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Study on Safety Distance Model of fleet based on vehicle communication

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Abstract

The Safety Distance Model (SDM) is a key component of the collision prevention system. The SDM research rarely considers vehicle fleet as the research target, as the traditional SDMs only focus on the communication between two vehicles. This paper presents the updated SDMs established on vehicle communication technology characterized by on-time measurement and communication. The research focus is on analyzing vehicle queuing in single lanes which are under car-following status. The absolute and relative SDMs accounting for both the braking theory and driver prediction model, are obtained, which could provide decision-making information to driver. The proposed SDMS are proved to be able to increase the efficiency of vehicle collision prevention.

Keywords: vehicle communication; safety distance; automatic vehicle following; collision prevention system.

1. Introduction

The survey indicates that most malignant accidents are rear-ending chain collisions, which occurs regularly in the condition of lack of sight distance and reducing of road adhesion coefficient reduced. The Safety Distance Model (SDM) is one key research of the collision prevention system to provide theoretical guarantees and technical support for drivers.

The SDM research rarely takes the vehicle fleet as the research target because of the complex and expensive communication apparatus and the parameters concerning the SDM are relative more and complex. But recently, the development of computer and wireless communication technologies enables the feasibility of vehicle communication, which forms a well suited basis for decentralized active safety applications and therefore will reduce accidents and their severity. The vehicle communication enables the measurement of real-time parameters

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and communications among several vehicles, which causes proposed SDM can cover all conditions of vehicles' operation although the vehicles location and state are constantly changing. This paper takes the whole fleet as the research object, which means the vehicle queue in single lane. The research of vehicle fleet can increase the density of road vehicles and road capacity; simplify the traffic control by reducing the number of control objects, and furthermore, by employing the air vehicle dynamics analysis and simulation, it is possible to reduce the air resistance to save the vehicle fuel consumption.

2. Traditional Safety Distance Models

At present, safety distance models can be summarized as four types. The first is a fixed safety distance model which fixed C as the alarm limit value, if lower than the value the system will alarm. The second is a safety distance model which based on the braking process. The typical braking process can be described as: the driver recognize the traffic situation ahead, aware of the need for emergency braking, move right foot to the brake pedal and make the emergency brake until the vehicle stops. The third model is established based on headway. In the actual traffic conditions, when the vehicles follow driving with a small relative speed, the relative of the distance between the target vehicle and itself and its speed is linear. This safety distance model is established on the basis of this phenomenon. The fourth model is established based on driver prediction. This model considers the importance of drivers' subjective feeling factor in the established model. Actual driving, the drivers always forecast the vehicles' running to determine the current operation.

Fixed safety distance method, which can be relatively convenient used, can be able to ensure the safety distance between vehicles in some extent without complex calculate or traffic information detection. But it also has some limitations, as the anterior vehicle would be in different movement condition, the distance maintained should be different, and the safety distance cannot be changed with the vehicle speed changing in real time. Safety braking distance model, based on kinematic analysis, using of the braking characteristics of vehicle, represents the actual braking distance required when vehicles slow down, and it can describe the the actual braking status of vehicle to some extent, especially for the anterior car's static or sudden deceleration to zero. But in this model, the traffic efficiency is ignored. So the result is that a longer safe distance is gotten by using this model. When the anterior and posterior vehicles are both running normally in the real highway, selecting a appropriate headway value can reflect the driver's subjective judgments to a certain extent. But the algorithm of the value does not fully take into account the driving habits and analytical skills of the driver on road and vehicle, alarm algorithm is relatively simple in form, and it is difficult to fit the driver's practical experience. Driver prediction model takes into account the driver's subjective feelings, investigates the judging process to danger of driver. Compared with the headway method, it pay more attention to the subjective feelings of human. There kinds of working conditions, i.e. static, emergency deceleration and driving, are discussed, and relevant safe distance models in different conditions are obtained, but the key parameters of the model is difficult to determine.

In view of the development of the vehicle communication technology, information communication between vehicles becomes feasible. Synthetically considering the merits of the two models, a safety distance model based on the vehicle communication technology is constructed.

3. Safety Distance Model Based on Vehicle communication

For the whole fleet, to analyze the motion characteristics, consider the stability and make the vehicle with minimum speed as the base vehicle. Because the vehicles behind will tend to the minimum speed in a certain period of time. In the long run, it is impossible drive faster than this speed. There are several vehicles in the fleet's special place require analysis separately. There are two classification methods in this paper. The one is absolute safety distance model and the other is relative safety distance model. Absolutely safety distance means the speed of the vehicle in front suddenly brakes to zero (this case contains the vehicle before the vehicle static

condition). Relatively safety distance is calculated based on the relative velocity between vehicles including the case of vehicle driving keeping an even speed in front. As the vehicle speed is real-time measurement and communications. The vehicles' location and state are constantly changing, so the model can cover all conditions of vehicles' operation. It can well describe vehicles' state and ensure safety, orderly and efficient operation.

3.1. Hypothesis

Firstly, the model should be established in terms of assumptions.
(1) The condition assumed in the highway. Vehicles lined up to drive and can communicate with each other.
(2) The parameters used in the paper are available and can used directly.
(3) Ignore time delay of the information transmission and assuming that vehicles can also get the traffic information at the same time.
(4) Ignore the safety distance algorithm's calculated time.

3.2. Models

First, determine the minimum speed of the vehicle fleet, then the following vehicles form a sub-team, and the vehicles in front of the fleet form the other sub-team and determine the minimum speed of the vehicle in this sub-team. Therefore, the model should consider the first fleet of vehicles, the minimum speed of the vehicle, close to the minimum speed of fleet vehicle and the vehicle behind it. As the first vehicle is a non-following state, and just consider a safety distance with the behind. Because the minimum speed of the vehicle is less than the speed of the vehicle in front and the distance between the two cars is constantly increasing, so its safety distance can be considered zero.

(a) The vehicle's safety distance model which close to the minimum speed vehicle

Minimum vehicle speed, whether its state is uniform or braking can impact on the state of the back vehicle. Therefore, the safety distance model can be divided into two cases: absolute safety distance model and relative safety distance model.

(1) Absolute safety distance model

Absolutely safety distance means the speed of the vehicle in front suddenly brakes to zero. Combined with vehicle's braking kinematics establish the following model, the specific derivation see Appendix B.

$$
\begin{aligned}
S_{ij} = v_0^i(T_{1i} + T_{2i}) + \sum_{j=0}^{n_i} \int_0^{\Delta t} (v_0^i + \sum_{j=0}^{j} a_j^i t)dt + (v_0^i + \sum_{j=0}^{n_i} a_j^i \Delta t) \cdot \left| \frac{v_n^i}{A^i} \right| + \frac{1}{2} A^i (\frac{v_n^i}{A^i})^2 \\
- [\sum_{j=0}^{n_{i-1}} \int_0^{\Delta t} (v_0^{i-1} + \sum_{j=0}^{j} a_j^{i-1} t)dt + (v_0^{i-1} + \sum_{j=0}^{n_{i-1}} a_j^{i-1} \Delta t) \cdot \left| \frac{v_n^{i-1}}{A^{i-1}} \right| + \frac{1}{2} A^{i-1} (\frac{v_n^{i-1}}{A^{i-1}})^2] + D_0
\end{aligned}
\tag{1}
$$

(2) Relative safety distance model

Relatively safety distance is calculated based on the relative velocity between vehicles including the case of vehicle driving keeping an even speed in front. There are two situations should be considered. The braking acceleration achieve maximum and the other situation not achieve maximum braking acceleration. Combined with vehicle's braking kinematics establish the following model.

$$
\begin{aligned}
S_{ij} = v_0^i(T_{1i} + T_{2i}) + \sum_{j=0}^{n_i} \int_0^{\Delta t} (v_0^i + \sum_{j=0}^{j} a_j^i t)dt + (v_0^i + \sum_{j=0}^{n_i} a_j^i \Delta t) \cdot \left| \frac{v_n^i - v_0^1}{A^i} \right| + \frac{1}{2} A^i (\frac{v_n^i - v_0^1}{A^i})^2 \\
- v_0^1(T_{1i} + T_{2i} + T_{3i} + T_{4i}) + D_0(a_{max})
\end{aligned}
\tag{2}
$$

$$
S_{ij} = v_0^i(T_{1i} + T_{2i}) + \sum_{j=0}^{n_i} \int_0^{\Delta t} (v_0^i + \sum_{j=0}^{j} a_j^i t)dt - v_0^1(T_{1i} + T_{2i} + t_i) + D_0(\text{not } a_{max})
\tag{3}
$$

(b) The safety distance models of the vehicles behind

Make the minimum speed vehicle as the base vehicle, i.e. the required shortest distance that the vehicle slow down to the minimum speed. Because of the communication the two adjacent vehicles can receivein the information in front, so in the braking process of the two vehicles both consider the driver's reaction time.

(1) The absolute safety distance model

$$S_{ij} = v_0^i(T_{1i} + T_{2i}) + \sum_{j=0}^{n_i}\int_0^{\Delta t}(v_0^i + \sum_{j=0}^{j}a_j^i t)dt + (v_0^i + \sum_{j=0}^{n_i}a_j^i\Delta t)\left|\frac{v_n^i}{A^i}\right| + \frac{1}{2}A^i(\frac{v_n^i}{A^i})^2$$
$$-[v_0^{i-1}(T_{1i-1} + T_{2i-1}) + \sum_{j=0}^{n_{i-1}}\int_0^{\Delta t}(v_0^{i-1} + \sum_{j=0}^{j}a_j^{i-1}t)dt + (v_0^{i-1} + \sum_{j=0}^{n_{i-1}}a_j^{i-1}\Delta t)\cdot\left|\frac{v_n^{i-1}}{A^{i-1}}\right| + \frac{1}{2}A^{i-1}(\frac{v_n^{i-1}}{A^{i-1}})^2] + D_0 \tag{4}$$

(2) The relative safety distance model

$$S_{ij} = v_0^i(T_{1i} + T_{2i}) + \sum_{j=0}^{n_i}\int_0^{\Delta t}(v_0^i + \sum_{j=0}^{j}a_j^i t)dt + (v_0^i + \sum_{j=0}^{n_i}a_j^i\Delta t)\cdot\left|\frac{v_n^i - v_0^1}{A^i}\right| + \frac{1}{2}A^i(\frac{v_n^i - v_0^1}{A^i})^2 - [v_0^{i-1}(T_{1i-1} + T_{2i-1})$$
$$+ \sum_{j=0}^{n_{i-1}}\int_0^{\Delta t}(v_0^{i-1} + \sum_{j=0}^{j}a_j^{i-1}t)dt + (v_0^{i-1} + \sum_{j=0}^{n_{i-1}}a_j^{i-1}\Delta t)\cdot\left|\frac{v_n^{i-1} - v_0^1}{A^{i-1}}\right| + \frac{1}{2}A^{i-1}(\frac{v_n^{i-1} - v_0^1}{A^{i-1}})^2] + D_0 \quad (\text{both achieve } a_{max}) \tag{5}$$

$$S_{ij} = v_0^i(T_{1i} + T_{2i}) + \sum_{j=0}^{n_i}\int_0^{\Delta t}(v_0^i + \sum_{j=0}^{j}a_j^i t)dt - [v_0^{i-1}(T_{1i-1} + T_{2i-1}) + \sum_{j=0}^{n_{i-1}}\int_0^{\Delta t}(v_0^{i-1} + \sum_{j=0}^{j}a_j^{i-1}t)dt] + D_0 (\text{neither achieve } a_{max}) \tag{6}$$

$$S_{ij} = v_0^i(T_{1i} + T_{2i}) + \sum_{j=0}^{n_i}\int_0^{\Delta t}(v_0^i + \sum_{j=0}^{j}a_j^i t)dt - [v_0^{i-1}(T_{1i-1} + T_{2i-1})$$
$$+ \sum_{j=0}^{n_{i-1}}\int_0^{\Delta t}(v_0^{i-1} + \sum_{j=0}^{j}a_j^{i-1}t)dt + (v_0^{i-1} + \sum_{j=0}^{n_{i-1}}a_j^{i-1}\Delta t)\cdot\left|\frac{v_n^{i-1} - v_0^1}{A^{i-1}}\right| + \frac{1}{2}A^{i-1}(\frac{v_n^{i-1} - v_0^1}{A^{i-1}})^2] + D_0 \tag{7}$$

（the first one achieve a_{max} and the second one not achieve）

$$S_{ij} = v_0^i(T_{1i} + T_{2i}) + \sum_{j=0}^{n_i}\int_0^{\Delta t}(v_0^i + \sum_{j=0}^{j}a_j^i t)dt + (v_0^i + \sum_{j=0}^{n_i}a_j^i\Delta t)\cdot\left|\frac{v_n^i - v_0^1}{A^i}\right| + \frac{1}{2}A^i(\frac{v_n^i - v_0^1}{A^i})^2 - [v_0^{i-1}(T_{1i-1} + T_{2i-1}) +$$
$$\sum_{j=0}^{n_{i-1}}\int_0^{\Delta t}(v_0^{i-1} + \sum_{j=0}^{j}a_j^{i-1}t)dt] + D_0 \quad (\text{the first one not achieve } a_{max} \text{ and the second one achieve}) \tag{8}$$

3.3. Model simplification and parameter calibration

The vehicle braking delay time and maximum acceleration of the vehicle should be made through experiments in the paper. To facilitate the calculation, the model is simplified without loss of generality. Taking into account the acceleration and braking time increased almost linearly in the braking acceleration of growth phase, it can be measured linear growth. So model can be simplified by $a_j = \frac{At}{T_{3i}}$.

(1) The safety distance model of the vehicle which close to the minimum speed vehicle

$$S_{ij} = v_0^i(T_{1i} + T_{2i}) + v_0^i T_{3i} + \frac{1}{6}A^i T_{3i}^2 + (v_0^i + \frac{1}{2}A^i T_{3i})\cdot\left|\frac{v_n^i}{A^i}\right| + \frac{1}{2}A^i(\frac{v_n^i}{A^i})^2$$
$$-[v_0^{i-1}T_{3i-1} + \frac{1}{6}A^{i-1}T_{3i-1}^2 + (v_0^{i-1} + \frac{1}{2}A^{i-1}T_{3i-1})\cdot\left|\frac{v_n^{i-1}}{A^{i-1}}\right| + \frac{1}{2}A^{i-1}(\frac{v_n^{i-1}}{A^{i-1}})^2] + D_0 \tag{9}$$

$$S_{ij} = v_0^i(T_{1i} + T_{2i}) + v_0^i T_{3i} + \frac{1}{6}A^i T_{3i}^2 + (v_0^i + \frac{1}{2}A^i T_{3i})\cdot\left|\frac{v_n^i - v_0^1}{A^i}\right| + \frac{1}{2}A^i(\frac{v_n^i - v_0^1}{A^i})^2 - v_0^1(T_{1i} + T_{2i} + T_{3i} + T_{4i}) + D_0(a_{max}) \tag{10}$$

$$S_{ij} = v_0^i(T_{1i} + T_{2i}) + v_0^i t_i + \frac{A^i}{6T_{3i}} t_i^3 - v_0^1(T_{1i} + T_{2i} + t_i) + D_0 \,(\text{not } a_{\max}) \tag{11}$$

(2)The safety distance model of vehicles behind the last one

$$S_{ij} = v_0^i(T_{1i} + T_{2i}) + v_0^i T_{3i} + \frac{1}{6} A^i T_{3i}^2 + (v_0^i + \frac{1}{2} A^i T_{3i}) \cdot \left|\frac{v_n^i}{A^i}\right| + \frac{1}{2} A^i (\frac{v_n^i}{A^i})^2 - [v_0^{i-1}(T_{1i-1} + T_{2i-1}) + v_0^{i-1} T_{3i-1}$$

$$+ \frac{1}{6} A^{i-1} T_{3i-1}^2 + (v_0^{i-1} + \frac{1}{2} A^{i-1} T_{3i-1}) \cdot \left|\frac{v_n^{i-1}}{A^{i-1}}\right| + \frac{1}{2} A^{i-1} (\frac{v_n^{i-1}}{A^{i-1}})^2] + D_0 \tag{12}$$

$$S_{ij} = v_0^i(T_{1i} + T_{2i}) + v_0^i T_{3i} + \frac{1}{6} A^i T_{3i}^2 + (v_0^i + \frac{1}{2} A^i T_{3i}) \cdot \left|\frac{v_n^i - v_0^1}{A^i}\right| + \frac{1}{2} A^i (\frac{v_n^i - v_0^1}{A^i})^2 - [v_0^{i-1}(T_{1i-1} + T_{2i-1}) + v_0^{i-1} T_{3i-1} +$$

$$\frac{1}{6} A^{i-1} T_{3i-1}^2 + (v_0^{i-1} + \frac{1}{2} A^{i-1} T_{3i-1}) \cdot \left|\frac{v_n^{i-1} - v_0^1}{A^{i-1}}\right| + \frac{1}{2} A^{i-1} (\frac{v_n^{i-1} - v_0^1}{A^{i-1}})^2] + D_0 \,(\text{both achieve } a_{\max}) \tag{13}$$

$$S_{ij} = v_0^i(T_{1i} + T_{2i}) + v_0^i t_i + \frac{A^i}{6T_{3i}} t_i^3 - [v_0^{i-1}(T_{1i-1} + T_{2i-1}) + v_0^{i-1} t_{i-1} + \frac{A^{i-1}}{6T_{3i-1}} t_{i-1}^3] + D_0 \,(\text{neither achieve } a_{\max}) \tag{14}$$

$$S_{ij} = v_0^i(T_{1i} + T_{2i}) + v_0^i t_i + \frac{A^i}{6T_{3i}} t_i^3 - [v_0^{i-1}(T_{1i-1} + T_{2i-1}) + v_0^{i-1} T_{3i-1} + \frac{1}{6} A^{i-1} T_{3i-1}^2 + (v_0^{i-1} + \frac{1}{2} A^{i-1} T_{3i-1}) \cdot \left|\frac{v_n^{i-1} - v_0^1}{A^{i-1}}\right|$$

$$+ \frac{1}{2} A^{i-1} (\frac{v_n^{i-1} - v_0^1}{A^{i-1}})^2] + D_0 \,(\text{the first one achieve } a_{\max} \text{ and the second one not achieve}) \tag{15}$$

$$S_{ij} = v_0^i(T_{1i} + T_{2i}) + v_0^i T_{3i} + \frac{1}{6} A^i T_{3i}^2 + (v_0^i + \frac{1}{2} A^i T_{3i}) \cdot \left|\frac{v_n^i - v_0^1}{A^i}\right| + \frac{1}{2} A^i (\frac{v_n^i - v_0^1}{A^i})^2 - [v_0^{i-1}(T_{1i-1} + T_{2i-1}) + v_0^{i-1} t_{i-1} + \frac{A^{i-1}}{6T_{3i-1}} t_{i-1}^3]$$

$$+ D_0 \,(\text{the first one not achieve } a_{\max} \text{ and the second one achieve}) \tag{16}$$

Calibration parameter:

Driver reaction time is taken as 0.56s. Hydraulic brake system response time is 0.015 ~ 0.03s, pneumatic brake system is 0.05 ~ 0.06s. The time of braking force growth impact by the brake's structure and generally the hydraulic brake take between 0.2 ~ 0.9 s and the pneumatic brake is 0.3~0.9 s. General, whichever is considered average, hydraulic brake system is 0.55s, pneumatic braking system is 0.6s. After the two vehicles both stop, there should be maintain the distance which usually take 2~5m. This paper considers security and system latency, the distance is taken as 3m.

4. Model Evaluation

The reasonable SDM should ensure the driving safety between vehicles and increase the road utilization rate together with the subjective feeling of drivers. The proposed SDMs take the whole fleet as the analysis object. The minimum speed vehicle, the vehicle with the minimum speed in the closing sub-team and vehicles in the following sub-team are the cores of the presented SDMs. Consequently, the sub-team composed by the vehicles at these three positions is representative and is taken as the simulation object.

The driving conditions of the first vehicle are mainly static, emergency braking and normal driving conditions. There are two situations corresponding to the driving condition changing of the first vehicle. One is the safe distance with the speed decelerating to zero, and the other is the maintained safe distance with speed decelerating to the minimum speed of the sub-team. Suppose vehicles use hydraulic brake system whose brake response time is 0.023s, growth time of braking acceleration is 0.55s, and road adhesion coefficient is 0.5, then the vehicle maximum braking acceleration can be achieved as 4.9m/s2.
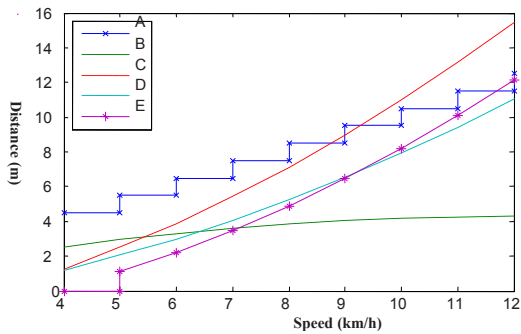
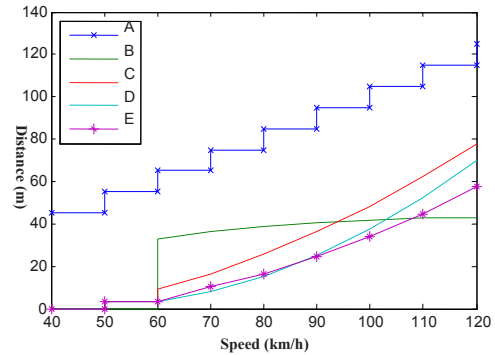Fig.1 Safety distances between the anterior two vehicles
(Emergency braking)

Fig.2 Safety distances between the behind two vehicles
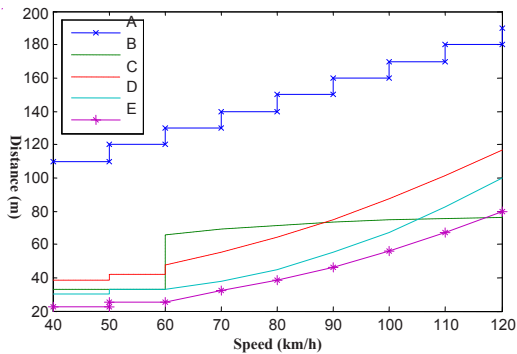(Emergency braking and normal driving

Fig.3 Safety distances sum of three vehicles (Emergency
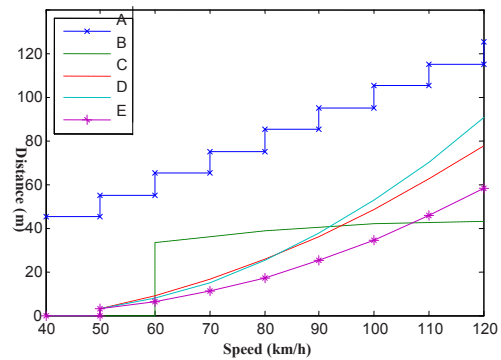braking)

Fig.4 Safety distances between the anterior two vehicles
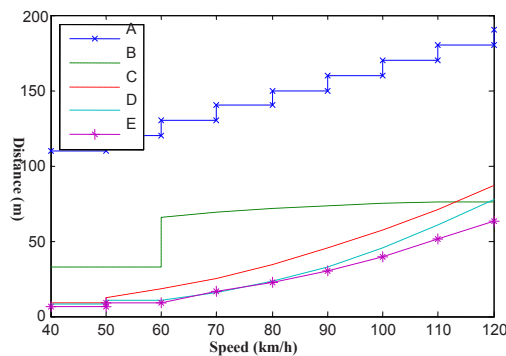(Normal driving)

Fig.5 Safety distances between the behind two
vehicles (Normal driving)

In order to evaluate the proposed SDM, the comparison analysis is performed among the new model and four traditional SDMs by using the three-vehicle model under the static, emergency braking and normal speed driving conditions. In the evaluating experiments, A indicates the fixed SDM. B indicates the headway SDM. C indicated

the SDM based on vehicle braking process. D indicated the improved driving prediction SDM.E indicates the vehicle communication based SDM proposed in this paper.

In theory, the model considers the process of braking kinematics and the condition of vehicle communication. And it can fit the vehicles under real world and better reflects the actual process of movement of vehicles. As the vehicles communicate with each other, the fleet of vehicles can achieve the minimum speed, distance information and so on. Take into account the working conditions to establish different models. It can alert drivers to reduce accidents. So the models are feasible in theory.

Comparison with other models from the analysis and the above charts analysis, when the first vehicle take an emergency braking, the safety distance is slightly higher than model D. And in normal driving, the model of the safety distance is smaller. It will be timely to remind drivers to be vigilant to ensure that the vehicle safety and avoid traffic accidents. In normal driving conditions, to maintain the relatively small distance can increase the utilization of the road.

5. Conclusion

Based on communication technology and the sharing information between vehicles, safety distance model established using the brake theory. Compared with other typical safety distance model verify that the model is more applicable to the real traffic environment. However, the article does not consider the vehicle lane changing, and with the side of the vehicle should be kept a safe distance, the model still needs further study.

Acknowledgements

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