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The effect of ACC vehicles to mixed traffic flow consisting of manual and ACC vehicles*

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This paper studies the effect of adaptive cruise control (ACC) system on traffic flow by using simulations. The multiple headway and velocity difference (MHVD) model is used to depict the motion of ACC vehicles, and the simulation results are compared with the optimal velocity (OV) model which is used to depict the motion of manual vehicles. Compared the cases between the manual and the ACC vehicle flow, the fundamental diagram can be classified into four regions: I, II, III, IV. In low and high density the flux of the two models is the same; in region II the free flow region of the MHVD model is enlarged, and the flux of the MHVD model is larger than that of the OV model; in region III serious jams occur in the OV model while the ACC system suppresses the jams in the MHVD model and the traffic flow is in order, but the flux of the OV model is larger than that of the MHVD model. Similar phenomena also appeared in mixed traffic flow which consists of manual and ACC vehicles. The results indicate that ACC vehicles have significant effect on traffic flow. The improvement induced by ACC vehicles decreases with the increasing proportion of ACC vehicles.

Keywords: car-following models, adaptive cruise control, fundamental diagram
PACC: 0550, 0520, 0570F, 0570J

1. Introduction

Traffic congestion is a serious problem on most freeways. Currently, the rapid development of the societal economy and the relative lag of the transportation have been a prominent problem all over the world. However, building new infrastructure is no longer a useful approach in most big cities. In order to suppress traffic jams and increase the capacity of road networks, many approaches of traffic control and management systems are introduced. Adaptive cruise control (ACC) system is one of the advanced traffic control system, which is now available on some vehicles. With the system, vehicle is able to detect the headways and velocities of preceding vehicles, and adjusts the velocity and headway of its own.

Obviously, ACC vehicles will impact traffic characteristics, including safety, efficiency, and capacity of free ways for their different behaviour in comparison with human drivers. The effect of ACC vehicles on freeway traffic has attracted much attention.[1−11] The effect of ACC vehicles on traffic flow stability is widely studied.[1−5] Treiber *et al*[6,7] reported that if 20% of vehicles are equipped with ACC systems, nearly all of the congestion will be eliminated. Even for only 10%, they found that the additional travel time due to traffic jams was reduced by more than 80%. Davis[8] showed that ACC system can suppress wide moving jams by making the flow string stable. He also proposed a cooperative merging for ACC vehicles to improve throughput and increase distance travelled in a fixed time.[9] Vander Werf *et al*[10] specifically considered the effects of ACC vehicles on highway capacity. Ioannou *et al*[11] analysed mixed traffic, considering the effects of unwanted cut-ins due to larger gaps in front of ACC vehicles.

A lot of research have been done on the traffic flow with ACC vehicles. However, to our knowledge, the relationship between density and flux with the effect of ACC vehicles has not been studied in detail. This paper applies numerical simulations to this problem. The optimal velocity (OV) model[12] is used to depict the motion of manual vehicles, and the multiple headway and velocity difference (MHVD) model[13] is used to depict the motion of ACC vehicles for considering multiple information of preceding cars. The fundamental diagram is given, and the effect of ACC vehicles in mixed traffic flow is also investigated. The

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results show that the ACC systems have significant effect on the mixed traffic flow. However, the improvement induced by ACC vehicles decreases with the increasing proportion of ACC vehicles.

This paper is organized as follows: in Section 2, the OV and the MHVD models are reviewed; in Section 3, numerical simulations are performed and the results and discussions are given; conclusions are summarized in Section 4.

2. Model

Car following models are a kind of microscopic model and have been widely researched by theoretical analysis and simulations.[14,15] Car following models depict the motion of each vehicles of the system and some of them are able to reproduce most surveys of traffic phenomena, such as traffic instabilities, the propagation of stop-and-go waves or other patterns of congestion traffic. As a result, car following models are appropriate to cope with the heterogeneity of mixed traffic flow. This paper uses the OV model and the MHVD model to depict the manual and ACC vehicles respectively.

2.1. The OV model

The OV model is a famous model proposed by Bando *et al*[12] and has attracted much attention. The OV and its extended models have been deeply investigated by theoretic analysis and numerical simulations.[16−21] The OV model is described as follows:

$$\frac{\mathrm{d}v_n(t)}{\mathrm{d}t} = a[V(\Delta x_n(t)) - v_n(t)], \quad (n = 1, 2, ..., N), \tag{1}$$

where $a = 1/\tau$ is the sensitivity of the driver, N is the total number of the vehicles, $x_n(t)$ is the position of vehicle n at time t, $v_n(t)$ is the velocity of vehicle n at time t, $\Delta x_n(t) = x_{n+1}(t) - x_n(t)$ is the headway of vehicle n at time t, $V(\cdot)$ is the OV function and the following form introduced by Bando *et al*[12] is

$$V(\Delta x_n) = \frac{1}{2} v_{\max}[\tanh(\Delta x_n - h_c) + \tanh(h_c)], \tag{2}$$

where $v_{\max}$ is the maximal velocity of vehicles, h_c is safety distance and it is assumed to be 4 in the simulations. Then the stability condition can be obtained as[14]

$$a > 2V'(h), \tag{3}$$

where h is the average headway when traffic flow is stable.

2.2. The MHVD model

The MHVD model[13] taken the information of multiple preceding vehicles is used to describe the motion of the ACC vehicles. The MHVD model is described as,[13]

$$\frac{\mathrm{d}v_n(t)}{\mathrm{d}t} = a[V(\Delta x_n(t), \Delta x_{n+1}(t), \ldots, \Delta x_{n+p-1}(t)) - v_n(t)] + \sum_{j=1}^{q} \kappa_j \Delta v_{n+j-1}(t), \tag{4}$$

where $\Delta v_{n+j-1}(t) = v_{n+j(t)} - v_{n+j-1}(t)$ is velocity difference between vehicle $n+j-1$ and its preceding vehicle $n+j$, p and q are the number of preceding vehicles taken into account, $\kappa_j = \lambda_j/\tau$ $(j = 1, 2, ..., q)$ is the coefficient of velocity difference. Apparently, the MHVD model is equal to the OV model if the parameters $p = 1$ and $\kappa_j = 0$. The OV $V(\cdot)$ depending on the car headways is,

$$V(\Delta x_n(t), \Delta x_{n+1}(t), \ldots, \Delta x_{n+p-1}(t)) = V\left(\sum_{l=1}^{p} \beta_l \Delta x_{n+l-1}\right), \tag{5}$$

where β_l $(l = 1, 2, ..., p)$ is the coefficient of headways, which is decreased with the increase of l. In this paper, we select $p = q = 3$, $\beta_1 = 6/7$, $\beta_2 = 6/7^2$, $\beta_3 = 1/7^2$, $\kappa_1 = 0.4$, $\kappa_2 = 0.08$, $\kappa_3 = 0.016$ in the numerical simulations. The uniform traffic flow is stable if[13]

$$a > \frac{2(V'(h) - \sum_{j=1}^{q} \kappa_j)}{\sum_{l=1}^{p} \beta_l (2l-1)}. \tag{6}$$

From Eqs.(3) and (6), it can be found that the stable region is apparently enlarged and traffic jams can be suppressed when the information of multiple preceding vehicles is considered.[13]

3. Simulations and results

To investigate the effect of the ACC vehicles on traffic flow, we simulate a system of length $L = 1000$ under periodic boundaries. The Euler formats of Eqs.(1) and (4) are applied in simulations. We define the density as $\rho = 1/\Delta x$, where Δx is the mean headway of the stable system. Traffic flux Q is defined as

$Q = \rho\bar{v}$, where $\bar{v}$ is the mean velocity. We start with random initialization, that is, vehicles are randomly distributed on lane with initial velocity $v_0 = 0$. The simulations were carried out for the parameters of sensitivity $a = 1$. The first 8000 seconds are discarded to avoid transient. The traffic flux is averaged over 2000 seconds.

3.1. Simulation results for the traffic flow of ACC vehicles and manual vehicles

Figure 1 shows the fundamental diagram for the traffic flow with only ACC vehicles and only manual vehicles respectively. The fundamental diagram can be classified into the regions I–IV: in region I, the traffic is in the free flow state and the flux of the two cases is the same; in region II, the flux of the manual vehicle traffic flow starts to decrease when the density is larger than $\rho_{c1} = 0.18$ while the traffic state of ACC vehicles is still in the free flow. The flux of the ACC vehicles increases continuously till the density reaches $\rho_c = 0.2$, and then decreases with the increase of density. It is clear that in this situation the flux of ACC vehicles is larger than that of the manual vehicles. In region III, the flux decreases continuously as the density increases under both cases, and the flux of manual vehicles is larger than that of ACC vehicles. In region IV, the density is high and the vehicles move slowly, and the flux of the two types of traffic flow becomes the same again. The four regions of the fundamental diagram will be discussed in detail in the following.

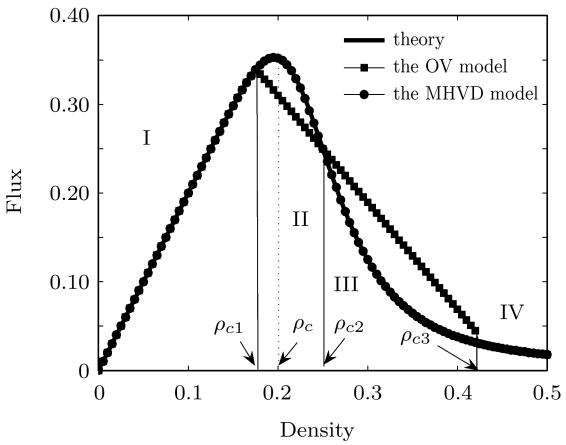


Fig.1. Fundamental diagram for traffic flow of manual vehicles (the OV model) and ACC vehicles (the MHVD model).

In region I, the density is low and the traffic is in the free flow state. There are no traffic jams and the fluxes of the two types of traffic flow are the same. The flux increases linearly with the density. For manual vehicles the flux reaches the maximum at the critical density $\rho_{c1} = 0.18$, but for ACC vehicles the flux does not reach the maximum till ρ_c. ACC vehicles do not have influence on the free flow state.

In region II, we find numerically that the critical density of ACC vehicles is higher than that of manual vehicles ($\rho_c > \rho_{c1}$). It indicates that the ACC system can enlarge the free flow region of traffic flow. In the density range (ρ_{c1}, ρ_c), for ACC vehicles the traffic flow is still in free flow situation while for manual vehicles traffic jams appear and the flux begins to decrease. When the density is larger than ρ_c the flux for ACC vehicles also begins to decrease but it is still larger than that of the manual vehicle traffic flow. To understand the reason we plot the spatio-temporal patterns of the traffic flow for only ACC vehicles and only manual vehicles at $\rho = 0.22$ (Fig.2). From Figs.2(a) and 2(b), it can be observed that the

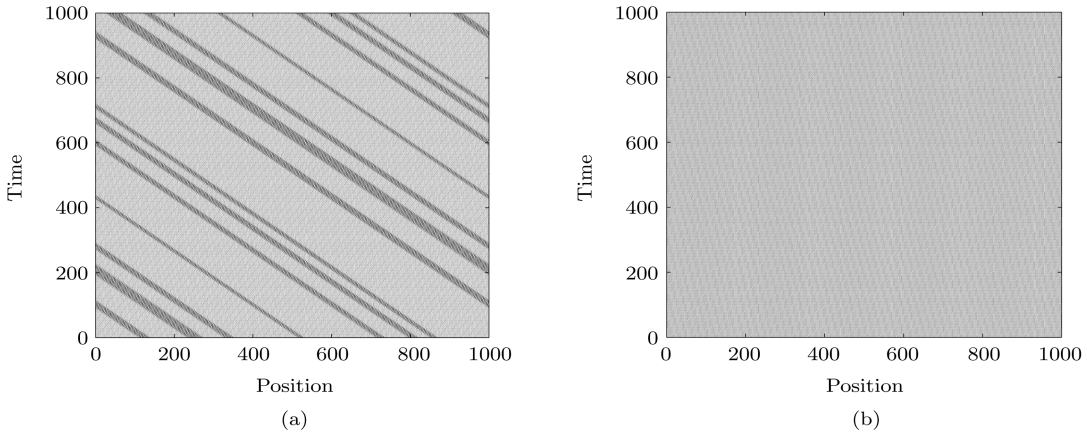


Fig.2. Spatio-temporal patterns of traffic flow at $\rho = 0.22$: (a) manual vehicles, (b) ACC vehicles.

stop-and-go waves appear in the traffic flow of manual vehicles and propagate backward. However, the density wave does not appear in the traffic flow of ACC vehicles. Because of introducing the ACC system drivers can react to the variation of the front car earlier and more carefully. This makes the headway and velocity more homogeneous and the flux larger than that of manual vehicles. Figures 3(a) and 3(b) show the headway and velocity at $t = 9000\,\mathrm{s}$ for the two types of traffic flow at $\rho = 0.22$ respectively. In Fig.3(a), traffic jams appear in manual vehicle traffic flow. The value of the headway is less than 5.7 and larger than 2.3. However, for ACC vehicles the traffic flow is stable and the headways equal the average value 4.5. The same conclusion can also be got from Fig.3(b). The simulation results indicate that the effect of ACC system can suppress the traffic jams and promote the flux effectively in the density region.

In region III, flux of the two types of traffic flow continues to decrease, but the flux of manual vehicles is larger than that of ACC vehicles. Figures 4(a) and 4(b) show the headway distance and velocity at $t = 9000\,\mathrm{s}$ for $\rho = 0.32$. From the figures, it can be seen that the ACC vehicles are homogeneous and their headways and velocities are about 3.1 and 0.3 respectively. However, jams in the manual vehicle traffic flow make the headway and velocity different. The value of the headway is less than 5.7 and larger than 2.3, and the velocity varies between 0 and 1.9. We guess that the ACC system makes the vehicles to move carefully and slowly, the traffic condition is better and no jams appear. However, the mean velocity is much smaller, and thus the flux is smaller than that of the traffic flow without ACC system.

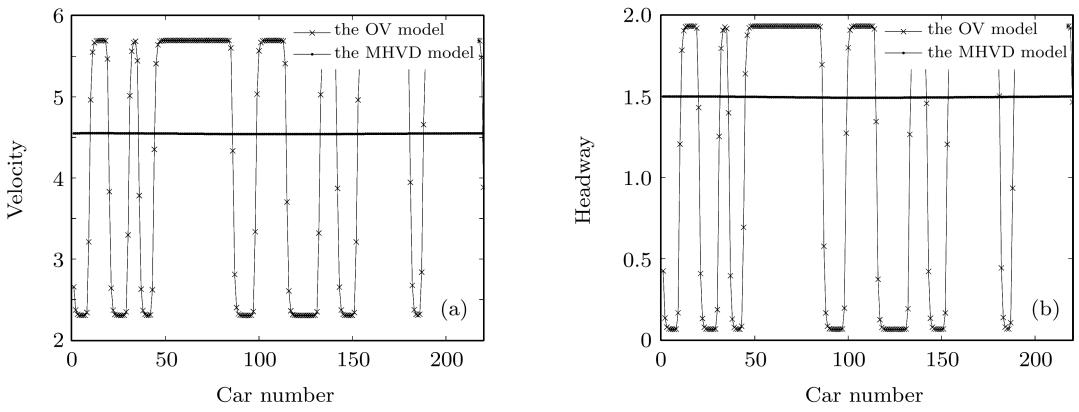


Fig.3. Headway and velocity for $\rho = 0.22$: (a) headway; (b) velocity.

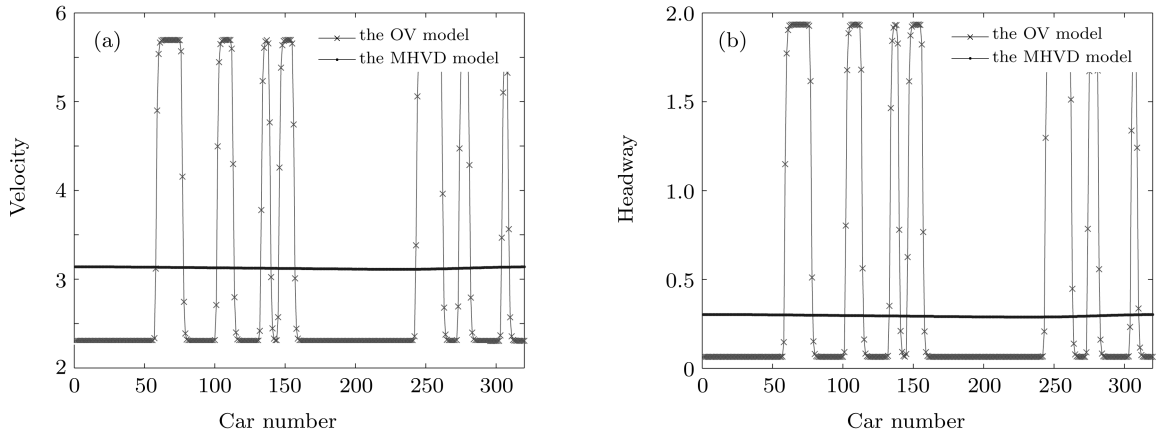


Fig.4. Headway and velocity for $\rho = 0.32$: (a) headway; (b) velocity.

In region IV, the headways are small, the vehicles move slowly, and the fluxes of the two types of traffic flow are the same. The ACC system has little influence in this region.

3.2. Simulation results for the traffic flow mixed with ACC vehicles and manual vehicles

Finally we study the condition of mixed traffic flow consisted of manual and ACC vehicles. Figure 5 shows the fundamental diagram for the percent of ACC vehicles at $p_{\rm ACC}$ = 10%, 20%, 30%, 40%, 50% and 70%. It can be found that the effect of ACC vehicles is prominent with the increase of $p_{\rm ACC}$ when $p_{\rm ACC} < 40\%$, while the increase of $p_{\rm ACC}$ has little influence on the flux when $p_{\rm ACC} > 40\%$. From Fig.5, it can also be found that the density-flux curves become closer to the theoretical curve with the increase of $p_{\rm ACC}$, and the fundamental diagram can also be classified into four regions. With the increase of $p_{\rm ACC}$, the free flow region, i.e. region I is enlarged, the critical points ρ_{c3} between region III and region IV decrease gradually, i.e. region III is reduced and region IV is enlarged. Particularly, the critical point ρ_{c2} between region II and region III is fixed at $\rho_{c2} = 0.25$ which is different from ρ_{c1} and ρ_{c3}. In addition, the improvement induced by ACC vehicles decreases with the increase of $p_{\rm ACC}$.

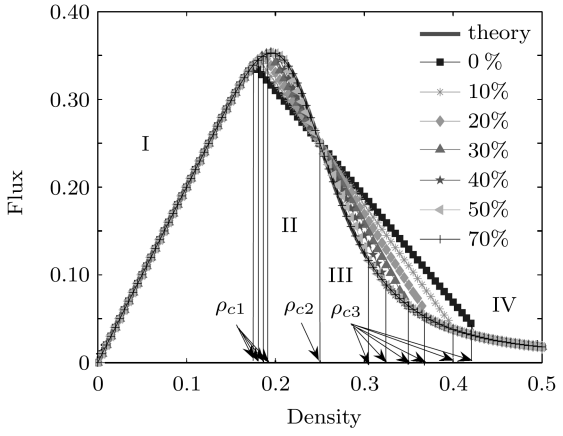


Fig.5. The fundamental diagram for mixed traffic flow of manual and ACC vehicles.

Apparently, the phenomena of Fig.5 can be explained similarly to that of Section 3.1. However, we want to give the explanation intuitively with the OV function defined by Eq.(2). Figure 6 is the curve of the OV function. On the curve there is a turning point at $\Delta x = h_c = 4$ which has the maximal slope rate on the curve, and the slope rate decreases continuously when the point apart from the turning point, i.e. compared with the stable state, the increasing value of velocity is less than the decreasing value in the unstable condition when the average headway is larger than h_c, contrarily the increasing value of velocity is larger than the decreasing value when the average headway is less than h_c, and they are equal to each other when the headway is h_c. As a result, the unstable region is divided into regions II and III in the fundamental diagram, and the critical point between region II and region III is fixed at $\rho_{c2} = 0.25$. Figures 7(a) and 7(b) show the headway and the velocity for $\rho_{c2} = 0.25$ at $t = 9000$. From the figures it can be found that jams appear, and the jams are more and more serious with the decrease of $p_{\rm ACC}$. From Fig.7(a), it can be seen that the headways of congestion (jam) state for the traffic flow of different $p_{\rm ACC}$ are different, as well as the free flow condition. However, the average values of the headways under two states are all about 4, which is the same as the turning point of the OV function. The average velocities are equal to the OV defined by Eq.(2), even though the traffic is unstable and jams appear in the traffic flow.

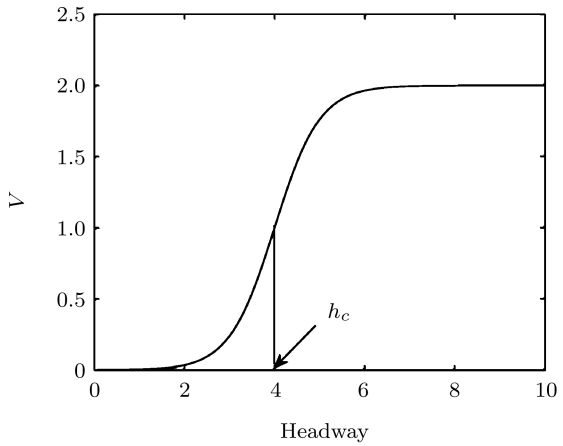


Fig.6. The curve of the OV function depicted by Eq.(2).

The simulation results indicate that ACC vehicles have significant effects in the mixed traffic flow. The stability of traffic flow condition is improved, and traffic jams are suppressed by ACC vehicles.

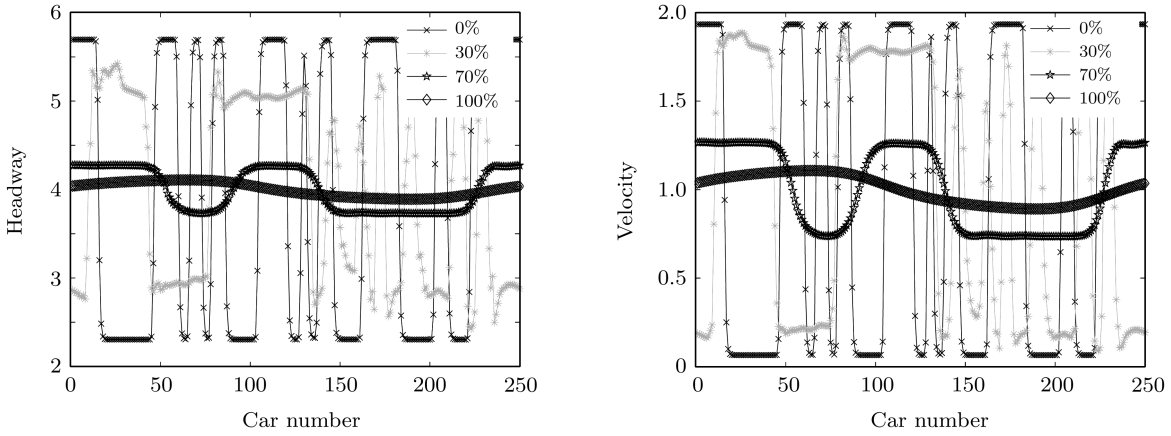


Fig.7. Headway and velocity at $\rho = 0.25$ for $p_{\mathrm{ACC}} = 0\%, 30\%, 70\%, 100\%$, respectively: (a) headway; (b) velocity.

4. Conclusions

This paper investigates the effect of ACC vehicles on traffic flow. We compare the fundamental diagram of ACC vehicle traffic flow with manual vehicle traffic flow and find that the fundamental diagram can be classified into four regions. In region I, the ACC system has no influence and the fluxes of the two types of traffic flow are the same. In region II, the free flow region of ACC vehicles is larger than that of manual vehicles. Jams appear in the manual vehicle traffic flow while traffic flow of ACC vehicles is still in free flow state. With the increase of the density the flux of ACC vehicles also starts to decrease and the flux of ACC vehicles is larger than that of the manual vehicles. In region III, jams in the manual vehicle traffic flow become more serious while traffic flow of ACC vehicles is homogeneous, the flux of the manual vehicles is larger than that of the ACC vehicles. In region IV, the density is high and the ACC system has little influence on traffic flow. The fundamental diagrams of mixed traffic flow consisted of manual and ACC vehicle are also studied and the results are similar. In addition, the simulation results indicate that the ACC system can enlarge the free flow region and alleviate traffic jams effectively and has significant effect on the flux. The improvement induced by ACC vehicles decreases with the increasing proportion of ACC vehicles.

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