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Effects of ACC and CACC vehicles on traffic flow based on an improved variable time headway spacing strategy

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Abstract: An improved variable time headway (VTH) spacing strategy for the adaptive cruise control (ACC) and cooperative ACC (CACC) system is proposed. On the basis of the novel strategy, the typical two-modes of ACC/CACC upper-level controller are redesigned. Numerical simulations for two traffic scenarios are performed to verify the efficiency of the improved strategy. The results demonstrate the suitability and advantages of the improved VTH strategy in comparison with the constant time headway strategy and the VTH strategy. Furthermore, the authors study the impact of ACC and CACC vehicles on traffic flow by multiple-types mixed scenarios: ACC/manual vehicles, CACC/manual vehicles and ACC/CACC/manual vehicles. The results illustrate that introducing the ACC/CACC vehicles into mixed traffic can improve traffic flow stability, enhance road capacity and alleviate the increasingly serious traffic congestion problem.

1 Introduction

The applications of Intelligent Transportation Systems (ITS) are important measures to reduce traffic congestion. The ITS integrate advanced science and technology into the transportation management system. Through effective management and control, vehicles, roads and pedestrians can effectively cooperate and interact to achieve multiple goals such as improving transportation efficiency, alleviating traffic congestion, decreasing traffic crashes and reducing traffic pollution. Advanced driver assistance systems (ADAS) equipped in vehicles are key technologies in the ITS. They can assist the driver in controlling the vehicle and improving driving safety and comfort. The adaptive cruise control (ACC) system is one of the ADAS. It can detect the position and speed of the preceding vehicle through various on-board sensors, and automatically adjust the speed according to the control strategy. Therefore, ACC vehicles can maintain an appropriate safety gap. With the development of the ACC system and the wireless communication technology, the cooperative ACC (CACC) system is gradually becoming an important issue. By transferring multi-vehicles information using the vehicle-to-vehicle communication, the CACC system can further shorten the following gap on the basis of ensuring safety. Thus, the CACC system plays an important role in improving traffic stability, reducing traffic energy consumption and enhancing traffic mobility [1, 2].

In the real traffic environment, although the number of vehicles installed with the ACC system is increasing, the popularity of ACC vehicles is a gradual development process. In a long period of time, ACC vehicles will co-exist with manual driving vehicles on the road. Moreover, the CACC system is still in a period of continuous development stage and its promotion will also be a long-term process. Therefore, it is of great theoretical and practical significance to investigate the impact of ACC/CACC vehicles on traffic system and traffic flow characteristics before large-scale deployment with the ACC/CACC systems.

1.1 Spacing strategy selection

As one of the important components of ACC and CACC systems, the spacing strategy determines the safe following gap and provides the reference input value for the subsequent control algorithms. Whether the design is reasonable will directly affect the vehicle safety and the road utilisation. For instance, too small spacing can easily lead to vehicle rear-end collision crashes, while too large spacing not only decreases the road capacity but also easily causes the insertion of vehicles from adjacent lanes. These situations do not meet the psychological expectations of the driver.

The spacing strategies are mainly divided into two categories: the constant spacing (CS) strategy [3] and the variable spacing (VS) strategy [4]. Swaroop and Hedrick [5], and Santhanakrishnan and Rajamani [6] point out that the CS strategy cannot balance the multiple control objectives, and adapt to the complex and changing driving environment. The user acceptance of ACC/CACC systems with the CS strategy is very low [7].

To remedy the shortcomings of the CS strategy, the VS strategy in which the gap changes with the driving environment is further proposed. The typical class is the safety spacing strategy based on the time-headway, which can be expressed as

$$\Delta x_{\text{des}} = t_h v_f + \Delta x_0, \tag{1}$$

where Δx_{des} is the desired safety distance; t_h is the desired time-headway; v_f is the speed of the considered vehicle; Δx_0 is the minimum safety gap when vehicles are completely stopped. If t_h is constant, it is the constant time headway (CTH) strategy that is most widely studied. The desired safety gap of the CTH strategy is a linear function of v_f. Different from the CTH strategy, when t_h is no longer kept constant but changes with the driving environment, it is called the variable time headway (VTH) strategy. The desired safety distance of the VTH strategy is a non-linear function of v_f.

In the VTH strategy designed for the intelligent cruise control system [8], t_h is proportional to v_f. Yanakiev and Kanellakopoulos [9] study the longitudinal control problem of automated heavy-duty trucks and design a real-time VTH strategy which is combined with the relative speed. This strategy can reduce transient errors and allow a platoon of cars to maintain smaller spacing. Luo [10] presents a multi-objective ACC algorithm based on a model predictive control framework and designs a VTH strategy in which the preceding vehicle acceleration is introduced to mimic the future change trend of the preceding vehicle speed. Wang and Rajamani [11, 12] propose a spacing strategy based on the macroscopic traffic flow theory in which

$$t_h = \frac{1}{\rho_{\text{jam}} * (v_{\text{free}} - v_f)}. \tag{2}$$

Here ρ_{jam} is the jam density and v_{free} is the free flow speed. This strategy is an unconditionally stable spacing strategy, which guarantees the stability of traffic flow under all boundary conditions.

1.2 Effect of ACC/CACC vehicles

In recent years, the research on the mixed traffic flow characteristics of ACC/CACC vehicles and manual vehicles has become a hot topic. Due to the diversification and complexity of mixed traffic, it is undoubtedly a challenge to study this issue and many scholars have made unremitting efforts.

In aspect of spacing strategy and control model: Bayar *et al.* [13] study the linear spacing strategy and the quadratic spacing strategy under the mixed scenario of ACC and manual vehicles. The results show that the latter performs better in reducing energy consumption and travel time, and significantly improves the platoon stability. Arem *et al.* [14] extend the CTH strategy to the CACC system and establish a multi-anticipated CACC control algorithm by considering the speed difference of multiple vehicles in front. Rajamani *et al.* [15] analyse the effect of mixing ACC vehicles with manual driving vehicles on the capacity and stability of the traffic system. They find that the mixed fleet has a higher speed oscillation compared with full ACC or manual vehicles due to using different control models. The road occupancy of ACC vehicles will significantly affect the speed distribution. As the time-headway is shortened and the response is increased, the road capacity will be significantly improved and vehicles will return to the steady state under internal and external disturbances in a short time. Xie *et al.* [16] apply the optimal velocity model and the multiple headway and velocity difference model to describe the motion law of manual vehicles and ACC vehicles, respectively. They study the effects of the ACC system on traffic flow. The CACC controller designed by Amoozadeh *et al.* [17] contains three modes: speed control mode, gap control mode and collision avoidance mode. They implement multi-scene mixed traffic simulations on VENTOS which is a vehicle network open simulator. Qin *et al.* [18] adopt the ACC and CACC models verified by the PATH laboratory of the University of California, Berkeley to study the heterogeneous traffic flow consisting of ACC, CACC and manual vehicles. They provide a reference value of t_h for designing the ACC/CACC upper-level controller.

In aspect of specific application scenario: Papacharalampous *et al.* [19] analyse, compare and evaluate three different controllers: ACC, traffic state-adaptive ACC (TSA-ACC) and CACC to mitigate traffic jams at sags which are road segments where the gradient from downhill to uphill has a significant change in a short distance. The simulation results show that TSA-ACC is most effective to save travel time for mixed fleet and to improve traffic flow on sags. Mersky and Samaras [20] introduce automatic vehicles to conventional fuel economy tests and study changes in fuel economy through simulation. The control law of automatic vehicles uses gap control and speed control. Davis [21] and Hua *et al.* [22] study the influence of mixed traffic flow on the freeway on-ramp. Through the simulation, they verify that ACC vehicles can effectively improve the on-ramp traffic flow and simultaneously suppress the intensity of traffic jams. Zhou *et al.* [23] propose an improved intelligent driver model (IDM) to investigate the effect of CACC vehicles on freeway merging areas and test the performance under different CACC vehicle penetration rates. They observe that the increase of the proportion of CACC vehicles can reduce total travel time, smooth traffic oscillations and maximise merging efficiency. Fyfe [24] integrates the microscopic traffic simulation software VISSIM with the surrogate safety assessment model to evaluate the safety performance of vehicle fleet. Two scenarios are used in the simulation. The first one is the vehicle fleet on freeway, in which CACC vehicles communicating via vehicle-to-vehicle mix with manual and ACC vehicles. The second one is the vehicle fleet at the signalised intersection of urban roads, in which the communication method is vehicle-to-infrastructure and the cumulative travel time intersection control algorithm [25] is adopted. Shladover *et al.* [26] study the effects of ACC and CACC vehicles on freeway capacity. The impacts of CACC on the case study of the ring road of Antwerp are investigated by Makridis *et al.* [27]. They perform simulation under various penetration rates and traffic demands. The results show that the coordination of vehicles can reduce traffic congestion and energy use. The impact of autonomous vehicles and connected autonomous vehicles on the same road network [27] is studied in [28]. Milanés *et al.* [29] design, implement and test a CACC system. Talebpour and Mahmassani [30] propose a modelling framework that uses different models to simulate different vehicle types. The theoretical analysis indicates that autonomous and connected vehicles can improve the string stability.

1.3 Main work

The CTH strategy currently most widely used in ACC and CACC systems is not ideal under complex traffic conditions such as frequent acceleration or deceleration of the preceding vehicle. Moreover, the stability of the CTH strategy for highway traffic flow depends on the boundary conditions [15]. In the VTH strategy [9], the time-headway considers the relative speed compared with the CTH strategy, but does not consider the preceding vehicle acceleration information and the driving environment of the vehicle. Therefore, there is much room for further improvement in this strategy.

The main work of this paper lies in the following two points. First, we propose an improved VTH strategy, in which the time-headway changes with the considered vehicle speed, the relative speed, the preceding vehicle acceleration, the free flow speed and the jam density. Compared with the CTH strategy, this strategy adapts well to the complex traffic environment, and further improves the stability and fluidity of traffic flow. In comparison with the VTH strategies [9], more adequate factors are taken into account to achieve more precise control. Second, based on the improved VTH strategy, we design the upper-level controller of ACC/CACC vehicles and investigate the impact of ACC/CACC vehicles on mixed traffic flow. We implement the control algorithm on the traffic simulation platform PTV-VISSIM9 [31] to verify the effectiveness of the proposed VTH strategy and the improvement of ACC/CACC vehicles for traffic.

2 Spacing strategy and control algorithm design

2.1 Improved VTH strategy

Yanakiev and Kanellakopoulos [9] propose the VTH strategy in which

$$t_h = t_0 - c_v*\left(v_p - v_f\right). \tag{3}$$

Here t_0 is a constant greater than zero, c_v is the positive weight coefficient of the relative speed and v_p is the preceding vehicle speed. In (3), t_h decreases with the increase of the relative speed so that this strategy can reduce the transient error and make the automatic platoon maintain a smaller spacing compared with the CTH strategy. However, regardless of whether the preceding vehicle is in an acceleration or deceleration state, the value of t_h is fixed when the relative speed is constant, which is unreasonable. For instance, the preceding vehicle is decelerating, a larger headway is required to avoid possible rear-end collisions. In addition, setting t_0 as a constant does not consider multiple types information of the macroscopic traffic flow, which may lead to unsatisfactory results of actual control.

Based on the VTH strategy [9, 11, 12], this paper considers the speed change trend of the preceding vehicle, that is, the influence of the preceding vehicle acceleration on the desired safety gap. Moreover, the jam density and the free flow speed are also taken into account. We design the following improved VTH strategy:

$$\Delta x_{\text{des}} = t_h v_f + \Delta x_0, \tag{4}$$

with

$$t_h = c_k*\frac{1}{\rho_{\text{jam}}*(v_{\text{free}} - v_f)} - c_v*(v_p - v_f) - c_a*a_p,$$

where c_k is the positive coefficient, a_p is the preceding vehicle acceleration and c_a is the positive weight coefficient of the preceding vehicle acceleration. With the help of wireless communication, CACC vehicles can further reduce the headway due to having shorter response time. Therefore, the value of c_k for CACC vehicles can be appropriately reduced compared with ACC vehicles. In the improved VTH strategy (4), the ACC/CACC vehicles are in a congested state when v_f is much smaller than v_{free}. In this condition, t_h reduces by a certain degree, which will relatively increase the traffic efficiency and capacity of the high-density fleet under the premise of ensuring driving safety. When v_f is close to v_{free}, ACC/CACC vehicles are moving at a high speed and t_h can be adaptively increased to avoid rear-end collisions.

Considering that t_h approaches infinity when v_f approaches v_{free} or t_h may be very small and even become negative, we adopt the method similar to that in [9, 10] and introduce the following saturation function to further limit the value of t_h in order to ensure the security and traffic efficiency

$$t_h = \begin{cases} t_{h\_\max}, & t_h > t_{h\_\max}, \\ t_{h\_\min}, & t_h < t_{h\_\min}, \end{cases} \tag{5}$$

where $t_{h\_\max} > 0$ is the upper limit and $t_{h\_\min} > 0$ is the lower limit.

2.2 Control algorithms for ACC/CACC upper-level controller

A typical ACC/CACC upper-level controller generally consists of two modes: velocity control (VC) mode and space control (SC) mode [26]. The specific control mode is switched by the preset threshold headway between the vehicle and the preceding vehicle.

2.2.1 VC mode: In this paper, the psycho-physical driver behaviour model developed by Wiedemann [32, 33] is employed to mimic the movement pattern of manual vehicles. This model includes four driving modes: free driving, following, approaching and braking. In the model, the acceleration of the manual driving vehicle can be calculated based on the current speed, the speed difference and the characteristic parameters of the driver and the vehicle.

In the VC mode, the space is larger than 50 m and the model of manual driving vehicles is used to compute the reference acceleration of the controlled vehicle. For example, the ACC/CACC vehicles exhibit free driving behaviour when the space is sufficient to drive at a predetermined speed. The desired acceleration of ACC/CACC vehicles for this case is as follows:

$$a_{vc} = K_{vc}*(V_d - v_f), s \geq 150 \text{ m}, \tag{6}$$

where K_{vc} is the speed control gain, V_d is the desired speed increasing with the increase of the relative speed [32] and s is the distance between the vehicle equipped with ACC/CACC system and the preceding vehicle.

2.2.2 SC mode: In the SC mode, the space between the target vehicle and the preceding vehicle is small. Compared with the VC mode, the SC mode is more complex. We construct the SC mode for ACC/CACC vehicles based on the improved VTH strategy designed in Section 2.1, which is the focus of this paper.

For ACC vehicles, the desired acceleration in the SC mode is determined by the speed difference between the target vehicle and the preceding vehicle, and the error of the current gap with the desired gap

$$a_{sc} = K_v*(v_p - v_f) + K_s*(s - s_d), \quad s \leq 50 \text{ m}, \tag{7}$$

$$s_d = \Delta x_{\text{des}} - l_p = t_h v_f + \Delta x_0 - l_p, \tag{8}$$

where K_v and K_s are the positive gains of the speed term and the spacing term, respectively, s_d is the desired gap and l_p is the length of the preceding vehicle.

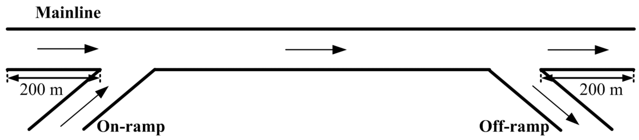

Fig. 1 *Schematic illustration of the simulated road*

For CACC vehicles, different from ACC vehicles, they can obtain the acceleration of the preceding CACC vehicle through wireless communication. Therefore, the desired acceleration in the SC mode is given by [1]

$$a_{sc} = K_a*a_p + K_v*(v_p - v_f) + K_s*(s - s_d), \quad s \leq 50 \text{ m}, \tag{9}$$

where K_a is the feedback gain of the acceleration term. However, if the preceding vehicle is not a CACC vehicle but an ACC or manual vehicle, the acceleration of the target CACC vehicle will degenerate to (7).

To further consider the driver's comfort in the ACC/CACC vehicle, the deceleration and acceleration in the SC mode are, respectively, limited by the minimum deceleration $a_{\min}$ and the maximum acceleration $a_{\max}$

$$a_{sc} = \max(a_{\min}, \min(a_{sc}, a_{\max})). \tag{10}$$

The ACC/CACC upper-level controller using the VC and SC modes can apply to a variety of traffic scenarios and ensure the safe and efficient driving, which will be validated in Section 3.

3 Simulation

We adopt the traffic simulation platform PTV-VISSIM9 [31] and implement our control algorithm on it. Given a 90% confidence interval and an allowed error of 10%, the six replications are enough to provide reliable results [34]. For each scenario, six replications are made with different random number seeds and the results reported are the average over the six replications. Fig. 1 shows a schematic illustration of the simulated road. Vehicles move on a single-lane freeway section up to 6 km with one on-ramp and one off-ramp. Both the on-ramp and the off-ramp are 200 m in length. The simulated time is 1800 s and the first 300 s is the warm-up time.

We first choose two scenarios: full ACC vehicle fleet and full CACC vehicle fleet to verify the efficiency of the improved strategy. In each scenario, we consider two cases in which the flow on the ramps is zero or non-zero. Next, we investigate the effect of ACC/CACC vehicles on the traffic flow under three scenarios including the mixed traffic of ACC and manual driving vehicles, mixed traffic of CACC and manual driving vehicles and multi-types mixing of ACC, CACC and manual driving vehicles.

3.1 Validity test of the improved VTH strategy

3.1.1 Scenario A – full ACC vehicle fleet: We consider the fleet consisting of complete ACC vehicles and compare the performance of three different spacing strategies: the CTH strategy, the VTH strategy with the desired time-headway (3) in [9] (abbreviated by the VTH strategy) and the new VTH (NVTH) strategy (4).

The parameters $K_v = 0.58 \text{ s}^{-1}$ and $K_s = 0.1 \text{ s}^{-2}$ are specified in accordance with [1]. The parameters are set to $\rho_{\text{jam}} = 0.2$ veh/m and $c_k = 1$ veh [11, 12, 15]. The value of c_v is chosen to be $0.05 \text{ s}^2/\text{m}$ [10].

Other parameters are set as

$$\begin{gathered} t_0 = 1.4 \text{ s}, \; c_a = 0.3 \text{ s}^3/\text{m}, \; a_{\min} = -3 \text{ m/s}^2, \; a_{\max} = 2 \text{ m/s}^2, \\ v_{\text{free}} = \frac{120}{3.6} \text{ m/s}, \; \Delta x_0 = 0 \text{ m}, \; t_{h\_\max} = 2.2\, s, \; t_{h\_\min} = 0.2\, s\, . \end{gathered} \tag{11}$$

For the CTH strategy, Wang *et al.* [35] point out that the term ‘constant time headway’ is misleading, since the desired time-headway is not constant but the desired time gap $t_d = t_h - l_p/v_f$ is

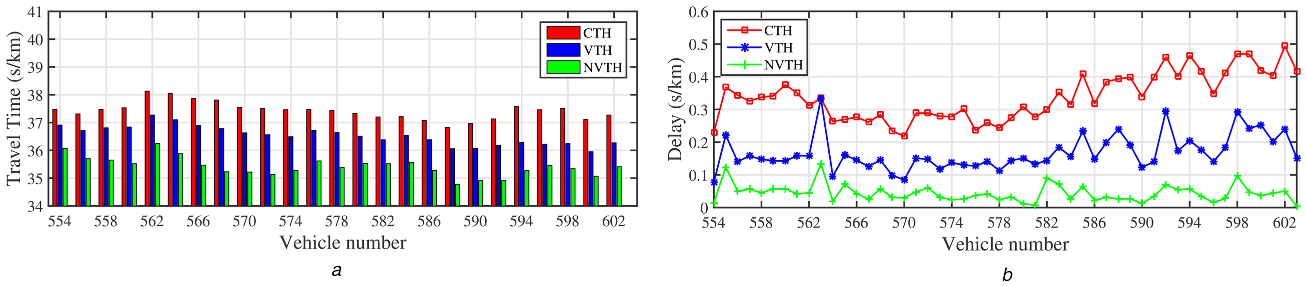

Fig. 2 *Results of full ACC vehicle fleet for zero flow on ramps*
(a) Travel time, ***(b)*** Delay

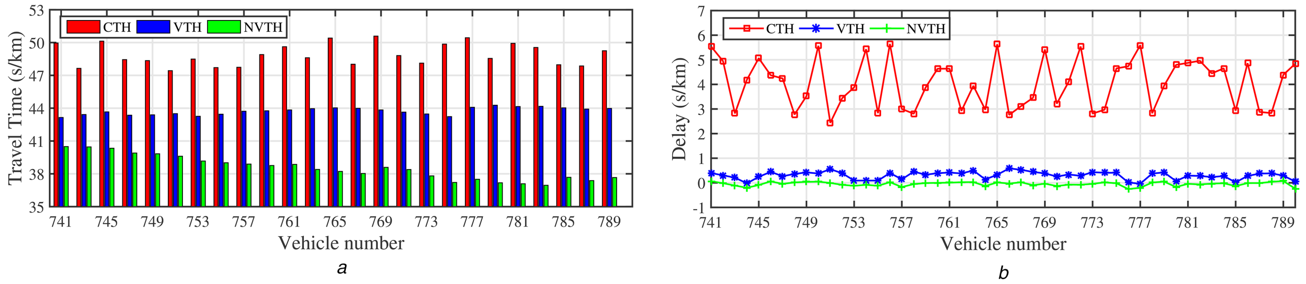

Fig. 3 *Results of full ACC vehicle fleet for non-zero flow on ramps*
(a) Travel time, ***(b)*** Delay

Table 1 Comparison of different strategies for full ACC vehicle fleet [the values in parentheses represent the relative representation of the results (%) for the VTH strategy and NVTH strategy compared with the CTH strategy]

Flow on ramps	Strategy	Travel time, s/km	Delay, s/km	Flow, veh/h
zero	CTH	37.44	0.34	1809.20
	VTH	36.53 (97.57%)	0.17	1810.00 (100.04%)
	NVTH	35.40 (94.55%)	0.04	1810.40 (100.07%)
non-zero	CTH	48.95	4.05	2116.00
	VTH	43.77 (89.42%)	0.30	2328.40 (110.04%)
	NVTH	38.58 (78.82%)	−0.05	2410.40 (113.91%)

constant. Therefore, in this subsection t_d is set to 1.4 s for the CTH strategy.

Fig. 2 shows the simulation results of the travel time histogram and delay line chart for the case of no vehicles entering from the on-ramp and exiting at the off-ramp. The freeway mainline input is set to 1800 veh/h. We count 50 ACC vehicles numbered 554–603. With the same mainline input, the next case considered is that the input flow of the on-ramp is 600 veh/h and 20% vehicles exit at the off-ramp. Fig. 3 illustrates the corresponding results. We count 50 ACC vehicles numbered 741–790. The results of two cases are summarised in Table 1. From Table 1 and Figs. 2 and 3, it can be observed that the NVTH strategy reduces the travel time and traffic delay for two cases compared with the CTH strategy and the VTH strategy. Moreover, the reduction of the travel time and delay is more obvious for the case of non-zero flow on ramps. The travel time reflects the road capacity to some extent and the traffic delay is due to the mutual interference of traffic flow. Both reductions indicate the NVTH strategy can improve traffic efficiency and traffic flow stability. It also can be seen from Table 1 that the use of the NVTH strategy increases the flow for the case of non-zero flow on ramps. The flow for the case of zero flow on ramps is almost equal for three strategies. This is because the total traffic flow loaded on the road is not large enough, which does not cause congestion.

The headway-speed distribution scatter plot for the case of zero flow on ramps is shown in Fig. 4. We can observe that the headway under the CTH strategy has a linearly increasing trend, while the headway under the NVTH strategy has a parabolic trend. Furthermore, the headway under the NVTH strategy is distinctly smaller than that under the CTH strategy in the low-speed interval. This indicates the fleet can be more compact, which is conducive to increasing the traffic efficiency. With the increase of speed, the headway of the NVTH strategy is significantly increased to ensure the driving safety and avoid the risk of rear-end crashes. The headway under the VTH strategy does not show a parabolic trend since there are only few samples, but it is smaller than that under the CTH strategy.

3.1.2 Scenario B – full CACC vehicle fleet: We next consider the fleet consisting of complete CACC vehicles and compare the performance of three different spacing strategies. In the CTH strategy, t_d is set as 0.5 s with respect to the operation of the CACC [1].

The simulation parameters are set as $K_a = 1$ and $c_k = 0.4$ veh. Other parameters are same as those in Section 3.1.1.

Fig. 5 illustrates the results of the travel time histogram and delay line chart for the case of zero flow on ramps. The mainline input is set to 3000 veh/h. We count 50 CACC vehicles numbered 801–850. Fig. 6 illustrates the results of the case of the on-ramp input of 600 veh/h in addition to the mainline input and 20% vehicles exiting at the off-ramp. We count 50 CACC vehicles numbered 890–939. The results of three strategies are summarised in Table 2. From Figs. 5 and 6, and Table 2, we can see that the NVTH strategy reduces the travel time in comparison with other two strategies and the reduction is more obvious for the case of non-zero flow on ramps. This result indicates that the control algorithm using the NVTH strategy for the CACC vehicles has a certain role in improving traffic efficiency on the basis of ensuring driving safety. The delay time of three strategies is very small and the difference is not significant. It can be observed from Table 2 that the flow slightly increases for the use of the NVTH strategy. Comparing with the results in Section 3.1.1, we can see that using the NVTH strategy improves the performance of ACC and CACC systems, and the improvement is more evident for the ACC system.

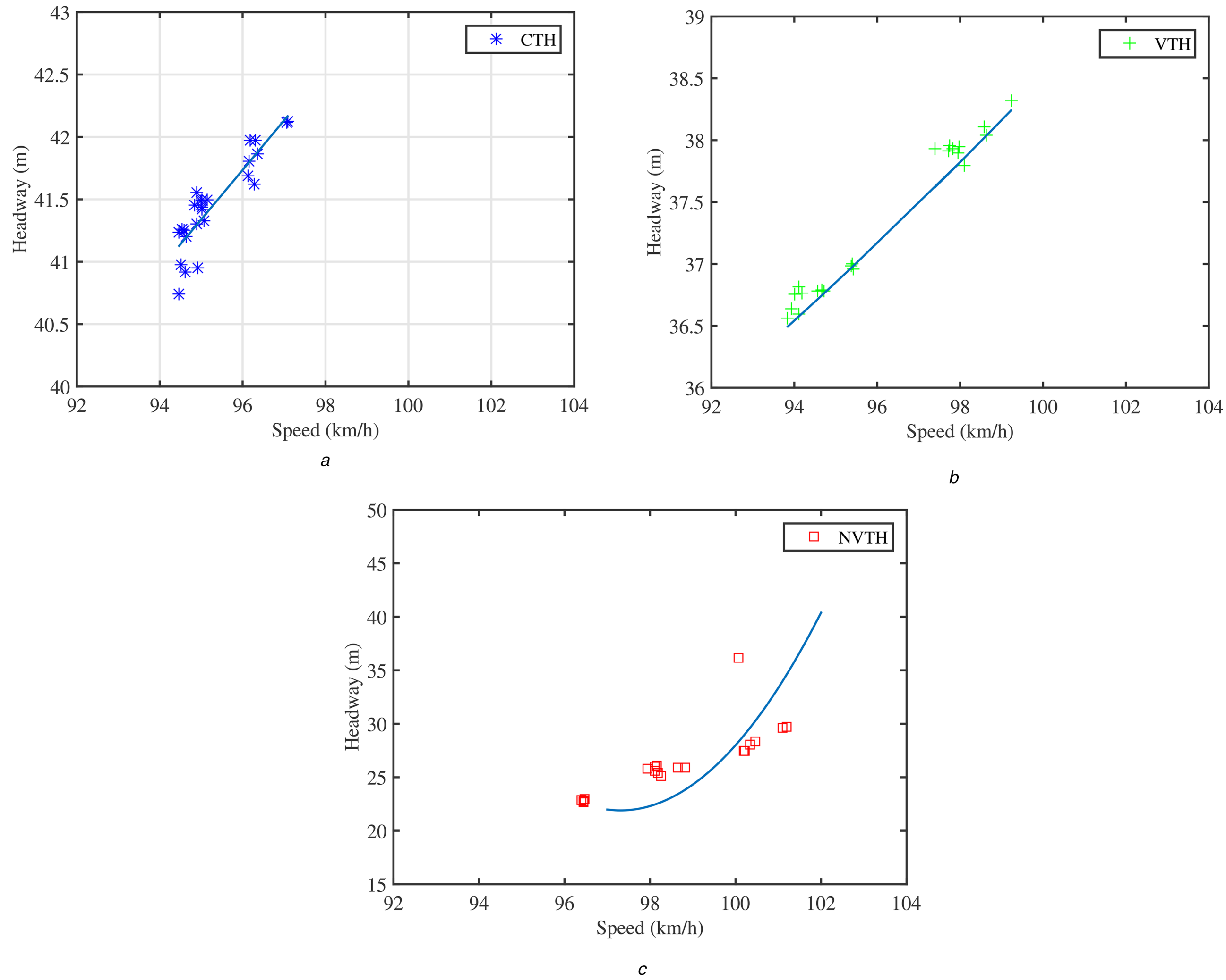

Fig. 4 *Headway-speed profile for different spacing strategies*
(a) CTH strategy, ***(b)*** VTH strategy, ***(c)*** NVTH strategy

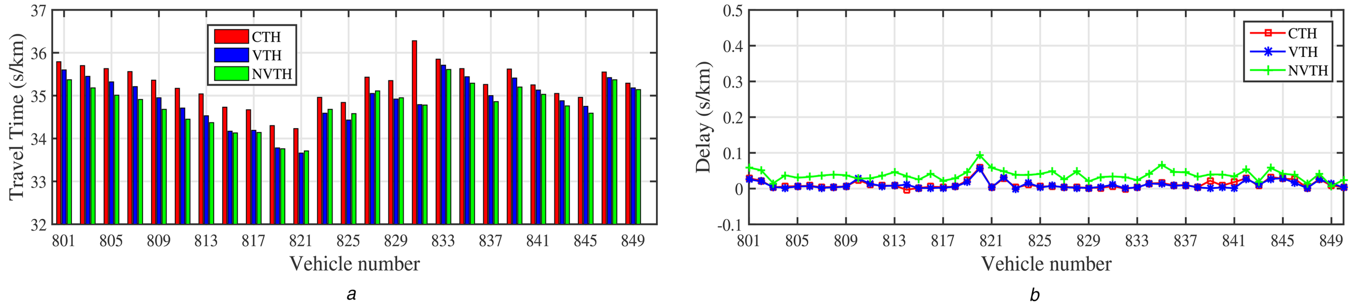

Fig. 5 *Results of full CACC vehicle fleet for zero flow on ramps*
(a) Travel time, ***(b)*** Delay

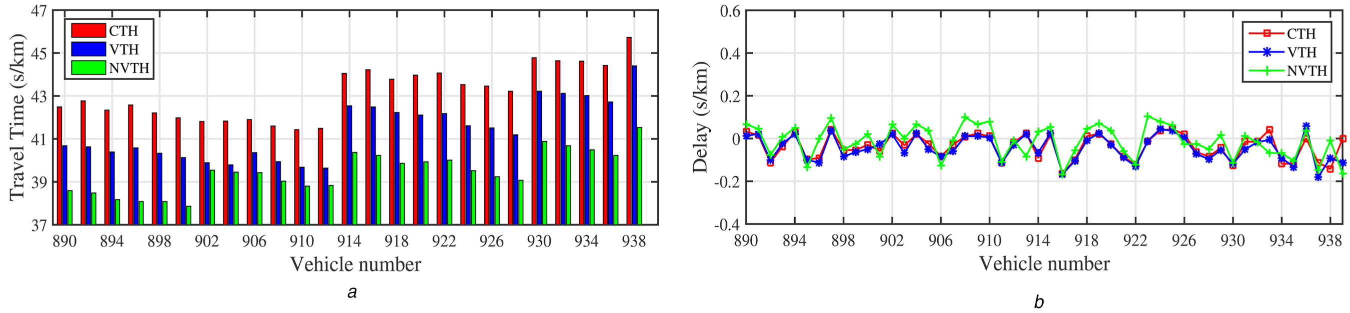

Fig. 6 *Results of full CACC vehicle fleet for non-zero flow on ramps*
(a) Travel time, ***(b)*** Delay

Table 2 Comparison of different strategies for full CACC vehicle fleet [the values in parentheses represent the relative representation of the results (%) for the VTH strategy and NVTH strategy compared with the CTH strategy]

Flow on ramps	Strategy	Travel time, s/km	Delay, s/km	Flow, veh/h
zero	CTH	35.31	0.01	3000.80
	VTH	34.87 (98.75%)	0.01	2999.20 (99.95%)
	NVTH	34.76 (98.44%)	0.04	2989.20 (99.61%)
non-zero	CTH	43.29	−0.04	3608.80
	VTH	41.48 (95.82%)	−0.04	3613.60 (100.13%)
	NVTH	39.53 (91.31%)	−0.01	3620.80 (100.33%)

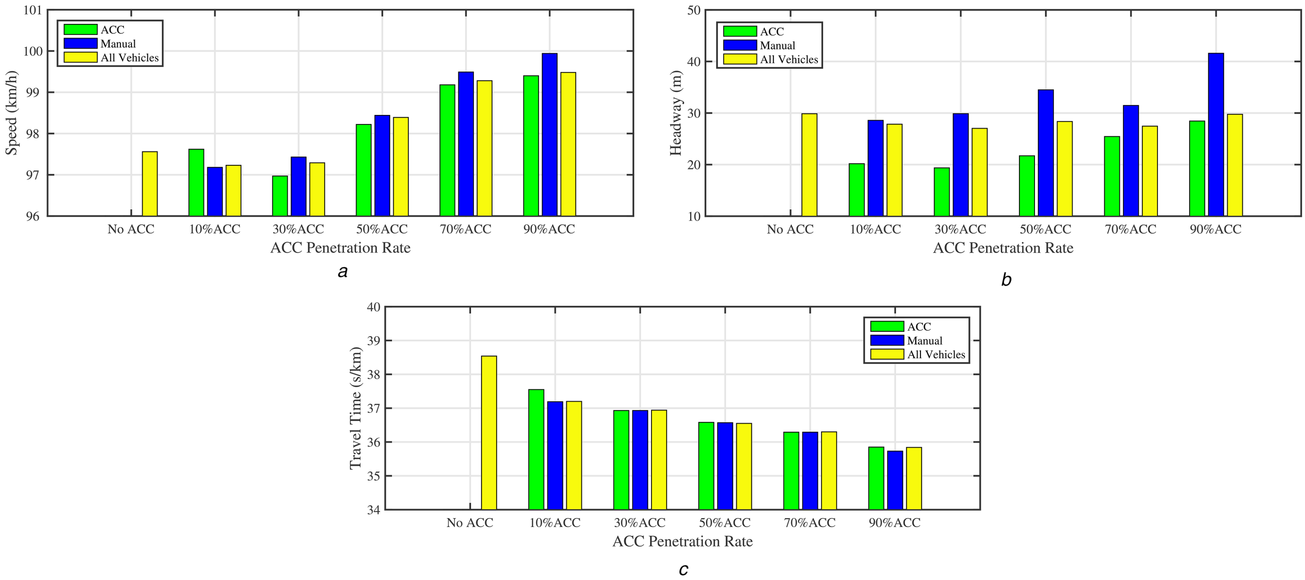

Fig. 7 *Average speed, headway and travel time with varying ACC penetration rates for ACC, manual and all counted vehicles*
(a) Average speed, ***(b)*** Average headway, ***(c)*** Average travel time

3.2 Effect of ACC/CACC vehicles on mixed traffic flow

3.2.1 Scenario A – mixed traffic with ACC vehicles and manual driving vehicles: In this subsection, we investigate the effect of the ACC penetration rate on the mixed traffic flow of ACC and manual vehicles. The NVTH strategy (4) is used in the control algorithm of ACC vehicles. The input flow on the mainline is 2200 veh/h. The flow on the ramps is zero. We count totally 50 ACC/manual vehicles numbered 596–645 under each penetration rate.

Fig. 7 shows the results of the average speed, headway and travel time with varying ACC penetration rates for ACC, manual and all counted vehicles. It can be seen from Fig. 7*a* that the average speed of manual vehicles increases and the average speed of ACC and all vehicles shows an obvious upward trend as the penetration rate of ACC vehicles increases. With the increase of the penetration rate of ACC vehicles, the headway (see Fig. 7*b*) of ACC vehicles first exhibits a downward trend and then an upward trend. The headway is increased to ensure the driving safety as the speed increases. From Fig. 7*c*, we can see that the average travel time of ACC and all vehicles distinctly decreases from 37.55 to 35.85 s/km and 38.54 to 35.84 s/km, respectively, as the penetration rate of ACC vehicles increases. The travel time of manual vehicles decreases from 37.19 to 35.73 s/km in the case of mixing. These results show that the increase of ACC vehicles' penetration rate can improve road capacity and alleviate traffic congestion status.

Fig. 8 shows the results of delay characteristics under different mixture ratios. From Fig. 8*a*, we can see that the overall average delay of mixed fleet can be reduced by up to 93% compared with that of full manual vehicles. As the penetration rate of ACC vehicles increases, the overall average delay of the mixed fleet (see Fig. 8*b*) has dropped significantly from 4.84 to 0.33 s, and the average delay of ACC vehicles has always been close to 0. In addition, the standard deviation (SD) of overall delay (see Fig. 8*c*) of mixed fleet also shows a downward trend, which indicates the traffic delay not only drastically decreases but also gradually maintains a stable and small value. In short, it is verified by this indicator that increasing the penetration rate of ACC vehicles can effectively improve the stability of traffic flow.

3.2.2 Scenario B – mixed traffic with CACC vehicles and manual driving vehicles: In this subsection, we study the effect of the CACC penetration rate on the mixed traffic flow of CACC and manual vehicles. The NVTH strategy (4) is applied in the control algorithm of CACC vehicles. The input flow on the mainline is 2200 veh/h. The flow on the ramps is zero. We count totally 50 CACC/manual vehicles numbered 596–645 under each mixture ratio.

Fig. 9 shows the simulation results of the average speed, headway, travel time and delay with varying CACC penetration rates for CACC, manual and all counted vehicles. It is observed from Fig. 9*a* that as the penetration rate of CACC vehicles increases, the average speed of manual and all vehicles increases. The average speed of CACC vehicles shows an obvious upward trend. With the increase of the penetration rate of CACC vehicles, the overall headway (see Fig. 9*b*) of the mixed fleet decreases, which indicates the gap between the following vehicle and the preceding vehicle can be further closed. When the penetration rate of CACC vehicles increases, the average travel time (see Fig. 9*c*) of CACC and manual vehicles decreases from 37.40 to 35.37 s/km and from 37.09 to 34.94 s/km in the case of mixing, respectively. The mean value of the overall travel time also decreases from 38.54 to 35.32 s/km. As the penetration rate of CACC vehicles increases, the overall average delay (see Fig. 9*d*) of the mixed fleet has dropped significantly from 4.84 to 0.29 s/km and the average delay of CACC vehicles has always been close to 0. In short, increasing the penetration rate of CACC vehicles in mixed fleet can improve traffic efficiency and traffic flow stability.

Figs. 10 and 11 show the results of the mixture of CACC and manual vehicles compared with that of ACC and manual vehicles. We compare differences through five indicators. In two mixed

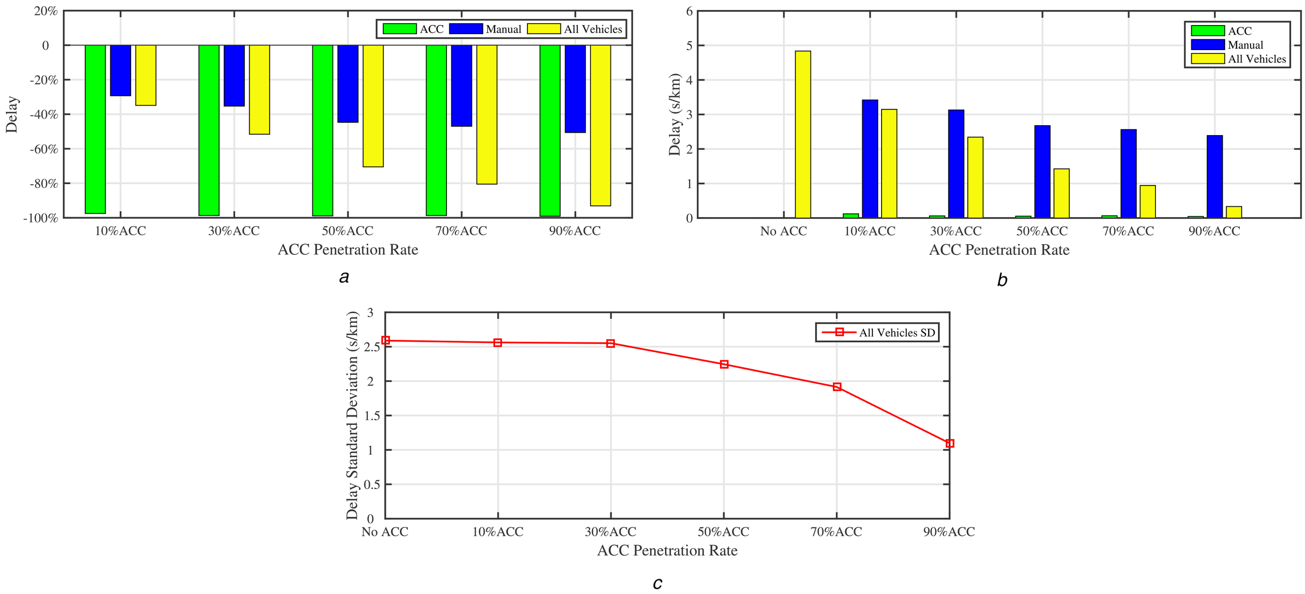

Fig. 8 *Delay characteristic changes with varying ACC penetration rates*
(a) Percent change in delay compared with the average delay for no ACC case, ***(b)*** Average delay, ***(c)*** Delay SD of all counted vehicles

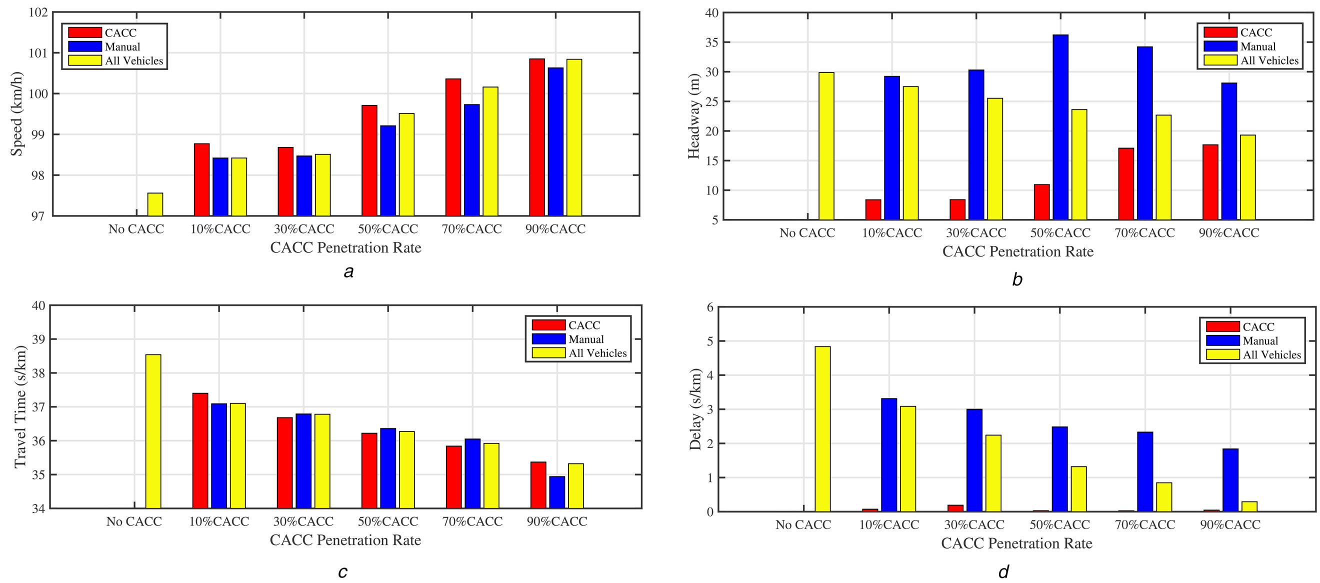

Fig. 9 *Average speed, headway, travel time and delay with varying CACC penetration rates for CACC, manual and all counted vehicles*
(a) Average speed, ***(b)*** Average headway, ***(c)*** Average travel time, ***(d)*** Average delay

cases, the speed shows an upward trend but the speed is larger for the former case (see Fig. 10*a*). Under the same penetration rate, the headway for the former case is smaller than that for the latter case (see Fig. 10*b*). In two cases, the travel time curve has a downward trend and the travel time is slightly smaller for the former case (see Fig. 10*c*). Both the overall average delay and delay SD show the downward trend (see Fig. 11). Moreover, under the same penetration rate the value of the indicator for the former case is slightly smaller than that for the latter case. The results of Figs. 10 and 11 demonstrate the advantages of mixing CACC vehicles.

3.2.3 Scenario C – multi-types mixing of ACC, CACC and manual driving vehicles: This subsection studies the mixing of ACC, CACC and manual driving vehicles when the NVTH strategy (4) is applied in the ACC/CACC control algorithms. The input flow on the mainline is 2200 veh/h. The flow on the ramps is zero. We focus on the effect of different penetration rates of ACC vehicles, thus the preset value of the penetration rate of CACC vehicle is maintained at 10% during the simulation process. The initial penetration rate of ACC vehicles is 0% with a gradual increase from 10 to 90%, and the proportion of manual driving vehicles is opposite.

We count totally 50 ACC/CACC/manual vehicles numbered 596–645 under each mixture ratio. For analysing the multi-types mixed traffic flow characteristics, Fig. 12 shows the simulation results of average speed, headway, travel time and delay with varying for CACC, ACC, manual and all counted vehicles. It is observed from Fig. 12*a* that as the penetration rate of ACC vehicles increases, the average speed of ACC, CACC, manual and all counted vehicles in multi-types mixed fleet shows an upward trend. When the ACC penetration rate is 90%, the average speed of ACC and CACC vehicles has a certain decrease. With the increase of the penetration rate of ACC vehicles, the headway of ACC vehicles increases (see Fig. 12*b*), which corresponds to the increase of speed to ensure the driving safety. When the penetration rate of ACC vehicles increases, the average travel time of ACC, CACC, manual and all vehicles decrease (see Fig. 12*c*). Increasing the penetration rate of ACC vehicles, the overall average delay of multi-types mixed fleet (see Fig. 12*d*) drops drastically from 3.07 to 0.04 s/km. Compared with the scenarios A and B discussed, respectively, in Sections 3.2.1 and 3.2.2, the overall average delay is smaller in this scenario. Furthermore, the average delay of ACC and CACC vehicles are kept at around 0.05 and 0.07 s/km, respectively.

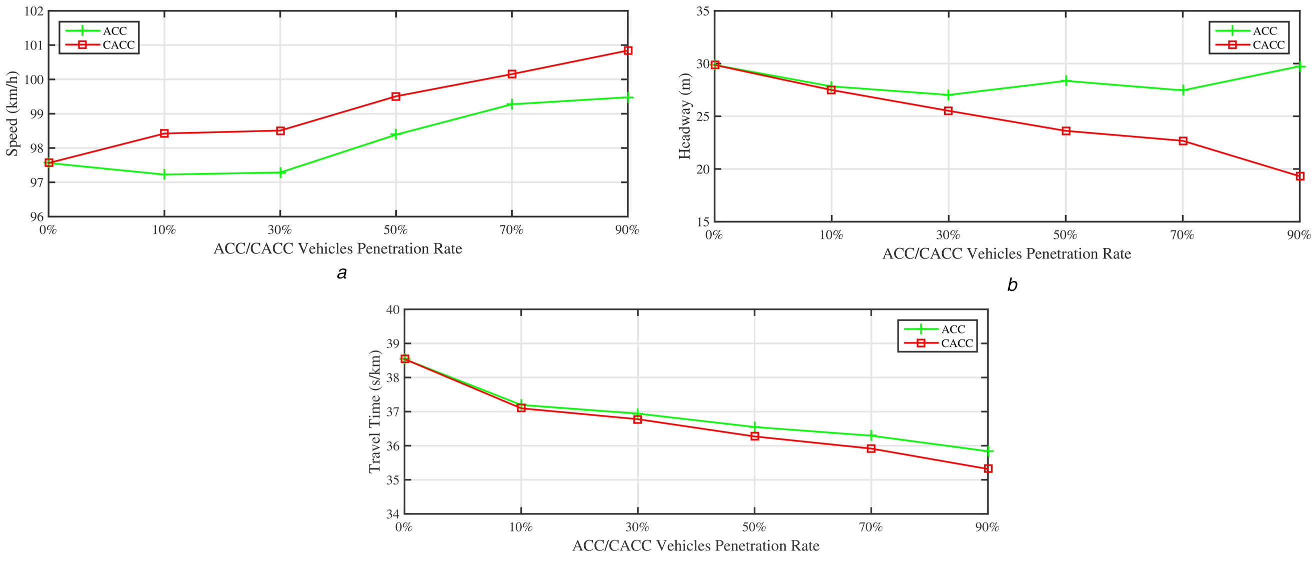

Fig. 10 *Comparison of ACC and CACC about speed, headway and travel time in mixed situations*
(a) Change in overall average speed, ***(b)*** Change in overall average headway, ***(c)*** Change in overall average travel time

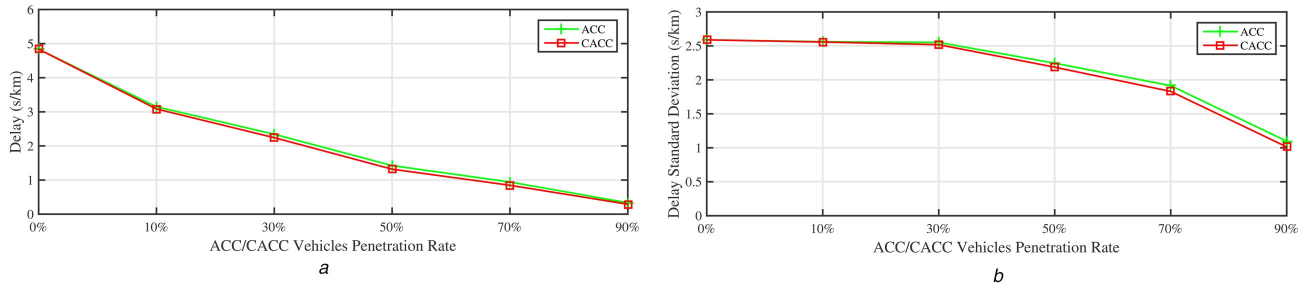

Fig. 11 *Comparison of ACC and CACC about delay in mixed situations*
(a) Change in overall average delay, ***(b)*** Change in overall average delay SD

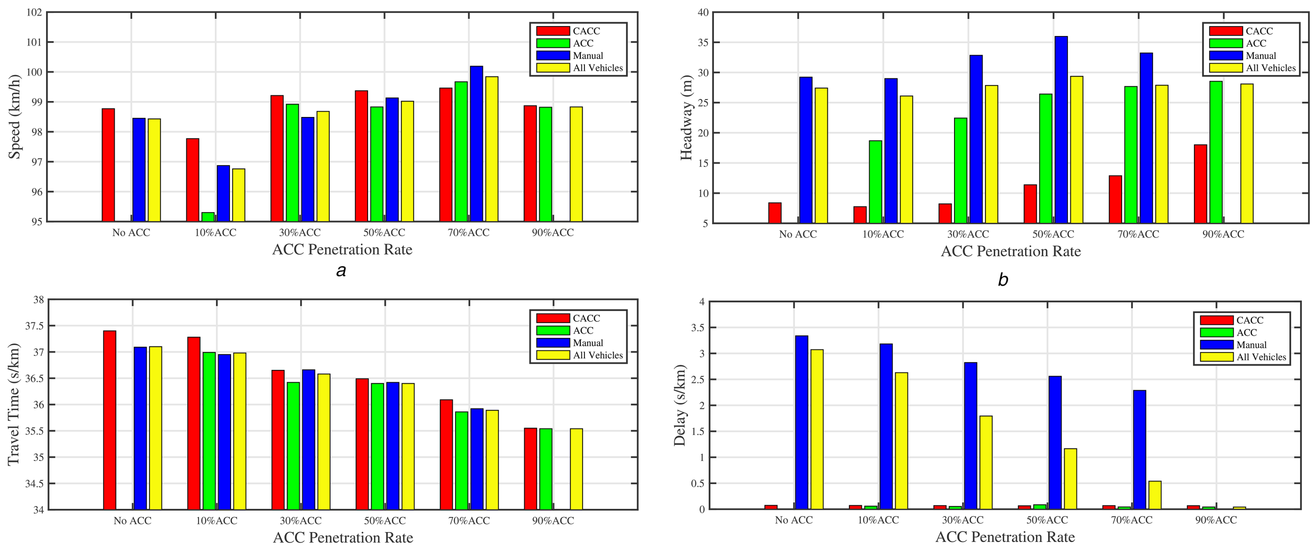

Fig. 12 *Average speed, headway, travel time and delay with varying ACC penetration rates for ACC,CACC, manual and all vehicles*
(a) Average speed, ***(b)*** Average headway, ***(c)*** Average travel time, ***(d)*** Average delay

In short, increasing the penetration rate of ACC vehicles in multi-types mixed fleet can effectively improve traffic efficiency and traffic flow stability.

4 Conclusions

In this paper, we have designed an improved VTH strategy for the ACC/CACC control system. The strategy combines the speed, speed difference, free flow speed, jam density and the preceding vehicle acceleration. Moreover, we have investigated the impacts of ACC and CACC vehicles on mixed traffic flow.

We have adopted two traffic scenarios: full ACC vehicle fleet and full CACC vehicle fleet, to test the improved VTH strategy which is compared with the CTH strategy and the VTH strategy [9]. For the scenario of full ACC vehicle fleet, the simulation results show that the travel time and traffic delay of using the NVTH strategy is smaller than that of using the VTH strategy, and the latter is smaller than that of using the CTH strategy. Compared with the CTH strategy, both the NVTH strategy and the VTH strategy increase the flow for the case of non-zero flow on ramps, but the former increases more than the latter. For the scenario of full CACC vehicle fleet, the simulation results show that the NVTH strategy reduces the travel time and slightly increase the flow for the case of non-zero flow on ramps compared with other two strategies. These results illustrate the effectiveness and suitability of the improved VTH strategy relative to the CTH strategy and the VTH strategy. The results also show that the VTH strategy performs better than the CTH strategy.

We have considered three traffic scenarios to explore the effect of ACC and CACC vehicles on traffic flow. The introduction of ACC/CACC vehicles into traffic can reduce the travel time to a certain extent and increase the average speed, thereby enhancing traffic capacity. Simultaneously, it is worth noting that the decrease of traffic delay indicator also verifies that introducing the ACC/CACC vehicles can reduce traffic disturbances and improve traffic stability.

It must be pointed out that the results reported in this paper depend on the simulation experiments that imply some limitations. The values of parameters are assumed and are not calibrated by the field tests. The parametrisation of Wiedermann model used in VISSIM is also not adjusted when introducing ACC/CACC vehicles. Furthermore, the simulation results depend on a great extent to the geometry and complexity of the adopted network.

In this paper, we have verified the efficiency of the presented strategy and investigated the effect of ACC/CACC vehicles on traffic flow in a single-lane freeway. Future research should study the performance of the improved strategy and the impacts of ACC/CACC systems on traffic flow in a more complicated network with more interactions. Designing or adding a lane changing model and comparing it with one lane is one of the important aspects.

We use the Wiedemann model to mimic the movement of manual vehicles. The choice of the car-following model also affects the final simulation results. Future work will consider making a comparison with the IDM [36].

The simulation results have a lot to do with the values of parameters. Thus, future work will be devoted to the sensitivity analysis of the model's parameters, which is important for assessment purposes.

In addition, extending the present framework and studying the traffic conflict to include an indicator of safety [24] is the subject of future research in order to better assess the performances of the NTVH strategy.

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