Dynamic Event-Triggered Platoon Control of Intelligent Vehicles under DoS Attacks

Yihui Xu, Xudong Zhao, Ning Zhao, and Kalidass Mathiyalagan

***Abstract*—This paper investigates platoon control under denial-of-service (DoS) attacks. Unlike conventional formations, this study primarily focuses on leaderless vehicle platoons and develops a corresponding model. Since communication among vehicles in the platoon is not only disrupted by DoS attacks but also constrained by limited network resources, a resilient dynamic event-triggered mechanism is proposed. Based on this mechanism, an event-triggered distributed formation control strategy is developed. Furthermore, a Lyapunov function is constructed, which provides a rigorous proof of system stability and a scheme for controller gain design. Finally, a simulation of a four-vehicle platoon model under DoS attacks based on sampled-data event-triggered is designed to further verify the effectiveness of the proposed control strategy and the stability of the vehicle platoon system.**

***Index Terms*—Leaderless vehicle platooning model, denial-of-service (DoS) attacks, dynamic event-triggered mechanism, distributed formation control**

I. INTRODUCTION

OVER the past decade, rapid advances in electric intelligent vehicle technology have transformed vehicles into widely accessible industrial products, resulting in a substantial increase in the vehicle population. As a result, road traffic density has increased, raising the urgent challenge of ensuring both efficiency and safety in transportation. To address this challenge, a traffic organization strategy based on vehicle platooning is proposed [1]. By integrating wireless communication technologies with multi-agent control theory [2, 3], vehicles can travel in platoons while maintaining prescribed safety distances. Such coordination not only reduces collision risk but also improves the utilization of existing road infrastructure. Although vehicle platoon control has been extensively studied, typically modeled as a leader-follower system [2, 4], research on leaderless platoon systems remains limited.

In vehicle platooning research, information exchange within the platoon is a fundamental issue. Ensuring secure and reliable transmission of information is paramount. Vehicle-to-vehicle (V2V) communication in platoons relies on wireless networks, whose openness inevitably exposes transmissions to malicious cyberattacks [5–10]. Among such threats, denial-of-service (DoS) attacks are the most common and easiest to launch. In these attacks, adversaries inject excessive data into the network, congesting resource-limited channels and ultimately disrupting communication. Consequently, significant research efforts have been devoted to mitigating or preventing DoS attacks, with substantial progress achieved in this area. For connected hybrid vehicles (CHVs) under DoS attacks, an attack-resilient control approach is proposed in Ref. [7], which guarantees both communication security and the economic operation of connected hybrid vehicles. Jiang et al. [8] developed a novel flexible output containment (FOC) control framework based on an adaptive observer, which effectively mltigated the impact of DoS attacks on the system through the introduction of adaptive gains. To enhance the resilience of nonlinear autonomous ground vehicles (AGVs) to DoS attacks, a novel control strategy incorporating a specific switching mechanism is proposed in Ref. [9]. This strategy not only improves control flexibility but also reduces the impact of DoS attacks on tracking control. In Ref. [10], a robust safety control method for connected vehicles is designed to address partial safety challenges in heterogeneous vehicle queue systems, encompassing time delays, dynamic uncertainties, and random DoS attacks. Although significant progress has been achieved, ensuring the safety and stability of vehicle platoons under DoS attacks remains an open and important research problem.

The convenience and indispensability of wireless networks in vehicular communications result in large volumes of vehicular data being transmitted over communication channels. Consequently, the efficient allocation of limited network resources has become an unavoidable challenge. To address this challenge, event-triggered mechanisms (ETMs) have been introduced into vehicle platoon communications, allowing data to be transmitted only when triggering conditions are satisfied. This approach significantly reduces unnecessary network resource consumption. Accordingly, substantial efforts have been devoted to studying this approach, leading to the advancement from static ETMs [11, 12] to dynamic ETMs [13–16]. Although extensive researches have been conducted on ETMs, further improvements in their effectiveness remain an important research direction. This issue also constitutes one of the focal points of the present studies.

In existing researches on safe control of vehicle platoons,

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studies on leaderless platoons that ensure both system stability under DoS attacks and efficient network resource usage remain limited. Addressing this issue requires tackling the following key challenges: (1) formulating a mathematical model that accurately represents a leaderless vehicle platoon; (2) designing an event-based control strategy that balances reduced network data transmission while maintaining platoon stability; and (3) constructing a Lyapunov function to rigorously verify the stability of the platoon under network attacks. These challenges constitute both a central focus of current research and the point of departure for this study.

To address these challenges, the main contributions of this study are summarized as follows:

(1) Unlike traditional platoon systems with a fixed and uncontrolled leader [2, 4], a leaderless vehicle platoon system is constructed, in which each vehicle incorporates control.

(2) A DoS attack model is established. Compared with the simplified model in Ref. [9], the constraint that attack instants be integer multiples of the sampling period is removed, thereby enhancing the model's realism and applicability across a broader range of scenarios.

(3) A novel control strategy based on a resilient dynamic ETM is proposed. Compared with Refs. [11, 12], the strategy not only significantly reduces the frequency of network data transmissions, thus conserving network resources, but also effectively mitigates the impact of DoS attacks.

The remainder of this paper is organized as follows. Section II presents the main problems and introduces the vehicle model, attack model, ETM, and control strategy design. Section III presents the exponential stability analysis of the tracking error system and the design scheme for the controller gain. Section IV validates the effectiveness and reliability of the proposed approach through simulations of a four-vehicle platoon. Finally, Section V concludes this paper.

Notation The n-dimensional identity matrix is denoted by I_n. The symbols 0_N and 1_N represent the N-dimensional zero vector and one vector, respectively. Diagonal matrices are denoted by diag. The symbol $\otimes$ represents the Kronecker product. $A>0$ (or <0) indicates that the matrix A is positive definite (or negative definite). A^{T} denotes the transpose of matrix A, and $\mathrm{He}\{A\}=A+A^{\mathrm{T}}$. The symbol $*$ denotes the symmetric element within the matrix.

II. Problem Formulation and Preliminaries

This study investigates safety control for N-vehicle platoons traveling in a single lane. As illustrated in Fig. 1, status information exchange between vehicles in the platoon is carried out through wireless networks. To reduce the frequency of data transmission, the status information generated by each vehicle undergoes two stages of processing: initial sampling and event-triggered condition filtering, before transmission. Subsequently, data from neighboring vehicles are received and used by controllers to adjust vehicle behaviors. While wireless networks offer significant benefits, they also introduce security vulnerabilities, particularly malicious cyberattacks. The following sections discuss these issues in detail.

A. Graph Theory

In the previous discussion, it is noted that vehicles in a platoon must exchange data, which requires a clear characterization of their communication channels. This can be described by a graph topology defined as $\mathcal{G}=(\mathcal{V},\mathcal{E},\mathcal{A})$, where $\mathcal{V}=\{1,2,\dots,N\}$ denotes the set of vehicle indices and $\mathcal{E}=\{(i,j)\mid i,j\in\mathcal{V}\}$ represents the set of edges between vehicles. The adjacency matrix is given by $\mathcal{A}=[a_{ij}]_{N\times N}$, with $a_{ij}\in\{0,1\}$. Specifically, $a_{ij}=1$ if vehicle i can transmit data to vehicle j, $(i,j)\in\mathcal{E}$; otherwise, $a_{ij}=0$. Based on this definition, the Laplacian matrix is expressed as $\mathcal{L}=\mathcal{B}-\mathcal{A}$, where $\mathcal{B}=\mathrm{diag}\{b_1,b_2,\dots,b_N\}$ and $b_i=\sum_{j=1}^{N}a_{ij}$.

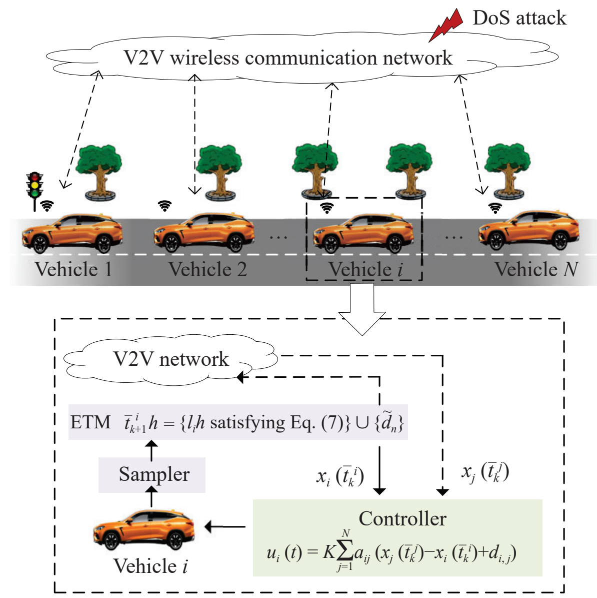

Fig. 1 Vehicle platooning system under DoS attacks. Sampler and ETM are used to reduce the amount of data in the network. Controller is used to implement the vehicle platoon control. V2V network represents the communication channel among vehicles.

B. Vehicle System Model

Consider a platoon of N vehicles traveling in the same lane. The vehicles share information via a V2V communication protocol. Using a platoon control strategy, they move along a line at constant velocity while maintaining safe spacing. The behavior of vehicle i is described by its longitudinal motion, which is given by

$$\dot{x}_i(t)=Ax_i(t)+Bu_i(t) \tag{1}$$

where $x_i(t)=[p_i(t)\ v_i(t)\ a_i(t)]^{\mathrm{T}}$ denotes the state vector of vehicle i, with $p_i(t)$, $v_i(t)$, and $a_i(t)$ representing its position, velocity, and acceleration, respectively. The system matrices are given by $A=\begin{bmatrix}0&1&0\\0&0&1\\0&0&-1/\pi\end{bmatrix}$ and $B=\begin{bmatrix}0\\0\\1/\pi\end{bmatrix}$, where π denotes the delay parameter of the power transmission system.

C. Denial-of-Service Attacks

When vehicles travel in a platoon on the road, their cooperation depends entirely on wireless communication. Because of the openness of wireless networks, information exchange within the platoon is highly vulnerable to cyberattacks. In particular, DoS attacks are the most common. In such attacks, attackers flood communication channels with excessive data packets, interrupting normal data transmission among vehicles. Moreover, attackers often use intermittent attack patterns to make the attacks more covert. This intermittent mode is quantitatively described through the subsequent definition of "non-attack interval" and "attack interval". Based on the above description, the attack model is constructed as

$$D_{\mathrm{DoS}}(t)=\begin{cases}1,\ t\in\Phi_n;\\ 0,\ t\in\bar{\Phi}_n\end{cases} \tag{2}$$

where $\Phi_n=[d_n,b_n)$ and $\bar{\Phi}_n=[b_n,d_{n+1})$ denote the n-th non-attack interval and the n-th attack interval, respectively, with d_n and b_n representing the starting times of the n-th non-attack and attack intervals. Since the attacks are intermittent, it is necessary to impose constraints and characterize their duration and frequency.

Assumption 1 Attack duration and frequency For $t\geqslant t_0\geqslant 0$, there are constants $T>1$ and $\bar{T}>0$ such that

$$\aleph(t_0,t)\leqslant\frac{t-t_0}{T},\quad \bar{\aleph}(t_0,t)\leqslant\frac{t-t_0}{\bar{T}} \tag{3}$$

where $\aleph(t_0,t)$ denotes the length of the set $(\cup_{n\in\mathbb{N}}\bar{\Phi}_n)\cap[t_0,t)$, $\bar{\aleph}(t_0,t)$ denotes the number of DoS attacks within $[t_0,t)$.

It should be further noted that the state information of each vehicle $x_i(t)$ is sampled as $x_i(kh)$ before subsequent processing. This implies that no information exchange occurs over the communication network between two consecutive sampling instants. Consequently, discrepancy arises between the attack interval and the actual effective interval during which the attack blocks transmission. To more precisely characterize the effective impact of DoS attacks, the following interval definition with respect to the sampling period h is introduced.

$$\tilde{\Phi}_n=[\tilde{d}_n,\tilde{b}_n),\quad \tilde{\bar{\Phi}}_n=[\tilde{b}_n,\tilde{d}_{n+1}) \tag{4}$$

where $\tilde{d}_n=\lceil d_n/h\rceil h$ and $\tilde{b}_n=\lfloor b_n/h\rfloor h+h$. Then, the effective attack interval satisfies the following assumption

$$\tilde{\aleph}(t_0,t)\ \leqslant\ \frac{t-t_0}{T}+\bar{\aleph}(t_0,t)h\ \leqslant\ \left(\frac{1}{T}+\frac{h}{\bar{T}}\right)(t-t_0) \tag{5}$$

where $\tilde{\aleph}(t_0,t)$ denotes the length of the set $(\cup_{n\in\mathbb{N}}\tilde{\bar{\Phi}}_n)\cap[t_0,t)$.

Remark 1 It should be noted that, after we redefine the intervals, the description of DoS attacks in Eq. (2) is accordingly modified as

$$D_{\mathrm{DoS}}(t)=\begin{cases}1,\ t\in\tilde{\Phi}_n;\\ 0,\ t\in\tilde{\bar{\Phi}}_n\end{cases} \tag{6}$$

D. Dynamic Event-Triggered Mechanism

The wireless communication bandwidth in vehicle platoons is limited, and real-time data transmission places significant demands on the network. To address this issue, a dynamic ETM is designed, which, based on sampling, applies a triggering condition to reduce network data transmission without compromising control performance. For vehicle i, a dynamic event-triggered mechanism is constructed, where the state information of vehicle i is transmitted to the V2V communication network only when the corresponding triggering condition is satisfied. The specific triggering condition is given as

$$t_{k+1}^i h=t_k^i h+\min_{l_i\geqslant 1}\{f_i(t_k^i h,l_i h)>0\} \tag{7}$$

where $f_i(t_k^i h,l_i h)=\eta_i^{\mathrm{T}}(t_k^i h+l_i h)\Psi\eta_i(t_k^i h+l_i h)-\bar{\sigma}_i z_i^{\mathrm{T}}(t_k^i h)\Psi z_i(t_k^i h)-\mu\vartheta_i(t_k^i h+l_i h)$, with $\eta_i(t_k^i h+l_i h)=x_i(t_k^i h)-x_i(t_k^i h+l_i h)$, $z_i(t_k^i h)=\sum_{j=1}^{N}a_{ij}(x_i(t_k^i h)-x_j(t_k^j h)-\bar{d}_{i,j})$, and $\bar{\sigma}_i$ is the threshold parameter.

In the above event-triggering condition, the dynamic parameter $\vartheta_i(t)$ is designed as

$$\dot{\vartheta}_i(t)=\begin{cases}-\lambda_1\vartheta_i(t)-\mu\vartheta_i(\ell h)+e_i^{\mathrm{T}}(\ell h)\Omega e_i(\ell h),\ t\in\tilde{\Phi}_n;\\ \lambda_0\vartheta_i(t),\ t\in\tilde{\bar{\Phi}}_n\end{cases} \tag{8}$$

where $l_i h=\ell h-t_k^i h$ and $l_j h=\ell h-t_k^j h$. Define positive parameters λ_1, λ_0, μ, and $\bar{\sigma}_i\in(0,1)$, initial values $\vartheta_i(0)>0$, $\Omega>0$, and $\Psi>0$. Define $\Sigma=\mathrm{diag}\{\bar{\sigma}_1,\bar{\sigma}_2,...,\bar{\sigma}_N\}$.

It should be noted that the dynamic variable $\vartheta_i(t)$ in the triggering condition always remains strictly positive. The proof is as follows. According to Ref. [17], it is readily established that $\vartheta_i(t)>0$ for $t\in\Phi_n$. Moreover, for $t\in\bar{\Phi}_n$, since $\beta_0>0$ and the initial value $\vartheta_i(b_n)$ at the start of each attack interval is strictly positive, it follows that $\dot{\vartheta}_i(t)>0$. This indicates that $\vartheta_i(t)$ is strictly increasing in $\bar{\Phi}_n$, and hence $\vartheta_i(t)>0$ holds throughout the entire interval. Therefore, $\vartheta_i(t)$ remains strictly positive for all t.

Furthermore, it should be noted that, after a period of DoS attacks, network data may remain outdated for an extended time. Once the attack ends, if the data do not satisfy the triggering condition and are therefore not updated promptly, the impact of the attack is prolonged. To mitigate this issue, the event-triggering condition is extended as

$$\bar{t}_{k+1}^i h=\{l_i h \text{ satisfying Eq. (7)}\}\cup\{\tilde{d}_n\} \tag{9}$$

E. Event-Based Distributed Controller

To achieve the platooning objective of maintaining safe spacing and constant velocity, an event-triggered distributed control strategy is developed in this subsection. The detailed design is given as

$$u_i(t)=K\sum_{j=1}^{N}a_{ij}(x_j(\bar{t}_k^j)-x_i(\bar{t}_k^i)+\bar{d}_{i,j}) \tag{10}$$

where K denotes the control gain, which will be designed in the subsequent section. For stability analysis, we define the tracking error as $e_i(t)=x_i(t)-x_1(t)+\bar{d}_{i,1}$, with $\bar{d}_{i,1}=[d_{i,1}\ 0\ 0]^{\mathrm{T}}$, where $d_{i,1}$ represents the safety distance between vehicle i and vehicle 1. Accordingly, Eq. (10) can be rewritten as

$$u_i(t)=K\sum_{j=1}^{N}a_{ij}(\eta_j(\ell h)+e_j(\ell h)-\eta_i(\ell h)-e_i(\ell h)) \tag{11}$$

It should be noted that, when vehicle communication is subject to DoS attacks, i.e., $t\in\bar{\Phi}_n$, data transmission is interrupted and the control input satisfies $u_i(t)=0$.

Furthermore, since it is straightforward to observe that $e_1(t)\equiv 0$ in practice, we define a new tracking error as $e_m(t)=x_m(t)-x_1(t)+\bar{d}_{m,1}$, $m=2,3,\ldots,N$. Then, the following expression can be obtained

$$\begin{aligned}\dot{e}_m(t) = \dot{x}_m(t) - \dot{x}_1(t) = \\ Ax_m(t) + Bu_m(t) - Ax_1(t) - Bu_1(t) = \\ Ae_m(t) + BK\sum_{j=1}^{N} a_{mj}[\eta_j(\ell h) + e_j(\ell h) - \\ \eta_m(\ell h) - e_m(\ell h)] - BK\sum_{j=1}^{N} a_{1j}[\eta_j(\ell h) + \\ e_j(\ell h) - \eta_1(\ell h) - e_1(\ell h)]\end{aligned} \tag{12}$$

Furthermore, we define vectors

$$\begin{aligned}\bar{e}(t) &= [\ e_2^{\mathrm{T}}(t) \quad e_3^{\mathrm{T}}(t) \quad e_4^{\mathrm{T}}(t) \quad \cdots \quad e_N^{\mathrm{T}}(t)\ ]^{\mathrm{T}}, \\ \eta(t) &= [\ \eta_1^{\mathrm{T}}(t) \quad \eta_2^{\mathrm{T}}(t) \quad \eta_3^{\mathrm{T}}(t) \quad \cdots \quad \eta_N^{\mathrm{T}}(t)\ ]^{\mathrm{T}}\end{aligned} \tag{13}$$

Based on the above vector definitions and taking into account the impact of DoS attacks, Eq. (12) can be reformulated as

$$\dot{\bar{e}}(t) = \begin{cases} (I_{N-1}\otimes A)\bar{e}(t) - (E_1\mathcal{L}E_2\otimes BK)\bar{e}(\ell h) - \\ \quad (E_1\mathcal{L}\otimes BK)\eta(\ell h),\ t\in\tilde{\Phi}_n; \\ (I_{N-1}\otimes A)\bar{e}(t),\ t\in\tilde{\bar{\Phi}}_n \end{cases} \tag{14}$$

where $E_1 = [\ -1_{N-1} \quad I_{N-1}\ ]$ and $E_2^{\mathrm{T}} = [\ 0_{N-1} \quad I_{N-1}\ ]$.

III. Main Results

In the following section, a Lyapunov function is constructed to derive sufficient conditions for the exponential stability of the vehicle platoon system. Based on these conditions, specific design schemes for the event-triggering parameter matrices and the control gain matrix are then presented.

Theorem 1 Given the gain matrix K, the event-triggering weighting matrices Ψ and Ω, and the positive parameters $\bar{T}$, T, h, λ_0, λ_1, and $\bar{\sigma}_i$, and under the condition that the following inequality holds

$$\bar{\lambda} = -\lambda_1 + (\lambda_1 + \lambda_0)\left(\frac{1}{T} + \frac{h}{\bar{T}}\right) < 0 \tag{15}$$

If there exist $3(N-1)$-dimensional positive definite matrices Ω, Ψ, Z_1, Z_0, P, and R and matrices G_1, G_2, G_3, Q_1, and Q_2 ensuring that the following matrix inequalities hold

$$\mathrm{diag}(P, 0_{n(N-1)\times n(N-1)}) + hQ > 0 \tag{16}$$

$$Q = \begin{bmatrix} \mathrm{He}(Q_1)/2 & -Q_1 + Q_2 \\ * & \mathrm{He}(Q_1/2 - Q_2) \end{bmatrix} \tag{17}$$

$$\Theta_1 = \begin{bmatrix} \Theta_1^{11} & \Theta_1^{12} & \Theta_1^{13} & \Theta_1^{14} & \Theta_1^{15} \\ * & \Theta_1^{22} & \Theta_1^{23} & \Theta_1^{24} & \Theta_1^{25} \\ * & * & \Theta_1^{33} & \Theta_1^{34} & \Theta_1^{35} \\ * & * & * & \Theta_1^{44} & \Theta_1^{45} \\ * & * & * & * & \Theta_1^{55} \end{bmatrix} < 0 \tag{18}$$

$$\Theta_2 = \begin{bmatrix} \Theta_2^{11} & \Theta_2^{12} & \Theta_1^{13} & \Theta_2^{14} \\ * & \Theta_2^{22} & \Theta_1^{23} & \Theta_2^{24} \\ * & * & \Theta_1^{33} & \Theta_1^{34} \\ * & * & * & \Theta_2^{44} \end{bmatrix} < 0 \tag{19}$$

$$\Theta_0 = \begin{bmatrix} \Theta_0^{11} & \Theta_0^{12} \\ * & \Theta_0^{22} \end{bmatrix} < 0 \tag{20}$$

$$\begin{aligned}
&\Theta_1^{11} = \lambda_1 P + \mathrm{He}(-Q_1/2 - G_1 + I_{N-1}\otimes Z_1 A), \\
&\Theta_1^{12} = Q_1 - Q_2 + G_1 - G_3^{\mathrm{T}} - E_1\mathcal{L}E_2\otimes Z_1 BK, \\
&\Theta_1^{22} = -\mathrm{He}(Q_1/2 - Q_2 - G_3) + \\
&E_2^{\mathrm{T}}\mathcal{L}^{\mathrm{T}}\Sigma\mathcal{L}E_2\otimes\Psi - \\
&I_{N-1}\otimes\Omega, \\
&\Theta_1^{13} = -E_1\mathcal{L}\otimes Z_1 BK, \\
&\Theta_1^{23} = E_2^{\mathrm{T}}\mathcal{L}^{\mathrm{T}}\Sigma\mathcal{L}\otimes\Psi, \\
&\Theta_1^{33} = \mathcal{L}^{\mathrm{T}}\Sigma\mathcal{L}\otimes\Psi - I_N\otimes\Psi, \\
&\Theta_1^{14} = P^{\mathrm{T}} - G_2^{\mathrm{T}} + (I_{N-1}\otimes Z_1 A)^{\mathrm{T}} - I_{N-1}\otimes Z_1, \\
&\Theta_1^{24} = G_2^{\mathrm{T}} - (E_1\mathcal{L}E_2\otimes Z_1 BK)^{\mathrm{T}}, \\
&\Theta_1^{34} = -(E_1\mathcal{L}\otimes Z_1 BK)^{\mathrm{T}}, \\
&\Theta_1^{44} = -\mathrm{He}(I_{N-1}\otimes Z_1), \\
&\Theta_1^{15} = hG_1 + h(I_{N-1}\otimes Z_1 A)^{\mathrm{T}}, \\
&\Theta_1^{25} = hG_3 - h(E_1\mathcal{L}E_2\otimes Z_1 BK)^{\mathrm{T}}, \\
&\Theta_1^{35} = -h(E_1\mathcal{L}\otimes Z_1 BK)^{\mathrm{T}}, \\
&\Theta_1^{45} = hG_2 - h(I_{N-1}\otimes Z_1)^{\mathrm{T}}, \\
&\Theta_1^{55} = -he^{-\lambda_1 h}R, \\
&\Theta_2^{11} = \Theta_1^{11} + \beta_1 h\mathrm{He}(Q_1)/2, \\
&\Theta_2^{12} = \Theta_1^{12} + \beta_1 h(-Q_1 + Q_2), \\
&\Theta_2^{22} = \Theta_1^{22} + \beta_1 h\mathrm{He}(Q_1/2 - Q_2), \\
&\Theta_2^{14} = \Theta_1^{14} + h\mathrm{He}(Q_1)/2, \\
&\Theta_2^{24} = \Theta_2^{14} + h(-Q_1 + Q_2), \\
&\Theta_2^{44} = hR - \mathrm{He}(I_{N-1}\otimes Z_1), \\
&\Theta_0^{11} = -\lambda_0 P + \mathrm{He}(I_{N-1}\otimes Z_0 A), \\
&\Theta_0^{12} = P^{\mathrm{T}} - (I_{N-1}\otimes Z_0) + (I_{N-1}\otimes Z_0 A)^{\mathrm{T}}, \\
&\Theta_0^{22} = -\mathrm{He}(I_{N-1}\otimes Z_0)
\end{aligned} \tag{21}$$

then, the error system shown in Eq. (14) is guaranteed to converge to zero, indicating that the vehicle platoon can maintain safe and stable operation under DoS attacks.

Proof A Lyapunov function incorporating $D_{\mathrm{DoS}}(t)$ is constructed to distinguish between attack and non-attack intervals and is defined as

$$V(t) = V_1(t) + V_2(t) + V_3(t) + V_4(t) \tag{22}$$

where

$$\begin{aligned}
&V_1(t) = \bar{e}^{\mathrm{T}}(t)P\bar{e}(t), \\
&V_2(t) = D_{\mathrm{DoS}}(t)((\ell+1)h - t)\tilde{e}^{\mathrm{T}}(t)Q\tilde{e}(t), \\
&V_3(t) = D_{\mathrm{DoS}}(t)((\ell+1)h - t)\int_{\ell h}^{t} e^{\lambda_1(s-t)}\dot{\bar{e}}^{\mathrm{T}}(s)R\dot{\bar{e}}(s)\mathrm{d}s, \\
&V_4(t) = \vartheta(t), \\
&\tilde{e}(t) = [\bar{e}^{\mathrm{T}}(t), \bar{e}^{\mathrm{T}}(\ell h)]^{\mathrm{T}}, \\
&\vartheta(t) = \vartheta_1(t) + \vartheta_2(t) + \cdots + \vartheta_N(t)
\end{aligned} \tag{23}$$

Next, the analysis is conducted separately for the two cases: non-attack intervals and attack intervals.

Case 1: When $t\in[\ell h, (\ell+1)h)\cap\tilde{\Phi}_n$, $D_{\mathrm{DoS}}(t) = 1$, the derivative of $V(t)$ is given by

$$\dot{V}(t) = \dot{V}_1(t) + \dot{V}_2(t) + \dot{V}_3(t) + \dot{V}_4(t) \tag{24}$$

$$\begin{aligned}&\dot{V}_1(t)=-\lambda_1V_1(t)+2\bar{e}^{\mathrm{T}}(t)P\dot{\bar{e}}(t)+\lambda_1\bar{e}^{\mathrm{T}}(t)P\bar{e}(t),\\&\dot{V}_2(t)=-\lambda_1V_2(t)-\tilde{e}^{\mathrm{T}}(t)Q\tilde{e}(t)+\\&\qquad 2((\ell+1)h-t)\tilde{e}^{\mathrm{T}}(t)Q\dot{\tilde{e}}(t),\\&\dot{V}_3(t)\leqslant-\lambda_1V_3(t)+((\ell+1)h-t)\dot{\bar{e}}^{\mathrm{T}}(t)R\dot{\bar{e}}(t)-\\&\qquad e^{-\lambda_1h}\textstyle\int_{\ell h}^{t}\dot{\bar{e}}^{\mathrm{T}}(s)R\dot{\bar{e}}(s)\mathrm{d}s,\\&\dot{V}_4(t)=-\lambda_1V_4(t)-\mu\vartheta(t)+\bar{e}^{\mathrm{T}}(t)(I_{N-1}\otimes\Omega)\bar{e}(t)\end{aligned}\tag{25}$$

Next, applying Jensen's inequality to the integral term $\int_{\ell h}^{t}\dot{\bar{e}}^{\mathrm{T}}(s)R\dot{\bar{e}}(s)\mathrm{d}s$ yields

$$\int_{\ell h}^{t}\dot{\bar{e}}^{\mathrm{T}}(s)R\dot{\bar{e}}(s)\mathrm{d}s\geqslant(t-\ell h)\zeta^{\mathrm{T}}(t)R\zeta(t)\tag{26}$$

where $\zeta(t)=\dfrac{1}{t-\ell h}\int_{\ell h}^{t}\dot{\bar{e}}(s)\mathrm{d}s$. By applying the Newton-Leibniz formula and introducing free-weighting matrices G_1, G_2, and G_3, the following can be obtained

$$\begin{aligned}&2[\bar{e}^{\mathrm{T}}(t)G_1+\dot{\bar{e}}^{\mathrm{T}}(t)G_2+\bar{e}^{\mathrm{T}}(\ell h)G_3]\times\\&\qquad[-\bar{e}(t)+\bar{e}(\ell h)+(t-\ell h)\zeta(t)]=0\end{aligned}\tag{27}$$

Similarly, by introducing the free-weighting matrix Z_1 and combining it with Eq. (14), we obtain

$$\begin{aligned}&2[\dot{\bar{e}}^{\mathrm{T}}(t)(I_{N-1}\otimes Z_1)+\bar{e}^{\mathrm{T}}(t)(I_{N-1}\otimes Z_1)+\\&(t-\ell h)\zeta^{\mathrm{T}}(t)(I_{N-1}\otimes Z_1)][-\dot{\bar{e}}(t)+(I_{N-1}\otimes A)\bar{e}(t)-\\&(E_1\mathcal{L}E_2\otimes BK)\bar{e}(\ell h)-(E_1\mathcal{L}\otimes BK)\eta(\ell h)]=0\end{aligned}\tag{28}$$

Considering the previously defined variables $\bar{e}(t)$ and $\eta(t)$, the event-triggering condition in Eq. (7) can be reformulated as the following matrix inequality

$$\begin{aligned}&\eta^{\mathrm{T}}(\ell h)(I_N\otimes\Psi)\eta(\ell h)\leqslant\\&\quad\eta^{\mathrm{T}}(\ell h)[(\mathcal{L}^{\mathrm{T}}\Sigma\mathcal{L})\otimes\Psi]\eta(\ell h)+\\&\quad\eta^{\mathrm{T}}(\ell h)[(\mathcal{L}^{\mathrm{T}}\Sigma\mathcal{L}E_2)\otimes\Psi]\bar{e}(\ell h)+\\&\quad\bar{e}^{\mathrm{T}}(\ell h)[(E_2^{\mathrm{T}}\mathcal{L}^{\mathrm{T}}\Sigma\mathcal{L})\otimes\Psi]\eta(\ell h)+\\&\quad\bar{e}^{\mathrm{T}}(\ell h)[(E_2^{\mathrm{T}}\mathcal{L}^{\mathrm{T}}\Sigma\mathcal{L}E_2)\otimes\Psi]\bar{e}(\ell h)+\mu\vartheta(\ell h)\end{aligned}\tag{29}$$

Combining Formulas (24)–(29) and defining vectors

$$\begin{aligned}&\xi_1(t)=[\bar{e}^{\mathrm{T}}(t),\bar{e}^{\mathrm{T}}(\ell h),\eta^{\mathrm{T}}(\ell h),\dot{\bar{e}}^{\mathrm{T}}(t),\zeta^{\mathrm{T}}(t)]^{\mathrm{T}},\\&\xi_2(t)=[\bar{e}^{\mathrm{T}}(t),\bar{e}^{\mathrm{T}}(\ell h),\eta^{\mathrm{T}}(\ell h),\dot{\bar{e}}^{\mathrm{T}}(t)]^{\mathrm{T}}\end{aligned}\tag{30}$$

the following inequality is obtained

$$\begin{aligned}\dot{V}(t)+\lambda_1V(t)\leqslant{}&\frac{t-\ell h}{h}\xi_1^{\mathrm{T}}(t)\Theta_1\xi_1(t)+\\&\frac{(\ell+1)h-t}{h}\xi_2^{\mathrm{T}}(t)\Theta_2\xi_2(t)\end{aligned}\tag{31}$$

When matrices Θ_1 and Θ_2 are negative definite, i.e., conditions in Eqs. (18) and (19) are satisfied, Formula (31) can be rewritten as

$$\dot{V}_1(t)\leqslant-\lambda_1V_1(t)\tag{32}$$

Further calculations yield

$$\dot{V}_1(t)\leqslant e^{-\lambda_1(t-\ell h)}V_1(\ell h)\tag{33}$$

Case 2: When $t\in\bar{\tilde{\Phi}}_n$ and $D_{\mathrm{DoS}}(t)=0$, the derivative of $V(t)$ is given by

$$\dot{V}(t)=\dot{V}_1(t)+\dot{V}_4(t)\tag{34}$$

$$\begin{aligned}&\dot{V}_1(t)=\lambda_0V_1(t)+2\bar{e}^{\mathrm{T}}(t)P\dot{\bar{e}}(t)+\lambda_0\bar{e}^{\mathrm{T}}(t)P\bar{e}(t),\\&\dot{V}_4(t)=\lambda_0V_4(t)\end{aligned}\tag{35}$$

By introducing the free-weighting matrix Z_0 and combining with Eq. (14), the following is obtained

$$\begin{aligned}&2[\dot{\bar{e}}^{\mathrm{T}}(t)(I_{N-1}\otimes Z_0)+\bar{e}^{\mathrm{T}}(t)(I_{N-1}\otimes Z_0)][-\dot{\bar{e}}(t)+\\&\qquad(I_{N-1}\otimes A)\bar{e}(t)]=0\end{aligned}\tag{36}$$

Combining Eqs. (34) and (36) and defining the vector $\xi_3(t)=\mathrm{col}(\bar{e}(t),\dot{\bar{e}}(t))$, the following inequality is obtained

$$\dot{V}(t)-\lambda_0V(t)\leqslant\xi_3^{\mathrm{T}}(t)\Theta_0\xi_3(t)\tag{37}$$

When condition in Eq. (20) is satisfied, the following is obtained

$$\dot{V}(t)\leqslant\lambda_0V(t)\tag{38}$$

Further calculations yield

$$V(t)\leqslant e^{\lambda_0(t-\tilde{b}_n)}V(\tilde{b}_n)\tag{39}$$

By analyzing the Lyapunov function, the following equations can be readily obtained

$$\begin{aligned}&V((\ell h)^-)=V(\ell h),\\&V(\tilde{d}_n^-)=V(\tilde{d}_n),\\&V(\tilde{b}_n^-)=V(\tilde{b}_n)\end{aligned}\tag{40}$$

Next, based on the classifications in case 1 and case 2, and by combining Formulas (33), (39), and (40), the following derivation is obtained.

When $t\in[\ell h,(\ell+1)h)\cap\tilde{\Phi}_n$, we have

$$\begin{aligned}V(t)\leqslant{}&e^{-\lambda_1(t-\ell h)}V(\ell h)=\\&e^{-\lambda_1(t-(\ell h)^-)}V((\ell h)^-)\leqslant\\&e^{-\lambda_1(t-(\ell h)^-)-\lambda_1((\ell h)^--(\ell-1)h)}V((\ell-1)h)\leqslant\\&\cdots\leqslant\\&e^{-\lambda_1(t-\tilde{d}_n)}V(\tilde{d}_n)=\\&e^{-\lambda_1(t-\tilde{d}_n^-)}V(\tilde{d}_n^-)\leqslant\\&e^{-\lambda_1(t-\tilde{d}_n^-)+\lambda_0(\tilde{d}_n^--\tilde{b}_{n-1})}V(\tilde{b}_{n-1})\leqslant\\&e^{-\lambda_1(t-\tilde{d}_n^-)+\lambda_0(\tilde{d}_n^--\tilde{b}_{n-1}^-)}V(\tilde{b}_{n-1}^-)\leqslant\\&\cdots\leqslant\\&e^{-\lambda_1(t-|\tilde{\aleph}(0,t)|)+\lambda_0|\tilde{\aleph}(0,t)|}V(0)\end{aligned}\tag{41}$$

When $t\in\bar{\tilde{\Phi}}_n$, we have

$$\begin{aligned}V(t)\leqslant{}&e^{\lambda_0(t-b_n)}V(b_n)=\\&e^{\lambda_0(t-b_n^-)}V(b_n^-)\leqslant\\&e^{\lambda_0(t-b_n^-)-\lambda_1(s_n-\ell_{\max}h)}V(\ell_{\max}h)\leqslant\\&\cdots\leqslant\\&e^{\lambda_0(t-b_n^-)-\lambda_1(b_n-\tilde{d}_n)}V(\tilde{d}_n)=\\&e^{\lambda_0(t-b_n^-)-\lambda_1(b_n-\tilde{d}_n^-)}V_0(\tilde{d}_n^-)\leqslant\\&\cdots\leqslant\\&e^{-\lambda_1(t-|\tilde{\aleph}(0,t)|)+\lambda_0|\tilde{\aleph}(0,t)|}V(0)\end{aligned}\tag{42}$$

By substituting Formula (5) into Formulas (41) and (42), the following inequality is derived

$$V(t)\leqslant e^{\bar{\lambda}t}V(0),\ t\geqslant0\tag{43}$$

where $\bar{\lambda}=-\lambda_1+(\lambda_1+\lambda_0)\left(\dfrac{1}{T}+\dfrac{h}{\bar{T}}\right)$. When condition in Eq. (15) is satisfied, Formula (43) ensures that Eq. (14) achieves exponential stability, thereby confirming the stability of the vehicle platoon studied in this work. ■

Theorem 2 If there exist positive parameters $\bar{T}$, T, h, λ_0, λ_1, and $\bar{\sigma}_i$ satisfying $\bar{\lambda} = -\lambda_1 + (\lambda_1 + \lambda_0)\left(\frac{1}{T} + \frac{h}{\bar{T}}\right) < 0$, and matrices $\mathcal{P} > 0$, $\mathcal{R} > 0$, $\mathcal{Q}_1$, $\mathcal{Q}_2$, X_1, X_0, $\mathcal{G}_1$, $\mathcal{G}_2$, $\mathcal{G}_3$, $\bar{K}$, $\hat{\Psi}$, and $\hat{\Omega}$ satisfying the following inequalities

$$\mathrm{diag}(\mathcal{P}_1, 0_{n(N-1)\times n(N-1)}) + h\mathcal{Q} > 0 \tag{44}$$

$$\mathcal{Q} = \begin{bmatrix} \mathrm{He}[\mathcal{Q}_1]/2 & -\mathcal{Q}_1 + \mathcal{Q}_2 \\ * & \mathrm{He}[\mathcal{Q}_1/2 - \mathcal{Q}_2] \end{bmatrix} \tag{45}$$

$$\bar{\Theta}_1 = \begin{bmatrix} \bar{\Theta}_1^{11} & \bar{\Theta}_1^{12} & \bar{\Theta}_1^{13} & \bar{\Theta}_1^{14} & \bar{\Theta}_1^{15} \\ * & \bar{\Theta}_1^{22} & \bar{\Theta}_1^{23} & \bar{\Theta}_1^{24} & \bar{\Theta}_1^{25} \\ * & * & \bar{\Theta}_1^{33} & \bar{\Theta}_1^{34} & \bar{\Theta}_1^{35} \\ * & * & * & \bar{\Theta}_1^{44} & \bar{\Theta}_1^{45} \\ * & * & * & * & \bar{\Theta}_1^{55} \end{bmatrix} < 0 \tag{46}$$

$$\bar{\Theta}_2 = \begin{bmatrix} \bar{\Theta}_2^{11} & \bar{\Theta}_2^{12} & \bar{\Theta}_1^{13} & \bar{\Theta}_2^{14} \\ * & \bar{\Theta}_2^{22} & \bar{\Theta}_1^{23} & \bar{\Theta}_2^{24} \\ * & * & \bar{\Theta}_1^{33} & \bar{\Theta}_1^{34} \\ * & * & * & \bar{\Theta}_2^{44} \end{bmatrix} < 0 \tag{47}$$

$$\bar{\Theta}_0 = \begin{bmatrix} \bar{\Theta}_0^{11} & \bar{\Theta}_0^{12} \\ * & \bar{\Theta}_0^{22} \end{bmatrix} < 0 \tag{48}$$

$$\begin{aligned}
&\bar{\Theta}_1^{11} = \lambda_1\mathcal{P}_1 + \mathrm{He}[-\mathcal{Q}_1/2 - \mathcal{G}_1 + I_{N-1}\otimes AX_1^{\mathrm{T}}],\\
&\bar{\Theta}_1^{12} = \mathcal{Q}_1 - \mathcal{Q}_2 + \mathcal{G}_1 - \mathcal{G}_3^{\mathrm{T}} - E_1\mathcal{L}E_2\otimes B\bar{K},\\
&\bar{\Theta}_1^{22} = -\mathrm{He}[\mathcal{Q}_1/2 - \mathcal{Q}_2 - \mathcal{G}_3] +\\
&E_2^{\mathrm{T}}\mathcal{L}^{\mathrm{T}}\Sigma\mathcal{L}E_2\otimes\hat{\Psi} - I_{N-1}\otimes\hat{\Omega},\\
&\bar{\Theta}_1^{13} = -E_1\mathcal{L}\otimes B\bar{K},\\
&\bar{\Theta}_1^{23} = E_2^{\mathrm{T}}\mathcal{L}^{\mathrm{T}}\Sigma\mathcal{L}\otimes\hat{\Psi},\\
&\bar{\Theta}_1^{33} = \mathcal{L}^{\mathrm{T}}\Sigma\mathcal{L}\otimes\hat{\Psi} - I_N\otimes\hat{\Psi},\\
&\bar{\Theta}_1^{14} = \mathcal{P}_1^{\mathrm{T}} - \mathcal{G}_2^{\mathrm{T}} + (I_{N-1}\otimes AX_1^{\mathrm{T}})^{\mathrm{T}} - I_{N-1}\otimes X_1^{\mathrm{T}},\\
&\bar{\Theta}_1^{24} = \mathcal{G}_2^{\mathrm{T}} - (E_1\mathcal{L}E_2\otimes B\bar{K})^{\mathrm{T}},\\
&\bar{\Theta}_1^{34} = -(E_1\mathcal{L}\otimes B\bar{K})^{\mathrm{T}},\\
&\bar{\Theta}_1^{44} = -\mathrm{He}[I_{N-1}\otimes X_1^{\mathrm{T}}],\\
&\bar{\Theta}_1^{15} = h\mathcal{G}_1 h(I_{N-1}\otimes AX_1^{\mathrm{T}})^{\mathrm{T}},\\
&\bar{\Theta}_1^{25} = h\mathcal{G}_3 - h(E_1\mathcal{L}E_2\otimes B\bar{K})^{\mathrm{T}},\\
&\bar{\Theta}_1^{35} = -h(E_1\mathcal{L}\otimes B\bar{K})^{\mathrm{T}},\\
&\bar{\Theta}_1^{45} = h\mathcal{G}_2 - h(I_{N-1}\otimes X_1^{\mathrm{T}})^{\mathrm{T}},\\
&\bar{\Theta}_1^{55} = -he^{-\lambda_1 h}\mathcal{R},\\
&\bar{\Theta}_2^{11} = \bar{\Theta}_1^{11} + \lambda_1 h\mathrm{He}[\mathcal{Q}_1]/2,\\
&\bar{\Theta}_2^{12} = \bar{\Theta}_1^{12} + \lambda_1 h(-\mathcal{Q}_1 + \mathcal{Q}_2),\\
&\bar{\Theta}_2^{22} = \bar{\Theta}_1^{22} + \lambda_1 h\mathrm{He}[\mathcal{Q}_1/2 - \mathcal{Q}_2],\\
&\bar{\Theta}_2^{14} = \bar{\Theta}_1^{14} + h\mathrm{He}[\mathcal{Q}_1]/2,\\
&\bar{\Theta}_2^{24} = \bar{\Theta}_1^{14} + h(-\mathcal{Q}_1 + \mathcal{Q}_2),\\
&\bar{\Theta}_2^{44} = h\mathcal{R} - \mathrm{He}[I_{N-1}\otimes X_1^{\mathrm{T}}],\\
&\bar{\Theta}_0^{11} = -\lambda_0\mathcal{P}_0 + \mathrm{He}[I_{N-1}\otimes AX_0^{\mathrm{T}}],\\
&\bar{\Theta}_0^{12} = \mathcal{P}_0^{\mathrm{T}} - (I_{N-1}\otimes X_0^{\mathrm{T}}) + (I_{N-1}\otimes AX_0^{\mathrm{T}})^{\mathrm{T}},\\
&\bar{\Theta}_0^{22} = -\mathrm{He}[I_{N-1}\otimes X_0^{\mathrm{T}}]
\end{aligned} \tag{49}$$

then, the error system in Eq. (15) will ultimately converge to zero, indicating that the vehicle platoon can maintain safe and stable operation under DoS attacks. Meanwhile, the expressions for the control gain and event-triggering parameter matrices are given by

$$K = \bar{K}X_1^{-\mathrm{T}}, \quad \Psi = X_1^{-1}\hat{\Psi}X_1^{-\mathrm{T}}, \quad \Omega = X_1^{-1}\hat{\Omega}X_1^{-\mathrm{T}} \tag{50}$$

Proof Define $X_1 = Z_1^{-1}, X_0 = Z_0^{-1}, \mathcal{U} = (I_{N-1}\otimes X_1)U(I_{N-1}\otimes X_1^{\mathrm{T}})$, $\tilde{\mathcal{U}} = (I_{N-1}\otimes X_0)\tilde{U}(I_{N-1}\otimes X_0^{\mathrm{T}})$, and $\bar{\mathcal{U}} = X_1^{\mathrm{T}}\bar{U}X_1$. Then, we have $(U,\mathcal{U}) \in \{(P,\mathcal{P}_1),(Q_1,\mathcal{Q}_1),(Q_2,\mathcal{Q}_2),(R,\mathcal{R})\}$, $(\tilde{U},\tilde{\mathcal{U}}) \in \{(P,\mathcal{P}_0)\}$, and $(\bar{U},\bar{\mathcal{U}}) \in \{(\Psi,\hat{\Psi}),(\Omega,\hat{\Omega}),(G,\mathcal{G})\}$.

Next, define $Y_1 = (I_{4(N-1)+N}\otimes X_1)$, $Y_2 = (I_{4(N-1)}\otimes X_1)$, and $Y_3 = I_{2(N-1)}\otimes X_0$. By pre-multiplying and post-multiplying Formula (18) (Formula (19)) by Y_1 (Y_2) and Y_1^{T} (Y_2^{T}), we obtain Formula (46) (Formula (47)), which is equivalent to the original one. Similarly, pre-multiplying and post-multiplying Formula (20) by Y_3 and Y_3^{T} yields the equivalent Formula (48).

Finally, by solving the set of inequalities, the control gain and event-triggering parameter matrices are obtained as $K = \bar{K}X_1^{-\mathrm{T}}$, $\Psi = X_1^{-1}\hat{\Psi}X_1^{-\mathrm{T}}$, and $\Omega = X_1^{-1}\hat{\Omega}X_1^{-\mathrm{T}}$. ■

IV. SIMULATION

In this section, to effectively validate the safety and stability of the leaderless vehicle platoon and the distributed control strategy, a vehicle platoon model, as shown in Fig. 2, is established. The communication topology of the vehicle platoon model is constructed as

$$\mathcal{L} = \begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 3 & -1 & -1 \\ 0 & -1 & 1 & 0 \\ 0 & -1 & 0 & 1 \end{bmatrix} \tag{51}$$

Furthermore, the fixed safety distances between vehicles in the platoon are set as $\bar{d}_{12} = 5$ m, $\bar{d}_{13} = 10$ m, and $\bar{d}_{14} = 15$ m. The specific parameter values associated with Theorems 1 and 2 are given as $h = 0.1$, $\lambda_0 = 0.35$, $\lambda_1 = 0.24$, and $\bar{\sigma}_1 = \bar{\sigma}_2 = \bar{\sigma}_3 = \bar{\sigma}_4 = 0.01$. Using these parameters and substituting them into the sufficient conditions of Theorem 2 yield the following explicit expressions for the control gain matrix and event-triggering parameter matrices

$$\begin{aligned}
K &= \begin{bmatrix} 0.0742 & 0.5957 & 0.3349 \end{bmatrix},\\
\Psi &= \begin{bmatrix} 0.0097 & 0.0770 & 0.0432 \\ 0.0770 & 0.6166 & 0.3463 \\ 0.0432 & 0.3463 & 0.2007 \end{bmatrix},\\
\Omega &= \begin{bmatrix} 0.0519 & 0.3741 & 0.1760 \\ 0.3741 & 2.7301 & 1.2851 \\ 0.1760 & 1.2851 & 0.6112 \end{bmatrix}
\end{aligned} \tag{52}$$

Fig. 3 shows, from top to bottom, the number of data transmissions, transmission frequency, and transmission interval

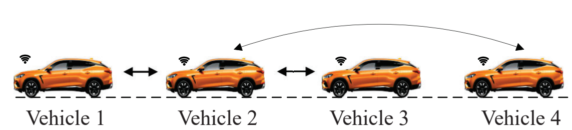

Fig. 2 Vehicle formation communication topology.

(i.e., the number of event triggers, their frequency, and their interval) for vehicles 1–4. To further demonstrate the efficacy of the dynamic ETM proposed in this study, detailed data are provided. The numbers of event triggers for vehicles 1–4 are 345, 122, 68, and 140, respectively, with mean triggering intervals of 0.1739, 0.4910, 0.8824, and 0.4279 s, respectively.

Figs. 4 and 5 depict the operating states of the vehicles. Fig. 4 illustrates the tracking errors of the vehicle platoon, with position errors, velocity errors, and acceleration errors from top to bottom. After approximately 20 s, the position errors converge to the safe inter-vehicle distance while the velocity errors approach zero, indicating that all vehicles in the platoon maintain both safe spacing and synchronized velocity. Fig. 5 further illustrates this conclusion by visually demonstrating the position, velocity, and acceleration information for vehicles 1–4 from top to bottom. The plots clearly exhibit all vehicles in the platoon maintaining a 5 m safe spacing and synchronized velocity of 1.167 m/s.

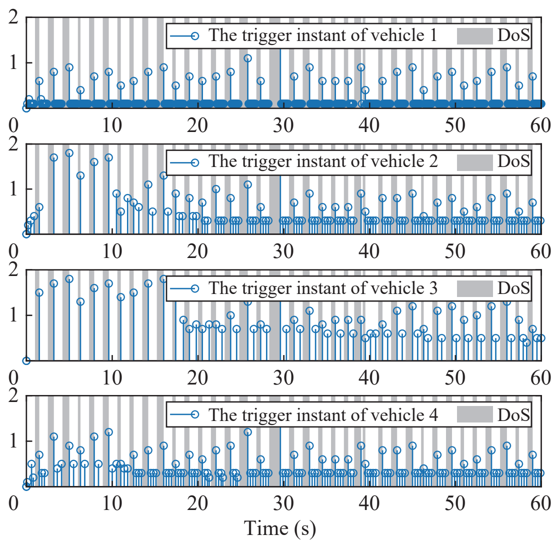

Fig. 3 Event-triggered frequency and interval.

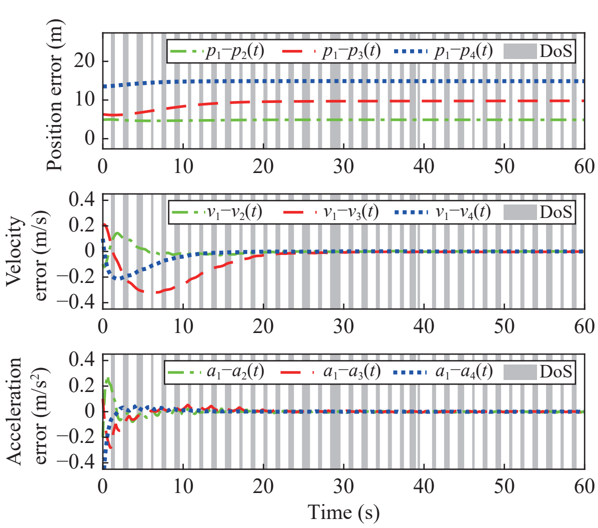

Fig. 4 Vehicle formation tracking error.

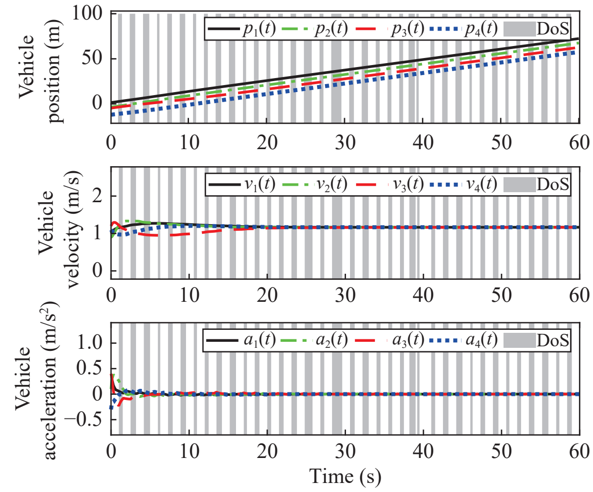

Fig. 5 Vehicle status information.

V. Conclusion

This paper addresses the safety control of vehicle platoons under malicious DoS attacks. A leaderless vehicle platoon model is established for road vehicles. Subsequently, a dynamic ETM is formulated to efficiently mitigate communication resource constraints. Based on this mechanism, a distributed control strategy is designed. This strategy not only ensures that the vehicle formation maintains a constant safe distance and speed, but also guarantees safe operation under DoS attacks. Furthermore, a Lyapunov function is constructed, providing a rigorous theoretical proof of system stability and a design scheme for the controller gain. Simulation results confirm the effectiveness and stability of the proposed control strategy.

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References

[1] R. Wu, H. Jia, Q. Huang, J. Tian, H. Gao, and G Wang, Multi-lane unsignalized intersection cooperation strategy considering platoons formation in a mixed connected automated vehicles and connected human-driven vehicles environment, *IEEE Trans. Intell. Transp. Syst.*, 2024, 25(2), 1569–1585.

[2] S.-L. Dai, S. He, H. Cai, and C. Yang, Adaptive leader-follower formation control of underactuated surface vehicles with guaranteed performance, *IEEE Trans. Syst. Man Cybern. Syst.*, 2022, 52(3), 1997–2008.

[3] M. Sharma and H. Shanmugam, Prescribed-time formation control of second-order multi-agent systems in presence of actuator faults, *IEEE Control Syst. Lett.*, 2024, 8, 3440–3445.

[4] M. A. Maghenem, A. Loría, and E. Panteley, Cascades-based leader-follower formation tracking and stabilization of multiple nonholonomic vehicles, *IEEE Trans. Automat. Control*, 2020, 65(8), 3639–3646.

[5] X. Qi, C. Li, W. Ni, Q. Sheng, and H. Ma, Practical prescribed time control framework for decentralized robust steering of connected automated vehicles under deception attacks, *IEEE Trans. Syst. Man Cybern. Syst.*, 2025, 55(7), 4915–4929.

[6] D. Pan, D. Ding, X. Ge, Q.-L. Han, and X.-M. Zhang, Edge-based event-triggered platooning control of heterogeneous connected automated vehicles under replay attacks, *IEEE Trans. Veh. Technol.*, 2024, 73(11), 17443–17456.

[7] Q. Fan, C. Yang, J. Fang, X. Du, and H. Liu, Resilient predictive control of connected hybrid vehicles considering denial-of-service attacks, *IEEE Internet Things J.*, 2025, 12(8), 10783–10794.

[8] D. Jiang, G. Wen, A. Rahmani, S. Ifqir, C. Sueur, and T. Huang, Adaptive resilient flexible-containment control for fully heterogeneous MASs subject to DoS attacks and asynchronous semi-Markov chains, *IEEE Trans. Cybern.*, 2025, 55(10), 4943–4955.

[9] Y. Ren, X. Xie, and A. T. Nguyen, Security control of autonomous ground vehicles under DoS attacks via a novel controller with the switching mechanism, *IEEE Trans. Fuzzy Syst.*, 2024, 32(6), 3669–3681.

[10] X. Song, X. Liu, H. Shan, and R. Lu, Time-delay robust safety control of connected vehicles under stochastic DoS attack, *IEEE Internet Things J.*, 2025, 12(15), 29485–29494.

[11] W. Xing, P. Shi, R. K. Agarwal, and L. Li, Robust H_∞ pinning synchronization for complex networks with event-triggered communication scheme, *IEEE Trans. Circuits Syst. I: Regul. Pap.*, 2020, 67(12), 5233–5245.

[12] Z. Li, Y. Liu, and Z. Shen, Event-triggered platooning control for connected vehicle systems under denial-of-service attacks and external disturbances, *IEEE Trans. Intell. Veh.*, 2025, 10(5), 3303–3317.

[13] R. Silva, A. T. Nguyen, T. M. Guerra, F. O. Souza, and L. Frezzatto, Switched dynamic event-triggered control for string stability of nonhomogeneous vehicle platoons with uncertainty compensation, *IEEE Trans. Intell. Veh.*, 2025, 10(4), 2876–2891.

[14] Y. Liu, Y. Liu, and H. Chen, Adaptive dynamic event-triggered control for strict-feedback nonlinear system with time-varying parameters, *Int. J. Intell. Control Syst.*, 2025, 30(2), 115–122.

[15] Z. Chen, S. Pan, K. Yu, X. Tang, W. Gao, and Z. Zhou, Dynamic event-triggered and fast natural logarithmic sliding mode path tracking control for autonomous ground vehicles with the experiment validation, *IEEE Trans. Veh. Technol.*, 2025, 74(1), 362–377.

[16] Y.-C. Sun, Z. Zhang, L. Yao, and A.-Y. Lu, Observer-based dynamic event-triggered resilient control for heterogeneous multi-agent systems under DoS attacks, *IEEE Trans. Autom. Sci. Eng.*, 2025, 22, 19723–19734.

[17] N. Zhao, P. Shi, and W. Xing, Dynamic event-triggered approach for networked control systems under denial of service attacks, *Int. J. Robust Nonlinear Control*, 2021, 31(5), 1774–1795.

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