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Effect of communication delays and packet dropouts on vehicle platoon control

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Abstract: *The influence of both inter-vehicular communication delays and packet dropouts on platoon control performance is studied. The conditions for achieving platoon mean square stability (MSS) are derived for three cases: undirected information flow (UIF) topology with time delays and identical packet losses, general information flow topology (IFT) with time delays and identical packet losses, and general IFT with time delays and non-identical packet losses. These conditions explicitly reveal how packet dropout rates, time delays, and IFT jointly affect vehicular stability. In this paper, the provided conditions are easily determinable, and the offered controllers are simple to implement, with low computational complexity. Finally, simulations are conducted to compare different time delays and packet loss rates, which validate the theoretical discoveries, also demonstrate the robustness and feasibility of the proposed methods using a platoon of passenger cars and realistic vehicle dynamics.*

Keywords: *Packet losses, Vehicle platoon, Time delays, Distributed control*

1. Introduction

In recent years, significant advancements in wireless communication technologies [1,2] have enabled the exchange of information between vehicles, commonly referred to as vehicle-to-vehicle (V2V) communication using dedicated short-range communication or cellular-based communication technologies. This exchange includes crucial data such as control commands and vehicular kinetic information. These developments open up new opportunities to enhance both traffic safety and transportation efficiency [3]. However, the reliability of wireless communication is influenced by various impairments, such as channel fading, shadowing, and interference. Ignoring these issues can pose a significant risk to the safety of the entire platoon. Therefore, it is essential to develop innovative distributed control strategies that consider the deficiencies in the network [4].

Nevertheless, the methods described in the previously mentioned studies, which focus on addressing either time delays or packet dropouts, cannot be directly extended to situations where both communication delays and packet dropouts coexist in the communication channels. Regarding this problem, the study in [5] addressed the vehicle platooning problem in the presence of external disturbances and network imperfections, placing particular emphasis on the coexistence of communication delays and random packet dropouts. However, there were certain limitations in the work [5] that should be acknowledged. These limitations include: (1) It provided sufficient conditions using high-dimensional linear matrix inequalities, leading to high computational complexity; (2) It did not specify the explicit conditions that needed to be satisfied for packet dropouts and time delays; (3) It only considered the case of identical packet dropouts. Given these constraints, this article focuses on the vehicle platoon with the following characteristics: (1) Sufficient conditions, based on packet loss rates and time delays, will be provided for platoon stability. These conditions can be used to determine whether the vehicle platoon can achieve cooperative control based on the channel characteristics. (2) The provided controller only needs to compute an MRI with the same dimension as the vehicle dynamics, resulting in a significant reduction in computational complexity compared to that in [2]. (3) We discuss the inter-vehicle communication networks, including both identical and non-identical packet losses.

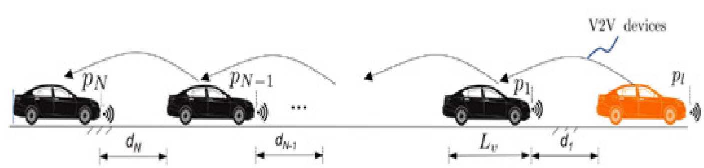


Fig 1.1. A connected homogeneous vehicle platoon

We continue to employ network control techniques to explore the influence of imperfect communication channels on the performance of platoon control. Our objective is to gain insights into how the characteristics of communication delays and packet dropouts can affect the overall control performance of the platoon. Moreover, We develop decentralized controllers that adapt to communication channels where packet dropouts and time delays coexist, allowing the platoon to sustain stability and achieve desired performance even in the presence of imperfect communication channels. A flowchart for the proposed solution can be seen in Fig 1.1.

2. Problem formulation

This paper focuses on the study of a connected homogeneous vehicle platoon that operates on a smooth road, as depicted in Fig 1.1. A platoon of vehicles can be considered as a combination of the following four components:

(1) Vehicle dynamics: This component represents the behavior of each vehicle involved in the platoon; (2) Distributed controller: This component performs feedback control based on neighboring information to ensure coordinated movement within the platoon; (3) Information flow network: This component describes how vehicles exchange information with each other, including information flow quality and topology; (4) Formation geometry: This component defines the required spacing distance between vehicles during platooning, ensuring proper alignment and safety.

3. Platoon control with time delays and identical packet losses - a general IFT

The general IFT considered includes both the UIF topology and directed IFT, for the latter, it is assumed that the eigenvalues of matrix H_p are assumed to be distinct.

However, in the case of directed IFT, the main difference is that the nonzero eigenvalues of H_p are not necessarily real numbers.

__Assumption 1__. The general IFT considered includes both the UIF topology and directed IFT; for the latter, it is assumed that the eigenvalues of H_p are distinct.

Based on Assumption 2, we can present the following theorem.

__Theorem 1__. Under Assumptions 1 and 2, the platoon dynamics (17) achieves MSS by the protocol (10) under a connected general IFT subject to both time delays and identical packet dropouts if

$$\eta_g \triangleq \frac{(\tau+1)(1-p)}{2\tau(1-p)+1} 1-\left|1-\omega\lambda_i\right|^2 > 0$$

Where λ_i, i = 1, 2,..., N are the eigenvalues of matrix H_p. Moreover, if (30) holds, there exists a positive definite solution W to the MRI:

$$\mathrm{W} > A'\mathrm{W}A - \eta_g A'\mathrm{WB}(\mathrm{B'W}B)^{-1}\mathrm{B'WA}$$

Where $A = (\tau+1)a - \tau I$

$$K_g = \frac{\omega^*}{2\tau(1-p)+1}(B'\mathrm{WB})^{-1}B'\mathrm{W}A'$$

Where $\omega^* = \arg\min_{\omega \in R} \left|1-\omega\lambda_i\right|^2$

4. Simulations

Take a platoon of passenger cars as an example to carry out numerical simulations, which will verify the research results presented in this paper. Throughout the following simulations to verify Theorems 1, The inertial lag of vehicle longitudinal dynamics is selected as v = 0.8 and the sampling period is chosen as h = 0.01 s.

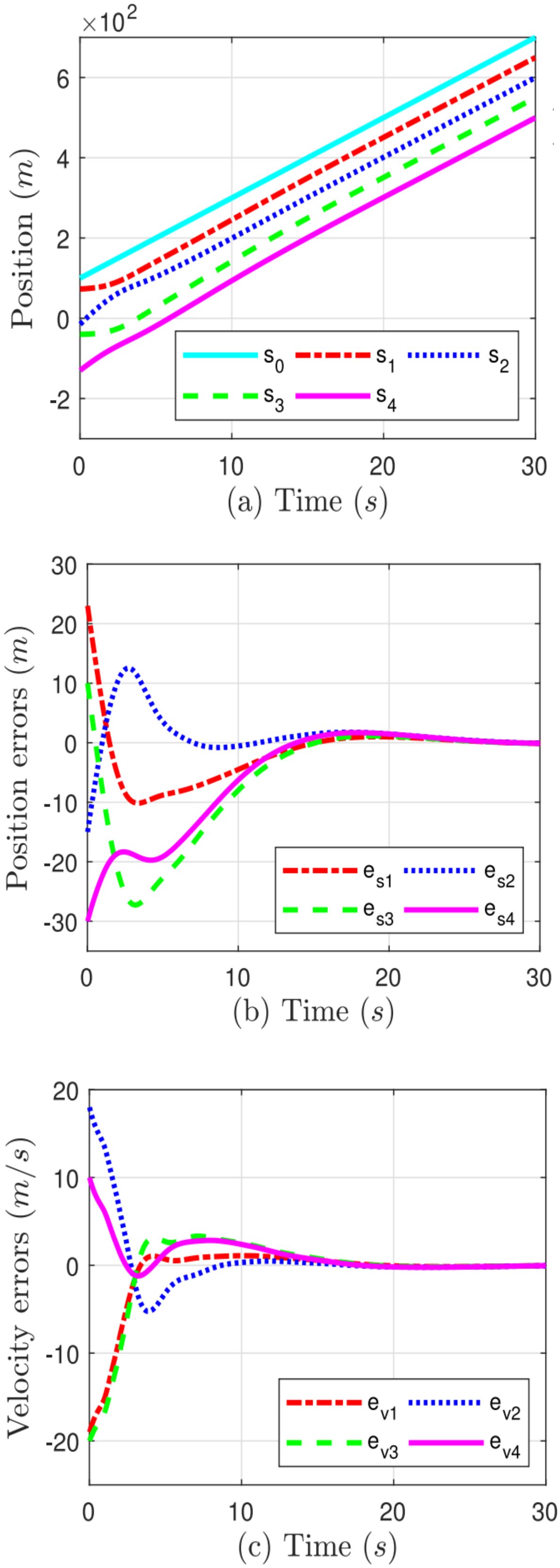
In the following, simulation examples are provided to prove the validity of the controller algorithm for a general IFT. We consider the asymmetric network topology. The Laplacian matrix is selected as:

$$\Gamma = \begin{bmatrix} 1 & 0 & -1 & 0 \\ -1 & 1 & 0 & 0 \\ 0 & -1 & 1 & 0 \\ -1 & 0 & 1 & 1 \end{bmatrix}$$

The pinning matrix is chosen as a diagonal matrix, expressed as p = diag{1, 1, 1, 1}. Consequently, the eigenvalues of the matrix H_p can be readily computed as follows: $\lambda_1 = 1.0$, $\lambda_2 = 2.0$, $\lambda_3 = 2.5 - 0.8660i$, và $\lambda_4 = 2.5 + 0.8660i$.

First, we conduct simulations for the case without packet loss and time delay, and subsequently, these uncertainties are taken into account. The calculation of the corresponding controller gain K_g is based on Theorem 1.

The simulation results are provided in Figs 2.1. It can be seen from Figs 2.1(b) that the designed controller can always make the platoon dynamics stable regardless of whether there is packet loss or time delay. However, when there is neither packet loss nor communication delay, as depicted in Fig 2.1(b), the platoon dynamics take approximately 10 s to achieve stability.



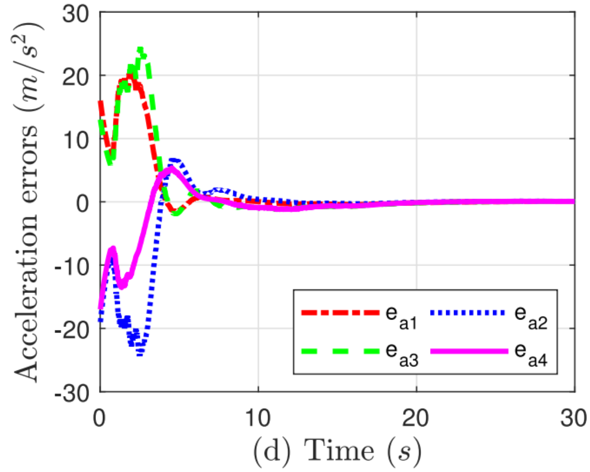


Fig 2.1. The states of platoon for the topology subject to time delays and packet dropouts.

5. Conclusion

This paper focuses on the existence condition and design scheme of a distributed controller for a vehicle platoon system, where the communication network topology is affected by both packet losses and time delays. We provide a sufficient condition for vehicular platoon stability in the case of inter-vehicular communication with time delays and identical packet losses. This condition explicitly reveals the joint impact of packet dropout rates, time delays, and IFT on vehicular platoon stability. The result is obtained by solving the simultaneous stabilization problem.

Cooperative control of heterogeneous vehicle platoons in the presence of simultaneous communication time-varying delays, packet dropouts, intermittent observations, and system noises is a possible future work

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