Cooperative Adaptive Cruise Control of Vehicles Using a Resource-Efficient Communication Mechanism

Shixi Wen, Ge Guo, *Senior Member, IEEE*, Bo Chen, and Xiue Gao

***Abstract*—In this study, a resource-efficient communication mechanism is investigated for the cooperative adaptive cruise control (CACC) of vehicles subject to actuator delay and disturbances. Specifically, a dynamic event-triggered communication mechanism (DECM) is designed for a tracking error (spacing error, velocity error, and acceleration error) based sampled-data feedback controller. Under the DECM, the transmissions of sampled velocity and acceleration from a preceding vehicle to the controller can be significantly reduced. Sufficient conditions for the stability of the CACC system are obtained for the DECM-based sampled-data feedback controller. According to the obtained conditions, parameter design criteria are established for the DECM to guarantee the stable performance of CACC systems. Simulation studies illustrate that the proposed DECM-based CACC system can not only save inter-vehicle communication resources, but also guarantee stable performance.**

***Index Terms*—Cooperative adaptive cruise control, sampled-data feedback control, resource-efficient communication mechanism, platoon stability, actuator delay, disturbance.**

I. Introduction

IN RECENT years, increasing traffic throughput has placed a heavy burden on road traffic systems. Traffic jams, road safety and environmental effects are the main issues facing current traffic systems [1], [2]. The most efficient way to alleviate severe traffic issues is to develop an intelligent vehicle highway system (IVHS) [3], [4]. One desirable feature of the IVHS is that vehicles are automatically organized into vehicle platoons to maintain the small inter-vehicle space/time gaps. Experiments have shown that heavy-duty vehicles platoons can lead to fuel savings of approximately 10% [5]. Since the 1980s, the IVHS has become a hot research topic around the world. IVHS programs include the PATH program in California [6], GCDC in the Netherlands [7], SARTRE in Europe [8], and Energy-ITS in Japan [9].

The first technique applied to IVHS was the adaptive cruise control (ACC) system. In an ACC system, desired distance maintenance and velocity tracking are implemented purely based on sensing devices (radar or scanning lidar) [10], [11]. In order to guarantee traffic safety, current ACC systems maintain relatively large inter-vehicle distances [10], which has limited their ability to increase traffic capacity. With the rapid deployment of vehicle-to-vehicle communication and vehicle-to-infrastructure communication technology, the ACC system has been transmitted into the cooperative adaptive cruise control (CACC) system by utilizing inter-vehicle communication. Vehicles in CACC system can not only measure inter-vehicle distances and relative velocities, but also obtain useful data (i.e., position, velocity, acceleration, etc.) and share those data with neighboring vehicles [14]–[24]. Therefore, smaller inter-vehicular distances are facilitated by CACC systems, which further reduces aerodynamic drag. Compared to ACC, CACC systems are more suitable as an enabling technique for IVHS because they guarantee satisfactorily enhanced mobility, greatly increased traffic capacity, largely reduced adverse environmental effects, and a safer and more comfortable driving experience [12], [13].

The structure of the CACC system is defined by three important aspects: vehicles, inter-communication, and a controller. The basic mechanism of these three aspects is that a distributed controller generates the control inputs for each vehicle according to a vehicle model, spacing/headway strategy, and information obtained from sensing devices and vehicle inter-communication. Because the three aspects are closely tied to each other, important issues that must be investigated in CACC systems stem from individual or multiple aspects that may affect or degrade the performance of a CACC system. For example, [14] described a distributed model predictive controller for vehicles with nonlinear dynamics under perfect inter-communication conditions. [15] addressed fuel and brake delays, and lags in the actuators of vehicles by utilizing a sliding mode controller. [16] investigated the H_∞ control method for a platoon of heterogeneous vehicles with uncertain vehicle dynamics and uniform communication delay. The authors in [17] and [18] proposed a switched controller structure handle contingent failures or limited capacity

Manuscript received December 12, 2017; revised April 22, 2018; accepted July 8, 2018. Date of publication December 13, 2018; date of current version February 22, 2019. This work was supported in part by the National Natural Science Foundation of China under Grants 61273107, 61573077, 61803062, and U1808205, in part by the Natural Science Foundation of Liaoning province of China under Grant 20180550794, and in part by the Doctoral Research Foundation of Dalian University under Grant 2017QL007. *(Corresponding author: Shixi Wen.)*

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Digital Object Identifier 10.1109/TIV.2018.2886676

in the measurements of on-board sensors, which are caused by poor visibility as result of rain or sandstorms, low battery power, and interference of radar signals [19]. [20] investigated the H_∞ multi-objective control problem for vehicles in ACC mode and CACC mode. The designed H_∞ control allows an IVHS to make trade-offs between vehicle following performance, system robustness, and string stability. An adaptive switched control strategy was proposed in [21] for uncertain heterogeneous platoons, where the switched control model mainly utilized CACC mode, but switched to ACC mode in the event of inter-vehicle communication loss. The authors of [22] proposed a synthesis co-design approach for both local controllers and the overall communication structure by utilizing a spatially invariant system approach, which guarantees the stability requirements for infinite-length vehicular strings without requiring a priori designed controller and a priori defined communication topology. A robust distributed control method was presented in [23] for vehicular platoons with bounded parameter uncertainty of inertial time delay and a broad spectrum of interaction topologies. A novel delay-based spacing policy combined with the notion of disturbance string stability was introduced in [24]. The delay-based spacing policy specifies the desired inter-vehicular distances and guarantees that all vehicles track the same spatially varying reference velocity profile. Disturbance string stability is the notion of that the string stability of vehicle platoons is subject to external disturbances on all vehicles.

In order to avoid the *slinky effect* phenomenon [25]–[27], which may cause an uncomfortable riding experience or rear-end accidents in a CACC system, rigorous string stability analysis has been focus of researchers. Existing approaches to string stability can be divided into three types: 1) the Lyapunov stability approach [25], 2) Spatially invariant linear systems approach [26] and 3) Frequency-domain approach [27]. Other interesting problems faced by CACC systems can be found in the survey papers [1], [2], [4], [12], and [28]. In [28], the author explored the effect of a dual-mass flywheel on the torsional vibration characteristics of a power-split hybrid powertrain. The dynamic equations governing the torsional vibrations of the power-split hybrid driveline were presented and a novel torsional vibration dynamic model was established by utilizing ADAMS.

It should be noted that most of existing results on CACC systems including those mentioned above, are based on the periodic time-triggered communication mechanism (TCM), meanings the data transmission between successive vehicles is performed continually at every time step or periodically at equidistant sampling points. Such a communication mechanism places a heavy burden on inter-vehicle communication systems for the following reasons: 1) limited wireless network bandwidth or limited coverage of roadside network; 2) the inter-communication of moving vehicles cannot be guaranteed all times. The TCM follows a periodic schedule to transmit sampled data and update the control input for the CACC system, even for two successive sampled data points with very little fluctuation. This is a waste of the limited communication resources available in the IEEE 802.11p communication protocol based on vehicular ad hoc networks (VANETs) and dedicated short-range communications [29]. Based on the digital nature of inter-vehicle communication networks, the rate at which data -packages can be transmitted is limited. As reported in [30], high communication rates degrade the reliability of inter-vehicle communication channels and increase transmission delays. There is no doubt that inter-vehicle communication imperfections can have a significant impact on the performance of CACC systems [16], [21], [31]. In order to secure the reliability and quality of inter-vehicle communication, it is important that only the information that is actually required to establish a stable CACC system is transmitted and that the transmission of unnecessary information is avoided. Hence, how to efficiently use scarce communication resources has become a major concern for CACC systems. To the best of our knowledge, the problem of a resource-efficient communication mechanism for CACC systems is still open and few results have been published on this topic in the literature. Difficulties may arise from handing intermittent data transmission and determining when inter-vehicle communication must be performed to guarantee the desired performance for the vehicle platoon, which gives rise to the first motivation for this study.

Recently, as an alternative to the TCM, the event-triggered communication mechanism (ECM) has become a hot research topic in the field of networked systems [32]–[35]. The core idea behind the ECM is that the transmission of the sampled data is only executed after the occurrence of an event, rather than a certain amount of time has passed. Generally, event is defined by an event-triggering condition, which is related to the system states and a threshold parameter. The sampled data is transmitted by the communication network only when a defined event is satisfied. In this manner, the transmission frequency over the communication network can be significantly reduced to save limited communication resources. Generally, there are two types of ECM: static ECM (SECM) and dynamic ECM (DECM). Unlike SECM, which has a prescribed constant threshold parameter, the threshold parameter of DECM can be determined real time by adjusting rules [34], [35]. The threshold parameter determines when or how frequently data transmission occurs, which is closely related to data transmission rates over inter-vehicle communication network. Since the IEEE 802.11p standard can provide various data rates at 3, 4.5, 6, 9, 12, 18, 24, and 27 Mbps, the threshold parameter should dynamically change over time to reflect these time-varying data transmission rates. However, how the DECM can be extended to CACC systems is unclear. Therefore, the second motivation of this paper is to design a DECM for CACC systems and apply it to facilitate velocity tracking and maintain inter-vehicle spacing.

In this study, we aim to design a resource-efficient communication mechanism for CACC systems considering the effects of actuator delay (e.g., fueling and braking delay) and disturbances (caused by acceleration of preceding vehicles). For maintaining distance and tracking velocity, a tracking-error-based sampled-data feedback controller for CACC systems is designed by considering heterogeneous information feedback. Here, we assume that the controller gain of the sampled-data feedback controller has a prescribed value that can guarantee string stability requirement conditions. Specifically, spacing error can be computed by on-board sensors directly, whereas the velocity and acceleration error of the i-th following vehicle must be calculated from the velocities and accelerations of preceding vehicle, which are transmitted via the inter-vehicle communication. To save the limited communication resources of inter-vehicle communication networks, the DECM is used as a resource-efficient communication mechanism for a CACC system, where the threshold parameter can be determined in real time by predefined adjusting rules. Under the DECM, the sampled velocity and acceleration of the *i*-th following vehicle will be authorized to be transmitted to the next vehicle only when a defined event is trigged. This significantly reduces the transmission frequency of sampled data. Next, a series of sufficient conditions for the stability of the platoon tracking error system under the DECM-based sampled-data feedback controller are obtained. Additionally, design criteria for determining the parameters of the DECM are established to guarantee the performance of the CACC system. A simulation study demonstrates that the CACC system with the DECM not only reduces the transmission frequency of inter-vehicle communication, but also guarantees a tracking error level below the H_∞ disturbance attenuation level. The main contributions of this paper are summarized as follows:

1) A resource-efficient control architecture is proposed for CACC systems to save the limited communication resources of the inter-vehicle communication network. In contrast to the traditional sampled-data vehicle control system, the transmission of sampled velocity and acceleration value is determined by an event-triggered condition.
2) A series of sufficient conditions are obtained to guarantee the stability of a DECM-based sampled-data CACC system subject to actuator delay and disturbance. Those conditions manage the tradeoff between communication resources consumption and control performance.
3) A resource-efficient H_∞ robust communication control design framework is established for the CACC system. In this framework, the parameters of the DECM are determined based on the communication resources consumption and stability requirements of the CACC system.

The remainder of this paper is organized as follows. Section II discusses the modeling of a single vehicle and CACC system. It also contains a description of the DECM, model transformation, and control objective of the CACC system. Section III presents stability analysis results and the parameter design of the DECM for the CACC system. Numerical simulations and comparative results are presented in Section IV to illustrate the effectiveness of the proposed algorithm.

Notations: $\arg\min_p\{f(p)\}$ is the value of p for which $f(p)$ attains its minimum value. The symbol $\otimes$ denotes a matrix Kronecker product. $diag\{a_i\}$ is a diagonal matrix containing diagonal entries of a_i. I is an identity matrix of the appropriate dimensions. $P > 0$ indicates that P is a positive definite matrix. The symbol $*$ denotes the symmetric term in a symmetric matrix.

II. Problem Formulation

Consider a CACC systems containing $N + 1$ vehicles driving on a horizontal road (see Fig. 1) in a VANET environment. z_i, v_i and a_i denote the *i*-th $(i = 0, 1, \ldots, N)$ vehicle's position, velocity, and acceleration, respectively, where $i = 0$ represents the leading vehicle. Each following vehicle is equipped with an onboard sensor to measure the distance between it and the preceding vehicle. Each vehicle transmits its state information (i.e., velocity and acceleration) to its following vehicle over the VANET. Considering the limited communication resources in the VANET, the distributed DECM will be applied to reduce the transmission frequency of the sampled velocity and acceleration values.

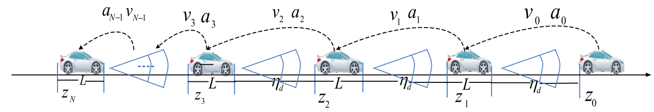

Fig. 1. Vehicle platoon control system.

A. Vehicle Model

For each following vehicle, its dynamics include the engine, drive line, braking system, aerodynamic drag, tire friction, rolling resistance and gravitational force, etc. In order to derive a concise model for platoon control, the following reasonable assumptions are added [36]:

1) Tire longitudinal slip in negligible and the powertrain dynamics are combined into a first-order inertial transfer function.
2) The vehicle body is considered to be rigid and symmetric.
3) The influence of pitch and yaw motions is neglected.
4) The driving and baking torques are controllable inputs.

According to the above assumptions, a simplified nonlinear vehicle dynamic model can be written as follows

$$\begin{cases} \dot{z}_i(t) = v_i(t) \\ \dot{v}_i(t) = \frac{1}{m_i}\left(\varpi_{T,i}\frac{T_i(t)}{R_i} - C_{A,i}v_i^2(t) - m_i g f\right) \\ \varsigma_i \dot{T}_i(t) + T_i(t) = T_{i,\,des}(t) \end{cases} \tag{1}$$

where m_i is the mass of the vehicle, $C_{A,i}$ is the combined aerodynamic drag coefficient, g acceleration due to gravity, f is the coefficient of rolling resistance, $T_i(t)$ denotes the actual driving/breaking torque, $T_{i,des}(t)$ is the desired driving/breaking torque, ς_i is the inertial delay of vehicle dynamics, R_i denotes the tire radius, and $\varpi_{T,i}$ is the mechanical efficiency of the driveline.

Based on the widely used exact feedback linearization technique [17], [18], [36], the nonlinear vehicle dynamic model (1) can be converted into a linear model for controller design. The position output combined with a relative degree tree is used to construct a feedback linearization law, which is written as follows:

$$T_{i,des}(t) = \frac{1}{\varpi_{T,i}}(C_{A,i}v_i(t)(2\tau_i\dot{v}_i + v_i) + m_i g f + m_i u_i)R_i \tag{2}$$

where u_i is the new input signal after linearization. Then, we obtain the following linear model for vehicle dynamics:

$$\begin{cases} \dot{z}_i(t) = v_i(t) \\ \dot{v}_i(t) = a_i(t) \\ \dot{a}_i(t) = -a_i(t)/\varsigma_i + u_i(t)/\varsigma_i \end{cases} \tag{3}$$

In engineering practice, both vehicle dynamics and the controller for the platoon control system can be different, which implies that the vehicle platoon is heterogeneous. However, a platoon is often formed by the vehicles of the same-type (e.g., either by only trucks or by only passenger cars [1], [2]). In such cases, vehicle dynamics are very consistent. In this paper, it is assumed that vehicles are homogeneous (i.e., $\varsigma_i = \varsigma$), and their controllers $u_i(t)$ are designed to be identical. However, a more realistic dynamic model should consider actuating delay in the vehicles (e.g., fueling delay and braking delay). Here, for simplicity, we utilize a single lumped delay τ to represent actuator time delay. Therefore, the third equation in (3) can be rewritten as

$$\dot{a}_i(t) = -a_i(t)/\varsigma + u_i(t-\tau)/\varsigma \tag{4}$$

We define the spacing error, velocity error, and acceleration error, respectively, as

$$\begin{cases} e_i^\delta(t) = \delta_i(t) - \delta_i^d(t) \\ e_i^v(t) = v_{i-1}(t) - v_i(t) \\ e_i^a(t) = a_{i-1}(t) - a_i(t) \end{cases} \tag{5}$$

where $\delta_i(t) = z_{i-1}(t) - z_i(t) - L$ is the distance between successive vehicles and $\delta_i^d(t) = h_v v_i(t) + z_0$ is the desired distance. h_v is the time gap, z_0 is a given minimum distance, and L is the length of a vehicle. Here, a constant-time headway-spacing policy is adopted for the CACC system to regulate the spacing between vehicles.

In this paper, the tracking error (e.g., spacing error, velocity error and acceleration error) based controller for the *i*-th following vehicle is designed as follows

$$u_i(t) = k_p e_i^\delta(t) + k_v e_i^v(t) + k_a e_i^a(t) \tag{6}$$

where k_p, k_v, and k_a are the prescribed feedback controller gains.

Assumption 1: The gain for the tracking-error-based sampled-data feedback controller (6) was designed by utilizing the method in [18] such that the magnitude of the string stability transfer function satisfies $\|G_{\Delta_i}(s)\| \le 1$, where $G_{\Delta_i}(s) = \frac{\Delta_i(s)}{\Delta_{i-1}(s)}$ and Δ_i is the signal of interest (e.g., relative distance error, velocity, or acceleration).

Note that the feedback controller (6) refers to heterogeneous information feedback. Specifically, the spacing error $e_i^\delta(t)$ can be computed from its own velocity $v_i(t)$ and the distance $\delta_i(t)$ measured by on-board sensors. However, the velocity error $e_i^v(t)$ and acceleration error $e_i^a(t)$ must be calculated based on the velocity and acceleration of the preceding vehicle, which are transmitted via the inter-communication network. For this reason, the overall measurement output state $[e_i^\delta v_i(t) a_i(t)]^T$ of the *i*-th following vehicle is split into two parts, $x_i^o(t)$ and $x_i^c(t)$, which respectively denote the portion of measurement supplied by the on-board sensors and that transmitted via the VANETs with $x_i^o(t) = [e_i^\delta(t) 0\, 0]^T$ and $x_i^c(t) = [0\ v_i(t) a_i(t)]^T$. Correspondingly, the control input $u_i(t)$ is also divided into two parts such:

$$u_i(t) = u_i^o(t) + u_i^c(t) = K_i^o x_i^o(t) + K_i^c[x_i^c(t) - x_{i-1}^c(t)] \tag{7}$$

where $K_i^o = [k_p 0\, 0]$ and $K_i^c = [0\ k_v\ k_a]$.

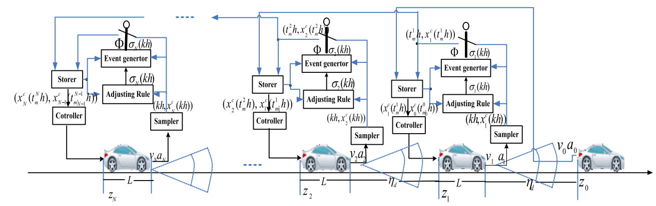

Fig. 2. DECM.

B. The DECM

For conventional CACC systems, each vehicle's velocity and acceleration are sampled periodically by onboard sensors at sampling times *kh*, $k \in N$, where $h>0$ is the sampling period. The *i*-th vehicle then transmits the sampled data $v_i(kh)$ and $a_i(kh)$ to the next vehicle at each sampling time *kh* via the VANETs, regardless of the state of the CACC system and communication resource occupation. This periodic communication TCM has advantages in terms of simplicity of modeling and implementation. However, it inevitably leads to excessive consumption of inter-vehicle communication resources, such as limited bandwidth and data transmission rates. From a resource conservation perspective, an efficient communication mechanism should be applied to CACC systems to avoid unnecessary data exchange between the vehicles to achieve better communication resource efficiency.

Instead of utilizing the TCM, in this paper, the DECM is adopted (as shown in Fig. 2). The core idea behind the DECM is that whether or not the sampled data $v_i(kh)$ and $a_i(kh)$ should be transmitted depends on the following defined event:

$$\alpha_i^T(kh)\Phi\alpha_i(kh) \ge \sigma_i(kh) y_i^T(kh)\Phi y_i(kh), k > t_m^i, m \in Z^+ \tag{8}$$

where $t_m^i h$ denotes the *m*-th transmitted instance of sampled data from the *i*-th vehicle. $\Phi > 0$ is a weighting matrix and $\alpha_i(kh) = x_i^c(kh) - x_i^c(t_m^i h)$. $y_i(kh) = x_i^c(kh) - x_{i-1}^c(t_{m'_{i-1}}^{i-1} h)$, where $x_{i-1}^c(t_{m'_{i-1}} h)$ is the latest local measurement from its preceding vehicle with $m'_{i-1} = \arg\min_p\{t_m^i + q_i - t_p^{i-1} | t_m^i + q_i > t_p^{i-1}, p \in Z^+\}$ and $\sigma_i(t_m^i h + q_i h)$ represents a dynamic threshold parameter. Therefore, the velocity $v_i(kh)$ and acceleration $a_i(kh)$ are transmitted to the next vehicle only if the defined event (8) is satisfied (i.e., the event is triggered). One can see from the defined event condition (8) that at the *k*-th sampling instance, the defined event-triggered condition for vehicle *i* is closely related to the sampled data error $\alpha_i(kh)$ and the sampled data $y_i(kh)$ including the latest transmitted sampled data $x_i^c(t_m^i h)$ from vehicle *i* and latest transmitted sampled data from the preceding vehicle. Therefore, the defined event condition is related to the vehicle's state.

Remark 1: It can be seen from (8) that the next broadcasting instance of vehicle *i* is not only related to its own sampled data, but also to the preceding vehicles' sampled data. Because the CACC system is a cascaded control system, varying velocity and acceleration values (e.g., *harsh brakes or harsh accelerations*) can be transmitted to next vehicles under condition (8) in a timely manner. Therefore, the defined event condition (8) can help the CACC system to maintain its desired formation model.

According to the defined event condition (8), the next transmission instance $t_{m+1}^i h$ of the *i*-th following vehicle is determined by

$$t_{m+1}^i h = t_m^i h + \min_{q_i \geq 1} \{ q_i h | \alpha_i^T (t_m^i h + q_i h) \Phi \alpha_i (t_m^i h + q_i h) \geq \sigma_i (t_m^i h + q_i h) y_i^T (t_m^i h + q_i h) \Phi y_i (t_m^i h + q_i h) \} \quad (9)$$

where $q_i \in N$.

The dynamic rule for adjusting the threshold parameter $\sigma(t_m^i h + q_i h)$ is chosen as

$$\sigma(t_m^i h + q_i h) = \sigma(t_m^i h + q_i h - h) - \theta \sigma(t_m^i h + q_i h) \sigma(t_m^i h + q_i h - h) y_i^T (t_m^i h + q_i h - h) \Phi y_i (t_m^i h + q_i h - h) \quad (10)$$

where $\theta > 0$ is a predefined constant and $\sigma(0) = \sigma_0 \in [0, 1)$ is the given initial condition.

Remark 2: It should be noted that the "storer" in Fig. 2 is employed to gather the sampled velocity and acceleration of the *i*-th vehicle and its preceding vehicle. When new sampled data from the *i*-th vehicle and its preceding vehicle are detected, the storer will immediately update its information. Then, the controller of the *i*-th following vehicle updates its input based on the received sampled data from the storer, which implies that the controller update of the *i*-th vehicle is driven by both its own and its preceding vehicle's event instances.

Remark 3: For the given initial condition $\sigma_0 \in [0, 1)$, the defined event-triggered condition (9) with the dynamic adjusting law (10) has the following feature [34], [35]

$$\alpha_i^T (kh) \Phi \alpha_i (kh) \leq \sigma_i (kh) y_i^T (kh) \Phi y_i (kh) \quad (11)$$

where the threshold parameter $\sigma(kh)$ satisfies the following inequality:

$$0 \leq \sigma(kh) \leq \sigma_0 < 1 \quad (12)$$

Furthermore, $\{\sigma(kh)\}$ is a monotone non-increasing sequence for all $k \in N$.

Remark 4: The DECM can efficiently save inter-vehicle communication resources. For example, if

$$\alpha_i^T (t_m^i h + q_i h) \Phi \alpha_i (t_m^i h + q_i h) < \sigma(t_m^i h + q_i h) y_i^T (t_m^i h + q_i h) \Phi y_i (t_m^i h + q_i h),$$

then no triggering signal is created by the event generator. Therefore, the current sampled data is not transmitted to the next vehicle because the fluctuation between the two successive sets of sampled data is very small. In this manner, the frequency of sampled-data transmission via the inter-vehicle communication network can be significantly reduced.

Remark 5: The DECM with the threshold adjusting rule (10) includes both the static ECM and TCM. Specifically, if $\theta = 0$ in (10) and the threshold parameter of (9) is set to $\sigma_i (t_m^i h + q_i h) = \sigma_i$ with a constant σ_i, then the DECM becomes as an SECM with the following form

$$t_{m+1}^i h = t_m^i h + \min_{q_i \geq 1} \{ q_i h | \alpha_i^T (t_m^i h + q_i h) \Phi \alpha_i (t_m^i h + q_i h) \geq \sigma_i y_i^T (t_m^i h + q_i h) \Phi y_i (t_m^i h + q_i h) \}$$

Furthermore, if we set $\theta = 0$ in (10) and $\sigma(\cdot) \to 0$ in (9), then we can derives that $\alpha_i^T (t_m^i h + q_i h) \Phi \alpha_i (t_m^i h + q_i h) \geq 0$, which implies that the sampled velocity and acceleration of the *i*-th vehicle are transmitted at each sampling instance. Therefore, the ECM is converted into the TCM.

Under the DECM using (9), $u_i^c(t)$from the sampled data feedback controller can be represented as:

$$u_i^c(t) = K_i^c \left[x_i^c (t_m^i h) - x_{i-1}^c \left(t_{m'_{i-1}(t)}^{i-1} h \right) \right] t \in \left[t_m^i h, t_{m+1}^i h \right) \quad (13)$$

where $m'_{i-1}(t) = \arg \min_p \{ t - t_p^{i-1} | t > t_p^{i-1}, p \in Z^+ \}$.

We define the measurement error for sampled data at the *k*-th sampling time for each vehicle as

$$e_i^c (kh) = x_i^c (kh) - x_i^c (t_m^i h), t_m^i < k < t_{m+1}^i \quad (14)$$

Because the release time intervals $[t_m^i h, t_{m+1}^i h) = \bigcup_{k=t_m^i}^{t_{m+1}^i - 1} [kh, (k+1)h)$ and $[t_m^i h, t_{m+1}^i h)$ can be divided into $t_{m+1}^i - t_m^i$ sampling intervals, $u_i^c(t)$ in (13) for $[kh, (k+1)h)$ can be represented as

$$u_i^c(t) = K_i^c \left[x_i^c (kh) - x_{i-1}^c (kh) - e_i^c (kh) + e_{i-1}^c (kh) \right] \quad (15)$$

By combining (7) and (15), the sampled data feedback controller $u_i(t)$, $t \in [kh, (k+1)h)$for each vehicle can be represented as follows:

$$\begin{aligned} u_i(t) &= K_i^o x_i^o (kh) \\ &\quad + K_i^c \left[x_i^c (kh) - x_{i-1}^c (kh) - e_i^c (kh) + e_{i-1}^c (kh) \right] \\ &= K_i x_i (th) + K_i \left[e_{i-1}^c (kh) - e_i^c (kh) \right] \end{aligned} \quad (16)$$

where $x_i(t) = x_i^o(t) + x_i^c(t) - x_{i-1}^c(t)$ denotes the tracking error vector and $K_i = K_i^o + K_i^c$ is the feedback controller gain.

We now define an "artificial delay" $\tau'(t) = t - kh$, where $t \in [kh, (k+1)h)$. It is clear that $\tau'(t)$ is piecewise-linear and discontinuous at $t = kh$, meaning it satisfies $0 \leq \tau'(t) < h$ and $\dot{\tau}'(t) = 1$ at $t \neq kh$. Therefore, the controller $u_i(t)$ in (16) can be rewritten with the following form

$$u_i(t) = K_i x_i (t - \tau'(t)) + K_i [e_{i-1}^c (t - \tau'(t)) - e_i^c (t - \tau'(t))] \quad (17)$$

C. Model Transformation and Control Objective for the CACC System

We define $x(t) = \mathrm{Col}[x_i(t)]_{i=1}^N$, $u(t) = \mathrm{Col}[u_i(t)]_{i=1}^N$ and $w(t) = \mathrm{Col}[a_i(t)]_{i=0}^{N-1}$ as the tracking error, control input vector, and disturbance vector, respectively, where "Col" denotes a column vector. Based on (4), (5), and (17), the state-space equation for the platoon can be written as

$$\dot{x}(t) = Ax(t) + Bu(t - \tau) + Dw(t) \, t \in [kh, (k+1)h), \quad (18)$$

where

$$A=\begin{bmatrix}A_1 & 0 & \cdots & 0\\ 0 & A_2 & \cdots & 0\\ \cdots & \ddots & \ddots & \cdots\\ 0 & \cdots & 0 & A_N\end{bmatrix},\ B=\begin{bmatrix}B_1 & 0 & \cdots & 0\\ -B_1 & B_2 & \cdots & 0\\ \cdots & \ddots & \ddots & \cdots\\ 0 & \cdots & -B_{N-1} & B_N\end{bmatrix},$$

$$D=\begin{bmatrix}d_1 & & \\ & \ddots & \\ & & d_N\end{bmatrix}, A_i=\begin{bmatrix}0 & 1 & h_v\\ 0 & 0 & 1\\ 0 & 0 & -\frac{1}{\varsigma}\end{bmatrix}, B_i=\begin{bmatrix}0\\ 0\\ -\frac{1}{\varsigma}\end{bmatrix}, d_i=\begin{bmatrix}h_v\\ 0\\ 0\end{bmatrix}.$$

Then, the tracking-error-based sampled-data feedback controller for the CACC system can be defined as

$$u(t-\tau)=K[x(t-\tau(t))+\varepsilon(t-\tau(t))]\ t\in[kh,(k+1)h), \tag{19}$$

where $\tau(t)=\tau'(t)+\tau, 0\leq\tau(t)<h'$ with $h'=h+\tau, \dot{\tau}(t)=1$ at $t\neq kh$. Additionally $K=diag\{K_1,\cdots,K_N\}$ and $\varepsilon(t)=(L\otimes I_3)e(t)$ with $e(t)=\mathrm{Col}[e_i^c(t)]_{i=1}^N$ and

$$L=\begin{bmatrix}1 & 0 & \cdots & 0\\ -1 & 1 & \cdots & 0\\ \cdots & \ddots & \ddots & \cdots\\ 0 & \cdots & -1 & 1\end{bmatrix}.$$

By substituting (19) in to (18), the state space equation for the CACC system in $t\in[kh,(k+1)h)$ can be rewritten as

$$\dot{x}(t)=Ax(t)+BKx(t-\tau(t))+BK\varepsilon(t-\tau(t))+Dw(t), \tag{20}$$

where the initial condition of the state is assumed to be $x(t)=\phi(t)=\phi(t_0)$ for $t\in[-h',0]$.

The control objective for this paper is to design a DECM (9) utilizing the threshold parameter adjusting rule (10) for the CACC systems under the sampled-data feedback controller (16) such that each vehicle can track the speed of the leading vehicle while maintaining the desired distance between any two consecutive vehicles. Specifically, the following criteria must be met:

1) Steady-state performance: the tracking error $x_i(t)$ is asymptotically stable.
2) Disturbance rejection performance: with an initial value of zero, the tracking error $x(t)$ of the CACC system satisfies the following H_∞ disturbance attenuation level with $\gamma>0$:

$$\|x(t)\|_2\leq\gamma\|w(t)\|_2 \tag{21}$$

for all non-zero $w(t)\in l_2[0,\infty)$.

III. Main Results

A. Stability Analysis for the CACC System

We are now in a position to derive sufficient conditions for the existence of the proposed DECM (9) and sampled-data feedback controller (16) for the CACC system. The main results of this derivation are contained in the following theorem.

Theorem 1: Consider a CACC system with the DECM (9) with the threshold parameter adjusting rule (10). For given scalars $h>0$, $\tau>0$, $\sigma_0\in[0,1)$, and $\gamma>0$, and the feedback gain matrix *K*, if there exist real matrices $P=P^T>0$, $Q=Q^T>0$, and $R=R^T>0$, and appropriate dimensions such that the following inequalities hold:

$$\begin{bmatrix}R & S\\ * & R\end{bmatrix}\geq 0, \tag{22}$$

$$\begin{bmatrix}\Gamma & h'\Omega & \gamma^{-1}I_{3N}\\ * & -R & 0\\ * & * & -I_{3N}\end{bmatrix}<0, \tag{23}$$

where $\Gamma=[\Gamma_{pq}]_{5\times5}$ is a symmetric block matrix with its entries given by $\Gamma_{11}=PA+A^TP+Q-R$, $\Gamma_{12}=PBK+R+S$, $\Gamma_{13}=-S$, $\Gamma_{14}=PB$, $\Gamma_{15}=PD$, $\Gamma_{22}=-S-S^T-2R+(L\otimes I_3)^T(\sigma_0I_N\otimes\Phi)(L\otimes I_3)$, $\Gamma_{23}=R+S$, $\Gamma_{24}=(L\otimes I_3)^T(\sigma_0I_N\otimes\Phi)$, $\Gamma_{33}=-R-Q$, and $\Gamma_{44}=(L\otimes I_3)^T(\sigma_0I_N\otimes\Phi)(L\otimes I_3)-I_N\otimes\Phi$, and the other entries is zero, then the tracking error of the CACC system is asymptotically stable with an H_∞ disturbance attenuation level of γ.

Proof: We choose the following Lyapunov-Krasovskii function for the CACC systems:

$$V(t)=\sum_{i=1}^{3}V_i(t),\ t\in[kh,(k+1)h) \tag{24}$$

where $V_1(t)=x^T(t)Px(t)$, $V_2(t)=\int_{t-h'}^{t}x^T(s)Qx(s)ds$, and $V_3(t)=\int_{-h'}^{0}\int_{t+\theta}^{t}\dot{x}^T(s)R\dot{x}(s)dsd\theta$ for the positive definite matrices *P*, *Q*, and *R*.

Taking the time derivative of $V(t)$ along the trajectories of (17), one can obtain that

$$\begin{aligned}\dot{V}_1(t)&=x^T(t)\big[PA+A^TP\big]x(t)+2x^T(t)PBKx(t-\tau(t))\\ &\quad+2x^T(t)PBK\varepsilon(t-\tau(t))+2x^T(t)PDw(t)\end{aligned} \tag{25}$$

$$\dot{V}_2(t)=x^T(t)Qx(t)-x^T(t-h)Qx(t-h) \tag{26}$$

$$\dot{V}_3(t)=h^2\dot{x}^T(s)R\dot{x}(s)-h\int_{t-\tau(t)}^{t}\dot{x}^T(s)R\dot{x}(s)ds \tag{27}$$

According to the reciprocally convex inequality given in [37, Lemma 1], we find that

$$-h\int_{t-\tau(t)}^{t}\dot{x}^T(s)R\dot{x}(s)ds\leq[\,\phi_1^T\ \phi_2^T\,]\begin{bmatrix}-R & S\\ * & -R\end{bmatrix}\begin{bmatrix}\phi_1\\ \phi_2\end{bmatrix} \tag{28}$$

where $\phi_1=x(t-\tau(t))-x(t)$, $\phi_2=x(t-h)-x(t-\tau(t))$ and *S* is a real matrix satisfying (22).

Based on the DECM from (9), (10), and (12), we can derive that

$$\begin{aligned}&\varepsilon^T(kh)(I_N\otimes\Phi)\varepsilon(kh)\\ &\quad=e^T(kh)\left[(L\otimes I_3)^T(I_N\otimes\Phi)(L\otimes I_3)\right]e(kh)\\ &\quad\leq x^T(kh)[(L\otimes I_3)^T(\sigma_0I_N\otimes\Phi)(L\otimes I_3)]\,x(kh),\end{aligned} \tag{29}$$

which means that

$$\begin{bmatrix} x(t-\tau(t)) \\ \varepsilon(t-\tau(t)) \end{bmatrix}^T \begin{bmatrix} \Pi_1 & \Pi_2 \\ * & \Pi_3 \end{bmatrix} \begin{bmatrix} x(t-\tau(t)) \\ \varepsilon(t-\tau(t)) \end{bmatrix} \geq 0 \tag{30}$$

where $\Pi_1 = (L \otimes I_3)^T(\sigma_0 I_N \otimes \Phi)(L \otimes I_3)$, $\Pi_2 = \Gamma_{24}$ and $\Pi_3 = \Gamma_{44}$.

By combining (25)–(28) and (30), one can obtain that

$$\dot{V}(t) \leq \Psi^T(t)(\Gamma + h'^2 \Omega^T R \Omega)\Psi(t) \tag{31}$$

where $\Psi(t) = \mathrm{col}\{x(t), x(t-\tau(t)), x(t-h), \varepsilon(t-\tau(t)), w(t)\}$ and $\Omega = [\,A\ BK\ 0\ BK\ D\,]$.

By Schur complement to (23), we can derive that

$$\begin{bmatrix} \Gamma & h'\Omega \\ * & -R \end{bmatrix} < 0, \tag{32}$$

Based on the Schur complement of (31), one can find that $\Gamma + h'^2\Omega^T R\Omega < 0$, meanings $\dot{V}(t) \leq 0$. Therefore, the error tracking system (18) is asymptotically stable.

In the following analysis we consider the H_∞ disturbance attenuation for the CACC system. For this purpose, we add the term $x^T(t)x(t) - \gamma^2 w^T(t)w(t)$ to both sides of (31). According to condition (23) in Theorem 1 and the Schur complement, we know that

$$\begin{aligned} &\dot{V}(t) + x^T(t)x(t) - \gamma^2 w^T(t)w(t) \\ &\leq \Psi^T(t)(\Gamma + h'^2\Omega^T R\Omega)\Psi(t) + x^T(t)x(t) - \gamma^2 w^T(t)w(t) < 0 \end{aligned}$$

which means that $\int_0^{h'} \dot{V}(t) + x^T(t)x(t) - \gamma^2 w^T(t)w(t) < 0$.

Therefore, we have $\int_0^\infty x^T(t)x(t) \leq \gamma^2 \int_0^\infty w^T(t)w(t)$ under the condition of zero initial error, namely, $\|x(t)\|_2 \leq \gamma\|w(t)\|_2$for all non-zero $w(t) \in l_2[0,\infty)$. The proof is completed.

Remark 6: The proposed DECM-based sampled-data controller can significantly reduce the transmission frequency of sampled data but does not affect the control performance of the CACC system. We will now elaborate on this concept. According to the properties of the event-triggered condition, one can obtain condition (29), where the measurement error $e_i^c(kh)$ is defined in (14). The conditions in Theorem 1 guarantee that the state *x*(*kh*) of the CACC system can be stabilized. Therefore, the measurement error $e_i^c(kh)$ is stable, which means that the current sampled data $x_i^c(kh)$ has very little fluctuation with respect to the latest transmitted data $x_i^c(t_m^i h)$. Therefore, it is not necessary to transmit the current data via the VANET for controller input updating. Comparative results are presented in the simulation study section to illustrate that the control performance of the DECM-based sampled-data controller is similar to that of the TCM-based sampled-data controller.

B. Parameter Design for the DECM

Theorem 2: Consider a CACC system with the DECM (9) with the threshold parameter adjusting rule (10). For given scalars $h > 0, \tau > 0, \sigma_0 \in [0,1), \gamma > 0$, and $\kappa > 0$ and the feedback gain matrix *K*, if there exist real matrices $\tilde{P} = \tilde{P}^T > 0$, $\tilde{Q} = \tilde{Q}^T > 0$, and $\tilde{R} = \tilde{R}^T > 0$, and appropriate dimensions $\tilde{S}$ such that the following inequalities hold:

$$\begin{bmatrix} \tilde{R} & \tilde{S} \\ * & \tilde{R} \end{bmatrix} \geq 0, \tag{33}$$

$$\begin{bmatrix} \Gamma & h'\Omega & \gamma^{-1} I_{3N} \\ * & -R & 0 \\ * & * & -I_{3N} \end{bmatrix} < 0, \tag{34}$$

where $\Gamma = [\Gamma_{pq}]_{5\times5}$ is a symmetric block matrix with its entries given by $\Gamma_{11} = \tilde{P}A + A^T\tilde{P} + \tilde{Q} - \tilde{R}$, $\Gamma_{12} = B\tilde{K} + \tilde{R} + \tilde{S}$, $\Gamma_{13} = -\tilde{S}$, $\Gamma_{14} = B\tilde{K}$, $\Gamma_{15} = \tilde{P}D$, $\Gamma_{22} = -S - S^T - 2R + (L \otimes I_3)^T\sigma_0\tilde{\Phi}(L \otimes I_3)$, $\Gamma_{23} = \tilde{R} + \tilde{S}$, $\Gamma_{24} = (L \otimes I_3)^T \sigma_0\tilde{\Phi}$, $\Gamma_{33} = -\tilde{R} - \tilde{Q}$, and $\Gamma_{44} = (L \otimes I_3)^T\sigma_0\tilde{\Phi}(L \otimes I_3) - I_N \otimes \tilde{\Phi}$, and the other entries are zero, then the tracking error of the CACC system is asymptotically stable with an H_∞ disturbance attenuation level of γ. Furthermore, the event-triggering weight matrix in (9) is defined as

$$\Phi = \tilde{P}^{-1}\tilde{\Phi}\tilde{P}^{-1}. \tag{35}$$

TABLE I
PARAMETERS FOR THE SIMULATION

Parameters	Notation	Value
Inertial lag	ς	0.25s
sampling period	h	0.1s
Length of vehicle	L	6m
Actuator time delay	τ	0.1s
Desired spacing	δ_d	5m
H_∞ disturbance attenuation level	γ	1.25

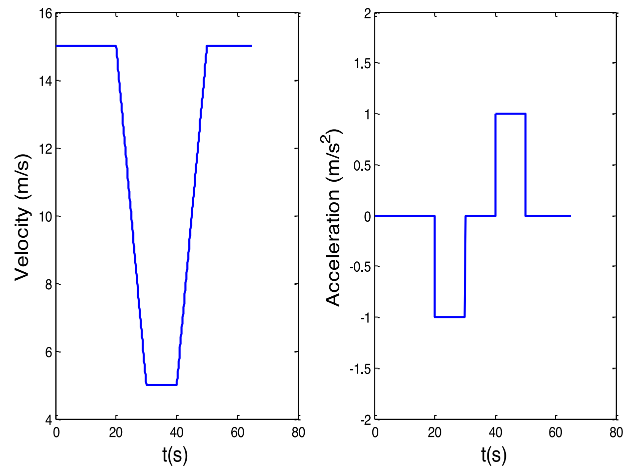

Fig. 3. Velocity and acceleration of the leading vehicle.

IV. Simulation Study

In this section, numerical example are presented to illustrate how the proposed DECM can be applied to a six-vehicle CACC system with a sampled-data feedback controller. For the simulations, the necessary parameters for the DECM are listed in Table I. The velocity and acceleration of the leading vehicle are presented in Fig. 3.

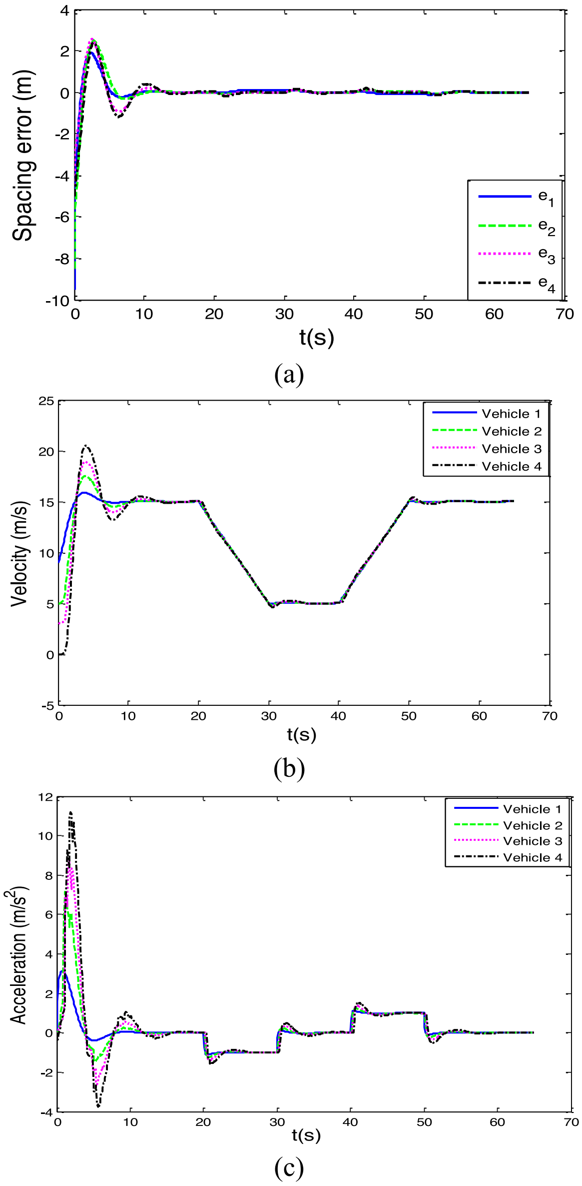

Fig. 4. The spacing error, velocity, acceleration of each vehicle in the DECM-based sampled-data controller.

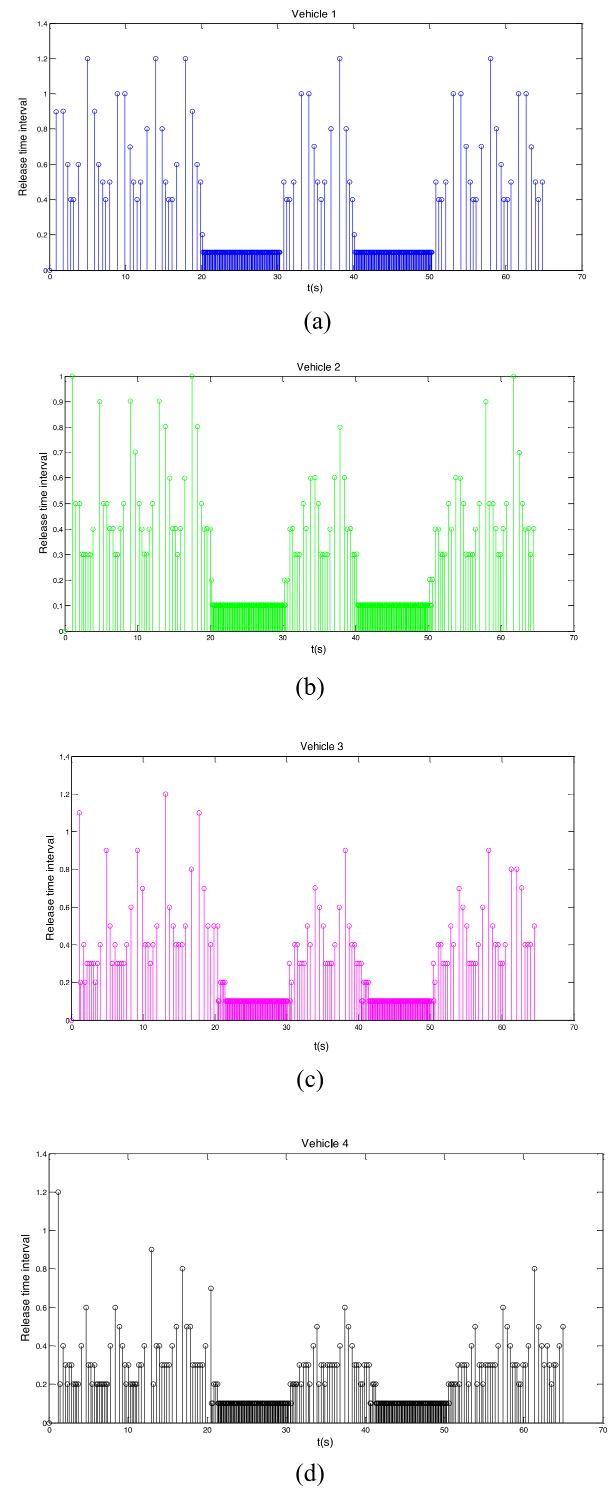

Fig. 5. Transmission instance and release time intervals for inter-vehicle communication for each vehicle under the DECM.

A. TCM Versus DECM

By using the controller design method in [18] without sensor failures, the sampled-data feedback controller gain for the CACC systems can be obtained as $K_i = [10\ 11\ 12]$, which satisfies the stability conditions in Theorem 1 and guarantees the string stability requirement. By utilizing Theorem 2 with the obtained controller gain and simulation parameters listed in Table I, the design problem for the DECM for the CACC system is solvable. The designed parameter for the DECM was set to $\Phi = \begin{bmatrix} 0.061 & 0.007 & 0.005 \\ * & 0.053 & 0.006 \\ * & * & * \end{bmatrix}$ with $\theta = 8$, $\kappa = 1$ and $\sigma_0 = 0.6$.

In the DECM-based sampled-data feedback controller, the spacing error, velocity and, acceleration of each vehicle are presented in Fig. 4 and the dynamic threshold parameters $\sigma(k)$ are presented in Fig. 6. The corresponding transmission time instance and release time intervals are presented in Fig. 5. From these figures, it is clear that each vehicle can accurately and rapidly trace the velocity of the leading vehicle and maintain the desired space between successive vehicles. In contrast to, the spacing error, velocity and acceleration of following vehicle are presented in Fig. 7 for the TCM-based sampled-data

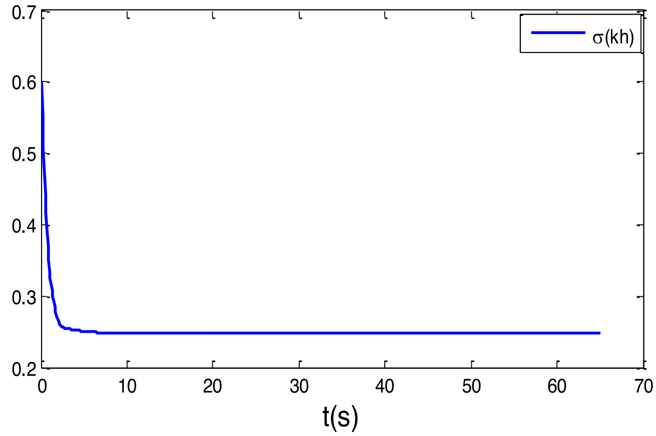

Fig. 6. Dynamic threshold parameters $\sigma(k)$ with $\sigma_0 = 0.6$ and $\theta = 8$.

controller of [18]. It can be observed that the control performance of the DECM-based sampled-data controller appears very similar to that of the TCM-based sampled-data controller. The sampled-data transmission ratios (STR) and average release time intervals (ARTI) of each vehicle under the DECM are listed in Table II, where the maximum value of the release time interval is approximately 1.2 s. The mean STR and ARTI values for the CACC system are (42% + 46% + 44% + 51%)/4 = 45.75% and (0.24 s + 0.20 s + 0.22 s + 0.20 s)/4 = 0.215 s, respectively. Therefore, only 298 data samples needed to be transmitted over the VANET an average time interval of 0.22 s in [0, 65 s) when utilizing the DECM. However, all 650 sampled-data packets must be transmitted in [0, 65 s) under the TCM-based sampled-data controller from [18]. This is a waste of the limited communication resources in the CACC system. In comparison to the TCM, the DECM can significantly reduce the data transmission frequency over the VANET to save the limited communication resources.

B. DECM Versus SECM

In the following analysis, we present the comparative results by utilizing the SECM. In this case, the parameters in (10) are set to $\sigma(kh) = \sigma_0 = 0.6$ and $\theta = 8$. Under the SECM, the spacing error, velocity, and acceleration of each vehicle are presented in Fig. 8. The corresponding transmission time instance and release time intervals are presented in Fig. 9. The STR and the ARTI of each vehicle can be found in Table II. Based on the simulation results discussed above, we have present the following conclusions:

1) The SECM generates fewer transmissions of sampled data for the CACC system (see form Table II). The main reason for this is that the threshold parameter $\sigma(kh)$ is always fixed as σ_0. In contrast, under the DECM, $\sigma(kh)$ is monotonically non-increasing, as shown in Fig. 6. The larger the value of the threshold parameter is, the fewer data packets are transmitted. The maximum release time interval of the CACC system under the SECM is 2 s (see Fig. 9(b)), which is larger than that under the DECM.

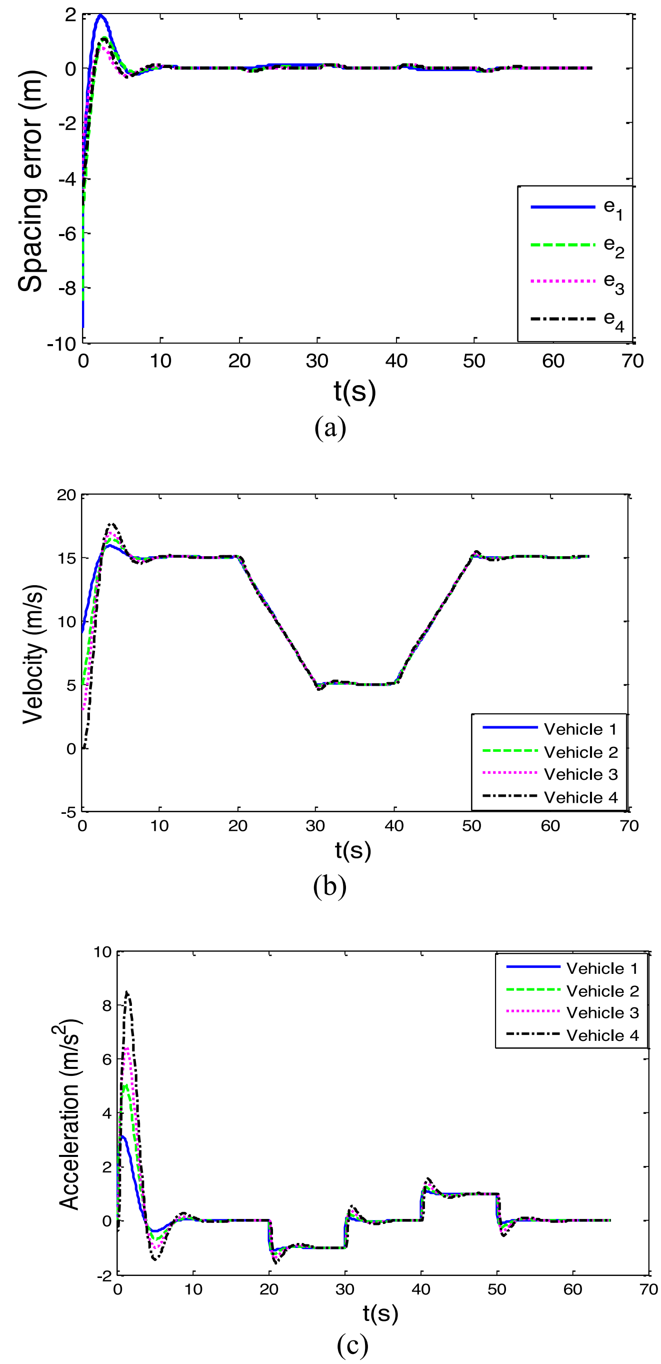

Fig. 7. The spacing error, velocity, and acceleration of each vehicle in the TCM-based sampled-data controller from [18].

TABLE II
STR AND ARTI OF THE DECM AND SECM

	DECM		SECM	
	STR	ARTI	STR	ARTI
i=1	42%	0.24s	36%	0.29s
i=2	46%	0.20s	36%	0.25s
i=3	44%	0.22s	39%	0.20s
i=4	51%	0.20s	41%	0.20s

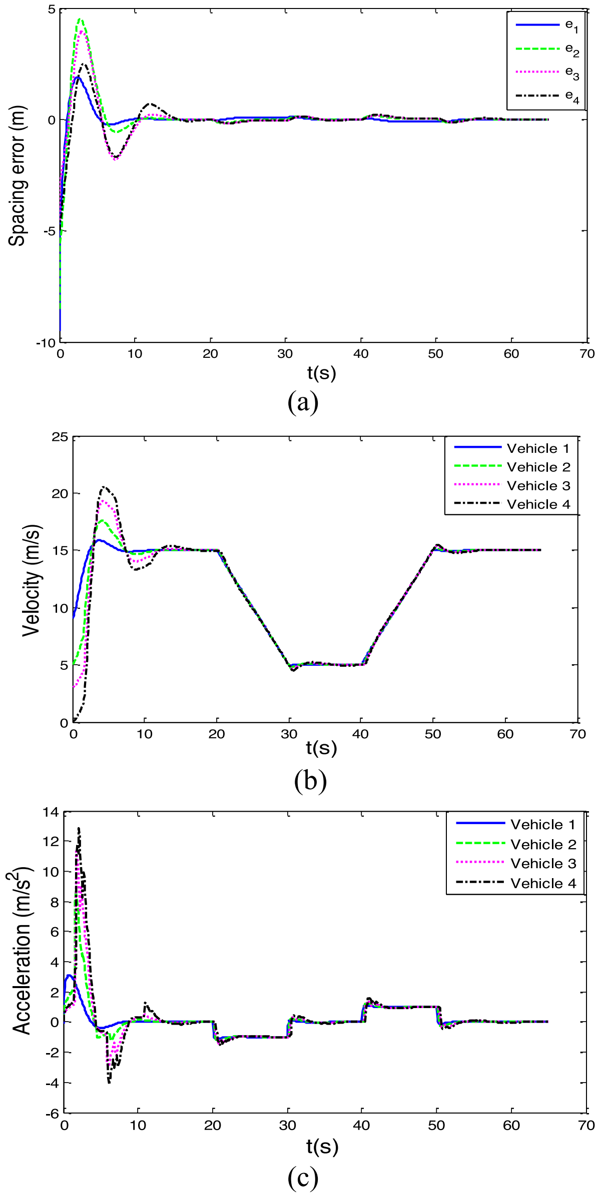

Fig. 8. The spacing error, velocity, acceleration and position of each following vehicle under SECM-based sampled-data controller.

2) The CACC system with the DECM achieves better overall performance. Although the SECM facilitates fewer data packet transmissions, the un-transmitted sampled data may contain important information for the CACC systems and its non-transmission may lead to the performance degradation. This point is illustrated by Figs. 4(a)–(c) and 8(a)–(c). Compared to the DECM, the spacing error, velocity, and acceleration of each vehicle under the SECM, present larger fluctuations in the time interval [0, 20 s)

C. Advantages of DECM-Based Sampled-Data Feedback Controller

1) The proposed DECM-based sampled-data feedback controller can facilitate a larger upper bound for the time-varying delay and has less computational complexity involved in the obtained stability criterion than those proposed in [18]. For the same Lyapunov-Krasovskii function (24), the reciprocally convex inequality (RCI) [37] is used in our paper to find the stability criteria for the time-delayed CACC system. Compared to the approach used in [18], the RCI can provide a less conservative stability condition with fewer slack matrix variables. We will discuss an example to illustrate this point. In our paper, the proposed stability criterion for Theorem 1 only has one slack matrix variable. However, the stability

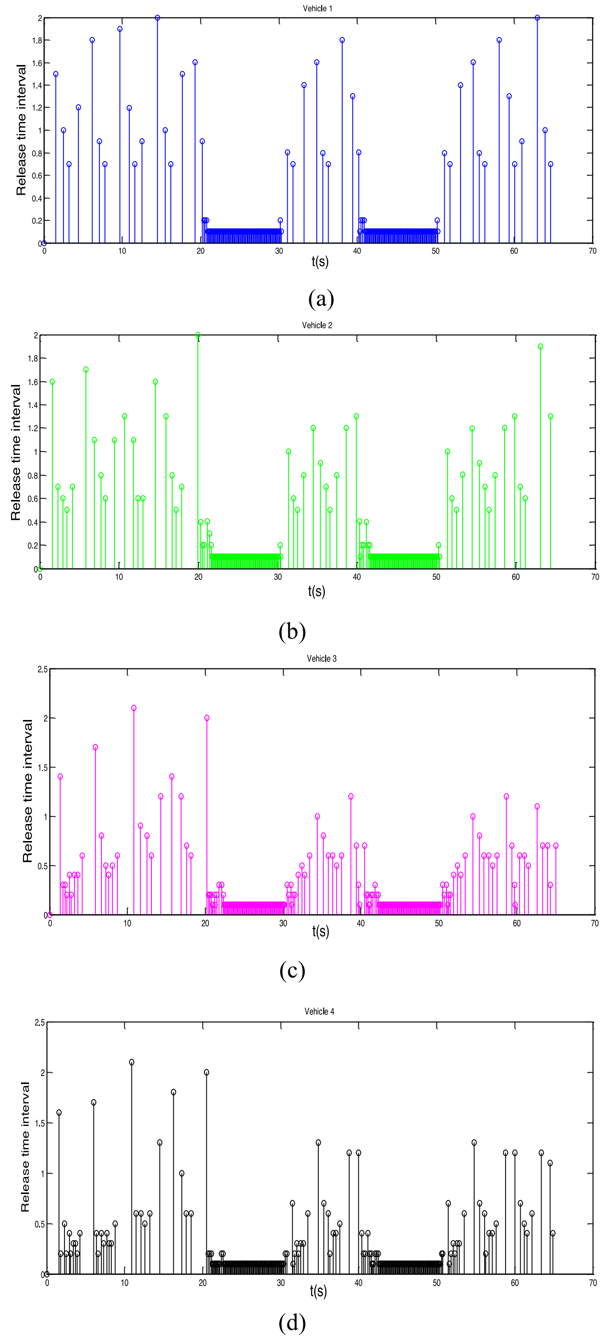

Fig. 9. Transmission instances and release time intervals of inter-vehicle communication for each vehicle under the SECM.

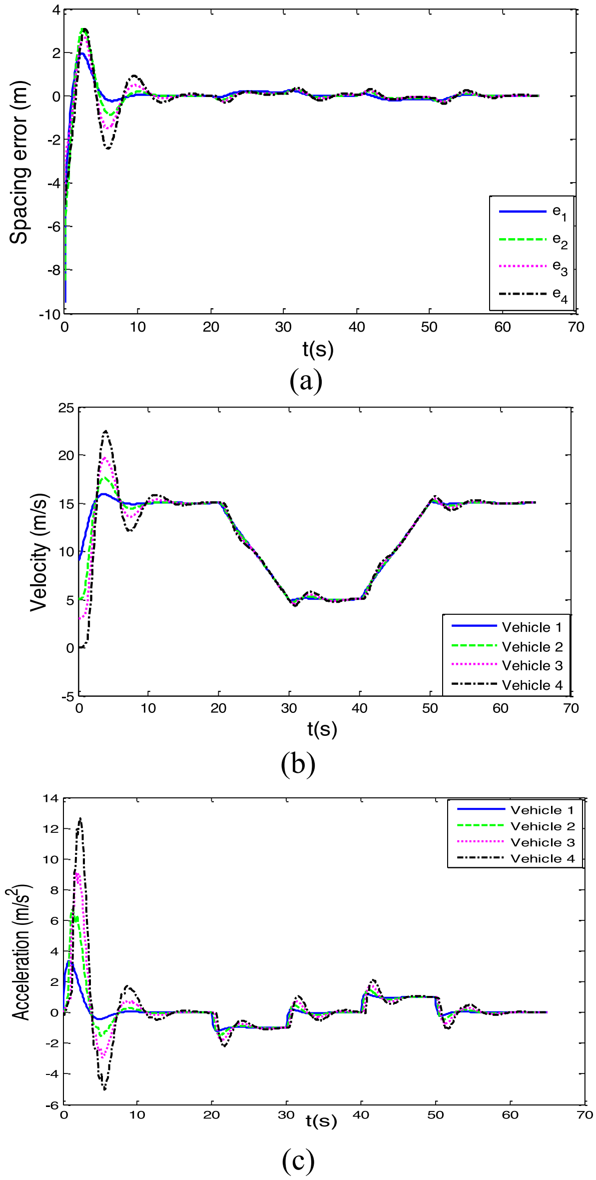

Fig. 10. The spacing error, velocity, and acceleration of each vehicle in the DECM-based sampled-data controller with a lumped time delay of 0.29 s.

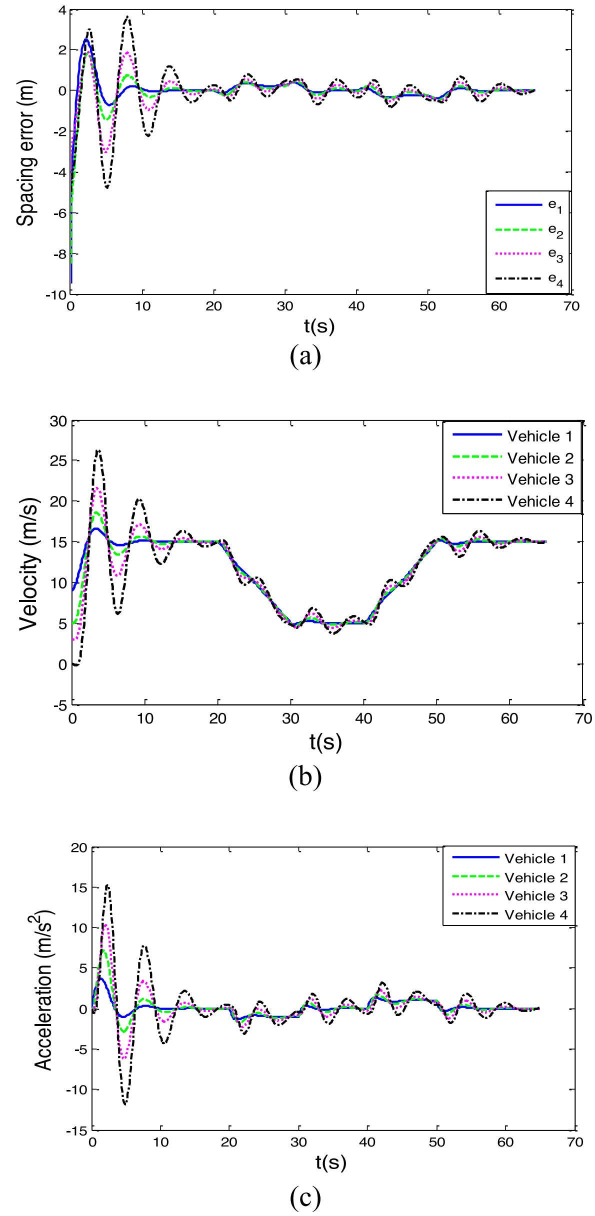

Fig. 11. The spacing error, velocity, and acceleration of each vehicle in the TCM-based sampled-data controller from [18] with a lumped time delay of 0.29 s.

criterion in [18] requires three slack matrix variables, which adds to the computational complexity of the CACC algorithm. By utilizing the LMI toolbox to find a feasible solution for the stability criteria proposed in our paper and in [18], the obtained upper bounds for the time-varying delay are respectively 0.31 s and 0.18 s. We set the lumped delay for the time-delay CACC system to 0.29 s. By using the sampled-data feedback controller with a gain of $K_i = [10\ 11\ 12]$, the spacing error, velocity, and acceleration of each vehicle under the DECM-based sampled-data feedback controller and TCM-based sampled-data feedback controller are presented in Figs. 10 and 11, respectively. The response to spacing errors, velocity, and acceleration of each following vehicle in [18] is not as stable as that in the proposed system, which is oscillating. Therefore, the proposed DECM-based sampled-data

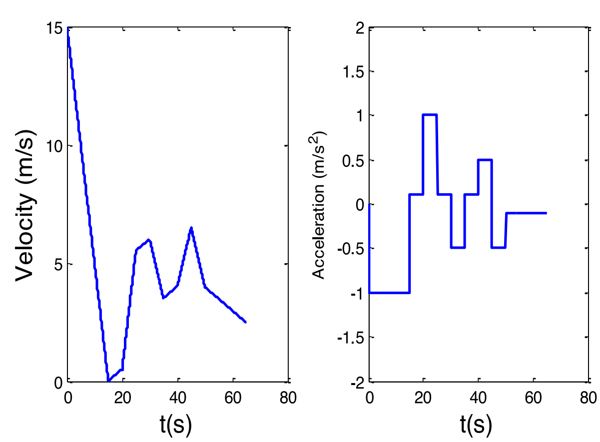

Fig. 12. Varying acceleration of the leading vehicle.

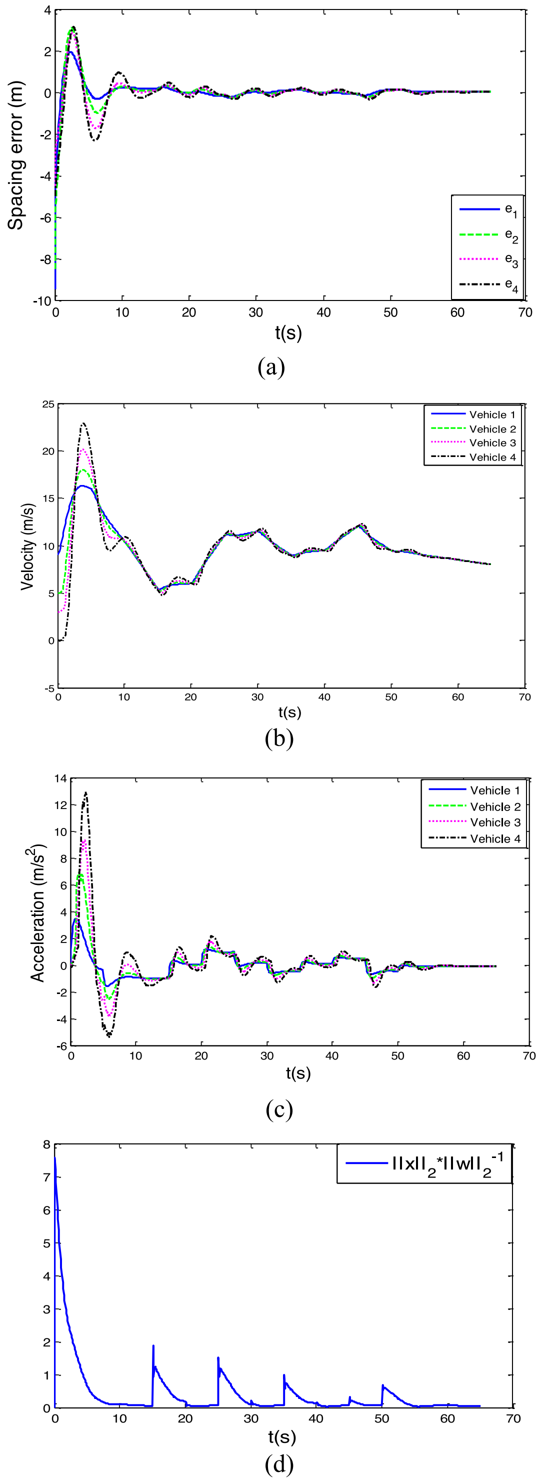

Fig. 13. The spacing error, velocity, acceleration and $\|x(t)\|_2 * \|w(t)\|_2{}^{-1}$ of each vehicle in the DECM-based sampled-data controller with controller gain $K_i = [13 \quad 15 \quad 11]$.

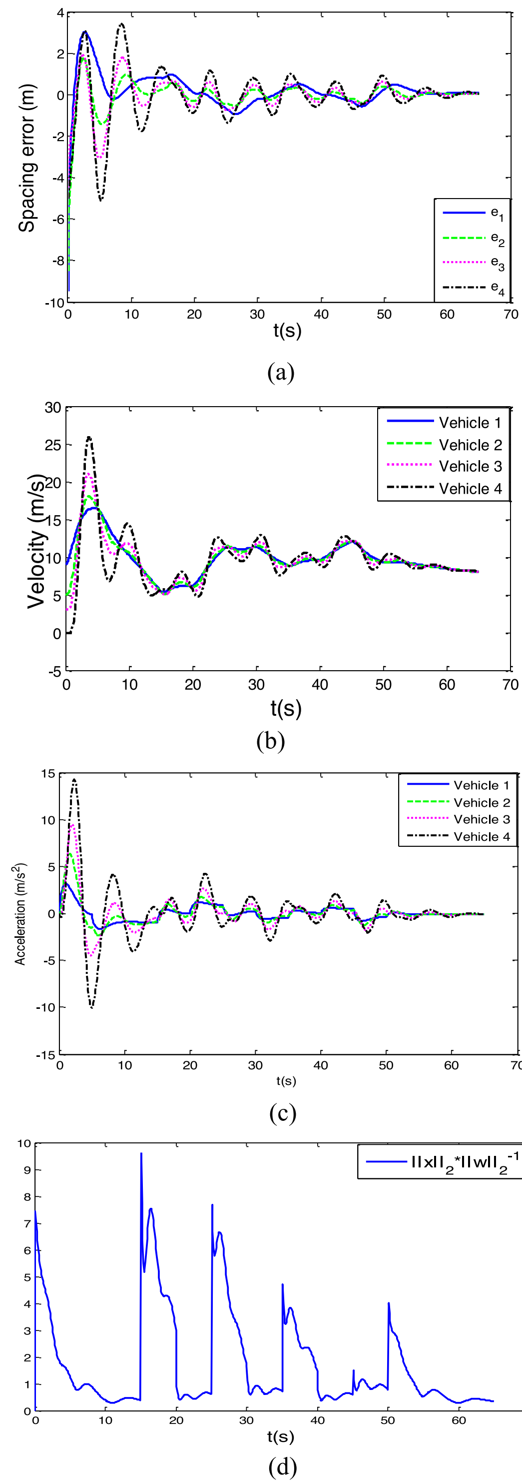

Fig. 14. The spacing error, velocity, acceleration and $\|x(t)\|_2 * \|w(t)\|_2{}^{-1}$ of each vehicle in the TCM-based sampled-data controller from [18] with controller gain $K_i = [10 \quad 11 \quad 12]$.

feedback controller can facilitate a larger time delay for the sampled-data CACC system.

2) In terms of the disturbances yielded by the varying acceleration of the preceding vehicles, the DECM-based sampled-data feedback controller has more stable performance. We will discuss an example to illustrate this point.

Here, it is assumed that the acceleration of the leading vehicle varies frequently, as shown in Fig. 12. We aim to design the DECM-based sampled-data feedback controller such that the desired H_∞ disturbance attenuation level defined in (21) satisfies $\|x(t)\|_2 * \|w(t)\|_2{}^{-1} \leq \gamma = 8$. Under such circumstance, we found that the controller gain $K_i = [10\ 11\ 12]$ used in the previous simulation study cannot guarantee that the conditions in Theorem 1 have feasible solution. So, we find a new controller gain $K_i = [13\ 15\ 11]$ by using the [18, Algorithm 1], which satisfies the condition of Theorem 1 in our paper and guarantees the string stability requirement for the CACC system. The spacing error, velocity and acceleration of each vehicle under the DECM-based sampled-data feedback controller (controller gain is $K_i = [13\ 15\ 11]$) and TCM-based sampled-data feedback controller (controller gain is $K_i = [10\ 11\ 12]$) are presented in Figs. 13 and 14, respectively, where the value of $\|x(t)\|_2 * \|w(t)\|_2{}^{-1}$ is given in Figs. 13(d) and 14(d). For the proposed DECM-based sampled-data controller, the tracking error of the CACC system can satisfy the given H_∞ disturbance attenuation level γ. This is because the H_∞ robust control method is used in the CACC algorithm in our system (e.g., the proposed stability conditions in Theorem 1 include the H_∞ disturbance attenuation level γ). However, the H_∞ disturbance attenuation level of the TCM-based sampled-data controller in [18] appears to reach values of $\gamma > 8$ (see Fig. 14(d)). Furthermore, $\|x(t)\|_2 * \|w(t)\|_2{}^{-1}$ in our paper is smaller than it in [18]. From Figs. 13 and 14, it is clear that the DECM-based sampled-data controller has better stability than the TCM-based sampled-data controller proposed in [18] when subjected to acceleration disturbances.

V. Conclusion

A DECM has been designed for CACC systems to save limited inter-vehicle communication resources. By utilizing the DECM, the number of sampled velocity and acceleration that needs to be transmitted to successive vehicles is significantly reduced. The DECM-based sampled-data controller for CACC systems was transformed into a stabilization problem for an error-tracking system with time-varying delays. According to Lyapunov stability theory, sufficient conditions have been obtained under which all tracking errors of each vehicle can be asymptotically stabilized by the DECM and sampled-data feedback controller. By utilizing the obtained conditions, we established a unified framework to design the parameters for the DECM. The effectiveness and advantages of the proposed DECM-based sampled-data feedback controller over the existing SECM and TCM were demonstrated through by the numerical experiments.

In future work, we will focus on optimization of CACC systems in term of fuel consumption and communication resources. An optimal event-triggered sampled-data controller is required for CACC systems to optimize these performance indexes. In contrast to, the generalized optimal problem, the performance indexes should include the transmission statuses of sampled velocity and acceleration values. Another interesting problem is to extend the proposed resource-efficient communication mechanism to nonlinear CACC systems with uncertainty, such as uncertain vehicle mass and engine time constants. The difficulty in this problem is how to obtain the parameters for the DECM by utilizing the adaptive control approach.

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