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A new adaptive cruise control strategy and its stabilization effect on traffic flow

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Abstract

Connected and autonomous vehicle (CAV) technologies are likely to be gradually implemented over time. In this paper, an adaptive cruise control, named Smart Driver Model (SDM), is proposed to describe the autonomous vehicles flow. The stability criteria is proposed for SDM to judge the stability of homogeneous traffic flow. Numerical simulations were conducted to verify the results of the theoretical analysis. Single-lane vehicle dynamics in a traffic stream with connected and autonomous vehicles are simulated by varying model parameters. Simulation results are consistent with the results of linear stability analysis. As a result, a set of parameters is proposed to investigate the stabilization effect of the proposed model on homogeneous traffic flow considering realistic driving cycle and cut-in condition. By simulating a platoon with a lead vehicle which follows the Urban Dynamometer Driving Schedule (UDDS), we find out that the proposed model can stabilize the traffic flow with proposed parameters. The results from simulation and linear stability analysis show that SDM outperforms the IDM-ACC and the ACC proposed by Milanés and Shladover in terms of stabilization effect on homogeneous traffic flow. The simulation result shows that the SDM-equipped vehicles are able to stabilize the homogeneous traffic flow under cut-in condition.

Keywords: Autonomous vehicle, Adaptive cruise control, Traffic flow stability

1 Introduction

Connected and autonomous vehicle (CAV) technologies have gained a lot of attention all over the world because of its potential in improving safety and congestion of the road transportation system. In particular, adaptive cruise control (ACC) is one of the most important CAV technologies that can enhance driving comfort, reduce driving errors, improve safety, increase traffic capacity and reduce fuel consumption [1].

Existing ACC methods are categorized into optimization-based ACCs, artificial intelligence technique-based ACCs and rule-based ACCs. Considering the fuel efficiency, signalized intersection, and road geometry, several optimization-based ACCs have been developed [2–6]. Naranjo et al. [7] proposed an ACC based on artificial intelligence techniques. Moreover, existing rule-based ACCs are based on three main headway selection policies: Constant Space-Headway (CSH), Constant Time-Headway (CTH) and Variable Time-Headway (VTH) [8]. CSH is not string stable and not suitable for ACC systems [9–11]. Among these three headway selection policies, the ACCs based on CTH are most closely related to normal manual car-following behavior. Moreover, Swaroop et al. [12] pointed out that the control design and stabilization challenges of the CTH-based car following criteria are significantly easier for other rule-based car-following models. As a result, in this paper, we focus on rule-based ACCs with constant time headway policies.

Several rule-based ACC methods have been proposed in the literature. Davis [13] proposed an ACC that automatically maintained a safe distance and minimized the speed difference between the following vehicle and its immediate preceding vehicle. Kesting et al. [14] proposed an ACC based on intelligent driver model (IDM) and inherited its intuitive parameters proposed by Treiber et al. [15]. The ACC proposed by Kesting et al. partially eliminates the unrealistic behavior of IDM in cut-in situations. However, since the ACC proposed by Kesting et al. inherits the instability of IDM under homogenous traffic flow condition [16]. Moreover, an ACC, which is proprietary to Nissan, was described by Shladover et al. [17]. Since this ACC is simplified

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representation for computation efficiency in simulation, it is not able to describe the ACC car-following behavior in the field test. Consequently, Milanés and Shladover [18] developed an ACC system to match the experimental result obtained from the production vehicle road tests. However, their research did not consider the stability in multi-car following scenarios.

By modeling ACC-equipped vehicles' behavior, the impact of ACC on traffic flow is widely studied [10, 19, 20]. Davis showed that the traffic congestions are not formed when the ACC-equipped vehicle reaches 20% [13]. Kesting et al. reported that the traffic congestion was completely eliminated when the share of the ACC-equipped vehicle reaches 25% [14]. Jerath and Brennan reported that the highway capacity drastically increases when the percentage of the ACC-equipped vehicle approaches 100% [21]. Moreover, by simulating a mixed traffic consisting of ACC-equipped and manually driven vehicles, Jiang et al. found that the introduction of ACC-equipped vehicles would enhance the free flow stability [22]. Yuan et al. investigated the transition probability from the synchronized flow to congestion and pointed out that ACC-equipped vehicles enhance the traffic stability of synchronized flow [23].

Consequently, scholars paid a lot of attention to the stabilization effect of ACC-equipped vehicles on traffic flow. Darbha and Rajagopal [11] mathematically investigated the stability of an intelligent cruise control system with a constant time headway policy and provided a framework for designing cruise control laws. Liang and Peng [10] proposed a framework to analysis string-stability of a string with ACC-equipped vehicles and human-driven vehicles. Davis [24] investigated the effect of vehicle response time and delay on string stability of adaptive cruise control systems. Later, Davis [25] investigated the impact of mechanical response of the dynamics and string stability of a platoon of adaptive cruise control vehicles. Hu et al. [26] derived a stability criteria of a platoon of ACC-equipped vehicles with actuator lag and sensor delay. Considering different models with the technology-appropriate assumption, Talebpour and Mahmassani [16] proposed a framework to investigate the impact of the connected and autonomous vehicle on traffic flow stability. Moreover, Davis [25] investigated the impact of mechanical response on string stability of a platoon of ACC-equipped vehicles. Considering the delay, Xing et al. [27], Wang et al. [28] and Besselink and Johansson [29] proposed appropriate control strategies to enhance string stability of ACC-equipped vehicle platoon. Moreover, Li et al. [30] proposed an extended intelligent driver model and analyzed the stability against a small perturbation by use of the linear stability method for the proposed model on a single lane. They found that the traffic flow stability can be improved by increasing the proportion of the direct power cooperation of the preceding vehicle. Recently, Wen-Xing and Li-Dong [31] proposed two lemmas and one theorem as criteria to judge the stability of homogeneous autonomous vehicles flow.

Among existing studies, most of the existing rule-based adaptive cruise control strategies are derived based on the human driver models, such as Intelligent Driver Model [15], Full Velocity Difference Model [32] and Optimal Velocity Model [33]. These adaptive cruise control strategies may inherit the limitation of the human driver models, such as instability [16, 34] and unrealistic behavior [13, 15, 33]. In this paper, we propose a rule-based adaptive cruise control to improve the stability and behavior of Intelligent Driver Model [15]. The stabilization effect of the proposed adaptive cruise control on traffic flow is discussed theoretically. Moreover, in order to estimate the performance of the proposed ACC, the stabilization effect of the proposed adaptive cruise control is compared with existing models.

The rest of the paper is organized as follows: section 2 presents the proposed adaptive cruise control strategy. The linear stability analysis of the proposed model is represented in Section 3. Section 4 provides results from simulating single-lane vehicle dynamics with or without cut-in scenarios. The conclusions and limitations are presented in Section 5.

2 Smart driver model

In the past decades, numbers of car-following models have been introduced to simulate manually driven vehicle, such as Multi-anticipative Model [35], Tampere Model [36], Newell Model [37], Gipps Model [38], Full Velocity Difference Model [32] and Optimal Velocity Model [33]. Based on Gipps model, Treiber et al. proposed a human driver model named Intelligent Driver Model (IDM) [15]. By capturing different congestion dynamics, IDM provides greater realism than most of the deterministic acceleration modeling frameworks [16]. The IDM is formulated as follows:

$$a^n_{IDM} = a_{max}\left[1-\left(\frac{v_n}{v_0}\right)^{\delta}-\left(\frac{s^*}{\Delta x}\right)^2\right] \tag{1}$$

$$s^* = s_0 + v_n T + \frac{v_n(v_n-v_{n-1})}{2\sqrt{a_{max}b}} \tag{2}$$

where,

a^n_{IDM} is the acceleration of the following vehicle based on Intelligent Driver Model (m/s^2);

δ is the acceleration exponent;

s_0 is the standstill distance between stopped vehicles (m);

a_{max} is the maximum acceleration (m/s^2), which is predetermined and less than the Planck acceleration;

Δx is the gap between the leading and the following vehicle (m);

T is the desired time gap (s);

v_0 is the maximum speed (m/s);

v_n is the speed of the following vehicle (m/s);

v_{n-1} is the speed of the leading vehicle (m/s);

s^* is the desired gap (m); and.

b is the desired deceleration (m/s^2).

In recent years, car-following models have evolved to describe the behavior of vehicles with advanced cruise controls, which take advantage of the sensing and vehicle to vehicle/vehicle to infrastructure (V2*V*/V2I) communication technologies. By using constant-acceleration heuristic (CAH) as an indicator, Kesting et al. proposed a rule-based adaptive cruise control based on IDM [34] (IDM-ACC). The ACC proposed by Kesting et al. partially eliminates the unrealistic behavior of IDM in cut-in situations. However, since the ACC proposed by Kesting et al. inherits its intuitive behavioral parameters of IDM, it inherits the instability of IDM under homogenous traffic flow condition [16].

A rule-based ACC, named Smart Driver Model (SDM) is proposed to address the instability of IDM under homogenous traffic condition. In this study, a single-lane car-following scenario is considered and the lane changing behavior is ignored. In this paper, we assume that on-board sensors measure vehicle speed, gap (relative distance) and relative speed with respect to the preceding vehicle on regular time intervals [28].

The acceleration of the following vehicle equipped with SDM is determined by the following equation:

$$a_{SDM}^n = a_{max}\left[1-\left(\frac{v_n}{v_0}\right)^{\delta}\right] - \frac{a_{max}\left[1-\left(\frac{v_n}{v_0}\right)^{\delta}\right] + \frac{v_n^2-v_{n-1}^2}{2\Delta x}}{exp\left(\frac{\Delta x}{s_0+v_n\times T}-1\right)} \tag{3}$$

where,

a_{SDM}^n is the acceleration of the following vehicle that is equipped with SDM (m/s^2);

According to Eq. 1, SDM inherits the acceleration maneuver from Intelligent Driver Model [15]. As a result, the acceleration exponent is set as 4 according to existing studies [15, 34, 39]. Therefore, the vehicles equipped with SDM tend to accelerate with $a_{max}[1-(\frac{v_n}{v_0})^4]$ when Δx is large. An SDM-equipped vehicle will brake while the speed of the SDM-equipped vehicle is greater than the leading vehicle speed and Δx is less than the desired spacing. $\frac{a_{max}[1-(\frac{v_n}{v_0})^{\delta}]+\frac{v_n^2-v_{n-1}^2}{2\Delta x}}{exp(\frac{\Delta x}{s_0+v_n\times T}-1)}$ is used to describe the deceleration maneuver. In the deceleration term, $a_{max}[1-(\frac{v_n}{v_0})^{\delta}]$ is used to offset the acceleration term. Moreover, considering the range policy, it ensures that the real deceleration is equal to or slight larger than the expected deceleration, which is $\frac{v_n^2-v_{n-1}^2}{2\Delta x}$. Moreover, since $\exp(\cdot)>0$ and $\exp(0)=1$, $\frac{1}{\exp(\frac{\Delta x}{s_0+v_n\times T}-1)}$ is applied to describe the dependence of deceleration term on the ratio between actual spacing and desired spacing. Therefore. when there is no speed difference between the leading and following vehicle, a SDM-equipped vehicle 's acceleration increases with the ratio of Δx to the desired spacing. According to the characteristics of the exponential function, the jerk of SDM-equipped vehicle, which represents the changing rate of SDM-equipped vehicle 's acceleration, decreases with the ratio of Δx to the desired spacing. Consequently, the vehicle equipped with SDM can achieve smoother acceleration and deceleration which is able to stabilize the traffic flow.

Several properties of SDM are discussed as follows, considering special cases:

First, when SDM-equipped vehicle is cruising (i.e. $a_{SDM}^n=0, v_n-v_{n-1}=0$), the speed-dependent spacing Δx between the preceding and the following vehicle is given by

$$\Delta x = s_0 + v_n \times T \tag{4}$$

The speed-dependent spacing Δx equals to the desired spacing, that is, $\Delta x = s_0 + v_n \times T$.

Second, when the traffic density is low (i.e. Δx is much larger than the desired spacing), SDM-equipped vehicles will accelerate to the maximum speed. When the leading vehicle is out of the detection range of SDM-equipped vehicle ($\Delta x \to \infty$), $\frac{v_n^2-v_{n-1}^2}{2\Delta x}$ is close to 0 and $e^{(\frac{\Delta x}{s_0+v_n\times T}-1)}$ is close to infinity. As a result, the acceleration of SDM is approximately equal to the maximum acceleration, $a_{SDM}^n \approx a_{max} \times [1-(\frac{v_n}{v_0})^4]$. After the speed of the SDM-equipped vehicle reaches the maximum speed, acceleration of SDM is 0.

Third, when SDM-equipped vehicle is following a slower vehicle or approaching a stopped vehicle (i.e. $v_n - v_{n-1} > 0$) with the limited spacing ($\Delta x \to s_0 + v_0 \times T$), the acceleration equation of SDM is given by

$$a_{SDM}^n \to -\frac{v_n^2-v_{n-1}^2}{2(s_0+v_n\times T)} \tag{5}$$

Especially, when a SDM-equipped vehicle with the maximum speed approaches a stopped vehicle (i.e. $v_n = v_0$, $v_{n-1} = 0$), the maximum kinematic deceleration is applied to avoid a collision, as follows.

$$a_{\mathrm{SDM}}^{\mathrm{n}} = -\frac{v_0^2}{2(s_0 + v_0 \times T)} \tag{6}$$

Forth, when the spacing is much smaller than the desired spacing ($\Delta x \ll s_0 + v_0 \times T$) and there is no significant speed differences ($v_n - v_{n-1} \approx 0$), the acceleration is determined as follows:

$$a_{SDM}^{n} \approx a_{\max}\left(1-\frac{1}{e^{\left(\frac{\Delta x}{s_0+v_n\times T}-1\right)}}\right) \tag{7}$$

Especially, when $\Delta x \to 0$, Eq. 5 reduces to

$$a_{SDM}^{n} \approx a_{\max}(1-e) \tag{8}$$

3 Linear stability analysis

Linear stability method is widely applied to analyze the stabilization performance of car-following models [40–47]. In this section, we apply the linear stability method for the Smart Driver Model described in the last section. The general form of time-continuous car-following models is

$$\ddot{x}_n(t+\tau) = f(v_n(t), s_n(t), \Delta v_n(t)) \tag{9}$$

Where,
f is a general nonlinear function;
$\ddot{x}_n(t)$ is the acceleration;
τ is the time delay;
$v_n(t)$ is the speed of vehicle n;
$s_n(t)$ is the spacing between vehicles n and n + 1; and.
$\Delta v_n(t)$ is the relative velocity between vehicles n and n + 1.

Moreover, the steady state of Eq. 1 is set as

$$\overline{x_n}(t) = (N-n)s_e + v_e t, n = 1, 2, 3, \ldots, N \tag{10}$$

Where,
s_e is the spacing of adjacent vehicles in homogenous flow;
N is the total number of vehicles in homogenous flow;
v_e is the speed of vehicles in homogenous flow; and.
$\overline{x_n}(t)$ is the location of vehicle n at time t.

Moreover, $y_n(t)$ is introduced as a small perturbation from the steady state solution of the vehicle n at time t with the linear Fourier-mode expanding:

$$y_n(t) = x_n(t) - \overline{x_n}(t), y_n(t) \to 0 \tag{11}$$

By taking the second derivative of Eq. 9, we can obtain

$$\ddot{y}_n(t+\tau) = \ddot{x}_n(t+\tau) - (\overline{x_n}(t+\tau))'' = \ddot{x}_n(t+\tau) \tag{12}$$

By substituting Eq. 7 into Eq. 10, we have

$$\ddot{y}_n(t+\tau) = f(v_n(t), s_n(t), \Delta v_n(t)) \tag{13}$$

By linearizing Eq. 11, we get the following equation

$$\begin{aligned}\ddot{y}_n(t+\tau) = f_v \dot{y}_n(t) + f_s(y_n(t) - y_{n-1}(t)) \\ + f_{\Delta v}(\dot{y}_n(t) - \dot{y}_{n-1}(t))\end{aligned} \tag{14}$$

Where $f_v = \frac{\partial f}{\partial v_n}\big|_{(v_e, s_e, 0)} \le 0$, $f_{\Delta v} = \frac{\partial f}{\partial \Delta v_n}\big|_{(v_e, s_e, 0)} \le 0$, and $f_s = \frac{\partial f}{\partial s_n}\big|_{(v_e, s_e, 0)} \ge 0$.

We rewrite Eq. 12 to obtain the difference equation

$$\begin{aligned}y_n(t+2\tau) - \dot{y}_n(t+\tau) = \tau f_s(y_n(t) - y_{n-1}(t)) + f_v(y_n(t+\tau) - y_n(t)) \\ + f_{\Delta v}(y_n(t+\tau) - y_n(t) - y_{n-1}(t+\tau) + y_{n-1}(t))\end{aligned} \tag{15}$$

By substituting $y_n(t) = ce^{ia_k n + zt}$ into Eq. 13, we have

$$(e^{\tau z} - 1)\left[e^{\tau z} z - f_v - f_{\Delta v}\left(1 - e^{-2ia_k}\right)\right] = \tau f_s\left(e^{-ia_k} - 1\right) \tag{16}$$

Where c is constant, $a_k = 2\pi k/N (k = 0, 1, \ldots, N-1)$.

By expanding $z = z_1(ia_k) + z_2(ia_k)^2 + \ldots$, $e^{\tau z} = 1 + \tau z + \frac{\tau^2 z^2}{2} + \cdots$, and inserting it into Eq. 13, then the first order and second order terms of coefficients of the expression of z are described as follows

$$z_1 = \frac{f_s}{f_v} \tag{17}$$

$$z_2 = \frac{\left(1 - \frac{\tau}{2} f_v\right) z_1^2 - f_{\Delta v} z_1 - \frac{1}{2} f_s}{f_v} \tag{18}$$

If $z_2 < 0$, the homogenous traffic flow is unstable. Alternatively, If $z_2 > 0$, the homogenous traffic flow is stable. Therefore, the stability condition is described as follows

$$Stability = \frac{1}{2} f_v^2 - f_s + f_v f_{\Delta v} + \frac{\tau}{2} f_v f_s > 0 \tag{19}$$

This stability condition is consistent with existing studies [30, 48].

In order to investigate the stabilization effect of the SDM model on homogeneous traffic flow, we have

$$a_{SDM}^{n} = a_{max}\left[1-\left(\frac{v_n}{v_0}\right)^{\delta}\right]-\frac{a_{max}\left[1-\left(\frac{v_n}{v_0}\right)^{\delta}\right]+\frac{v_n^2-v_{n-1}^2}{2\Delta x}}{exp\left(\frac{\Delta x}{s_0+v_n\times T}-1\right)}$$

$$f_s = \frac{a_{\max}\left[1-\left(\frac{v_e}{v_0}\right)^4\right]}{(s_0+v_e\times T)} \tag{20}$$

$$f_{\Delta v} = -\frac{v_e}{(s_0+v_e\times T)} \tag{21}$$

$$f_v = -\frac{a_{\max}T}{(s_0+v_e\times T)}\left[1-\left(\frac{v_e}{v_0}\right)^4\right]-\frac{8a_{max}v_e^3}{v_0^4} \tag{22}$$

By substituting Eqs. 18–20 into Eq. 17, the stable condition is derived as follows

$$\frac{\tau}{2}<\frac{1}{2}\frac{\left(\frac{a_{max}T}{(s_0+v_e\times T)}\left[1-\left(\frac{v_e}{v_0}\right)^4\right]+\frac{8av_e^3}{v_0^4}\right)(s_0+v_e\times T)}{a_{max}\left[1-\left(\frac{v_e}{v_0}\right)^4\right]} -\frac{1}{\left(\frac{a_{max}T}{(s_0+v_e\times T)}\left[1-\left(\frac{v_e}{v_0}\right)^4\right]+\frac{8a_{max}v_e^3}{v_0^4}\right)}+\frac{v_e}{a_{max}\left[1-\left(\frac{v_e}{v_0}\right)^4\right]} \tag{23}$$

According to Eq. 23, the phase transition curves are derived. Figure 1 shows the neutral stability curves for different time delays, where the maximum acceleration a = 1.4 m/s^2, maximum speed v_0 = 30 m/s, and the standstill distance s_0 = 1.5 m. The traffic flow is stable with uniform velocity steady state above the neutral stability line; conversely, the traffic is unstable and the traffic congestion emerges. From Fig. 1, one can observe that the neutral stability line moves up with the increase of time delay. The effect of the stability of traffic flow by considering the time delay can be further illustrated in Fig. 2, where the average speed v_e = 4 m/s, maximum speed v_0 = 30 m/s, and the standstill distance s_0 = 1.5 m. Same as in the study conducted by Van Arem et al. [49], the maximum comfortable acceleration is 2 m/s^2. From Fig. 2, one can see that by increasing the maximum acceleration a, the neutral stability curve changes down, which means that traffic flow will become more and more stable if the maximum acceleration of SDM-equipped vehicle increases, i.e., the traffic stability can be improved by raising the maximum acceleration. However, by increasing the maximum acceleration may make driving less comfortable. The improvement in traffic stability by decreasing the time delay also can be found here.

According to Eq. 19, the stability of SDM is compared with IDM-ACC and the ACC proposed by Milanés and Shladover [18] by using the typical parameters from literature [18, 34]. Since IDM-ACC only eliminates the unrealistic behavior of IDM in cut-in situations, the linear stability of IDM-ACC is the same as the linear stability of IDM. As shown in Fig. 3, the ACC proposed by Milanés and Shladover is unstable with the proposed parameters. Same as the result in [16], the platoon of vehicles equipped with IDM-ACC is stable for speeds below 3.5 m/s and unstable for speed above 3.5 m/s. Moreover, the stability curve of SDM is above 0. When the speed is

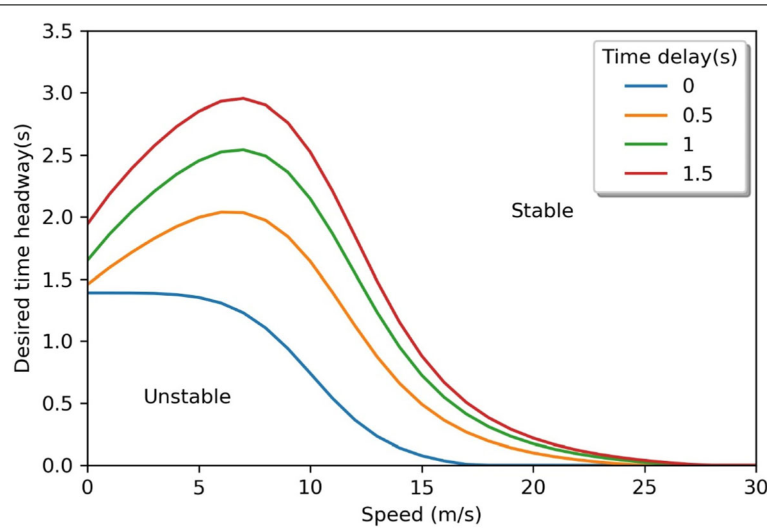

Fig. 1 Phase diagram in the velocity-desired time gap for different time delay, where the maximum acceleration a = 1.4 m/s2, maximum speed v_0 = 30 m/s, and the standstill distance s_0 = 1.5 m

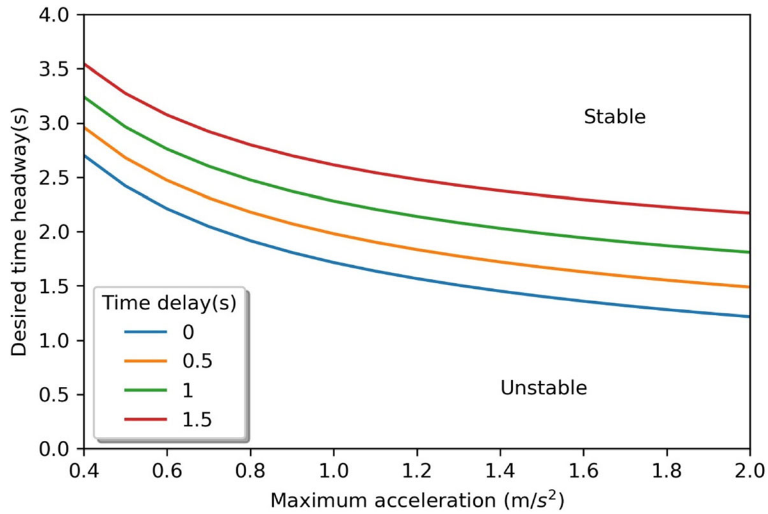

Fig. 2 Phase diagram in the Maximum acceleration-desired time gap for different time delay, where the average speed v_e = 4 m/s, maximum speed v_0 = 30 m/s, and the standstill distance s_0 = 1.5 m

larger than 3.5 m/s, SDM outperforms IDM-ACC in terms of stability.

4 Numerical simulations

4.1 Platoon without cut-in

To validate the results of our theoretical stability analysis, a platoon with 100 vehicles are simulated on a one-lane highway (no lane-changing) with an infinite length. Moreover, the time delay of ACC-equipped vehicle are ignored to investigate the stabilization performance of the proposed model under ideal conditions. Two cases are conducted in this section.

4.1.1 Case 1

A simple case is applied to investigate the impacts of desired time gap and maximum acceleration on the stabilization performance of the proposed model. Initially, the speed $v_{initial}$=10 m/s, stand still distance s_0= 1.5 m and the spacing $s_{initial}$=$s_0 + v_{initial} \times T$. The initial steady state will be broken when the leading vehicle brakes urgently from 10 to 4 m/s during the time period 10 s ≤ t ≤ 13 s, followed by the following vehicle moving according to Eq. (4). As shown in Fig. 4(a), the traffic flow is unstable when the desired time gap is less than 1.6, where the maximum acceleration is 1.4 m/s^2. Moreover, while the desired time gap is 1.6, the traffic flow is unstable when the maximum acceleration is 0.8 m/s^2.

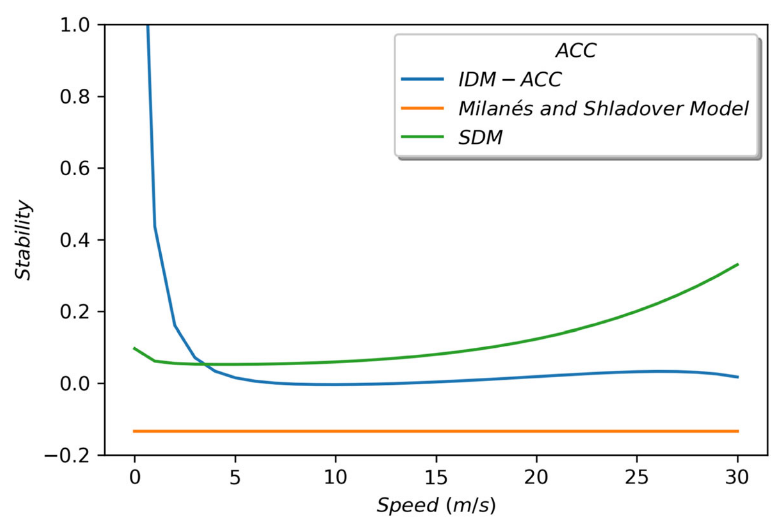

Fig. 3 Stability of vehicle with different ACCs, which is using the typical parameters from literature [18, 34]

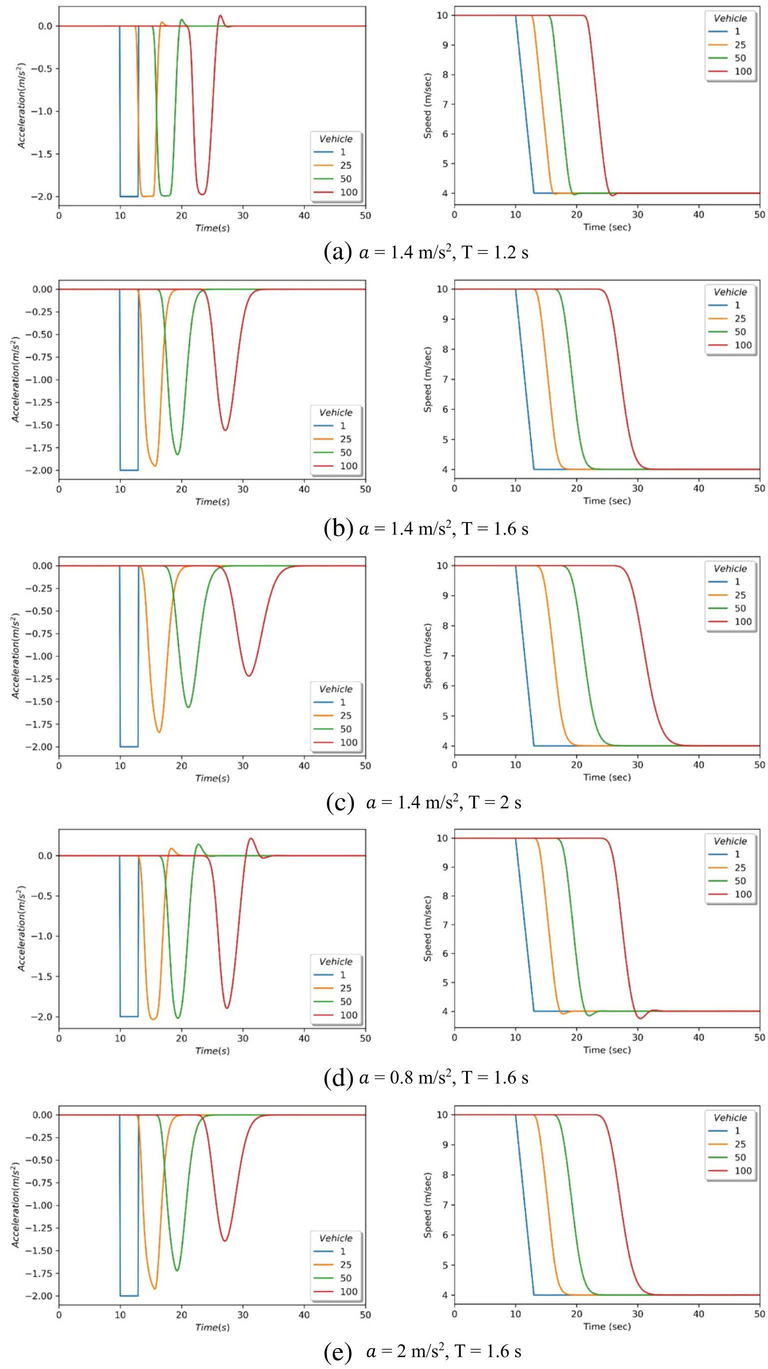

Fig. 4 Acceleration and speed profiles of 1st, 25th, 50th, and 100th vehicle for different maximum acceleration and desired time gap

The results are consistent with the results derived in last section.

4.1.2 Case 2

In order to investigate the stabilization effect of the proposed model considering the realistic driving cycle, we assume the lead vehicle of platoon follows the Urban Dynamometer Driving Schedule (UDDS), as shown in Fig. 5. Moreover, the initial spacing and time headway are the desired spacing and desired time gap, respectively. According to the result of case 1, we set the maximum acceleration a = 1.4 m/s^2, desired time gap T = 1.6 s, maximum speed v_0 = 30 m/s, and the standstill distance s_0 = 1.5 m. The parameters from case 1 is similar to the parameters of IDM-ACC proposed by Kesting et al. [34]. Moreover, the ACC proposed by Milanés and

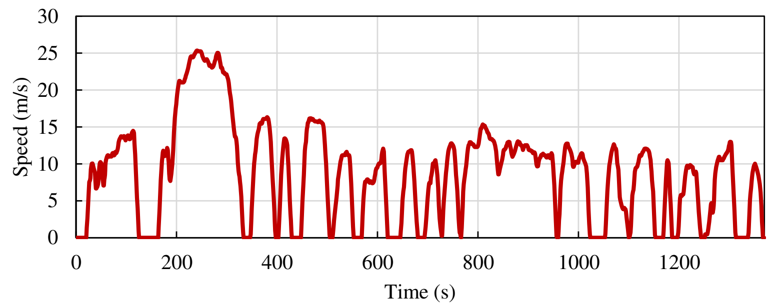

Fig. 5 Urban Dynamometer Driving Schedule (UDDS) [52]

Shladover [18] is also simulated to compare with the IDM-ACC and SDM. In order to avoid the instability of the ACC proposed by Milanés and Shladover [18], we have $k_1 = 0.49$ and $k_2 = 0.07$, where the stability calculated based on Eq. 19 is 0.02. Therefore, the parameters from case 1 is used in the simulation for both IDM-ACC and SDM. As shown in Fig. 6, the acceleration variance is significantly decreasing for the SDM-equipped vehicle towards the end of the platoon. With before mentioned parameters, the proposed model can stabilize the homogeneous traffic flow considering a realistic driving cycle. Moreover, SDM outperforms the IDM-ACC and Milanés and Shladover Model in terms of stabilization effect on homogeneous traffic flow.

4.2 Platoon with cut-in

Based on the simulation conducted by [50], a platoon with 16 vehicles, when a cut-in occurs between the

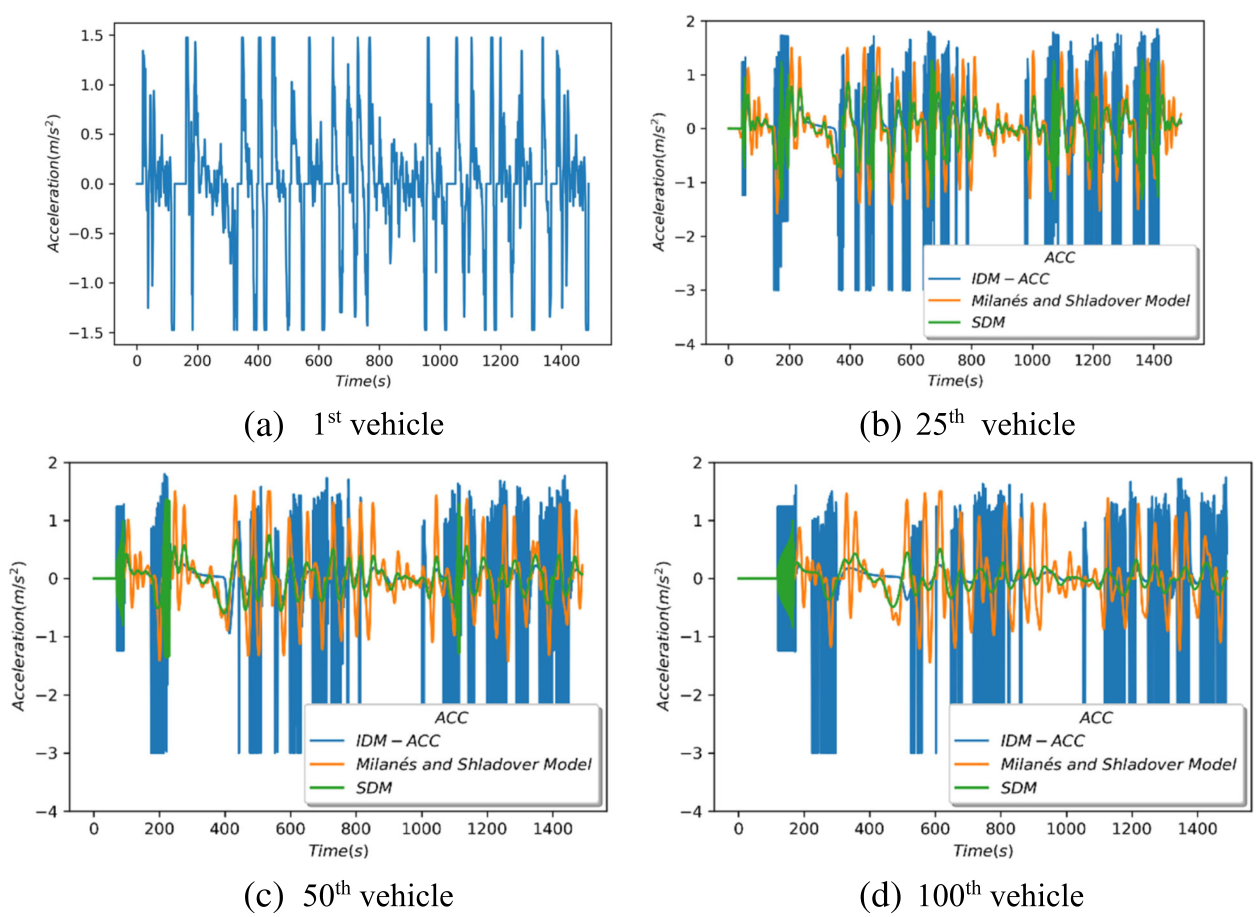

Fig. 6 Acceleration profiles of 1st, 25th, 50th, and 100th vehicle equipped with Milanés and Shladover Model, IDM-ACC and SDM

fourth and fifth positions, is simulated to investigate the stability of SDM under cut-in condition. The cut-in rules and parameters are based on the study conducted by Davis [51]. The simulation starts with the 16 SDM-equipped vehicles. The leading vehicle is manually driven and its speed profile is generated using real data from experimental tests. The other vehicles follow the leading vehicle. One can appreciate how the speed changes are not amplified upstream. Then a vehicle cuts in between the fourth and fifth vehicles. For the sake of clarity in the figure, the speeds of the first four vehicles have been removed from the plots of the results for the rest of the simulation. From second 340, the cut-in vehicle depicted in the graph with the red solid lane splits the string in two. This vehicle is computer generated and it is assumed that it is manually driven with small speed oscillations around 25 m/s. As shown in Fig. 7, the oscillations from the cut-in vehicle are reduced by the 5th to the 16th vehicles. With the proposed parameters, the proposed model can stabilize the homogeneous traffic flow under cut-in condition.

5 Conclusion and future work

In this paper, an adaptive cruise control, named Smart Driver Model (SDM), is proposed to describe the autonomous vehicles flow. Meanwhile, the stability criteria is proposed for SDM to keep the homogeneous traffic flow stable. Numerical simulations were conducted to verify the results of the theoretical analysis. We find that simulation results are consistent with the results of linear stability analysis. Considering a platoon without cut-in, the simulation result shows that the proposed

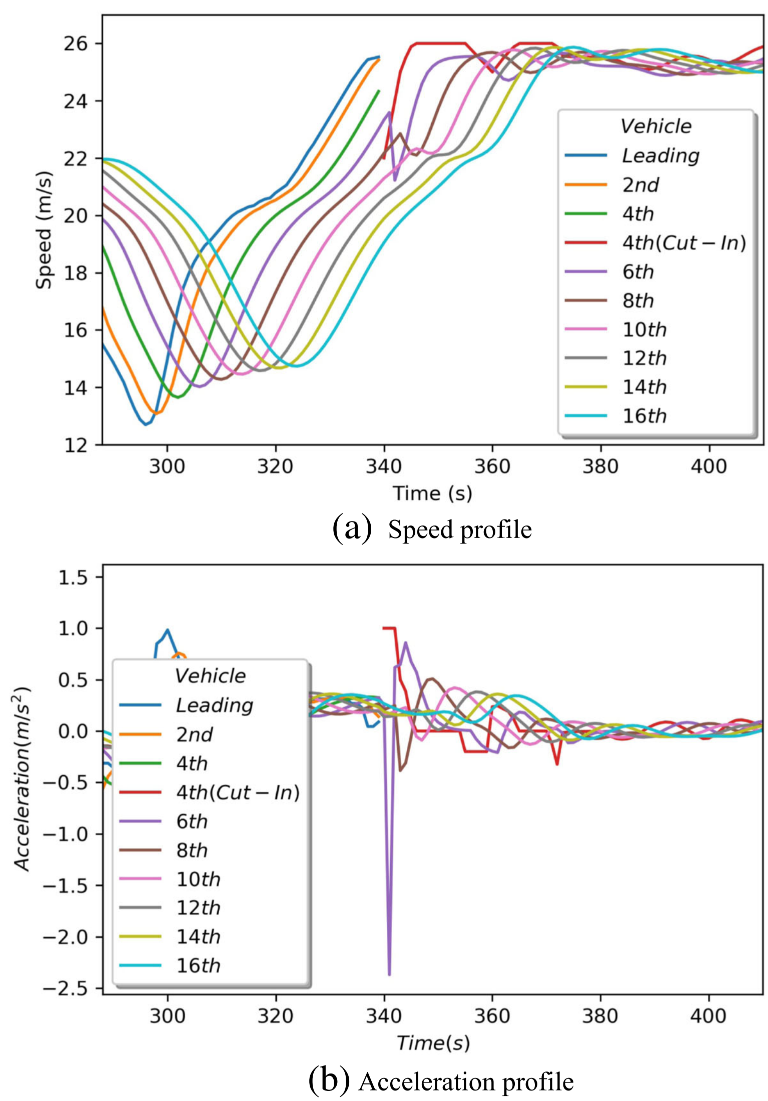

Fig. 7 Simulation results from a vehicle performing a cut-in in the fourth position of 16 ACC vehicles

model can stabilize the homogeneous traffic flow considering a realistic driving cycle. Moreover, the results from simulation and linear stability analysis show that SDM outperforms the IDM-ACC and the ACC proposed by Milanés and Shladover in terms of stabilization effect on homogeneous traffic flow. Considering a platoon with cut-in, a platoon with 16 vehicles, when a cut-in occurs between the fourth and fifth positions, is simulated to investigate the stability of SDM under cut-in condition. The simulation result shows that the SDM-equipped vehicles are able to stabilize the homogeneous traffic flow under cut-in condition. In the future, considering the information from multiple preceding vehicles and the surrounding traffic, SDM can be extended to energy-efficient control strategies and personalized information systems.

The present paper has the following limitations. First, the stability analysis is based on the theoretical model and simulation. Second, the lane-changing behavior is ignored to investigate the stability of the proposed model. Third, heterogeneous traffic conditions with ACC-equipped vehicles and human-driven vehicles is not considered in this paper. The fourth limitation comes from the same model parameter setting within a vehicle string in the simulation experiments. The impacts of different driver characteristics, such as reaction time, acceleration capabilities, and desired time gaps, within a string can be found by a sensitive analysis in subsequent simulations. In the future, the data collected from SDM-equipped vehicles should be used to validate the theoretical results. The proposed model will be implemented in an advanced and sophisticated traffic simulation model to discover the traffic impact of ACC vehicles on heterogeneous traffic flow. Moreover, specific lane-change maneuver needs to be designed for SDM in order to improve the stabilization effect of autonomous vehicles on the road transportation system.

Authors' contributions
CL developed the ACC and drafted the paper. AA participated in the design of the study. Both authors read and approved the final manuscript.

Competing interests
The authors declare that they have no competing interests.

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