Event-Triggered Interval Type-2 Fuzzy Consensus Control of Full-Vehicle Suspension Systems Using a Leader-Following Approach

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***Abstract*— This paper proposes an innovative event-triggered interval type-2 (IT-2) fuzzy consensus control method for agent-based full-vehicle suspension systems (FSSs) using a leader-following approach. By developing a novel IT-2 Takagi-Sugeno (T-S) fuzzy model, the amalgamation of heterogeneous agent-based FSSs into a cohesive homogeneous multi-agent framework becomes feasible, thereby reducing control complexity and effectively dealing with system uncertainty. Within the proposed agent-based architecture, a virtual leader is designed at the core of the agent-based FSS, and the four interconnected quarter-vehicle suspension systems are construed as the following agents. To optimize network bandwidth between the agents, a new event-triggered mechanism (ETM) is established, which is sensitive to significant state changes, particularly when deviations from consensus among the following agents arise abruptly. Sufficient conditions are derived to ensure both the optimal attitude performance and ride comfort of FSSs. Finally, a simulation example of agent-based FSSs is presented to validate the advantages of the proposed approach in optimizing ride comfort and system robustness.**

***Index Terms*— Agent-based FSSs, interval type-2 T–S fuzzy control, event-triggered mechanism.**

I. Introduction

VEHICLE suspension systems (SSs) play a critical role in delivering a comfortable ride, ensuring passenger safety, improving road handling, and minimizing road damage, which have drawn numerous investigations in recent decades [1], [2], [3]. However, achieving these requirements simultaneously can be quite challenging, given that they are partially conflicting in nature. For example, enhancing riding comfort can lead to a more significant suspension stroke while decreasing damping in the wheel-hop mode [4]. It is evident that achieving these partially conflicting objectives requires implementing sophisticated suspension techniques that can effectively balance the trade-offs among them under a broad range of operating road conditions. Compared to conventional passive SSs, active SSs, as a kind of advanced SS, have been developed in recent years due to their flexible structure, reduced physical constraints, and intelligent methodology for dealing with random vibrations [5], [6], [7]. Moreover, the development of different control algorithms for the core part of active SSs has contributed significantly to the overall improvement in suspension performance, such as fuzzy control [8], H_∞ control [9], and sliding mode bifurcation control [10], [11].

Due to the uncertainty of vehicle parameters, the vehicle suspension system (SS) exhibits nonlinear dynamics. The Takagi-Sugeno (T-S) fuzzy approach approximates the behavior of a nonlinear system using a set of local linear models [12], [13], [14]. This approximation is advantageous for control design, where a linear control law is designed for each local linear model and combined using fuzzy logic to manage the nonlinear system as a whole [15]. However, the conventional T-S fuzzy approach has limitations in addressing uncertain system attributes, as its membership functions (MFs) do not explicitly incorporate uncertain information. This can result in suboptimal approximations and performance degradation in uncertain environments. To overcome this issue, researchers have proposed the IT-2 fuzzy logic approach, which represents uncertainty using intervals rather than fuzzy sets [16]. An innovative method for enhancing risk assessment models for cyber-security utilizing an IT-2 fuzzy logic controller with lower membership functions (LMFs) and upper membership functions (UMFs) was presented in [17], [18], [19], and [20]. In [21], LMFs and UMFs were used to analyze Type-1 (T-1) fuzzy models with uncertain MFs. The IT-2 fuzzy approach was developed for QSSs based on the Markov model to address uncertain suspension parameters in [22]. However, the structural complexity and uncertainties of multiple parameters make the FSS a significant challenge for IT-2 fuzzy control design. This study explores a multi-agent approach by treating each QSS as an agent. Few studies has been conducted on this issue, which motivates our current research.

Advancements in communication and digital technology have transformed the evolution of networked active SSs, which connect the SSs, sensors, event generators, controllers, and actuators through the communication network. This integration

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enables efficient coordination across all system components, significantly enhancing vehicle performance and safety. For example, cloud computing in the framework of cloud-aided SSs can provide unlimited computing power to implement prediction, optimization, and collaborative control strategies and improve control performance by providing up-to-date road profile information from a cloud database [23]. In [24], an adaptive backstepping control strategy was presented for cloud-aided active SSs, where the controller was updated using stored information in the cloud. The transmission of information over a network is a critical feature of networked active SSs. However, the limited bandwidth of such networks poses a significant challenge in allocating and utilizing these resources effectively. Recently, ETM has gained considerable attention as a practical approach to reduce network communication load while maintaining system performance within acceptable limits [26], [27], [28]. For instance, a new networked robust dissipative tracking control system with ETM is proposed in [29] to address network load reduction and account for the probability density distribution of network-induced delays. A dynamic ETM was put forward for switched T–S fuzzy systems, by which the amount of transmitted data can be efficiently reduced. An adaptive ETM was proposed in [31], where the event-triggered condition threshold is dynamically adjusted, replacing the fixed threshold to save more network bandwidth. This approach offers the potential for improved system performance and efficiency compared to fixed threshold methods. Similarly, ETM also has been developed in networked active SSs. Compared to fixed-threshold methods, this approach offers potential improvements in system performance and efficiency [32], [33], [34]. To enhance the security of cloud-aided active QSSs, a memory-based ETM was proposed in [25]. This approach was designed to be more sensitive to deception attacks while also reducing the network bandwidth load.

In this study, Although significant progress has been made in ETMs, several challenges remain to be addressed in the context of multi-agent systems with network communication. For instance, in existing studies, the triggering condition of one agent often has a substantial impact on the triggering conditions of others, which serves as an additional motivation for this study.

Motivated by the previous discussion, the problem of IT-2 fuzzy event-triggered consensus control of agent-based FSSs is investigated in this paper. The main contributions of this work are outlined as:

1) Unlike existing full-vehicle suspension system (FSS) models, such as in [24], an agent-based FSS model is developed. The control problem is reformulated as a multi-agent consensus control problem, simplifying modeling while leveraging communication networks and cloud technology for a more accurate and practical FSS representation.
2) Unlike the T-1 T–S model, such as in [4] and [33], a novel IT-2 T–S fuzzy model is introduced to characterize the uncertainty of agent-based FSSs by defining the new LMFs and UMFs. This model unifies heterogeneous systems into a homogeneous multi-agent framework, reducing control complexity while effectively handling system uncertainty.
3) Unlike traditional ETMs, such as in [36] and [37], a novel ETM is proposed for agent-based FSSs. The event-triggering condition incorporates the error between the mth interconnected QSS and the virtual leader, preventing excessive data transmission when one or more agents deviate from consensus. By balancing control performance and communication bandwidth, the proposed method enhances system efficiency.

The subsequent sections of this paper are structured as follows. Section II presents the IT-2 T–S fuzzy model for agent-based FSSs and introduces the problem formulation. An event-triggered IT-2 fuzzy controller for agent-based FSSs using leader-following approach is developed in Section III. To confirm the method's efficacy as outlined in Section III, a simulation example of agent-based FSSs is provided in Section IV. Finally, Section V summarizes the contributions of this paper and concludes the study.

II. Problem Formulation

Similar to [25], we consider the following two-degree-of-freedom quarter-vehicle active SS:

$$\dot{x}(t) = A(t)x(t) + B(t)u(t) + D(t)\omega(t), \tag{1}$$

where

$$A(t) = \begin{bmatrix} 0 & 0 & 1 & -1 \\ 0 & 0 & 0 & 1 \\ -\frac{k_s(t)}{m_s(t)} & 0 & -\frac{c_s}{m_s(t)} & \frac{c_s}{m_s(t)} \\ \frac{k_s(t)}{m_u(t)} & -\frac{k_t(t)}{m_u(t)} & \frac{c_s}{m_u(t)} & -\frac{c_s+c_t}{m_u(t)} \end{bmatrix},$$
$$B(t) = \begin{bmatrix} 0 & 0 & \frac{1}{m_s(t)} & -\frac{1}{m_u(t)} \end{bmatrix}^T,$$
$$D(t) = \begin{bmatrix} 0 & -1 & 0 & \frac{c_t}{m_u(t)} \end{bmatrix}^T.$$

In (1), $m_s(t), m_u(t), k_s(t)$ and $k_t(t)$ denote the uncertain sprung mass, unsprung mass, suspension stiffness and pneumatic tire compressibility, respectively. The remaining symbols can be found in [25]. In this study, we suppose: $m_s(t) \in [m_{smin}, m_{smax}]$, $m_u(t) \in [m_{umin}, m_{umax}]$, $k_s(t) \in [k_{smin}, m_{smax}]$ and $k_t(t) \in [k_{tmin}, k_{tmax}]$.

Inspired by [33], we define the premise variables as $\theta_1(t) = \frac{k_s(t)}{m_s(t)}$, $\theta_2(t) = \frac{k_t(t)}{m_u(t)}$ and $\theta_3(t) = \frac{k_s(t)}{m_u(t)}$.

Then, choose the MFs as follow

$$\begin{aligned} L_1(\theta_1(t)) &= \frac{\theta_{1max} - \theta_1(t)}{\theta_{1max} - \theta_{1min}}, L_2(\theta_1(t)) = \frac{\theta_1(t) - \theta_{1min}}{\theta_{1max} - \theta_{1min}}, \\ M_1(\theta_2(t)) &= \frac{\theta_{2max} - \theta_2(t)}{\theta_{2max} - \theta_{2min}}, M_2(\theta_2(t)) = \frac{\theta_2(t) - \theta_{2min}}{\theta_{2max} - \theta_{2min}}, \\ N_1(\theta_3(t)) &= \frac{\theta_{3max} - \theta_3(t)}{\theta_{3max} - \theta_{1min}}, N_2(\theta_3(t)) = \frac{\theta_3(t) - \theta_{3min}}{\theta_{3max} - \theta_{3min}}. \end{aligned} \tag{2}$$

Remark 1: Unlike existing T-S fuzzy modeling methods for suspension systems, such as those presented in [4], [25], and [33], this study introduces new premise variables: $\theta_1(t)$, $\theta_2(t)$, and $\theta_3(t)$, along with their corresponding membership functions $L_1(\theta_1(t))$, $L_2(\theta_1(t))$, $M_1(\theta_2(t))$, $M_2(\theta_2(t))$,

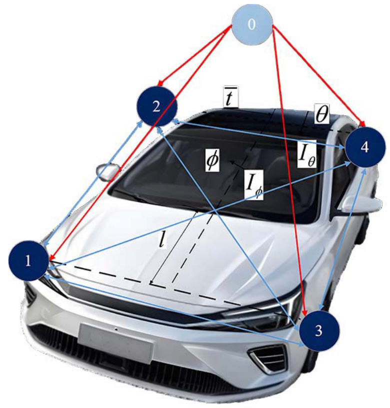


Fig. 1. The topological structure of agent-based FSSs.

$N_1(\theta_3(t))$, and $N_2(\theta_3(t))$. These new variables and functions offer a more accurate representation of the suspension system, particularly in capturing the time-varying nature of suspension stiffness and pneumatic tire compressibility.

In this study, the FSS is considered. As shown in Fig. 1, each quarter-vehicle suspension is treated as an agent. Specifically, the agents labeled 1–4 correspond to the front-right, rear-right, front-left, and rear-left QSSs, respectively. Additionally, a virtual leader is positioned at the center of the active FSS. This central placement effectively captures the motion states of the QSSs, facilitating the optimal performance of the FSS.

Remark 2: By modeling the FSS as four interconnected agents, this framework reduces the analytical challenges of directly addressing the FSS while maintaining a comprehensive representation of its dynamics.

Assumption 1: In this study, we assume that each QSS can receive information from the virtual leader at any given sampling instant, and that the agents can communicate with each other through the network.

Based on Assumption 1, we have the Laplacian matrix $\hat{L} = L + \hat{A}$ with $\hat{A} = \mathrm{diag}\{a_{10}, a_{20}, a_{30}, a_{40}\}$.

To simplify the following description, we define MF, LMF and UMF as $\hbar_{G_i^p}(\theta_p(t))$, $\underline{\hbar}_{G_i^p}(\theta_p(t))$ and $\bar{\hbar}_{G_i^p}(\theta_p(t))$, respectively. Then the ith rule of the mth uncertain active QSS can be presented by the following IT-2 T–S fuzzy model:

Plant Rule i: **IF** $\theta_1(t)$ is $G_i^1, \cdots,$ and $\theta_p(t)$ is G_i^p, **THEN**

$$\begin{cases} \dot{x}_m(t) = A_i x_m(t) + B_i u_m(t) + D_i \omega_m(t) + g_{wm}(t) \\ \dot{x}_0(t) = (A_i + B_i K_0) x_0(t) + D_i \omega_0(t), \end{cases} \tag{3}$$

where $i \in \mathscr{J} \triangleq \{1, 2, 3, 4, 5, 6\}$, $p \in \mathscr{P} \triangleq \{1, 2, 3\}$, G_i^p and $\theta_p(t)$ denote the fuzzy set and the premise variable, respectively. A_i, B_i and D_i are system matrices, K_0 and $\omega_0(t)$ are given by the data stored in the cloud. The ith rule of $\theta_1(t)$, $\theta_2(t)$, and $\theta_3(t)$ can be obtained from Table I. The UMFs and LMFs can be found in Table II.

In (3), $g_{wm}(t) = \sum_{n \in N_m} a_{mn}[f_{wm}(x_m(t)) - f_{wn}(x_n(t))]$ represents the mutual coupling between each QSS, and the nonlinear function $f_{wm}(x_m(t))$ for $m \in \{1, 2, \cdots, N\}$ satisfies

$$\| f_{wm}(x_m(t)) - f_{wn}(x_n(t)) \|_2 \leq \| \mathscr{T}(x_m(t) - x_n(t)) \|_2, \tag{4}$$

where $\mathscr{T}$ is a known matrix.

TABLE I
RULE i OF $\theta_1(t)$, $\theta_2(t)$, AND $\theta_3(t)$

Rule	$\theta_1(t)$	$\theta_2(t)$	$\theta_3(t)$
$i=1$	$\frac{k_{smin}}{m_{smax}}$	$\frac{k_{tmin}}{m_{umax}}$	$\frac{k_{smin}}{m_{umax}}$
$i=2$	$\frac{k_{smin}}{m_{smax}}$	$\frac{k_{tmax}}{m_{umin}}$	$\frac{k_{smin}}{m_{umin}}$
$i=3$	$\frac{k_{smax}}{m_{smin}}$	$\frac{k_{tmin}}{m_{umax}}$	$\frac{k_{smax}}{m_{umax}}$
$i=4$	$\frac{k_{smax}}{m_{smin}}$	$\frac{k_{tmax}}{m_{umin}}$	$\frac{k_{smax}}{m_{umin}}$
$i=5$	$\frac{k_{smax}}{m_{smax}}$	$\frac{k_{tmax}}{m_{umin}}$	$\frac{k_{smax}}{m_{umin}}$
$i=6$	$\frac{k_{smin}}{m_{smin}}$	$\frac{k_{tmin}}{m_{umax}}$	$\frac{k_{smin}}{m_{umax}}$

Remark 3: In practice, the four QSSs are not identical, making it challenging to analyze their heterogeneity. In this study, we employ an IT-2 fuzzy approach to unify these heterogeneous systems into a homogeneous framework. This method reduces the complexity of control and effectively manages the uncertainties present in the system.

To simplify the fuzzy rules and fuzzy sets, we set $\theta_{im}(t) = \theta_i(t)$ and $G_{im}^p = G_i^p$. Moreover, $A_{im} = A_i$, $B_{im} = B_i$, $C_{im} = C_i$ and $D_{im} = D_i$.

Define the interval sets

$$\mathcal{M}_G^i(\theta(t)) = [\underline{\mathscr{G}}_i(\theta(t)), \overline{\mathscr{G}}_i(\theta(t))] \tag{5}$$

as the firing strength of the ith rule, where $\theta(t) = [\theta_1(t), \theta_2(t), \theta_3(t)]$. Then, the LMF and the UMF can be, respectively, redefined as

$$\underline{\mathscr{G}}_i(\theta(t)) = \prod_{p=1}^{3} \underline{\hbar}_{G_i^p}(\theta_p(t)), \overline{\mathscr{G}}_i(\theta(t)) = \prod_{p=1}^{3} \bar{\hbar}_{G_i^p}(\theta_p(t)).$$

With the aid of center-average defuzzifier, product interference and singleton fuzzifier, the overall IT-2 T–S fuzzy model of agent-based FSSs can be written as

$$\begin{cases} \dot{x}_m(t) = \sum_{i=1}^{6} \mu_i(\theta(t))[A_i x_m(t) + B_i u_m(t) \\ \qquad + D_i \omega_m(t) + g_{wm}(t)], \\ \dot{x}_0(t) = \sum_{i=1}^{6} \mu_i(\theta(t))[(A_i + B_i K_0) x_0(t) + D_i \omega_0(t)], \end{cases} \tag{6}$$

where the IT-2 MF $\mu_i(\theta(t))$ is expressed by

$$\mu_i(\theta(t)) = \frac{\partial_G^i(\theta(t))}{\sum_{i=1}^{6}(\partial_G^i(\theta(t)))},$$

with $\partial_G^i(\theta(t)) = \underline{\lambda}_i(\theta(t))\underline{\mathscr{G}}_i(\theta(t)) + \bar{\lambda}_i(\theta(t))\overline{\mathscr{G}}_i(\theta(t))$. In item $\partial_G^i(\theta(t))$, $\underline{\lambda}_i(\theta(t))$ and $\bar{\lambda}_i(\theta(t))$ are nonlinear weighting functions, which satisfies $\underline{\lambda}_i(\theta(t)) + \bar{\lambda}_i(\theta(t)) = 1$, $0 < \underline{\lambda}_i(\theta(t)) < 1$ and $0 < \bar{\lambda}_i(\theta(t)) < 1$. It is clear that $\sum_{i=1}^{6} \mu_i(\theta(t)) = 1$ and $0 < \mu_i(\theta(t)) < 1$.

TABLE II
THE UMFs AND THE LMFs OF THE FSSs

UMFs	LMFs
$\bar{h}_{G_1^1}(\theta_1(t)) = \frac{\theta_{1max}-\theta_1(t)}{\theta_{1max}-\theta_{1min}}$ (with $k_s(t)=k_{smin}$)	$\underline{h}_{G_1^1}(\theta_1(t)) = \frac{\theta_{1max}-\theta_1(t)}{\theta_{1max}-\theta_{1min}}$ (with $k_s(t)=k_{smax}$)
$\bar{h}_{G_1^2}(\theta_2(t)) = \frac{\theta_{2max}-\theta_2(t)}{\theta_{2max}-\theta_{2min}}$ (with $k_t(t)=k_{tmin}$)	$\underline{h}_{G_1^2}(\theta_2(t)) = \frac{\theta_{2max}-\theta_2(t)}{\theta_{2max}-\theta_{2min}}$ (with $k_t(t)=k_{tmax}$)
$\bar{h}_{G_1^3}(\theta_3(t)) = \frac{\theta_{3max}-\theta_3(t)}{\theta_{3max}-\theta_{3min}}$ (with $k_s(t)=k_{smin}$)	$\underline{h}_{G_1^3}(\theta_3(t)) = \frac{\theta_{3max}-\theta_3(t)}{\theta_{3max}-\theta_{3min}}$ (with $k_s(t)=k_{smax}$)
$\bar{h}_{G_2^1}(\theta_1(t)) = \frac{\theta_{1max}-\theta_1(t)}{\theta_{1max}-\theta_{1min}}$ (with $k_s(t)=k_{smin}$)	$\underline{h}_{G_2^1}(\theta_1(t)) = \frac{\theta_{1max}-\theta_1(t)}{\theta_{1max}-\theta_{1min}}$ (with $k_s(t)=k_{smax}$)
$\bar{h}_{G_2^2}(\theta_2(t)) = \frac{\theta_2(t)-\theta_{2min}}{\theta_{2max}-\theta_{2min}}$ (with $k_t(t)=k_{tmax}$)	$\underline{h}_{G_2^2}(\theta_2(t)) = \frac{\theta_2(t)-\theta_{2min}}{\theta_{2max}-\theta_{2min}}$ (with $k_t(t)=k_{tmin}$)
$\bar{h}_{G_2^3}(\theta_3(t)) = \frac{\theta_3(t)-\theta_{3min}}{\theta_{3max}-\theta_{3min}}$ (with $k_s(t)=k_{smax}$)	$\underline{h}_{G_2^3}(\theta_3(t)) = \frac{\theta_3(t)-\theta_{3min}}{\theta_{3max}-\theta_{3min}}$ (with $k_s(t)=k_{smin}$)
$\bar{h}_{G_3^1}(\theta_1(t)) = \frac{\theta_1(t)-\theta_{1min}}{\theta_{1max}-\theta_{1min}}$ (with $k_s(t)=k_{smax}$)	$\underline{h}_{G_3^1}(\theta_1(t)) = \frac{\theta_1(t)-\theta_{1min}}{\theta_{1max}-\theta_{1min}}$ (with $k_s(t)=k_{smin}$)
$\bar{h}_{G_3^2}(\theta_2(t)) = \frac{\theta_{2max}-\theta_2(t)}{\theta_{2max}-\theta_{2min}}$ (with $k_t(t)=k_{tmin}$)	$\underline{h}_{G_3^2}(\theta_2(t)) = \frac{\theta_{2max}-\theta_2(t)}{\theta_{2max}-\theta_{2min}}$ (with $k_t(t)=k_{tmax}$)
$\bar{h}_{G_3^3}(\theta_3(t)) = \frac{\theta_{3max}-\theta_3(t)}{\theta_{3max}-\theta_{3min}}$ (with $k_s(t)=k_{smin}$)	$\underline{h}_{G_3^3}(\theta_3(t)) = \frac{\theta_{3max}-\theta_3(t)}{\theta_{3max}-\theta_{3min}}$ (with $k_s(t)=k_{smax}$)
$\bar{h}_{G_4^1}(\theta_1(t)) = \frac{\theta_1(t)-\theta_{1min}}{\theta_{1max}-\theta_{1min}}$ (with $k_s(t)=k_{smax}$)	$\underline{h}_{G_4^1}(\theta_1(t)) = \frac{\theta_1(t)-\theta_{1min}}{\theta_{1max}-\theta_{1min}}$ (with $k_s(t)=k_{smin}$)
$\bar{h}_{G_4^2}(\theta_2(t)) = \frac{\theta_2(t)-\theta_{2min}}{\theta_{2max}-\theta_{2min}}$ (with $k_t(t)=k_{tmax}$)	$\underline{h}_{G_4^2}(\theta_2(t)) = \frac{\theta_2(t)-\theta_{2min}}{\theta_{2max}-\theta_{2min}}$ (with $k_t(t)=k_{tmin}$)
$\bar{h}_{G_4^3}(\theta_3(t)) = \frac{\theta_3(t)-\theta_{3min}}{\theta_{3max}-\theta_{3min}}$ (with $k_s(t)=k_{smax}$)	$\underline{h}_{G_4^3}(\theta_3(t)) = \frac{\theta_3(t)-\theta_{3min}}{\theta_{3max}-\theta_{3min}}$ (with $k_s(t)=k_{smin}$)
$\bar{h}_{G_5^1}(\theta_1(t)) = \frac{\theta_{1max}-\theta_1(t)}{\theta_{1max}-\theta_{1min}}$ (with $k_s(t)=k_{smin}$)	$\underline{h}_{G_5^1}(\theta_1(t)) = \frac{\theta_{1max}-\theta_1(t)}{\theta_{1max}-\theta_{1min}}$ (with $k_s(t)=k_{smax}$)
$\bar{h}_{G_5^2}(\theta_2(t)) = \frac{\theta_2(t)-\theta_{2min}}{\theta_{2max}-\theta_{2min}}$ (with $k_t(t)=k_{tmax}$)	$\underline{h}_{G_5^2}(\theta_2(t)) = \frac{\theta_2(t)-\theta_{2min}}{\theta_{2max}-\theta_{2min}}$ (with $k_t(t)=k_{tmin}$)
$\bar{h}_{G_5^3}(\theta_3(t)) = \frac{\theta_3(t)-\theta_{3min}}{\theta_{3max}-\theta_{3min}}$ (with $k_s(t)=k_{smax}$)	$\underline{h}_{G_5^3}(\theta_3(t)) = \frac{\theta_3(t)-\theta_{3min}}{\theta_{3max}-\theta_{3min}}$ (with $k_s(t)=k_{smin}$)
$\bar{h}_{G_6^1}(\theta_1(t)) = \frac{\theta_1(t)-\theta_{1min}}{\theta_{1max}-\theta_{1min}}$ (with $k_s(t)=k_{smax}$)	$\underline{h}_{G_6^1}(\theta_1(t)) = \frac{\theta_1(t)-\theta_{1min}}{\theta_{1max}-\theta_{1min}}$ (with $k_s(t)=k_{smin}$)
$\bar{h}_{G_6^2}(\theta_2(t)) = \frac{\theta_{2max}-\theta_2(t)}{\theta_{2max}-\theta_{2min}}$ (with $k_t(t)=k_{tmin}$)	$\underline{h}_{G_6^2}(\theta_2(t)) = \frac{\theta_{2max}-\theta_2(t)}{\theta_{2max}-\theta_{2min}}$ (with $k_t(t)=k_{tmax}$)
$\bar{h}_{G_6^3}(\theta_3(t)) = \frac{\theta_{3max}-\theta_3(t)}{\theta_{3max}-\theta_{3min}}$ (with $k_s(t)=k_{smin}$)	$\underline{h}_{G_6^3}(\theta_3(t)) = \frac{\theta_{3max}-\theta_3(t)}{\theta_{3max}-\theta_{3min}}$ (with $k_s(t)=k_{smax}$)

A. Performance Indicators

It is known that ride comfort constitutes a crucial performance index for assessing the effectiveness of active FSSs. To evaluate this index, pitch acceleration $\ddot{\theta}$ and roll acceleration $\ddot{\phi}$, as utilized in [24], are employed.

From Fig. 1, the expressions for $\ddot{\theta}$ and $\ddot{\phi}$ can be derived as follows:

$$\begin{aligned} I_\theta\ddot{\theta} &= -l[\mathscr{S}_1(t)+\mathscr{S}_3(t)] + l[\mathscr{S}_2(t)+\mathscr{S}_4(t)], \\ I_\phi\ddot{\phi} &= -\bar{t}[\mathscr{S}_1(t)+\mathscr{S}_2(t)] + \bar{t}[\mathscr{S}_3(t)+\mathscr{S}_4(t)], \end{aligned} \tag{7}$$

where $\mathscr{S}_m(t) = c_s\dot{\mathcal{Z}}_m(t)+k_s\mathcal{Z}_m(t)+u_m(t)$; $\mathcal{Z}_m(t) = z_{um}(t)-z_{sm}(t)$. The distance between the fore axle and the core of active FSSs is denoted by l, while $\bar{t}$ refers to half of the fore axle.

To simplify the description, we define $l_\theta = \frac{l}{I_\theta}, t_\phi = \frac{\bar{t}}{I_\phi}, C_\theta = l_\theta\tilde{C}, D_{1\theta} = l_\theta, \tilde{C} = \begin{bmatrix}-k_s(t) & 0 & -c_s & c_s\end{bmatrix}$, $C_\phi = t_\phi\tilde{C}, D_{1\phi} = t_\phi$.

Then, from (7) and IT-2 fuzzy rule, it yields that

$$\begin{aligned} z(t) &= col\{z_\theta(t), z_\phi(t)\}, \\ z_\theta(t) &= \sum_{i=1}^{6}\mu_i(\theta(t))\mathscr{I}_\theta[\mathcal{C}_{\theta i}\alpha(t)+\tilde{\mathcal{D}}_{1\theta}\alpha_u(t)], \\ z_\phi(t) &= \sum_{i=1}^{6}\mu_i(\theta(t))\mathscr{I}_\phi[\mathcal{C}_{\phi i}\alpha(t)+\tilde{\mathcal{D}}_{1\phi}\alpha_u(t)], \end{aligned} \tag{8}$$

where

$$\begin{aligned} &\mathcal{C}_{\theta i} = I_N\otimes C_{\theta i}, \tilde{\mathcal{D}}_{1\theta} = I_N\otimes D_{1\theta}, \mathcal{C}_{\phi i} = I_N\otimes C_{\phi i}, \\ &\tilde{\mathcal{D}}_{1\phi} = I_N\otimes D_{1\phi}, \alpha(t) = col\{x_1(t),x_2(t),x_3(t),x_4(t)\}, \\ &\alpha_u(t) = col\{u_1(t),u_2(t),u_3(t),u_4(t)\}, \\ &\mathscr{I}_\theta = \begin{bmatrix}-1 & 1 & -1 & 1\end{bmatrix}, \mathscr{I}_\phi = \begin{bmatrix}-1 & -1 & 1 & 1\end{bmatrix}. \end{aligned}$$

Then, the following is used to evaluate the attitude performance of FSSs:

$$\| z(t) \|_2 \leq \gamma \| \omega(t) \|_2, \tag{9}$$

where γ is the predetermined H_∞ performance level.

B. Event-Triggered Mechanism

The block diagram of the consensus control for agent-based FSSs is shown in Fig. 2. The m-th QSS acts as one of these agents, with its real-time states, $x_m(t)$, sampled by the m-th sampler. These sampled states, $x_m(qh)$, are transmitted to the control unit via a communication network, regulated by the ETM to reduce communication bandwidth requirements by transmitting data only when necessary. The ETM is defined as follows,

$$t_{k+1}^m h = t_k^m h + \min_{l^m}\{l^m h | \Psi_m(t) > \kappa_m\}, \tag{10}$$

where h is the sampling period, and $t_k^m h$ is the releasing instant of the mth quarter-vehicle.

$$\begin{aligned} \Psi_m(t) &= e_m^T(t)\Omega_m e_m(t) + \nu_m\varphi_m^T(t)\Omega_m\varphi_m(t) \\ &\quad - \sigma_m\xi_m^T(t)\Omega_m\xi(t), \\ e_m(t) &= x_m(t_k^m h) - x_m(qh), \varphi_m(t) = x_m(qh) - x_0(qh), \\ \xi_m(t) &= \sum_{n\in N_m} a_{mn}[x_m(t_k^m h) - x_n(t_k^n h)] + \end{aligned}$$

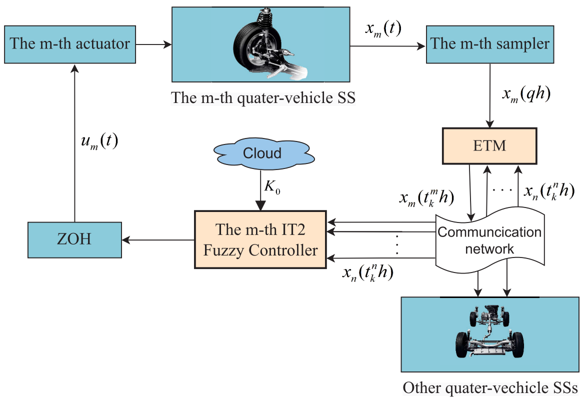


Fig. 2. The block diagram of agent-based FSSs.

$$a_{m0}[x_m(t_k^m h) - x_0(qh)], qh = t_k^m h + l^m h, q \in \mathbb{N},$$

σ_m and ν are predefined parameter, $N_m = \{n|(v_n, v_m) \in \mathcal{E}\}$ denotes the set of neighbors of node m, and (v_m, v_n) is the ordered pair of nodes; κ_m is positive constant and $\sum_{m=1}^{N} \kappa_m = \kappa$.

Remark 4: When some QSSs deviate from the virtual leader due to local interference, the need for more updated control information increases. However, if they do not meet the triggering condition, this results in poor control performance. By incorporating $\varphi_m(t)$ that indicates the error between the states of the QSS and the virtual leader, this issue can be mitigated, as the leader's information can be accessed at any sampling instant according to Assumption 1.

Remark 5: In (10), $\nu_m \in (0, 1)$ represents the weight of $\varphi_m(t)$ in $\Psi_m(t)$. If one sets $\nu_m = 0$ $(m \in \{1, 2, \cdots, N\})$, the proposed ETM degenerates into the traditional ETM.

C. Controller Design

Considering the proposed ETM in (10), the event-triggered IT-2 fuzzy-based consensus controller for the jth rule can be designed as follows:

Controller Rule j: **IF** $\theta_1(t_k^m h)$ is G_j^1, $\cdots$, and $\theta_p(t_k^m h)$ is G_j^p, **THEN**

$$u_m(t) = K_j \xi_m(t_k^m h) + K_0 x_0(t), \tag{11}$$

where $j \in \mathscr{J}$ means the jth fuzzy rule, $\theta_p(t_k^m h)$ and G_j^p for $p \in \mathscr{P}$ denote the jth premise variable and fuzzy set, respectively; K_j is the control gains to be designed.

Similar to (5), we define

$$\mathcal{M}_G^j(\theta(t_k^m h)) = [\underline{\mathscr{G}}_j(\theta(t_k^m h)), \overline{\mathscr{G}}_j(\theta(t_k^m h))] \tag{12}$$

as the firing strength of the jth rule, where $\theta(t_k^m h) = [\theta_1(t_k^m h), \theta_2(t_k^m h), \theta_3(t_k^m h)]$, $\underline{\mathscr{G}}_j(\theta(t_k^m h)) = \prod_{p=1}^{3} \underline{\hbar}_{G_j^p}(\theta_j(t_k^m h))$, $\overline{\mathscr{G}}_j(\theta(t_k^m h)) = \prod_{p=1}^{3} \bar{\hbar}_{G_j^p}(\theta_j(t_k^m h))$.

Let the MF of the controller be:

$$\mu_j(\theta(t_k^m h)) = \frac{\partial_G^j(\theta(t_k^m h))}{\sum_{j=1}^{6}(\partial_G^j(\theta(t_k^m h)))}, \tag{13}$$

where $\partial_G^j(\theta(t_k^m h)) = \underline{\lambda}_j(\theta(t_k^m h))\underline{\mathscr{G}}_j(\theta(t_k^m h)) + \overline{\lambda}_j(\theta(t_k^m h))\overline{\mathscr{G}}_j(\theta(t_k^m h))$. It is clear that $\sum_{j=1}^{6} \mu_j(\theta(t_k^m h)) = 1$ and $0 < \mu_j(\theta(t_k^m h)) < 1$. For brevity, we define $\mu_i^t = \mu_i(\theta(t))$ and $\mu_j^k = \mu_j(\theta(t_k^m h))$ in what follows.

Then, the event-triggered IT-2 fuzzy-based controller can be expressed as follows:

$$u_m(t) = \sum_{j=1}^{6} \mu_j^k [K_j \xi_m(t_k^m h) + K_0 x_0(t)]. \tag{14}$$

Define $\eta_m(t) = t - t_k^m h - l^m h$ and $\chi_m(t) = x_m(t) - x_0(t)$. From the definition of $e_m(t)$, one can obtain that

$$\begin{aligned} u_m(t) = \sum_{j=1}^{6} \mu_j^k K_j \Big\{ &\sum_{n \in N_m} a_{mn}[e_m(t) - e_n(t) \\ &+ \chi_m(t - \eta_m(t)) - \chi_n(t - \eta_n(t))] \\ &+ a_{m0}[e_m(t) + \chi_m(t - \eta_m(t))]\Big\} + BK_0 x_0(t). \end{aligned} \tag{15}$$

Define

$$\begin{aligned} \chi(t) &= col\{\chi_1(t), \chi_2(t), \ldots, \chi_N(t)\}, \\ \chi(t - \eta(t)) &= col\{\chi_1(t - \eta_1(t)), \chi_2(t - \eta_2(t)), \\ &\quad \ldots, \chi_N(t - \eta_N(t))\}. \\ e(t) &= col\{e_1(t), e_2(t), \ldots, e_N(t)\}, \\ \omega(t) &= col\{\tilde{\omega}_1(t), \tilde{\omega}_2(t), \ldots, \tilde{\omega}_N(t)\}, \\ \tilde{\omega}_m(t) &= col\{\omega_m(t), \omega_0(t)\}, \\ \iota(t) &= col\{\chi(t), \chi(t - \eta(t)), e(t)\}, \\ g_w(t) &= col\{g_{w1}(t), g_{w2}(t), \ldots, g_{wN}(t)\}, \\ \varkappa(t) &= col\{\varkappa_v(t), e(t), \varkappa_{w1}(t), \varkappa_{w2}(t), \omega(t), g_w(t)\}, \\ \varkappa_v(t) &= col\{\chi(t), \chi(t - \eta(t)), \chi(t - h)\}, \\ \varkappa_{w1}(t) &= \frac{1}{\eta(t)} \int_{t-\eta(t)}^{t} \chi(s) ds, \\ \varkappa_{w2}(t) &= \frac{1}{h - \eta(t)} \int_{t-h}^{t-\eta(t)} \chi(s) ds. \end{aligned}$$

Combining (6), (8), and (15), the closed loop of event-triggered IT-2 fuzzy agent-based FSSs can be expressed by

$$\begin{cases} \dot{\chi}(t) = \sum_{i=1}^{6} \sum_{j=1}^{6} \mu_i^t \mu_j^k [\hat{\mathcal{A}} \iota(t) + \mathcal{D}_{\chi i} \omega(t) + \mathcal{I}_g g_w(t)], \\ z(t) = \sum_{i=1}^{6} \sum_{j=1}^{6} \mu_i^t \mu_j^k \hat{\mathcal{C}} \iota(t) \end{cases} \tag{16}$$

where

$$\begin{aligned} &\hat{\mathcal{A}} = \begin{bmatrix} \mathcal{A}_i & \mathcal{B}_i \mathcal{K}_j & \mathcal{B}_i \mathcal{K}_j \end{bmatrix}, \mathcal{A}_i = I_N \otimes A_i, \mathcal{B}_i = \hat{L} \otimes B_i, \\ &\hat{\mathcal{C}} = col\{\hat{\mathcal{C}}_\phi, \hat{\mathcal{C}}_\theta\}, \mathcal{D}_{\chi i} = I_N \otimes D_{\chi i}, \mathcal{I}_g = I_N \otimes I, \\ &\hat{\mathcal{C}}_\theta = \begin{bmatrix} \mathscr{I}_\theta \mathcal{C}_{\theta i} & \mathscr{I}_\theta \mathcal{D}_{1\theta} \mathcal{K}_j & \mathscr{I}_\theta \mathcal{D}_{1\theta} \mathcal{K}_j \end{bmatrix}, \mathcal{K}_j = I_N \otimes K_j, \\ &\hat{\mathcal{C}}_\phi = \begin{bmatrix} \mathscr{I}_\phi \mathcal{C}_{\phi i} & \mathscr{I}_\phi \mathcal{D}_{1\phi} \mathcal{K}_j & \mathscr{I}_\phi \mathcal{D}_{1\phi} \mathcal{K}_j \end{bmatrix}, \\ &\mathcal{D}_{1\theta} = \hat{L} \otimes D_{1\theta}, \mathcal{D}_{1\phi} = \hat{L} \otimes D_{1\phi}, D_{\chi i} = \begin{bmatrix} D_i & -D_i \end{bmatrix}. \end{aligned}$$

The main objective of this study is to design an IT-2 fuzzy consensus controller for the IT-2 fuzzy agent-based FSS under the ETM in subsection II-B to satisfy the performance indicators in subsection II-A.

III. Event-Triggered IT-2 Fuzzy Consensus Controller Design for FSSs

Before proceeding, it is crucial to introduce the following definition.

Theorem 1: For given scalars $\kappa, \sigma_m, \nu_m \in (0, 1)$, $m \in \{1, 2, 3, 4\}$, ρ_i, ρ_j, and matrices K_j with $i, j \in \{1, 2, 3, 4, 5, 6\}$, the event-triggered IT-2 fuzzy agent-based FSS in (16) under the ETM in (10) is UUB with H_∞ performance indicators in (9), if there exist symmetric matrices $\Omega > 0, \mathcal{P} > 0, \mathcal{Q} > 0, \mathcal{R} > 0, \mathcal{H}_1 > 0, \mathcal{H}_3 > 0$, and matrices $\mathcal{H}_2$, $\mathcal{M}_i^T = \mathcal{M}_i$ such that

$$\Phi_{ij} - \mathcal{M}_i < 0, \tag{17}$$

$$\Psi_{ii} < 0, \tag{18}$$

$$\Psi_{ij} + \Psi_{ji} < 0, \ (i < j), \tag{19}$$

$$\check{\mathcal{R}} = \begin{bmatrix} \hat{\mathcal{R}} & * \\ \mathcal{H}^T & \hat{\mathcal{R}} \end{bmatrix} > 0, \tag{20}$$

where

$$\Psi_{ij} = \rho_j(\Phi_{ij} - \mathcal{M}_i) + \mathcal{M}_i,$$

$$\Phi_{ij} = \begin{bmatrix} \Theta_{11}^{ij} & * \\ \Theta_{21}^{ij} & \Theta_{22}^{ij} \end{bmatrix}, \Theta_{11}^{ij} = \begin{bmatrix} \Xi_{11}^{ij} & * \\ \Xi_{21}^{ij} & \Xi_{22}^{ij} \end{bmatrix},$$

$$\Theta_{22}^{ij} = \mathrm{diag}\{-\mathcal{R}^{-1}, -I, -I, -\mathcal{P}^{-1}\},$$

$$\Xi_{11}^{ij} = \begin{bmatrix} \Pi_{11}^{ij} & * & * & * \\ \Pi_{21}^{ij} & \Pi_{22}^{ij} & * & * \\ \Pi_{31}^{ij} & \Pi_{32}^{ij} & \Pi_{33}^{ij} & * \\ \Pi_{41}^{ij} & \Pi_{42}^{ij} & 0 & \Pi_{44}^{ij} \end{bmatrix}, \Theta_{21}^{ij} = \begin{bmatrix} h\mathscr{A}_{ij} \\ \mathscr{B}_{ij} \\ \mathscr{C}_{ij} \\ \mathscr{D}_{ij} \end{bmatrix},$$

$$\Xi_{21}^{ij} = \begin{bmatrix} \Pi_{51}^{ij} & \Pi_{52}^{ij} & \Pi_{53}^{ij} & 0 \\ \Pi_{61}^{ij} & \Pi_{62}^{ij} & \Pi_{63}^{ij} & 0 \\ \Pi_{71}^{ij} & 0 & 0 & 0 \\ \mathcal{I}_g^T\mathcal{P} & 0 & 0 & 0 \end{bmatrix},$$

$$\Xi_{22}^{ij} = \begin{bmatrix} \Pi_{55}^{ij} & * & * & * \\ \Pi_{65}^{ij} & \Pi_{66}^{ij} & * & * \\ 0 & 0 & \Pi_{77}^{ij} & * \\ 0 & 0 & 0 & -\mathcal{P} \end{bmatrix},$$

$$\Pi_{11}^{ij} = \mathrm{He}(\mathcal{P}\mathcal{A}_i) + \mathcal{Q} - 4\mathcal{R} + \sqrt{\kappa}\mathcal{P},$$

$$\Pi_{21}^{ij} = \mathcal{K}_j^T\mathcal{B}_i^T\mathcal{P} - 2\mathcal{R} - \mathcal{H}_1^T - \mathcal{H}_2 - \mathcal{H}_2^T - \mathcal{H}_3^T,$$

$$\Pi_{22}^{ij} = \mathcal{L}^T\hat{\Lambda}\Omega\mathcal{L} - \hat{\Lambda}_\nu\Omega - 8\mathcal{R} + \mathcal{H}_1^T + \mathcal{H}_1 - \mathcal{H}_3^T - \mathcal{H}_3,$$

$$\Pi_{31}^{ij} = \mathcal{H}_1^T - \mathcal{H}_2 + \mathcal{H}_2^T - \mathcal{H}_3^T, \mathcal{P} = I_N \otimes P, \mathcal{T}_g = L \otimes \mathscr{T},$$

$$\Pi_{32}^{ij} = -2\mathcal{R} - \mathcal{H}_1^T + \mathcal{H}_2 + \mathcal{H}_2^T - \mathcal{H}_3^T, \Pi_{33}^{ij} = -\mathcal{Q} - 4\mathcal{R},$$

$$\Pi_{41}^{ij} = \mathcal{K}_j^T\mathcal{B}_i^T\mathcal{P}, \Pi_{42}^{ij} = \mathcal{L}^T\hat{\Lambda}\Omega\mathcal{L}, \Pi_{44}^{ij} = \mathcal{L}^T\hat{\Lambda}\Omega\mathcal{L} - \Omega,$$

$$\Pi_{51}^{ij} = 6\mathcal{R}, \Pi_{52}^{ij} = 6\mathcal{R} + 2\mathcal{H}_3 + 2\mathcal{H}_2, \Pi_{53}^{ij} = -2\mathcal{H}_2 + 2\mathcal{H}_3,$$

$$\Pi_{55}^{ij} = -12\mathcal{R}, \Pi_{61}^{ij} = 2\mathcal{H}_3^T + 2\mathcal{H}_2, \Pi_{62}^{ij} = 6\mathcal{R} + 2\mathcal{H}_3^T - 2\mathcal{H}_2,$$

$$\Pi_{63}^{ij} = 6\mathcal{R}, \Pi_{65}^{ij} = -4\mathcal{H}_3^T, \Pi_{66}^{ij} = -12\mathcal{R},$$

$$\Pi_{71}^{ij} = \mathcal{D}_{\chi i}^T\mathcal{P}, \Pi_{77}^{ij} = -\gamma^2 I, \Omega = \{\Omega_1, \Omega_2, \ldots, \Omega_N\},$$

$$\mathscr{A}_{ij} = \begin{bmatrix} \mathcal{A}_i \ \mathcal{B}_i\mathcal{K}_j \ 0 \ \mathcal{B}_i\mathcal{K}_j \ 0 \ 0 \ \mathcal{D}_{\chi i} \ \mathcal{T}_g \end{bmatrix},$$

$$\mathscr{B}_{ij} = \begin{bmatrix} \mathscr{I}_\theta\mathcal{C}_{\theta i} \ \mathscr{I}_\theta\mathcal{D}_{1\theta}\mathcal{K}_j \ 0 \ \mathscr{I}_\theta\mathcal{D}_{1\theta}\mathcal{K}_j \ 0 \ 0 \ 0 \ 0 \end{bmatrix},$$

$$\mathscr{C}_{ij} = \begin{bmatrix} \mathscr{I}_\phi\mathcal{C}_{\phi i} \ \mathscr{I}_\phi\mathcal{D}_{1\phi}\mathcal{K}_j \ 0 \ \mathscr{I}_\phi\mathcal{D}_{1\phi}\mathcal{K}_j \ 0 \ 0 \ 0 \ 0 \end{bmatrix},$$

$$\mathscr{D}_{ij} = \begin{bmatrix} \mathcal{T}_g \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \end{bmatrix}, \mathcal{L} = \hat{L} \otimes I_p,$$

$$\hat{\Lambda} = \Lambda \otimes I_p, \Lambda = \mathrm{diag}\{\sigma_1, \sigma_2, \ldots, \sigma_N\},$$

$$\hat{\Lambda}_\nu = \Lambda_\nu \otimes I_p, \Lambda_\nu = \mathrm{diag}\{\nu_1, \nu_2, \ldots, \nu_N\},$$

$$\hat{\mathcal{R}} = \begin{bmatrix} \mathcal{R} & 0 \\ 0 & 3\mathcal{R} \end{bmatrix}, \mathcal{H} = \begin{bmatrix} \mathcal{H}_1 & * \\ \mathcal{H}_2 & \mathcal{H}_3 \end{bmatrix}.$$

Proof: For the event-triggered IT-2 fuzzy active FSS using agent-based modeling approach in (16), we choose the following Lyapunov function

$$V(t) = \chi^T(t)\mathcal{P}\chi(t) + \int_{t-h}^{t} \chi^T(v)\mathcal{Q}\chi(v)dv + h\int_{-h}^{0}\int_{t+s}^{t} \dot{\chi}^T(v)\mathcal{R}\dot{\chi}(v)dvds, \tag{21}$$

where $\mathcal{P} = I_N \otimes P$, $\mathcal{Q}$, and $\mathcal{R}$ is a symmetric positive definite matrix.

Taking derivative on $V(t)$, we have

$$\dot{V}(t) \leq 2\chi^T(t)\mathcal{P}\dot{\chi}(t) + \chi^T(t)\mathcal{Q}\chi(t) - \chi^T(t-h)\mathcal{Q}\chi(t-h) + h^2\dot{\chi}^T(t)\mathcal{R}\dot{\chi}(t) - h\int_{t-h}^{t}\dot{\chi}^T(v)\mathcal{R}\dot{\chi}(v)dv. \tag{22}$$

By using the Wirtinger inequality in [38] and [39], it can be inferred that

$$\begin{aligned} &-h\int_{t-h}^{t}\dot{\chi}^T(s)\mathcal{R}\dot{\chi}(s)ds \\ &\leq -\begin{bmatrix} \Upsilon_1(t) \\ \Upsilon_2(t) \end{bmatrix}^T \begin{bmatrix} \frac{h}{\eta(t)}\hat{\mathcal{R}} & 0 \\ 0 & \frac{h}{h-\eta(t)}\hat{\mathcal{R}} \end{bmatrix} \begin{bmatrix} \Upsilon_1(t) \\ \Upsilon_2(t) \end{bmatrix} \\ &\leq -\begin{bmatrix} \Upsilon_1(t) \\ \Upsilon_2(t) \end{bmatrix}^T \check{\mathcal{R}} \begin{bmatrix} \Upsilon_1(t) \\ \Upsilon_2(t) \end{bmatrix}. \end{aligned} \tag{23}$$

where

$$\Upsilon_1(t) = \begin{bmatrix} T_{11} \\ T_{12} \end{bmatrix}\varkappa(t), \Upsilon_2(t) = \begin{bmatrix} T_{13} \\ T_{14} \end{bmatrix}\varkappa(t),$$

$$T_{11} = [I \quad -I \quad 0 \quad 0 \quad 0 \quad 0 \quad 0 \quad 0],$$

$$T_{12} = [I \quad I \quad 0 \quad 0 \quad -2I \quad 0 \quad 0 \quad 0],$$

$$T_{13} = [0 \quad I \quad -I \quad 0 \quad 0 \quad 0 \quad 0 \quad 0],$$

$$T_{14} = [0 \quad I \quad I \quad 0 \quad 0 \quad -2I \quad 0 \quad 0].$$

For $\chi^T(t)\mathcal{P}\chi(t) > \sqrt{\kappa}$, one has

$$\chi^T(t)\sqrt{\kappa}\mathcal{P}\chi(t) - \kappa > 0. \tag{24}$$

Combining the ETM in (10), one can obtain that

$$e^T(t)\Omega e(t) + \chi^T(t-\eta(t))\hat{\Lambda}_\nu\Omega\chi(t-\eta(t)) < \mathfrak{F}^T(t)\mathcal{L}^T\hat{\Lambda}\Omega\mathcal{L}\mathfrak{F}(t) + \chi^T(t)\sqrt{\kappa}\mathcal{P}\chi(t), \tag{25}$$

where $\mathfrak{F}(t) = \chi(t-\eta(t)) + e(t)$.

By referencing (4), it can be derived that

$$g_w^T(t)\mathcal{P}g_w(t) \leq \chi^T(t)\mathcal{T}_g^T\mathcal{P}\mathcal{T}_g\chi(t). \tag{26}$$

Note that

$$h^2\dot{\chi}^T(t)\mathcal{R}\dot{\chi}(t) \leq h\sum_{i=1}^{6}\sum_{j=1}^{6}\mu_i^t\mu_j^k\varkappa^T(t)\mathscr{A}_{ij}^T\mathcal{R}\mathscr{A}_{ij}\varkappa(t). \tag{27}$$

From (22)-(27), using Schur complement yields that

$$\dot{V}(t) + z^T(t)z(t) - \gamma^2\omega^T(t)\omega(t) \leq \sum_{i=1}^{6}\sum_{j=1}^{6}\mu_i^t\mu_j^k\varkappa^T(t)\Phi_{ij}\varkappa(t). \tag{28}$$

Employing a comparable technique as that used in [21] for addressing the problem of asynchronous MF, one can conclude that

$$\sum_{i=1}^{6}\sum_{j=1}^{6}\mu_i^t\mu_j^k\varkappa^T(t)\Phi_{ij}\varkappa(t) \leq \sum_{i=1}^{6}\sum_{j=1}^{6}\mu_i^t\mu_j^k\varkappa^T(t)\Psi_{ii}\varkappa(t) + \sum_{i=1}^{6}\sum_{i<j}\mu_i^t\mu_j^k\varkappa^T(t)[\Psi_{ij}+\Psi_{ji}]\varkappa(t) \tag{29}$$

Based on the preceding analysis, it can be concluded that equations (17) - (20) are adequate conditions to guarantee that

$$\dot{V}(t) + z^T(t)z(t) - \gamma^2\omega^T(t)\omega(t) < 0. \tag{30}$$

Then, we can conclude that event-triggered IT-2 fuzzy agent-based FSS in (16) is UUB with H_∞ performance indicators. The proof is completed. ■

Theorem 2: For given scalars $\kappa, \sigma_m, \nu_m \in (0,1)$, $m \in \{1,2,3,4\}$, $\rho_i, \rho_j, \varepsilon, i, j \in \{1,2,3,4,5,6\}$, the event-triggered IT-2 fuzzy agent-based FSS in (16) under the proposed ETM in (10) is UUB with H_∞ performance indicators in (9), if there exist symmetric matrices $\mathscr{X} > 0, \tilde{\mathcal{Q}} > 0, \tilde{\mathcal{R}} > 0, \tilde{\Omega} > 0, \tilde{\mathcal{H}}_1 > 0, \tilde{\mathcal{H}}_3 > 0$, and matrices $\tilde{\mathcal{H}}_2$, $\tilde{\mathcal{M}}_i^T = \tilde{\mathcal{M}}_i$ such that

$$\tilde{\Phi}_{ij} - \tilde{\mathcal{M}}_i < 0, \tag{31}$$

$$\tilde{\Psi}_{ii} < 0, \tag{32}$$

$$\tilde{\Psi}_{ij} + \tilde{\Psi}_{ji} < 0, \ (i<j), \tag{33}$$

$$\tilde{\tilde{\mathcal{R}}} = \begin{bmatrix} \tilde{\hat{\mathcal{R}}} & * \\ \tilde{\mathcal{H}}^T & \tilde{\hat{\mathcal{R}}} \end{bmatrix} > 0, \tag{34}$$

where

$$\tilde{\Psi}_{ij} = \rho_j(\tilde{\Phi}_{ij} - \tilde{\mathcal{M}}_i) + \tilde{\mathcal{M}}_i,$$

$$\tilde{\Phi}_{ij} = \begin{bmatrix} \tilde{\Theta}_{11}^{ij} & * \\ \tilde{\Theta}_{21}^{ij} & \tilde{\Theta}_{22}^{ij} \end{bmatrix}, \tilde{\Theta}_{11}^{ij} = \begin{bmatrix} \tilde{\Xi}_{11}^{ij} & * \\ \tilde{\Xi}_{21}^{ij} & \tilde{\Xi}_{22}^{ij} \end{bmatrix},$$

$$\tilde{\Xi}_{11}^{ij} = \begin{bmatrix} \tilde{\Pi}_{11}^{ij} & * & * & * \\ \tilde{\Pi}_{21}^{ij} & \tilde{\Pi}_{22}^{ij} & * & * \\ \tilde{\Pi}_{31}^{ij} & \tilde{\Pi}_{32}^{ij} & \tilde{\Pi}_{33}^{ij} & * \\ \tilde{\Pi}_{41}^{ij} & \tilde{\Pi}_{42}^{ij} & 0 & \tilde{\Pi}_{44}^{ij} \end{bmatrix}, \tilde{\Theta}_{21}^{ij} = \begin{bmatrix} h\tilde{\mathscr{A}}_{ij} \\ \tilde{\mathscr{B}}_{ij} \\ \tilde{\mathscr{C}}_{ij} \\ \tilde{\mathscr{D}}_{ij} \end{bmatrix},$$

$$\tilde{\Theta}_{22}^{ij} = \mathrm{diag}\{-2\varepsilon\mathscr{X} + \varepsilon\tilde{\mathcal{R}}^2, -I, -I, -\mathscr{X}\}, \mathscr{X} = I_N \otimes X,$$

$$\tilde{\Xi}_{21}^{ij} = \begin{bmatrix} \tilde{\Pi}_{51}^{ij} & \tilde{\Pi}_{52}^{ij} & \tilde{\Pi}_{53}^{ij} & 0 \\ \tilde{\Pi}_{61}^{ij} & \tilde{\Pi}_{62}^{ij} & \tilde{\Pi}_{63}^{ij} & 0 \\ \tilde{\Pi}_{71}^{ij} & 0 & 0 & 0 \\ \tilde{\Pi}_{81}^{ij} & 0 & 0 & 0 \end{bmatrix},$$

$$\tilde{\Xi}_{22}^{ij} = \begin{bmatrix} \tilde{\Pi}_{55}^{ij} & * & * & * \\ \tilde{\Pi}_{65}^{ij} & \tilde{\Pi}_{66}^{ij} & * & * \\ 0 & 0 & \tilde{\Pi}_{77}^{ij} & * \\ 0 & 0 & 0 & -\mathscr{X} \end{bmatrix},$$

$$\tilde{\Pi}_{11}^{ij} = \mathrm{He}(\mathcal{A}_i\mathscr{X}) + \tilde{\mathcal{Q}} - 4\tilde{\mathcal{R}} + \sqrt{\kappa}\mathscr{X},$$

$$\tilde{\Pi}_{21}^{ij} = \mathcal{Y}_j^T\mathcal{B}_i^T - 2\tilde{\mathcal{R}} - \tilde{\mathcal{H}}_1^T - \tilde{\mathcal{H}}_2 - \tilde{\mathcal{H}}_2^T - \tilde{\mathcal{H}}_3^T,$$

$$\tilde{\Pi}_{22}^{ij} = \mathcal{L}^T\hat{\Lambda}\tilde{\Omega}\mathcal{L} - \hat{\Lambda}_\nu\tilde{\Omega} - 8\tilde{\mathcal{R}} + \tilde{\mathcal{H}}_1^T + \tilde{\mathcal{H}}_1 - \tilde{\mathcal{H}}_3^T - \tilde{\mathcal{H}}_3,$$

$$\tilde{\Pi}_{31}^{ij} = \tilde{\mathcal{H}}_1^T - \tilde{\mathcal{H}}_2 + \tilde{\mathcal{H}}_2^T - \tilde{\mathcal{H}}_3^T,$$

$$\tilde{\Pi}_{32}^{ij} = -2\tilde{\mathcal{R}} - \tilde{\mathcal{H}}_1^T + \tilde{\mathcal{H}}_2 + \tilde{\mathcal{H}}_2^T - \tilde{\mathcal{H}}_3^T, \tilde{\Pi}_{33}^{ij} = -\tilde{\mathcal{Q}} - 4\tilde{\mathcal{R}},$$

$$\tilde{\Pi}_{41}^{ij} = \mathcal{Y}_j^T\mathcal{B}_i^T, \tilde{\Pi}_{42}^{ij} = \mathcal{L}^T\hat{\Lambda}\tilde{\Omega}\mathcal{L}, \tilde{\Pi}_{44}^{ij} = \mathcal{L}^T\hat{\Lambda}\tilde{\Omega}\mathcal{L} - \tilde{\Omega},$$

$$\tilde{\Pi}_{51}^{ij} = 6\tilde{\mathcal{R}}, \tilde{\Pi}_{52}^{ij} = 6\tilde{\mathcal{R}} + 2\tilde{\mathcal{H}}_3 + 2\tilde{\mathcal{H}}_2, \tilde{\Pi}_{53}^{ij} = -2\tilde{\mathcal{H}}_2 + 2\tilde{\mathcal{H}}_3,$$

$$\tilde{\Pi}_{55}^{ij} = -12\tilde{\mathcal{R}}, \tilde{\Pi}_{61}^{ij} = 2\tilde{\mathcal{H}}_3^T + 2\tilde{\mathcal{H}}_2, \tilde{\Pi}_{62}^{ij} = 6\tilde{\mathcal{R}} + 2\tilde{\mathcal{H}}_3^T - 2\tilde{\mathcal{H}}_2,$$

$$\tilde{\Pi}_{63}^{ij} = 6\tilde{\mathcal{R}}, \tilde{\Pi}_{65}^{ij} = -4\tilde{\mathcal{H}}_3^T, \tilde{\Pi}_{66}^{ij} = -12\tilde{\mathcal{R}},$$

$$\tilde{\Pi}_{71}^{ij} = \mathcal{D}_{\chi i}^T, \tilde{\Pi}_{77}^{ij} = -\gamma^2 I, \tilde{\Pi}_{81}^{ij} = \mathscr{X}, \tilde{\Omega} = \{\tilde{\Omega}_1, \tilde{\Omega}_2, \ldots, \tilde{\Omega}_N\},$$

$$\tilde{\mathscr{A}}_{ij} = [\mathcal{A}_i\mathscr{X} \ \mathcal{B}_i\mathcal{Y}_j \ 0 \ \mathcal{B}_i\mathcal{Y}_j \ 0 \ 0 \ \mathcal{D}_{\chi i} \ \mathcal{T}_g],$$

$$\tilde{\mathscr{B}}_{ij} = [\mathscr{I}_\theta\mathcal{C}_{\theta i}\mathscr{X} \ \mathscr{I}_\theta\mathcal{D}_{1\theta}\mathcal{Y}_j \ 0 \ \mathscr{I}_\theta\mathcal{D}_{1\theta}\mathcal{Y}_j \ 0 \ 0 \ 0 \ 0],$$

$$\tilde{\mathscr{C}}_{ij} = [\mathscr{I}_\phi\mathcal{C}_{\phi i}\mathscr{X} \ \mathscr{I}_\phi\mathcal{D}_{1\phi}\mathcal{Y}_j \ 0 \ \mathscr{I}_\phi\mathcal{D}_{1\phi}\mathcal{Y}_j \ 0 \ 0 \ 0 \ 0],$$

$$\tilde{\mathscr{D}}_{ij} = [\mathcal{T}_g\mathscr{X} \ 0 \ 0 \ 0 \ 0 \ 0 \ 0 \ 0],$$

$$\tilde{\hat{\mathcal{R}}} = \begin{bmatrix} \tilde{\mathcal{R}} & 0 \\ 0 & 3\tilde{\mathcal{R}} \end{bmatrix}, \tilde{\mathcal{H}} = \begin{bmatrix} \tilde{\mathcal{H}}_1 & * \\ \tilde{\mathcal{H}}_2 & \tilde{\mathcal{H}}_3 \end{bmatrix}.$$

Furthermore, the feedback gains and the triggering matrix can be obtained by $\mathcal{K}_j = \mathcal{Y}_j\mathscr{X}^{-1}$ and $\Omega = \mathscr{X}^{-1}\tilde{\Omega}\mathscr{X}^{-1}$, respectively.

Proof: Define $\mathscr{Q} = \mathrm{diag}\{\mathscr{X}, \mathscr{X}, \mathscr{X}, \mathscr{X}, \mathscr{X}, \mathscr{X}, I, \mathscr{X}, \mathscr{X}, I, I, \mathscr{X}\}, \tilde{\Omega} = \mathscr{X}\Omega\mathscr{X}, \mathcal{Y}_j = \mathcal{K}_j\mathscr{X}^{-1}, \tilde{\mathcal{R}} = \mathscr{X}\mathcal{R}\mathscr{X}, \tilde{\mathcal{Q}} = \mathscr{X}\mathcal{Q}\mathscr{X}, \tilde{\mathcal{H}}_1 = \mathscr{X}\mathcal{H}_1\mathscr{X}, \tilde{\mathcal{H}}_2 = \mathscr{X}\mathcal{H}_2^T\mathscr{X}, \tilde{\mathcal{H}}_3 = \mathscr{X}\mathcal{H}_3^T\mathscr{X}, \mathscr{X} = I_N \otimes X, X = P^{-1}$.

Pre- and post-multiplying (17) with the matrix $\mathscr{Q}$ and using the nature of $\mathcal{R}^{-1} \leq -2\varepsilon\mathcal{X} + \varepsilon^2\tilde{\mathcal{R}}$, we can conclude that (31) is a sufficient condition to (17) hold, and it is similar to (32), (33) and (34). Thus, the proof is completed. ■

Remark 6: The Wirtinger inequality is used in this study to reduce conservatism. Although this increases the complexity of deriving the theorems, the control gains can be obtained offline. This means that the complexity of implementing the control in the closed loop remains unaffected.

TABLE III
THE RANGES OF UNCERTAIN PARAMETERS

Parameter	Minimum	Maximum	Unit
$m_s(t)$	230	470	kg
$m_u(t)$	35	45	kg
$k_s(t)$	16200	19800	N/m
$k_t(t)$	190000	220000	N/m

IV. SIMULATION

In this section, we will validate the effectiveness of the proposed method for the FSS. The ranges of uncertain parameters are listed in Table III, which refer to a type of C-class vehicle. The remaining relevant parameters are taken from [33] and [35].

To investigate the impact of shocks and vibrations, such as bumps, on the performance of the vehicle SS, the road

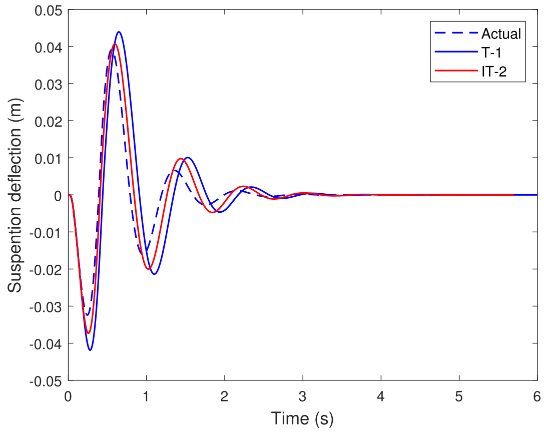


Fig. 3. Suspension deflection of passive QSSs using different fuzzy approach.

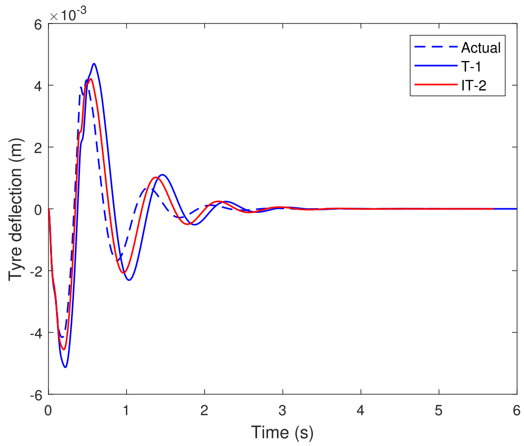
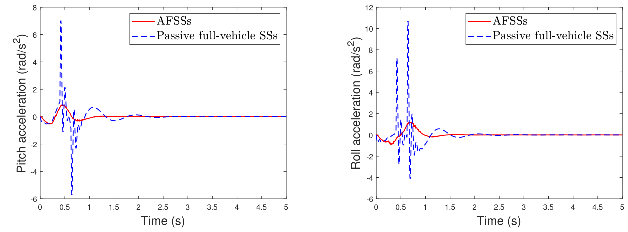
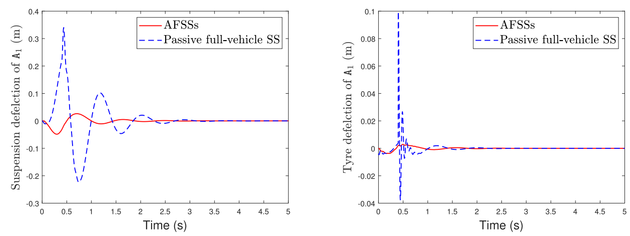


Fig. 4. Tyre deflection of passive QSSs using different fuzzy approach.



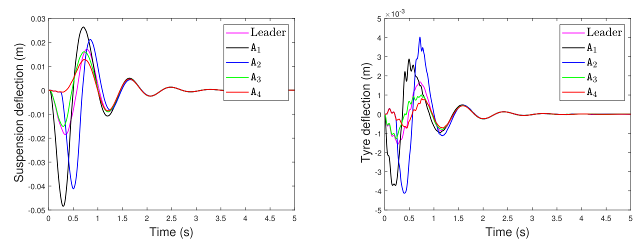
(a) Pitch acceleration (b) Roll acceleration

Fig. 5. Attitude performance.



(a) Suspension deflection (b) Tyre deflection

Fig. 6. Suspension and tyre deflection of $\mathbb{A}_1$.



(a) Suspension deflection (b) Tyre deflection

Fig. 7. Trajectories of the leader and the agent $\mathbb{A}_m$.

disturbance $z_{rm}, m \in \{0, 1, 2, 3, 4\}$ is selected from [40]. Observing Fig. 1 yields that

$$L = \begin{bmatrix} 3 & -1 & -1 & -1 \\ -1 & 3 & -1 & -1 \\ -1 & -1 & 3 & -1 \\ -1 & -1 & -1 & 3 \end{bmatrix}, \hat{A} = \mathrm{diag}\{1, 1, 1, 1\}.$$

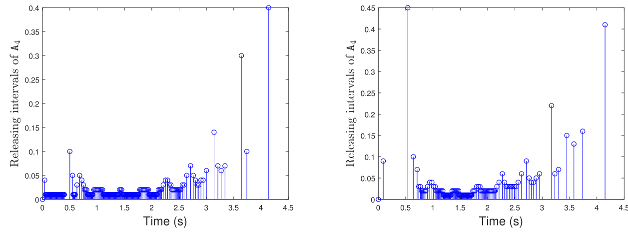
Fig. 3 and Fig. 4 illustrate the suspension deflection and tyre deflection using both the T-1 fuzzy approach and the proposed IT-2 fuzzy approach for a passive QSS. The results indicate that the IT-2 fuzzy approach provides a more accurate representation of the uncertainties inherent in QSSs compared to the T-1 fuzzy approach.

Suppose the sampling period is $h = 0.01s$, and let the H_∞ level be $\gamma = 5$. The event-triggered parameters are $\sigma_1 = 0.005$, $\sigma_2 = 0.012$, $\sigma_3 = 0.010$, $\sigma_4 = 0.005$, $\nu_1 = 0.05$, and $\nu_2 = \nu_3 = \nu_4 = 0.15$. The T–S fuzzy parameters are $\rho_1 = 0.35$, $\rho_2 = 0.4$, $\rho_3 = 0.2$, $\rho_4 = 0.3$, $\rho_5 = 0.35$, $\rho_6 = 0.3$, and $\underline{\lambda}_i(t) = \overline{\lambda}_i(t) = 0.5$ The mutual coupling function is $f_{wm}(x_m(t)) = \sin(\mathscr{T} x_m(t))$, where $\mathscr{T} = \mathrm{diag}\{0.2, 0.2, 0.2, 0.2\}$, $\kappa = 0.0004$, and $\varepsilon = 0.2$.

In practice, K_0 is an optimal result by cloud computing. In this study, $K_0 = 10^3 \times [-0.3807\ 0.2160\ 0.1512\ -0.8648]$ is got from [33].

By solving the criterion presented in Theorem 2, we can obtain the IT-2 fuzzy controller gains of agent-based FSSs K_1 to K_6 and triggering matrices of ETM Ω_1 to Ω_4.

For the sake of simplification, we denote Agent m as $\mathbb{A}_m$ hereafter. As shown in Figs. 5, the attitude performance for pitch acceleration ($\ddot{\theta}$) and roll acceleration ($\ddot{\phi}$) significantly decreases compared to the passive FSS (SS), indicating enhanced stability and a smoother ride experience. Fig. 6 presents the suspension and tire deflection for $\mathbb{A}_1$ in both the passive FSS and the agent-based FSS. Due to the space limitation, the results for agents $\mathbb{A}_m$, where $m = 2, 3, 4$, are omitted. It can be observed that both suspension deflection and dynamic tire load are considerably smaller in the agent-based FSS compared to the passive system, indicating improved vehicle response to road irregularities and better handling characteristics. Fig. 7 shows that trajectory errors between the followers and the leader attenuate quickly, hinting that each QSS can effectively track the virtual leader. This demonstrates the efficacy of our proposed method in facilitating better coordination and synchronization among vehicles. Therefore, we conclude that the proposed event-triggered IT-2 fuzzy consensus control approach is effective in mitigating the impact of common road disturbances on FSSs.



(a) $\mathtt{A}_4$ with our proposed ETM (b) $\mathtt{A}_4$ with the ETM in [36], [37] ($\nu_m = 0$)

Fig. 8. Releasing intervals and instants.

TABLE IV

$\mathscr{R}_m$ UNDER THE PROPOSED ETM

	$\mathtt{A}_1$	$\mathtt{A}_2$	$\mathtt{A}_3$	$\mathtt{A}_4$
$\mathscr{N}_{rm}$	171	103	156	196
$\mathscr{R}_m$	34.2%	20.6%	31.2%	39.2%

TABLE V

$\mathscr{R}_m$ IN TIME INTERVAL $0-1$s

Strategy	$\mathtt{A}_1$	$\mathtt{A}_2$	$\mathtt{A}_3$	$\mathtt{A}_4$
ETM in (10)	47%	31%	53%	67%
ETM in [36] and [37]	38%	24%	41%	15%

The releasing intervals and instants (RIIs) can clearly observe the status of the data packet at each instant. To save space, we only select the RIIs of A4 to analyze the obtained results. Fig. 8 displays the RII for A4 under our proposed ETM and the traditional ETM, such as in [36] and [37]. It is evident from Fig. 8 that both our proposed ETM and the traditional ETM can significantly save network bandwidth. For the case of other QSSs, we record the number of data releases in Table IV. In Table IV, $\mathscr{N}$rm denotes the number of data releases of the mth interconnected QSS over a finite time interval, and $\mathscr{R}m = \frac{\mathscr{N}\mathrm{rm}}{\mathscr{N}\mathrm{sm}}$ denotes the data release rate, where $\mathscr{N}_{\mathrm{sm}}$ is the number of samples in this time interval. Similar conclusions can be drawn from Table IV.

Table V presents the data release rates of the quarter-vehicles $\mathtt{A}_1$-$\mathtt{A}_4$ under our proposed ETM and the traditional ETM as in [36] and [37] during the time interval of 0 to 1s. During this period, they have relatively significant interferences. It is evident that the proposed ETM achieves a significantly higher data release rate compared to the general ETM in [36] and [37]. This improvement is particularly notable for $\mathtt{A}_4$. The same conclusion is supported by the observations in Fig. 8(a) and Fig. 8(b). Sufficient information is beneficial for achieving precise decision-making by the controller, thereby ensuring optimal control performance, as stated in Remark 4.

V. CONCLUSION

This study has addressed the event-triggered consensus control problem for IT-2 agent-based FSSs. An IT-2 fuzzy model has been proposed, utilizing LMFs and UMFs to accurately represent the uncertain suspension parameters. This model can effectively capture the complexity and nonlinearity of the suspension system, leading to enhanced decision-making and control performance. Furthermore, the consensus controller design has been developed to employ cloud-stored road information, which replicates optimal driving conditions for actual vehicles. The proposed ETM can not only conserve network bandwidth between agents but also release more data packets during periods when quarter-vehicles deviate from consensus, compared to the traditional ETMs, thereby ensuring performance standards. In the construction of the agent-based FSS model, the coupling relationships between quarter-vehicles have been simplified by using a nonlinear function $f_{wm}(x_m(t))$ in this study, which needs to be further investigated in the further work. Moreover, the issue of conservatism in control design, as well as the use of professional simulation software such as CarSim and ADAMS, along with dedicated platforms for FSSs, will also be explored in future research.

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