Traffic flow of adaptive cruise control vehicles on highway with an on-ramp

Rui Jiang1, Mao-Bin Hu1,2, Qing-Song Wu1, and Yong-Hong Wu2

1School of Engineering Science, University of Science and Technology of China, Hefei 230026, China
2Department of Mathematics and Statistics, Curtin University of Technology, Perth WA6845, Australia

Abstract

Recently, adaptive cruise control (ACC) systems are equipped on some vehicles to provide convenience and comfort and to alleviate the driving burden of the drivers. This paper studies traffic flow features near an on-ramp in a car-following model of ACC vehicles. In the car-following model and the related gap acceptance model in the road merging section, (i) Traffic flow stability is always maintained; (ii) There is no large acceleration and deceleration; (iii) Safety is guaranteed and no collision happens even without the intervention of drivers. The dependence of the system capacity on the inflow rates on main road and on-ramp is studied. The effect of aggressive parameter is also investigated. The desired and undesired traffic flow features are revealed.

Keywords: Traffic flow; adaptive cruise control; on-ramp

1. Introduction

Long distance driving along highway is tiring. Recently, adaptive cruise control (ACC) systems are equipped on some vehicles to provide convenience and comfort and to alleviate the driving burden of the drivers (Van Arem et al., 2006; Zhang and Ioannou, 2006; Ioannou and Stefanovic, 2005; Zheng and McDonald, 2005). An ACC-equipped vehicle detects the presence of a preceding vehicle and measures the distance (range) as well as the relative speed (range rate) by using a forward-looking sensor. It automatically adjusts the vehicle speed to keep a proper range when a preceding vehicle is detected (Ioannou, 2003; VanderWerf et al., 2001; Shladover, 2000).

Some criteria of a good rule of ACC vehicles (including car-following rule, lane changing rule, range policy, gap acceptance rule, etc.) are: (i) Traffic flow stability should be guaranteed (Kikuchi et al., 2003; Yi and Horowitz, 2005); (ii) There is no large acceleration and deceleration; (iii) Safety should be guaranteed and no collision happens even without the intervention of drivers (Rakha et al., 2001; Wang and Rajamani, 2004a).

In this paper, we study traffic flow features near an on-ramp in a car-following model of ACC vehicles, using the constant time headway policy (Zhou and Peng, 2005; Wang and Rajamani, 2004b). The above mentioned criteria are met in the car-following model and the related gap
acceptance model in the road merging road section. The dependence of the system capacity on the inflow rates on main road and on-ramp is studied. The effect of aggressive parameter is also investigated.

The paper is organized as follows. In the next section, the car-following model of ACC vehicles as well as the gap acceptance model at the road merging section is introduced. Section 3 presents and discusses the simulation results. The conclusion is given in section 4.

2. Model

In this section, we introduce the car-following model of ACC vehicles and the gap acceptance model at the road merging section. For the car-following model, the constant time headway policy is adopted. The dynamics of the ACC vehicles can be modeled by the following equation (Davis, 2004)

\[
\frac{dv_n}{dt} = \frac{1}{\tau} \left[ \min \left( \frac{\Delta x_n-D}{T}, v_{\text{max}} \right) - v_n \right] + \frac{\lambda}{\Delta x_n} \Delta v_n
\]  

(1)

Here \( v_n \) is the velocity of vehicle \( n \), \( x_n \) is the position of vehicle \( n \). \( \Delta x_n = x_{n-1} - x_n \) is the distance headway between vehicle \( n \) and its preceding vehicle \( n-1 \). \( \Delta v_n = v_{n-1} - v_n \) is the velocity difference between vehicle \( n \) and vehicle \( n-1 \). \( \tau \) is the vehicle response time, which is typically 0.5-1.0 s. \( T \) is the preferred time headway in the constant time headway policy. \( D \) is the average length of vehicles. \( \lambda \) is a parameter reflecting the response to the range rate.

Note the model of ACC vehicles is actually a full velocity difference model with the optimal velocity \( V(\Delta x_n) = \min((\Delta x_n-D)/T, v_{\text{max}}) \) (Jiang et al., 2001). Therefore, the stability of ACC vehicles could be maintained provided that \( V'(\Delta x_n) = 1/T < \frac{1}{2\tau} + \frac{\lambda}{\Delta x_n} \) for \( \Delta x_n \leq \Delta x_c = v_{\text{max}}T + D \) is met (Jiang et al., 2001; Liang and Peng, 2000).

Furthermore, in order to provide comfort to the passengers, large acceleration and deceleration are prohibited. In this paper, we restrict \( a^- \leq \frac{dv_n}{dt} \leq a^+ \), and set \( a^+ = 2 \) m/s\(^2\) and \( a^- = -3 \) m/s\(^2\). In order to avoid collision, the deceleration \( a^- = -3 \) m/s\(^2\) is applied when

\[
\frac{v_n^2}{2} > \frac{v_{n-1}^2}{2} + \Delta x_n - D
\]

(2)

Here \( a_c \) is a comfortable deceleration and it is set to \( a_c = -2 \) m/s\(^2\). Therefore, \( \frac{v_n^2}{2 |a_c|} \) denotes
the distance traveled by vehicle \( n \) when it decelerates with \( a_c \).

Next we present the gap acceptance model at the road merging section. For simplicity, we assume the main road is a single-lane road. We suppose a vehicle on acceleration lane could change to the main road lane provided that the following criterion is met (see Fig.1):

\[
\gamma \left( \frac{v_n^2}{2 |a_c|} - \frac{v_a^2}{2 |a_c|} \right) < \Delta x_- - D \quad \text{and} \quad \gamma \left( \frac{v_n^2}{2 |a_c|} - \frac{v_a^2}{2 |a_c|} \right) < \Delta x_+ - D
\] (3)

Here \( \gamma \) is an aggressive parameter, \( \Delta x_+ \) is the distance between the preceding vehicle on main road and vehicle \( n \) on acceleration road, \( \Delta x_- \) is the distance between vehicle \( n \) on acceleration road and the following vehicle on main road. \( v_n \) is the velocity of vehicle \( n \) on acceleration road, \( v_+ \) is the velocity of the preceding vehicle on main road and \( v_- \) is the velocity of the following vehicle on main road.

![Figure 1. Sketch of the on-ramp system.](image1)

![Figure 2. Trajectories of 40 vehicles. Initially the vehicles are moving with velocity 30 m/s and headway 60 m. The leading vehicle decelerates at \( t = 0 \) with deceleration \(-2 \text{ m/s}^2\) until it reaches 20 m/s. One can see the following vehicles decelerate accordingly and the string stability is maintained.](image2)
3. Simulation Results

In this section, the simulation results are presented and discussed. In the simulations, the parameters used are: \( v_{\text{max}} = 30 \text{ m/s} \), \( T = 1.25 \text{ s} \), \( D = 7.5 \text{ m} \), \( \tau = 0.714 \text{ s} \), \( \lambda = 10.0 \text{ m/s} \).

3.1. Traffic stability

Given the parameters, it can be verified that \( 1/T < \frac{1}{2\tau} + \frac{\lambda}{\Delta x_n} \) is always met when \( \Delta x_n \leq \Delta x_c = 45 \text{ m} \). Therefore, traffic flow stability could be always maintained. This can also be seen from Fig.2, where the leading vehicle of a platoon of vehicles with initial headway \( \Delta x = 60 \text{ m} \) decelerates to 20 m/s with deceleration \(-2 \text{ m/s}^2\).

![Figure 3. Trajectories of vehicles on the main road near the on-ramp. (a) \( \alpha = 0.5 \); (b) \( \alpha = 0.8 \);](image-url)
3.2. Traffic flow near an on-ramp

In this subsection, the traffic flow patterns and the flow rate on a highway with an on-ramp are studied. The on-ramp setup is shown in Fig.1. The acceleration lane is assumed to start from \( x = 500 \text{ m} \) and end at \( x = 600 \text{ m} \). At the entrance of the main road and on-ramp, it is assumed that a vehicle with velocity 30 m/s arrives with probability \( \alpha \) and \( \beta \) per 1.5 s, so that the maximum flow rate 2400 vehicles/h could be reached on the main road when \( \alpha = 1 \).

Fig.3 shows the trajectories of vehicles on the main road near the on-ramp. The parameters are \( \beta = 0.4, \gamma = 0.7 \). One can see that the vehicles can merge into the main road only when enough space is available on the main road. The vehicles on the main road are only slightly affected by vehicles that merge from acceleration lane, and congestion never happens on main road. With the increase of \( \alpha \), the flow rate on main road increases. As a result, the available space long enough for the merging of vehicles from acceleration lane appears less frequently. As a result, the merging flow rate decreases. This can be seen by comparing Fig.3(a) and (b). When \( \alpha \geq 0.9 \), there is essentially no space available for the merging of vehicles. Consequently, a complete jam appears on the on-ramp (see, e.g., Fig.3(c)).

Fig.4 shows the dependence of system capacity (which is recorded by detector 1 downstream of the merging region as shown in Fig.1) on parameters \( \alpha \) and \( \beta \). One can see that three regions are classified in the space of \( (\alpha, \beta) \). In region A, both main road and on-ramp are in free flow state. The system capacity increases with the increase of \( \alpha \) and/or \( \beta \), and it remains constant provided \( \alpha + \beta \) does not change. In region B, on-ramp flow becomes congested. In this region, system capacity is essentially independent of \( \alpha \) and \( \beta \). However, it is much smaller than the maximum flow rate of 0.6667 vehicle/s (i.e., 2400 vehicles/h). In region C, system capacity is independent of \( \beta \) and it increases with the increase of \( \alpha \) until it reaches 0.6667 vehicle/s at \( \alpha = 1 \).
Figure 4. Dependence of system capacity on parameters $\alpha$ and $\beta$. The bottom plot shows the projection in the space of $(\alpha, \beta)$. Here $\gamma = 0.7$. 
Figure 5. dependence of flow rate $q_1$ on parameters $\alpha$ and $\beta$.

Fig.5 shows the dependence of flow rate $q_1$, which is recorded by detector 2 upstream of the merging region as shown in Fig.1, on parameters $\alpha$ and $\beta$. One can see $q_1$ is independent of $\beta$ and increases linearly with $\alpha$.

Fig.6 shows the dependence of merging flow rate, i.e., the flow rate of vehicles that successfully merge into the main road from the acceleration lane, on parameters $\alpha$ and $\beta$. One can see that two regions are classified in the space of $(\alpha, \beta)$. In the upper right part, the merging flow rate is independent of $\beta$ and it decreases with the increase of $\alpha$. In the lower left part, the merging flow rate is independent of $\alpha$ and it increases with the increase of $\beta$.

Next we investigate the effect of the aggressive parameter $\gamma$ on the system capacity. Fig.7 shows the capacity at different values of $\gamma$ with a fixed $\beta=0.2$. It can be seen that with the decrease of $\gamma$, the capacity increases in the intermediate range of $\alpha$. This is because more vehicles on acceleration lane could merge into main road with the decrease of $\gamma$. However, to guarantee the safety of vehicles, $\gamma$ cannot be too small. Our simulations show that if $\gamma$ is set to 0.5, collision will happen without the intervention of drivers.
Figure 6. Dependence of the merging flow rate on parameters $\alpha$ and $\beta$. The bottom plot shows the projection in the space of $(\alpha, \beta)$. 
4. Conclusions

In this paper, we have studied the traffic flow near an on-ramp in a car-following model of ACC vehicles, using the constant time headway policy. In the car-following model and the related gap acceptance model at the road merging section, (i) Traffic flow stability is always guaranteed; (ii) There is no large acceleration and deceleration; (iii) Safety is guaranteed and no collision happens even without the intervention of drivers.

It is found (i) the traffic flow on the main road is essentially independent of the traffic flow on the on-ramp, and no congestion appears on the main road; (ii) In contrast, the traffic flow on the on-ramp depends on the traffic flow of the main road. When the main road traffic reaches the maximum flow rate, there is no gap that could be accepted by the vehicles on the on-ramp. As a result, no vehicle could merge into the main road. (iii) With the decrease of flow rate on the main road, the capacity of the system decreases; (iv) The capacity depends on the aggressive parameter in the gap acceptance model. With the decrease of the parameter, the capacity is enhanced. Nevertheless, when the parameter is smaller than a threshold, the safety could not be guaranteed and collision might happen. Feature (i) is desired but feature (iii) is undesired, which needs to be removed. One possibility is using other range policy, which needs further investigations. Moreover, in our future work, we need to consider the situation that the main road has more than one lane.

Acknowledgement:

We acknowledge the support of National Basic Research Program of China (No.2006CB705500), the National Natural Science Foundation of China (NNSFC) under Project Nos. 10532060, 70601026, 10672160, the NCET and the FANEDD. Y.-H. Wu acknowledges the support of the
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