Nonlinear Longitudinal Control for Vehicle Platoon Considering the Effect of Electronic Throttle Opening Angle

Yongxin Zhu[1], Yongfu Li[1*], Shuyou Yu[2]

1. Key Laboratory of Intelligent Air-Ground Cooperative Control for Universities in Chongqing, College of Automation, Chongqing University of Posts and Telecommunications, Chongqing 400065, China
E-mail: liyongfu@cqupt.edu.cn

2. Department of Control Science & Engineering, Jilin University, Changchun 130012, China
E-mail: shuyou@jlu.edu.cn

Abstract: This paper proposes a homogeneous vehicle platoon longitudinal controller considering the effect of electronic throttle opening angle. In particular, a nonlinear longitudinal controller is proposed by integrating the consensus between connected autonomous vehicles (CAVs), the influence of interactions between vehicles and the effect of electronic throttle (ET) opening angle. Then, the convergence condition is deduced analytically by using the Routh–Hurwitz stability criterion. The controller can not only ensure the consensus of CAVs, but also avoid rear-end collision and negative velocity. Finally, simulations are carried out in the presence of external interference to verify the robustness and effectiveness of the proposed controller with respect to position, velocity and acceleration/deceleration profiles.

Key Words: Connected autonomous vehicles, Platoon control, Electronic throttle opening angle, Routh–Hurwitz stability criterion

1 INTRODUCTION

Cooperative control of vehicular platoons has attracted much attention of researchers and automobile manufacturers for its advantages of safety improvement, traffic efficiency and fuel consumption reduction [1]. Through the vehicle-to-vehicle (V2V) communication technology, the sensing range of vehicles equipped with communication equipment will be expanded. Within the communication range, a vehicle in the platoon can perceive much information from its neighboring vehicles[2]. In addition, vehicles in a platoon pattern may increase the road throughput and also reduce the risk of collision , especially under the non-lane-discipline road [3-4]. Due to these potential benefits, the vehicle platoon control in a V2V communication environment has been extensively studied [5-6].

The purpose of vehicle platoon control is to regulate vehicles in a string to form a special pattern with the same velocity and smaller inter-vehicle gap. In this context, extensive studies have been proposed to address this problem. Meng et al. [7] investigated both first-order and second-order cases of leader-follower consensus control protocol with input and communication delays. Chen et al. [8] proposed a controller for the multi-vehicle system based on the constant spacing policy. Santini et al. [9] proposed a novel controller for vehicle platoon and the string stability can be guaranteed even in the presence of strong interference, communication delays, and fading conditions. Zheng et al. [10] proposed a cooperative distributed controller for heterogeneous vehicles based on the constant space policy. These studies mainly focus on the vehicle platoon control by considering vehicle dynamics and communication topology. However, there is less attention to the interactions between vehicles.

On the other hand, the behavior of vehicles in a platoon should be consistent with traffic flow theory. To handle this issue, Li et al. [11] proposed a finite-time nonlinear platoon controller under fixed and switched communication topologies based on the vehicle kinematics model. Later, Li et al. [12] proposed a new nonlinear platoon controller in the presence of communication delays based on the third-order model. In this study, the controller considers the car-following interactions and guarantees that the behavior of vehicles is consistent with the traffic flow theory. However, this study does not consider the impacts of vehicle dynamics such as the ET opening angle, which may affect the behavior of vehicle.

The purpose of this study is to develop a new control algorithm to address the vehicle platoon by considering the impacts of interactions between vehicles and the vehicle dynamics. To this end, we propose a new nonlinear platoon controller that incorporates car-following interactions between vehicles and considers the ET opening angle as well. The stability condition of the proposed controller is derived by using the Routh Hurwitz stability criterion. The contributions of this paper can be summarized as follows：

(i) We propose a new platoon controller that incorporates car-following interactions between vehicles and considers the ET opening angle.
(ii) The convergence condition of the proposed controller is derived by using the Routh-Hurwitz stability criterion.
(iii) Compared with [11], the proposed controller can improve passenger comfort by decreasing the acceleration amplitude.

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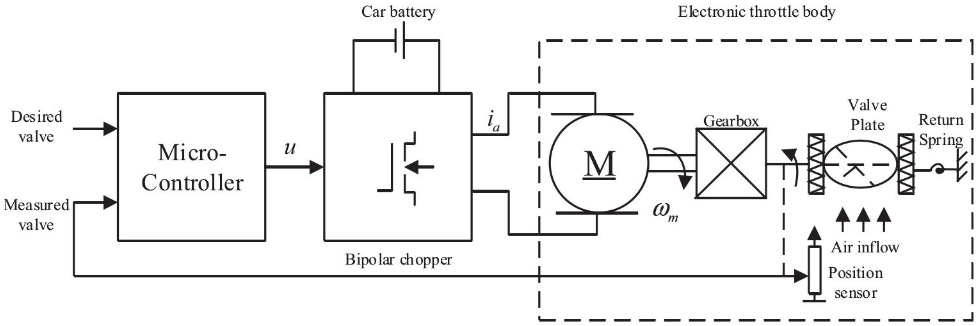

Fig. 2: Schematic of electronic throttle.

The rest of this paper is organized as follows. Section 2 presents the formulation and preliminaries. Section 3 proposes the distributed controller for a heterogonous vehicle platoon. Section 4 analyzes the convergence of the controller. Section 5 executes the numerical experiment. The final section concludes this study.

2 FORMATTING AND PRELIMINARIES

2.1 Communication Topology and Graph Theory

As shown in Fig. 1, the platoon is consist of $N+1$ homogeneous vehicles on straight road that includes a leader (noted as vehicle L) and N followers (noted as vehicles 1 to n), we propose the predecessor-leader following (PLF) topology to use the communication capacity efficiently, each vehicle has its controller, which obtains the states of other controllers.

The communication topology can be modeled as a directed graph between vehicles. We define a directed graph $G=\{V,E,A\}$ containing N vehicles (nodes) [11], where $V=\{1,2,\dots,n\}$ is the set of nodes of G, and $E\subseteq V\times V$ denotes the edge of G. An adjacency matrix $A=[a_{ij}]_{n\times n}\in R^{n\times n}$ can be used to describe the connections between nodes in the graph G, if node i can recieve information from node j, then $a_{ij}=1$, otherwise $a_{ij}=0$. We define the linked matrix $K=diag(k_1,k_2,\dots,k_n)$, where an edge is k_{iL}, denoting a directional communication link between the leader and followers. If there is a connection between them, then $k_{iL}=1$, else $k_{iL}=0$. Graph G is a directed graph.

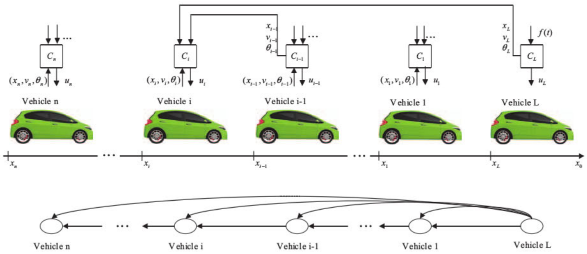

Fig. 1: Distributed cooperative platoon controller.

Graph G describes the link status and information flow among CAVs. In this paper, links between vehicles are all directed. In Fig. 1, an independent node in graph G is used to represents each vehicle. The links between each pair of nodes represent links between each pair of vehicles, which means that vehicles can exchange position, velocity, and the information of vehicle dynamics (e.g. the ET opening angle) based on communication links.

2.2 Electronic Throttle and Application Scenario

An ET system consists of a DC drive (powered by the chopper), a gearbox, a valve plate, a dual return spring, and a position sensor. Fig. 2 shows the functional scheme of the ET [13]. As shown in Fig. 2, the driver can control the velocity and acceleration of the vehicle by controlling the angle of the electronic throttle. Similarly, in CAVs, the microcontroller plays a driving role. In this study, the ET opening angle is introduced into platoon control protocol to achieve the control aims. The dynamic equation of the ET opening angle to vehicle velocity is as follows [14]:

$$a_i(t)=-b(v_i(t)-v_0)+c\overline{\theta}_i+\psi_i \tag{1}$$

where v_0 is the steady state of vehicle velocity for throttle input θ_0 and $\overline{\theta}_i=\theta_i-\theta_0$ is the deviation of θ_0; b and c vary with v_0; ψ_i represents the perturbation that captures the effect of unmolded dynamics; $v_i(t)$ and $a_i(t)$ represent the velocity and acceleration of the vehicle i at time t, respectively.

2.3 Formulation

Based on the communication topology that is labeled as the PLF topology, the dynamics of the leader vehicle can be described as follows [15]:

$$\begin{cases}\dot{p}_L(t)=q_L(t)\\ \dot{q}_L(t)=u_L(t)\end{cases} \tag{2}$$

where $p_L(t)\in R$ and $q_L(t)\in R$ represent the position and velocity of the leader. $u_L(t)\in R$ is the input of the leader vehicle.

The dynamics of the follower vehicles can be described as follows [11]:

$$\begin{cases}\dot{p}_i(t)=q_i(t)\\ \dot{q}_i(t)=u_i(t)\end{cases} \tag{3}$$

where $p_i(t)\in R$ and $q_i(t)\in R$ are the position and velocity of the follower, $u_i(t)\in R$ is control input.

The purpose of this study is to design a distributed nonlinear controller considering the effect of the ET opening angle that keeps the vehicle driving with the same velocity and inter-vehicle gap. The purpose of platoon control can be equivalently described solving the following consensus problem:

$$p_i(t) \to p_L(t) - i \cdot (d_c + l_c),\ q_i(t) \to q_L(t) \tag{4}$$

where l_c is the length of vehicle, and d_c is the desired longitudinal safe inter-vehicle gap. Based on the equilibrium (4), the position and velocity error can be defined as follows:

$$\begin{cases} \tilde{p}_i(t) = p_L(t) - p_i(t) - i \cdot (l_c + d_c) \\ \tilde{q}_i(t) = q_i(t) - q_L(t) \end{cases} \tag{5}$$

Further, we denote $\tilde{p} \triangleq [\tilde{p}_1, \ldots, \tilde{p}_n]^T$, $\tilde{q} \triangleq [\tilde{q}_1, \ldots, \tilde{q}_n]^T$, and $\tilde{\varepsilon} \triangleq [\tilde{p}^T \tilde{q}^T]^T$. Hence, we can rewrite (4) as follows [11]:

$$\lim_{t\to\infty} \|\tilde{\varepsilon}\| = 0 \tag{6}$$

3 PLATOON CONTROLLER

Based on traffic flow theory, we design a distributed nonlinear controller with local information exchange and considering the effect of electronic throttle opening angle for these $N+1$ vehicles:

$$\begin{aligned} u_i(t) = \sum_{j=1}^{n} a_{i,j}[&\alpha(V_i(h_{i,j}(t)) - q_i(t)) + \beta(q_j(t) - q_i(t)) \\ &+ \gamma(p_j(t) - p_i(t) - r_{i,j}) + \delta(\theta_j - \theta_i)] \\ &+ k_{i,j}(\beta(q_L(t) - q_i(t)) + \gamma(p_L(t) - p_i(t) - r_{i,L}) \\ &+ \delta(\theta_L - \theta_i)) \end{aligned} \tag{7}$$

where $\alpha > 0$, $\beta > 0$, $\gamma > 0$, $\delta > 0$ are constant control gains used to adjust vehicle platoon consensus. $r_{i,L} = i \cdot (l_c + d_c)$, and $r_{i,j} = r_{iL} - r_{jL} = (i-j)(l_c + d_c)$ are the desired longitudinal inter-vehicle gap between vehicle i and the leader, and vehicle i and vehicle j, respectively. θ_i, θ_j and θ_L are the ET opening angle of vehicle i, vehicle j and the leader, respectively. In addition, the following nonlinear function is defined to capture the interactions between vehicles i and j, which is associated with the average bumper-to-bumper distance [11].

$$V_i(h_{i,j}(t)) = V_1 + V_2 \tanh(C_1(h_{i,j}(t)) - C_2) \tag{8}$$

where V_1, V_2, C_1, C_2 are positive constants.

The average position difference between vehicles i and j can be described as follows:

$$h_{i,j}(t) = (p_j(t) - p_i(t) - (i-j)l_c)/(i-j) \tag{9}$$

In practice, because of the PLF topology, vehicles in the platoon can only communicate with the vehicle in front of them. The position differences $h_{i,j}(t)$ can be any positive value.

4 CONVERGENCE ANALYSIS

Some lemmas are introduced for preparations before analyzing the convergence of the proposed controller.

Lemma 1 [15]. Assuming that $\mathrm{Re}(z_1)$ is real and positive, the roots of a second-order polynomial with complex coefficients

$$f(s) = s^2 + z_1 s + z_2 \tag{10}$$

$f(s)$ is stable if and only if $\mathrm{Re}(z_1) > 0$ and $\mathrm{Re}(z_1)\mathrm{Im}(z_1)\mathrm{Im}(z_2) + (\mathrm{Re}(z_1))^2\mathrm{Re}(z_2) - (\mathrm{Im}(z_2))^2 > 0$.

Based on (1), this paper mainly studies homogeneous vehicles, assuming that all vehicles are subjected to the same disturbance d_i and the initial throttle opening angle θ_0. So $\theta_j - \theta_i$ and $\theta_L - \theta_i$ can be rewritten as:

$$\theta_j(t) - \theta_i(t) = \frac{1}{c}((\dot{q}_j(t) - \dot{q}_i(t)) + b(q_j(t) - q_i(t))) \tag{11}$$

$$\theta_L(t) - \theta_i(t) = \frac{1}{c}((\dot{q}_L(t) - \dot{q}_i(t)) + b(q_L(t) - q_i(t))) \tag{12}$$

Based on (7), (11) and (12), rewrite the control input $u_i(t)$ and equation (3) with the error equation (5). (3) can be rewritten as follows:

$$\begin{cases} \dot{\tilde{p}}_i(t) = \tilde{q}_i(t) \\ \dot{\tilde{q}}_i(t) = \sum_{j=1}^{n} a_{i,j}[\alpha(V_i(h_{i,j}(t)) - V_i(h^*_{i,j}(t)) - \tilde{q}_i(t)) \\ \quad + \beta(\tilde{q}_j(t) - \tilde{q}_i(t)) + \gamma(\tilde{p}_j(t) - \tilde{p}_i(t) - r_{i,j}) \\ \quad + \frac{\delta}{c}((\dot{\tilde{q}}_j(t) - \dot{\tilde{q}}_i(t)) + b(\tilde{q}_j(t) - \tilde{q}_i(t)))] \\ \quad + k_{i,j}(\beta(q_L(t) - \tilde{q}_i(t)) + \gamma(p_L(t) - \tilde{p}_i(t) - r_{i,L}) \\ \quad + \frac{\delta}{c}((\dot{q}_L(t) - \dot{\tilde{q}}_i(t)) + b(q_L(t) - \tilde{q}_i(t)))) \end{cases} \tag{13}$$

where $h^*_{i,j}(t) = h_c$, $V_i(h^*_{i,j}(t)) = q_L(t)$.

Based on (8), the following equation can be obtained by Taylors expansion:

$$V_i(h_{i,j}(t)) = V_i(h^*_{i,j}(t)) + V_i'(h^*_{i,j}(t))(h_{i,j}(t) - h^*_{i,j}(t)) \tag{14}$$

Since the leader moves with a constant velocity, it implies that $\dot{q}_L(t) = 0$, after algebraic manipulation, (13) can be rewritten as follows:

$$\begin{cases} \dot{\tilde{p}}_i(t) = q_i(t) \\ \dot{\tilde{q}}_i(t) = \frac{c}{c+2\delta}(\sum_{m=1}^{i}(\frac{\delta}{c+2\delta})^{i-m}(\\ \quad \sum_{j=1}^{n} a_{m,j}[(\alpha V_m'(h^*_{m,j}(t)) + \gamma)(\tilde{p}_j(t) - \tilde{p}_m(t)) \\ \quad + \beta\tilde{q}_j(t) - (\alpha+\beta)\tilde{q}_m(t)] \\ \quad - k_{m,L}(\beta\tilde{q}_m(t) + \gamma\tilde{p}_m(t)))) \end{cases} \tag{15}$$

Then we can rewrite (15) in a more compact form:

$$\dot{\tilde{\varepsilon}}(t) = F\tilde{\varepsilon}(t) \tag{16}$$

where

$$F = \begin{bmatrix} 0_{n\times n} & I_{n\times n} \\ -[(\alpha V'_{m,j}(h^*_{m,j}(t)) + \gamma)L + K\gamma] & -[\beta L + \alpha B + K\beta] \end{bmatrix}_{n\times n}$$

$$L = \begin{bmatrix} \varphi_1 a_{m1} & \cdots & \varphi_1 a_{mn} \\ \vdots & \ddots & \vdots \\ \varphi_n a_{m1} & \cdots & \varphi_n a_{mn} \end{bmatrix} - \begin{bmatrix} a_{11} + \ldots + a_{1n} & & \\ \vdots & \ddots & \\ a_{11} + \ldots + a_{1n} & \cdots & a_{n1} + \ldots + a_{nn} \end{bmatrix}$$

$$B = \begin{bmatrix} \varphi_1 a_{m1} & \cdots & \varphi_1 a_{mn} \\ \vdots & \ddots & \vdots \\ \varphi_n a_{m1} & \cdots & \varphi_m a_{mn} \end{bmatrix}$$

a_{ij} is the communication link between vehicle i and j ($i, j = 1,2\ldots,n$), if $i = j$, $a_{ij} = 0$. φ_i is an defined operator for simplicity and $\varphi_i = \frac{c}{c+2\delta}\sum_{m=1}^{i}(\frac{\delta}{c+2\delta})^{i-m}$.

Theorem 1: Suppose the matrix F is Hurwitz stable if and only if control gains $\alpha > 0$, $\beta > 0$, $\gamma > 0$ and $\delta > 0$ such that the inequalities hold for

$$\mathrm{Re}(w_i) > 0 \tag{17}$$

$$\mathrm{Re}(w_i)\mathrm{Im}(w_i)\mathrm{Im}(c_i)+(\mathrm{Re}(w_i))^2\mathrm{Re}(c_i)\text{-}(\mathrm{Im}(c_i))^2 > 0 \tag{18}$$

where $\omega_i \in \sigma(-D_1)$ and $\chi_i \in \sigma(-D_2)$, $i = 1,\ldots,n$, $\sigma(-D_1)$, $\sigma(-D_2)$ are the set of all eigenvalues of $-D_1$ and $-D_2$, $D_1 = -[(\alpha V'_{m,j}(h^*_{m,j}(t)) + \gamma)L + K\gamma], D_2 = -[\beta L + \alpha B + K\beta]$.

Proof: Let λ be the eigenvalue of F , the

$$\begin{aligned}\det(\lambda I_{2n} - F) &= \begin{vmatrix}\lambda I_n & -I_n \\ -D_1 & \lambda I_n - D_2\end{vmatrix} \\ &= \det(\lambda^2 I_{2n} - \lambda D_1 - D_2) \\ &= \prod_{i=1}^{n}(\lambda^2 + \lambda\omega_i + \chi_i)\end{aligned} \tag{19}$$

According to the Lemma 1, the Hurwitz stability of matrix F is equivalent to that of polynomial: $R(\lambda) = \lambda^2 + \lambda\omega_i + \chi_i$, we have:

(1) $\mathrm{Re}(\omega_i) > 0$,which holds by the positive stable matrix F

(2) $\mathrm{Re}(\omega_i)\mathrm{Im}(\omega_i)\mathrm{Im}(\chi_i) + (\mathrm{Re}(\omega_i))^2\mathrm{Re}(\chi_i) - (\mathrm{Im}(\chi_i))^2 > 0$, which can be satisfied by the condition (18). We have $\lim_{t\to\infty}\|\tilde{\varepsilon}\| = 0$. Thus, Theorem 1 holds.

5 CONVERGENCE ANALYSIS

In this section, the effectiveness of the controller is verified by numerical experiments. For this purpose, we use the example of a ten-vehicle platoon including one leader vehicle and nine follower vehicles in a straight lane. The parameters of the controller can refer to [11]. The communication link is shown in Fig. 1.

5.1 Simulation Setting

The initial position of vehicles are set as $x(0) = [0,19,38,58,79,101,124,148,172,196]^{\mathrm{T}}\,\mathrm{m}$ on the lane. The initial velocities are set as $= [10,10,10,10,10,10,10,10,10,10]^{\mathrm{T}}\,\mathrm{m/s}$. Base on the literature [19-20], the values of relevant parameters related to the controllers are set as follows: $\alpha = 3.5\mathrm{s}^{-1}$, $\beta = 0.1\mathrm{s}^{-2}$, $\gamma = 0.52\mathrm{s}^{-1}$, $b = 0.8$, $c = 0.27$, $V_1 = 6.75\mathrm{m/s}$, $V_2 = 7.91\mathrm{m/s}$, $C_1 = 0.13\mathrm{m}^{-1}$, $C_2 = 1.59$, $d_c = 5\mathrm{m}$, $l_c = 5\mathrm{m}$. In order to study the effect of the ET opening angle, the control gain $\delta = 2.5$. In order to study the effectiveness of the controller under different stable velocities, the expected velocities for the leader are given by:

$$v_L(t) = \begin{cases} 10\mathrm{m/s}, & 0 \le t < 60\mathrm{s} \\ (10 + \frac{7}{1+e^{-0.2t+20}})\mathrm{m/s}, & 60\mathrm{s} \le t < 180\mathrm{s} \\ 17\mathrm{m/s}, & 180\mathrm{s} \le t < 190\mathrm{s} \\ (17 - \frac{17}{1+e^{-0.2t+50}})\mathrm{m/s}, & \text{otherwise} \end{cases} \tag{20}$$

The disturbance on the leader is specified as follows:

$$\xi_L(t) = 0.4\sin(0.3\pi(t\text{-}60))e^{-(t-60)/10}, \quad t \ge 60\mathrm{s} \tag{21}$$

where the disturbance is only acted on the lead vehicle.

5.2 Discussion of Results

The drive cycles of vehicles in the platoon are presented in Figs. 3, 4, 5and 6.

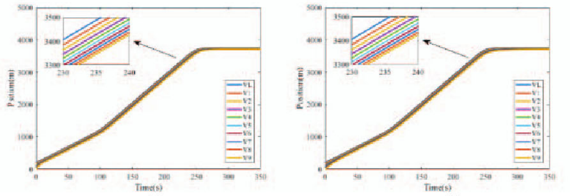
(a) (b)

Fig. 3. Position profile: (a) reference [11]; (b) δ=2.5 .

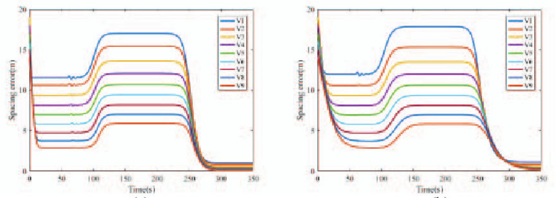
(a) (b)

Fig. 4. Spacing error profile: (a) reference [11]; (b) δ=2.5 .

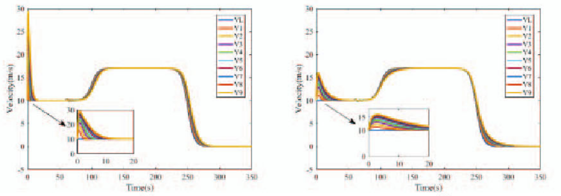
(a) (b)

Fig. 5. Velocity profile: (a) reference [11]; (b) δ=2.5 .

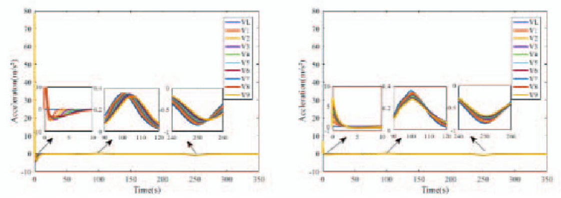
(a) (b)

Fig. 6. Acceleration profile: (a) reference [11]; (b) δ=2.5 .

Fig. 3 shows the position profiles. Based on Fig. 3(b), under the proposed controller (7), the follower vehicle can follow the leader vehicle smoothly, and then gradually stop behind the front vehicle, and the vehicle can maintain a certain safe and constant distance between vehicles. The spacing error shown in Fig. 4 further illustrates this phenomenon. It can be seen in Fig. 4(b) that the spacing errors of different initial values converge to positive constant value during the time $20\mathrm{s} \le t \le 90\mathrm{s}$. After an acceleration process, the spacing errors converge to another positive constant value during the time $150\mathrm{s} \le t \le 240\mathrm{s}$. In the end, the spacing errors converge to zero smoothly. It shows that the controller considers the longitudinal safety gap between vehicles. This means that the agreement on the position contour and collision avoidance can be guaranteed under the proposed controller (7).

Fig. 5 shows the velocity profiles, the velocities of follower vehicles can converge the leader vehicle. As shown in Fig. 5(b), when the leader maintains a constant initial velocity, the maximum velocity of follower vehicles is about 15m/s, which is significantly less than the reference [11](i.e. 29m/s).

Fig. 6 shows the Acceleration profiles. It can be seen obviously that the maximum accelerations of follower vehicles under the controller in the reference [11] are about 78.5m/s^2 ,which are more than that of follower vehicles under the proposed controller (7) (below 10m/s^2). And during $0\text{s} \leq t \leq 10\text{s}$, Fig. 6(a) shows the maximum decelerations of the follower vehicles are beyond 1m/s^2 , From Fig. 6(b), we can observe the maximum decelerations of follower vehicles do not exceed 1m/s^2 . It implies that the proposed controller (7) in this study can reduce the magnitude of acceleration/deceleration required by the convergence of the CAVs

In summary, from Figs. 3(b)-6(b), the convergence of the controller can be verified by position, velocity and acceleration curves. In addition, the controller can avoid negative spacing error and negative velocity, and meet the stability of the string under external interference according to the distribution of spacing error, velocity and acceleration. The robustness of the controller is verified. An analysis of the effect of the ET opening angle suggests that the ET opening angle can reduce the peak acceleration/deceleration and effectively improve the passenger comfort.

6 CONCLUDING REMARKS

In this study, a distributed nonlinear controller is proposed for vehicle platoon control by considering the car-following interactions and the ET opening angle. Through the proposed controller, the unrealistic phenomenon of negative spacing error and negative velocity can be effectively avoided. Also, passenger comfort can be improved by a small acceleration/deceleration amplitude. In addition, the convergence condition of the proposed controller is rigorously analyzed by using the Routh-Hurwitz stability criterion. Extensively simulations are performed and results verify the effectiveness of the proposed controller with respect to position, velocity and acceleration/deceleration profiles.

REFERENCES

[1] P. Varaiya, Smart cars on smart roads: problems of control, IEEE Trans. on Automatic Control, Vol.38, No.2, 195-207, 1993.

[2] X. Cheng et al., An improved parameter computation method for a mimo v2v rayleigh fading channel simulator under non-isotropic scattering environments, IEEE Communications Letters, Vol.17, No.2, 265-268, 2013.

[3] W. Ren, Consensus based formation control strategies for multi-vehicle systems, Proceedings of the 2006 American Control Conference, 4237-4242, 2006.

[4] W. Ren and E. Atkins. Distributed multi - vehicle coordinated control via local information exchange, Proceedings of International Journal of Robust & Nonlinear Control, 1002-1033, 2010.

[5] Y. Li, B. Yang, T. Zheng, Y. Li, M. Cui and S. Peeta, Extended-state-observer-based double-loop integral sliding-mode control of electronic throttle valve, IEEE Trans. on Intelligent Transportation Systems, Vol.16, No.5, 2501-2510, 2015.

[6] S. K. Yadlapalli, S. Darbha and K. R. Rajagopal, Information flow and its relation to stability of the motion of vehicles in a rigid formation, IEEE Trans. on Automatic Control, Vol.51, No.8, 1315-1319, 2006.

[7] Z. Meng, W. Ren, Y. Cao and Z. You, Leaderless and leader-following consensus with communication and input delays under a directed network topology, IEEE Trans. on Systems, Man, and Cybernetics, Part B (Cybernetics), Vol.41, No.1, 75-88, 2011.

[8] Y. Chen, G. Zhang and Y. Ge, Formation control of vehicles using leader-following consensus, Proceedings of 16th International IEEE Conference on Intelligent Transportation Systems, The Hague, 2071-2075, 2013.

[9] S. Santini, A. Salvi, A. S. Valente, A. Pescapé, M. Segata, and R. Lo Cigno, A consensus-based approach for platooning with inter vehicular communications and its validation in realistic scenarios, IEEE Trans. on Vehicular Technology, Vol.66, No.3,1985-1999, 2017.

[10] Y. Zheng, Y. Bian, S. Li and S. E. Li, Cooperative control of heterogeneous connected vehicles with directed acyclic interactions, IEEE Intelligent Trans. Systems Magazine, DOI:10.1109/MITS.2018.2889654, 2019.

[11] Y. Li, C. Tang, S. Peeta and Y. Wang, Nonlinear consensus-based connected vehicle platoon control incorporating car-following interactions and heterogeneous time delays, IEEE Trans. on Intelligent Transportation Systems, Vol.20, No.6, 2209-2219, 2019.

[12] Y. Li, C. He, H. Zhu and T. Zheng, Nonlinear longitudinal control for heterogeneous connected vehicle platoon in the presence of communication delay. Acta Automatica Sinica, DOI:10.16383/j.aas.c190442.

[13] Y. Li, L. Zhang, S. Peeta et al. A car-following model considering the effect of electronic throttle opening angle under connected environment, Nonlinear Dynamics, Vol 85, No.4, 2115-2125, 2016.

[14] Ioannou. P., Xu. Z, Throttle and brake control system for automatic vehicle following. Intell. Veh. Highway Syst. Vol.1, No.4, 345–377, 1994.

[15] .Z. Zuo, B. Tian, M. Defoort and Z. Ding, Fixed-time consensus tracking for multi-agent systems with high-order integrator dynamics, IEEE Trans. on Automatic Control, Vol.63, No.2, 563-570, 2017.

[16] D. Jia, R. Zhang, K. Lu, and J. Wang, Enhanced cooperative car-following traffic model with the combination of V2V and V2I communication, Transportation Research Part B, 90:172-191, 2016.