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A Disturbance-Adaptive Design for VANET-Enabled Vehicle Platoon

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***Abstract*—In highway systems, grouping vehicles into *platoons* can improve road capacity and energy efficiency. With the advance of technologies, the performance of platoons can be further enhanced by *vehicular ad-hoc network* (VANET). In the past few years, many studies have been conducted on the dynamics of VANET-enabled platoon under traffic disturbance, which is a common scenario on a highway. However, most of them do not consider the impact of platoon dynamics on the behaviors of VANET. Moreover, most existing studies focus on how to maintain the stability of a platoon, and do not address how to mitigate negative effects of traffic disturbance, such as uncomfortable passenger experience, increased fuel consumption, and increased exhaust emission. In this paper, we will investigate the dynamics of VANET-enabled platoon from an integrated perspective. In particular, we first propose a novel *disturbance-adaptive platoon* (DA-Platoon) architecture, in which a platoon controller shall adapt to the disturbance scenario and shall consider both VANET and platoon dynamics requirements. Based on a specific realization of the DA-Platoon architecture, we then analyze the traffic dynamics inside a platoon and derive desired parameters, including intra-platoon spacing and platoon size, so as to satisfy VANET constraints under traffic disturbance. To mitigate the adverse effects of traffic disturbance, we also design a novel driving strategy for the leading vehicle of platoon, with which we can determine the desired inter-platoon spacing. Finally, we conduct extensive simulation experiments, which not only validate our analysis but also demonstrate the effectiveness of the proposed driving strategy.**

***Index Terms*—Vehicle platoon, traffic disturbance, vehicular ad-hoc networks (VANET), platoon dynamics, platoon parameters, driving strategy, disturbance-adaptive platoon (DA-Platoon), Intelligent Driver Model (IDM).**

I. INTRODUCTION

When traveling on a highway, a group of consecutive vehicles can form a *platoon*, in which a non-leading vehicle maintains a small distance with the preceding one, as shown in Fig. 1. In the literature, it has been shown that there are many benefits to drive vehicles in platoon patterns [1], [2]. First, since adjacent vehicles are close to each other, the road capacity can be increased and the traffic[1] congestion may be decreased accordingly. Second, the platoon pattern can reduce the energy consumption and exhaust emissions considerably because the streamlining of vehicles in a platoon can minimize air drag. Third, with the help of advanced technologies, driving in a platoon can be safer and more comfortable.

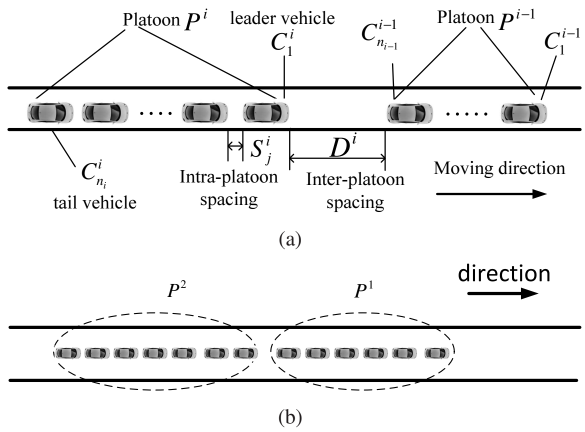

Fig. 1. (a) An example of platoon with platoon parameters, (b) Two large adjacent platoons with small inter-platoon spacing

To facilitate platoons, two important technologies have been introduced in the past decade, specifically, *autonomous cruise control* (ACC) [3] and *vehicular ad-hoc network* (VANETs) [4]–[6]. The ACC system with laser or radar sensors can obtain the distance to the preceding vehicle and can regulate the movements of individual vehicles in a platoon. On the other hand, VANET not only can help to form and maintain a platoon, but also can enable a vehicle to exchange traffic information with neighboring vehicles or infrastructures, which may improve traffic safety, efficiency, and comfortability.

In the past few years, a lot of studies have been conducted on such VANET-enabled platoons [7], which can be classified into two categories. In the first one, studies mainly address VANET issues, such as VANET connectivity, data dissemination protocol and routing techniques, MAC scheduling, etc., [8]–[10], based on an existing platoon. In the second category, most studies are about the traffic dynamics control and performance optimization by managing and controlling platoons [1], [11]–[25], with the help of an existing VANET. In this paper, we assume that a VANET has already been set up and we will investigate the dynamics of a VANET-enable platoon system.

Specifically, we investigate the dynamics of VANET-enabled platoon under traffic disturbance, which is a common scenario on a highway. As an example, Fig. 2 illustrates a typical disturbance scenario [16], where the leading vehicle of a platoon has to decelerate from a stable velocity v_{stb}

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[1] In this paper, "traffic" is limited to the context of vehicle transportation.

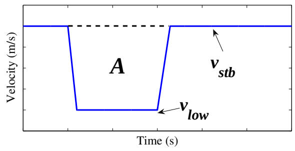
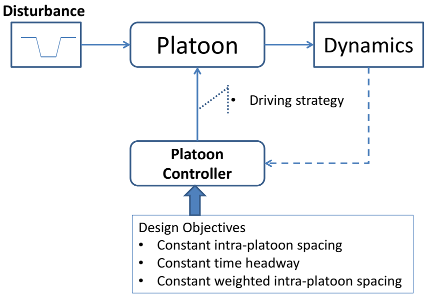
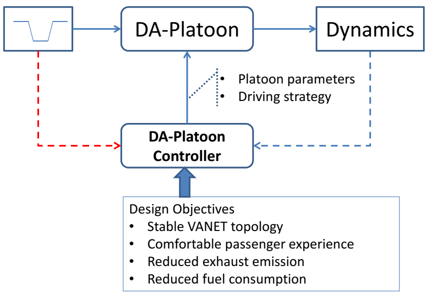


Fig. 2. A typical disturbance scenario.



(a)



(b)

Fig. 3. (a) The platoon dynamic system in existing studies, (b) The DA-platoon dynamic system.

to a lower velocity v_{low}, and then maintains this speed for a period of time before accelerating to the original speed. Clearly, we can consider a formed platoon as a system and regard a disturbance scenario as the input and traffic dynamics as the outputs, as shown in Fig. 3(a).

In practice, such a system may be unstable under certain disturbance scenarios. Therefore, in the literature, most existing studies on VANET-enabled platoon system were focused on maintaining the stability of platoon. Typically, they address the design and evaluation of the platoon controller, which specifies the driving strategy based on the observed traffic dynamics with different design objectives.

For instance, for intra-platoon dynamics, [19] assumed that each vehicle only has the relative position to its preceding vehicle, and assumed that a predecessor-following control strategy is applied. For such a system, the authors studied disturbance propagation in a platoon and showed error amplification of intra-platoon spacing. To maintain constant intra-platoon spacing, predecessor-leader control strategy was proposed in [16] and [18], wherein each vehicle should get information from both its preceding vehicle and the platoon leader. In [21], the constant-time headway policy was applied while each vehicle can get the kinematics status (location, velocity, acceleration, etc.) of the preceding vehicle via VANET.

Although existing studies are important to the applicability of platoon, there are still many open issues. First, it is unclear how platoon dynamics can affect the behaviors of VANET during disturbance. For example, the acceleration of a preceding vehicle can enlarge the gap between vehicles or the distance between adjacent platoons, which may lead to not only platoon splitting but also unreliable V2V communication with high packet loss and large delay. On the other hand, the deceleration of the preceding vehicle may lead to the merger between adjacent platoons with close distance, as shown in Fig. 1(b).

The second issue is that most existing studies focus on how to maintain the stability of a platoon (e.g., constant intra-platoon spacing), and do not address how to mitigate negative effects of traffic disturbances, such as uncomfortable passenger experience, increased fuel consumption, and increased exhaust emission. In practice, traffic disturbances could cause frequently and sharply accelerating and decelerating, which results in not only the uncomfortable driving patterns, but also significant fuel consumption and exhaust emissions [17]. In this case, it will be desirable to utilize the capability of VANET to mitigate such negative effects.

To address these issues, in this paper, we investigate the dynamics of VANET-enabled platoon from an integrated perspective. In particular, we first propose a novel *disturbance-adaptive platoon* (DA-Platoon) architecture, with which a DA-Platoon dynamic system can be defined. As illustrated in Fig. 3(b), the DA-Platoon system includes a controller that shall adapt to the disturbance scenario and shall consider both VANET requirements and platoon dynamics requirements.

Our main contributions in this paper are listed as follows:

1) We propose a novel *disturbance adaptive platoon* (DA-Platoon) architecture in which we consider both traffic dynamics under disturbances and the constraints due to VANET communications.
2) We investigate the characteristic of DA-Platoon dynamics under disturbance. Based on the analytical model, we derive the desired DA-Platoon parameters that can satisfy both traffic dynamics requirements and VANET connectivity requirements.
3) To mitigate the negative effects of traffic disturbances, we propose a novel driving strategy for the leading vehicle of a platoon, with which we can obtain a desired inter-platoon spacing that can help to achieve the desired traffic dynamics and that does not violate the VANET constraints in disturbance scenarios.

The organization of this paper is described as follows. In Section II, we first overview related work, especially on platoon dynamics under traffic disturbances. In Section III, we propose the DA-Platoon architecture, and we specify a particular DA-Platoon scenario to be investigated. In Section IV, we introduce the *intelligent driver model* (IDM), based on which we investigate the dynamics of DA-Platoon and obtain the desired DA-Platoon parameters. In Section V, we propose a novel driving strategy for DA-Platoon leader to mitigate adverse effects between adjacent DA-Platoons in disturbance scenarios. In Section VI, we present numerical results, before concluding the paper in Section VII.

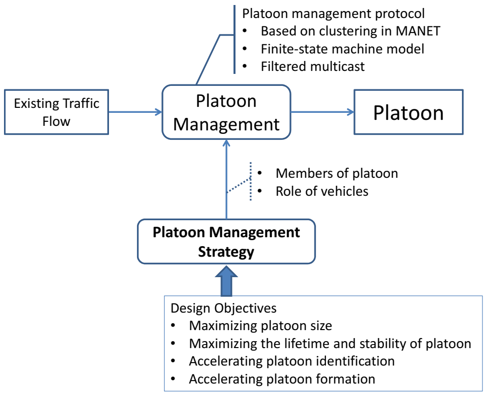


Fig. 4. The platoon management system in existing studies.

II. Related Work

In this section, we first discuss how to manage platoons with the help of VANET. We then elaborate on the platoon dynamics in related work. In particular, we classify existing studies into two groups: intra-platoon and inter-platoon.

A. The Platoon Management System

In the literature, some studies assume that an existing platoon is formed naturally [13], while others consider platoon formation, merging, splitting with the help of VANET [26]. Based on existing studies, we illustrate the platoon management system in Fig. 4. As shown in this figure, existing studies can be distinguished according to the platoon management protocol and the platoon management strategy. The platoon management protocol can enable vehicles to communicate with one another. The platoon management strategy determines the members of a platoon and the roles of individual vehicles based on various design objectives.

In terms of platoon management protocol, a filter-multicast protocol was proposed in [12] to realize dynamic platoon-ID allocation, platoon dynamic formation and management. A finite-state machine model was developed in [14] to describe the operating process of the platooning protocol. In a more general sense, many existing protocols for clustering in mobile ad hoc networks (MANETs) can be applied to support platoon management. For example, Tarik Taleb *et al.* presented a dynamic clustering mechanism to form clusters with a cooperative collision-avoidance (CCA) scheme [6].

In terms of platoon management strategy, [12] categorized vehicles into three roles, master, member and normal vehicle, according to their relative positions and communication range, and then formed platoon based on the roles of nearby vehicles. In [14], the main objective is to quickly identify the platoon, where a prediction scheme was designed to accelerate platoon formation when some vehicles are moving towards a different direction (i.e., platoon splitting). In [1], the objectives included (1) to maximize the platoon size and (2) to maximize the life time of platoon. To reach these goals, the authors designed a scheme to group vehicles based on their destination at the entrance ramp.

Compared to existing studies on platoon management system, our study can be considered as a platoon management strategy, in which our objective is to satisfy both VANET connectivity requirements and traffic dynamics requirements. Therefore, existing platoon management protocols can be used to form a platoon with the desired platoon parameters.

B. Intra-Platoon Dynamics

For a single platoon, many previous studies have been focused on the intra-platoon dynamics, which describe the transient and steady responses of a platoon, including intra-platoon spacing, velocity and acceleration trajectory of each vehicle, etc., under certain spacing policy and control strategy [18]–[20].

In [19], the authors analyzed disturbance propagation in a platoon and showed error amplification of intra-platoon spacing under a *predecessor-following* control strategy, in which each vehicle only has the relative position to its preceding one. To maintain constant intra-platoon spacing, *predecessor-leader* control strategy [18] is proposed wherein each vehicle should get information from both its preceding vehicle and the platoon leader. To realize this strategy, the *cooperative ACC* (CACC) has been proposed to maintain the stability of a given platoon [15], [16], [21]–[23].

Theoretical and experimental results showed that V2V communications enable driving at small inter-vehicle distances while string stability is guaranteed. A general design of the CACC system has been proposed in [21] adopting *constant-time headway* policy in a decentralized control framework. In [16], it has been shown that the *constant-spacing* policy with V2V communications can increase the traffic throughput. A new platoon control method, called *consensus control*, is proposed in [23], where vehicles are deployed to converge the weighted intra-platoon spacing to a constant and maintain a constant platoon length at the same time.

Normally a vehicle has two operational modes: spacing control mode and speed control mode. To get an optimized traffic flow performance, it is critical for the vehicle to design a suitable switching logic that decides when to switch between the two operational modes. In [25], a switching strategy is proposed for ACC-equipped vehicles in platoon, which designs a constant-deceleration spacing control model by way of Range (R) vs. Range-rate diagram.

Despite the potentials, it is very challenging to apply VANET for intra-platoon control because it is still difficult to guarantee reliable communications in realistic scenarios, where transmission delay and errors can occur due to the mobility of vehicles, the transmission contention, and the topology change in VANET. Therefore, in this paper we only apply ACC for intra-platoon control. In particular, we apply the *Intelligent Driver Model* (IDM), which is essentially based on the *constant-time headway* control.

C. Inter-Platoon Dynamics

For multiple platoons, existing studies have been mainly focused on platoon merging and splitting. Several major projects have proposed inter-platoon coordination model, such as the PATH project and The AUTO21 CDS framework [7], aiming at developing communication and coordination methodologies

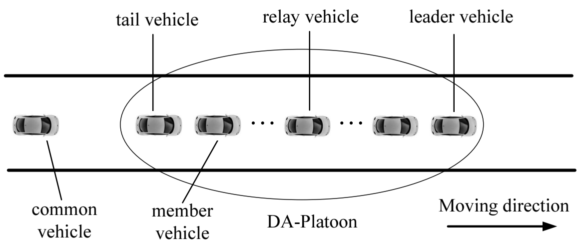


Fig. 5. DA-Platoon architecture

for platoon merging and splitting actions. The authors in [24] investigated inter-platoon dynamics, where smooth platoon merging is regulated by a proportional controller which supplies an acceleration to the leading vehicle of a following platoon that is proportional to the inter-platoon spacing. When two platoons move close to a certain distance, the leading vehicle of the following platoon will switch to the intra-platoon spacing control strategy. In [15], it has been demonstrated that significant disturbance can propagate from a preceding platoon to the following one if two large adjacent platoons have small inter-platoon spacing, as illustrated in Fig. 1 (b).

Clearly, how the merging or splitting affect the VANET has not been a major concern. For instance, if two large platoons merge into a "huge" one after the disturbance, serious VANET connectivity problems may occur due to unreliable multi-hop data transmission. Note that V2V communication in such huge platoon is more vulnerable to uncertain transmission delay in VANET with contention-based access mechanism [27], which could cause vital results in critical safety applications.

In this paper, we consider that adjacent platoons should maintain suitable inter-platoon spacing. To this end, we design a novel platoon architecture that can alleviate the traffic disturbance and can efficiently enable cooperative strategy among consecutive platoons, which will be discussed in the next section. In Section V, we will also propose a new driving strategy for the leading vehicle of platoon, whose main idea is to allow the leading vehicle to react to the disturbance as soon as necessary, which has not been reported in the literature.

III. The DA-Platoon Architecture

In this section, we first propose a general DA-Platoon architecture. We then specify one particular instance to be investigated.

A. The DA-Platoon Architecture

Although there are many existing studies on the platoon dynamic system under disturbance, we note that there are still many open issues, including the impact of platoon dynamics on VANET behaviors and how to mitigate negative effects due to traffic disturbance. To address these important issues, we propose a new *disturbance adaptive platoon* (DA-Platoon) architecture, where we jointly consider VANET requirements and traffic dynamics requirements under disturbances.

Fig. 5 illustrates a general architecture of DA-Platoon. In this architecture, vehicles can communicate through VANET. Vehicles of one platoon share a unique DA-Platoon identification (ID). According to the spatial position and functionalities, members in a platoon can be classified into four roles: leader, relay, tail, and member.

- *Leader*: The leader is the leading vehicle in the platoon. It is responsible for creating and managing the platoon, e.g., identifying and periodically broadcasting the DA-Platoon ID, deciding whether a vehicle can join the platoon and then assigning role to the vehicle, and determining whether a platoon shall be split or whether two platoons shall be merged into one.
- *Tail*: The tail vehicle locates at the end of a platoon. It is responsible for communicating with the following vehicles, especially the leader of the next platoon.
- *Relay*: The relay vehicles act as data-forwarding nodes in a multi-hop VANET environment. In this way, the information from the leader can be efficiently disseminated to all vehicles in a platoon.
- *Member*: Other member vehicles are regular vehicles that receive information from the relay and shall follow a specified driving strategy.

With such a design, the topology of VANET becomes simpler because a backbone is formed by the leader, relays, and tail. Moreover, the few relays can efficiently determine the transmission schedule of each vehicle in the platoon, which can significantly improve the reliability of VANET communications.

As noted in Section II, we consider our design as a platoon management strategy. Therefore, we can apply existing platoon management protocols to facilitate the implementation of the management strategy.

B. Specification for A DA-Platoon Scenario

1) Platoon Parameters: To facilitate further discussions, we let intra-platoon spacing be the distance between adjacent vehicles in the same platoon, and we let inter-platoon spacing be the gap between the tail of a preceding platoon and the leader of the next platoon. Based on these definitions, we can define platoon parameters, as illustrated in Fig. 1(a), where P^i means the i-th platoon, C^i_j denotes the j-th vehicle in P^i, S^i_j denotes the intra-platoon spacing between C^i_{j-1} and C^i_j, and D^i is the inter-platoon spacing between P^{i-1} and P^i.

2) Knowledge of Traffic Information: To acquire traffic information, we assume that each vehicle is equipped with *global positioning system* (GPS) and other sensors that can collect all needed local information from neighbors, including acceleration, velocity, location, direction, etc. In addition, ACC and VANET components are equipped on each vehicle.

3) The VANET Communication Model: From a physical layer perspective, many factors may affect VANET connectivity, such as transmission range, transmit power, data rate, interference, etc. As an initial step of our investigation, in this paper, we only consider the transmission range as the major impact on VANET connectivity. Moreover, to reliably deliver data amongst vehicles, we deem that the topology of the VANET shall be maintained even under disturbances.

TABLE I
NOTATIONS

a	the maximum acceleration
a_j^i	the acceleration of C_j^i
b	the comfortable deceleration
D^{des}	the desired inter-platoon spacing
D^i	the inter-platoon spacing between P^{i-1} and P^i
D_{MTR}	the fixed minimum transmission range
d_0	the minimum inter-platoon spacing (at standstill)
l^i	the length of platoon P^i
L_0	the length of a vehicle
n^i	the number of vehicles in platoon P^i
S_j^i	intra-platoon spacing between C_{j-1}^i and C_j^i
s_0	minimum intra-platoon spacing (at standstill)
T_0	the desired time headway
v_0	the maximum speed
v_j^i	the velocity of C_j^i
x_j^i	the position of C_j^i

4) The Platoon Driving Strategy: Due to strong interaction among adjacent vehicles within the same platoon, the most common vehicle mobility model is the *car-following* model, which can effectively describe ACC-equipped platoon dynamics [28]. In this paper, we consider that all vehicles, except the leaders, move according to a car-following model.

For the leader of a platoon, on the other hand, it is important to maintain suitable inter-platoon spacing between two adjacent platoons in some cases. Therefore, the leader is supposed to be controlled by a certain strategy with the help of V2V communications, which will be addressed in section V.

In summary, different from traditional platoon or cluster proposed for VANET, our DA-Platoon takes into consideration both the vehicle mobility and VANET connectivity, which will be demonstrated in the following sections.

IV. INTRA-PLATOON DYNAMICS AND PARAMETERS

In this section, we first present key assumptions regarding DA-Platoon. We then introduce the *Intelligent Driver Model* (IDM), with which we further investigate the corresponding platoon dynamics. Based on the understanding of the dynamics, we then investigate platoon parameters, including intra-platoon spacing and platoon size, under consideration of VANET connectivity in disturbance scenarios.

A. Assumptions and Notations

1) Identical vehicle: To simplify the analysis, we assume that a DA-Platoon consists of identical vehicles driving on a single lane (which means overtake is not allowed for the vehicle).

2) Disturbance Scenario: In this paper, we consider the classic "stop and go" scenario [4] for traffic disturbance. Specifically, the disturbance scenario is defined as the velocity trajectory of C_1^i, which initially changes its velocity from v_{stb} to a lower velocity v_{low}, then maintains at v_{low} for a period of time, and finally resumes to v_{stb}, as shown in Fig. 2. Note that the semantics of disturbance is different from the small perturbation in vicinity of the velocity v_{stb}.

3) Notations: To facilitate further discussions, important notations are summarized in table I, where variables have been sorted according to the alphabetic order. Note that, for convenience, the platoon index is skipped in the rest of this section because we are discussing a single platoon.

B. The Intelligent Driver Model (IDM)

In general, a car-following model can be described as a function $f(S, v, \Delta v)$, which determines the acceleration of a vehicle at time t by:

$$a_j(t) = \frac{dv_j(t)}{dt} = f(S_j(t), v_j(t), \Delta v_j(t)), \tag{1}$$

where the acceleration of vehicle C_j depends on its own velocity $v_j(t)$, the intra-platoon spacing $S_j(t)$, and the velocity difference $\Delta v_j(t) := v_j(t) - v_{j-1}(t)$ to the preceding vehicle. To implement the car-following model in a vehicle, practically numerical integration should be executed on vehicle by the following equations [29]:

$$v_j(t + \Delta t) = v_j(t) + a_j(t)\Delta t \tag{2}$$

$$x_j(t + \Delta t) = x_j(t) + v_j(t)\Delta t + \frac{1}{2}a_j(t)\Delta t^2 \tag{3}$$

where x_j is the position of C_j and the intervals Δt is called update time. For ACC-equipped vehicles, these operations are executed automatically and normally the update time can be set to a small value (about 100ms order). Therefore, we can regard DA-Platoon dynamics as strictly conforming to the time-continuous car-following model.

In this paper, we apply a typical car-following model for ACC-equipped vehicle, knows as the *Intelligent Driver Model* (IDM) [30], which is based on the stimulus-response approach and can be expressed as follows:

$$S_j^*(t) = s_0 + v_j(t)T_0 + \frac{v_j(t)\Delta v_j(t)}{2\sqrt{ab}} \tag{4}$$

$$a_j(t) = a\Big[1 - \Big(\frac{v_j(t)}{v_0}\Big)^4 - \Big(\frac{S_j^*(t)}{S_j(t)}\Big)^2\Big] \tag{5}$$

where $S_j^*(t)$ is the desired gap to the preceding vehicle and the other parameters can be found in Table I. In the IDM, the instantaneous acceleration consists of a free acceleration on the road where no other vehicles are ahead $a[1-(v_j(t)/v_0)^4]$, and an interaction deceleration with respect to its preceding vehicle $-a(S_j^*(t)/S_j(t))^2$.

Fig. 6 illustrates traffic dynamics of DA-Platoon consisting of 10 vehicles implemented by the Simulation of Urban Mobility (SUMO) [31] traffic simulator.

We can see that, when the leader experienced a disturbance, the following vehicles did not strictly change their velocities with the leader in that some distortions as well as the overshoot occurred in the velocity curve. As a result, the platoon length also varied when experiencing disturbance. In Fig. 6, the stable length is about 400m, while there also appears an overshoot of 450m during the disturbance period. Therefore, to guarantee VANET connectivity for the DA-Platoon, the impact of traffic disturbance cannot be ignored.

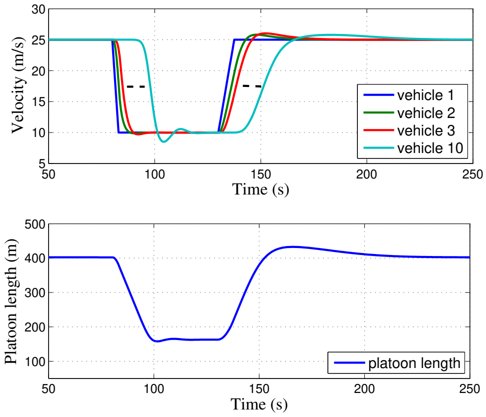


Fig. 6. Traffic dynamics of a DA-Platoon in disturbance scenario.

C. The DA-Platoon Dynamics

To investigate vehicle dynamics, linearization is applied in [29] for a car-following model at the equilibrium point, which shows that the intra-spacing deviation can be expressed as typical damped linear oscillator. Based on this method, we further explore how the related parameters influence the platoon dynamics regulated by the IDM. Next, we first define the equilibrium point as below.

Definition 1 (Equilibrium point of DA-Platoon): A DA-Platoon is at an equilibrium point e if the velocity differences and accelerations for all vehicles in the same platoon are equal to 0, i.e., $\forall j > 1$,

$$a_j(t) = 0, \Delta v_j(t) = 0, v_j(t) = v_{j-1}(t) = v_e,$$

where v_e is called the equilibrium velocity at e.

With this definition, we have the following lemma.

Lemma 1: For the IDM, the intra-platoon spacing of DA-Platoon is locally asymptotically stable at any equilibrium point e.

Proof: To prove this lemma, we first perform the linearization at equilibrium point e for DA-Platoon dynamics proposed in [29]. The velocity $v_j(t)$ is split into the velocity of the preceding vehicle $v_{j-1}(t) = v_e$ and the velocity difference $\Delta v_j(t)$, and the gap $S_j(t)$ is split into the equilibrium intra-platoon spacing S_e and a small deviation $y_j(t)$, that is

$$v_j(t) = v_e + \Delta v_j(t) \tag{6}$$

$$S_j(t) = S_e + y_j(t) \tag{7}$$

Using the method in [29], we can derive a second order linear differential equation for the gap deviation:

$$\frac{d^2 y_j(t)}{dt^2} + 2\zeta\omega_0 \frac{dy_j(t)}{dt} + \omega_0^2 y_j(t) = 0 \tag{8}$$

which represents a typical damped linear oscillator. In Eq. (8), ω_0 is the *natural frequency* of the system and ζ is referred to as the *damping ratio* for the system, which can be calculated by

$$\omega_0^2 = \left.\frac{\partial f}{\partial S}\right|_e \tag{9}$$

$$\zeta\omega_0 = -\frac{1}{2}\left(\left.\frac{\partial f}{\partial v}\right|_e + \left.\frac{\partial f}{\partial \Delta v}\right|_e\right) \tag{10}$$

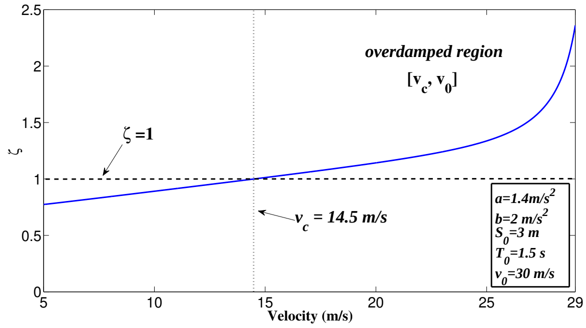


Fig. 7. Relationship between ζ and velocity

By applying the IDM expressions Eq. (4) and Eq. (5), the relevant equilibrium derivatives are given by:

$$\frac{\partial f}{\partial S} = \frac{2a(S_j^*)^2}{S^3}, \frac{\partial f}{\partial v} = -\frac{4av^3}{v_0^4} - \frac{2aT_0 S_j^*}{S^2}, \frac{\partial f}{\partial \Delta v} = -\frac{avS_j^*}{S^2\sqrt{ab}} \tag{11}$$

The eigenvalues of Eq. (8) are $\lambda = -\zeta\omega_0 \pm \sqrt{\omega_0^2(\zeta^2 - 1)}$. To guarantee the local asymptotical stability, ζ and ω_0 should be both positive, which obviously can be satisfied by IDM. ■

For a DA-Platoon consisting of n vehicles, the total equilibrium deviation $\sum_{j=2}^{n} y_j(t)$ will converge to 0 as $t \to \infty$, which means the the DA-Platoon length will converge to constant at any equilibrium point e.

Furthermore, considering the damping ratio:

(1) If $\zeta \geq 1$, then we get negative real eigenvalues, and Eq. (8) is called *overdamped*. In this case, the gap deviation $y_j(t)$ experiences no overshoot from the transient stage to the final equilibrium point, which leads to monotonic accelerations or decelerations process for the following vehicle.

(2) If $0 < \zeta < 1$, then the solution is oscillatory and Eq. (8) is said to be *underdamped*. In this case, the gap deviation $y_j(t)$ will overshoot and oscillate near the equilibrium point with certain frequency, which means the following vehicle will experience numerous alternations of acceleration and deceleration before getting back to the equilibrium point.

Therefore, the damping ratio ζ plays an important role in determining the characteristic of DA-Platoon traffic dynamics. To understand the relationship between ζ and v_e, we set reasonable IDM parameters and illustrate ζ vs. v_e in Fig. 7, where we can observe that ζ is monotonically increasing with v_e. In our analysis, this rule holds if IDM parameters are set in a reasonable range.

Here we define the critical velocity v_c at point $\zeta = 1$. Combining Eq. (9) and Eq. (10), we can derive the following equation:

$$\frac{\partial f}{\partial S}|_{v_c} = \frac{1}{4}\left(\frac{\partial f}{\partial v}|_{v_c} + \frac{\partial f}{\partial \Delta v}|_{v_c}\right)^2 \tag{12}$$

By substituting Eq. (11) and Eq. (4) into Eq. (12), we can derive Eq. (13) and obtain v_c accordingly. Obviously, the region $[v_c, v_0]$ corresponding to $\zeta \geq 1$ is called overdamped region, as shown in Fig. 7.

D. Equilibrium intra-platoon Spacing

Intra-platoon spacing determined by IDM is calculated as follows.

$$\frac{2av_c^3}{v_0^4}+\frac{aT_0\left(1-\left(\frac{v_c}{v_0}\right)^4\right)}{s_0+v_cT_0}+\frac{av_c\left(1-\left(\frac{v_c}{v_0}\right)^4\right)}{2\sqrt{ab}(s_0+v_cT_0)}=\frac{\sqrt{2a}\left(1-\left(\frac{v_c}{v_0}\right)^4\right)^{0.75}}{\sqrt{s_0+v_cT_0}} \tag{13}$$

Lemma 2: The intra-platoon spacing $S_j(t)$ is a monotonically increasing function of the velocity $v_j(t)$, and at the equilibrium point e,

$$S_e=\frac{S_e^*}{\sqrt{1-\left(\frac{v_e}{v_0}\right)^4}}=\frac{s_0+v_eT_0}{\sqrt{1-\left(\frac{v_e}{v_0}\right)^4}} \tag{14}$$

Proof: According to Eq. (5) and Eq. (4), we can calculate the intra-platoon spacing:

$$S_j(t)=\frac{s_0+v_j(t)T_0+\frac{v_j(t)\Delta v_j(t)}{2\sqrt{ab}}}{\sqrt{1-\left(\frac{v_j(t)}{v_0}\right)^4-\frac{a_j(t)}{a}}} \tag{15}$$

Obviously we can see that $S_j(t)$ is monotonically increasing with the velocity $v_j(t)$.

When DA-Platoon is at equilibrium point e, according to definition 1, we have $a_j(t)=0$, $\Delta v_j(t)=0$ and $v_j(t)=v_e$. By substituting these values into Eq. (15), we can get the equilibrium intra-platoon spacing Eq. (14). ■

E. Platoon Size

In previous discussions, we have obtained analytical results about intra-platoon spacing. In this subsection, we investigate the maximal platoon size n. To facilitate the discussions, we assume that there is only one relay vehicle C_r in the middle of the platoon. As shown in Fig. 5, to maintain the VANET topology in the DA-Platoon, we further assume that the distance between the relay and every vehicle is less than D_{MTR}. In other words, both distance $l_{1,r}$ (between C_r and C_1) and distance $l_{r,n}$ (between C_r and C_n) are suppose to be no more than D_{MTR}, that is:

$$\begin{cases} l_{1,r}=r\times L_0+\sum\limits_{j=2}^{r}s_j(t)\\ \quad =r\times L_0+\sum\limits_{j=2}^{r}S_e+\sum\limits_{j=2}^{r}y_j(t)\le D_{MTR};\\ l_{r,n}=(n-r)\times L_0+\sum\limits_{j=r+1}^{n}s_j(t)\\ \quad =(n-r)\times L_0+\sum\limits_{j=r+1}^{n}S_e+\sum\limits_{j=r+1}^{n}y_j(t)\le D_{MTR}. \end{cases} \tag{16}$$

Next, we generalize a disturbance scenario into three cases and evaluate the platoon size respectively.

1) If $v_{low}\ge v_c$: In this case the velocity trajectory of platoon is in overdamped region and the corresponding intra-platoon spacing has no overshoot at the final equilibrium $v_e=v_{stb}$, i.e., $y_j(t)\le 0$. Accordingly, the constraints Eq. (16) can be rewritten as follows:

$$\begin{cases} r\times L_0+(r-1)\times S_e\le D_{MTR}\\ (n-r)\times L_0+(n-r)\times S_e\le D_{MTR}\end{cases} \tag{17}$$

Thus we get the constraint $r\le\left\lfloor\frac{D_{MTR}+S_{stb}}{L_0+S_{stb}}\right\rfloor$. Moreover, if the relay vehicle is selected as the one at about the spatial center of DA-Platoon by calculating the center position between the referred leader vehicle and tail vehicle, i.e., $n=2r-1$, we can get the maximum platoon size in this case.

$$n\le 2\left\lfloor\frac{D_{MTR}+S_{stb}}{L_0+S_{stb}}\right\rfloor-1 \tag{18}$$

2) If $v_{low}<v_c$ and $v_{stb}\ge v_c$: In this case the intra-platoon spacing will experience overshoot but without oscillation before return to equilibrium v_{stb}. Accordingly, the maximum $y_j(t)$ nonlinearly varies with many factors and is intractable. Nevertheless, numerous experiments show that if there are enough members between two vehicles within the same DA-Platoon, the total overshoot $\sum y_j(t)$ between the two vehicles will converge to 0. Therefore, normally we can approximately calculate the platoon size by Eq. (18).

3) If $v_{stb}<v_c$: In this case the intra-platoon spacing is underdamped and will oscillate around the equilibrium S_{stb}. Moreover, $\sum y_j(t)$ cannot be regarded as approximately equal to zero in this condition. To estimate the maximum platoon size n, we first introduce a simple parameter θ_1 to estimate the approximate intra-platoon spacing: $\widetilde{S}_{stb}=(1+\theta_1)S_{stb}$, where normally we can limit θ_1 in a reasonable experimental range. To conservatively estimate platoon size, θ_1 should be set to its maximum. Then n can be calculated similar to Eq. (18):

$$n\le 2\left\lfloor\frac{D_{MTR}+S_{stb}}{L_0+\widetilde{S}_{stb}}\right\rfloor-1 \tag{19}$$

Finally, we note that the above analysis can be extended for the DA-Platoon with multiple relay vehicles and different transmission range cases.

V. A Novel Driving Strategy for Platoon Leaders

In this section, we propose a driving strategy for leaders in DA-Platoon that exploits V2V communications. We first discuss and justify the objectives of our design. To achieve the design goals, we then elaborate on the strategy. Finally, we investigate a key platoon parameter, i.e., the desirable inter-platoon spacing.

A. The Design Objectives

In general, the outcome of a driving strategy can be represented by the velocity trajectory, over time, of a vehicle. In this section, we aim to design a driving strategy that considers two main objectives associated with the velocity trajectory, namely, improving the comfortability and reducing the fuel consumption during disturbance.

Usually, drivers and passengers feel uncomfortable during sharp acceleration and deceleration. On the other hand, frequent and sharp acceleration and deceleration significantly consume more fuel and thus emit more exhaust [17]. Therefore, to bring more comfortable driving experience and to reduce fuel consumption, we will design a driving strategy that smooth the acceleration and deceleration.

To evaluate the overall acceleration and deceleration during the disturbance period, we utilize the metric of acceleration noise [17], which is defined as the standard deviation of acceleration:

$$AN_j = \sqrt{\frac{1}{T}\int_0^T (a_j(t) - \bar{a}_j)^2 dt} \tag{20}$$

where $\bar{a}_j$ is the average acceleration and we assume that a disturbance occurs during a time period from 0 to T. Since $\bar{a}_j$ can be described by

$$\bar{a}_j = \frac{1}{T}\int_0^T a_j(t)dt = \frac{1}{T}(v_j(T) - v_j(0)), \tag{21}$$

we note that $\bar{a}_j = 0$ in our disturbance scenario.

B. The Driving Strategy for Platoon Leaders

In our previous analysis, we have seen that there are two velocity states in disturbance scenario, including the stable state when the velocity is about v_{stb} and acceleration is about 0, and the disturbance state when the vehicle is experiencing the traffic disturbance. Therefore, it is reasonable to design a driving strategy for platoon leaders according to the present state.

Particularly, for the stable state, we adopt the *constant-spacing* controller proposed in [18] that utilizes a sliding mode approach. This control mechanism can ensure a constant desired inter-platoon spacing D^{des}, using only the velocity information of the tail of the preceding platoon. According to [18], the control law of C_1^i can be described by:

$$\varepsilon^i = D^i - D^{des} \tag{22}$$

$$a_1^i = a_{n^{i-1}}^{i-1} - 2\xi\omega_n\dot{\varepsilon}^i - \omega_n^2\varepsilon^i \tag{23}$$

where ε^i is the inter-platoon spacing error, ω_n is a control gain representing the bandwidth of the controller, normally taken as 0.2, ξ is a control gain representing the damping coefficient, typically taken as 1.

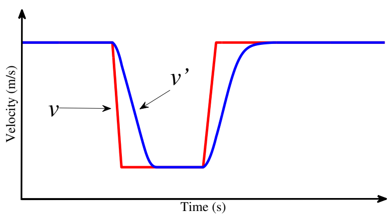


Fig. 8. Two acceleration/deceleratio schemes in the same disturbance scenario.

For disturbance state, our primary objective is to minimize the acceleration noise. Intuitively, for a given disturbance scenario, we can reduce the acceleration noise by prolonging the corresponding acceleration/deceleration phase. As an example, Fig. 8 depicts two different velocity trajectories in the same disturbance. Obviously, v' represents smoother acceleration and deceleration phases than those of v.

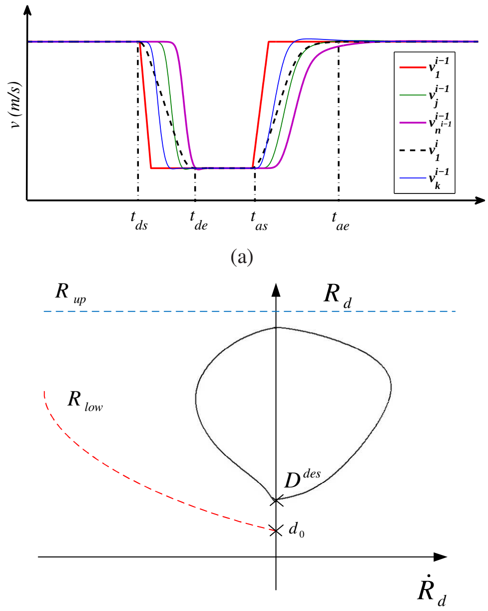


Fig. 9. (a) Velocity trajectories of vehicles in P^{i-1}, (b) Range vs. Range-rate of C_1^i and $C_{n^{i-1}}^{i-1}$.

To achieve v'-like velocity trajectory for C_1^i, we shall first understand the velocity trajectories of vehicles in P^{i-1}. To this end, Fig. 9 (a) shows typical velocity trajectories of vehicles in platoon P^{i-1} (represented by solid lines), where t_{ds} denotes the time at which C_1^{i-1} begins to decelerate, t_{de} represents the moment that $C_{n^{i-1}}^{i-1}$ first decelerates to v_{low}, t_{as} denotes the epoch that C_1^{i-1} starts to accelerate, and t_{ae} represents the moment that $C_{n^{i-1}}^{i-1}$ first resumes to v_{stb}. Clearly, $[t_{ds}, t_{ae}]$ denotes the disturbance duration of the total platoon.

Based on the aforementioned principle, to reduce the acceleration noise, C_1^i shall accelerate/decelerate as long as possible. Therefore, we can design a strategy such that C_1^i can smoothly decelerate from t_{ds} to t_{de}, and accelerate from t_{as} to t_{ae}, as shown by the dash line v_1^i in Fig. 9 (a). Such a trajectory can be obtained by a linear combination of all vehicles' acceleration in P^{i-1}, which is:

$$a_1^i = \sum_{j=1}^{n^{i-1}} \lambda_j a_j^{i-1} \tag{24}$$

where $\forall j$, $\lambda_j \geq 0$ and $\sum_{j=1}^{n^{i-1}} \lambda_j = 1$.

Next, to realize the designed velocity trajectory, two constraints have to be satisfied:

1) D^i should not be too small to avoid collision between $C_{n^{i-1}}^{i-1}$ and C_1^i.
2) D^i should not be too large to guarantee connectivity between two adjacent platoons.

We then utilize the Range (R) vs. Range-rate diagram [32] to identify the constraints. Here the Range (R) vs. Range-rate diagram describes the relationship of the relative position and relative velocity of the pair: (C_1^i, $C_{n^{i-1}}^{i-1}$), that is,

$$R_d = D^i; \dot{R}_d = v_{n^{i-1}}^{i-1} - v_1^i \tag{25}$$

which is shown in Fig. 9 (b). In this figure, the lower and upper boundaries are imperative to guarantee C_1^i not colliding with $C_{n^{i-1}}^{i-1}$ and maintain connectivity in the meantime, which are given in Eq. (26) and Eq. (27), respectively.

$$R_{low} = \frac{\dot{R}_d^{\,2}}{2b} + d_0 \tag{26}$$

$$R_{up} = D_{MTR} \tag{27}$$

With the discussion above, we can formally describe our driving strategy for the leader of DA-Platoon.

1) In the stable state, C_1^i drives under the spacing control mode Eq. (23) to maintain a desired inter-platoon spacing D^{des} between two adjacent platoons P^{i-1} and P^i.
2) When disturbance occurs, C_1^i will receive the disturbance information from C_1^{i-1} and the corresponding control strategy depends on the following conditions.
   a) when $D^i > R_{low}$, then C_1^i shall regulate its acceleration by Eq. (28) where we let all λ_j be the same to simplify the design.

$$a_1^i = \frac{1}{n^{i-1}} \sum_{j=1}^{n^{i-1}} a_j^{i-1}, \tag{28}$$

   b) when $D^i \le R_{low}$, which means the distance between C_1^i and $C_{n^{i-1}}^{i-1}$ is too close, C_1^i shall switch back to the spacing control mode Eq. (23) to maintain desired inter-platoon spacing to $C_{n^{i-1}}^{i-1}$.
   c) when P^{i-1} is close to the stable state, i.e., $v_1^{i-1} \approx v_{n^{i-1}}^{i-1} \approx v_{stb}$ and $l_{i-1} \approx n^{i-1}L_0 + (n^{i-1}-1)S_{stb}$, then C_1^i switch to the spacing control mode.

C. The Desired Inter-Platoon Spacing

In this subsection we investigate the range of D^{des} under the proposed leader driving strategy. In Fig. 9 (a), we can first observe that, at the time t_{de}, D^i gets the maximum:

$$D^i|_{t=t_{de}} = \int_{t_{ds}}^{t_{de}} (v_{n^{i-1}}^{i-1} - v_1^i)dt + D^{des} \tag{29}$$

where the integral part can be theoretically derived according to Eq. (28) as well as the IDM model Eq. (5).

To simplify the derivation, we first estimate the square A_{diff} enclosed by v_1^{i-1} and $v_{n^{i-1}}^{i-1}$ in the deceleration phase $[t_{ds}, t_{de}]$, which is obtained by

$$\begin{aligned} A_{diff} &= \int_{t_{ds}}^{t_{de}} (v_{n^{i-1}}^{i-1} - v_1^{i-1})dt = l_{i-1}|_{t=t_{ds}} - l_{i-1}|_{t=t_{de}} \\ &\le 2D_{MTR} - n^{i-1}L_0 - (n^{i-1}-1)(1+\theta_1)S_{low} \\ &\approx 2D_{MTR} - n^{i-1}L_0 \\ &\quad - (n^{i-1}-1)(1+\theta_1)(s_0 + v_{low}T_0) \end{aligned} \tag{30}$$

where S_{low} denotes the intra-platoon spacing at velocity v_{low}.

Based the observation in Fig. 9 (a), we can estimate the integral part of Eq. (29) by introducing parameter θ_2 and

$$\int_{t_{ds}}^{t_{de}} (v_{n^{i-1}}^{i-1} - v_1^i)dt \approx \theta_2 A_{diff}, 0 < \theta_2 < 1 \tag{31}$$

According to our numerical analysis, θ_2 is approximately 0.5 in most cases. Combining it with Eq. (30), we can further estimate D^{des} by

$$D^{des} \le \frac{n^{i-1}L_0 + (n^{i-1}-1)(1+\theta_1)(s_0 + v_{low}T_0)}{2} \tag{32}$$

where θ_1 gets its minimum for conservative estimation. Under this constraint, the inter-platoon connectivity is guaranteed by:

$$D^i|_{t=t_{de}} \le D_{MTR}$$

On the other hand, to eliminate the overshoot of intra-platoon spacing at equilibrium point caused by traffic disturbance, the desired inter-platoon spacing should also hold the following inequality:

$$D^{des} \ge l - nL_0 - (n-1)S_{stb} + d_0 \tag{33}$$

especially, in case $v_{low} \ge v_c$, D^{des} get the minimum: d_0. Combined Eq. (32) and Eq. (33), we can identify the suitable range for desired inter-platoon spacing D^{des}.

Finally, with a specific D^{des}, we can further estimate the traffic capacity with disturbance scenarios concerned. Traffic capacity is regarded as the basic metric to indicate the traffic condition in macroscopic view, which can be expressed as follows in platoon-based traffic pattern [33]:

$$C = v_{stb} \times \rho = v_{stb} \times \frac{n}{nL_0 + (n-1)S_{stb} + D^{des}} \tag{34}$$

VI. Numerical Results

In this section, we conduct extensive simulation experiments to validate theoretical analysis in previous sections and to evaluate the performance of the proposed intra- and inter-platoon control strategies. In the rest, we first explain the simulation settings, then elaborate on the intro-platoon dynamics and parameters, and finally we discuss the impact of the proposed leader driving strategy.

A. Simulation Settings

In this paper, we use a software tool, Veins [34], to implement our experiments. Veins is an open source inter-vehicular communication simulation framework composed of network simulator OMNeT++/MiXiM and SUMO. OMNET++/MiXiM is used to simulate V2V communication based on 802.11p standard, while SUMO can simulate the vehicle dynamics with the IDM. Both components are couple with each other through standard traffic control interface (TraCI) by exchanging TCP messages, while OMNeT++/MiXiM is acting as the TraCI client and SUMO is acting as the TraCI server.

As described in section III, two different control strategies are implemented on vehicles in a DA-Platoon: 1) All member vehicles except the leader are controlled by the IDM, which is implemented in SUMO. (2) The leader vehicle is controlled by the proposed scheme in the previous section, which has been

TABLE II
IDM MODEL PARAMETERS

Parameter	Typical value	Reasonable range
a [m/s^2]	1.4	0.3-3
b [m/s^2]	2.0	0.5-3
D_{MTR} [m]	450	300-600
L_0 [m]	3	2-5
s_0 [m]	3.0	1-5
T_0 [s]	1.5	1.0-3
$v_0 [m/s]$	30	20-40

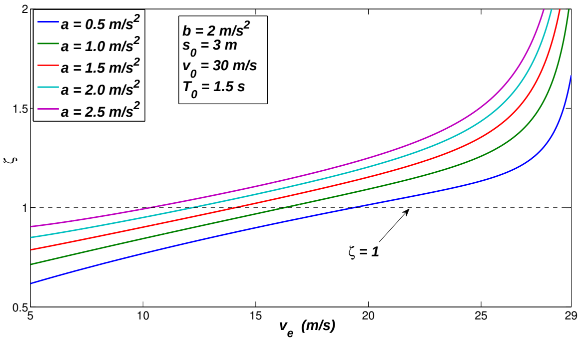


Fig. 10. ζ vs. v_e ($L_0 = 3m$, $b = 2m/s^2$, $T_0 = 1.5s$, $S_0 = 3m$, $v_0 = 30m/s$).

implemented by using the TraCI package from the OMNET++ program.

In our experiments, we choose realistic IDM parameters, which are summarized in Table II, including typical settings and reasonable parameter ranges. On the other hand, default parameters are used in OMNET++. Additionally, traffic information of all vehicles will be updated 10 times per second.

B. Intra-Platoon Dynamics and Parameters

As we have mentioned in section IV, the damping ratio ζ plays an important role in deciding the characteristic of vehicle dynamics in the transient stage. Fig. 10 illustrates ζ versus v_e with various a, from $0.5m/s^2$ to $2.5m/s^2$. In this figure we can see that ζ monotonically increases with the increase of v_e. Moreover, a higher a can increase the whole value of ζ and decrease critical velocity v_c accordingly. As depicted in Fig. 10, v_c is approximate $19.3m/s$ at $a = 0.5m/s^2$ and it becomes $10.3m/s$ at $a = 2.5m/s^2$. These results indicate that the overdamped region $[v_c, v_0]$ is enlarged with a larger a.

Next, Fig. 11 compares the platoon dynamics in three typical disturbance cases where $n = 10$. In case (a), $a = 1.4m/s^2$, the corresponding critical velocity $v_c \approx 15m/s$, $v_{stb} = 25m/s$ with $\zeta|_{v_{stb}} = 1.34$, and $v_{low} = 15m/s$ with $\zeta|_{v_{low}} = 1.01$; in case (b), $a = 1.4m/s^2$, $v_c \approx 15m/s$, $v_{stb} = 25m/s$ with $\zeta|_{v_{stb}} = 1.34$, and $v_{low} = 5m/s$ with $\zeta|_{v_{low}} = 0.77$; in case (c), $a = 0.7m/s^2$,$v_c \approx 17.9m/s$, $v_{stb} = 15m/s$ with $\zeta|_{v_{stb}} = 0.93$, and $v_{low} = 5m/s$. All other IDM parameters are typical values selected from table II. For each case, we present three profiles: vehicle velocity, intra-platoon spacing, and platoon length.

In Fig. 11 we can observe that, in case (a), there is no overshoot for the three profiles near the equilibrium points (i.e., $v_e = v_{stb}$ and $v_e = v_{low}$), which is in accordance with

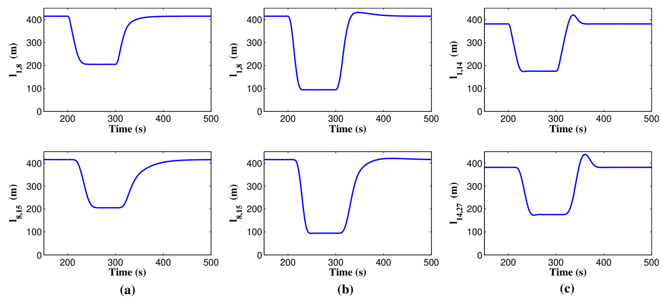


Fig. 12. Verification of VANET connectivity within a DA-Platoon in three cases

our theoretical analysis. In case (b), there is overshoot but with no oscillation for velocity profile near the equilibrium $v_e = v_{stb}$. Moreover, magnitude of gap deviation $y_j(t)$ decreases with the increase of j. Experiment results also show that, if the platoon size increases enough, the overshoot of platoon length will converge to 0, which means that the maximum platoon length is determined by the equilibrium intra-platoon spacing at v_{stb}. In case (c), intra-platoon spacing oscillates around the equilibrium points $v_e = v_{stb}$ and $v_e = v_{low}$. In addition, intra-platoon spacing deviation increases with j and thus the overshoot of platoon length increases accordingly.

Based on the experimental results, we can also estimate the corresponding DA-Platoon parameters. For both case (a) and (b), the equilibrium intra-platoon spacing $S_j \approx 56.3m$ and the maximum platoon size $n = 15$, where vehicle C_8 acts as the only relay vehicle. While for case (c), the equilibrium intra-platoon spacing $S_j \approx 26.3m$, and the maximum platoon size $n = 27$, where vehicle C_{14} acts as the relay vehicle. Fig. 11 illustrates the distances $l_{1,r}$ (between leader and relay) and $l_{r,n}$ (between relay and tail) in three cases, respectively. We can observe all the distances are less than $D_{MTR} = 450m$, which can maintain VANET topology during disturbance.

Moreover, we can calculate the range of the desired inter-platoon spacing based on Eq. (33) and Eq. (32). In both case (a) and (b), for example, if we choose d_0 approximately equal to one intra-platoon spacing, i.e., $d_0 = 60m$, $\theta_1 = -0.2$, the minimum velocity in disturbance $v_{low} = 5m/s$, then $60 \leq D^{des} \leq 80m$. To mitigate the impact of underdamped intra-platoon spacing at v_{low}, we can choose the maximal value of D^{des}, i.e., $D^{des} = 80m$. In such a case, we can further estimate the traffic capacity, which is about 1410 vehicles per hour. Similarly, the traffic capacity is estimated to reach up to 1590 vehicles per hour for case (c).

C. Performance of the Driving Strategies

In this subsection, we illustrate the performance of the proposed driving strategies for three consecutive platoons. We choose case (b) in the previous subsection as the disturbance scenario, which represents a typical disturbance scenario in practice. In each platoon, we let $n = 15$ and we apply typical IDM parameters in Table II.

First, we verify the proposed driving strategy for leaders. Assuming that the first leader C_1^i experiences traffic disturbance starting at time $300s$, then we investigate the trajectories

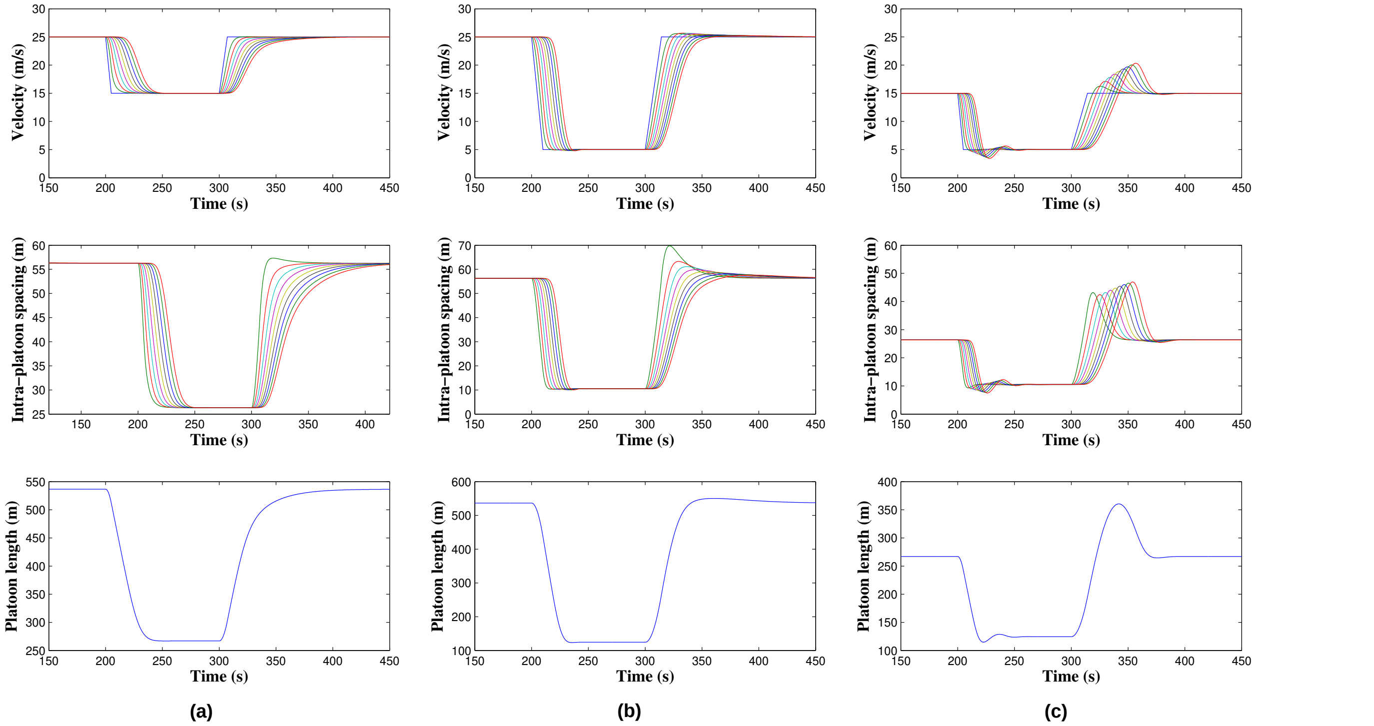


Fig. 11. Platoon dynamics in three typical disturbance cases with 10 vehicles in a platoon. For velocity vs. time, the 10 curves represent $v_1, v_2, \cdots, v_{10}$, from left to right. For intra-platoon spacing vs. time, the 9 curves represent $S_2, S_3, \cdots, S_{10}$, from left to right.

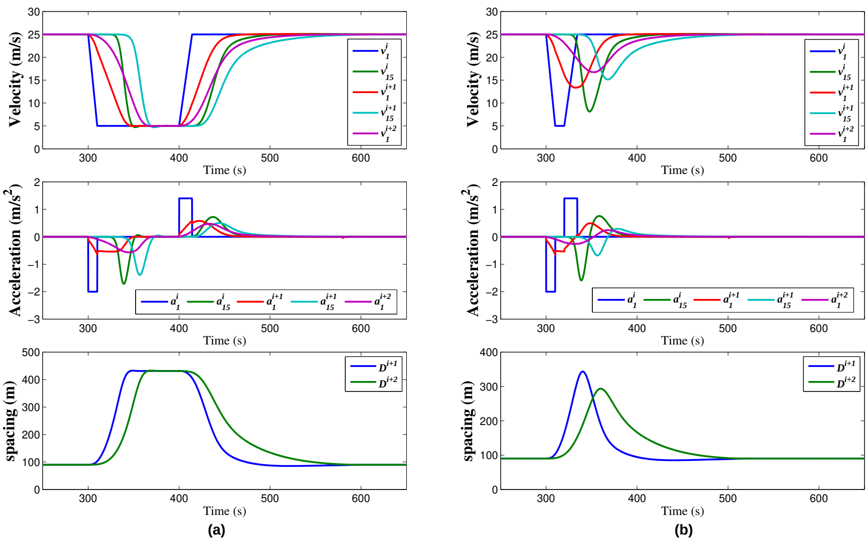


Fig. 13. Trajectory comparison in difference disturbance scenarios (a) with longer duration: $T_d = 100s$, (b) with shorter duration: $T_d = 20s$.

of the following DA-Platoon leaders in disturbance scenario with different duration T_d.

1) disturbance with longer duration $T_d = 100s$: In this case, all vehicles decelerated to v_{low} and maintained this velocity for a certain duration. The simulation results are illustrated in Fig. 13 (a). We can observe a smoother velocity change and smaller acceleration variation trajectories of C_1^{i+1} during the disturbance period compared to that of any vehicle in P^i. Moreover, similar effects also occurred at C_1^{i+2}. Additionally, the maximum inter-platoon spacing D^i is about $430m$, which is less than D_{MTR} and thus can guarantee good connectivity between two adjacent platoons.

2) disturbance with shorter duration $T_d = 20s$: In this case, the tail of P^i, C_{15}^i, did not decelerate to v_{low} due to the shorter disturbance duration. We can also see the similar results in Fig. 13 (b) compared to that in Fig. 13 (a). Furthermore, each following DA-Platoon leader experienced a smaller velocity variation compared to its preceding one, which considerably mitigated the original traffic disturbance.

For the two cases aforementioned, the corresponding acceleration noise metric is illustrated in Fig. 14. In general, we observe different acceleration noise levels for the two

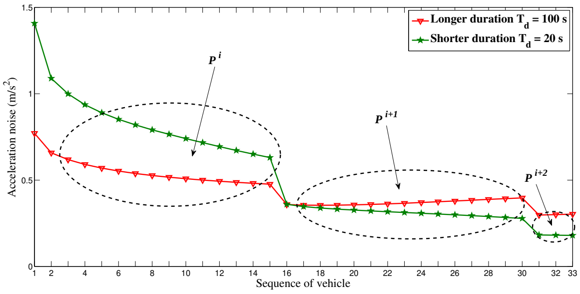


Fig. 14. Acceleration noise comparison in difference disturbance scenarios

TABLE III
FUEL CONSUMPTION AND CO_2 EMISSION COMPARISON

Energy/Emissions	Fuel Consumption [ml]	CO_2 [g]
C_1^i (1)	392.5	984
C_{15}^i (2)	372.8	935
C_1^{i+1} (3)	347.5	872
C_{15}^{i+1} (4)	360.6	905
C_1^{i+2} (5)	333.8	837
Difference 1 and 3	11.4%	11.4%
Difference 2 and 3	6.7%	6.7%
Difference 1 and 5	15%	15%

following DA-Platoons, each of which has a smaller average value than its preceding one. This means that the proposed leader driving strategy can effectively improve the traffic flow smoothness. In addition, this improvement becomes more noticeable in sharp disturbance with shorter duration and larger velocity difference of v_{stb} and v_{low}, as illustrated in case (b).

To evaluate the proposed strategies' impact on exhaust emissions and fuel consumption, we apply the emission model in HBEFA (the Handbook of Emission Factors for Road Transport) to calculate vehicle emissions and fuel consumption. Specifically, we assume that all vehicles belong to the same emission class "PKWBEuro2 1.4-2L" selected from HBEFA passenger and light delivery vehicle clusters. The experimental disturbance scenario is the same to Fig. 13 (a), while other parameters are aforementioned. We then estimate the CO_2 emissions and fuel consumption during the whole disturbance period, as shown in Table III. We can clearly observe a considerable fuel consumption and emissions reduction among C_{15}^i vs. C_1^{i+1}, C_1^i vs. C_1^{i+1} and C_1^i vs. C_1^{i+2}. Note that, if a leader only applies the constant-spacing strategy, its performance will be the same as that of the tail of the preceding platoon. The results clearly demonstrate the advantages of the proposed driving strategies, in terms of both exhaust emissions and fuel consumption.

VII. CONCLUSIONS

In this paper, we have investigated the dynamics of VANET-enabled platoon under disturbance. In particular, we first proposed a novel *disturbance-adaptive platoon* (DA-Platoon) architecture, in which both platoon dynamics and VANET behaviors are taken into consideration. With a specific design of the DA-Platoon architecture, we have analyzed the intra-platoon dynamics and we have identified three possible transient responses to different disturbance scenarios. Based on the analysis, we have further derived the desirable intra-platoon spacing and platoon size, under traffic disturbance and VANET constraints. Next, to mitigate the adverse effects of traffic disturbance, we have also designed a novel driving strategy for the leading vehicle of DA-Platoon, with which we can determine the desired inter-platoon spacing. Finally, extensive simulation experiments have been conducted, which validate our analysis and demonstrate the effectiveness of the proposed driving strategies, in terms of acceleration noise, fuel consumption and exhaust emissions.

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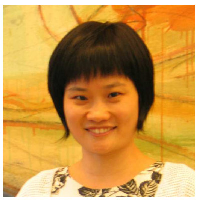

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