Research on the Method that Improving the Space Headway Simulation Accuracy of Gipps Model

Dongyang Sui¹, Tongfei Shang¹,² and Bo Li¹, *

¹The School of Electronic and Information Engineering, Xi’an Jiaotong University, Xi’an, Shaanxi, 710049, P.R China
²College of Information and Communication, National University of Defense Technology, Xi’an 710106, P.R China

*E-mail: boble@xjtu.edu.cn

Abstract. Gipps model is a typical car-following model based on safe distance and is widely used in computer simulation. However, in order to avoid collision with the preceding vehicle, the model has strict restrictions on the following spacing, that makes the model has a certain error at the simulation of vehicle space headway in complex traffic environment. Due to that, based on the mathematical expression of the following spacing in Gipps model, this paper proposes a method of adding influence coefficient to improve the simulation accuracy of space headway. Furthermore, the effectiveness of the method is proved by simulation experiments, and the experimental results illustrate that the simulation results of the improved model are closer to the field data in complex traffic environment than the original model.

1. Introduction
As one of the basic car-following models in traffic simulation, Gipps model has many advantages and is widely used. But the model has strict restrictions on the following spacing ensure that continuous vehicles will not collide, which is inconsistent with the reality, and the consequence is that in complex traffic environment, the simulation accuracy of model about the space headway is not ideal. Irene Soria et al. [1] evaluated Gipps model using field data from different traffic (congested vs. uncongested) and weather conditions (rain vs. sun) and various driver types (aggressive, average and conservative). The results showed that under different traffic and weather conditions, Gipps model is relatively accurate in simulating the velocity of subsequent vehicle, but the error in vehicle space headway is larger; In experiment with different driver types, Gipps model can well simulates the average type driver's vehicle trajectory, however, for aggressive and conservative drivers, the simulation result of space headway is deviate greatly. Therefore, by studying the mathematical expression of following spacing in Gipps model, then proposes a method that adding influence coefficient to the function expression of the following spacing, and this method solves the problem that the original model is not accurate for the space headway simulation in the complex traffic environment to a certain extent.

2. Gipps Model
Gipps model [2] is based on the assumption that the required acceleration and braking acceleration are limited for each following vehicle. In order to prevent collision in the longitudinal distance of vehicle running, the velocity of next time step will be calculated by the following spacing relationship between the following vehicle and the preceding vehicle. That is, when two continuous vehicles stop, the tail of
front vehicle n-1 should exceed the head of rear vehicle n. The formula of this process is as follows.

\[ x_{n-1}(t) + \frac{v_{n-1}^2(t)}{2b_{n-1}} - s_{n-1} \geq x_n(t) + \frac{v_n(t) + v_n(t + \tau)}{2} \tau + v_n(t + \tau)\theta + \frac{v_n^2(t + \tau)}{2b_n} \]  \hspace{1cm} (1)

Where \( x_{n-1}(t) \) is the head position of preceding vehicle n-1 at time t, and \( v_{n-1}(t) \) is the velocity of vehicle n-1 at time t, \( b_{n-1} \) is the braking acceleration of vehicle n-1, \( s_{n-1} \) is the length of vehicle n-1 and the spacing naturally maintained when the vehicle stops. \( x_n(t) \) is the head position of the following vehicle n at time t, \( v_n(t) \) is the velocity of vehicle n at time t, \( \tau \) is the driver reaction time of vehicle n, \( v_n(t + \tau) \) is the velocity that the next simulation time step \( t + \tau \) of vehicle n, and \( \theta \) is an additional safety reaction time generally taken as \( \tau/2 \), and \( b_n \) is the maximum braking rate of vehicle n.

Equation (1) is transformed to obtain the expression of vehicle n's velocity at \( t + \tau \):

\[ v_n(t + \tau) \geq -b_n\tau + \left\{ b_n^2\tau^2 + b_n \left[ 2[x_{n-1}(t) - s_{n-1} - x_n(t)] - v_n(t)\tau + \frac{v_{n-1}(t)^2}{b_{n-1}} \right] \right\}^{\frac{1}{2}} \hspace{1cm} (2)

Taking the equality part in Eq. (2) as the velocity expression of the Gipps model's congestion-following state, combined with the equation representing the free-running state, composes the complete model, and selects the minimum value in the two states as the velocity of the next simulation time step of the following vehicle n. The complete formula is expressed as follows:

\[ v_n(t + \tau) = \min \left\{ \frac{v_n(t) + 2.5a_n\tau \left( 1 - \frac{v_n(t)}{V_n} \right) (0.025 + \frac{v_n(t)}{V_n})^{\frac{1}{2}}}{-b_n\tau + b_n^2\tau^2 + b_n \left[ 2[x_{n-1}(t) - s_{n-1} - x_n(t)] - v_n(t)\tau + \frac{v_{n-1}(t)^2}{b} \right]^{\frac{1}{2}}} \right\} \hspace{1cm} (3)

Among them, \( a_n \) is the maximum acceleration of vehicle n, \( V_n \) is the expect velocity that vehicle n want to reach, and \( \hat{b} \) is the maximum braking acceleration of the preceding vehicle n-1 which estimated by vehicle n.

3. Influence Coefficient

The focus of this paper is to improve the setting of following spacing in the model, indirectly affects the space headway in the simulation, so that the model can cope with complex traffic environment. Through the analysis of different conditions, it can be concluded that good weather and road conditions have a positive impact on the driver's keeping space headway. For example, the drivers usually keep a small space headway with good weather conditions, while bad weather is the opposite. According to the type of drivers, aggressive driver will keep a smaller space headway than average driver, and conservative driver always leave a larger space headway than average driver and so on.

Therefore, an influence coefficient acting on the expression of the following spacing function is needed. Its function is to change the space headway without affecting the accuracy of the model according to different traffic conditions, so that the simulation results of space headway can meet the forecasting requirements under complex traffic conditions.

According to the above discussion and analysis, transform the Eq. (1) at first:

\[ x_{n-1}(t) - x_n(t) - s_{n-1} = \frac{v_n(t) + v_n(t + \tau)}{2} \tau + v_n(t + \tau)\theta + \frac{v_n^2(t + \tau)}{2b_n} - \frac{v_{n-1}^2(t)}{2b_{n-1}} \hspace{1cm} (4)

Equation (4) corresponds to the inter-vehicle following spacing at time t, takes the equal sign on both sides is because that in development of the model, only the minimum following spacing condition, that is, the equality part in Eq. (2) is considered. The velocity \( v_n(t + \tau) \) which needs to be calculated is
used to maintain the safe following spacing in the model. Equation (4) can also be expressed as:

\[ D_s_n(t) = x_{n-1}(t) - x_n(t) - S_{n-1} = \frac{v_n(t) + v_{n-1}(t + \tau)}{2} \tau + v_n(t + \tau) \theta + \frac{v_n^2(t + \tau)}{2b_n} - \frac{v_{n-1}^2(t)}{2b_{n-1}} \] (5)

\( D_s_n(t) \) is the safe following spacing between vehicle \( n \) and \( n-1 \) at time \( t \). It is now assumed that there exists a certain size relationship \( \gamma \) (influence coefficient) between the actual space headway \( Dr_n(t) \) and \( D_s_n(t) \) at time \( t \). This makes it possible that:

\[ Dr_n(t) = \gamma \ast D_s_n(t) \] (6)

Move \( \gamma \) in Eq. (6) to the left of the equal sign, and use the method of zooming in and out to get the \( D_s_n(t) \):

\[ \frac{Dr_n(t)}{\gamma} = \frac{D_s_n(t)'}{\gamma} = D_s_n(t) \] (7)

The \( D_s_n(t) \) in Eq. (7) is the safe following spacing improved by the influence coefficient \( \gamma \), which guarantees invariance of the element equilibrium relationship in the original model while changing the following spacing. Combining Eq. (3), (5), (7), a new model is obtained, which is called IC Gipps in this paper.

\[ v_n(t + \tau) = \min \left\{ \begin{array}{l}
v_n(t) + 2.5a_n \tau \left( 1 - \frac{v_n(t)}{V_n} \right) \left( 0.025 + \frac{v_n(t)}{V_n} \right)^2, \\
-b_n \tau + \left( b_n^2 \tau^2 + b_n \left[ 2\frac{x_{n-1}(t) - s_{n-1} - x_n(t)}{y} - v_n(t) \tau + \frac{v_{n-1}(t)^2}{b} \right] \right)^{1/2}
\end{array} \right\} \] (8)

As an extension, and increasing the persuasiveness of simulation experiment, the enhanced safety distance model [3] was improved using the influence coefficient method. This paper refers to it as IC ESD, and the mathematical expression is as follows:

\[ v_n(t + \tau) = \min \left\{ \begin{array}{l}
v_n(t) + 2.5a_n \tau \left( 1 - \frac{v_n(t)}{V_n} \right) \left( 0.025 + \frac{v_n(t)}{V_n} \right)^2, \\
-b_n \tau + \left( b_n^2 \tau^2 + b_n \left[ 2\frac{x_{n-1}(t) - s_{n-1} - x_n(t)}{y} - v_n(t) \tau + \frac{v_{n-1}(t)^2}{b} \right] \right)^{1/2}
\end{array} \right\} \] (9)

Where, \( a_1 \) and \( a_2 \) are two parameters that need to be calibrated, \( \Delta v_n(t) \) is the velocity difference between vehicle \( n-1 \) and \( n \) at time \( t \), and \( H(x) \) is the Heaviside function which indicates a jump state of 0 to 1. The coefficient \( \gamma \) before the velocity difference function expression is the assumed influence coefficient, and the rest of the model remains unchanged.

4. Simulation Analysis
In this section, IC Gipps, IC ESD, Enhanced Safety Distance Model and Gipps Model will be used to simulate realistic vehicle trajectories, then compared with actual vehicle trajectory data, to discuss the simulation effect of influence coefficient method on space headway in complex traffic environment.

The selection of field data set is the US Highway 101 Dataset collected by NGSIM [4], on the one hand, this data set records real vehicle trajectory data for different traffic conditions and driver types under the same weather conditions, and on the other hand because this data set has been used in the research of YANG et al. [3] to calibrate the parameters of Gipps model and enhanced safe distance model. On this basis, the value of influence coefficient \( \gamma \) is calibrated. Meanwhile, the effective range of \( \gamma \) is studied, and the range is determined to be between 0.9 and 3.5. When \( \gamma \) is less than 0.9, the
equilibrium conditions [5] of the original equation will be destroyed and the calculation results will be wrong. When $\gamma$ is greater than 3.5, the model will always be in a free-running state, which makes the model meaningless. The calibration results of the four models are shown in Table 1.

### Table 1. The Parameter calibration results

| Model              | $a_n$ $(m \cdot s^{-2})$ | $b_n$ $(m \cdot s^{-2})$ | $b_{n-1}$ $(m \cdot s^{-2})$ | $\alpha_1$ | $\alpha_2$ | $\gamma$ |
|--------------------|--------------------------|--------------------------|-----------------------------|-------------|-------------|----------|
| Gipps              | 3.59                     | -3.0                     | -4.2                        | -           | -           | -        |
| Enhance Safe Distance | 3.37                   | -5.3                     | -4.2                        | 0.073       | 0.069       | -        |
| IC Gipps           | 3.59                     | -3.3                     | -3.0                        | -           | -           | 1.211    |
| IC ESD             | 3.37                     | -5.3                     | -4.2                        | 0.073       | 0.069       | 1.298    |

For the simulation experiment, using the four parameter calibrated models simulate 100 vehicles on a straight road respectively, the velocity of these vehicles oscillated through 300 simulation time steps and eventually stabilized at a congestion state about 5 m/s, a slightly congested state of about 10 m/s and a free-following state about 16 m/s. The average value of the simulated space headway in different states is compared with the average of the corresponding state in the field data set. The result is shown in Figure 1.

![Figure 1. Comparison the space headway between different model and field data](image)

From the experimental results of Figure 1, compared with the original models, the improved two models using the influence coefficient method can effectively improve the simulation accuracy of vehicle space headway in congestion state and slightly congested state, and compared with the field data, the error is smaller. The simulation accuracy of space headway in free-following state is also improved, but the lifting effect is not as good as the first two states, the reason is that the acceleration equation of the free-running state of the model is involved in this state, and the specific mean error is shown in Table 2. From the overall perspective, the simulation experiment proves that the addition of influence coefficient has a positive effect on improving the simulation accuracy of the model.
Table 2. The mean error of space headway in different states

| Model            | Mean Error |
|------------------|------------|
|                  | Congestion | Slight Congestion | Free    |
| Gipps            | 1.80       | 2.63              | 5.59    |
| Enhanced Safe Distance | 1.94       | 3.58              | 8.04    |
| IC Gipps         | 0.38       | -0.07             | 1.57    |
| IC ESD           | -0.02      | -0.16             | 2.75    |

5. Conclusions
In this paper, the main problem of Gipps model in the simulation of vehicle space headway is analyzed, that is, the simulation accuracy of the space headway in complex traffic environment cannot be well satisfied. Although Biagio et al. [6] proposed that calibrate the model for different specific situations, the accuracy of the model can be improved. However, there are so many factors affecting the simulation accuracy in the real traffic environment, and it is impossible to calibrate each factor in turn. In view of the above reasons, the method of adding influence coefficient to the safe following spacing expression of the model is proposed. By changing the influence coefficient, the model can meet the prediction requirements of the space headway very well under different conditions and improve the simulation precision.

Although the method of adding influence coefficient to the model can achieve better results, the improvement of simulation accuracy is limited only by simply adding influence coefficients. A better way is to allocate the proportion of vehicles with different influence coefficients in the simulation reasonably, and combine with multi-agent simulation system to make it more flexible and accurate to reflect the real traffic situation, which is also the future research direction.

Reference:
[1] Irene Soria, Lily Elefteriadou, Alexandra Kondyli. Assessment of car-following models by driver type and under different traffic, weather conditions using data from an instrumented vehicle. *Simulation Modelling Practice and Theory* 40 (2014) 208–220.
[2] Gipps P G. A behavioural car-following model for computer simulation. *Transportation Research. Part B: Methodological*, 1981, 15(2): 105-111.
[3] YANG Da, ZHU Li-Ling, YU Dan. An Enhanced Safe Distance Car-Following Model. *J. Shanghai Jiaotong Univ. (Sci.)*, 2014, 19(1): 115-122
[4] NGSIM Homepage. FHWA. http://ngsim.fhwa.dot.gov.
[5] Wilson R E, Ward J A. Car-following models: Fifty years of linear stability analysis — A mathematical perspective [J]. *Transportation Planning and Technology*, 2011, 34(1): 3-18.
[6] Biagio Ciuffo, Vincenzo Punzo, Marcello Montanino. Thirty Years of Gipps’ Car-Following Model Applications, Developments, and New Features. *Transportation Research Record: Journal of the Transportation Research Board*, 2315:89–99, December 2012.