For office use only	Team Control Number	For office use only
T1 ________________	**24466**	F1 ________________
T2 ________________	Problem Chosen	F2 ________________
T3 ________________	**A**	F3 ________________
T4 ________________		F4 ________________

Summary

There are two automobiles driving rules in the current world, on the right and on the left. In this paper, we are aimed at constructing a mathematical model to analyze the performance of the car driving rule, that is, the keep-right-except-to-pass rule in counties where driving on the right is the norm. We determine that the problem is a classical traffic flow problem, take cellular automata (CA) as the basic model, and construct our final model. Thus, our model results are mostly from the computer simulation.

Firstly, we build a single lane cellular automata model to set up the basic forward movement rules in driving process. Since the cellular automata is popular in study the traffic flow problem, based on the previous research, we build the single lane cellular automata model. In the model, we prove that cellular automata is useful to solve our problem, because our simulation result of the model is corresponding to the previous research result. In the simulation, we find that it causes serious traffic jam with heavy traffic flow rate.

Secondly, we build a two-lane traffic rule analysis model by adding the lane changing rules on the previous rules used in the single lane CA model, where the keep-right-except-to-pass rule is one of the lane changing rules. By computer simulation on MATLAB, we obtain the microscopic space-time phase diagram. And for the convenience of model verification, we use space mean to transform the microscopic to the macroscopic. And the verification result indicates that our model is correct and reliable. And we get the following important conclusions:

1. The keep-right-except-to-pass rule seems like a good rule and can work well in many traffic conditions. However, the rule may lose effect in the heavy traffic condition.
2. High speed limitation means high transportation ability, low time cost and all we expect in that condition except safety problem. So if the highway operator has the ability to make highway stay in free flow state and deal accident in short time, increasing speed limitation is a good choose to increase transport efficient just like German Highway without speed limitation.
3. Different rule has the same trend when the traffic flow is high. Symmetry lane-change rule has the best transportation ability, and it reduce time cost.
4. Symmetry lane-Changing maybe a better rule than the keep-right rule or the keep-left rule on considering the safety.
5. Simulation result shows that no matter the vehicle is controlled by smart system or people, the traffic macroscopic statistics is very close. With the control of people the car changes less than with a smart system or machine.

Key words: cellular automata computer simulation two-lane traffic rules microscopic lane changing model

The Smartest Two-lane Traffic Rule Analysis Model Based on Cellular Automata

Content

I. Introduction

Driving automobiles on the right is the rule in most counties, such as USA, China and German and so on. Multi-lane freeways often employ a rule that require 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. That is, the drivers must obey ***the keep-right-except-to-pass rule*** in those countries. However, in some countries, that is, Great Britain, Australia, and some former British colonies, driving automobiles on the left is the norm. Certain traffic rule may affect the traffic flow, safety, and driving velocity, etc. To reduce traffic accidents and share quick and safe driving, analyzing the performance of specific traffic rule is significant.

In our paper, we construct a two-lane traffic rule analysis model based on cellular automata to analyze the performance of the keep-right-except-to-pass rule in both light and heavy traffic. By changing the rule, we are interested in finding out whether there are better alternatives that might promote greater traffic flow, safety, and other factors we find it with importance. Besides, we apply the model to analyze the performance of the driving left traffic rule and compare with the result of driving right traffic rule. Finally, we estimate the change extent of our earlier analysis result by controlling vehicle transportation under an intelligent system.

II. Problem Analysis

The problem given to analyze the performance of the keep-right-except-to-pass rule is belong to the traffic flow problem. The research on traffic flow problem have approximate eighty years. Generally, there are two methods to approach the problem, that is, microscopic method and macroscopic method. The advantages of macroscopic method are that both the amount of computation and the occupancy of memory space are small. But when the traffic flow is low, this method is inapplicable. On contrary, microscopic method is widely used without the restriction of traffic density.in spite that the amount of computation and the occupancy of memory space are big. In this paper, we adopt the traffic flow model based on microscopic method.

The mainstream microscopic method includes two models, the car following model and the cellular automata model. The car following model is of great amount of computation and high occupancy of memory space, and it is continuous in time and space. The cellular automata model is discrete in time and space, has high computational efficiency, and can adjust flexibly on operation. The great advantage of the cellular automata method is that it can simulate the complex dynamic system of the nonlinear behavior effectively.

Taking the two-lane freeway as our study object, and we would like to study the traffic density change from the lowest to the highest as well as other factors changes on the performance analysis of the traffic rule. Therefore, we need a model to study all the factors. It is obviously that the microscopic model is the best choice. And considering the occupancy of memory space in computer simulation, which is expected to be as small as possible, we use the cellular automata method. Primarily, we would like to study the traffic flow phenomena of a single lane with some elementary rules. Next, we have the keep-right-except-to-pass rule to add on the previous rules to analyze the performance of the keep-right-except-to-pass rule. That is, we construct the single lane cellular model at first, based on the first model, we propose the two-lane traffic rule analysis model based on cellular automata. After model construction, we would like to settle the given problem by computational simulation. The problem to solve is divided into the following steps:

(1) Simulating the performance of the rule in light and heavy traffic

(2) Determining the tradeoffs between traffic flow rate and safety

(3) Analyzing the performance of the rule on different speed limitations

(4) Simulating on different lane changing rules to find better traffic rule

(5) we study the effect of intelligent system on controlling vehicle transportation

III. Symbol Definitions

Table1. Symbol and Definition

Notation	Definition	Units
v_n	Velocity off the vehicle	$cell / time\_step$
x_n	Position of the vehicle	
$GapR-$	distance between the subject vehicle and its behind vehicle driving on the right lane	$cell$
$GapR+$	distance between the subject vehicle and its lead vehicle driving on the right lane	$cell$
$gapL-$	distance between the subject vehicle and its behind vehicle driving on the left lane	$cell$
$gapL+$	the distance between the subject vehicle and its lead vehicle driving on the right lane	$cell$
Gap	distance between two driving vehicles	$cell$
$\bar{v}$	mean traffic flow velocity	$cell / time\_step$
$\bar{\rho}$	mean traffic flow density	veh/ $cell$
$\bar{q}$	mean traffic flow rate	$cell / time\_step$

IV. The Single Lane Cellular Automata model

The cellular automata (CA) model can simulate the micro movement state of vehicle in traffic flow effectively, and it is helpful to understand the interaction mechanism between vehicles. Thus, the cellular automata model has been widely used in traffic research and development. In 1992, Nagel and Schreckenberg put forward the model, which considers the influence of gap between cars and brake probability on traffic flow, and indicates the change from free movement to local blocking. To better understand the two-lane traffic rule, first we would like to study the single lane CA model as the multi-lane CA model is extended from it [1].

4.1 Assumptions

Our models are based on cellular automata, the computer simulation is essential. To have a satisfactory result, we need to make a number of assumptions as follows:

(1) All the vehicles we study is ideally with the same length. The vehicle will not break down, tilt, or move in lateral swing in driving process.

(2) There is no direction change in driving process, and the acceleration is enough.

(3) The freeway we study is flat road, there is no exist and entrance for vehicles.

(4) Drivers have very high safe consciousness, they will keep a safe distance to avoid collision with the vehicle ahead.

4.2 foundation of the single lane CA model

In the single lane cellular automata model, we use one dimensional grid to represent a single lane. That is to say, dividing the studied single lane into n cells with each length of l, every grid represents a cell, the single lane lattice is shown in figure 1. Vehicle drives from the left hand side to the right hand side. The state of every cell is occupied or empty. Define that the velocity domain is

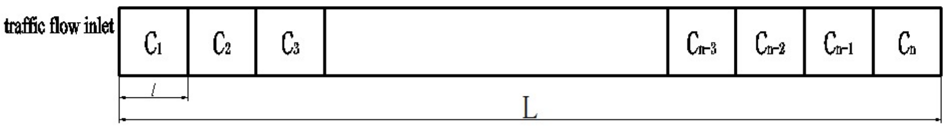


Figure 1 single lane lattice

$\{0,1,2,\cdots,v_{\max}\}$, where $v_{\max}$ is the maximum speed allowed. And in the model, vehicles update according to the following rules:

(1) **Acceleration rule:** Assume that the drivers always expect to drive on maximum speed. If the driving speed of the objective vehicle is smaller than the maximum speed $v_{\max}$, then the driving speed adds 1. If the driving speed of the objective vehicle is equal to the maximum speed, then the driving speed keeps the same. Assume that the car accelerate in acceleration probability p_a. that is,

$$\min(v_n+1, v_{\max}) \to v_n \tag{1}$$

(2) **Deceleration rule:** If the cell number between the lead vehicle and objective vehicle, which refers to distance between the two vehicles is less than the speed of the objective vehicle, then there will lead to traffic collision. To avoid the collision, the deceleration rule can be described as

$$\min(v_n, \mathrm{gap}) \to v_n \tag{2}$$

(3) **Randomization deceleration:** Due to uncertain factors, such as excessive brake and psychological factor and so on, the behavior of a driver id uncertain. Assume that the car decelerate in randomization deceleration probability p_d, that is,

$$\max(v_n-1, 0) \to v_n \tag{3}$$

(4) Location update: The vehicle moves forward on the road according to the determined speed in the former three steps, that is,

$$x_n + v_n \to x_n \tag{4}$$

4.3 Variables and measurement methods on traffic flow research

The following is some frequently-used variables and measurement methods on traffic flow research.

(1) **Traffic flow rate**

The traffic flow rate is referred to the vehicle number that passing through the observation point. The measurement methods is described as follows:

$$q = \frac{N}{T} \tag{5}$$

Where N is the vehicle number passing through the observation point in the observation time, T is the corresponding observation time.

(2) **Velocity**

By adding up the velocity of each vehicle in driving lane, mean velocity is described as

$$\bar{v} = \frac{1}{N}\sum_{i=1}^{N} v_i \tag{6}$$

Where v_i is the velocity in the i_{th} cell.

(3) **Traffic flow density**

We determined that the traffic flow density is measured in space average.

The mean traffic flow density for single lane is described as

$$\bar{\rho} = \frac{N}{L} \tag{7}$$

Where L is the length of the studied lane.

The mean traffic flow density in two lane is described as

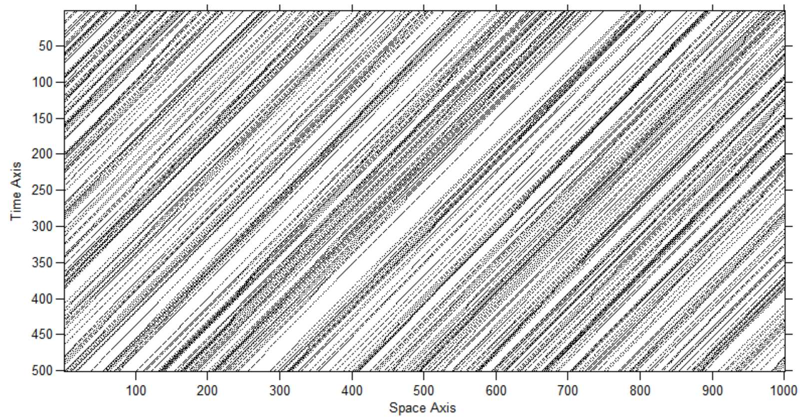
$$\bar{\rho} = \frac{\sum N_i}{2L} \tag{8}$$

Where $i = 1, 2$ represent the two lane.

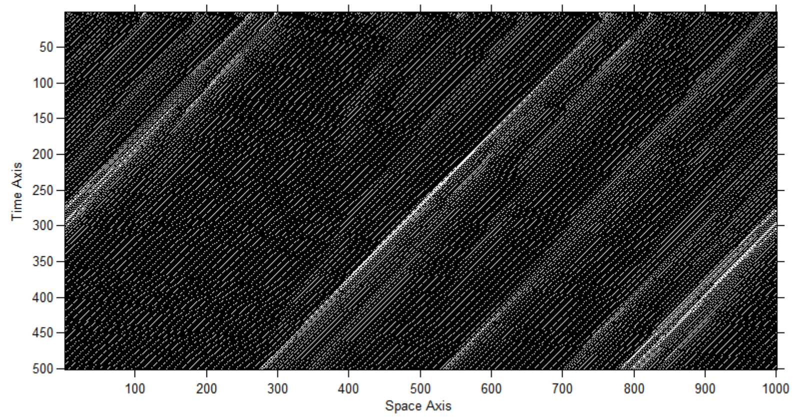
4.4 Simulation of single lane CA model

Obeying the driving rules, we would like to simulate the single lane CA model. There are some variables needing to specify. The car randomization deceleration probability p_d is equal to 0.25, the maximum velocity $v_{\max}$ is equal to 5, the length of the single lane L is equal to 2000, and simulation time step is 500. In order to compare simulation results to field measurements, the length of a cell l is taken as 7.5m. This means, for example, that $v_{\max} = 5$ cells/update corresponds to 135km/h.

We simulate the model in both light and heavy flow rate, the result is shown in figure 2, (a) is with the light flow rate, while (b) is with the heavy flow rate.



(a)



(b)

Figure 2 space-time plot of single lane, (a) is with the light flow rate, while (b) is with the heavy flow rate

According to the previously mature study, we simulate the single line CA model shown in picture 2. The black represents as the vehicle, which is easy to understand by comparing the two figures (a) and (b), since (a) is with the light flow rate, while (b) is with the heavy flow rate. Meanwhile, comparing the two pictures, we find that it causes serious traffic jam with heavy traffic flow rate.

V. Two-Lane Traffic Rule Analysis Model

As mentioned in the problem analysis, having the keep-right-except-to-pass rule to add on the previous rules used in the single lane CA model, we can analyze the performance of the keep-right-except-to-pass rule. And the smartest two-lane traffic rule analysis model is constructed based on cellular automata.

To establish the two-lane traffic rule analysis model, we use two dimensional grid to represent the two lanes. The two lanes are extended from the single lane, and the two lane lattice is shown in figure 3. In figure 3, we use Boole matrix with two rows and n columns to store the $2n$ cells, and for the element $C_{i,j}$ of $i = 1, 2$, $i = 1$ represents the right lane, while $i = 2$ represents the left lane. And we allow the traffic flow into the road by random choice of the two lane in a circle of length L. Also, the vehicles driving on the road is from left to right. As shown in figure 4, a vehicle occupies $C_{1,3}$, at the

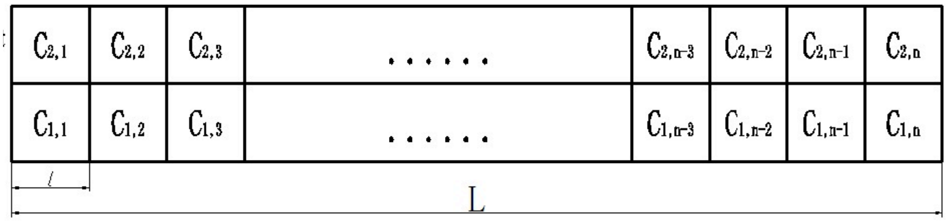


Figure 3 two lane lattice

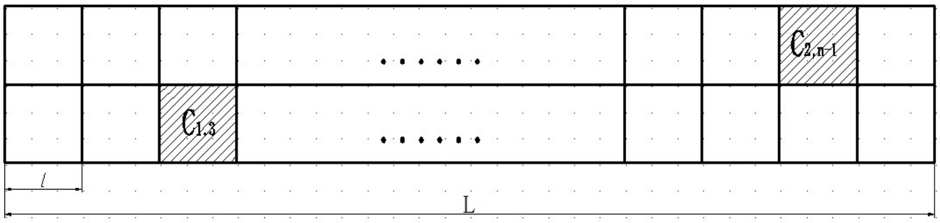


Figure 4 explanation of the relationship of vehicle and its velocity
with the matrix element

same time, another vehicle occupies $C_{2,n-1}$, and the record velocity corresponds to the velocity of the vehicle occupying the element. Define that the velocity domain is $\{0,1,2,\ldots,v_{\max}\}$, where $v_{\max}$ is the maximum speed allowed, the same with the elementary model. And in the model, an update step is divided into two major substeps: **lane changing** and **forward movement**.

5.1 Lane changing

There are three lane changing rules we expect to study. That is, symmetric lane changing rule, asymmetric lane changing rule with driving right, and asymmetric lane changing rule with driving left. We would like to state the three rules respectively. In order to understand the rules clearly, we define several gaps in figure 5. For the vehicle driving on the left lane, $GapR-$ refers to the distance with its behind vehicle driving on the right lane, while $GapR+$ refers to the distance with its lead vehicle driving on the right lane. For the vehicle driving on the right lane, $gapL-$ refers to the distance with its behind vehicle driving on the left lane, while $gapL+$ refers to the distance with its lead vehicle driving on the right lane. And Gap is the distance between two driving vehicles with no lane difference.

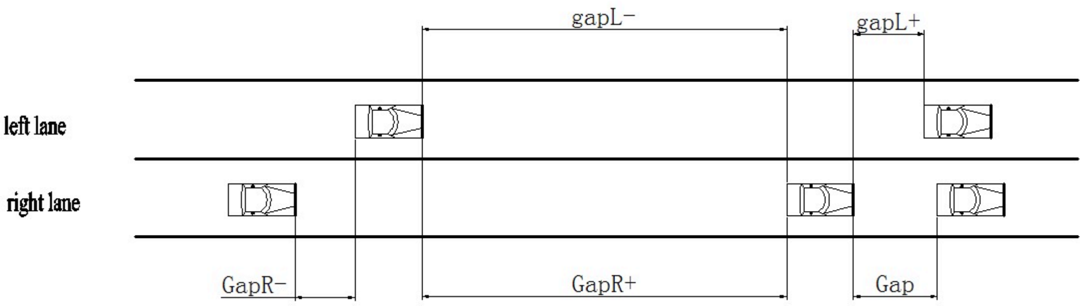


Figure 5 explanation of several gaps

Symmetric lane changing rule

$R \rightarrow L$:

For vehicles driving on the right lane, only when its driving conditions satisfy the following conditions it can choose to change lane. That is,

$$v > Gap \text{ and } gapL+ > v \tag{9}$$

$$gapL+ > Gap \text{ and } gapL- \geq d_{safe} \tag{10}$$

Which indicate that the vehicle cannot speed up on its driving lane, and the driving condition on the left lane is better, the security criterion is also satisfied.

$L \rightarrow R$:

For vehicles driving on the left lane, only when its driving conditions satisfy the following conditions it can choose to change lane. That is,

$$v > Gap \text{ and } GapR+ > v \tag{11}$$

$$GapR+ > gapL+ \text{ and } GapR- \geq d_{safe} \tag{12}$$

Which indicate that the vehicle cannot speed up on its driving lane, and the driving condition on the left lane is better, the security criterion is also satisfied.

Even though all the lane changing conditions are fulfilled, some drivers would rather not change their driving lane for many factors. So we define lane changing probability $p_{R \to L}$ and $p_{L \to R}$ to simulate the driving behavior more accurate, where $p_{R \to L}$ refers to the lane changing probability of the vehicle on the right lane, while $p_{L \to R}$ refers to the lane changing probability of the vehicle on the left lane.

In the symmetric lane changing rule, we have

$$p_{R \to L} = p_{L \to R} \tag{13}$$

Asymmetric lane changing rule with driving right

In counties where driving automobiles on the right is the rule, we would like to study the asymmetric lane changing rule performance.

$R \rightarrow L$:

For vehicles driving on the right lane, only when its driving conditions satisfy the following conditions it can choose to change lane. That is,

$$v > Gap \text{ and } gapL+ > v \tag{14}$$

$$gapL+ > v \text{ and } gapL- \geq d_{safe} \tag{15}$$

Which indicate that the vehicle cannot speed up on its driving lane, and the driving condition on the left lane is better, the security criterion is also satisfied.

The allowable conditions of changing lane is almost the same as in symmetric lane changing rule.

But the lane changing probability is different. The lane changing probability from driving lane to overtaking lane is less than the lane changing probability from overtaking lane to driving lane. That is,

$$p_{R\to L} < p_{L\to R} \tag{16}$$

$L \to R$:

For vehicles driving on the left lane, only when its driving conditions satisfy the following conditions it can choose to change lane. That is,

$$GapR+ \ > v \text{ and } GapR- \ \geq d_{safe} \tag{17}$$

Which indicate that the vehicle can return to the right lane only if its security criterion is fulfilled.

Asymmetric lane changing rule with driving left

In counties where driving automobiles on the left is the norm, we would like to study the asymmetric lane changing rule performance.

$R \to L$:

For vehicles driving on the right lane, only when its driving conditions satisfy the following conditions it can choose to change lane. That is,

$$gapL+ \ \geq v \text{ and } gapL- \ \geq d_{safe} \tag{18}$$

Which indicate that the vehicle can return to the right lane only if its security criterion is fulfilled.

$L \to R$:

For vehicles driving on the left lane, only when its driving conditions satisfy the following conditions it can choose to change lane. That is,

$$v > Gap \text{ and } GapR+ \ > gap \tag{19}$$

$$GapR+ \ > v \text{ and } GapR- \ \geq d_{safe} \tag{20}$$

Which indicate that the vehicle cannot speed up on its driving lane, and the driving condition on the left lane is better, the security criterion is also satisfied.

5.2 forward movement

The vehicle movement rules are taken as the single lane rule from Nagel and Schreckenberg, which mentioned in the single lane CA model. The vehicle movement rules can be described as follows:

1) Judging whether the vehicle in cells satisfy acceleration condition. If it is, then the vehicle accelerates with acceleration possibility p_a, and with aggressive acceleration possibility $1-p_a$.

   Then the velocity of the studied vehicle is different in two acceleration condition.

   When the acceleration is p_a, we have

$$\min(v_n+1, v_{\max}) \to v_n \tag{21}$$

   When the acceleration is $1-p_a$, we have

$$\min(v_n+2, v_{\max}) \to v_n \tag{22}$$

2) Judging whether the vehicle satisfy the lane changing rule. If it is, then the vehicle changes the

lane.

3) Judging whether the vehicle satisfy the deceleration rule. If it is, then the vehicle decelerates. And if the distance with the lead vehicle is Gap, Then the velocity of the studied vehicle is

$$\min(v_n, \mathrm{Gap}) \to v_n \tag{23}$$

4) In randomization deceleration, the aggressive deceleration probability is $1-p_d$, and the deceleration probability is p_d. The velocity of the studied vehicle is different in two acceleration condition.

   When the acceleration is p_d, we have

$$\max(v_n, 0) \to v_n \tag{24}$$

   When the acceleration is $1-p_d$, we have

$$\max(v_n - 1, 0) \to v_n \tag{25}$$

5) Location update: The vehicle moves forward on the road according to the determined speed in the former four steps, that is,

$$x_n + v_n \to x_{n+1} \tag{26}$$

$$v_n \to v_{n+1} \tag{27}$$

Obeying the certain traffic rule, the computer simulation process can be described by the flow chart below, shown as figure 6.

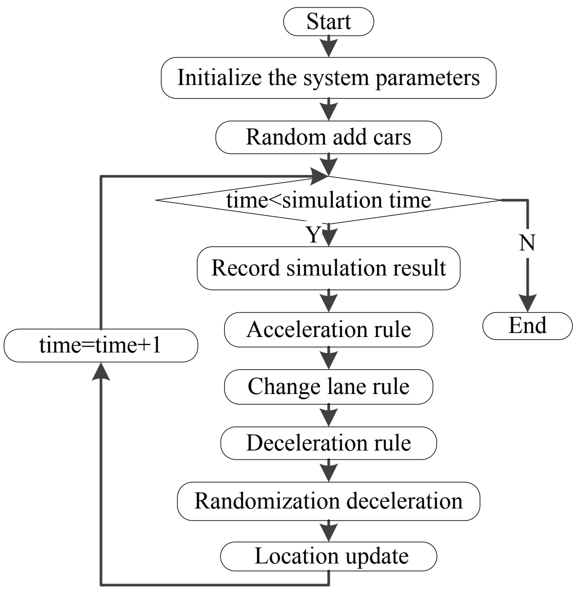


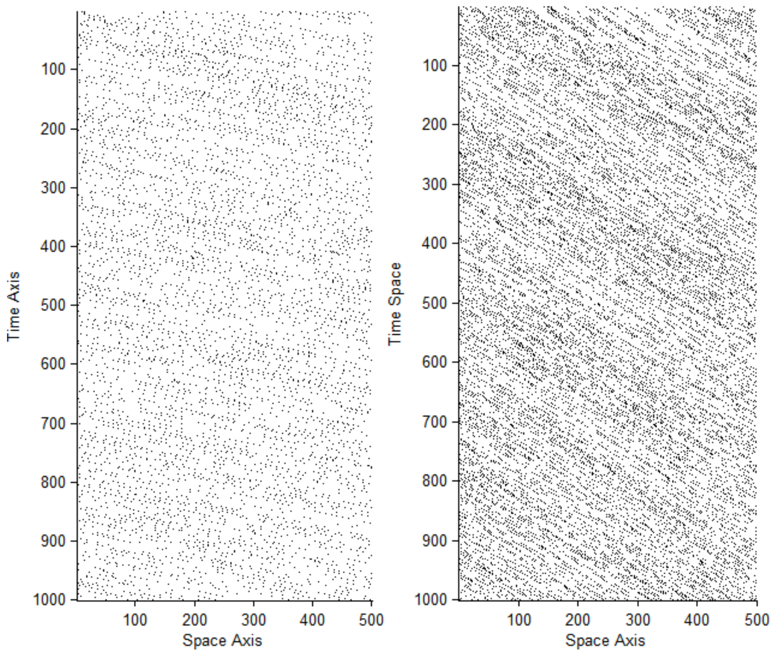
Figure 6 simulation flow chart

VI. Simulation of the Two-Lane Traffic Rule Analysis Model

Sequently, we would like to do model simulation using MATLAB. **First** we are interested in analyzing the performance of the keep-right-except-to-pass rule when the driving velocity is normal in countries where driving on the right is the rule. From the space-time phase diagram, we can have a microscopic view on the performance of the rule, while from the Velocity-flow plot, the flow-density plot and the velocity-density plot we can have a macroscopic view of the rule performance. **Next**, we study the performance of this rule in both light and heavy traffic. Since flow rate is the function of density and velocity, when the density of the traffic is changing, the flow rate changes, and the number of lane changing changes too. By analyzing the flow-density plot and the plot of lane changing times with density, we can find out the tradeoff between traffic flow rate and safety. **Then,** by changing the limited speed, we study the effect of high speed limitation and low speed limitation and make a comparison among three different speed limitations to make a clear understand of the speed limitation effect. **Finally,** we simulate the model in different lane changing rules to find out if we can find a better rule that might promote greater traffic flow, safety.

6.1 Performance of the keep-right-except-to-pass rule in heavy and light traffic

The time-space diagram can illustrate the traffic condition directly, so we first use three time-space diagrams to show heavy traffic, medium traffic and light traffic, respectively. The cellular automata has two lanes and 1000 cells. We first let 50 cars enter in these cells to simulate light traffic, and the result was showed below:

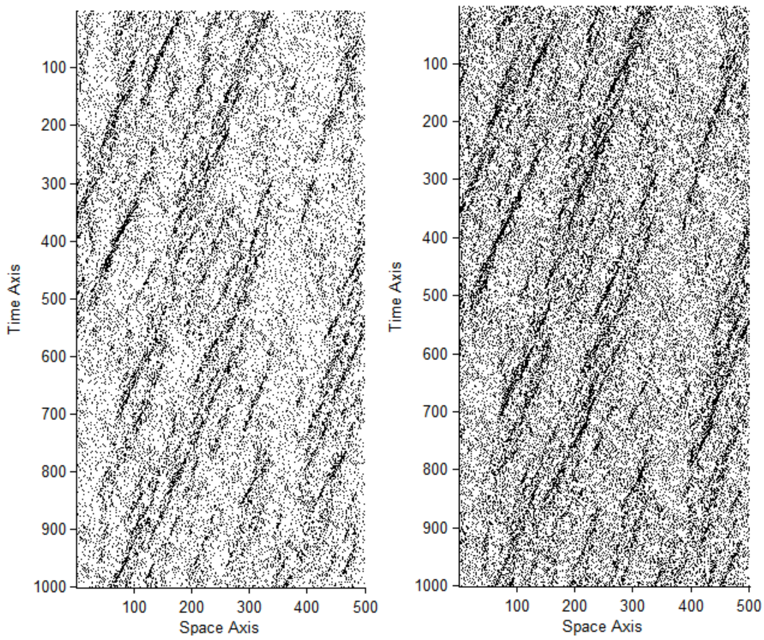


(a) Left lane (b) right lane

Figure 7 time-space diagram of two-lane traffic at light traffic flow,
(a) is the left lane, while (b) is the right lane.

Because of the traffic is low, there is no accumulation in both left lane and right lane. At the same time, these car's moving obeys the keep-right-except-to-pass rule, so the car will more like to stay at right lane and the car entering in the left lane is only for passing. So obviously, the car density on the right lane is higher than the car density on the left lane, which means that rule has been realized in our simulation. When traffic is low that rule works very well and the traffic system run on a high efficiency mode, or in another word, the traffic system run in a stable mode. Car's random deceleration cause destabilization in the lane. However, the gap is large enough and destabilization will not diffuse. As a result, these are now traffic waves in either lane.

Then we let 200 cars enter into these cells and simulate the medium traffic, the figure below shows the medium traffic time-space diagram.



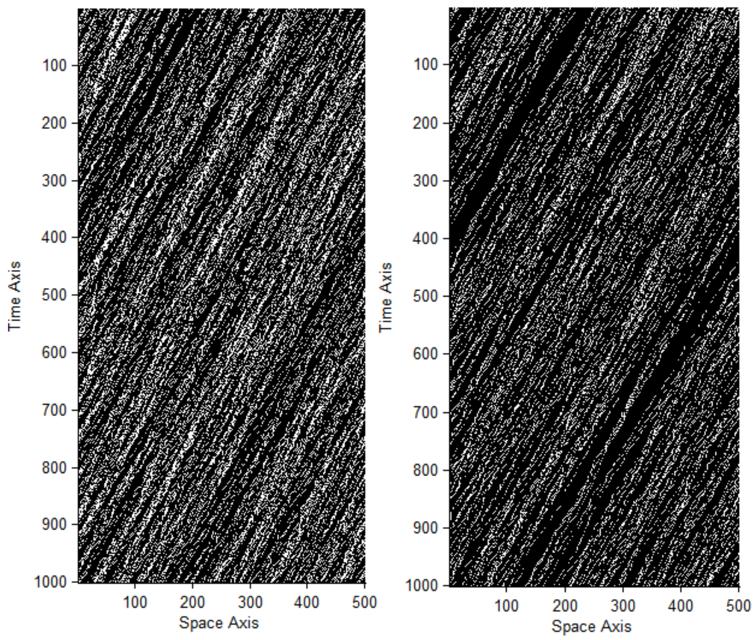
(a) Left lane (b) right lane

Figure 8 time-space diagram of two-lane traffic at middle traffic flow,
(a) is the left lane, while (b) is the right lane.

In the medium traffic, we can see a phenomenon that cars accumulate in some location, and the phenomenon contributes to traffic wave, the wave moves backward when vehicles move forward. The time-space diagram shows that the right lane has more cars than the left lane, which means the keep-right-except-to-pass rule works in that condition and our simulation can also realize the rule in the medium traffic condition.

So the keep-right-except-to-pass rule seems like a good rule and can work well in many traffic conditions. However the next simulation directly shows that rule may lose effect in the heavy traffic condition. Naturally, when the traffic is heavy there is no room for a car move to the next lane and people always want to enter into the lane where the traffic condition is better with enough room.

Lastly, we let 800 vehicles enter into cells and simulate heavy traffic. In that condition, the traffic phenomenon is more interesting: the keep-right-except-to-pass rule seems doesn't work and the left lane has similar car numbers with the right lane.



(a) Left lane (b) right lane

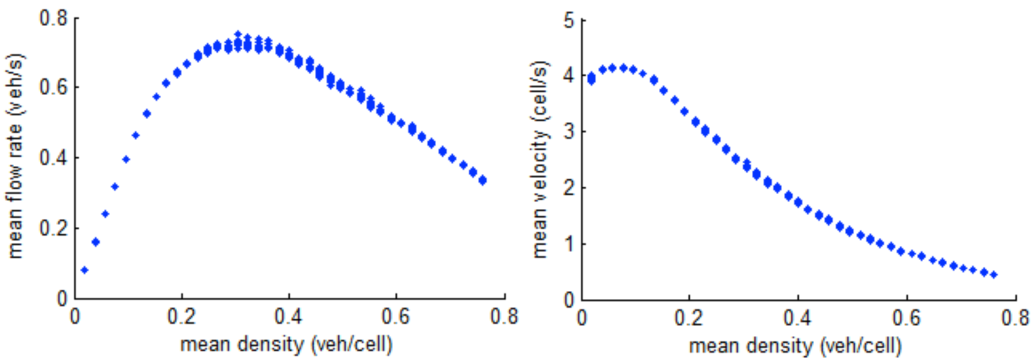
Figure 9 time-space diagram of two-lane traffic at heavy traffic flow,

(a) is the left lane, while (b) is the right lane.

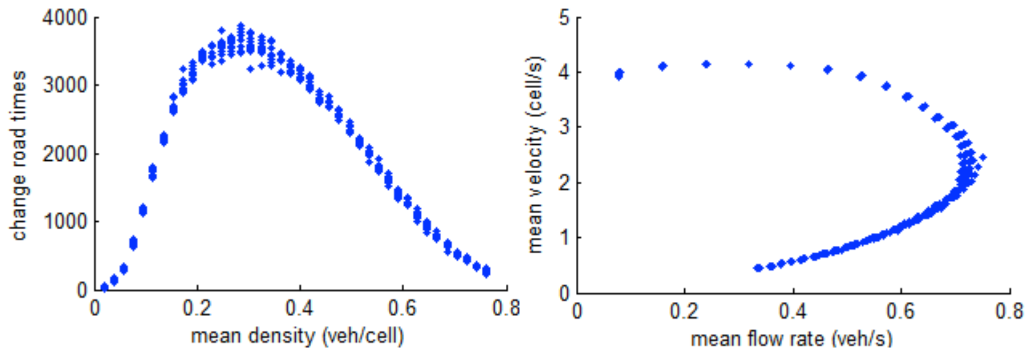
The density of the vehicle on the lane is too high, 800 vehicles in 1000 cells means occupation rate of lane is 80%, the traffic condition on the left lane is almost the same as the traffic condition on the right lane, which means the keep-right-except-to-pass rule does not work or the influence of that rule is quiet small. The both lanes are crowded and on the some areas of right lane we can see some vehicles is very close which means traffic jam has occurred.

Time-Space diagram show the microscopic mechanics of traffic phenomenon. At the same time, we also want to know the traffic flow macroscopic changes and trend when other state variables changed.

To illustrate the macroscopic character of our model, we use mean density, mean velocity and mean flow rate on our next simulation. We change mean density by changing vehicle number in cells and then get the mean velocity and mean flow rate relating to the mean density. The microscopic dynamic system show complex action in the macro scope. These figures below show the relationship among mean density, mean flow rate, mean velocity and totally overtaking times.



(a) (b)



(c) (d)

Figure 10 the relationship among mean density, mean flow rate, mean velocity and overtaking times. (a) is the diagram between mean flow rate and mean density, (b) is the diagram between mean velocity and mean density, (c) is the diagram between mean velocity and mean flow rate, (d) is the diagram between overtaking times and mean density

In diagram (a), the mean flow rate is a function of mean density. There is a critical density relating to the maximum mean flow rate, and the critical mean density divides the axis into two parts. On the left part, it means the traffic flow is free flow, vehicles can accelerate freely and decelerate freely, and the relationship between mean flow rate and mean density is almost linear. However, on the left part, it means the traffic flow is jam flow, when mean density increases, mean velocity decrease as diagram (b) shows. Then the mean flow rate decreases when mean density increases.

In diagram (b), the mean velocity is a function of mean density. When mean density is low, the mean velocity changes little. And when mean density becomes bigger, the mean velocity will be monotone decreasing, which means traffic pressure increases.

In diagram (c), also there is a maximum mean flow rate and relating to a critical velocity, which divides the axis into two areas: free flow area and crowded flow area.

In diagram (d), the times of change road is a function of mean density. There is an arrest point, and in that point change road times increases to the maximum. However, change road always relates to risk and become a factor of unsafety. So if the vehicle on the lane always change road, then driving on this lane must be dangerous. So change road times is also a index to evaluate the safety of traffic rule, a good traffic rule always doesn't make vehicle change road too often.

Moreover, vehicle in our cellular automata will never crash because of the forced decelerate rule. However, in reality, if the mean traffic density is too high, then the gap between vehicles must be small, and the crash might happen because of over accelerating. So the mean density of traffic is also an index to evaluation traffic safety.

In most time, we hope high traffic flow rate with low mean traffic density, it also means high mean vehicles velocity. Then the traffic safety is high and the time cost is small. For the rule of keep-right-except-to-pass rule performance better when mean density is low. However, when mean density is larger than the critical mean density, the traffic system state fork, traffic flow turn to crowded flow with bad safety and low efficient. On our simulation, the critical density is near 0.3, the critical velocity is near 2.5, the maximum flow rate near 0.8, and the maximum change road times related density is near 0.3. So when mean density of traffic flow is 0.3, the traffic system become rarely unstable and hopping from free flow and crowed flow.

6.2 Performance of the rule on different speed limitation

We simulate the rule in three kind speed limitations: low speed limitation, normal speed limitation and high speed limitation. Low speed limitation is the maximum velocity is 3 cells per time step which means 81 kilometers per hour in real world and normal speed limitation is 5 cells per time step which also means 135 kilometers per hour in real world and high speed limitation is 6 cells per time step which also means 162 kilometers per hour in real world.

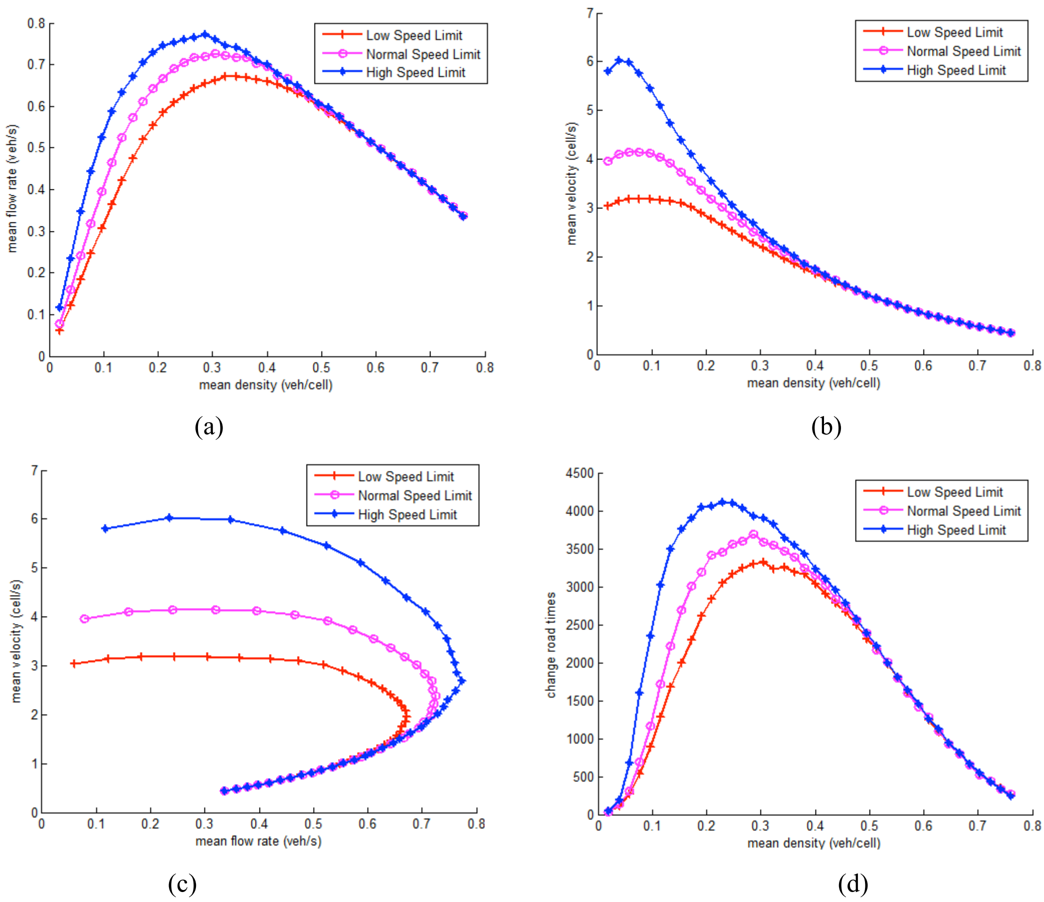


Figure 11 the relationship among mean density, mean flow rate, mean velocity and overtaking times. (a) is the diagram between mean flow rate and mean density, (b) is the diagram between mean velocity and mean density, (c) is the diagram between mean velocity and mean flow rate, (d) is the diagram between overtaking times and mean density

These figures above are about the relationship of mean density, mean velocity and mean traffic flow. All this figures have a common character, these curves of multi-color is difference when the traffic flow is free flow and these curves become the same when the traffic flow is crowded flow.

When traffic flow state is free slow state, the velocity limitation will affect the traffic in evidence. However, when traffic is crowded flow, the velocity limitation is no longer an important factor, So different speed limitations receive the same result when the mean density is high. When mean density is high and traffic is crowded, we could compare difference speed limitation's affect when mean density is low, or in another word, the traffic flow state is free flow.

From these pictures above, we can make a conclusion that high speed limitation relates to high mean density and high mean flow rate. High mean velocity and high mean flow rate are what we hope to happen. However high speed limitation also means more danger.

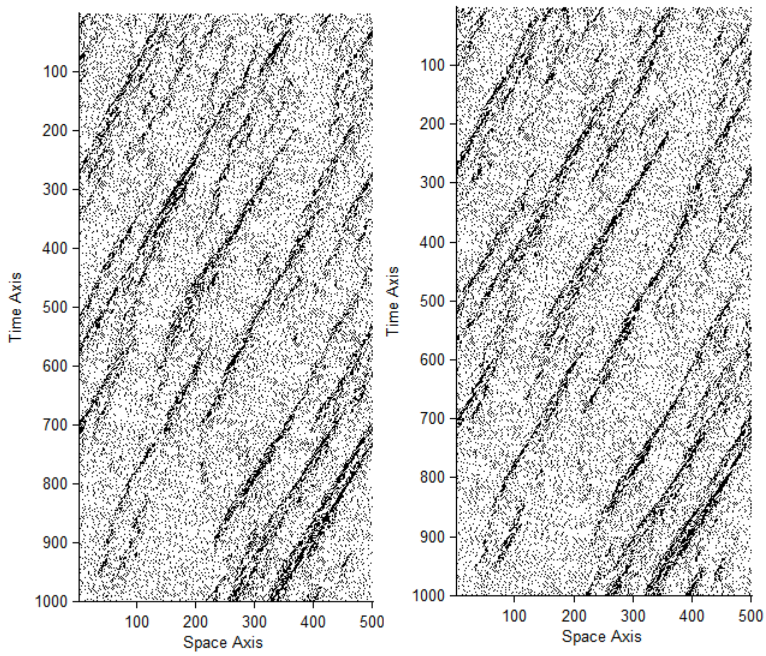
From the picture (d), we know, in the free flow state, high speed limitation cause high change road times. That is high speed limitation lead to traffic system more active and unstable, too frequently change road means high risk and unsafe.

So the conclusion is that high speed limitation means high transportation ability, low time cost and all we expect in that condition except safety problem. So the interesting situation is that if the highway operator has the ability to make highway stay in free flow state and deal accident in short time, increasing speed limitation is a good choose to increase transport efficient just like German Highway without speed limitation.

6.3 Simulation of different lane changing rules

Three lane changing rules has been defined, that is, keeping right, keeping left and symmetry lane changing rules. To illustrate the effect of different lane changing rules, we first draw the time-space diagram to show the microscopic mechanism. Then we draw the function relationship of macroscopic statistics like mean density mean velocity and mean flow rate.

The time-space diagram of symmetry lane changing rule with medium traffic is the figure below:

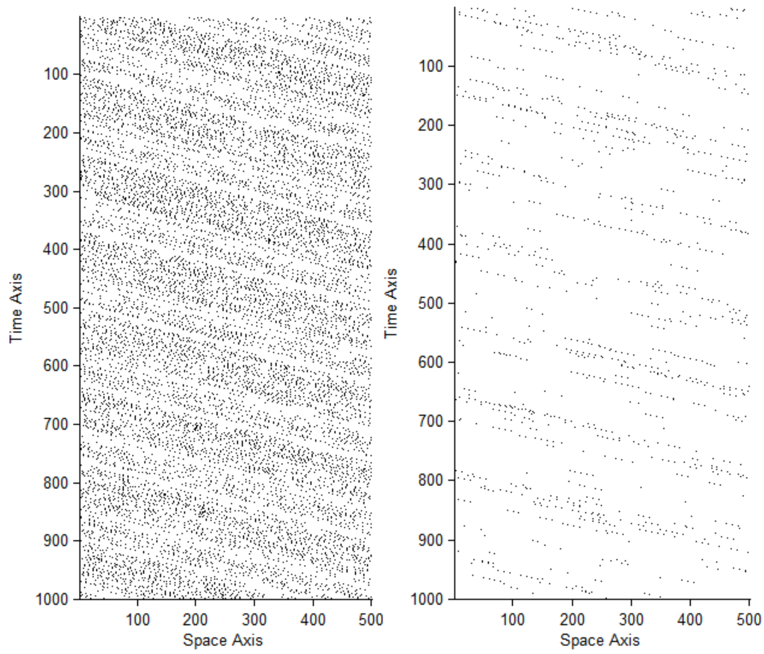


(a) Left lane (b) right lane

Figure 12 the time-space diagram of symmetry lane changing rule with medium traffic, (a) is the left lane, while (b) is the right lane.

Because lane changing rules is symmetry, so there is no difference between lane and overtaking lane. Each lane is the same in every aspect. Naturally, the time-space diagram of right lane and left lane should be similar. In that figure the left lane's time-space diagram is very close to the right lane's time-space diagram. The effect of symmetry lane changing rules had been realized.

The Second lane-changing rule is keeping right rule, the detail algorithm and result had also been described in the front paragraph. So only describe the result of keep-left rules. The Figure below is keep-left rule with low traffic.

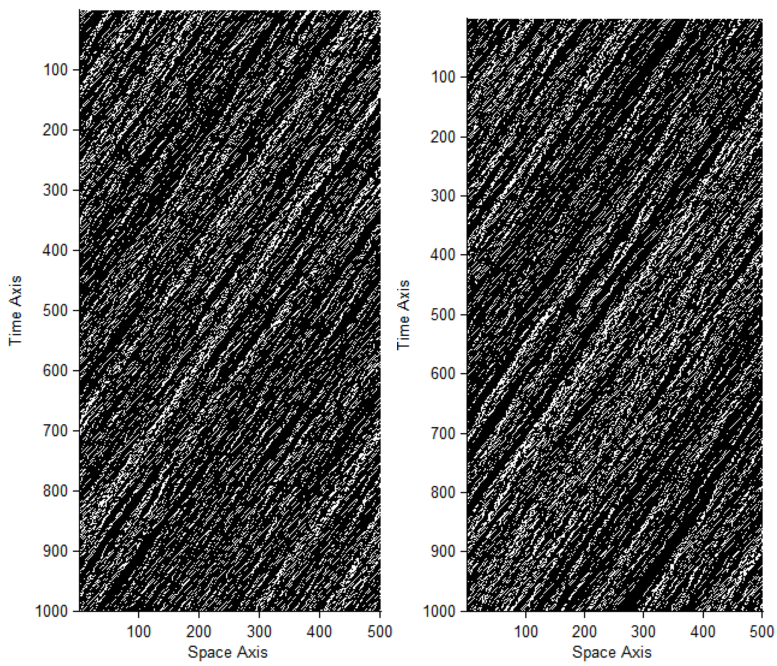


(a) Left lane (b) right lane

Figure 13 time-space diagram of two-lane traffic in keep-left rule with low traffic,
(a) is the left lane, while (b) is the right lane.

The left lane has more vehicle than the right lane, the rule of keep-left works. This result is similar to the result of keep-right rule with low traffic. In fact, if other conditions are the same as the keep-left rule, and keep-right rule are anti-symmetry rules, the result should be the same. However, the next shows the result of keep-left rule is not fully the same as keep-right rules.

The keep-left rule has the same problem as the keep-right rule. When traffic is high, the rule will lose its effect, and may not be so suitable in that condition. The figure below shows the keep-left rule with high traffic.



(a) Left lane (b) right lane

Figure 14 time-space diagram of two-lane traffic in keep-left rule with high traffic,
(a) is the left lane, while (b) is the right lane.

Although the lane changing rule is keep-left, the traffic flow rate is high and the rule can work well. So the left lane has similar vehicle number as the right lane.

Then the macroscopic statistics show the differences between different lane-changing rules, we expect the character of keep-left rule is the same as keep-right rule, however the result is not like that.

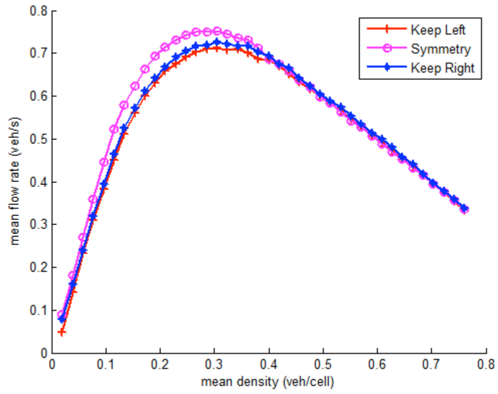


Figure 15 mean flow rate and mean density

The symmetry rule has a largest mean flow rate, the keep-left rule very similar to the keep-right rules, though there is some small difference. When the traffic flow become crowded traffic flow, these data of three rules become the same.

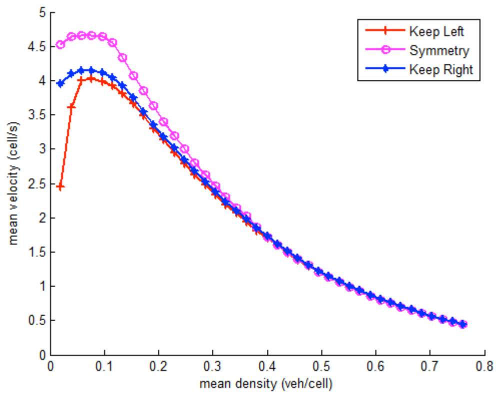


Figure 16 mean density and mean velocity

The symmetry lane-changing rule also have a largest mean velocity, the data of keep-left rule and keep-right rule is similar with small differences.

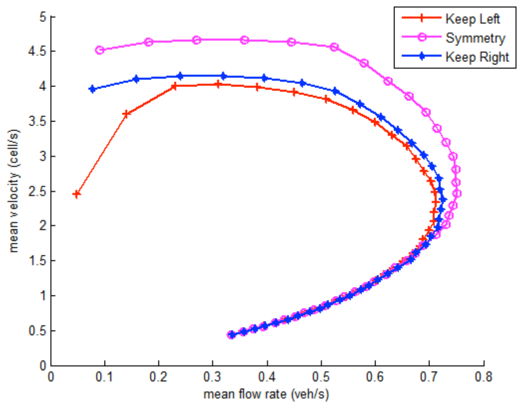


Figure 17 mean flow rate and mean velocity

We can come to a conclusion from these pictures: The data of different rule has the same trend when the traffic flow is high and symmetry lane-change rule have the best transportation ability, and it reduce time cost, However there is no symmetry lane changing rule in our current road.

Then we should consider the safety of different rules, the relationship between car density and lane changing times is as the figure below:

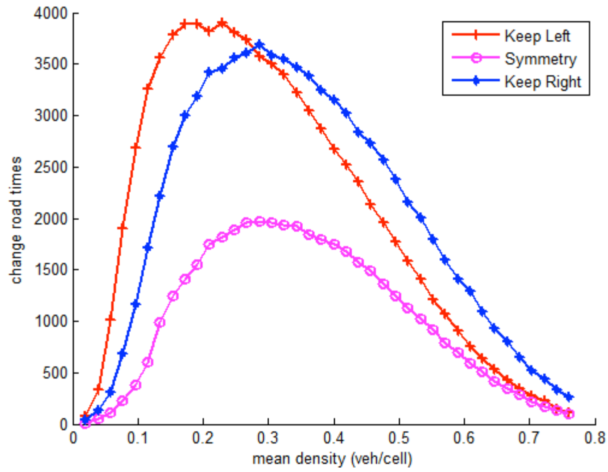


Figure 18 mean density and change road times

The symmetry lane changing rule have a lowest lane changing times, So Symmetry lane-Changing maybe a better rule than the keep-right rule or the keep-left rule on considering the safety . However this is only based on the fundamental research, the keep-right rule and keep-left rule now is widely used in the worldwide, and the better lane change rule has never been found in the modern traffic system.

6.4 the effect of intelligent system control

If the car is controlled by an intelligent system, then the car may change road in a fixed way, however a driver always change road in an agility way. When a driver judges that their driving condition allows them to change road, but the driver may not change road. However, with the control of smart system if the basic change road condition is fully satisfied, then the smart system must change the road.

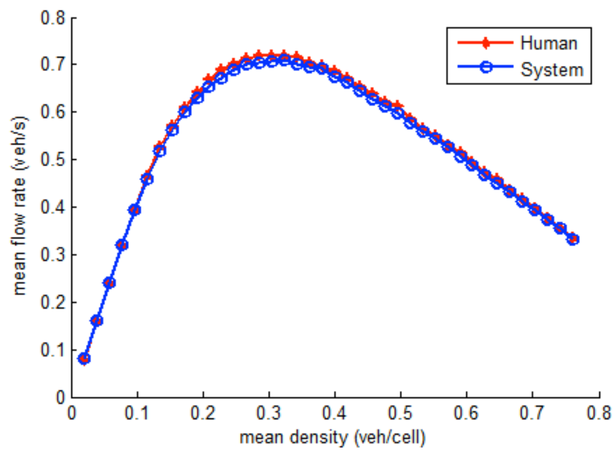


Figure 19 mean density and mean flow rate

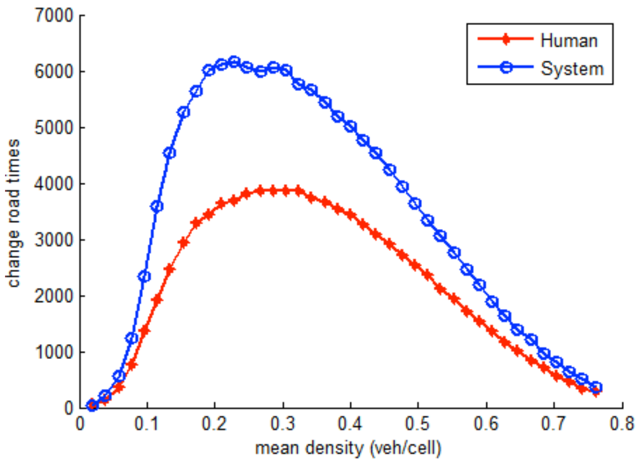


Figure 20 mean density and change road times

Simulation result shows that no matter the vehicle is controlled by smart system or people, the traffic macroscopic statistics is very close. With the control of people the car changes less than with a smart system or machine. High frequent change road may not be safe, however the smart system can make ensure to change road safe that's a complex problem.

VII. Model verification

Experimental observation of real traffic is a direct and simple way to examine the theoretical model. Therefore, we aim to verify the reality of our two-lane traffic rule analysis model by comparing the simulation results with real traffic data. As stated above, we are interested in microscopic observations of traffic flow quantities related to lane changing behavior on space and time, thus we adopt cellular

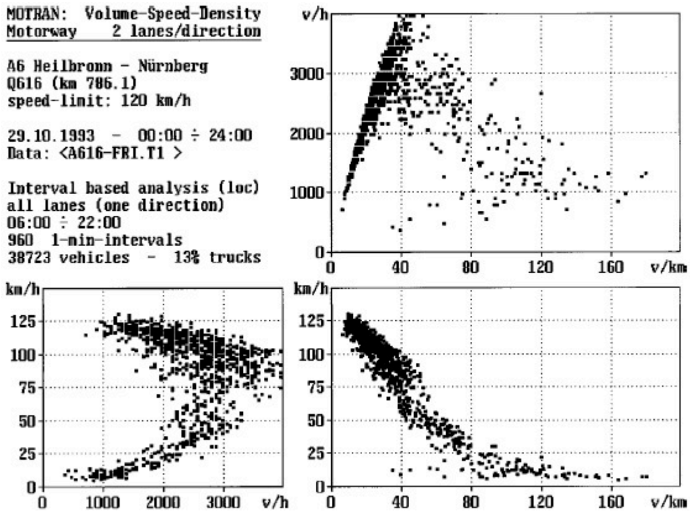


Figure 21 the relationship of real traffic among density, flow rate, velocity,

Data are from Wiedemann; see [10] for further information.

automata as the basic method to analyze the performance of the keep-right-except-to-pass rule on driving right. However, the observation of real traffic is macroscopic. Therefore, we transform the microscopic to the macroscopic, and obtain the velocity-flow plot, the flow-density plot, and velocity-density plot in different traffic rules. Thus, we can verify our model by comparing the plots with that of the real traffic on one German highway [10], shown in figure 21.

By analysis figure 10 and 21, we find that the simulation result of lane changing rule is identical to the actual results of the Germany freeway, which proves that our model is correct and reliable.

VIII. Strengths and Weaknesses

8.1 Strengths

In order to have the model more close to driver's driving behavior, we defined several probability such as the acceleration probability, random deceleration probability and so on, which lead to a more relaxed driving rule. In driving process, drivers may decelerate in confront with low velocity lead vehicle, some drivers may choose to change their driving lane, and for some timid drivers, they may stay on the same lane. Different drivers have different speed behavior, some may speed at a quiet high acceleration, and others are not. By changing the probabilities we define, we realize the purpose to simulate different driving behaviors.

The simulation result of lane changing rule is identical to the actual results of the Germany freeway, which proves that our model is correct and reliable.

Besides the keep-right-except-to-pass rule, we put forward several different lane changing rules to simulate the real traffic conditions, and compare the simulation result with that of the keep-right-except-to-pass rule. According to the simulation result, we give out the effect of different traffic rules on safety and traffic flow rate.

8.2 Weaknesses

The simulation road and vehicles are all ideal, at the same time, vehicles cycle on the road. To certain degree, it is different with the reality. It may take in simulation error, weaken the randomness of actual traffic flow. And this problem is valuable for us to do more work to solve out.

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