^i(t+1) = V_j^i(t) - g' \tag{12}$$

*2.2.3. Free driving*

When $TV_j^i(t) < D_j^i(t) + T\beta_j^i V_{j-1}^i(t)$ is correct, the $j$th vehicle is under the free driving. We introduce three parameters such as

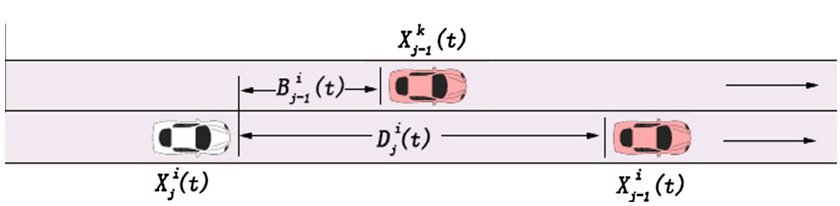


**Fig. 1.** The vehicle locations and distances ($i = R$ and $k = L$).

the accelerated probability $P_1$, decelerated probability $P_2$ and uniform speed probability $P_3$. Certainly, $P_1+P_2+P_3=1$. Generally, under the limitation of speed on highway, drivers must obey the highway traffic rules. so the vehicle speed should be among 7–13. If a vehicle speed is lower, it is more likely to accelerate (Qian, 2011). when the speed is less than 7, the driver has to accelerate. When the speed is among 9–11, $P_3$ becomes higher. In the lower speed, $P_1$ is higher than $P_2$. According to the actual situation, we choose some probability values of $P_1$, $P_2$ and $P_3$ showed in Table 1.

In the simulation, we assume a random variable $P$, a probability following uniform distribution in the closed interval $[0,1]$. During a unit time, there are three states as follows.

- If $P \leqslant P_1$, the $j$th vehicle accelerates.

$$V_j^i(t+1) = min\{V_{max}, V_j^i(t)+1\} \tag{13}$$

- If $P_1 < P \leqslant P_1+P_2$, the $j$th vehicle decelerates.

$$V_j^i(t+1) = max\{V_{min}, V_j^i(t)-1\} \tag{14}$$

- If $P_1+P_2 < P \leqslant P_1+P_2+P_3$, the $j$th vehicle keeps uniform velocity.

$$V_j^i(t+1) = V_j^i(t) \tag{15}$$

All the above steps finished, we should update the $j$th vehicle location at the moment $t+1$.

$$X_j^i(t+1) = X_j^i(t) - V_j^i(t) \tag{16}$$

*2.2.4. Overtaking based on driving on the right*

The process of the vehicle in the right side overtaking includes two steps.

**step 1.** The vehicle on the right side changing to the left

Let $T^L$ be the safe time for the $j$th vehicle on the main road changing its lane from the right to the left. It includes $t_1^L$, $t_2^L$ and $t_3^L$ like Eq. (8). This vehicle's changing lanes should satisfy the two conditions during the time $T^L$. First, its uniform motion will collide with the front vehicle in the same lane. Second, in the adjacent lane, it will collide with neither the front vehicle nor the rear. If the $j$th driver wants to overtake, he or she needs to observe the right and left side before entering the overtaking lane. Under the rule of driving on the right, the driver's psychological response time $(t_1^L)$ is longer than before. In the simulation, we assign $t_1^L = t_1 + 1(1.8\text{ s})$ and $T = 3.0$ s. The corresponding total safety time $T^L$ changes into 4.0 s. In fact, some drivers will not overtake even if they have a chance on the highway. Commonly, but if there is an opportunity to overtake, its possibility is usually larger than that of non-overtake. Therefore, we introduce another random variable $P'$ (Zhao and Mao, 2013), which expresses the probability of vehicle changing lane and follows the uniform distribution.

**Table 1**
The different values of $P_1$, $P_2$ and $P_3$ according to $V$.

| $V$ | 0–6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 |
|---|---|---|---|---|---|---|---|---|
| $P_1$ | 1 | 0.9 | 0.6 | 0.4 | 0.3 | 0.2 | 0.1 | 0 |
| $P_2$ | 0 | 0 | 0.1 | 0.2 | 0.3 | 0.4 | 0.6 | 0.9 |
| $P_3$ | 0 | 0.1 | 0.3 | 0.4 | 0.4 | 0.4 | 0.3 | 0.1 |

When $P' < 0.8$ (Barlovic, 2003), the two following inequalities are correct.

$$B_{j+1}^L(t) + T^L V_j^R(t) > T^L V_{j+1}^L(t),$$

$$D_j^R(t) + T^L \beta_j^R V_{j-1}^R(t) < T^L V_j^R(t) \leqslant B_{j-1}^L(t) + T^L \beta_j^L V_{j-1}^L(t) \tag{17}$$

Here, $B_{j+1}^L(t)$ is the distance between the $j$th vehicle in the right lane and its back one, closest to it in the left lane at the moment $t$. $B_{j-1}^L(t)$ is the distance between the $j$th vehicle in the right lane and its front one, closest to it in the left lane at the moment $t$. $V_j^R(t)$ is the velocity of the $j$th vehicle at the moment $t$. $V_{j-1}^R(t)$ is the velocity of the front vehicle, closest to the $j$th one in the same lane at the moment $t$. $V_{j-1}^L(t)$ is the velocity of the front vehicle, closest to the $j$th one in the adjacent lane at the moment $t$. $V_{j+1}^L(t)$ is the velocity of the back vehicle, closest to the $j$th one in the adjacent lane at the moment $t$. $D_j^R(t)$ is the distance between the $j$th vehicle in the right lane and its front one, closest to it in the same lane at the moment $t$ (Fig. 2).

Then the $j$th vehicle enters overtaking lane. Its location and speed can be expressed as follows.

$$X_j^L(t+1) = X_j^R(t) + T^L V_j^R(t),$$

$$V_j^L(t+1) = V_j^R(t). \tag{18}$$

Here, $X_j^L(t+1)$ is the location of the $j$th vehicle in the overtaking lane at the moment $t+1$. $X_j^R(t)$ is the location of the $j$th vehicle in the original lane at the moment $t$. $V_j^L(t+1)$ is the velocity of the $j$th vehicle in the overtaking lane at the moment $t+1$.

**step 2.** The vehicle in the overtaking lane changing back to the right

Let $T^R$ be the safe time for the $j$th vehicle in the overtaking road to change its lane to the right. The reaction time of the driver returning to the main road $(t_1^R)$ is longer than that of overtaking. In this condition, we assign $t_1^R = t_1^L + 1(2.8\text{ s})$, and then $T^R = 5.0$ s. the two following inequalities are correct.

$$B_{j+1}^{R'}(t) + T^R V_j^{L'}(t) > T^R V_{j+1}^{R'}(t),$$

$$T^R V_j^{L'}(t) \leqslant B_{j-1}^{R'}(t) + T^R \beta_j' V_{j-1}^{R'}(t). \tag{19}$$

Here, $B_{j+1}^{R'}(t)$ is the distance between the $j$th vehicle in the overtaking lane and its back one, closest to it in the right lane at the moment $t$. $B_{j-1}^{R'}(t)$ is the distance between the $j$th vehicle in the

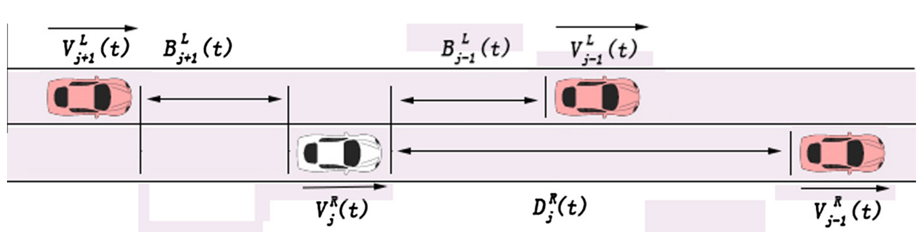


**Fig. 2.** Overtaking based on driving on the right.

overtaking lane and its front one, closest to it in the right lane at the moment $t$. $V_j^{L'}(t)$ is the velocity of the $j$th vehicle in the overtaking lane at the moment $t$. $V_{j-1}^{R'}(t)$ is the velocity of the front vehicle, closest to the $j$th one in the right lane at the moment $t$. $V_{j-1}^{R'}(t)$ is the velocity of the front vehicle, closest to the $j$one in the next lane at the moment $t$. $D_j^{L'}(t)$ is the distance between the $j$th vehicle in the overtaking lane and its front one, closest to it at the moment $t$ (Fig. 3).

Then the $j$th vehicle enters the main road. Its location and speed can be expressed as follows.

$$X_j^{R'}(t+1) = X_j^{L'}(t) + T^R V_j^{L'}(t),$$

$$V_j^{R'}(t+1) = V_j^{L'}(t). \tag{20}$$

Here, $X_j^{R'}(t+1)$ is the location of the $j$th vehicle in the right lane at the moment $t+1$, $X_j^{L'}(t)$ is the location of the $j$th vehicle in the overtaking lane at the moment $t$, $V_j^{R'}(t+1)$ is the velocity of the $j$th vehicle in the right lane at the moment $t+1$.

From the above analysis, under the driving on the right, the overtaking process of a vehicle is clearly described in Fig. 4.

*2.2.5. Free overtaking in the two-lane traffic flow*

On the two-lane highway, without the limitation of the main road and the overtaking one,drivers can freely choose to stay in any lane or overtake. Commonly, the driver seat is on the left. The vehicle generation rule is the same as before to express the traffic condition under the different congestion extent. Ideally, the density of the left and right lanes should be consistent. Meanwhile, the vehicle probability of the section is also consistent with the same parameters.

The reaction time to overtake on the right or left under the free overtaking rules is different from the above mentioned in 2.2.4. Certainly, the probabilities of overtaking on the left or right are also different. Let the probability of overtaking from the right lane to the left to be $P_4$, and $P_5$ is from the left to the right. Due to $T^L < T^R$, we can obtain $P_4 > P_5$.

The $j$th right driver to change lane also meets the inequalities like as Eq. (17).Its location and speed can be expressed as Eq. (18).

In the same way, the $j$th left driving vehicle meets the following conditions (Fig. 5).

$$B_{j+1}^{R'}(t) + T^R V_j^{L'}(t) > T^R V_{j+1}^{R'}(t),$$

$$D_j^{L'}(t) + T^R \beta_j L' V_{j-1}^{L'}(t) < T^R V_j^{L'}(t) \leqslant B_{j-1}^{R'}(t) + T^R \beta_j^{R'} V_{j-1}^{R'}(t) \tag{21}$$

In addition, we consider another rule that a driver should keep the lowest speed without overtaking. It refers to driving freely at between the minimum speed and the maximum one in any lane, but any driver can't overtake except traffic accidents. The highest speed is limited to $V_{max} = 15$, corresponding to actual speed 135 km h$^{-1}$. The lowest $V_{min} = 9$ is corresponding to 81km h$^{-1}$. We can obtain the conclusions through eliminating the process of overtaking and modifying the highest and lowest speed in the above formulas.

## 3. Experimental results

*3.1. The vehicle flow and density in different safety coefficients*

Let the simulation area include $2 \times 3000$ cellular units, $V_{max} = 13$ and $V_{min} = 7$. The initiate vehicle velocity follows normal

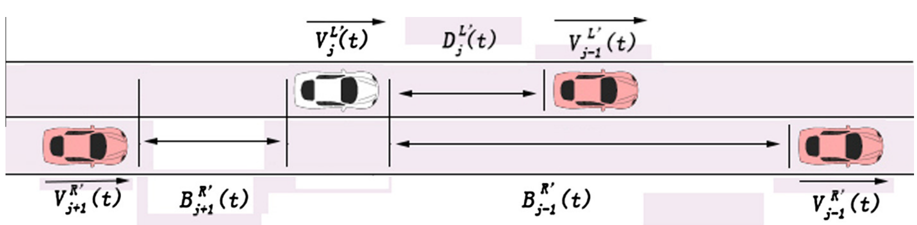


**Fig. 3.** The overtaking vehicle changing back to the main lane under driving on the right.

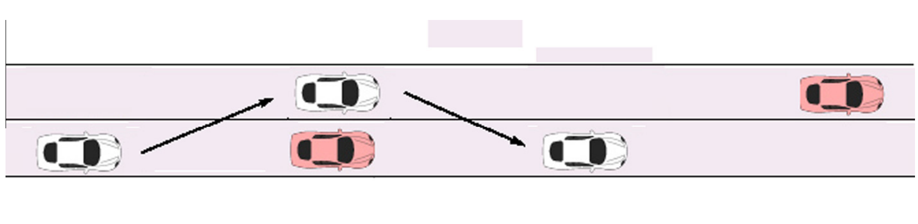

**Fig. 4.** Lane changing schematic.

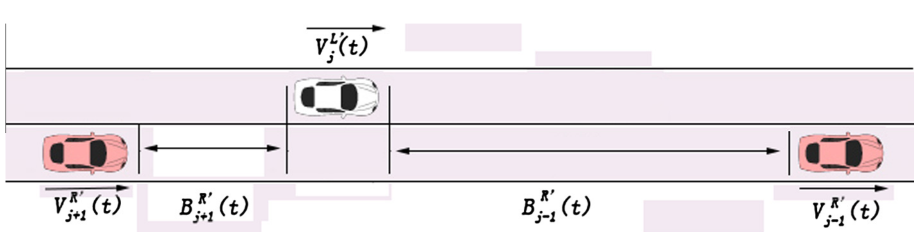


**Fig. 5.** The overtaking vehicle changing back to the right under the rule of free overtaking.

**Table 2**
The vehicle distribution in different densities under driving on the right.

| $\rho$ | 0.05 | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | 0.35 | 0.40 | 0.45 | 0.50 | 0.55 | 0.60 | 0.65 | 0.70 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N_l$ | 5 | 25 | 50 | 100 | 200 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 |
| $N_r$ | 95 | 175 | 250 | 300 | 300 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 |

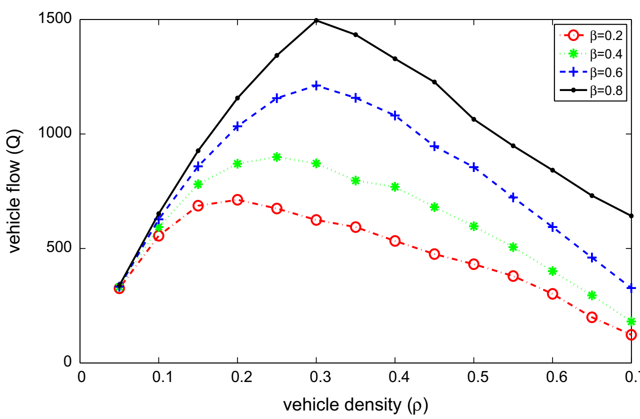


**Fig. 6.** The vehicle flow and density in different values of $\beta$ under driving on the right.

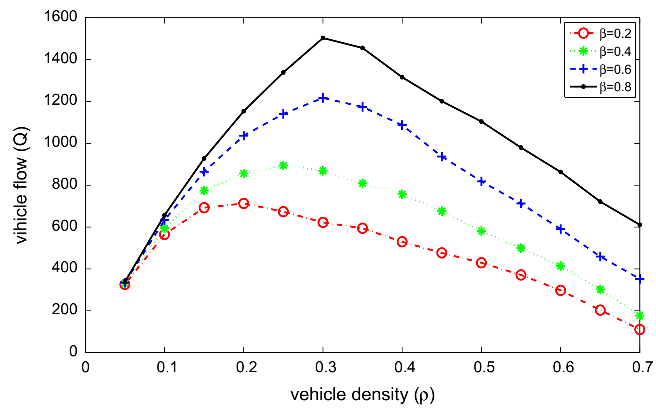


**Fig. 7.** The vehicle flow and density in different values of $\beta$ under free overtaking.

distribution whose mathematical expectation is 10. The number of the vehicles on the highway shows the smooth traffic or jam. In the process of the cellular automatic stimulation, we assume $N_l$ is the number of vehicles on the overtaking lane and $N_r$ on the key lane. Then, the vehicle density $\rho$, which is used to describe the extent of the traffic congestion, can be expressed as the following equation in this simulation area.

$$\rho = \frac{N_l + N_r}{2 \times 1000} \tag{22}$$

Initially, the vehicle position and speed are random distribution. Each simulation process has 3600 steps by iteration. The first 2600 steps will be removed for excluding the effects of transient. Based on the above formulas, we use the CVM (controlling variable method) and SIM (splint interpolation method) to simulate the vehicle flows in different density with the different mean $\beta$ of the safety coefficient (Hua et al., 2011). Then, we can obtain the relations between the vehicle flow Q and the vehicle density $\rho$ via Matlab programs.

Under driving on the right, the changes of vehicle flow in different densities are described in Table 2 and the stimulation results are demonstrated in Fig. 6.

Under the free overtaking, because of no limitation of the main and overtaking lanes, we assume the vehicles' distribution in different densities in Table 3. Based on the Section 2.2.5, let the probability $P_4 = 0.8$ and $P_5 = 0.6$, we can get the relations between the vehicle flow Q and the density $\rho$ in Fig. 7.

Under the minimum speed of no overtaking, we choose the same $\rho$ in Table 3 to simulate. Meanwhile, the vehicle minimum speed could not go lower than 9 or higher than 15. After modifying the rules, we simulate and get the relations between the vehicle flow Q and the density $\rho$ under the different safety coefficients in Fig. 8.

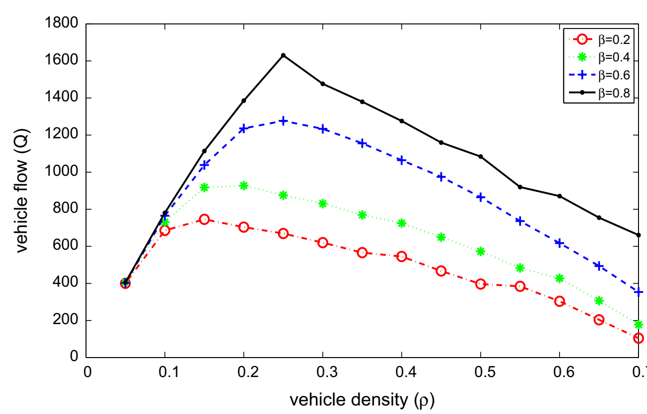


**Fig. 8.** The vehicle flow and density in different values of $\beta$ under no overtaking.

From Figs. 6–8, we can get some results as follows.

When $\rho < 0.1$, the impact of $\beta$ on the vehicle flow Q is very small. In this phase, the vehicle flow Q grows rapidly with the increase of the vehicle density $\rho$. They have a great slope of the curve. In fact, in the less vehicle flow, the vehicles' interactions are relatively weak. The traffic flow can be regarded as free flow, and there is no need for drivers to make deterministic deceleration or change lanes. In this case, regardless of the drivers' psychology being partial to safety or adventure, their driving behaviors are almost the same on the whole and the vehicle speed can reach the maximum.

When $\rho > 0.3$, differen values of $\beta$ impact the vehicle flow Q. However, the vehicle flow starts to decline with the increase of

**Table 3**
The vehicle distribution in different densities under free driving and no overtaking.

| $\rho$ | 0.05 | 0.10 | 0.15 | 0.20 | 0.25 | 0.30 | 0.35 | 0.40 | 0.45 | 0.50 | 0.55 | 0.60 | 0.65 | 0.70 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $N_l$ | 50 | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 |
| $N_r$ | 50 | 100 | 150 | 200 | 250 | 300 | 350 | 400 | 450 | 500 | 550 | 600 | 650 | 700 |

the vehicle density. In this case, there are more vehicles on the highway leading to the decline of the average speed because of the vehicles' interaction. For the partial adventurous drivers, they try to gain higher speed by judging the one of the front vehicles and changing lanes. Thus the traffic flow can be improved. But because of the low average speed and the small interval, it' s hard to gain higher speed under the lower partial adventure.

When $0.1 < \rho < 0.3$, the vehicle flow $Q$ shows more difference than the above. In this case, with the increase of the safety coefficient mean $\beta$, the maximum of vehicle flow $Q$ and the slope between the vehicle flow and density are larger. Notably, with the increase of security parameter $\beta$, the maximum flow in the optimum density also increases accordingly. Compared with the partial safety drivers, the partial adventure drivers can gain higher speed through relatively rare deterministic deceleration and changing lanes. Thus larger traffic flow can be gained in the same density. Meanwhile, the larger average speed makes the vehicle flow $Q$ to reach maximum.

### 3.2. The vehicle flow and density in the same $\beta$ under different rules

In order to find the relations between the vehicle flow and density with the same $\beta$ under different rules, we choose $\beta = 0.2$, $\beta = 0.4$, $\beta = 0.6$ and $\beta = 0.8$ to simulate respectively. The results are demonstrated in Figs. 9–12.

With the same value of $\beta$ , the flows of the driving on the right and under the rule of free overtaking are roughly similar. With the increase values of $\beta$ , the traffic flow increases correspondingly. When the traffic is in the low density, the traffic flow under the rule of non-overtaking with low speed limitation is higher than the others. There are two reasons for it. For one thing, the utilization of road is better. For another, the speed of vehicle is relatively higher. Under the moderate and high traffic, the traffic flows decrease with the increase of density. Because lots of vehicles lead to the decrease of the average speed. Therefore, no matter what traffic rules are, it is difficult for driver to speed up. In general, in the lighter traffic, the rule of non-overtaking is beneficial to improving traffic flow. And in the heavy traffic, the flow tends to be coincident under the three rules. In recent years, with the increase of vehicles, we support the rule of non-overtaking with low speed limitation to improve the traffic flow.

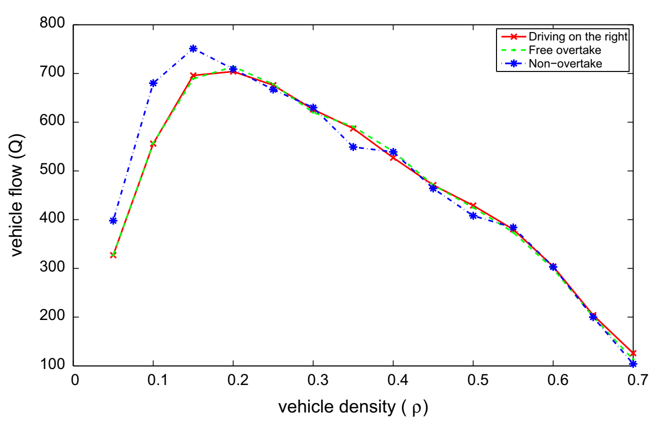


**Fig. 9.** The vehicle flow and density under the different rules ($\beta = 0.2$).

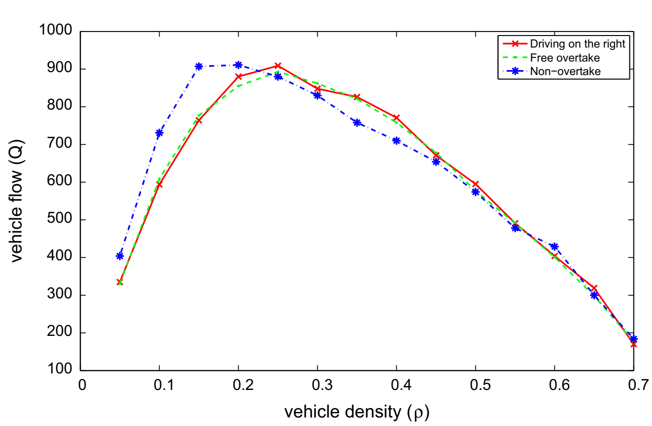


**Fig. 10.** The vehicle flow and density under the different rules ($\beta = 0.4$).

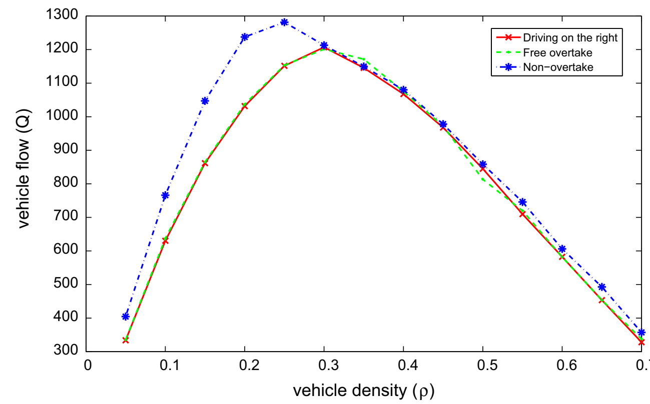


**Fig. 11.** The vehicle flow and density under the different rules ($\beta = 0.6$).

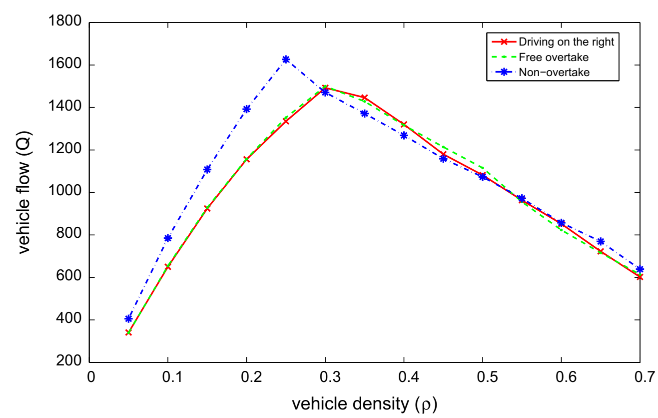


**Fig. 12.** The vehicle flow and density under the different rules ($\beta = 0.8$).

## 4. Conclusion

In this paper, we use the CA model to study the effect of the different drivers' psychology for the two-lane highway traffic. The safety parameter reflects the drivers' psychology. Its different values represent the cautious or risky psychology of drivers. Based on different means of the safety parameter, we compare three kinds of traffic rules such as driving on the right, free overtaking and non-overtaking with low speed limitation. Under these three rules, we can obtain some related curves between the vehicle flow and density. In addition, some other curves are also obtained with the same safety parameter mean under the three kinds of rules. Through the CA simulation, the results demonstrate that the safety parameter has less influence on the traffic flow under the lightest and heaviest traffic. Meanwhile, non-overtaking with the lowest speed limitation can increase the traffic flow in the low traffic. Free overtaking can improve the usage of the highway. With the increase of vehicles, non-overtaking with low speed limitation will be of benefit to improving the traffic flow.

Finally, this work ignores the influence caused by different vehicle types and multi-lanes. In fact, different vehicle types have different limitations of speed and there may be vehicles on emergency lane. To a certain extent, both of them will impact the vehicle flow. Therefore. Our following work will add them to the CA model.

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