Modeling and Numerical Simulation of Cellular Automation Traffic Flow Model

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Abstract—In recent years, the traffic is developing rapidly in China, the transportation is more and more convenient, but the traffic safety problem has become the focus problem in public life. Study of the traffic problem, which is beneficial to strengthening our country citizen's traffic safety consciousness, reduce the number of traffic accidents, so as to promote the development of transportation industry in China. First, in order to promote traffic smooth effectively, cellular automation traffic flow model is constructed. By studying the double lane flow, speed, mixed ratio and the conversion rate of driving ways, it is known that the cellular automation traffic flow rule improves the lane usage rate, and stimulate traffic smooth effectively. Second, construct intelligent transportation system cellular automation model. Compare the intelligent and non-intelligent system, and the traffic capacity in different lane-changing probability varies according to density fluctuation. That is, compare the analytical result of the contrastive analysis of figure to know too high lane-changing probability is not suitable for improving the traffic flow. In other words, under the control of intelligent transportation system, the improvement on the traffic flow is not obvious, which applies to the actual situation, because intelligent transportation system has its own limit after all. The last point needed to be highlighted is that cellular automation traffic flow model does not only apply to the double-lane changing situation, but also apply to the three-lane.

Index Terms—The Cellular Automation Traffic Flow Model; Intelligent Transportation System; Double-Lane Changing Situation; The Three Lane Model

I. INTRODUCTION

Nowadays, the traffic safety problem has become the focus of attention and making a sound and reasonable traffic rules and regulations is the trend. In countries where driving automobiles on the right is the rule, multi-lane freeways often employ a rule that requires drivers to drive in the right-most lane unless they are passing another vehicle, in which case they move one lane to the left, pass, and return to their former travel lane [1]. Therefore, it is of necessity to establish a model to analyze the traffic rules of driving on the right side, and improve it to make the model play a more effective role in stimulating traffic smooth. Finally consider whether the results will be influenced if traffic is completely intelligentized.

At present, with the rapid development of transportation, traffic safety problem has become a focus of discussion of the people daily life. Therefore, many scholars have carried on research to the problems of traffic safety, they presents suggestions, and draws the related conclusion.

Xu Hongguo reference to the large number of previous research results in "road traffic accident analysis and reappearance", through the road traffic accident reconstruction, using the logic analysis method, system analysis method, questionnaire survey method and other methods for its analysis, finally finds out the factors of road traffic accidents occur, and the causes of traffic accident [2]. The paper points out that: Nowadays, the traffic problem is very common, every hurt because of traffic accident, or even loss of life of people more and more, this is mainly because the management mechanism of transport is not perfect, traffic safety awareness of the public was not strong enough, security risks still exist in people's daily life.

Ren you starting from the driving behavior in traffic environment in the paper "driving behavior simulation and emergency driving reliability modeling in traffic environment", research vehicle emergency driving problems [3]. The paper applies many kinds of methods in mathematics, analysis of data, through questionnaires, field visits, to obtain first-hand information, and data processing, establish a safe driving reliability model based on traffic environment, and finally draws the conclusion: the specification of the driving behavior is an important prerequisite for traffic safety, emergency driving is to ensure that the key to ensure the personal safety of the driver in emergency conditions. By driving behavior simulation of traffic environment, establish the corresponding model, so that people have the further understanding on the traffic safety, and regulate their own driving behavior, driving safety, civilized travel [4].

Xin Desheng in the paper "Research on driver's visual impact on traffic safety and detection system", starting from the driver's visual angle, through logical analysis, systems analysis, literature and other mathematical methods, study the relationship between the driver's visual and traffic safety. The paper points out that: there are many traffic accidents because of the driver vision, this also proves that the key driver's visual is very important [5]. In order to increase the traffic safety, reduce traffic accidents, to avoid more casualties, we should strictly check the driver's vision, and enhance the reliability of the detection system [6].

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This paper researches thesis on the traffic safety, through the establishment of cellular automata traffic flow model [7], study two lane traffic, speed, mixing proportion of the different lane changing probability and driving mode conversion rate varies with the density. It provides a theoretical basis for improving road utilization rate. In addition, on the basis of this, establishes the intelligent transportation system of cellular automata model [8], and carries on the contrast analysis, by comparing the intelligent and non intelligent system, changing traffic flow channel probability density change, draws the conclusion: under the control of the intelligent transportation system, traffic improvement is not obvious, and the model is extended, the model is further applied to three lane change problem, which can broaden the scope of application of cellular automata traffic flow model, make a contribution to the study of traffic safety.

II. MODEL ESTABLISHMENT AND SOLUTION

A. Model Hypothesis

(1) assume that the vehicle model is of unification, and the vehicles in the team are of the same braking strength and efficiency, namely the braking distance is only related to its own speed;
(2) ignore the influence of weather, slope, road conditions, and other environmental factors on the speed;
(3) assume that the drivers’ identification of the surrounding environment is consistent;

B. Symbol Description

<table>
<thead>
<tr>
<th>No.</th>
<th>symbol</th>
<th>meaning</th>
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<tbody>
<tr>
<td>1</td>
<td>$F_r$</td>
<td>pedal braking force</td>
</tr>
<tr>
<td>2</td>
<td>$j$</td>
<td>automobile braking deceleration</td>
</tr>
<tr>
<td>3</td>
<td>$S$</td>
<td>safe distance</td>
</tr>
<tr>
<td>4</td>
<td>$a$</td>
<td>car-following deceleration</td>
</tr>
<tr>
<td>5</td>
<td>$t_s$</td>
<td>braking sluggish time</td>
</tr>
<tr>
<td>6</td>
<td>$v_0$</td>
<td>speed before the following car brake</td>
</tr>
<tr>
<td>7</td>
<td>$d$</td>
<td>Safety distance between the following and the leading car after the following car stops</td>
</tr>
<tr>
<td>8</td>
<td>$X_s$</td>
<td>required safety distance</td>
</tr>
</tbody>
</table>

Figure 1. People - car - road closed-loop System

In the process of driving, the driver receives dynamic stimulation of the road traffic environment, implement different vehicle handling behavior, and then change the car running state [9]. According to the cycle process of external information functioning in the people - car - road closed-loop system and stimulus- body - response model, it is concluded that vehicle driving behaviors include three stages of perception, judgment and decision, as well as operation [10]. See Figure 1 to know the information circulation model of people - car - road closed-loop system.

The driver's perception is primarily completed through eyes, ears, and other body sense organs [11]. Sight, hearing, smell, touch and so on can help drivers get to know the precise information of the cars’ basic information and the surrounding environment, such as the vehicle running status, traffic signal, road alignments, the movement of the vehicle and road landscape, etc.

On the basis of perception, combined with one’s own driving experience and skills, the driver can complete judgment and decision-making stage with central nervous system. The driver can process the information through the brain, as well as judge and respond to determine the pre-execution driving operation.

The drivers’ operation stage includes drivers’ comprehensive understanding, judgment, decision information, and it is the external manifestation of drivers’ behavior. It is the actual response and action of drivers in response to external stimulus, namely relying on human trunk to assist the limbs in accomplishing the operation stage, specifically refers to the action the hands and feet enforce on the car as well as the movement range [13].

C. Rule Establishment of the Traffic Flow Model of Cellular Automation

First of all, define two cellular chains consisted of 1000 cellular as the double lane, each cellular representation’s actual length is 7.5m. Thus the stimulated actual lane length is 7.5km, and the car is scattered on 1000 one-dimensional cellular. Build the double-lane model shown in Figure 2. Each grid point at any time is blank or occupied by one car. Consider the two driving categories: one is radical, the other one is conservative. In any lane, two kinds of driving way have a mixing distribution. Each car state is manifested by its own speed $V_i, V \in [0, V_{\text{max}}]$, and $V_{\text{max}}$ is the maximum speed required by the car. Assume the car moves from the left to the right, $X_i(t)$ and $V_i(t)$ respectively reflect the No. $i$ car’s position and speed at the time of $t$; $d_1(t)$ represents the space between the No. $i$ car and the close-neighbor front car at the point of $t$, $d_2(t) = X_i+1(t) - X_i(t) - 1$; $d_{\text{other}}(t)$ and $d_{\text{back}}(t)$ respectively represent the No. $i$ car’s space with the front car and back car on another lane at the point of $t$; $\Delta X_i(t)$ represents the displacement of No. $i$ car from the point of time $t$ to the time $t + 1$; $\Delta X_i(t) = X_i(t+1) - X_i(t) - p$ represents random decelerating probability of vehicles; $p_{\text{safe}}$ represents the safety speed cut probability; $p_{\text{lane}}$ represents the driving way changes probability; $p_{\text{lane}}^0$ represents the conservative cars’ lane-changing probability; $p_{\text{lane}}^1$. 

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represents the radical cars’ lane-changing probability. The defined variable \( \delta_i(t) \) represents the driving state of the No. \( i \) car at the point of \( t \); if \( \delta_i(t) = 1 \) represents that the No. \( i \) car at the point of \( t \) is the radical car, \( \delta_i(t) = 0 \) represents that the No. \( i \) car at the point of \( t \) is the conservative car.

In the above implementation of the double-lane cellular automation model, each time is divided into two sub-time steps: in the first sub-time step, each car in the system determines whether to change the lane or if it is possible according to one’s prime driving mode. If the condition is met, then change the lane according to corresponding rule, and determine the new way of driving by taking the new road environment into consideration; in the second sub-time space, two lanes are renewed according to each single lane’s renewing rules, and determines the next step prime way of driving based on its state and the road environment after information renewal.

1) Renewal Rules for Vehicle State Evolution

In this model, when \( \delta_i(t) = 0 \), considering the car driving safety, when its front car is static, the back close-neighbor car will slow down according to a certain safe probability, and the maximum distance is the blank position near the front car.

When \( \delta_i(t) = 0 \)

(1) acceleration:
\[
V_i(t+1/3) = \min \left(V_i(t)+1, V_{\text{max}} \right)
\]

(2) random deceleration at the probability of \( p \):
\[
V_i(t+2/3) = \max \left(V_i(t+1/3)-1,0 \right)
\]

(3) if \( V_{i,i}(t) = 0 \), slow down at the safe probability of \( p_{\text{safe}} \):
\[
V_i(t+1) = \max \left\{ \min \left[V_i(t+2/3), d_i(t) - 1\right], 0 \right\}
\]

(4) If \( V_{i,i}(t) \neq 0 \), the definite deceleration:
\[
V_i(t+1) = \min \left[V_i(t+2/3), d_i(t) \right]
\]

(5) Position Renewal:
\[
X_i(t+1) = X_i(t) + V_i(t+1).
\]

when \( \delta_i(t) = 1 \), consider the safety problem and introduce safe deceleration mechanism.

(1) acceleration:
\[
V_i(t+1/3) = \min \left(d_i(t), V_{\text{max}} \right)
\]

(2) if \( d_i(t)<V_{\text{max}} \), random deceleration at the probability of \( p \):
\[
V_i(t+2/3) = \max \left(V_i(t+1/3)-1,0 \right)
\]

(3) if \( V_{i,i}(t) = 0 \), slow down at the safety probability of \( p_{\text{safe}} \):
\[
V_i(t+1) = \max \left\{ \min \left[V_i(t+2/3), d_i(t) - 1\right], 0 \right\}
\]

(4) Position renewal:
\[
X_i(t+1) = X_i(t) + V_i(t+1)
\]

2) Vehicle Lane-Changing Rule

In view of the overtaking principle and safety principle, it is put forward that when \( \delta_i(t) = 0 \), \( V_{\text{hope}} = \min \left(V+1, V_{\text{max}} \right) \); when \( \delta_i(t) = 1 \), \( V_{\text{hope}} = V_{\text{max}} \).

Among the above, \( V_{\text{hope}} \) represents the expected speed of the vehicle.

Overtaking principle: \( V_{\text{hope}} > d \).

Safety principle: \( d_{\text{safe}} > d \), \( d_{\text{max}} \geq V_{\text{max}} \).

At the first sub-time step, when the above two principles are both satisfied, the conservative car changes lanes at the probability of \( p_{\text{lanc}} \), while the radical car changes lanes at the probability of \( p_{\text{lanc}}' \).

3) Vehicle Driving Rules

When \( V_i(t+1) > d_i(t+1) + \Delta X_{i,i}(t) - 1 \), \( \delta_i(t+1) = 0 \)

When \( V_i(t+1) < d_i(t+1) - 1 \), \( \delta_i(t+1) = 1 \)

Relative space and speed are used to define the change on the driving mode. When the car changes from the radical one to the conservative one, in order to avoid rear-end collision, the drivers consider deceleration to guarantee the safety; when the car changes from the conservative to radical, the driver expect to obtain high speed [14]. In order to guarantee the safety, the drive speeds up and make full use of the road resources as much as possible.

D. Results and Discussion on Simulation

Numerical simulation is carried out according to the above model rules. Under the periodic boundary conditions, at the beginning, the two driving vehicles on the road obey random distribution in accordance with the random initial mixing ratio \( f_a \), \( f_r \), and \( f_a + f_r = 1 \). \( f_a \) and \( f_r \) stand for radical and conservative vehicles. After the system reaches the steady state, the ratios for the two cars are \( f_a' \) and \( f_r' \) respectively. And \( f_a' + f_r' = 1 \). In driving mode conversion rate system, the number of its changing driving style for car \( i \) in the moment \( t \) is as follows:
\[
\alpha_i(t) = \begin{cases} 0 & \text{if } \delta_i(t) = 0 \\ 1 & \text{if } \delta_i(t) = 1 \\ 2 & \text{if } \delta_i(t) = 2 \end{cases}
\]
Set $N(t)$ as the total number of vehicle in the two-lane system at the moment of $t$. $T$ is the selected sample interval. The following formula shows the relationship among density, speed and volume and conversion rate.

$$\rho(t) = \frac{N(t)}{2L} \quad (1)$$

$$\bar{v}(t) = \frac{1}{N(t)} \sum_{j=1}^{2} \sum_{t'=1}^{T} \bar{V}_j(t') \quad (2)$$

$$J(t) = \rho(t) \times \bar{v}(t) \quad (3)$$

$$C(t) = \frac{1}{N(t)} \sum_{j=1}^{2} \sum_{t'=1}^{T} \alpha_j(t) \quad (4)$$

In the simulation, every time the evolution step is $1.1 \times 10^4$ step, in order to eliminate the influence at certain time, the calculation of speed will be gained from the later $10^3$ time step. The formula for average velocity and average driving mode conversion rate respectively are as follows:

$$\bar{V} = \frac{1}{T} \sum_{t=0}^{T} \bar{v}(t) \quad (5)$$

$$\bar{C} = \frac{1}{T} \sum_{t=0}^{T} C(t) \quad (6)$$

Take average value from 10 samples to obtain the average velocity of the system and the average driving style conversion rates. In this paper, unless otherwise noted, the parameters selected will be shown as in Table 1.

**TABLE I. PARAMETER VALUES**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>$p$</td>
<td>0.5</td>
</tr>
<tr>
<td>$p_{acc}$</td>
<td>0.5</td>
</tr>
<tr>
<td>$p_{brake}$</td>
<td>0.5</td>
</tr>
<tr>
<td>$f_c$</td>
<td>0.5</td>
</tr>
<tr>
<td>$p_{lane}^0$</td>
<td>0.5</td>
</tr>
<tr>
<td>$p_{lane}^1$</td>
<td>0.5</td>
</tr>
</tbody>
</table>

This paper has studied the impact of lane changing probability on traffic volume. (a) (b) (c) (d) in Figure 3 shows the changing situation of two-lane traffic volume, velocity, mixed ratio and driving mode conversion rate under different Lane changing probabilities. The value for $p_{lane}^0$ and $p_{lane}^1$ is as shown in Figure 3. In this model, it can be seen from Figure 3 that after evolution of the system, $p_{lane}^0$ and $p_{lane}^1$ have no effect on traffic volume, velocity, mixed ratio and driving mode conversion rate. As long as some vehicles running in the road want to surpass other cars, they will choose to change lanes, so it will not only improve their driving speed, but also it will not affect the adjacent lanes car driving ($d_{back} \geq V_{max}$), meanwhile it will provide more convenient driving environment for the cars in the original lane.
improves road usage, and effectively promotes the flow of traffic.

III. ESTABLISHMENT OF INTELLIGENT TRAFFIC SYSTEM OF CELLULAR AUTOMATA MODEL

The key is to understand the definition of Intelligent Transportation System, which was Intelligent Vehicle highway system, i.e., IVHS. It effectively integrates advanced information technology, data communication transmission technology, electronic sensor technology, electronic control technology and computer processing technology into the entire transportation management system [15]. It establishes a comprehensive, real-time, accurate, efficient transportation management system within a wide range. It is shown in Figure 4.

The intelligent transportation management system of traffic system, can be seen from the figure that the relationship between the parts of the transportation management system closely linked together, intelligent traffic system, each part in the whole play a role can not be ignored [16]. Therefore, in the research of intelligent transportation system, consideration should be given to each part of the transport management system in intelligent transportation system, to play its role, so that the intelligent transportation management system smooth operation of traffic system.

Based on the establishment of cellular automata traffic flow model, this paper puts forward new cellular automata traffic flow model which is applicable in intelligent traffic system information. It is regarded as the Intelligent Traffic System of Cellular Automata Model. Therefore, the cellular automata rules also need to meet:

**When the traffic is light, vehicles should move at the maximum speed [17].** The starting acceleration for stationary vehicle is smaller than motion acceleration of the vehicle to be small, then it can master the dynamic information for vehicle ahead through ITS to accelerate and diminish the space between the cars.

**When the traffic is neither light nor heavy, vehicles will mutually influence and drivers should pay attention to the brake lights from the vehicle ahead in the previous time.**

When the traffic is heavy, drivers should regulate vehicle speed based on the feedback information to maintain safety distance to avoid a crash [18].

Besides, there are five steps for the evolution of ITS cellular automata mode:

- Determine the parameters of random function

  \[ p = p(v_n(t), d_n(t), b_{n+1}(t), b_n(t+1)) = 0 \]

- Acceleration rules

  If \( b_{n+1}(t) = 0, b_n(t) = 0 \), then

  \[ v_n(t+1) = \min(v_n(t) + 1, v_{\text{max}}) \]

- Reduction rules

  \[ v_n(t+1) = \min(v_n(t), d_n^{(\text{off})}) \]

  \[ v_{n+1}(t+1) = \min(v_{n+1}(t), d_{n+1}^{(\text{off})}) \]

  \[ v_{n+2}(t+1) = \min(v_{n+2}(t), d_{n+2}^{(\text{off})}) \]

  \[ v_{n+3}(t+1) = \min(v_{n+3}(t), d_{n+3}^{(\text{off})}) \]

  If

  \( (v_n(t+1) < v_n(t)) \)

  Then

  \[ b_n(t+1) = 1 \]

- Random variation: If \( \text{rand}(< P) \), the

  \[ v_n(t+1) = \min(v_n(t+1) - 1, 0) \]

  \[ b_n(t+1) = 1 \]

- Location update

  \[ x_n(t+1) = x_n(t) + v_n(t+1) \]

The first step is to determine the random moderation parameter \( P \) according to the front braking light state \( b_{n+1}(t) = 1(0) \), the current car speed \( v_n(t) \) and the traffic space between two cars \( d_n(t) \); the next is three steps to calculate the No. \( n \) car’s speed \( v_n(t+1) \) in the next moment. The second step represents that the car will speed up until the maximum speed in the circumstances of no braking. If the front car and the current car’s stoplight are all closed, the current car will speed up. If the traffic space is sufficient, then the current car can reach the speed of \( v_{\text{max}} \). The third step is to utilize the deceleration rule for the sake of safety. With the help of information provided by intelligent transportation system, the drivers can receive the information of the front car, such as their speed and position [19]. Considering the effective space interval with the front car, in this way even shorten the distance between the front car and the current car can still guarantee the safety. If the current car slows down, the braking lights shines, then \( b_n(t+1) = 1 \).

The next step introduces the random moderation probability \( P \) determined by step one, making some cars to slowing down randomly. It is demonstrated that due to the subjective initiative of drivers, the cautious driver will make the brake while the radical drivers will not. In the
end, the vehicle position is renewed and initializes the braking light state.
Likewise, use the cellular automation model’s data and get the numerical simulation result, as is shown in Figure 5.

![Figure 5. Different lane changing probability with density changes under intelligent system](image)

Make analysis of figure 3 (a) and figure 5, it can be seen clearly that in both cases the graphics are significantly different, accordingly, under the control of the intelligent transportation system, this factor will exert a certain influence on the current result.

IV. MODEL EVALUATION AND PROMOTION

A. Model Evaluation
Advantages: Both the cellular automation traffic flow model and its improved model satisfy the lane-changing requirement of vehicles [20]. In addition, the cellular automation model’s features of space time discreteness and parallelism can be utilized to study the non-linear relationship of the traffic flow from micro traffic factors to macro traffic phenomena, which greatly simplifies the calculation process.

Disadvantages: Due to the time limit and insufficient data collect, the calculation result might have unavoidable deviations.

B. Model Promotion
Based on the cellular automation traffic flow model established in current study, its main study object is the double-lane changing situation. Hereby, we aims to promote the cellular automation traffic flow model and apply it to the three lane model.

First of all, assume the three lanes as the carriageway, and vehicles driving in the lanes have the same performance and vehicles are allowed to overtake other vehicles at any lane. It is known through computer numerical simulation that in the evolution process of the traffic flow state, the traffic flow and the lane utilization ratio is controlled by determining the vehicle deceleration probability. Select the proper deceleration probability to improve the vehicle flow state, improve lane utilization ratio and enhance the safety.

Second, based on the above condition, establish model by determining the first lane as the accelerating lane, and the rest two lanes as the driving lane. After meeting the above requirements, it is stipulated that the driving car on the overtaking lane must return to the second lane. The stimulated result shows that under the same condition, three lanes with the managed traffic flow model have similar traffic stream characteristics with that of the three lane traffic without regulation. However, the system lane-changing frequency and the lane utilization ratio vary. In this way, it is demonstrated that the three lanes with managed traffic flow model enhance the drive safety.

Finally, establish the three-lane managed mixed vehicle cellular automation traffic flow model. With no restrictions on the lane and driving vehicles, the only requirement is that the slow vehicle overtaking to the second lane must return to the third lane under certain conditions. The computer numerical simulation result shows that given the same deceleration probability, the flow and speed of the fast vehicle increases, the lane volume increases too.

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