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Research Article

Impacts of Cooperative Adaptive Cruise Control Links on Driving Comfort under Vehicle-to-Vehicle Communication

Yongchun Li and Chuanping Shan

China Railway Changjiang Transport Design Group Co., Ltd, Chongqing 401121, China

Correspondence should be addressed to Yongchun Li; lyc5136661@163.com

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Although automated vehicles could release drivers from the driving task, there are still passengers sitting in the vehicle. It is required that the driving comfort of passengers should be guaranteed. Cooperative adaptive cruise control (CACC) vehicle is of the one important type of automated vehicles using vehicle-to-vehicle (V2V) communications with various communication links. Different V2V communication links might have different driving comfort. Then, this paper focuses on exploring which link type for CACC vehicles is better from the perspective of improving driving comfort. To deal with this, car-following models of manual-driven vehicles (MDV) and CACC vehicles were first described. Then, simulations were performed using these car-following models, in which various CACC feedback link types, CACC penetration rates, and flow scenarios were taken into consideration. Simulations outputted microcosmic trajectory data of vehicles, based on which the driving comfort was evaluated using the comfort index described by the International Organization for Standardization (ISO) 2631-1. From the driving comfort perspective, simulation results suggest that CACC should monitor the immediately preceding vehicle and the third vehicle ahead when CACC penetration rates are less than approximately 50%. Additionally, if CACC penetration rates exceed 50%, the better choice is that CACC receives feedback links from two immediately successive vehicles ahead.

1. Introduction

In transportation systems, passenger comfort is arising great interest with the increase in transit time and consumer expectations [1]. However, human drivers have limitations with response time and driving mistakes to deal with disturbances downstream, thereby usually causing discomfort. Fortunately, cooperative adaptive cruise control (CACC) systems are developed for smooth vehicular flow, which is also helpful for improving passenger driving comfort [2]. CACC vehicles need vehicle-to-vehicle (V2V) communication to monitor multiple vehicles ahead [3]. Therefore, as in the previous studies [4–6], this paper also assumes that manual-driven vehicles (MDV) are equipped with V2V communication devices and can send their motion information to CACC vehicles, regardless of whether the MDV can receive information from other vehicles or not. Under such an assumption, the percentage of active CACC vehicles is equal to CACC penetration rate in the mixed traffic flow [7–10].

Although there are many studies conducted on the impacts of CACC on traffic flow, such as capacity [11–14], safety [15, 16], emissions [17, 18], and stability [19–23], only a few literature focused on driving comfort of CACC. Generally speaking, the existing literature can be divided into two categories. On the one hand, some literature [24–26] developed various vehicle speed control algorithms to smooth vehicular dynamics in order to improve driving comfort. On the other hand, Ref [1] reviewed the state-of-the-art of CACC driving comfort and pointed out a research gap in evaluating passenger comfort for the traffic flow mixed with different CACC penetration rates. This paper focuses on the driving comfort of the mixed CACC traffic flow.

To avoid confusion, the CACC feedback link is defined as the connectivity information from the vehicle ahead to the tail CACC in this paper. Therefore, the feedback link means the CACC can monitor the corresponding vehicle ahead. Although more feedback links for CACC are more helpful for anticipations of traffic flow dynamics downstream, it really also complicates CACC control design [2]. Therefore, within the V2V communication range, all available feedback links from vehicles ahead to the tail CACC are not necessarily the best choice. It needs to compare and determine which type of CACC feedback link is better from the perspective of improving driving comfort. However, to the best of our knowledge, little research was conducted to evaluate the impacts of CACC feedback link types on driving comfort for the mixed CACC traffic flow. Then, the objective of this paper is to compensate for the research in this area. To deal with this, the objective and car-following models are first described. Then, simulations are performed on the highway with an on-ramp using the car-following models. The comfort index is finally used to evaluate the driving comfort situations under various CACC feedback link types, CACC penetration rates, and traffic flow demands, thereby providing suggestions for the design of CACC feedback links with the increase of CACC penetration rates.

2. Objective and Models

2.1. Feedback Link Types of CACC. With V2V communication, CACC can monitor multiple vehicles ahead. Meanwhile, the maximum number of vehicles that one CACC can monitor is also limited by the V2V communication range. At the present stage, the V2V communication range is approximately 300 m, which means the feedback information can be sent from the fourth vehicle ahead to the tail CACC under any driving speed [4]. Moreover, it is found that multianticipation leads to significant improvements in stability and comfort for two to four leaders but hardly any further improvement for further leaders. Therefore, this paper defines that CACC can receive feedback information from one, two, three, or four vehicles ahead. Although more feedback links may be more helpful for anticipations of vehicular flow dynamics, it also complicates CACC control design [4]. Hence, all available feedback links from all four vehicles ahead for CACC are not necessarily the best choice. The previous study [4] suggested that two feedback links for CACC could satisfy the required driving tasks. Moreover, the feedback link from the immediately preceding vehicle to the tail CACC is essential to response traffic flow dynamics. Then, another feedback link comes from the second, third, or fourth vehicle downstream, respectively, as shown in Figure 1. Figure 1 shows three types of feedback links for CACC, named link type I, link type II, and link type III defined in this paper. Link type I means the tail CACC monitors feedback signals from the immediately preceding vehicle and the second vehicle ahead. The feedback is sent from the immediately preceding vehicle and the third vehicle ahead in the case of link type II. Besides, link type III contains one link from the immediately preceding vehicle and another one from the fourth vehicle ahead. The three feedback link types of CACC in Figure 1 are considered as the objective of this paper, whose respective impacts on driving comfort will be compared in order to determine which one is better from the driving comfort perspective.

2.2. Car-Following Models. Car-following models [27–31] are essential for microscopic simulations to evaluate impacts on driving comfort. In the case of the MDV model, the intelligent driver model (IDM) [32, 33] with response time is used. The model equation is written as

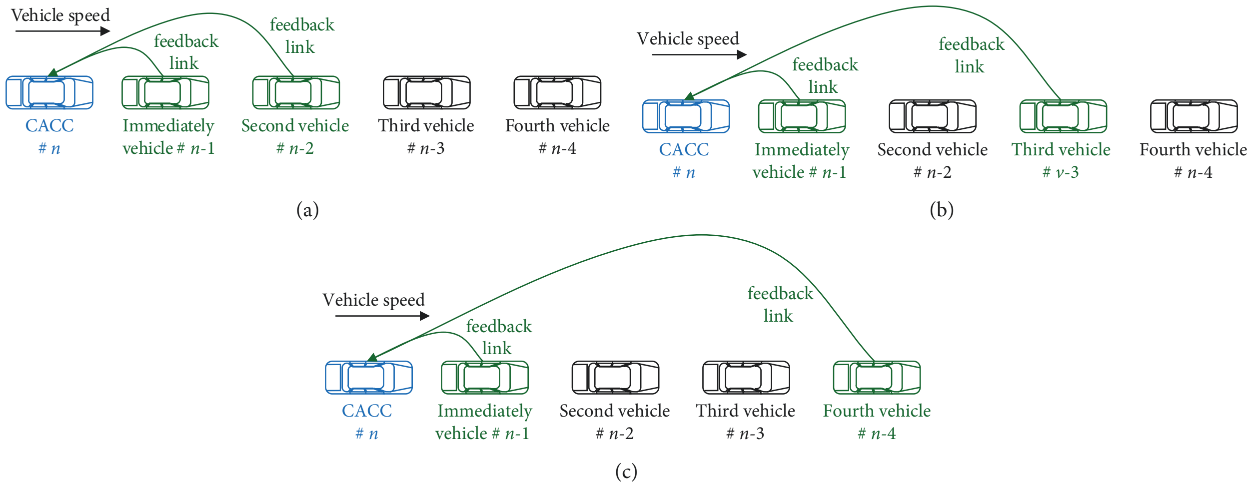
$$\dot{v}_n(t+\tau_1) = a\left[1-\left(\frac{v_n(t)}{v_0}\right)^{\delta}-\left(\frac{d+v_n(t)T-v_n(t)\left[v_{n-1}(t)-v_n(t)\right]/2\sqrt{ab}}{s_n(t)}\right)^2\right], \tag{1}$$

where $v_n(t)$ is the speed of vehicle n at time t, $v_{n-1}(t)$ is the speed of vehicle n–1 at time t, $s_n(t)$ is the distance gap between vehicle n and its preceding vehicle n–1, τ_1 is the response time of human drivers, $\dot{v}_n(t+\tau_1)$ is the acceleration of vehicle n after the delay time τ_1, a is the maximum acceleration, v_0 is the free flow speed, δ is the exponent coefficient, d is the minimum gap, T is the safety time gap, and b is the comfort deceleration. Based on real data, the calibration results of IDM parameters are [34] $\tau_1 = 1.3575$ s, $a = 1.2681\ \mathrm{m/s^2}$, $v_0 = 30.0$ m/s, $\delta = 3.0244$, $d = 9.6312$ m, $T = 1.7031$ s, and $b = 2.8638\ \mathrm{m/s^2}$.

In the case of the CACC car-following model, intelligent property can be described by the IDM model. Then, this paper adopts the model which is written as follows [35]:

$$\dot{v}_n(t+\tau_2) = a\left[1-\left(\frac{v_n(t)}{v_0}\right)^{\delta}-\left(\frac{d+v_n(t)T-v_n(t)\left[v_{n-1}(t)-v_n(t)\right]/2\sqrt{ab}}{s_n(t)}\right)^2\right]+\sum_{i=1}^{m} r_i\left(\theta_{n-i}(t)-\theta_n(t)\right), \tag{2}$$

where τ_2 is the V2V communication delay time that is set as 0.1 s, r_i is the feedback gain from the i-th vehicle ahead, m is the maximum number of vehicles that the CACC can monitor (set as 4 in this paper), and $\theta_n(t)$ is called the electronic throttle angle of vehicle n at time t, while $\theta_{n-i}(t)$ is that of vehicle n–i at time t. Based on the previous studies [35–37], the feedback information $\theta_{n-i}(t)$–$\theta_n(t)$ is an integration of speeds and accelerations, and $\theta_n(t)$ is modeled as follows:



(a)

(b)

(c)

Figure 1: CACC feedback link types studied as the objective of this paper. (a) Link type I. (b) Link type II. (c) Link type III.

$$\theta_{n-i}(t)-\theta_n(t)=\frac{1}{\beta}\left[\dot{v}_{n-i}(t)-\dot{v}_n(t)+\alpha\left(v_{n-i}(t)-v_n(t)\right)\right], \tag{3}$$

where v_e is the equilibrium speed, θ_e is the electronic throttle angle at the equilibrium state, α and β are sensitivity coefficients, which are set as 0.8 and 0.27, respectively [36].

The feedback gain r_i of the CACC model ranges from 0 to 1. Because low-frequency oscillations usually occur with too low values of feedback gain and too high gains may cause high-frequency instability, all the gains shall be kept around 0.5 [4]. Therefore, the four feedback gains of CACC are all considered as 0.5 in this paper.

3. Numerical Simulations

Numerical simulations are important and necessary before CACC implements in larger-scale real vehicles. The car-following models of MDV and CACC are used to perform the simulations, based on which simulation trajectory data of vehicles can be obtained. Then, a driving comfort measure will be used to evaluate driving comfort situations under different CACC link types and penetration rates.

3.1. Design and Measure. Because car-following models describe longitudinal movements of vehicles, the simulation segment is assumed to be a one-lane highway with an on-ramp located in the middle of the segment [20, 38]. The length of the simulation segment is 6.5 km, which is a straight road without a gradient. Different flow scenarios should be considered in simulations. Because driving comfort problems will not easily arise in light traffic flow, the main-line flow should not be too low in simulations. According to the previous studies [20, 38], the main-line flow is set as 1800 veh/hr and 1200 veh/hr, respectively, while the ramp flow is set as 360 veh/hr. The simulations are performed in Matlab software using car-following models, in which the total simulation time is 1 hour and the time step is 0.1 s. In simulations, the desired speed of vehicles is 30 m/s, the maximum acceleration is set as 4 m/s^2, and the emergency deceleration is considered to be –6 m/s^2. The vehicles randomly have a speed of 25–30 m/s when entering the simulation segment. Because what we are concerned about is the main-line flow [20, 38]., the simulation data of vehicles travelling on the main-line road are obtained after simulations. Different feedback links of CACC are illustrated in Figure 1 and various CACC penetration rates are taken into consideration in simulations. For each simulation, the vehicle orders are random. Hence, each simulation is repeated ten times to calculate the average value as the result.

Based on the simulation trajectory data of vehicles under each traffic flow scenario, such as CACC link types and penetration rates, an appropriate driving comfort measure should be used to evaluate the corresponding driving comfort. Here, we use the comfort index (CI) [39] as the driving comfort measure, which is described by the International Organization for Standardization (ISO) 2631-1. The value of CI is calculated by using instantaneous accelerations of vehicles and the calculation equation is as follows:

$$\mathrm{CI}=\left(\frac{1}{N}\sum_{i=0}^{N}a_i^2\right)^{1/2}, \tag{4}$$

where a_i is the ith acceleration obtained in simulations and N is the total number of accelerations that are used for the calculation. The smaller value of CI stands for a better comfort situation.

4. Results

The CI values of 0% CACC penetration rate are considered as the benchmark, compared with which the percentage reductions are calculated for different CACC penetration rates. As noted before, the main-line flow is set as 1800 veh/hr and 1200 veh/hr, respectively, and the three CACC link types illustrated in Figure 1 are considered in the calculations. The results are shown in Tables 1 and 2, in which Table 1 shows the percentage reductions of CI for the three link types with an increase of CACC penetration rates under main-line flow 1800 veh/hr, while Table 2 shows those underflow 1200 veh/hr. According to Tables 1 and 2, the

Table 1: Percentage reductions of CI under 1800 veh/hr flow.

CACC penetration rates (%)	Average reducing under 1800 veh/hr flow (%)		
	Link type I	Link type II	Link type III
0	0.00	0.00	0.00
10	13.32	23.45	27.12
20	30.51	38.57	36.91
30	32.62	41.39	38.95
40	34.87	43.99	42.44
50	38.68	45.60	42.51
60	53.83	47.01	43.87
70	59.55	56.65	56.71
80	61.41	62.03	58.08
90	61.93	62.76	61.35
100	62.19	63.13	61.62

Table 2: Percentage reductions of CI under 1200 veh/hr flow.

CACC penetration rates (%)	Average reducing under 1200 veh/hr flow (%)		
	Link type I	Link type II	Link type III
0	0.00	0.00	0.00
10	2.04	5.38	6.12
20	4.83	19.43	14.51
30	9.27	21.35	18.09
40	10.85	24.83	18.40
50	22.18	26.55	21.56
60	27.91	26.86	23.63
70	30.42	31.61	28.20
80	31.62	32.62	31.92
90	34.43	34.58	32.82
100	34.95	36.36	35.37

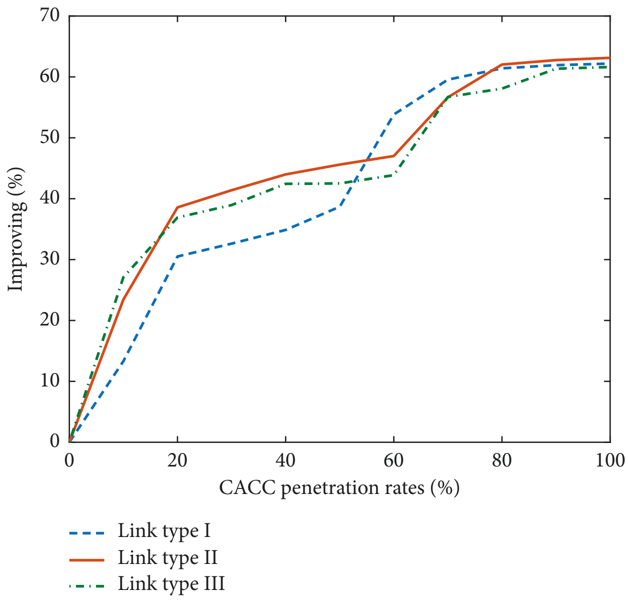


Figure 2: Comparison among CACC link types under 1800 veh/hr flow.

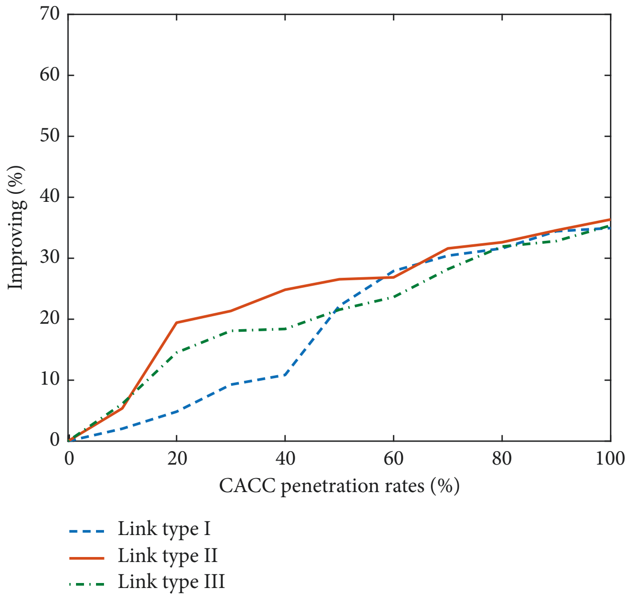


Figure 3: Comparison among CACC link types under 1200 veh/hr flow.

values of CI decrease with the increase of the CACC penetration rate, which means an improvement in driving comfort. Compared with the 0% CACC rate, 100% CACC vehicles can enhance driving comfort by 60% for all three link types under 1800 veh/hr flow, while the improvement is approximately 35% under 1200 veh/hr. This indicates that CACC vehicles are more helpful to improve driving comfort in more congestion situations of traffic flow because a larger main-line flow is apt to result in more congestion.

What is more concerning about this paper is the comparison among different CACC link types on improving driving comfort. To deal with this, we plot figures for better visualization, as shown in Figures 2 and 3. Figure 2 shows the comparison among CACC link types under 1800 veh/hr flow, while the comparison of CACC link types under 1200 veh/hr flow is illustrated in Figure 3. It can be seen that the CACC link types II and III have more improvement in driving comfort than link type I when the CACC penetration rate is less than approximately 50%. However, the CACC link type I is apt to have more driving comfort enhancement if the CACC penetration rate exceeds 50%. It should be noted that the control design is more complex if CACC monitors the farther vehicle ahead. Therefore, it is suggested that the CACC link type II should be chosen when the CACC penetration rate is below 50%, while the CACC link type I might be the better one if the CACC penetration rate is more than 50%. As described in Figure 1, link type I means the CACC monitors two immediately successive vehicles ahead, while link type II requires CACC monitors the third farther vehicle ahead. Therefore, the implements based on this paper's suggestion can reduce the CACC control complexity when CACC penetration rates are high for large-scale flow.

5. Conclusions

By using V2V communication, CACC can receive feedback information from multiple vehicles ahead to improve driving comfort. Although more feedback links for CACC might be useful for anticipations of traffic flow dynamics, it also complicates the control design work of CACC. Previous studies [4] indicated that two feedback links shall be enough to deal with vehicular flow dynamics downstream. However, two feedback links can be further divided into several types, which distinguish the specific two vehicles ahead. Moreover, little research has been conducted on determining which feedback link type for CACC is a better choice from the perspective of improving driving comfort. This paper makes an effort to deal with this within the farthest fourth vehicle ahead, taking into consideration the V2V communication range. The simulations are performed using car-following models, in which the highway with an on-ramp is considered as the simulation segment [20, 38]. The driving comfort is evaluated under various CACC feedback link types, CACC penetration rates, and flow scenarios. From the perspective of improving driving comfort, simulation results suggest that CACC should receive feedback information from the immediately preceding vehicle and the third vehicle ahead if CACC penetration rates are below approximately 50%. However, when CACC penetration rates are more than 50%, the better design is that CACC monitors two immediately successive vehicles ahead. This indicates that CACC might not need to monitor farther vehicles ahead when its penetration rate is high enough. Because the control design will be relatively more complex if CACC monitors the farther vehicle ahead, the suggestion proposed in this paper can also simplify the CACC control complexity with higher CACC penetration rates.

We should also mention that the conclusions obtained in this paper may depend on the models used. However, the study in this paper indicates that all available feedback links from vehicles ahead to the tail CACC are not necessarily the best choice. This makes us aware that we should compare and determine which type of CACC feedback links is better from the perspective of improving driving comfort. We are aware that real experimental tests are necessary to validate the conclusions, while implementations of large-scale CACC flow with different penetration rates are not easy in the present stage. Therefore, this paper provides an important insight into driving comfort from the perspective of CACC links before the real experimental test.

Data Availability

No data were used to support this study.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

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