Memory-Event-Triggered Tracking Control for Intelligent Vehicle Transportation Systems: A Leader-Following Approach

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***Abstract*— This paper addresses the problem of adaptive memory-event-triggered control for intelligent vehicle transportation systems (IVTSs). Unlike the existing methods for modeling IVTSs, the acceleration information is introduced in the desired distance to achieve better distance control performance of IVTSs. The information between vehicles interacts over a wireless network. In order to further reduce the amount of data transmission, a novel adaptive memory-event-triggered mechanism (METM) is developed, in which historical information is utilized. In addition, the proposed METM threshold is designed to vary with the system state of each autonomous vehicle to adjust the data-releasing rate adaptively. Under the adaptive METM, a distributed tracking controller with historical information is put forward to guarantee uniformly ultimately bounded (UUB) stability using the Lyapunov stability theory and linear matrix inequality (LMI) technique. Finally, simulation results are given to verify the superiority of the proposed method.**

***Index Terms*— Intelligent vehicle transportation system, adaptive memory event-triggered mechanism, distance control.**

I. Introduction

INTELLIGENT vehicles have been widely extended to container terminal, express delivery and some large transportation systems. With the increasing maturity of unmanned driving technology, research on tracking control for intelligent vehicle transportation systems (IVTSs) has received extensive attention due to its potential to enhance drive safety, alleviate road congestion, save energy, and reduce human resources [1], [2]. To reduce air drag and improve driving efficiency, IVTS-based vehicle formations are usually designed to form a queue and maintain a certain distance [3], [4]. Distance control is a crucial issue for ensuring the stability and safety of IVTSs. Two modeling methods in distance control for vehicle formation are usually adopted: constant distance control strategy and variable distance control strategy. For example, in [5], adaptive cruise control was studied for event-triggered based vehicles with sensor failures by controlling vehicles' speed to achieve equal spacing of the vehicle queue. The problem of speed planning and tracking control of a platoon of trucks on highways was investigated in [6]. Reference [7] investigated a distributed trajectory optimization and trajectory tracking control problem for a collection of vehicles. The authors in [8] proposed a variable distance control strategy that determines the vehicle distance according to the vehicle speed to adapt to uncertain road conditions and achieve elastic control. In [9], a new distributed double-layer control architecture based on internet of vehicle was developed to solve the coordinated control problem of multi-row negotiation access link constraints of intelligent vehicle with heterogeneous communication time-varying delays. A fault-tolerant control problem for heterogeneous vehicular platoons with actuator faults and saturation was studied in [10].

In recent years, the leader-following approach as an effective method has been promoted in the fields of UAV formation [11], [12], robot cooperation [13], and vehicle formations [14], [15]. The method simplifies the network structure and improves the control performance. However, an effective communication topology is needed for IVTSs, otherwise, a rear-end collision may occur since the actuator of vehicles can not receive other vehicle's state information [16]. Therefore, under the leader-following approach, the communication topology between vehicles is crucial to the stability of IVTSs [17], which increases the difficulty of the overall control of the vehicle platoon. Therefore, communication topology for IVTSs with lead-following mode has become a hot topic issue in the past decades. For example, in [19] and [20], the vehicle only received the state information of the adjacent preceding vehicle, while in [21], two adjacent vehicles could share information with each other. In [22], the problem of inter-vehicle communication topology assignment

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and control for vehicular platoons in LTE-V2V networks based on the cooperative awareness message dissemination mechanism was investigated. Furthermore, a sampled-data control problem for connected vehicles subject to switching topologies, communication delays, and external disturbances was studied in [23]. However, in the existing literature, it is assumed that communication between two adjacent vehicles should be kept well. Therefore, the reliability of IVTSs can not be guaranteed when one of a vehicle communication is interrupted. Meanwhile, if only the vehicle's speed is applied in the control strategy to ensure the expected distance, the dynamic performance of IVTSs will be affected. Based on the above analysis, optimizing communication structure and improving the dynamic performance of distance control are the main motivation of this study.

Time-triggered mechanism (TTM) is wildly used in networked control systems with wireless communication due to the advantages of fast control and easy implementation [26], [27]. Under the TTM, sensors sample and transmit data in a fixed period, and actuators complete the feedback control of the system. However, under such a communication mechanism, a large amount of redundant sampling information is transmitted over wireless networks, resulting in a waste of valuable and limited network resources. To solve these problems, the event-triggered mechanism (ETM) was proposed in [28]. Different from the TTM, only when the event-triggered condition is violated, data are allowed to be transmitted over the network [29], [30], thereby reducing the number of transmitted data. An overview on the issue of control and filtering for networked systems under ETMs was presented in [31], in which the design methods to guarantee the minimum inter-event time and jointly solve the parameters of both controller and ETM were reviewed. The authors studied event-triggered bounded control for general linear systems by decomposing the system into single subsystems to achieve global stabilization in [32]. In [33], H_∞ consensus problem of linear heterogeneous multi-agent systems (MASs) based on event-triggered output feedback control was studied, such that the linear heterogeneous MASs with unknown external disturbance achieved H_∞ consensus. Recently, many state-of-art results on the ETM have been put forward. In [34], the problem of event-triggered cooperative control of vehicle platoons with actuator delays caused by fueling and braking was dealt with. To mention a few, in [35] and [36], the triggering threshold was designed to be a variable that depends on the state informations at the latest release instant and the current sampling instant. By this way, the data releasing rate dynamically adjusts with the time-varying threshold to better adapt to the requirement of the control performance. The cooperative design of event-triggered communication scheduling and queue control in vehicular ad-hoc networks with limited communication resources was studied in [37]. In [34], based on ETM and platoon model transformation, the vehicle platoon cooperative control problem was transformed into the stabilization problem of vehicle tracking error system with time-varying delay. Memory-based ETM was studied in [38] and [39] for the consensus problem of MASs subject to actuator failures and aperiodic denial of service (DoS) attacks. It is a big challenge to compromise between a good control performance and a less data transmission for the design of IVTS tracking control with wireless communication that involves the distributed ETM and controller. However, few results concern this problem, which is another motivation for this study.

Inspired by above discussions, a new distance control strategy for IVTSs with an adaptive METM is investigated in this study. The main contributions can be summarized as follows:

1) Acceleration information is skillfully introduced in the desired distance. Compared to the existing results, such as [40], our approach leverages the inclusion of acceleration data and historical information to achieve a rapid and efficient response in distance control. This enhancement significantly boosts the dynamic performance of IVTSs, ultimately elevating the overall level of safety and reliability.
2) By constructing an adaptive threshold and using the historical information of the IVTS in the event-triggered condition, an adaptive METM is proposed to save the bandwidth of the communication network and improve distance control performance. Compared to the traditional ETM in [32], [33], and [34], the proposed method leverages historical triggering information to greatly mitigate unexpected transmissions resulting from sudden changes in system states caused by unknown disturbances. Additionally, the adaptive threshold we have implemented dynamically adjusts alongside state changes, allowing for a better balance between the limited network bandwidth and control performance. This novel approach represents a significant advancement in both efficiency and reliability for IVTSs.

The remainder of this article is organized as follows. Section II presents the system description and problem formulation with the proposed adaptive METM. In Section III, the consensus controlloer is designed. An example of IVTS with four FVs and one LV is given in Section IV to show the effectiveness of the proposed method. Section V summarizes the article.

Notations are as follows: $\otimes$ represents Kronecker product. I_n is a identity matrix with $n \times n$ dimension. col$\{\cdot\}$ denotes the column vector. diag$\{l_1, l_2, \ldots, l_n\}$ is a diagonal matrix with elements l_i.

II. Problem Formulation

A. Graph Theory

Suppose the IVTS have one leader vehicle (LV) and N following vehicles (FVs), and denote $\mathcal{G} = (\mathcal{A}, \mathcal{E}, L)$ as a directed graph, where $\mathcal{A} = \alpha_1, \alpha_2, \ldots, \alpha_N$ and $\mathcal{E} \subseteq \mathcal{A} \times \mathcal{A}$ are the sets of nodes and edges, respectively. A directed edge from α_j to α_i of $\mathcal{G}$ is represented by $e_{ji} = (\alpha_j, \alpha_i)$. $L = [l_{ij}]_{N\times N} \in \mathbb{R}^{N\times N}$ is a weighted adjacency matrix with $l_{ij} \geq 0$, and it is assumed that $l_{ii} = 0$ and $l_{ij} > 0$ if $e_{ji} \in \mathcal{E}$. A directed path from α_j to α_i is a sequence of distinct nodes $\alpha_{p_1}, \alpha_{p_2}, \ldots, \alpha_{p_n}$ with $\alpha_{p_1} = \alpha_j$ and $\alpha_{p_n} = \alpha_i$, such that $(\alpha_{p_i}, \alpha_{p_{i+1}}) \in \mathcal{E}$ for $i = 1, 2, \ldots, N-1$.

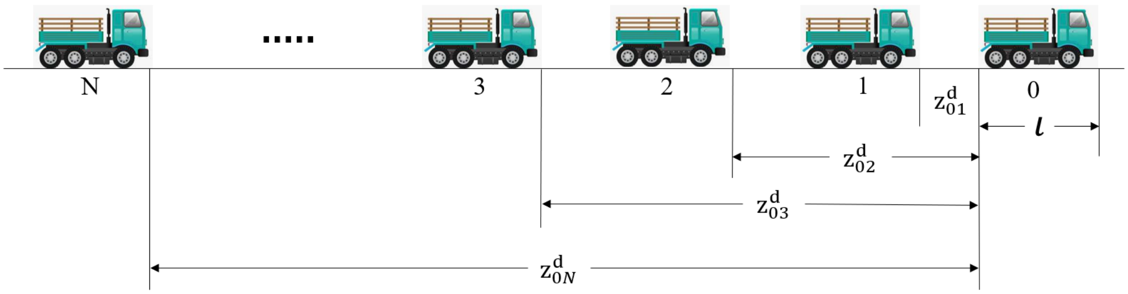


Fig. 1. IVTSs.

B. Vehicle Dynamics Model

As shown in Fig. 1, it is assumed that the IVTSs are composed of $N+1$ autonomous vehicles. The dynamics equations (DEs) of the i-th ($i = 1, 2, \ldots, N$) autonomous vehicle are described as follows [8]:

$$\begin{cases} \dot{z}_i = v_i \\ \dot{v}_i = a_i \\ \dot{a}_i = f_i(v_i, a_i) + g_i(v_i)n_i, \end{cases} \tag{1}$$

where z_i, v_i and a_i are defined as the position, velocity, and acceleration of vehicle i, respectively; n_i is the engine input of i-th autonomous vehicle; and functions $f_i(v_i, a_i)$ and $g_i(v_i)$ are given by

$$\begin{cases} f_i(v_i, a_i) = -\frac{1}{\varrho}(\dot{v}_i + \frac{\alpha M c_i}{2m}v_i^2 + \frac{f_m}{m}) - \frac{\alpha M c_i v_i a_i}{m} \\ g_i(v_i) = \frac{1}{\varrho m}, \end{cases} \tag{2}$$

where ϱ denotes the inertia time constant; α is the specific mass of the air; M, c_i, f_m and m represent cross-sectional area, drag, coefficient, mechanical drag and mass of every vehicle, respectively.

Remark 1: In (2), the range of inertial time constant can be solved as $0.34 \le \varrho \le 0.82$ by the approach of model identification using Matlab Toolbox [41].

Similar to [5], the engine input n_i is given by:

$$n_i = u_i m + \frac{\alpha M c_i}{2}v_i^2 + f_m + \varrho\alpha M c_i v_i a_i, \tag{3}$$

where u_i is the control input signal to be designed.

Combining (1), (2) and (3), one has

$$\dot{a}_i(t) = -\frac{1}{\varrho}a_i(t) + \frac{1}{\varrho}u_i(t). \tag{4}$$

Then, the DE of the leader vehicle is expressed as:

$$\begin{cases} \dot{z}_0(t) = v_0(t) \\ \dot{v}_0(t) = a_0(t) \\ \dot{a}_0(t) = -\frac{1}{\varrho}a_0(t), \end{cases} \tag{5}$$

and the DE of the following vehicle is presented by:

$$\begin{cases} \dot{z}_i(t) = v_i(t) \\ \dot{v}_i(t) = a_i(t) \\ \dot{a}_i(t) = -\frac{1}{\varrho}a_i(t) + \frac{1}{\varrho}u_i(t). \end{cases} \tag{6}$$

For convenience of design, we define

$$\begin{cases} x_i^z(t) = z_0(t) - z_i(t) - l - z_{0i}^d(t) \\ x_i^v(t) = v_0(t) - v_i(t) \\ x_i^a(t) = a_0(t) - a_i(t), \end{cases} \tag{7}$$

where $x_i^z(t)$, $x_i^v(t)$ and $x_i^a(t)$ denote the distance error, the velocity error, and the acceleration error, respectively. $z_{0i}^d(t) = h_v(v_i(t) - v_0(t)) + h_a(a_i(t) - a_0(t)) + (i-1)l + i z_{\min}$ is the desired distance between i-th ($i = 1, 2, \ldots, N$) vehicle and the leading vehicle; h_v and h_a are distance parameters; l denotes the vehicle length, and $z_{\min}$ is a specified minimum distance.

Defining the error vector $x_i(t) = [x_i^{zT}(t), x_i^{vT}(t), x_i^{aT}(t)]^T$ and i-th vehicle's disturbance $\omega_i(t)$, one can obtain the i-th vehicle spacing error as follows

$$\dot{x}_i(t) = Ax_i(t) + Bu_i(t) + D\omega_i(t), \tag{8}$$

where

$$A = \begin{bmatrix} 0 & 1 & h_v - \frac{h_a}{\varrho} \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\varrho} \end{bmatrix}, B = \begin{bmatrix} -\frac{h_a}{\varrho} \\ 0 \\ -\frac{1}{\varrho} \end{bmatrix}, D = \begin{bmatrix} h_v & 0 & 0 \\ 0 & h_a & 0 \\ 0 & 0 & 0 \end{bmatrix}.$$

Remark 2: Different from general models for IVTSs using the error of adjacent two vehicles such as in [5], the model of IVTSs in this study introduces a novel desired distance, in which the relative speed and acceleration between the LV and the i-th FV are considered. In this way, the situation that an FV goes out of control and the entire IVTS fails using traditional modeling methods can be avoided.

Remark 3: From (7), one can see that the acceleration information is introduced in the desired distance $z_{0i}^d(t)$ as shown in Fig. 1. Compared to [40], the accuracy and rapidity of FVs can be greatly improved when the system is disturbed, thereby increasing the safety of distance control caused by rear-end collision.

Remark 4: In (7), if one sets $h_a = 0$, the desired distance degrades into the general desired distance, such as the desired distance in [40].

C. An Adaptive METM

For the convenience of information exchange for IVTS, the distributed control signal is transmitted via a wireless network. However, the information interconnection between FVs will greatly burden network bandwidth. In order to

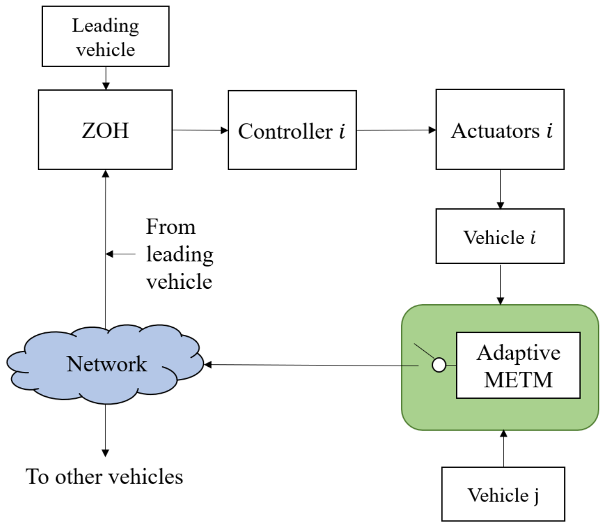


Fig. 2. Structure of adaptive ETM control for i-vehicle.

further relieve the heavy load on the network, a new event-triggered mechanism shown in Fig. 2 is proposed, by which the data transmission depends on the designed event-triggered condition rather than the fixed sampling period.

Denote the k-th transmitted instant of the i-th vehicle as $t_k^i h$, and define

$$
\begin{aligned}
\Delta(t) &= \max\Big\{m_i h \Big| \sum_{\nu=1}^{\bar{\nu}} \delta_{i,\nu} e_{i,\nu}^T(t)\Omega_i e_{i,\nu}(t) \\
&\qquad - \sigma_i(t)\bar{x}_i^T(t)\Omega_i \bar{x}_i(t) \leq \gamma_i\Big\},\\
\bar{x}_i(t) &= \frac{1}{\bar{\nu}}\sum_{\nu=1}^{\bar{\nu}} d_{i,\nu}(t),\\
e_{i,\nu}(t) &= \tilde{x}_i(k_s h) - \tilde{x}_i(t_{k-\nu+1}^i h),\\
d_{i,\nu}(t) &= \sum_{j\in N}[l_{ij}(\tilde{x}_i(t_{k-\nu+1}^i h) - \tilde{x}_j(t_{k-\nu+1}^j h))\\
&\qquad + b_i(\tilde{x}_i(t_{k-\nu+1}^i h) - \tilde{x}_0(k_s h))],\\
\sigma_i(t) &= \sigma_0 + \sigma_m e^{-\lambda\|x_i(k_s h)\|_2},\\
\tilde{x}_0(t) &= \begin{bmatrix} z_0(t) + h_v v_0(t) + h_a a_0(t) \\ v_0(t) \\ a_0(t) \end{bmatrix},\\
\tilde{x}_i(t) &= \begin{bmatrix} z_i(t) + h_v v_i(t) + h_a a_i(t) + i z_{\min} + il \\ v_i(t) \\ a_i(t) \end{bmatrix},
\end{aligned}
$$

where $\Delta(t)$ is the triggering interval for next transmission. $\bar{\nu}$ is a maximum amount of historical packets; $t_{k-\nu+1}^i$ is the past released instant for i-th vehicle with $\nu \in \{1, 2, 3, \ldots, \bar{\nu}\}$; $\delta_{i,\nu}$ is the weight of historical released information at instant $t_{k-\nu+1}^i$ for i-th vehicle; $k_s h$ is denoted as current time instant; $l_{ij} \geq 0$ is the coupling weight between followers, if the j-th vehicle can deliver information to i-th vehicle, then $l_{ij} > 0$; otherwise $l_{ij} = 0$; similarly, $b_i > 0$ is the coupling weight between leaders and each follower; γ_i, σ_0, σ_1 and λ are given positive constants; h is the sampling period and $\Omega_i > 0$ is the triggering matrix to be designed. According to the definition of $\sigma(t)$, it can be obtained that $\sigma_0 \leq \sigma_i(t) \leq \sigma_0 + \sigma_m = \bar{\sigma}$.

Then, the next transmission instant is determined by

$$
t_{k+1}^i h = t_k^i h + \Delta(t). \tag{9}
$$

Remark 5: In this study, we assume that the LV adopts TTM with a sampling period h, and the FVs take the adaptive METM in (9). In order to solve the problem of inconsistent sequence caused by the proposed ETM between the LV and FVs, two new variables $\tilde{x}_0(t)$ and $\tilde{x}_i(t)$ are defined. Then, the i-th error state in (8) can be obtained by $x_i(t) = \tilde{x}_0(t) - \tilde{x}_i(t)$.

Remark 6: In the proposed adaptive METM, one can see that the average state $\bar{x}_i(t)$ is introduced, which includes the past $\bar{\nu}$ triggering packets of FVs. In this way, unexpected transmission due to abrupt changes in system states can be significantly mitigated. Moreover, the inner time becomes smoother than that using traditional ETMs.

Remark 7: Generally, the weight $\delta_{i,\nu}$ takes a smaller value for the packets far away from the current time; that is, when ν takes a great value, the packets at $t_{k-\nu+1}^i$ turns unmeaning. However, it will waste storage resources and reduce the sensitivity of the current state. Therefore, we choose the maximum amount of historical packets $\bar{\nu} = 3$. Usually, the closer the triggering instant is to the current moment, the greater the weight is. Additionally, if one takes $\bar{\nu}$ as 1, the adaptive METM degrades into the traditional adaptive ETM.

Remark 8: To simplify the representation of symbols and facilitate the calculation, we assume that the weight δ_ν of each vehicle is the same, that is $\delta_{i,\nu} = \delta_\nu$.

Based on the above discussion, we design the distributed tracking controller for the i-th FV as follows:

$$
\begin{aligned}
u_i(t) &= -\sum_{\nu=1}^{\bar{\nu}} K_\nu d_{i,\nu}(t)\\
&= -\sum_{\nu=1}^{\bar{\nu}} K_\nu \sum_{j\in N}\big\{l_{ij}(\tilde{x}_i(t_{k-\nu+1}^i h)\\
&\quad - \tilde{x}_j(t_{k-\nu+1}^j h)) + b_i(\tilde{x}_i(t_{k-\nu+1}^i h) - \tilde{x}_0(k_s h))\big\}
\end{aligned} \tag{10}
$$

for $t \in [t_k^i h + \tau_k^i, t_{k+1}^i h + \tau_{k+1}^i)$, where $K_\nu \in \mathbb{R}^{1\times n}$ is the local controller gain of FVs to be designed, and τ_k^i is the network-induced delay at $t_k^i h$.

Define $\Xi_{t_k^i}^{m_i} \triangleq [t_k^i h + m_i h + \tau_k^{i,m_i}, t_k^i h + (m_i+1)h + \tau_{k+1}^{i,m_i+1})$, $\tau_k^{i,0} = \tau_k^i$ and $\tau_k^{i,M_i+1} = \tau_{k+1}^i$, where $m_i \in \{0, 1, 2, \ldots, M_i\}$ is the sampling step between adjacent triggering instant and $M_i = \max\{m_i\}$. Obviously, it holds that $[t_k^i h + \tau_k^i, t_{k+1}^i h + \tau_{k+1}^i) = \bigcup_{m_i=0}^{M_i} \Xi_{t_k^i}^{m_i}$.

For $t \in \Xi_{t_k^i}^{m_i}$, we define

$$
\tau_i(t) = t - t_k^i h - m_i h. \tag{11}
$$

Then, it has

$$
0 < \tau_i(t) < h + \tau_M^i \leq \tau_M, \tag{12}
$$

where $\tau_M = \max\{h + \tau_M^1, h + \tau_M^2, \ldots, h + \tau_M^N, \}$.

By the definition of $e_{i,\nu}(t)$, one can get

$$
\tilde{x}_i(t_{k-\nu+1}^i h) = \tilde{x}_i(t - \tau_i(t)) - e_{i,\nu}(t). \tag{13}
$$

From the adaptive METM in (9), combining (10) and (13) yields that

$$\begin{aligned} u_i(t) =& -\sum_{\nu=1}^{\bar{\nu}} K_\nu \sum_{j\in N} \{l_{ij}[\tilde{x}_i(t-\tau_i(t)) - e_{i,\nu}(t) \\ &- \tilde{x}_j(t-\tau_i(t)) + e_{j,\nu}(t)] + b_i[\tilde{x}_i(t-\tau_i(t)) \\ &- e_{i,\nu}(t) - \tilde{x}_0(t)]\} \\ =& -\sum_{\nu=1}^{\bar{\nu}} K_\nu \sum_{j\in N} \{l_{ij}[-x_i(t-\tau_i(t)) - e_{i,\nu}(t) \\ &+ x_j(t-\tau_i(t)) + e_{j,\nu}(t)] + b_i[-x_i(t-\tau_i(t)) \\ &- e_{i,\nu}(t)]\}. \end{aligned} \tag{14}$$

For simplifying analysis, we define

$$\begin{cases} x(t) = \mathrm{col}\{x_1(t), x_2(t), \dots, x_N(t)\}, \\ x(t-\tau(t)) = \mathrm{col}\{x_1(t-\tau_1(t)), \dots, x_N(t-\tau_N(t))\}, \\ e_\nu(t) = \mathrm{col}\{e_{1,\nu}(t), e_{2,\nu}(t), \dots, e_{N,\nu}^T(t)\}, \\ \omega(t) = \mathrm{col}\{\omega_1(t), \omega_2(t), \dots, \omega_N(t)\}. \end{cases}$$

Combining (8), (10), (13), and (14), the closed loop of IVTSs based on the proposed adaptive METM in (9) can be written as

$$\begin{aligned} \dot{x}(t) =& (I_N \otimes A)x(t) + (I_N \otimes D)\omega(t) \\ &+ \sum_{\nu=1}^{\bar{\nu}} (H \otimes BK_\nu)(e_\nu(t) + x(t-\tau(t))), \\ x(t_0) =& \zeta(t), \qquad t \in [-\tau_M, 0]. \end{aligned} \tag{15}$$

where $H = \bar{L} + \bar{B}$, $\bar{L} = \tilde{L} - L$ with $\tilde{L} = \mathrm{diag}\{\tilde{L}_1, \tilde{L}_2, \dots, \tilde{L}_N\}$, $\tilde{L}_i = \sum l_{ij}$, and $\bar{B} = \mathrm{diag}\{b_1, b_2, \dots, b_N\}$.

In this study, we will analysis the stability and stabilization of IVTSs under the proposed METM in (9) and the distributed controller in (14).

III. Main Results

In this section, the distributed error control will be developed to ensure the distance tracking performance of IVTSs with the proposed adaptive METM, which has been discussed in Section II. First, we will give the following assumption, lemma and definition.

Assumption 1: Assume that the digraph $\mathcal{G}$ has a spanning tree if there exist at least one node that has a directed path from LV to each FV in $\mathcal{G}$, and LV is the root node.

Lemma 1: [44], [45] Let $R_1 \in \mathbb{R}^{n_1\times n_1}, \cdots, R_N \in \mathbb{R}^{n_N\times n_N}$ be positive matrices. Then for all $e_1 \in \mathbb{R}^{n_1}, \cdots, e_N \in \mathbb{R}^{n_N}$, for all $\alpha_i > 0$ with $\sum_i^N \alpha_i = 1$ and for all $S_{ij} \in \mathbb{R}^{n_i\times n_j}$, $i = 1, \cdots, N$, $j = 1, \cdots, i-1$ such that

$$\begin{bmatrix} R_i & S_{ij} \\ * & R_j \end{bmatrix} \geq 0,$$

the following inequality holds:

$$\sum_{i=1}^N \frac{1}{\alpha_i} e_i^T R_i e_i \geq \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_N \end{bmatrix}^T \begin{bmatrix} R_1 & S_{12} & \dots & S_{1N} \\ * & R_2 & \dots & S_{2N} \\ * & * & & \vdots \\ * & * & \dots & R_N \end{bmatrix} \begin{bmatrix} e_1 \\ e_2 \\ \vdots \\ e_N \end{bmatrix}.$$

Before subsequent analysis, we will present the following definition similar to [46].

Definition 1: For constants $\varsigma > 0$ and $\mathcal{T} > 0$, $||x(t)||_2 < \varsigma$, $\forall t > t_0 + \mathcal{T}$, the IVTS (15) is said to be UUB, if there exist compact set $\mathbb{D} \in \mathbb{R}^n$ such that $x(t_0 + \kappa) = x_{t_0} \in \mathbb{D}$, $\kappa \in [-\tau_M, 0)$.

Theorem 1: Given scalars $\bar{\sigma}$, τ_M, γ, r, and distributed controller gains K_ν $(\nu = 1, 2, 3)$, the IVTS (15) are UUB if there exist positive definite matrices $P > 0$, $Q > 0$, $R > 0$, S and $\Omega_i > 0$ $(i = 1, 2, \cdots, N)$ such that

$$\Psi = \Gamma + \tau_M^2 \Phi^T R \Phi < 0, \tag{16}$$

$$\begin{bmatrix} R & * \\ S & R \end{bmatrix} > 0, \tag{17}$$

where

$$\Gamma = \begin{bmatrix} \hat{\Gamma}_{11} & * & * & * & * & * & * \\ \Gamma_{21} & \Gamma_{22} & * & * & * & * & * \\ -S & \Gamma_{32} & \Gamma_{33} & * & * & * & * \\ \Gamma_{41} & \Gamma_{42} & 0 & \Gamma_{44} & * & * & * \\ \Gamma_{51} & \Gamma_{52} & 0 & \Gamma_{54} & \Gamma_{55} & * & * \\ \Gamma_{61} & \Gamma_{62} & 0 & \Gamma_{64} & \Gamma_{65} & \Gamma_{66} & * \\ \Gamma_{71} & 0 & 0 & 0 & 0 & 0 & -r^2 I \end{bmatrix},$$

$$\Phi = \begin{bmatrix} I_N \otimes A & \Lambda & 0 & \Lambda_1 & \Lambda_2 & \Lambda_3 & I_N \otimes D \end{bmatrix},$$

$$\hat{\Gamma}_{11} = \Gamma_{11} + (\sqrt{\gamma} + 1)I,$$
$$\Gamma_{11} = P(I_N \otimes A) + (I_N \otimes A)^T P + Q - R,$$
$$\Gamma_{21} = (H \otimes B\hat{K})^T P + R + S, \ \Gamma_{33} = -Q - R,$$
$$\Gamma_{22} = -2R - S - S^T + \hat{\Omega}, \ \Gamma_{32} = R + S,$$
$$\Gamma_{41} = (H \otimes BK_1)^T P, \ \Gamma_{51} = (H \otimes BK_2)^T P,$$
$$\Gamma_{61} = (H \otimes BK_3)^T P, \ \Gamma_{42} = \Gamma_{52} = \Gamma_{62} = \frac{1}{3}\hat{\Omega},$$
$$\Gamma_{44} = -\delta_1\Omega + \frac{1}{9}\hat{\Omega}, \ \Gamma_{55} = -\delta_2\Omega + \frac{1}{9}\hat{\Omega}, \Gamma_{66} = -\delta_3\Omega + \frac{1}{9}\hat{\Omega},$$
$$\Gamma_{54} = \Gamma_{64} = \Gamma_{65} = \frac{1}{9}\hat{\Omega}, \Gamma_{71} = (I_N \otimes D)^T P,$$
$$\Lambda_\nu = H \otimes BK_\nu, \Lambda = \sum_{\nu=1}^{\bar{\nu}} \Lambda_\nu, \hat{K} = \sum_{\nu=1}^{\bar{\nu}} K_\nu,$$
$$\Omega = \mathrm{diag}\{\Omega_1, \Omega_2, \dots, \Omega_N\}, \hat{\Omega} = \bar{\sigma}(H^T \otimes I_n)\Omega(H \otimes I_n).$$

Proof: Choose a LyapunovKrasovskii function as follows:

$$V(t) = V_1(t) + V_2(t) + V_3(t), \tag{18}$$

where

$$\begin{aligned} V_1(t) &= x^T(t)Px(t), \\ V_2(t) &= \int_{t-\tau_M}^t x^T(s)Qx(s)ds, \\ V_3(t) &= \tau_M \int_{t-\tau_M}^t \int_\theta^t \dot{x}^T(s)R\dot{x}(s)dsd\theta, \end{aligned}$$

Taking the derivative of (18) along the trajectory of the closed-loop system (15), one can obtain

$$\begin{aligned} \dot{V}(t) &= \dot{V}_1(t) + \dot{V}_2(t) + \dot{V}_3(t) \\ &= 2x^T(t)P\dot{x}(t) + x^T(t)Qx(t) \end{aligned}$$

$$-x^T(t-\tau_M)Qx(t-\tau_M)+\tau_M^2\dot{x}^T(t)R\dot{x}(t)$$
$$-\tau_M\int_{t-\tau_M}^{t}\dot{x}^T(s)R\dot{x}(s)ds. \tag{19}$$

Appling the Jensens inequality in [42] yields that

$$\begin{aligned}&-\tau_M\int_{t-\tau_M}^{t}\dot{x}^T(s)R\dot{x}(s)ds\\ &\leq\begin{bmatrix}x(t)-x(t-\tau(t))\\ x(t-\tau(t))-x(t-\tau_M)\end{bmatrix}^T\begin{bmatrix}\frac{\tau_M}{\tau(t)}R & *\\ 0 & \frac{\tau_M}{\tau_M-\tau(t)}R\end{bmatrix}\\ &\quad\times\begin{bmatrix}x(t)-x(t-\tau(t))\\ x(t-\tau(t))-x(t-\tau_M)\end{bmatrix},\end{aligned} \tag{20}$$

then combining Lemma 1 in [43] and [45], we can derive the inequality as follows:

$$\begin{aligned}&\begin{bmatrix}x(t)-x(t-\tau(t))\\ x(t-\tau(t))-x(t-\tau_M)\end{bmatrix}^T\begin{bmatrix}\frac{\tau_M}{\tau(t)}R & *\\ 0 & \frac{\tau_M}{\tau_M-\tau(t)}R\end{bmatrix}\\ &\quad\times\begin{bmatrix}x(t)-x(t-\tau(t))\\ x(t-\tau(t))-x(t-\tau_M)\end{bmatrix}\\ &\leq\begin{bmatrix}x(t)-x(t-\tau(t))\\ x(t-\tau(t))-x(t-\tau_M)\end{bmatrix}^T\begin{bmatrix}R & *\\ S & R\end{bmatrix}\\ &\quad\times\begin{bmatrix}x(t)-x(t-\tau(t))\\ x(t-\tau(t))-x(t-\tau_M)\end{bmatrix}\\ &\leq\xi^T(t)W\xi(t),\end{aligned} \tag{21}$$

where

$$\xi(t)=\left[x^T(t)\ x^T(t-\tau(t))\ x^T(t-\tau_M)\right]^T,$$
$$W=\begin{bmatrix}-R & * & *\\ R+S & -2R-S-S^T & *\\ -S & R+S & -R\end{bmatrix}.$$

From the above derivation, we can obtain

$$-\tau_M\int_{t-\tau_M}^{t}\dot{x}^T(s)R\dot{x}(s)ds\leq\xi^T(t)W\xi(t). \tag{22}$$

From the adaptive METM in (9), one has

$$\sum_{\nu=1}^{3}\delta_\nu e_\nu^T(t)\Omega e_\nu^T(t)<\mathcal{F}^T(t)\hat{\Omega}\mathcal{F}(t)+\gamma, \tag{23}$$

where $\mathcal{F}(t)=x(t-\tau(t))+\frac{1}{3}\sum_{\nu=1}^{3}e_\nu(t)$ and $\gamma=\sum_{i=1}^{N}\gamma_i$.

Combining (19)-(23) leads to

$$\dot{V}(t)-r^2\omega^T(t)\omega(t)+x^T(t)x(t)\leq\phi^T(t)\Psi\phi(t)+\gamma$$
$$-\sqrt{\gamma}x^T(t)x(t), \tag{24}$$

where $\phi(t)=\operatorname{col}\{x(t),x(t-\tau(t)),x(t-\tau_M),e_s(t),\omega(t)\}$, and $e_s(t)=\operatorname{col}\{e_1(t),e_2(t),e_3(t)\}$.

From (24), one knows that if $x^T(t)x(t)\geq\sqrt{\gamma}$, then (16) is a sufficient condition to guarantee $\dot{V}(t)<0$ by using Schur complement. Therefore, the control scheme under the proposed adaptive METM can obtain a UUB distance performance according to Definition 1. This completes the proof. ■

Theorem 1 gives the stability conditions to guarantee a UUB of the closed-loop system (15). Next, we aim to design the distributed controller K_ν in (10) and the weight matrices of the proposed adaptive METM Ω_i in (9) based on Theorem 1.

Theorem 2: Given scalars $\bar{\sigma}$, τ_M, γ and r, the IVTS (15) is UUB if there exist positive definite matrices $\tilde{P}>0$, $\tilde{Q}>0$, $\tilde{R}>0$, $\tilde{S}$, $\tilde{\Omega}_i>0$ $(i=1,2,\cdots,N)$, and matrices $\tilde{K}_\nu$ $(\nu=1,2,3)$ with appropriate dimensions such that

$$\tilde{\Psi}=\begin{bmatrix}\tilde{\Gamma} & *\\ \tilde{\Psi}_{21} & \tilde{\Psi}_{22}\end{bmatrix}<0, \tag{25}$$

$$\begin{bmatrix}\tilde{R} & *\\ \tilde{S} & \tilde{R}\end{bmatrix}>0, \tag{26}$$

where

$$\tilde{\Gamma}=\begin{bmatrix}\tilde{\Gamma}_{11} & * & * & * & * & * & *\\ \tilde{\Gamma}_{21} & \tilde{\Gamma}_{22} & * & * & * & * & *\\ -\tilde{S} & \tilde{\Gamma}_{32} & \tilde{\Gamma}_{33} & * & * & * & *\\ \tilde{\Gamma}_{41} & \tilde{\Gamma}_{42} & 0 & \tilde{\Gamma}_{44} & * & * & *\\ \tilde{\Gamma}_{51} & \tilde{\Gamma}_{52} & 0 & \tilde{\Gamma}_{54} & \tilde{\Gamma}_{55} & * & *\\ \tilde{\Gamma}_{61} & \tilde{\Gamma}_{62} & 0 & \tilde{\Gamma}_{64} & \tilde{\Gamma}_{65} & \tilde{\Gamma}_{66} & *\\ \tilde{\Gamma}_{71} & 0 & 0 & 0 & 0 & 0 & -r^2I\end{bmatrix},$$

$$\tilde{\Psi}_{21}=\begin{bmatrix}\Pi_{11} & \Pi_{12} & 0 & \Pi_{14} & \Pi_{15} & \Pi_{16} & \Pi_{17}\\ (\sqrt{\gamma}+1)^{\frac{1}{2}}\tilde{P} & 0 & 0 & 0 & 0 & 0 & 0\end{bmatrix},$$

$$\tilde{\Psi}_{22}=\begin{bmatrix}\mu^2\tilde{R}-2\mu\tilde{P} & *\\ 0 & -I\end{bmatrix},$$

$$\tilde{\Gamma}_{11}=(I_N\otimes A)\tilde{P}+\tilde{P}(I_N\otimes A)^T+\tilde{Q}-\tilde{R},$$
$$\tilde{\Gamma}_{21}=(I_N\otimes\tilde{K})^T(H\otimes B)^T+\tilde{R}+\tilde{S},$$
$$\tilde{\Gamma}_{22}=-2\tilde{R}-\tilde{S}-\tilde{S}^T+\bar{\sigma}(H\otimes I_n)^T\tilde{\Omega}(H\otimes I_n),$$
$$\tilde{\Gamma}_{32}=\tilde{R}+\tilde{S},\ \tilde{\Gamma}_{33}=-\tilde{Q}-\tilde{R},$$
$$\tilde{\Gamma}_{41}=(I_N\otimes\tilde{K}_1)^T(H\otimes B)^T,$$
$$\tilde{\Gamma}_{51}=(I_N\otimes\tilde{K}_2)^T(H\otimes B)^T,$$
$$\tilde{\Gamma}_{61}=(I_N\otimes\tilde{K}_3)^T(H\otimes B)^T,$$
$$\tilde{\Gamma}_{42}=\tilde{\Gamma}_{52}=\tilde{\Gamma}_{62}=\frac{1}{3}\bar{\sigma}(H\otimes I_n)^T\tilde{\Omega}(H\otimes I_n),$$
$$\tilde{\Gamma}_{44}=-\delta_1\tilde{\Omega}+\frac{1}{9}\bar{\sigma}(H\otimes I_n)^T\tilde{\Omega}(H\otimes I_n),$$
$$\tilde{\Gamma}_{55}=-\delta_2\tilde{\Omega}+\frac{1}{9}\bar{\sigma}(H\otimes I_n)^T\tilde{\Omega}(H\otimes I_n),$$
$$\tilde{\Gamma}_{66}=-\delta_3\tilde{\Omega}+\frac{1}{9}\bar{\sigma}(H\otimes I_n)^T\tilde{\Omega}(H\otimes I_n),$$
$$\tilde{\Gamma}_{54}=\tilde{\Gamma}_{64}=\tilde{\Gamma}_{65}=\frac{1}{9}\bar{\sigma}(H\otimes I_n)^T\tilde{\Omega}(H\otimes I_n),$$
$$\tilde{\Gamma}_{71}=(I_N\otimes D)^T,$$
$$\Pi_{11}=\tau_M(I_N\otimes A)\tilde{P},\ \Pi_{12}=\tau_M(H\otimes B)(I_N\otimes\tilde{K}),$$
$$\Pi_{14}=\tau_M(H\otimes B)(I_N\otimes\tilde{K}_1),\Pi_{15}=\tau_M(H\otimes B)(I_N\otimes\tilde{K}_2),$$
$$\Pi_{16}=\tau_M(H\otimes B)(I_N\otimes\tilde{K}_3),\Pi_{17}=\tau_M(I_N\otimes D).$$

Furthermore, the distributed controller gains and the weight matrix of the proposed adaptive METM are $K_\nu=\tilde{K}_\nu\tilde{P}_s^{-1}$ and $\Omega_i=\tilde{P}_s^{-1}\tilde{\Omega}_i\tilde{P}_s^{-1}$, respectively.

Proof: Define $P=(I_N\otimes P_s)$ in Theorem 1, $\tilde{P}_s=P_s^{-1}$, $\tilde{P}=P^{-1}$, $\tilde{Q}=\tilde{P}Q\tilde{P}$, $\tilde{R}=\tilde{P}R\tilde{P}$, $\tilde{S}=\tilde{P}S\tilde{P}$, $\tilde{\Omega}=\operatorname{diag}\{\tilde{\Omega}_1,\tilde{\Omega}_2,\ldots,\tilde{\Omega}_N\}$, $\tilde{\Omega}_i=\tilde{P}_s\Omega_i\tilde{P}_s$, $\tilde{K}=\hat{K}\tilde{P}_s$, $\tilde{K}_\nu=K_\nu\tilde{P}_s$.

By using Schur complement lemma and the property of $-R^{-1} = -\tilde{P}\tilde{R}^{-1}\tilde{P} \leq \mu^2\tilde{R} - 2\mu\tilde{P}$, one knows that (16) in Theorem 1 is a sufficient condition to guarantee

$$\hat{\Psi} = \begin{bmatrix} \hat{\Gamma} & * & * \\ \tau_M\Phi & \mu^2\tilde{R} - 2\mu\tilde{P} & * \\ \hat{\Psi}_{31} & 0 & -I \end{bmatrix} < 0, \tag{27}$$

where $\hat{\Psi}_{31} = \left[(\sqrt{\gamma}+1)^{\frac{1}{2}}I\ 0\ 0\ 0\ 0\ 0\ 0\right]$ and $\hat{\Gamma}$ is the matrix Γ in Theorem 1 by replacing $\hat{\Gamma}_{11}$ with Γ_{11}. Then, one can get (25) and (26) hold by pre-multiplying and post-multiplying inequalities (27) and (17) with $\operatorname{diag}\{\tilde{P}, \tilde{P}, \tilde{P}, \tilde{P}, \tilde{P}, \tilde{P}, I, I\}$ and $\operatorname{diag}\{\tilde{P}, \tilde{P}\}$, respectively. The proof is completed. ■

As mentioned in Remark 7, the proposed METM will be degraded into the traditional ETM when one sets $\nu = 1$. The following Corollary can be obtained for this scenario.

Corollary 1: Given scalars $\bar{\sigma}$, τ_M, γ and r, the IVTS (15) is UUB if there exist positive definite matrices $\tilde{P} > 0$, $\tilde{Q} > 0$, $\tilde{R} > 0$, $\tilde{S}$, $\tilde{\Omega}_i > 0$ $(i = 1, 2, \cdots, N)$ and matrix $\tilde{K}$ with appropriate dimensions such that

$$\bar{\Psi} = \begin{bmatrix} \bar{\Gamma} & * \\ \bar{\Psi}_{21} & \bar{\Psi}_{22} \end{bmatrix} < 0, \tag{28}$$

$$\begin{bmatrix} \tilde{R} & * \\ \tilde{S} & \tilde{R} \end{bmatrix} > 0, \tag{29}$$

where

$$\bar{\Gamma} = \begin{bmatrix} \bar{\Gamma}_{11} & * & * & * & * \\ \bar{\Gamma}_{21} & \bar{\Gamma}_{22} & * & * & * \\ -\tilde{S} & \bar{\Gamma}_{32} & \bar{\Gamma}_{33} & * & * \\ \bar{\Gamma}_{41} & \bar{\Gamma}_{42} & 0 & \bar{\Gamma}_{44} & * \\ \bar{\Gamma}_{51} & 0 & 0 & 0 & -r^2 I \end{bmatrix},$$

$$\bar{\Psi}_{21} = \begin{bmatrix} \bar{\Pi}_{11} & \bar{\Pi}_{12} & 0 & \bar{\Pi}_{14} & \bar{\Pi}_{15} \\ (\sqrt{\gamma}+1)^{\frac{1}{2}}\tilde{P} & 0 & 0 & 0 & 0 \end{bmatrix},$$

$$\bar{\Psi}_{22} = \begin{bmatrix} \mu^2\tilde{R} - 2\mu\tilde{P} & * \\ 0 & -I \end{bmatrix},$$

$$\bar{\Gamma}_{11} = (I_N \otimes A)\tilde{P} + \tilde{P}(I_N \otimes A)^T + \tilde{Q} - \tilde{R},$$

$$\bar{\Gamma}_{21} = (I_N \otimes \tilde{K})^T(H \otimes B)^T + \tilde{R} + \tilde{S},$$

$$\bar{\Gamma}_{22} = -2\tilde{R} - \tilde{S} - \tilde{S}^T + \bar{\sigma}(H \otimes I_n)^T\tilde{\Omega}(H \otimes I_n),$$

$$\bar{\Gamma}_{32} = \tilde{R} + \tilde{S},\ \ \bar{\Gamma}_{33} = -\tilde{Q} - \tilde{R},$$

$$\bar{\Gamma}_{41} = (I_N \otimes \tilde{K})^T(H \otimes B)^T,$$

$$\bar{\Gamma}_{42} = \bar{\sigma}(H \otimes I_n)^T\tilde{\Omega}(H \otimes I_n),$$

$$\bar{\Gamma}_{44} = -\tilde{\Omega} + \bar{\sigma}(H \otimes I_n)^T\tilde{\Omega}(H \otimes I_n),$$

$$\bar{\Gamma}_{51} = (I_N \otimes D)^T,$$

$$\bar{\Pi}_{11} = \tau_M(I_N \otimes A)\tilde{P},\ \ \bar{\Pi}_{12} = \tau_M(H \otimes B)(I_N \otimes \tilde{K}),$$

$$\bar{\Pi}_{14} = \tau_M(H \otimes B)(I_N \otimes \tilde{K}), \bar{\Pi}_{15} = \tau_M(I_N \otimes D).$$

Moreover, the distributed controller gain $K = \tilde{K}\tilde{P}_s^{-1}$ and the weight matrix $\Omega_i = \tilde{P}_s^{-1}\tilde{\Omega}_i\tilde{P}_s^{-1}$ of the adaptive ETM can be given by solving LMIs (28) and (29).

Proof: The proof is similar to Theorems 1 and 2. Therefore, it is omitted here. ■

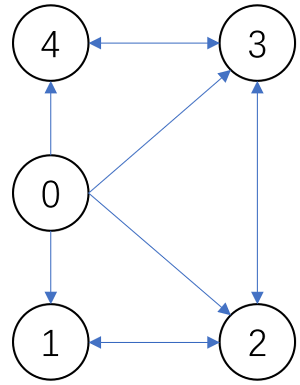


Fig. 3. The communication topology.

IV. Simulation

In the section, an IVTS with four FVs and one LV is applied to manifest the advantages of our proposed method.

Similar to [41], we choose $\varrho = 0.35$, $h_v = 1$, $l = 5$, and $z_{\min} = 25$. Set the sampling period $h = 0.01$, $\sigma_0 = 0.05$, $\sigma_m = 0.01$, and the parameters $\gamma = 0.002$, $\tau_M = 0.005$, $r = 8$, $\mu = 1$, $\delta_1 = 0.5$, $\delta_2 = 0.3$, $\delta_3 = 0.2$, and $h_a = 1$.

From Assumption 1 and Fig. 3, we can obtain $\bar{B}$ and the Laplacian matrix $\bar{L}$ as follows:

$$\bar{B} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \bar{L} = \begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 2 & -1 & 0 \\ 0 & -1 & 2 & -1 \\ 0 & 0 & -1 & 1 \end{bmatrix},$$

Choose the initial states and the disturbance of road conditions as follows: $x_1(t_0) = [75, 20, 0]^T$, $x_2(t_0) = [40, 19, 0]^T$, $x_3(t_0) = [15, 17, 0]^T$, $x_4(t_0) = [5, 15, 0]^T$, $z_0(t_0) = 100$, $v_0(t_0) = 20$, $a_0(t_0) = 0$, and $\omega_i(t) = [0.3\ e^{-0.16t}\sin(t),\ 0,\ 0]$.

From Theorem 2, the distributed tracking controller gains of the IVTS and the parameters of the proposed adaptive METM can be solved as follows:

$$\begin{aligned} K_1 &= \begin{bmatrix} 0.6881 & 0.8463 & 0.0442 \end{bmatrix}, \\ K_2 &= \begin{bmatrix} 0.2903 & 0.3571 & 0.0187 \end{bmatrix}, \\ K_3 &= \begin{bmatrix} 0.0914 & 0.1125 & 0.0061 \end{bmatrix}, \end{aligned} \tag{30}$$

$$\begin{aligned} \Omega_1 &= \begin{bmatrix} 0.2697 & 0.3214 & 0.0187 \\ 0.3214 & 0.3969 & 0.0166 \\ 0.0187 & 0.0166 & 0.0083 \end{bmatrix}, \\ \Omega_2 &= \begin{bmatrix} 0.2535 & 0.3036 & 0.0170 \\ 0.3036 & 0.3745 & 0.0159 \\ 0.0170 & 0.0159 & 0.0066 \end{bmatrix}, \\ \Omega_3 &= \begin{bmatrix} 0.2535 & 0.3036 & 0.0170 \\ 0.3036 & 0.3745 & 0.0159 \\ 0.0170 & 0.0159 & 0.0066 \end{bmatrix}, \\ \Omega_4 &= \begin{bmatrix} 0.2697 & 0.3214 & 0.0187 \\ 0.3214 & 0.3969 & 0.0166 \\ 0.0187 & 0.0166 & 0.0083 \end{bmatrix}. \end{aligned} \tag{31}$$

The distance between the LV and the i-th FV is shown in Fig. 4, from which one can see that no rear-end collision occurs. The adjacent vehicles keep a desired safe distance, and this safe distance tends to be constant after the stabilization of

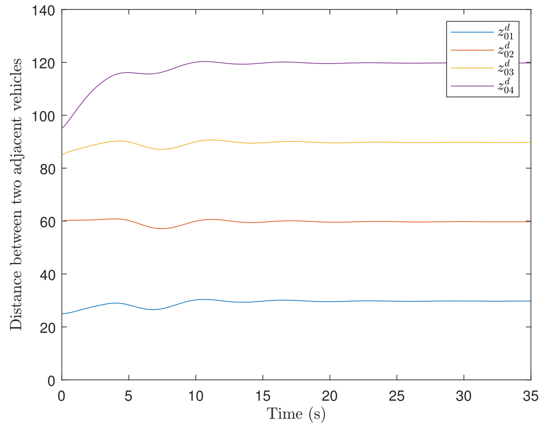
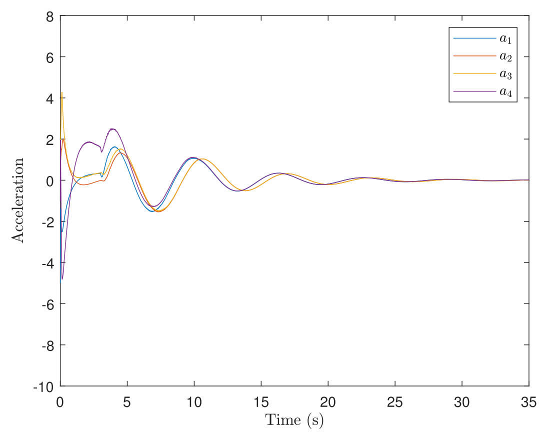
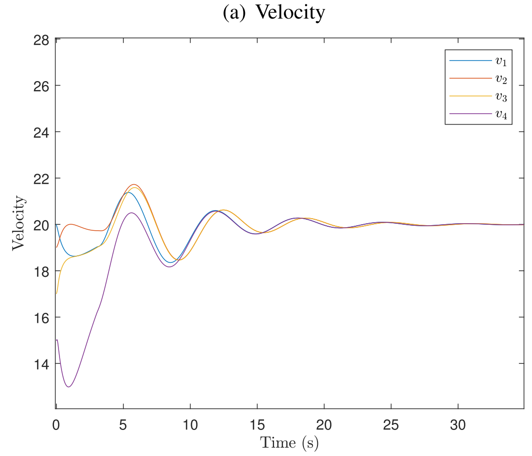


Fig. 4. Distances between the LV and the i-th FV under the proposed strategy.

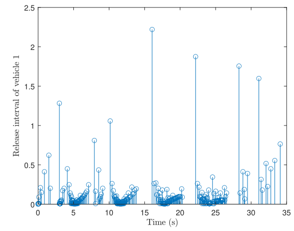


(a) Velocity

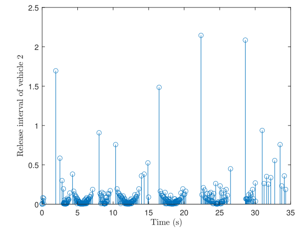


(b) Acceleration

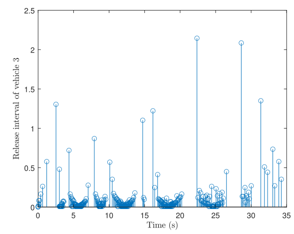
Fig. 5. The velocity and acceleration of vehicle i under the proposed strategy.



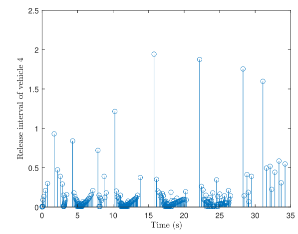
(a) Vehicle 1



(b) Vehicle 2



(c) Vehicle 3



(d) Vehicle 4

Fig. 6. Release intervals of vehicle i under the proposed strategy.

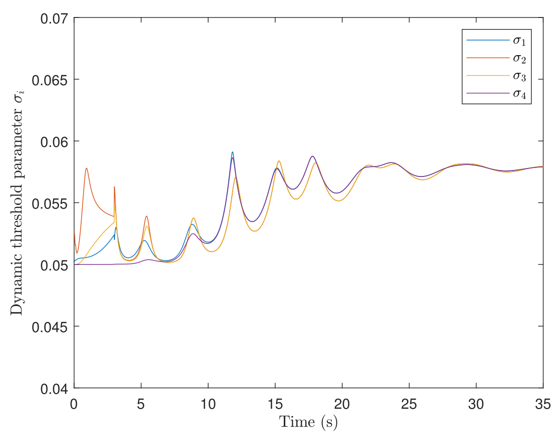


Fig. 7. Dynamic threshold σ_i of the adaptive METM.

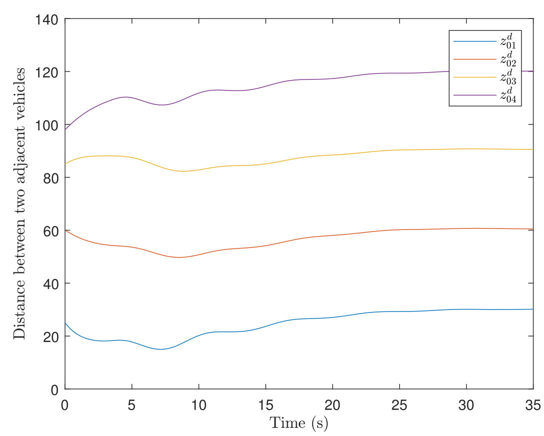
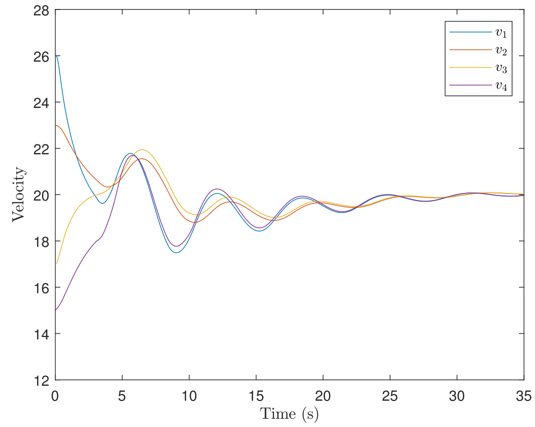


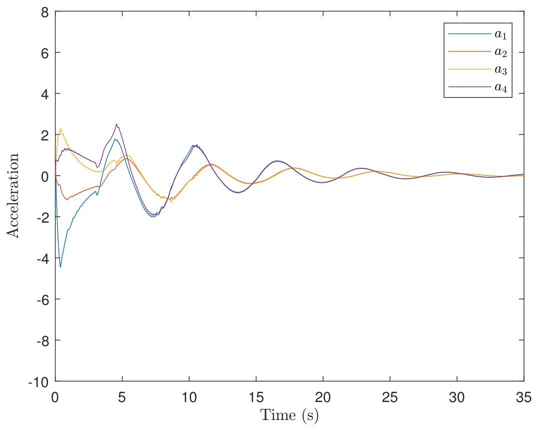
Fig. 8. Distances between the LV and the i-th FV under the control strategy with $h_a = 0$.

the IVTS. Fig. 5 presents the velocity and acceleration of the i-th FV. It can be observed that using the proposed distributed control strategy can lead to a good dynamic process so as to maintain the desired safe distance.

In this study, the acceleration information is introduced to the desired distance, by which the tracking performance can be improved. As discussed in Remark 4, if one sets $h_a = 0$, the results become similar to the case studied in [40]. Using a similar method, we can depict the distance between the LV and the i-th FV, velocity and acceleration responses presented in Fig. 8 and Fig. 9 under the same initial conditions other than $h_a = 0$. Comparing Fig. 4 and Fig. 8, one can observe that the distance between adjacent vehicles by using our proposed method reaches a stabilization faster than that using the traditional method. Moreover, one can see that better dynamic performances with less settle time and overshoot for



(a) Velocity



(b) Acceleration

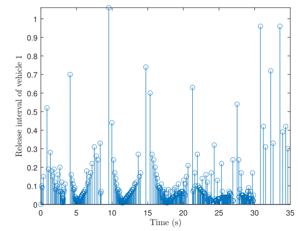
Fig. 9. The velocity and acceleration of vehicle i under the control strategy with $h_a = 0$.

TABLE I
TRIGGERING NUMBERS UNDER DIFFERENT SCHEMES FOR VEHICLE i

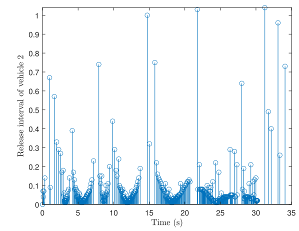
Modeling	1	2	3	4
Adaptive METM in (9)	502	751	748	499
Conventional ETM in [28]	659	836	858	667

the velocity and acceleration responses can be achieved under our proposed method in comparison with Fig. 5 and Fig. 9. In fact, such satisfactory results are not only attributed to the introduction of acceleration information into the control input but also to the historical information, which is given in (14). From (30), one can see that the historical information is unequal: the further away the time is from the current instant, the smaller the control gain is. Therefore, we can conclude that IVTSs with our control strategy increase safety and tracking performance.

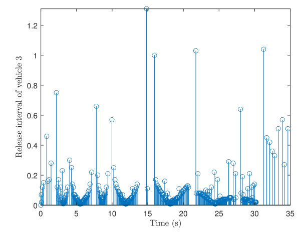
As mentioned above, the vehicle information is transmitted via a wireless network. Fig. 6 shows the release intervals of four FVs by using such an adaptive METM, from which one can see that the interval of data release is not a fixed period as traditional TTM. From Fig. 6 and Table I, one can calculate that the data discarding rate of four FVs is 86.2%, 79.1%, 79.1% and 86.7%, respectively. Consequently, the proposed adaptive METM can effectively mitigate the



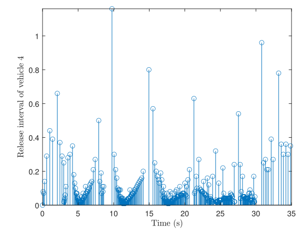
(a) Vehicle 1



(b) Vehicle 2



(c) Vehicle 3



(d) Vehicle 4

Fig. 10. Release intervals of the i-th FV under the conventional ETM in [28].

burden of network bandwidth. To better balance the control and network performance, we apply an adaptive threshold method which plays a critical role in determining the release intervals in real time. Fig. 7 shows the dynamic variation of the threshold. It can be seen that the threshold tends to be a constant when the system becomes stable, and the threshold during 25-35s is greater than the one at the beginning, resulting in less data release rate when the system states are stable.

Next, we will discuss the potential advantages of our proposed communication mechanism. In Remark 7, we have known that if we set $\bar{\nu} = 1$, the case then degrades to the general adaptive ETM. The responding results are derived in Corollary 1. Under the same initial conditions, we can obtain the distributed controller gain K and triggering matrices Ω_i as follows:

$$K = \begin{bmatrix} 1.0144 & 1.3049 & 0.0145 \end{bmatrix},$$
$$\Omega_1 = \begin{bmatrix} 0.2499 & 0.3161 & 0.0022 \\ 0.3161 & 0.4099 & 0.0066 \\ 0.0022 & 0.0066 & 0.0049 \end{bmatrix},$$
$$\Omega_2 = \begin{bmatrix} 0.2454 & 0.3114 & 0.0025 \\ 0.3114 & 0.4031 & 0.0062 \\ 0.0025 & 0.0062 & 0.0040 \end{bmatrix},$$
$$\Omega_3 = \begin{bmatrix} 0.2454 & 0.3114 & 0.0025 \\ 0.3114 & 0.4031 & 0.0062 \\ 0.0025 & 0.0062 & 0.0040 \end{bmatrix},$$
$$\Omega_4 = \begin{bmatrix} 0.2499 & 0.3161 & 0.0022 \\ 0.3161 & 0.4099 & 0.0066 \\ 0.0022 & 0.0066 & 0.0049 \end{bmatrix}.$$

Fig. 10 depicts the releasing intervals of four FVs under the general adaptive ETM. Comparing the releasing intervals under our proposed METM, as shown in Fig. 6, we can see that under the proposed adaptive METM, a greater average releasing period can meet the requirement of each FVs, which means that our communication mechanism can better mitigate the burden of network bandwidth. The detailed amount of releasing data is given in Table I for proposed adaptive METM and conventional ETM in [28].

V. Conclusion

In this paper, the problem of tracking control for IVTS has been investigated by using a leader-following approach. To increase the reliability of safety distance and the dynamic tracking performance, we take two main measures: 1) introduce the acceleration information into the desired distance; 2) introduce historical information into the control input. To balance the bandwidth of wireless network and tracking control performance, an adaptive METM is proposed by introducing historical information into the communication mechanism. The effectiveness of the proposed tracking control scheme is verified by an IVTS with one LV and four FVs. The proposed adaptive METM introduces historical data, which takes computing power into account. However, this approach may lead to the depletion of storage resources and reduce the sensitivity of the current condition. In future research, the controller design of IVTS will consider the reduction of calculation and network security, including protection against cyber-attacks. Furthermore, we will introduce the optimizing control method and string stability method to handle heterogeneous vehicle characteristics in real-world scenarios.

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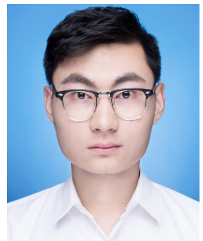

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