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Scalable Platooning Based on Directed Information Flow Topology With Granulating Method

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ABSTRACT Vehicle platooning is of great importance in future autonomous driving and intelligent transportation systems, due to its advantages in road safety, traffic efficiency, energy consumption and exhaust emissions. This paper focuses on the scalability performance of platooning control, which aims to achieve long platoon size under the premise of ensuring consensus behavior of the platooning vehicles. However, in classical platooning schemes such as ACC (adaptive cruise control) and CACC (cooperative adaptive cruise control), as the number of platoon members increases, the communication range of the leader and the cascaded sensor delay affect the scalability of platoon. In this paper, a scalable platooning scheme, CACC-granulation, is proposed to improve the scalability of platooning based on a novel information flow topology. The granulating method is used to solve the problem of limited communication range of leader for CACC by forwarding their own information to platoon members through some vehicles. The CACC-granulation granulates platoon information flow topology and enhances the platoon scalability by reducing information flow topology matrix. Simulation experiments are conducted to verify the consensus and scalability performance of CACC-granulation. Compared with other two platooning schemes which can get long platoon size, i.e., ACC-cascade and ACC-CACC-integration, the simulation results indicate the performance advantages of the proposed CACC-granulation, which not only meets the consensus of platooning control, but also enhances the scalability of platooning control.

INDEX TERMS Platoon, consensus, scalability, ACC (adaptive cruise control), CACC (cooperative adaptive cruise control), granulating method.

I. INTRODUCTION

Vehicle platooning is one of the important application scenarios in future autonomous driving, aiming to improve road safety, increase traffic efficiency, and decrease energy consumption and exhaust emissions [1], [2]. vehicle platooning is a group of vehicles in a closely linked manner, nose-to-tail, so that the vehicles move like a train with virtual string attached between vehicles [3], [4].

This paper focuses on the longitudinal control of the platoon. Longitudinal control can be centralized or decentralized [5]. In the centralized control, vehicles get their control commands from centralized units. They are therefore not autonomous and communication is fundamental: any loss or delay in communication is critical. While in a decentralized control, each vehicle receives data from other vehicles, but calculates its own control in a stand-alone manner, so that communication remains very important, but that its loss is not as critical as the centralized case [6]. Multiplatooning is typical of decentralized control. Furthermore, recent technological advances in vehicle automation (e.g., Google's driveless car [7]) are opening a new prospect for platooning and multiplatooning. With the help of the leader vehicle in each platoon, a multiplatoon enables higher vehicle traffic flow and lower management complexity than a single large platoon, particularly in a highly dynamic scenario [8], [9].

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However, due to the lack of centralized control of multiplatoon, the inter-platoon distance is larger than intra-platoon distance. For platoon, the smaller inter-vehicle distance, the higher fuel efficiency [10]. Therefore, a long size platoon with small inter-vehicle distance is expected.

Control, communication and computing technologies are integrated together to achieve stability, scalability, reliability and efficiency of the platooning system [1], [11]. In a platoon system, radars, sensors and wireless communications are employed to share status information (such as speed, heading and intentions, etc.) among vehicles. The information flow topologies and wireless communication quality significantly impact the performance of platooning control [12]–[14].

This paper focuses on the scalability performance of platooning control, in which a long platoon is expected. The more vehicles are driven in a platoon, the more significantly it can improve the traffic efficiency. However, in general, platoon reduces its stability margin with increasing number of vehicles [11], [15]. Therefore, how to improve the scalability of the platooning control under the premise of ensuring consensus behavior of the platooning vehicles is an important issue in platooning control [16].

Actually, ACC (adaptive cruise control) [17] and CACC (cooperative adaptive cruise control) [18], as the classical platooning control schemes, follows different information flow topologies. Typical information flow topologies include predecessor-following (PF), predecessor-leader following (PLF), two predecessor-following (TPF), two predecessor-leader following (TPLF), bidirectional (BD) [19]. ACC follows the PF information flow topology and usually uses radars and sensors for information exchange among vehicles [20]. The actions performed by the leader are only perceived by the following member vehicles through the one-by-one information propagation [21]. Therefore, with the increase of platoon size, the information delay of the vehicle at the tail of the platoon will be amplified, thus to degrade the stability and limit the scalability of platooning consequently. As for CACC, it needs wireless communication technologies such as IEEE 802.11p and C-V2X to acquire the state information of the leader and the preceding vehicle. PLF is the dominant topology for CACC. Because all platoon members need information from the leader, this particular topology subjects to scalability issue. The main reason is that the effective communication range of the leader vehicle is limited (e.g., defined as 300m in IEEE 802.11p [22], [23] and 80m among vehicles in C-V2X [4]) depending on the transmission power and the reliability of the communication [24], [25]. This limits the scalability of CACC platooning. The easiest way to solve it is to use PF topology, since conceptually the number of vehicles in the platoon is not limited by the communication range [26]. But PF topology is not suitable for transmitting road safety information of leader because of topology constraints. In general, the scalability of platooning is affected by the information exchange and platooning control schemes. Therefore, this paper explores to improve the scalability of platooning control from the perspective of information flow topology.

Some efforts have been devoted to improve scalability of platoon based on different information flow topologies. S.K.Yadlapalli et al. pointed out that one vehicle should communicate to a large number of other vehicles if the spacing errors in the platoon need to be guaranteed insensitive to the platoon size [27]. But platoon scalability is more than just connecting more vehicles to the platoon. It has a lot to do with platoon stability. S.Darbha et al. indicated that the motion would lose stability beyond platoon scale [28]. The information flow topology dictates the pattern of communication between vehicles and is essential for effective platoon control, therefore, plays a critical role in the design and performance analysis of platooning control strategies. Y. Zheng et al. use matrix eigenvalue analysis, the scalability is investigated for platoons under two typical information flow topologies, i.e., bidirectional topology and bidirectional-leader topology [11]. Y. Zheng et al. also study the influence of information flow topology on the close-loop stability of homogeneous vehicular platoon moving in a rigid formation with algebraic graph theory and Routh-Hurwitz stability criterion [29]. And Y. Zheng et al. provide some tools, such as the algebraic graph theory and matrix factorization technique, are employed to model and analyze scalability limitations [15]. But few papers consider the instability of the platoon caused by the interference between the sensors and the delay of different information flows.

Accordingly, in order to improve the scalability of platoon, this paper proposed a platoon strategy. CACC-granulation uses a novel information flow topology, which is proposed based on the idea of granulation in artificial intelligence [30], [31]. The artificial intelligence granulating method is applied to the platoon information flow topology. The idea of granulation is a way of intelligent computing, which is derived from physics. From the 1970s to the early 1980s, people introduced the idea of dividing large substances into particles, molecules, and atoms in physics into the information field to deal with inaccurate and incomplete massive information in the real world to realize intelligent systems [32]. In the granulating platoon, several small platoons are merged into one large platoon, and the large platoon can also be divided into multiple small platoons. After granulation operation, the platoon member vehicles being the first vehicle of each platoon granulation will behave as both the leader of a platoon and the tail of the preceding platoon, thus to overcome the limitation of wireless communication range and enhance the scalability of platoon. The main contributions of this paper are as follows:

- Applying the idea of granulation to design a novel information flow topology to enhance the scalability of CACC platoon and granulating the platooning information flow topology by matrix transformation.
- According to the dynamic model of the vehicles, three platoon strategies which may result in long platoon

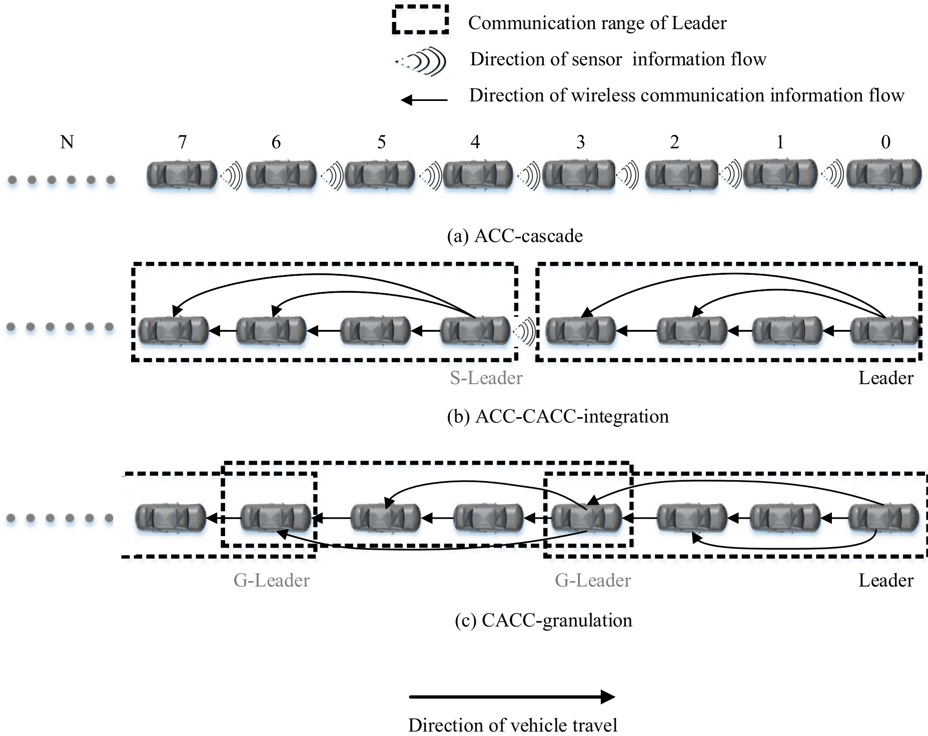


FIGURE 1. **The scheme of platoon scalability.**

size are discussed. They are ACC-cascade, ACC-CACC-integration, and CACC-granulation.

- The results show that CACC-granulation can achieve best scalability, i.e., can maintain consensus for a long platoon size. And it has more than just consensus; it also has the smallest error disturbance.

The rest of this paper is organized as follows. The definition and introduction of platoon scalability is presented in section I. Three scalable platooning schemes include ACC-cascade, ACC-CACC-integration and CACC-granulation are analyzed in section II. The assumptions about the platooning system are given in section III. The proposed CACC-granulation for scalable platooning control is introduced and discussed in section IV. Simulation comparison experiments of ACC-cascade, ACC-CACC-integration and CACC-granulation are shown in section V.

II. SCALABLE PLATOONING SCHEME

There are ACC and CACC in classical platoon control. Among them, vehicles under ACC control exchange information by means of radars or sensors. And the vehicles under the control of CACC exchange information by means of wireless communication. Based on these two technologies, there are three schemes to enhance platoon scalability as depicted in Fig.1.

ACC-cascade scheme is shown in Fig. 1(a). It can be considered as the multiplatoon, with only one vehicle per platoon. Each vehicle is equipped with sensors that are controlled by the ACC and connected one by one in the direction of sensor information flow. This cascade method is based on PF topology and easy to get long size platoon. But with more and more vehicles are connected to the platoon tail, the delay time of information to the tail vehicle will be accumulated. In order to solve the safety of platoon, we construct the ACC-cascade control formula (1) with constant time headway. In order to maintain platoon safety, the time headway will be set more than one second because the ACC platoon control only uses dynamics of preceding vehicle [33]. But as more and more vehicles are connected to the tail for multiplatoon that each platoon includes one vehicle, the whole platoon consensus is getting worse.

ACC-CACC-integration scheme is shown in Fig. 1(b). Every vehicle is equipped with sensors and on-board unit in a CACC platoon. Two or more CACC platoons are connected into the multiplatoon. Some CACC platoons based on PLF topology are connected together based on PF topology to enhance the scalability of platoon. In Fig. 1(b), the control input of ACC-CACC-integration has ACC sensors delay time and CACC communication delay time, because sensors is the easiest way to obtain preceding vehicle dynamics under PF topology. ACC-CACC-integration is a simple way to enhance scalability of platoon. Each small platoon is an CACC platoon, and the subsequent platoons are connected to the tail of the previous platoon. These CACC platoons are connected one after another to form the multiplatoon.

In order to enhance scalability of platoon, we design the scheme of scalable platooning that can overcome the limitation of communication range of the leader under the most dominant PLF topology as shown in Fig. 1(c). Each vehicle is equipped with on-board unit, and the dynamics information of the first vehicle of each platoon granulation is transmitted to the first vehicle of next platoon granulation (e.g., the leader sends itself's dynamic information to the third vehicle and the third vehicle sends itself's dynamic information to the sixth vehicle as depicted in Fig. 1) by wireless communication. We use the granulating method to rearrange PLF information flow topology of CACC according to the limitation of communication range of leader. Finally, the platoon is divided into several small platoons, and small platoons can also be combined into a large platoon. In other words, multiplatoon containing multiple small platoons are more closely connected through directed information flow topology with granulating method.

III. ASSUMPTIONS

A platooning system can be considered as a combination of four important components: vehicle longitudinal dynamics, information exchange flow, decentralized controllers and inter-vehicle spacing policies [34]–[37]. Because we focus on the novel information flow topology to improve the scalability of vehicle platooning, the assumptions of the other components are as follows:

(1) Vehicle longitudinal dynamics include the engine, drive line, brake system, aerodynamics drag, etc. In this paper, we consider that every vehicle has the homogeneous double-integrator model [38].

(2) Information flow topology is important to this paper, three different topologies are discussed, including: ACC-cascade, ACC-CACC-integration and the proposed CACC-granulation (as depicted in Fig. 1).

(3) Decentralized controller is adopted in this paper. Decentralized control is that each vehicle controls its own vehicle status based on other vehicles' information.

(4) There are two major spacing policies for classical vehicular platoons: the constant time headway policy and constant distance policy [25], [36]. For the constant time headway policy, the desired inter-vehicle distance varies with vehicle velocity. In the constant distance policy, the desired distance between two consecutive vehicles is independent of vehicle velocity. Here, we consider the constant time headway policy used for ACC control, because the vehicles can only get the information of the predecessor. In order to ensure the safety of the vehicles, inter-vehicle distance needs to change with the speed of the predecessor. For CACC control, we consider a constant distance, which means that the vehicles are controlled to move in a rigid platoon while following a leader, because the vehicles can get the information of the predecessor and leader.

Considering N vehicles driving along a highway, three schemes that may improve the platoon size are depicted in Fig. 1, including ACC-cascade, ACC-CACC-intergration and CACC-granulation. Platoon member (vehicle i) is to follow its preceding vehicle driving at a desired inter-vehicle distance S. Here S is constant time headway in ACC strategy or a constant distance in CACC strategy [33], [39], [40].

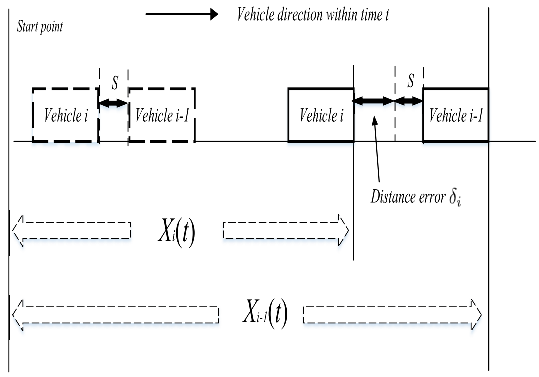


FIGURE 2. Distance error dynamic.

Two platoon members are schematically depicted in Fig. 2 with S being the distance between vehicle i and its preceding vehicle $i-1$. The main objective of each vehicle is to follow its preceding vehicle at a desired distance S. But, inter-vehicle distance will be changed due to sensor delay, communication delay, and weather, etc. causing a distance error δ_i.

For ACC-cascade, ACC-CACC-integration, CACC-granulation, they have same distance error expression. Here $x_i(t)$ and $x_{i-1}(t)$ are distances of vehicles i and $i-1$ from the start point within time t, respectively. $\delta_i = x_i(t) - x_{i-1}(t) + N_{i-1}+S$ is the distance error [41]. N_{i-1} is the length of vehicle $i-1$.

IV. CACC-GRANULATION FOR SCALABLE PLATOONING

The CACC-granulation granulates the classical CACC information flow topology to achieve the scalability of platoon. For the scalable classic ACC platoon and CACC platoon with limited vehicle communication range restrictions, two enhanced platoon scalability schemes of ACC-cascade and ACC-CACC-integration were proposed as benchmark schemes for the CACC-granulation scheme. Three schemes, ACC-cascade, ACC-CACC-integration and CACC-granulation (as shown in Fig. 1), are considered in this section to acquire the long platoon size. Each scheme is discussed to get the desired acceleration of the platoon members.

A. ACC-CASCADE

ACC-cascade scheme is as shown in Fig. 1(a). Every vehicle in the platoon is equipped with sensors, controlled by ACC and connect each other one by one followed by the direction of information flow. This cascade method is easy to connect more vehicles. But with more and more vehicles connected to the platoon tail. The delay time of tail vehicle will be accumulated. In order to solve the safety of platoon, we construct the ACC-cascade control formula (1) with constant time headway. The ACC method only using preceding vehicle information, and in order to maintain platooning safe the time headway will be set more than one second [33].

ACC-cascade is the simplest platoon. Firstly, the control information of vehicle is from radar and sensor, platoon member is unlimited under cascade method. Meanwhile, the delay time is cumulative along with the number of vehicles increases. ACC-cascade vehicular acceleration is calculated as follows. This was constructed according to previous literature by Segata *et al.* [33].

$$\begin{aligned} \ddot{x}_i^{des}(t) &= -\frac{1}{T_s}(\dot{\xi}_i + \lambda\delta_i) \\ \delta_i &= x_i(t) - x_{i-1}(t) + N_{i-1} + S \\ \dot{\xi}_i &= \dot{x}_i(t) - \dot{x}_{i-1}(t) \\ S &= T_s\dot{x}_i(t) \end{aligned} \tag{1}$$

where $\ddot{x}_i^{des}(t)$ is desired acceleration of vehicle i at time t, λ is a design parameter strictly greater than 0 (default set to 0.1). δ_i is the distance error. $\dot{\xi}_i$ is relative speed between vehicle i and vehicle $i-1$. T_s is time headway, S is desired inter-vehicle distance. In order to ensure the safety of passengers, [25] said it must be $T_s \geq 2L$, here L is actuation lag [42]. In order to compute δ_i and $\dot{\xi}_i$, let $\dot{x}_i(t) = \int_0^t \ddot{x}_i^{des}(t)\,dt$ and $x_i(t) = \iint_0^t \ddot{x}_i^{des}(t)\,dtdt$, bring into formula (1). Finally,we can get relationship of desired acceleration between vehicle i and vehicle $i-1$ over time t :

$$\begin{aligned} \ddot{x}_i^{des}(t) &= ((t+\Delta t) + 0.5\lambda(t+\Delta t)^2 + \lambda)\ddot{x}_{i-1}^{des}(t+\Delta t) \\ &\quad - \lambda(T_s w_1 + N_{i-1}))/(T_s + (t+\Delta t) \\ &\quad + 0.5\lambda(t+\Delta t)^2 + \lambda(t+\Delta t)T_s + \lambda w_2(t+\Delta t)) \\ &where \\ \Delta t &= delaytime_{ACC}, \quad 1 \leq i \leq N \end{aligned} \tag{2}$$

where $delaytime_{ACC}$ is the sensor delay time of ACC-cascade, N is vehicular number, t is time of platoon travel. w_1 is the start speed of vehicle $i-1$, and w_2 is the start speed of vehicle i within Δt.

B. ACC-CACC-INTEGRATION

ACC-CACC-integration scheme is as shown in Fig. 1(b). Each vehicle in the CACC platoon is equipped with sensors and on-board unit. Two or more CACC platoons are connected by sensors. There are two reason for ACC-CACC-integration, the first one is the communication range of leader of CACC platoon is limited for vehicle. The second reason is existing classical vehicle platoon control strategy that is not controlled by wireless communication is ACC. So the control input of ACC-CACC-integration has ACC sensor delay time and CACC communication delay time. ACC-CACC-integration is a simple way to enhance scalability of platoon and we use the $S-Leader$ algorithm to choose next leader in the platoon.

Under CACC, platoon members get information not only from predecessor vehicle but also from leader of platoon. At this time, some of platoon members are within the range of leader. When vehicles being outside the range, it can be connected by ACC. We establish the CACC formula (3) using constant distance to ensure vehicle safety. This was constructed according to previous literature by Segata *et al.* [33].

$$\begin{aligned} \ddot{x}_i^{des}(t) &= a\ddot{x}_{i-1}(t) + b\ddot{x}_0(t) + c\dot{\xi}_i + d(\dot{x}_i(t) - \dot{x}_0(t)) + e\delta_i \\ \delta_i &= x_i(t) - x_{i-1}(t) + N_{i-1} + S \\ \dot{\xi}_i &= \dot{x}_i(t) - \dot{x}_{i-1}(t) \\ S &= gap_{des} \end{aligned} \tag{3}$$

where gap_{des} is constant distance. Because the delay time of CACC from wireless is much smaller than ACC delay time from sensor, we choose constant distance to represent desired inter-vehicle distance S of CACC. $\dot{x}_0(t)$ and $\ddot{x}_0(t)$ is speed and acceleration of leader respectively. a, b, c, d, e is parameter depicted as follows:

$$\begin{aligned} a &= 1 - W \\ b &= W \\ c &= -(2\zeta - W(\zeta + \sqrt{\zeta^2 - 1}))b_w \\ d &= -W(\zeta + \sqrt{\zeta^2 - 1})b_w \\ e &= -b_w^2 \end{aligned} \tag{4}$$

where W is weighting factor between the acceleration of leader and preceding vehicle. ζ is drag coefficient and always be set 1. b_w is receiving signal frequency. Since the distance between the leader and vehicle i is different from that between the vehicle $i-1$ and vehicle i, the delay times of vehicle $i-1$ and leader transmitting information to the vehicle i are different.

In order to indicate that CACC communicate not only with the leader but also with the predecessor, we constructed graph-based topological modelling. For example, 8 vehicles matrix under ideal CACC controlling represent as follows:

$$CACC_{ij} = \begin{array}{c} \\ 0 \\ 1 \\ 2 \\ 3 \\ 4 \\ 5 \\ 6 \\ 7 \end{array} \begin{array}{c} \begin{array}{cccccccc} 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{array} \\ \begin{pmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{pmatrix} \end{array} \tag{5}$$

The information flow among platoon is described by a directed graph $\Gamma_N = \{E_N, U, A_N\}$ with a set of vehicular nodes $U = \{1, 2, 3, N\}$, a set of edges $E_N = U \times U$ and the adjacency matrix $A_N = [a_{ij}] \in R^{N\times N}$. Edge (i, j) represents that vehicle j transmits information to vehicle i. If $a_{ij} = 1$, vehicle j transmits information to i, else $a_{ij} = 0$.

In order to maintain a desired acceleration and desired distance we define the following high-order consensus problem.

$$
\begin{aligned}
&\ddot{x}_i(t) \rightarrow \ddot{x}_i^{des}(t) \\
&x_i(t) \rightarrow \frac{1}{\sum\limits_{j=0}^{N} a_{ij}} \left(\sum_{j=0}^{N} a_{ij}(x_j(t) + d_{ij}) \right) \\
&s.t\ L \ \leq \ L_{ecr} \qquad (6)
\end{aligned}
$$

where L is the length of platoon, L_{ecr} is effective communication range of leader(e.g 80m [4]), $x_i(t)$ is the absolute position of $i-$vehicle, d_{ij} is desired distance between vehicle i and j. The relationship between $d_{i,0}$ and L_{ecr} depicted as follows:

$$
d_{i,0} - L_{ecr} \leq 0 \quad 1 \leq i \leq N \qquad (7)
$$

when $L > L_{ecr}$, we choose some vehicles as S-Leader for ACC-CACC-integration. A S-Leader vehicle connects preceding vehicle by ACC sensor, because vehicles behind S-Leader are beyond the communication range of leader. The selecting $S-Leader$ algorithm is depicted as follows.

Algorithm 1 The Algorithm of $S-Leader$

```
Require: Input
    d_ij, L_ecr, i, j, N;
Ensure: Output
    S-Leader[ ];
j = 0, m = 0;
for(i = 1; i < N; i++) {
    if(d_i,j − L_ecr > 0   and   d_(i−1),j − L_ecr ≤ 0) {
        S-Leader[m] = j;
        j = i;
        m = m + 1;
    }
    else continue;
}
```

Considering formula (3) (4) (6) and the transformation process from formula (1) to formula (2), we get formula of ACC-CACC-integration desired acceleration with time:

$$
\begin{aligned}
&\ddot{x}_i^{des}(t) \\
&\quad = (\ddot{x}_{i-1}^{des}(t+\Delta t)(a - c(t+\Delta t) - 0.5e(t+\Delta t)^2) \\
&\qquad + \ddot{x}_{S\text{-}Leader}^{des}(t+\Delta t)(b - d(t+\Delta t)) + e(\text{-}gap_{des} - N_{i-1}))/ \\
&\qquad \times (1 - (t+\Delta t)(c+d) - 0.5e(t+\Delta t)^2) \\
&where \\
&\Delta t = delaytime_{CACC} + delaytime_{ACC} \cdot m \\
&\ 1 \leq i \leq N \qquad (8)
\end{aligned}
$$

where $delaytime_{CACC}$ is communication delay-time of S-Leader, m is the number of S-Leader. ACC-CACC-integration shows that when platoon members being outside the rang of wireless communication of leader, S-Leader can be connected to the tail of the preceding platoon. And then, the vehicle control behind vehicles by broadcasting acceleration and speed of leader. The scalability of platoon can be enhanced by this method.But we use S-Leader controls platoon by different link method, it will cause an additional delay time every linking to preceding vehicle.

For example, [43] using CVS (connected vehicle systems) theory to solve the problem of network scalability. But this method established under CCC (connected cruise control) vehicle and traditional vehicle. The network scalability is enhanced by increasing the number of CCC vehicles. It means we need to always ensure the number of CCC vehicles on the roads. But that will increase the traffic pressure.

But this method is inadequate in the scalable platoon, and have not fundamentally solved the information flow problem of platoon scalability. Next, this paper provides a CACC-granulation method that comes from artificial intelligence to optimize the platoon topology flow and reduces platoon delay time.

C. CACC-GRANULATION

In order to enhance scalability of platoon, we must optimize the platoon topology flow, and overcome the limited communication range of leader. CACC-granulation scheme is a good way to overcome these disadvantage as shown in Fig. 1(c). Each vehicle equipped with on-board unit, the information of leader passed to the G-Leader by wireless. Then G-Leader passed itself vehicle dynamic to the next G-Leader, the whole platoon can receive the information of G-Leader. We rearrange the information flow topology of CACC using granulating method. The improved $S-Leader$ algorithm is used in CACC-granulation, $G - Leader = S-Leader$-1. It overcomes the limited communication range of the leader, and the platoon additional delay-time caused by ACC-CACC-integration.

In the platoon, leader is always equipped with experienced driver or auto-vehicle. For CACC-granulation, *platoon granulation* is a part of platoon, and every *platoon granulation* is a completed platoon with CACC. Each G-Leader communicate with next G-Leader by wireless communication. G-Leader is the trail of preceding *platoon granulation* and the leader of next *platoon granulation*. It does not retransmit preceding G-Leader information to its granulation member, it directly transmits itself information to them.

If $x_1, x_2, \cdots, x_t (t \geq 1)$ is a group data of U, where $x_i \in U(i = 1, 2, \cdots, t)$. The representation of merging data may be associated with the subset $\{x_1, x_2, \cdots, x_t\}$ after merging $x_1, x_2, \cdots, x_t$. Then we can use $\{x_1, x_2, \cdots, x_t\}$ to represent joint reconstruction or combined normalization of $x_1, x_2, \cdots, x_t$. The situation $t = 1$, say $\{x_1\}$, it means x_1 not be combined with other data, then $\{x_1\}$ and x_1 are the same. If merging data $x_1, x_2, \cdots, x_t$ is defined as $\{x_1, x_2, \cdots, x_t\}$ and the other merging data x can be expressed as a single data set $\{x\}$, then this representation of data U can be regarded as the division of data U.

Definition 1: Let U be a platoon. Considering the set $E = \{E_1, E_2, \cdots, E_k\}$, where $E_i(i = 1, 2, \cdots, k)$ is a subset of U, i.e. $E_i \subseteq U$. E is called consolidated-granulating set of U if it satisfies following conditions:

- $E_i \neq \emptyset (i = 1, 2, \cdots, k)$;
- $E_i \cap E_j = \emptyset (i \neq j \text{ and } 1 \leq i, j \leq k)$;
- $E_1 \cup E_2 \cup \cdots \cup E_k = U$.

The element $E_i(i = 1, 2, \cdots, k)$ in E is called *platoon granulation*. If $E_i = \{x_1, x_2, \cdots, x_t\}$ and $t > 1$, we say that the platoon granulation E_i is *merging data* or *granulating representation*; If $E_i = \{x_1\}$ and $t = 1$, we say that the grain E_i is called *reserved data*.

If E satisfies three conditions as above, then consolidated-granulating set $E = \{E_1, E_2, \cdots, E_k\}$ is a kind of division of U. E provides a plan that merging data or reserved data and E is a representation of merging data or reserved data. This method of data processing is the same way with granular computing [30], [31].

For example 8 vehicles platoon, the effective communication range of leader can only arrive to the 4-th vehicle, but we want to form an 8 vehicles ideal CACC controlling matrix (5). Considering three vehicles as a *platoon granulation*. The matrix reduction of *platoon granulation* as follows.

$$\begin{array}{c} \\ \{0,1,2\} \\ \{3,4,5\} \\ \{6,7\} \end{array} \begin{array}{c} \begin{matrix} 0 & 1 & 2 & 3 & 4 & 5 & 6 & 7 \end{matrix} \\ \begin{pmatrix} 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 1 & 1 & 1 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 \end{pmatrix} \end{array} \tag{9}$$

$$\begin{array}{c} \\ \{0,1,2\} \\ \{3,4,5\} \\ \{6,7\} \end{array} \begin{array}{c} \begin{matrix} \{0,1,2\} & \{3,4,5\} & \{6,7\} \end{matrix} \\ \begin{pmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 1 & 1 \end{pmatrix} \end{array} \tag{10}$$

Comparing with the original matrix (5), granulating matrix (9) neglects connection between 0 and 4, 5, 6, 7. This matrix (10) transmits connection between 0 and 1, 2, 3 into connection between {0, 1, 2} and {3, 4, 5}. It means that leader do not directly communicate with followers that outside effective communication range. But the information can reach the followers by *platoon granulation*. If we continue this way, we can get a corresponding granulating matrix for endless vehicle. The final matrix is expressed as follows:

$$\begin{array}{c} \\ 0 \\ 1 \\ \cdots \\ \cdots \\ \cdots \\ k \end{array} \begin{array}{c} \begin{matrix} 0 & 1 & \cdots & \cdots & \cdots & k \end{matrix} \\ \begin{pmatrix} 1 & 0 & & & & \\ 1 & 1 & & & & \\ & \cdots & \cdots & & & \\ & & \cdots & \cdots & & \\ & & & \cdots & \cdots & \\ & & & & 1 & 1 \end{pmatrix} \end{array} \tag{11}$$

The granulating matrix is described by a directed graph with a set of granulation E. Edge (i, j) represents that *platoon granulation* j transmits information to *platoon granulation* i by G-Leader. If $a_{ij} = 1$, *platoon granulation* j has G-Leader transmitting information to i, else $a_{ij} = 0$. When $i = j$, $a_{ij} = 1$ represents that all vehicles receive information from $G - Leader$ in one *platoon granulation*. When $i = j + 1$ $a_{ij} = 1$ represents that $G - Leader$ transmits itself information to next *platoon granulation*. Simultaneously, matrix computing is easy to transmit into program, so this method is easy to embed in the onboard computer. Combining with formula (8), CACC-granulation formula is constructed as follows:

$$\begin{aligned} &\dddot{x}_i^{des}(t) \\ &\quad = (\dddot{x}_{i-1}^{des}(t+\Delta t)(a - c(t+\Delta t) - 0.5e(t+\Delta t)^2) \\ &\qquad + \dddot{x}_{G\text{-}Leader}^{des}(t+\Delta t)(b - d(t+\Delta t)) + e(\text{-}gap_{des} - N_{i-1}))/ \\ &\qquad \times (1 - (t+\Delta t)(c+d) - 0.5e(t+\Delta t)^2) \\ &\textit{where} \\ &\Delta t = delaytime_{CACC} \\ &\quad 1 \leq i \leq N \end{aligned} \tag{12}$$

Formula (8) and formula (12) are almost the same. But the G-Leader in formula (12) forwards itself information, the delay of the entire platoon is only one $delaytime_{CACC}$ under CACC-granulation. In general, not only granulating matrix simplifies the matrix expression, but also the inverse of matrix is a new way of information flow topologies for platoon. If the G-Leader can maintain the consensus of platoon by forwarding its own information in CACC-granulation, it means that the information flow of the leader can be transmitted in this way instead of the multi-hop method of wireless communication. Next section, we will make a simulation analysis of platoon consensus and scalability to verify the feasibility of definition 1.

TABLE 1. Vehicle Parameters.

Experiment time	$30s$
$delaytime_{ACC}$	$1s$
$delaytime_{CACC}$	$0.1s$
Time headway (T_s)	$1.2s$
Constant distance (gap_{des})	$5m$
Packet transmission frequency	10Hz
Vehicle length	$10m$
Start speed ($\dot{x}_i(0)$)	$100km/h$
Acceleration disturbance	$\sin t$
Effective communication range of leader (L_{ecr})	$60m$
Start acceleration($\ddot{x}_i(0)$)	$2m/s^2$

V. SIMULATION RESULTS AND ANALYSIS

Firstly, the consensus of platoon under different schemes is simulated, and then the platoon scalability is simulated. Refer to [33], [44] for the platoon simulation, and we get a lot of parameters with actual vehicles test. Then we set the following vehicle parameters table 1 to verify the three schemes in Fig.1.

A. DEFINITION OF CONSENSUS AND SCALABILITY

Definition 2: An important indicator of vehicular platoon is string stability. A platoon is said to be string stable if the disturbances are not amplified when propagated downstream along the vehicle string [45]. String stability is important to vehicular safe, but it does not represent the consensus of platoon [16]. A platoon is said to be consensus if the follows move like the leader. We consider consensus-based

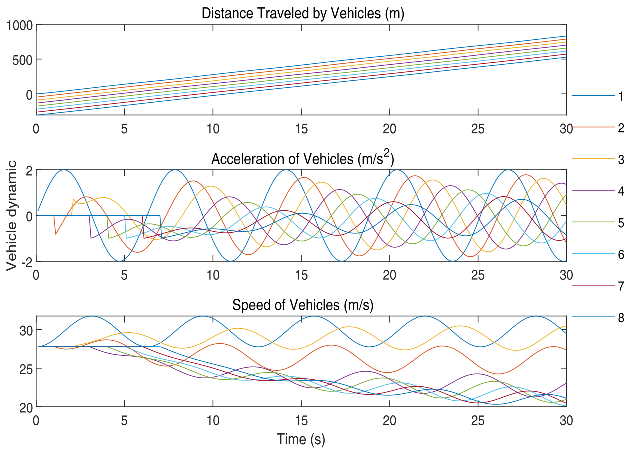


FIGURE 3. 8 Vehicles dynamic of ACC-cascade.

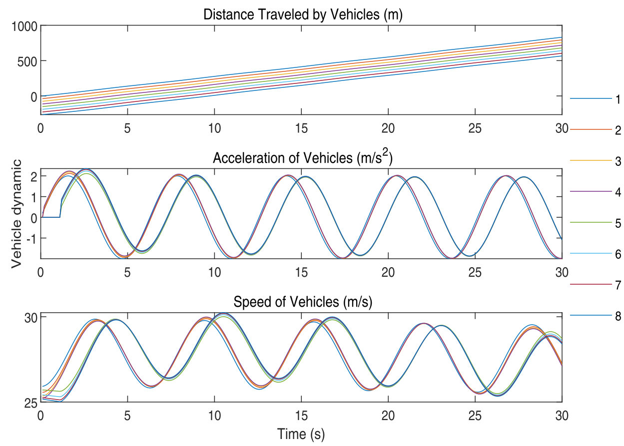


FIGURE 4. 8 Vehicles dynamic of ACC-CACC-integration.

error. Vehicle distance, speed and acceleration consensus coefficient be calculated as follows:

$$\begin{aligned} D_i &= x_i(t) - x_0(t) + i \cdot S + \sum_{w=1}^{i} N_{w-1} \\ V_i &= \dot{x}_i(t) - \dot{x}_0(t) \\ A_i &= \ddot{x}_i(t) - \ddot{x}_0(t) \\ & where \\ & 1 \leq i \leq 7 \end{aligned} \quad (13)$$

where i indicted i-th vehicle, w is variable. D_i is distance consensus error between vehicle i and leader. V_i is speed consensus error between vehicle i and leader. A_i is acceleration consensus error between vehicle i and leader. Simulation results are shown in Fig 6, 7, 8.

Definition 3: In theory, the feasibility to handle the scalability of platoons depends on whether the eigenvalues of Laplacian matrix and Pinning matrix are analytically obtainable [46], [47]. In general, to analytically obtain these matrix eigenvalues is rather difficult. Up to now, Y. Zheng et al. conclude that if the leader information is broadcasted to every follower, resulting in the so-called bidirectional-leader topology, the scalability of platoon can be significantly improved [11]. From Pete Seiler et al. theorem, we conclude that this strategy will always lack scalability because the gain from disturbances to errors grows without bound as the platoon length grows [48]. So a platoon is said to be scalability if error disturbances e is close to zero. We construct the error disturbance formula along the direction of information flow as follows:

$$e = \ddot{x}_i(t) - \ddot{x}_{i-1}(t) \quad 0 \leq t \leq n \quad (14)$$

where $n \geq 2\pi$ is because that acceleration disturbance from leader is periodic. We choose actual acceleration difference e of vehicle i and $i-1$ to represent error disturbance at the time that tail vehicle receives acceleration disturbance from leader. The result is shown in figure 12, 13, 14.

B. SIMULATION RESULTS

From the beginning, eight vehicles driving along the highway with $100km/h$ and desired inter-vehicle distance, but this status is broken up by leader with $2sint$ acceleration. All vehicles dynamic happens the time that received acceleration disturbance. According the scheme of platoon scalability of Fig 1 and vehicle parameters in table 1, we can get figure 3, 4, 5 of 8 vehicles dynamic by MATLAB.

Under the control of ACC-cascade, the vehicle displacement, acceleration, and speed change with time as shown in Figure 3. It can be seen that the vehicle has a cascaded delay time. Due to the effect of the delay, the vehicle does not immediately make acceleration change after the preceding vehicle has traveled.

Under the control of ACC-CACC-integration, the vehicle displacement, acceleration, and speed change with time as shown in Figure 4. The change of the 4th, 5th, 6th, and 7th vehicles acceleration, speed and displacement cannot be same with the changes of 0th, 1th, 2th, and 3th vehicles at the same time. That because the ACC sensors delay time $delaytime_{ACC}$. According to Algorithm 1, S-Leader is only connected to the next CACC platoon, and the information of platoon leader cannot be sent to the rear vehicle in time.

Under the control of CACC-granulation, the vehicle displacement, acceleration, and speed change with time as shown in Figure 5. It can be seen that 0th, 1th, 2th, 3th, 4th, 5th, 6th and 7th vehicles haves a smooth and short communication delay time $delaytime_{CACC}$ at all vehicles receive acceleration disturbance. Then all On the basis of Algorithm 1, we choose the vehicle of s-leader as the leader of platoon. At this point, the s-leader is not only the tail of the previous CACC platoon, but also the leader of the next CACC platoon, which can timely transmit the information of the S-Leader to the rear, enhancing the scalability of the platoon.

The first four vehicles of Figure 4 have the same $delaytime_{CACC}$ as the first four vehicles of Figure 5, and the

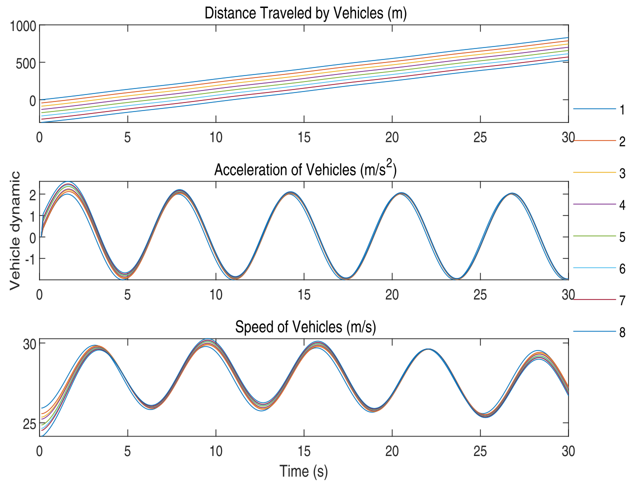


FIGURE 5. 8 Vehicles dynamic of CACC-granulation.

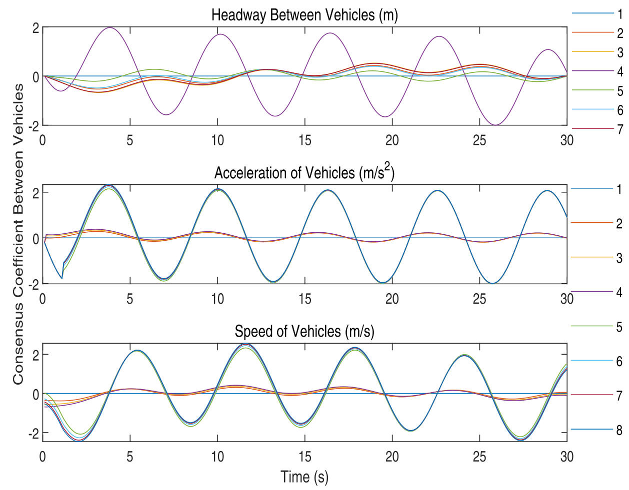


FIGURE 7. Consensus-based error of ACC-CACC-integration.

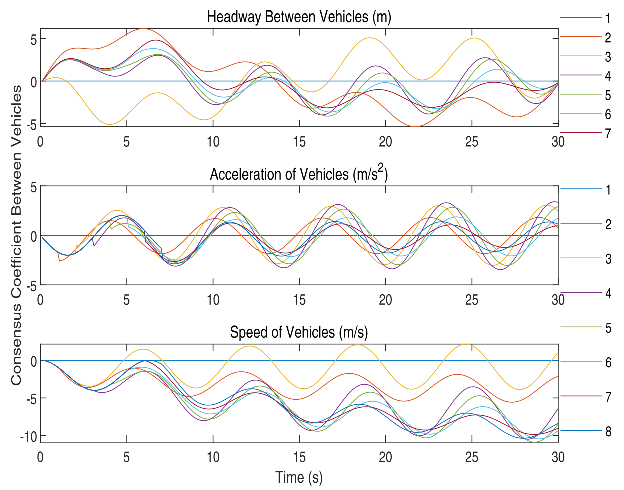


FIGURE 6. Consensus-based error of ACC-cascade.

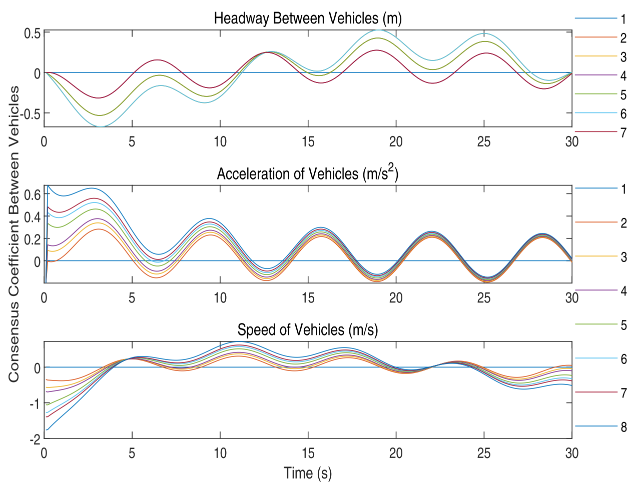


FIGURE 8. Consensus-based error of CACC-granulation.

motion state is similar. But in terms of consensus, the first four vehicles in Figure 4 have better consensus than the first four vehicles in Figure 5. The $delaytime_{ACC}$ in Figure 4 is much larger than the $delaytime_{CACC}$ in Figure 5, so the scalability of ACC-CACC-integration is poor. We proposed a granulating method to avoid the emergence of $delaytime_{ACC}$ in Figure 4, highlighting the advantages of our granulating method.

Evaluating platoon scalability, it means that the information of the leader can be transmitted to the rear vehicle in time. In order to ensure smooth information transmission and avoid the error of the control model itself, we need to evaluate the scalability under the premise of ensuring consensus behavior of platoon.

C. CONSENSUS ANALYSIS

According to *definition* 2, it can be seen from figure 6, 7, 8, the simulated data indicated that the CACC-granulation is better than the others in terms of consensus-based stability. The behavior of the front and rear vehicle is consensus in Fig 8. That is to say, S-Leader in CACC-granulation can be used as the representative of the leader to share the communication burden of leader.

In ACC-cascade of Fig 6, platoon members do not keep up with dynamic of leader because of delay time with sensor. For ACC-CACC-integration, the consensus of acceleration, speed, headway has a jump as shown in fig 7 because of the limitation of leader communication range. Meanwhile, it is not timely to pass the leader vehicle information to the rear vehicle through an ACC control.

In CACC-granulation of Fig 8, the consensus performance of the vehicle in terms of vehicle headway, acceleration and speed is close to perfect, but this only shows that the information that the rear vehicle can receive the leader vehicle in time cannot fully explain the scalability of the vehicle.

In Fig 8, it can be seen that motivation of platoon member is almost the same with leader at headway, acceleration and speed. However, with the simulation time increasing,

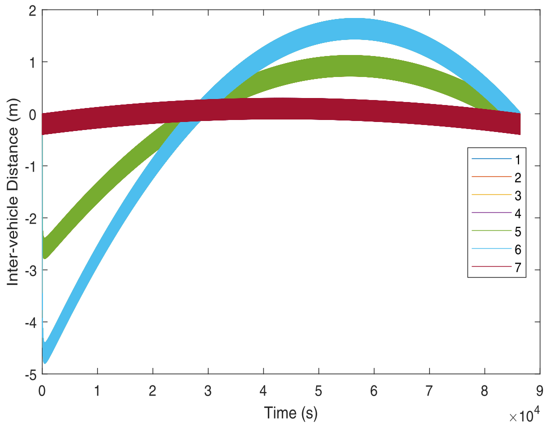


FIGURE 9. 24-hour inter-vehicle error of CACC-granulation.

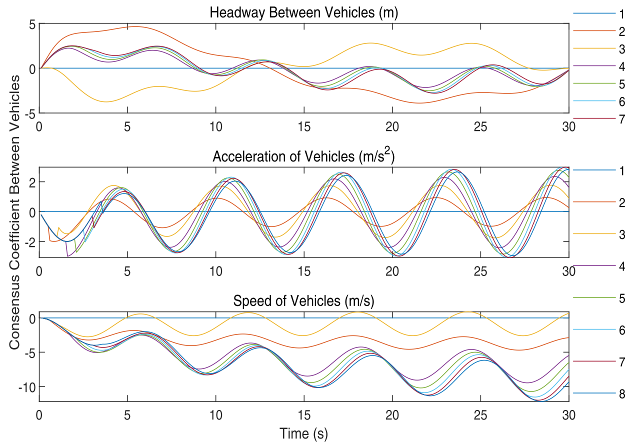


FIGURE 10. Consensus of ACC-cascade under $delaytime_{CACC}$.

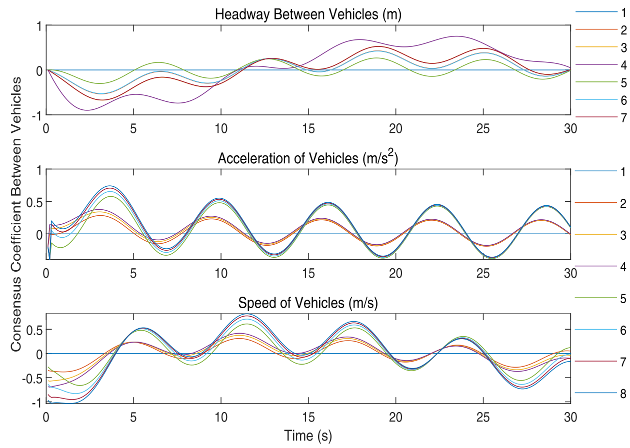


FIGURE 11. Consensus of ACC-CACC-integration under $delaytime_{CACC}$.

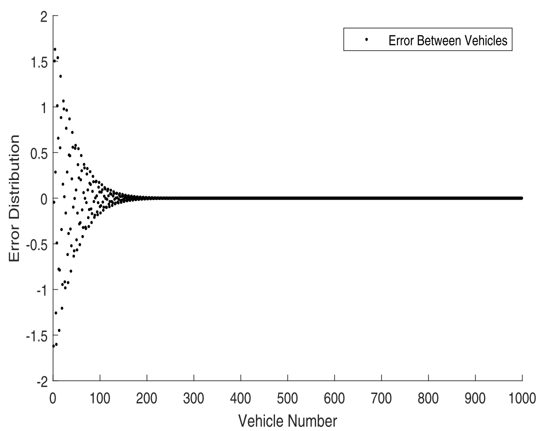


FIGURE 12. Error disturbance of ACC-cascade.

the trend of a slight increase in the distance between vehicles is due to the influence of communication delay. According to formula (14), 24 hours experimental simulation for inter-vehicle distance as follows:

The 30s simulation has a tendency to increase the distance between the predecessor and the vehicle in Fig 8. For Fig 9, the 24-hour inter-vehicle error simulation results show that the inter-vehicle distance range between the vehicle and the previous vehicle is less than the constant distance gap_{des}. That is to say, the consensus-based error is not amplify with t, the platoon is always driving safety, the stability of platoon can always be maintained.

All three schemes of Fig 1 are based on technologies that have been implemented today. In order to prove that the granulating method can improve the platoon consensus. We assume $\Delta t = delaytime_{CACC}$ in ACC-cascade and ACC-CACC-integration.

The consensus coefficient of acceleration is reduced for ACC-cascade in Figure 10. And the consensus coefficient of acceleration, speed and headway are reduced for ACC-CACC-integration in Fig 11. But they have worse consensus than CACC-granulation. In general, ACC-cascade and ACC-CACC-integration consensus does not exceed Figure 8, not because of their different delay-time but because of the superiority of the granulating method.

D. SCALABILITY ANALYSIS

According to definition 3, we analysis the scalability of platoon. Refer the article [48] and formula (14) error disturbances e, we can get results as follows. Simulation is the time of the last vehicle of platoon starts making sinusoidal acceleration changes. The scalability of ACC-cascade as depicted in Fig 12. As the number of vehicles increases, the error disturbance is close to zero, which indicated that the scalability of platoon is better and the convergence speed is very fast. But the error distribution range is relatively large.

The scalability of ACC-CACC-integration as depicted in Fig 13, as the number of vehicles increases, the error disturbance of the vehicle is almost near the zero, but there are always some jumping points due to the additional delay-time. It hardly converges, but the error range is smaller than ACC-cascade. The scalability of CACC-granulation as depicted in Fig 14, with the increase of the number of vehicles, the error disturbance of the vehicle is near to zero. Compared with ACC-cascade, CACC-granulation error distribution range is smaller. But the convergence speed is slower than ACC-cascade. Compared with ACC-CACC-integration,

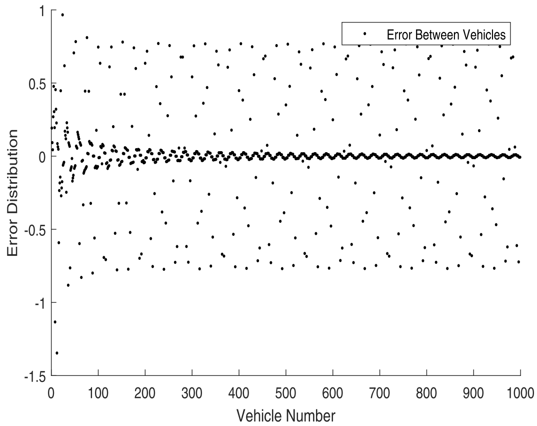


FIGURE 13. Error disturbance of ACC-CACC-integration.

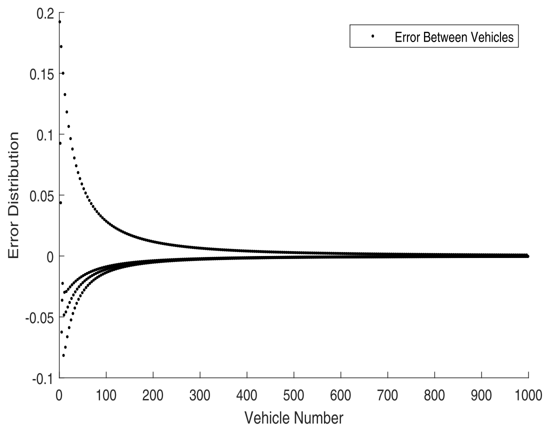


FIGURE 14. Error disturbance of CACC-granulation.

CACC-granulation has a smaller error disturbance and convergence speed.

In general, evaluating platoon scalability is based on stability. ACC-cascade is easy to connect more vehicles, but due to the cascading delay-time, the platoon consensus is worse. The CACC-granulation complements ACC-cascade shortcomings. Although the error disturbance convergence speed is slower than ACC-cascade, the error disturbance is small, the platoon consensus is strong. The ACC-CACC-integration has a good consensus, but has poor scalability because of error disturbance dispersion. Finally, the best method to enhance platoon scalability is CACC-granulation. It has almost perfect platoon consensus and scalability.

VI. CONCLUSION

This paper focuses on improving the scalability of platooning control by using a novel information flow topology based on granulating method. CACC-granulation is proposed, in which the granulating method effectively solve the limitation of leader communication range and accumulated sensor delay. Since the granulating process is reversible, the granulating method simplifies the platoon information flow topology, and also expands the information flow topology of leader through G-Leader. According to the simulation results, CACC-granulation not only maintains platoon consensus but also enhances scalability of platoon. In the future, the influence of the undirected information flow topology on the choice of granulation method is worth studying under different control strategies. For different environment, the choice of communication mode and control strategy for platoon is also crucial.

REFERENCES

[1] D. Jia, K. Lu, J. Wang, X. Zhang, and X. Shen, "A survey on platoon-based vehicular cyber-physical systems," *IEEE Commun. Surveys Tuts.*, vol. 18, no. 1, pp. 263–284, 1st Quart., 2016.

[2] J. Wu, F. Yan, and J. Liu, "Effectiveness proving and control of platoon-based vehicular cyber-physical systems," *IEEE Access*, vol. 6, pp. 21140–21151, 2018.

[3] A. M. Filho, M. H. Terre, and D. F. Wolf, "Safe optimization of highway traffic with robust model predictive control-based cooperative adaptive cruise control," *IEEE Trans. Intell. Transp. Syst.*, vol. 18, no. 11, pp. 3193–3203, Nov. 2017.

[4] *Technical Specification Group Services and System Aspects; Study on Enhancement of 3GPP Support for 5G V2X Services (V16.2.0, Release 16)*, document 3rd Generation Partner Ship Project 22.886, 3GPP, 2018.

[5] R. Rajamani, H.-S. Tan, B. K. Law, and W.-B. Zhang, "Demonstration of integrated longitudinal and lateral control for the operation of automated vehicles in platoons," *IEEE Trans. Control Syst. Technol.*, vol. 8, no. 4, pp. 695–708, Jul. 2000.

[6] A. Ali, "Modeling and control of a platoon of urban autonomous vehicles," Ph.D. dissertation, Res. Inst. Commun. Cybern. Nantes, Nantes, France, 2015.

[7] CBC News. (Jun. 2015). *Google's Newest Self-Driving Cars Hit Public Roads This Summer*. [Online]. Available: http://www.cbc.ca/news/technology/google-s-newest-self-driving-cars-hit-public-roads-this-summer-1.3069370

[8] P. Fernandes and U. Nunes, "Multiplatooning leaders positioning and cooperative behavior algorithms of communicant automated vehicles for high traffic capacity," *IEEE Trans. Intell. Transp. Syst.*, vol. 16, no. 3, pp. 1172–1187, Jun. 2015.

[9] H. Peng, D. Li, K. Abboud, H. Zhou, H. Zhao, W. Zhuang, and X. Shen, "Performance analysis of IEEE 802.11p DCF for multiplatooning communications with autonomous vehicles," *IEEE Trans. Veh. Technol.*, vol. 66, no. 3, pp. 2485–2498, Mar. 2017.

[10] K. Liang, J. Mårtensson, and K. H. Johansson, "Heavy-duty vehicle platoon formation for fuel efficiency," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 4, pp. 1051–1061, Apr. 2016.

[11] Y. Zheng, S. E. Li, J. Wang, L. Y. Wang, and K. Li, "Stability and scalability of homogeneous vehicular platoon: Study on the influence of information flow topologies," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 1, pp. 14–26, Jan. 2016.

[12] Y. Zheng, S. E. Li, K. Li, and W. Ren, "Platooning of connected vehicles with undirected topologies: Robustness analysis and distributed H-infinity controller synthesis," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 5, pp. 1353–1364, May 2018.

[13] S. Li, X. Qin, Y. Zheng, J. Wang, K. Li, and H. Zhang, "Distributed platoon control under topologies with complex eigenvalues: Stability analysis and controller synthesis," *IEEE Trans. Control Syst. Technol.*, vol. 27, no. 1, pp. 206–220, Jan. 2019.

[14] P. Seiler and R. Sengupta, "An H_∞ approach to networked control," *IEEE Trans. Autom. Control*, vol. 50, no. 3, pp. 356–364, Mar. 2005.

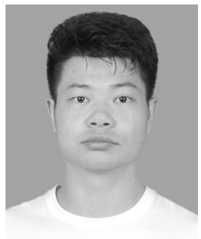
[15] Y. Zheng, S. Li, K. Li, and L.-Y. Wang, "Stability margin improvement of vehicular platoon considering undirected topology and asymmetric control," *IEEE Trans. Control Syst. Technol.*, vol. 24, no. 4, pp. 1253–1265, Jul. 2016.

[16] S. Santini, A. Salvi, A. S. Valente, A. Pescapé, M. Segata, and R. L. Cigno, "A consensus-based approach for platooning with intervehicular communications and its validation in realistic scenarios," *IEEE Trans. Veh. Technol.*, vol. 66, no. 3, pp. 1985–1999, Mar. 2017.

[17] X. Lingyun and G. Feng, "A comprehensive review of the development of adaptive cruise control systems," *Vehicle Syst. Dyn.*, vol. 48, no. 10, pp. 1167–1192, 2010.

[18] K. C. Dey, L. Yan, X. Wang, Y. Wang, H. Shen, M. Chowdhury, L. Yu, C. Qiu, and V. Soundararaj, "A review of communication, driver characteristics, and controls aspects of cooperative adaptive cruise control (CACC)," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 2, pp. 491–509, Feb. 2016.

[19] Z. Wang, G. Wu, and M. J. Barth, "A review on cooperative adaptive cruise control (CACC) systems: Architectures, controls, and applications," in *Proc. IEEE 21st Int. Conf. Intell. Transp. Syst.*, Nov. 2018, pp. 2884–2891.
[20] R. Abou-Jaoude, "ACC radar sensor technology, test requirements, and test solutions," *IEEE Trans. Intell. Transp. Syst.*, vol. 4, no. 3, pp. 115–122, Sep. 2003.
[21] F. Dressler, F. Klingler, M. Segata, and R. L. Cigno, "Cooperative driving and the tactile Internet," *Proc. IEEE*, vol. 107, no. 2, pp. 436–446, Feb. 2019.
[22] F. Martelli, M. Elena Renda, G. Resta, and P. Santi, "A measurement-based study of beaconing performance in IEEE 802.11p vehicular networks," in *Proc. IEEE INFOCOM*, Mar. 2012, pp. 1503–1511.
[23] S. Ucar, S. C. Ergen, and O. Ozkasap, "IEEE 802.11p and visible light hybrid communication based secure autonomous platoon," *IEEE Trans. Veh. Technol.*, vol. 67, no. 9, pp. 8667–8681, Sep. 2018.
[24] M. Segata, B. Bloessl, S. Joerer, C. Sommer, M. Gerla, R. Lo Cigno, and F. Dressler, "Toward communication strategies for platooning: Simulative and experimental evaluation," *IEEE Trans. Veh. Technol.*, vol. 64, no. 12, pp. 5411–5423, Dec. 2015.
[25] M. Segata, "Safe and efficient communication protocols for platooning control," Ph.D. dissertation, Univ. Innsbruck, Innsbruck, Austria, Feb. 2016.
[26] Z. Wang, G. Wu, and M. J. Barth, "Developing a distributed consensus-based cooperative adaptive cruise control system for heterogeneous vehicles with predecessor following topology," *J. Adv. Transp.*, vol. 2017, Aug. 2017, Art. no. 1023654.
[27] 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. Autom. Control*, vol. 51, no. 8, pp. 1315–1319, Aug. 2006.
[28] S. Darbha and P. R. Pagilla, "Limitations of employing undirected information flow graphs for the maintenance of rigid formations for heterogeneous vehicles," *Int. J. Eng. Sci.*, vol. 48, no. 11, pp. 1164–1178, 2010.
[29] Y. Zheng, S. E. Li, J. Wang, L. Y. Wang, and K. Li, "Influence of information flow topology on closed-loop stability of vehicle platoon with rigid formation," in *Proc. 17th Int. IEEE Conf. Intell. Transp. Syst. (ITSC)*, Oct. 2014, pp. 2094–2100.
[30] P. Hońko, "Association discovery from relational data via granular computing," *Inf. Sci.*, vol. 234, pp. 136–149, Jun. 2013.
[31] L. Yan, *Fundamentals of Mathematical Logic and Granular Computing*. Beijing, China: Science Press, 2007, pp. 155–165.
[32] J. Zhang, T. Li, and H. Chen, "Composite rough sets for dynamic data mining," *Inf. Sci.*, vol. 257, pp. 81–100, Feb. 2014.
[33] M. Segata, S. Joerer, B. Bloessl, C. Sommer, F. Dressler, and R. L. Cigno, "Plexe: A platooning extension for veins," in *Proc. IEEE Veh. Netw. Conf. (VNC)*, Dec. 2014, pp. 53–60.
[34] S. E. Li, Y. Zheng, K. Li, and J. Wang, "An overview of vehicular platoon control under the four-component framework," in *Proc. IEEE Intell. Veh. Symp. (IV)*, Jun. 2015, pp. 286–291.
[35] H. Hao, P. Barooah, and P. G. Mehta, "Stability margin scaling laws for distributed formation control as a function of network structure," *IEEE Trans. Autom. Control*, vol. 56, no. 4, pp. 923–929, Apr. 2011.
[36] H. Chehardoli and A. Ghasemi, "Adaptive centralized/decentralized control and identification of 1-D heterogeneous vehicular platoons based on constant time headway policy," *IEEE Trans. Intell. Transp. Syst.*, vol. 19, no. 10, pp. 3376–3386, Oct. 2018.
[37] J. Zhou and H. Peng, "Range policy of adaptive cruise control vehicles for improved flow stability and string stability," *IEEE Trans. Intell. Transp. Syst.*, vol. 6, no. 2, pp. 229–237, Jun. 2005.
[38] C.-Y. Liang and H. Peng, "Optimal adaptive cruise control with guaranteed string stability," *Vehicle Syst. Dyn.*, vol. 32, nos. 4–5, pp. 313–330, Nov. 1999.
[39] G. J. L. Naus, R. P. A. Vugts, J. Ploeg, M. J. G. van de Molengraft, and M. Steinbuch, "String-stable CACC design and experimental validation: A frequency-domain approach," *IEEE Trans. Veh. Technol.*, vol. 59, no. 9, pp. 4268–4279, Nov. 2010.
[40] D. Swaroop and J. K. Hedrick, "Constant spacing strategies for platooning in automated highway systems," *J. Dyn. Syst. Meas. Control*, vol. 121, no. 3, pp. 462–470, 1999.
[41] R. Rajamani, *Vehicle Dynamics and Control*, vol. 6. Springer, 2012.
[42] M. Wang, S. P. Hoogendoorn, W. Daamen, B. van Arem, B. Shyrokau, and R. Happee, "Delay-compensating strategy to enhance string stability of adaptive cruise controlled vehicles," *Transportmetrica B, Trans. Dyn.*, vol. 6, no. 3, pp. 211–229, 2016.
[43] L. Zhang and G. Orosz, "Motif-based design for connected vehicle systems in presence of heterogeneous connectivity structures and time delays," *IEEE Trans. Intell. Transp. Syst.*, vol. 17, no. 6, pp. 1638–1651, Jun. 2016.
[44] M. Segata. *2014-2018 and Contributors*. Accessed: Jun. 1, 2018. [Online]. Available: http://plexe.car2x.org/
[45] D. Swaroop and J. K. Hedrick, "String stability of interconnected systems," in *Proc. Amer. Control Conf.*, vol. 3, Jun. 1995, pp. 1806–1810.
[46] A. Ghasemi, R. Kazemi, and S. Azadi, "Stable decentralized control of a platoon of vehicles with heterogeneous information feedback," *IEEE Trans. Veh. Technol.*, vol. 62, no. 9, pp. 4299–4308, Nov. 2013.
[47] H. Hao and P. Barooah, "Stability and robustness of large platoons of vehicles with double-integrator models and nearest neighbor interaction," *Int. J. Robust Nonlinear Control*, vol. 23, no. 18, pp. 2097–2122, 2013.
[48] P. Seiler, A. Pant, and K. Hedrick, "Disturbance propagation in vehicle strings," *IEEE Trans. Autom. Control*, vol. 49, no. 10, pp. 1835–1842, Oct. 2004.



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