Journal of Computers Vol. 28, No. 5, 2017, pp. 338-349
doi:10.3966/199115992017102805029

Inter-vehicle Force Based Mobility Model Generation for VANETs

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Received 24 July 2017; Revised 24 August 2017; Accepted 24 September 2017

Abstract. An appropriate vehicle mobility model plays an important role for simulation of protocols in VANET. After the research of existing vehicle mobility models, an Inter-vehicle force based Mobility Model generation method in VANETs was proposed. Compared with inter-molecular force in physics, the proposed method described the relationship between the running vehicles, and achieved the vehicle mobility modeling. The model extended from a simple case of single-lane to two-lane lane-changing model after introducing the lane-changing conditions. The simulation results verify the feasibility of the new vehicle mobility model.

Keywords: Inter-vehicle force, single-lane model, two-lane model, VANETs, vehicle mobility model

1 Introduction

The development of intelligent transportation system (ITS) plays a very important role in solving the increasingly serious traffic problems [1]. The Vehicular Ad Hoc Network (VANET) is an important part of intelligent transportation system, and it is a special mobile ad hoc network (MANET) which uses vehicles as mobile nodes. The network can make the car drivers understand the status information (speed, location, direction, etc.) about the surrounding vehicles in a larger range and the information about current road traffic, which can let the drivers make judgments timely. Not only can it improve the traffic efficiency and the traffic conditions, but also it can give the drivers to provide greater security [2]. Many network protocols emerge in order to meet the security requirements of vehicular ad hoc network [3-4]. However, due to the complexity of the actual test environment and the restriction on economic problems, simulation has become an important method to verify the vehicular ad hoc network protocol. As the first step of the simulation environment design, it is very important to select a precise and simple vehicle moving model for the whole simulation.

The vehicle mobility model is shown in Fig. 1. In the early stage, the mobile model is mainly a simple random mobility model, such as Random Waypoint Mobility Model (RWM) [5] and so on. Considering the current vehicle will be affected by the surrounding vehicles, the researchers proposed vehicle flow models, such as the Car Following Models (CFM) [6]. In succession, the model of intelligent driver and cellular automaton model are put forward, which is widely used in many kinds of traffic simulator [7-8]. Taking into account the motion of the vehicle is not random, so the researchers put forward a new traffic model. Tian introduced the geographical space constraints, and proposed a Graph-based Mobility Model (GBMM) [9]. Bettstetter proposed a Smooth Mobility Model (SMM) [10], which can change to the speed and direction in the next moment according to the current speed and direction of mobile vehicle. In order to reflect the real situation of vehicle movement, trace-based model describe the actual movement of

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vehicles accurately through collecting the information of the vehicle for a long time [11-13]. However, the complexity of this method is high and it needs a lot of computation, which brings a lot of inconvenience for the practical application. In addition to the traditional methods, researchers have begun to explore and design a new model of vehicle movement. However, due to the different characteristics of these models and their indifference in adaptive scene, they have some limitations and poor scalability.

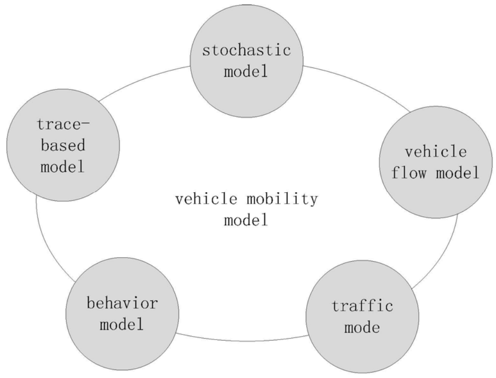

Fig. 1. Vehicle mobility model and classification

In this paper, combined with the actual running state of the vehicle, the idea of intermolecular force in physics is connected with the change of distance between vehicles. We propose a new vehicle movement model based on the inter-vehicle force, which provides a new method and idea for the vehicle mobility modeling. The proposed mobility model can realize single-lane model and two-lane model for lane-changing. We verify the feasibility of new vehicular mobility models through the simulation, and make some analysis for the properties of the model.

2 The Principle and Model

2.1 Interaction Force between Vehicles

In actual vehicle flow, the relationship between the vehicles is similar with the force between molecules. The approaching process of the vehicle is similar to the attraction of the intermolecular forces in the long range. The leaving process of the vehicle is similar to the rejection of the intermolecular forces in the short range. The steady running state of a vehicle is similar to the balanced state of the intermolecular forces. The inter-molecule force can be ignored when the distance is so large, the same to the inter-vehicle relationship. In order to facilitate the description, in a pair of interacting vehicles, we call the front of the vehicle as the car in front (forward) and the rear of the vehicle as the car behind (back). By means of the formula of intermolecular force, the formula of the interaction force between the vehicles is defined:

$$F = \frac{\lambda(v)}{r^s} - \frac{\mu(v)}{r^t}. \quad \textbf{(1)}$$

In (1), r is the distance between the vehicle behind and the vehicle in front, λ, μ, s, t are the preset parameters. $\lambda(v), \mu(v)$ are the functions of the latter vehicle's speed. s, t are the positive integers, $s > t$.

We describe the interaction force between the vehicles by setting the values of these four parameters λ, μ, s, t. $\lambda(v), \mu(v)$ can be expressed as the power function form of the speed v. The specific function can be adjusted by adding appropriate correction items on the basis of simple power function. So it can realize the approximation of the real vehicle operation. In the simple case, $\lambda(v), \mu(v)$ can be expressed as：

$$\lambda(v) = (\sigma v)^s . \tag{2}$$

$$\mu(v) = (\sigma v)^t . \tag{3}$$

In general, σ is not less than 4. The specific design reasons are given in the following analysis. The variables s, t represent the changes of the interaction force between vehicles. According to the formula of intermolecular forces, the range of s is defined as 9 to15 and the range of t is defined as 4 to 7. The s used in the simulation are 12 and the t used in the simulation are 6. The interaction force between the vehicles is shown in Fig. 2.

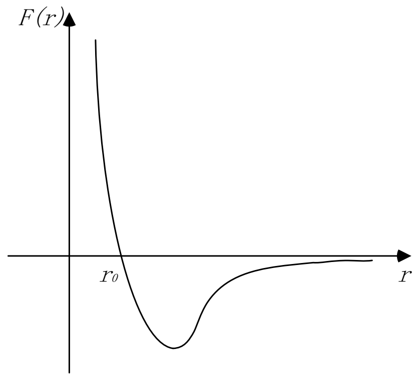

Fig. 2. Interaction force between vehicles

2.2 Analysis of Interaction Force between Vehicles

As the intermolecular force, the interaction force between the vehicles is divided into two parts, which $\frac{\lambda(v)}{r^s}$ represents the repulsion force between vehicles, and $\frac{\mu(v)}{r^t}$ represents the attraction force between vehicles. The difference between the repulsive force and the attraction force causes the vehicle to show the repulsive or attractive cases. When the vehicle interaction is negative, the vehicle performance is mutually attractive. When the vehicle interaction is positive, the vehicle is mutually exclusive. When the interaction force between vehicles is zero, the vehicle is in a state of balance. The interaction force between the vehicles is described and analyzed in detail by means of the vehicle interaction diagram of Fig. 3. In Fig. 3, r_0 represents the balance position between vehicles, r_1 represents the maximum distance between vehicles.

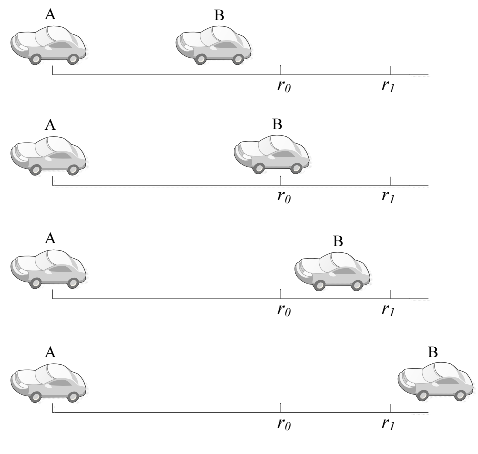

Fig. 3. The interaction between vehicles

(1) When the repulsive force $\frac{\lambda(v)}{r^s}$ is larger than the attractive force $\frac{\mu(v)}{r^t}$, namely the interaction force F is greater than zero, the interaction force behaves the repulsive force and the rear vehicle slows down.

(2) When the repulsive force $\frac{\lambda(v)}{r^s}$ is equal to the attractive force $\frac{\mu(v)}{r^t}$, namely the interaction force F is equal to zero, the rear car keeps running at a constant speed. At this time, the distance between the vehicle in front and the vehicle behind is the balance distance, named r_0, defined as：

$$r_0 = r_0(v) = s - t\sqrt{\frac{\lambda(v)}{\mu(v)}} \, . \tag{4}$$

According to the actual operation of the vehicle, the balance distance between vehicles at a low speed will be higher than the distance at a high speed. So $r_0(v)$ is a monotonically increasing function of v. When $\lambda(v), \mu(v)$ are expressed as $\lambda(v) = (\sigma v)^s, (\sigma v)^t$ then

$$r_0 = \sigma v \, . \tag{5}$$

According to the provisions of forty third of "People's Republic of China Road Traffic Safety Law"[14], for the vehicles in the same lane, the vehicle behind should keep a certain distance enough to the car in front to take emergency braking measures. The traffic control department gives some explanation for the safe distance. Vehicle safety distance (unit for meter) can be approximated as the value of the vehicle speed with km/m as the unit. That is, the speed of 100km/h corresponds to a safe distance of about 100m. The speed m/s and km/h conversion ratio is 3.6, and the balance distance should be greater than the safety distance. So the design value σ is not less than 4.

(3) When the repulsive force $\frac{\lambda(v)}{r^s}$ is less than the attractive force $\frac{\mu(v)}{r^t}$, that is the interaction force F is less than zero, the interaction force behaves attractive，the vehicle behind performs operation to accelerate.

(4) When the distance between the vehicles is greater than a certain distance (r_1 in the figure), the repulsive force $\lambda(v)/r^s$ between vehicles is still less than the attractive force $\mu(v)/r^t$. But because the two have become very small, the resulting attractive force is small enough to be ignored. The force is approximately equal to zero, and the vehicles are running independently.

2.3 Vehicle Mobility Model for Single-lane

The realization process of the vehicle mobility model can be summarized as follows:

Step1: Initialization settings. Set the number of vehicles and the total time of the simulation and assign the values for parameters of the interaction force between vehicles. Set the initial state of the vehicle, including the speed range of all vehicles, the acceleration of all vehicles, the initial speed of each vehicle, the initial distance between vehicles.

Step 2: Calculate the interaction force between vehicles. Calculate the interaction force between vehicles according to the distance between vehicles and the parameters of the interaction force. Then we can judge the operation of the vehicle and calculate the corresponding acceleration. We can get the maximum value F_{min} of the gravitational force by analyzing the formula of the interaction force between the vehicles. We define the corresponding maximum positive acceleration of the vehicle as α_{max}. For convenience, the threshold value of the repulsive force between vehicles is also chosen as the absolute value of the maximum gravity $|F_{min}|$. We define the corresponding maximum negative acceleration of the vehicle as b_{max}, so the corresponding relationship between the acceleration of the vehicle and the force between the vehicles can be defined as a simple linear relationship. It is shown in the following formula:

$$a=\begin{cases}\dfrac{F}{F_{min}}\times a_{max}, & F\le 0\\ \dfrac{F}{|F_{min}|}\times b_{max}, & 0<F<|F_{min}|\\ b_{max}, & F\ge|F_{min}|\end{cases}. \quad \textbf{(6)}$$

Step3: Calculate the safety speed based on the current vehicle distance. Vehicles need to keep in a safe speed to avoid the traffic accidents. Otherwise, the front vehicle's braking suddenly can lead to an accidents. In this paper, the safety speed of the vehicle can adapt to the scene that when the front vehicle's speed reduces to zero with the maximum negative acceleration and the latter vehicle's speed also reduces to zero with the maximum negative acceleration after the driver's response time, the two vehicles can't collide. We can calculate the safe speed $v_{safe,i}$ of the i th vehicle based on the current distance between vehicles with the following formula.

$$v_{safe,i}=b_{max}\times T+\sqrt{\left(b_{max}\times T\right)^2+v_{i+1}{}^2-2\times b_{max}\times(d_{i,i+1}+l)}\,. \quad \textbf{(7)}$$

In (7), T is the reaction time for the driver. v_{i+1} is the speed of the car in front. $d_{i,i+1}$ is the distance between the vehicle in front and the vehicle behind. l is the length of the vehicle.

Step 4: Update the movement status of vehicle. The current vehicle can get v_{up} according to the acceleration computed from the interaction force between vehicles. v_{up} needs to satisfy the limit of the safe vehicle speed $v_{safe,i}$ and the maximum speed $v_{\max}$ of the vehicle. v_{up} and the final speed v are calculated as followed.

$$v_{up}=v_i+a\times\Delta t\,. \quad \textbf{(8)}$$

$$v=min\{v_{up},v_{safe,i},v_{\max}\}\,. \quad \textbf{(9)}$$

According to the kinematic formula, the position of the vehicle and the distance between the vehicles are updated based on v.

Step 5: Repeat the step 2 to 4 until the end.

2.4 Conditions of Lane-changing

In the actual operation of the vehicle, the driver will change the way to get a more efficient driving environment. In this paper, the condition of lane changing is based on the following strategy: the latter vehicle's speed is greater than the front vehicle's speed in the same lane, the latter vehicle's speed is less than the front vehicle's speed in the neighbor lane, the distance between the vehicle behind and the vehicle in front in the neighbor lane is greater than a certain distance, the distance between the vehicle behind and the vehicle behind in the neighbor lane is greater than a certain distance. Among them, the first two are the demand for the latter vehicle in current lane to change lane, the last two are the demand for the safe distance to change to the neighbor lane. The concrete formulas of the lane-changing conditions are as follows:

$$v_{l,i}>v_{l,i+1}\,. \quad \textbf{(10)}$$

$$v_{l,i}<v_{l',i+1}\,. \quad \textbf{(11)}$$

$$d_{l,i}^{l',f}>c_0\times v_{l,i}\,. \quad \textbf{(12)}$$

$$d_{l,i}^{l',b}>d_0\times v_{l',i-1}\,. \quad \textbf{(13)}$$

Here l and l' represent the current lane and the neighbor lane, respectively. c_0 , d_0 are the lane changing parameter[15]. $v_{l,i}$ represents the speed of the i th vehicle in the l th lane. $d_{l,i}^{l'f}$ represents the distance between the i th vehicle in the lane l and the (i+1) th vehicle in the neighbor lane l'.

2.5 Vehicle Mobility Model in Two Lane

The vehicle mobility model in two lanes is formed with the vehicle mobility model in the single-lane and the lane-changing condition. The specific process is as follows：

Step 1: Initialization settings. Set the number of vehicles and the total time of the simulation and assign the values for parameters of the interaction force between vehicles and the conditions of changing lane. Set the initial state of the vehicle, including the speed range of all vehicles, the acceleration of all vehicles, the initial speed of each vehicle, the initial distance between vehicles. Assign the values for parameters c_0 and d_0 in lane-changing condition.

Step 2: Calculate the interaction force between vehicles. Calculate and discuss the interaction force, based on the distance between the vehicles and the parameters of the interaction force.

If the interaction force is attractive, the lane-changing operation is not carried out. The vehicle acceleration is calculated according to that the interaction force is attractive in the single lane.

If the interaction force is repulsive, the condition of the lane changing is judged. If the condition is satisfied, the lane is changed. After changing to the neighbor lane, the distance between the vehicle and the vehicle in front in the neighbor lane, the interaction force between the vehicles and the corresponding acceleration should be calculated again. If the lane changing condition is not satisfied, the operation of the current vehicle is the same as the case when the interaction force is repulsive in the single lane.

Step 3: Calculate the safe speed based on the current distance between vehicles. According to the results of the last step, it is divided into two kinds of situations: lane changing and no lane changing. Respectively, they are described as follows:

If the vehicle does not change lane, calculating the safe speed $v_{safe,i}$ according to the case in the single lane.

If the vehicle changes the lane, then the safe speed in the lane changed is calculated, based on the front vehicle speed in the neighbor lane and the distance between the vehicle and the front vehicle in the neighbor lane. Assuming that the vehicle changes lane from l *to* l', the safe speed's calculation formula is changed to:

$$v_{safe,i}^{l'} = b_{max} \times T + \sqrt{\left(b_{max} \times T\right)^2 + v_{i+1}^{l'\,2} - 2 \times b_{max} \times (d_{l,i}^{l',f} + l)} \,. \tag{14}$$

Step 4: Updated vehicle movement status. The current vehicle can get v_{up} according to the acceleration computed from the interaction force between vehicles. v_{up} needs to satisfy the limit of the safe vehicle speed $v_{safe,i}$ and the maximum speed $v_{\max}$ of the vehicle. We can calculate the v_{up} by the formula (5). The final formula of the vehicle speed is as followed.

$$v = min\{v_{up}, v_{safe,i}^{l'}, v_{\max}\} \,. \tag{15}$$

According to the kinematic formula, we can update the position of the vehicle and the distance between the vehicles on the basis of υ.

Step 5: Repeat the step 2 to 4 until the end.

3 Simulation and Analysis

The verification process of the vehicle mobility model is based on the following assumptions:

(1) The basic parameters of the vehicles are the same, including the maximum speed, the maximum acceleration and the length of vehicles, etc.

(2) The arrival of vehicles in the network follows the stochastic Poisson process.

(3) The initial velocity of each vehicle obeys the uniform distribution. Its distribution range is [v_{0min}, v_{0max}].

In this paper, the author uses the software MATLAB to realize the simulation of the vehicle mobility model based on the interaction force. The feasibility of the model has been verified, and some performance of the model have been analyzed, including the basic scene of the mobility model adopt and the different scenes corresponding to different actual cases. Some general simulation parameters are shown in Table 1. The remaining parameters are set in the following analysis.

Table 1. Simulation parameters

Parameters	Values
Number of vehicles	50
Time for simulation	200s
Step time for simulation	1s
Reaction time T	1s
Length of vehicle l	4m
Lane changing parameter c_0	>1.2s
Lane changing parameter d_0	>2.0s
Initial minimum speed v_{0min}	15 m/s
Initial maximum speed v_{0max}	25 m/s
Maximum speed v_{max}	40 m/s
Maximum acceleration a_{max}	3m/s^2
Maximum negative acceleration b_{max}	-5m/s^2

3.1 Feasibility Verification

We make the verification and simulation for mobility model by using the single-lane mobility model. In the actual vehicle flow, when the distance between the front vehicle and the latter vehicle is small, the movement state of two vehicles can have a high similarity. When the distance is big, the movement state of the two vehicles can become irrelevant. It is similar to that the interaction force becomes obvious when the vehicles have a small distance and the force is negligible when the vehicles have a large distance. Therefore, we select two pairs of neighboring vehicles from the simulation results. One pair of them has a large distance and the other of them has a small distance. Their speed's changes are as shown in Fig. 4 and Fig. 5.

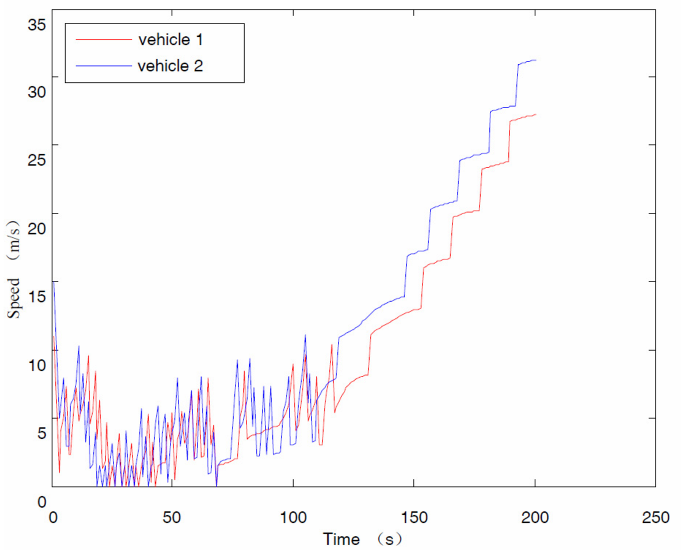

Fig. 4. Speed changes of neighbor vehicles

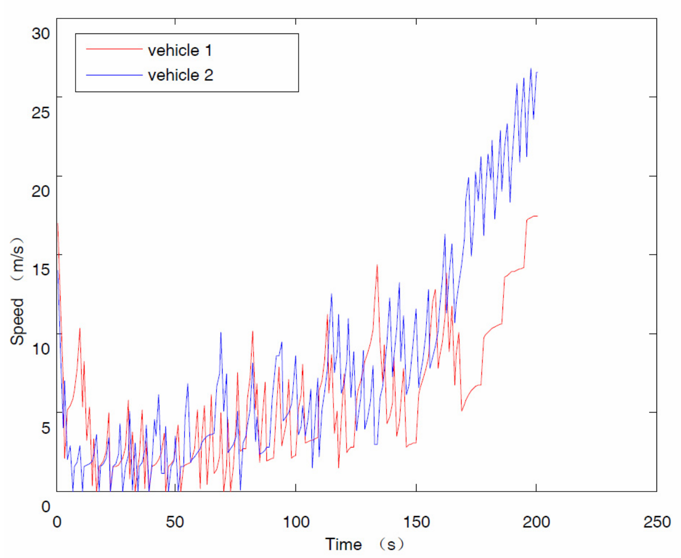

Fig. 5. Speed changes of vehicles between which have a long distance

Through the simulation results, we can see in the mobility model based on the interaction force between vehicles, the speed change of the neighbor vehicles have the characteristics of repetition and imitation. The trend and extent of the changes are basically the same, and there is a certain delay between the two vehicles. The speed change of the vehicles which have a large distance between them is not similar. The operating states are basically independent of each other, respectively. There are the similar changes of the position and acceleration.

3.2 Analysis of Distance between Vehicles

In the actual operation of the vehicle, the distance between vehicles is a very important parameter. Not only is it an important aspect of the study in traffic, but also it is an important condition for the communication in the vehicles. After the simulation of the mobility model based on the interaction force between vehicles, the author makes a statistical analysis of the distance between the vehicles and makes the distribution fitting of data.

By consulting other related research, we find that there is no uniform conclusion about the distribution of the distance between vehicles at present. But we can see that they are basically consistent with the shape of the lognormal distribution from the statistical results. The author makes the Table 2 by the statistical data from the single-lane vehicle mobility simulation proposed in this paper.

Table 2. Statistics of the distance between vehicles

Interval	Frequency	Interval	Frequency
(0,10]	63	(90,100]	5
(10,20]	211	(100,110]	6
(20,30]	94	(110,120]	3
(30,40]	24	(120,130]	2
(40,50]	18	(130,140]	0
(50,60]	7	(140,150]	2
(60,70]	5	(150,160]	2
(70,80]	6	(160,170]	3
(80,90]	1	(170,+∞]	4

The above data were fitted by dfittool, which is a distribution fitting tool in MATLAB. We can find that the fitting result of the lognormal distribution is the best. Therefore, we fit the data of distance between vehicles with the lognormal distribution. The original data and the fitting results are shown in Fig. 6.

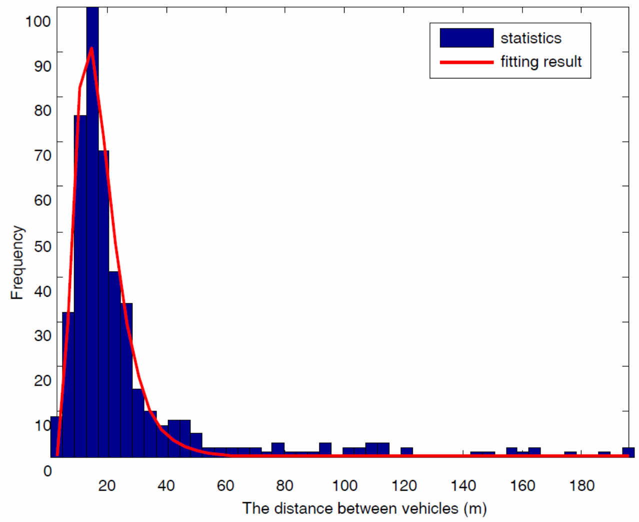

Fig. 6. Fitting results of the lognormal distribution about the distance between vehicles

We can see that the distribution of the vehicles accords with the lognormal distribution basically from the figure above. So we can draw the following conclusions: the distance between vehicles of the single-lane vehicle mobility model based on the interaction force obeys the lognormal distribution.

3.3 Study on Two-lane Model

Based on the lane changing conditions in section 2.4, we study the vehicle mobility model of two lanes. The research emphasis of the two-lane model is the situation of lane-changing, including the conditions of lane-changing and the times of lane-changing.

The vehicle driver is the subjective judge of whether the vehicle lane will be changed. The driver's differences will lead to different situations. In this paper, the drivers will be divided into two categories: aggressive driver and conservative driver. The degree of conservatism of the driver is described by the lane changing parameters. The aggressive driver has the smaller c_0 and d_0, the conservative driver has the larger c_0 and d_0. The smaller c_0 and d_0 correspond to the loose conditions for lane-changing. So the vehicles can change the lanes more times and the vehicle speed is faster and the distance between the vehicles is larger. On the contrary, the larger c_0 and d_0 correspond to the more stringent conditions for the changing lane. So the vehicles can change the lanes less times and the distance between the vehicles is smaller. We make the simulation about the distance influence between vehicles under the two conditions of aggressive and conservative, respectively. The results of statistical distribution of the distance between vehicles in two conditions have shown in Fig. 7 and Fig. 8.

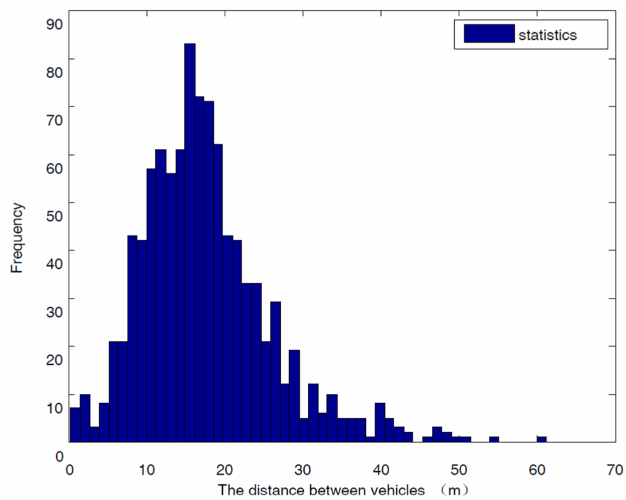

Fig. 7. The frequency statistics of distance between vehicles for aggressive driver

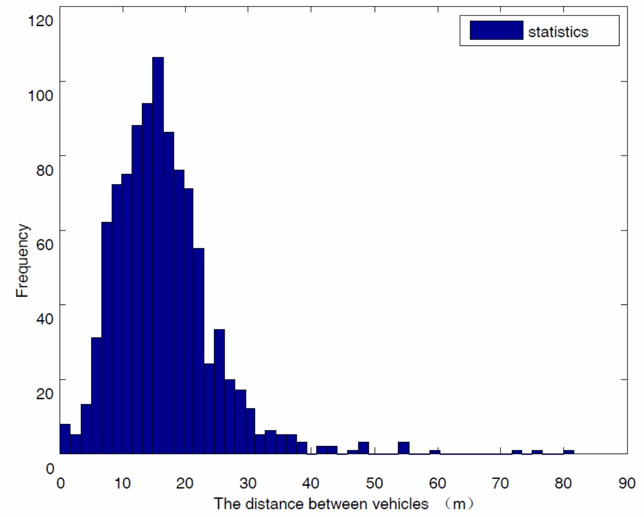

Fig. 8. The frequency statistics of distance between vehicles for conservative driver

According to the results above, we can see that if the driver is aggressive, the mean value of distance between vehicles and the range of values are larger. But if the driver is conservative, the mean value of distance between vehicles and the range of values are smaller. Those are consistent with the previous analysis.

Actually, there are both aggressive driver and conservative driver in vehicle flow. We study the changes of the times of lane-changing through changing the ratio of aggressive drivers. The changes of the times of lane-changing in different ratio for aggressive driver are as showed in Fig. 9 and Fig. 10.

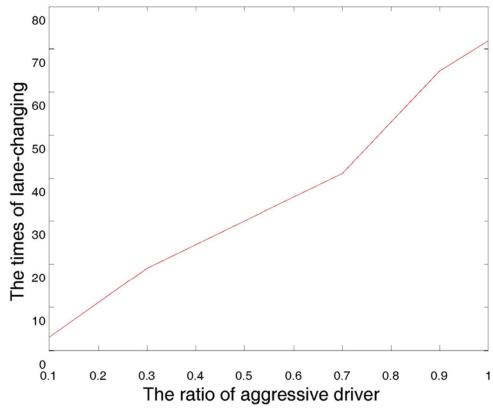

Fig. 9. The times of lane-changing in current lane

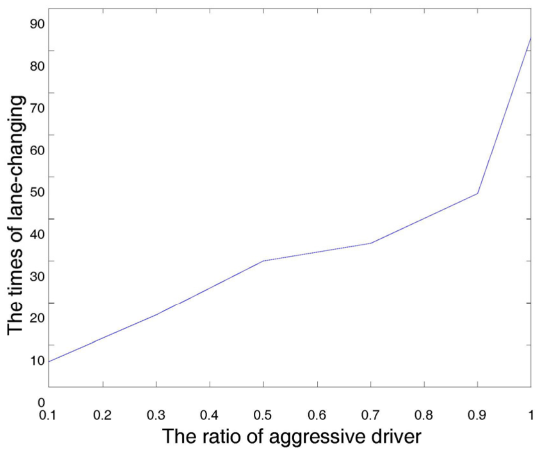

Fig. 10. The times of lane-changing in neighbor lane

As can be seen from above figures, the times of lane-changing in two lanes both show a growing trend with the increasing ratio of aggressive driver, which conforms to the actual operation law of the vehicle.

4 Conclusions

In this paper, we propose a new vehicle mobility model based on the interaction force between vehicles. Combining the idea of the interaction force between molecules in physics with the changes of the distance between vehicles, we make a more accurate description to the relationship between vehicles. And we provide a new method for vehicle mobility model in the VANET environment. The model is easy to implement and has good expansibility. In this paper, the single-lane and two-lane (lane-changing) mobility models are simulated by MATLAB. We verify the feasibility of the proposed model and make the analysis for it. The results show that the model can effectively reflect the running state of the vehicles actually.

Acknowledgements

This work was supported by New Century Excellent Talents in University (No. NCET-13-0657) and the State Key Laboratory of Rail Traffic Control and Safety Contract No.RCS2016ZT015, Beijing Jiaotong University. And it is supported in part by the Chinese National Programs for High Technology Research and Development 863 project (No.2015AA016005).

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