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ORIGINAL RESEARCH

An adaptive fuzzy control technique for a high-speed vehicular platoon experiencing communication delays

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Abstract

Vehicle platooning is seen as an enabler to improve driving safety, traffic congestion and stress-free driving. A platoon is a highly non-linear system and fuzzy control is able to deal with those systems. This paper presents a pioneering solution to the complex problem of vehicle platooning. Our adaptive controller seamlessly integrates fuzzy logic with conventional PID control technology, thereby ensuring safe and efficient travel for vehicles within a platoon. The key objectives of this controller encompass the maintenance of a consistent inter-vehicle time gap and the consideration of time-varying parameter uncertainties and communication delays between vehicles. It provides mathematical proof of the stability of the platoon formation using the Routh–Hurwitz theorem and a set of equations that describe the platoon's overall performance. Simulation results show that the proposed controller is effective in controlling vehicle platoons, even in the presence of random communication delays, resulting in improved driving safety and reduced traffic congestion.

1 | INTRODUCTION

Increased car volume has resulted in major traffic safety, congestion, and pollution challenges during the last few decades. To address these issues, researchers are devoting more time and resources to the study of intelligent transportation systems (ITS). An ITS can be achieved through various innovative technologies such as V2V or Vehicle-to-Infrastructure (V2I) communication systems [1]. Organizing several vehicles into a compact platoon has been shown to be a cost-effective and efficient strategy to boost traffic through-put, reduce pollution, and improve passenger safety [2]. Any platoon communication requires an ITS to address these traffic needs [3]. Ongoing and past projects of platoon systems around the globe are worth mentioning which includes the European Safe Road Trains for the Environment (SARTRE) project [4], the Japanese Energy-Intelligence Transportation System (Energy-ITS) project [5], the United States Project for Assistance in Transition from Homeless-ness (US PATH) project [6], and the Tracked Electric Vehicle (TEV) project [7]. Most of the vehicle platooning systems are based on heavy-duty trucks. TEV is based on electric cars and is the only platoon, where the front car experiences the same energy reduction as the follower cars [8]. Due to cost, many research in platooning is conducted via simulation. For example, [9] examined the effects of passenger car platooning on energy-saving by employing the simulation software XFlow. For a heterogeneous platoon of heavy-duty trucks with temporal delays simulation, [10] suggests an Eco-CACC method.

The spacing between cars is a challenging task to be controlled and as such a well-defined platoon controller holds the key for a safe and energy-efficient journey. Various concepts to materialize the spacing challenge have been proposed, including passive vehicle platoon control and inter-vehicular communication. A passive platoon control uses radars and laser sensors to optimize the speed and distance of vehicles in a platoon which helps the vehicle to manage itself [11]. On the contrary, an inter-vehicular communication system can range from that of a V2V or V2I communication in which the vehicles exchange information like speed, distance, and position [12]. The inter-vehicular communication system also helps the vehicle in a platoon to calculate its constant distance (CD) or constant time headway (CTH) [13]. The set distance between two neighbouring vehicles is known as the CD policy, and it can be measured in metres or inches. And The CTH is a time gap between two adjacent vehicles, with seconds as the measurement. That is to say, the real distance increases with speed under the CTH policy. The Internet of Things (IoT) has become a trend due to the rapid advancement of communication technology. Scholars have conducted the following research using V2V and V2I technology and the aforesaid control policy. Research has analysed incooperated and Co-operative Adaptive Cruise Control (CACC) system [14] as a form of Network Control System (NCS) that can help in reducing network-induced imperfections caused by wireless communications. Moreover, some researchers have examined dynamic network consistency while examining the vehicle platoon system, addressing the problems of nodes, edges, and network topology [15]. Furthermore, other researchers have investigated the platoon system through four basic modules [16, 17], including the four-element vehicle platoon model based on the algebraic graph theory, feedback linearization, and matrix analysis.

In all of the studies, it is shown that a platoon is a highly non-linear system. Fuzzy logic happens to be a strategy for controlling non-linear systems [18]. As such various work has been published in this field. In [19], fuzzy formation control of multiple autonomous vehicles is implemented to achieve platooning with prioritized missions. Reference [20] has employed fuzzy control in an attempt to examine the optimal longitudinal control of vehicular platoon. Reference [21] has used an adaptive neuro-fuzzy predictor-based control method in the CACC platoon system and showed that the proposed control strategy for the CACC system could significantly reduce fuel consumption while ensuring driving comfort and safety. Despite the fact that fuzzy logic is a popular method for controlling non-linear systems, there are other methods developed to address the system from different perspectives. For instance, model predictive control (MPC) has been shown to be an effective approach to the presence of constraints in non-linear systems [22]. Additionally, adaptive control techniques, such as sliding mode control (SMC) [17] and backstepping control [23], have also been applied to non-linear systems with some success. However, fuzzy logic shows more potential to improve the stability and robustness of the vehicle platoon, some researchers attempt to integrate the fuzzy method with other algorithms. A preliminary study has been conducted on a fuzzy controller to control the time gap between two cars by using an adaptive PID method [24]. In [25], a hybrid fuzzy controller is proposed for inter-vehicle distance control in a vehicle platoon. But the platoon is either tiny (2 cars) or homogeneous, and communication delay was not taken into account.

This research introduces an adaptive control architecture that seamlessly integrates fuzzy logic with standard PID control technology. The term adaptive underscores the controller's inherent capacity to dynamically adapt and respond to evolving conditions, thereby ensuring the platoon's resilience in real-world scenarios. Matlab/Simulink is used to verify and simulate the performance of this innovative controller. The developed adaptive fuzzy controller is built on the principle of the device error (e) and deviation rate of the system error (e_c). It continuously monitors e and e_c during system operation. This research demonstrates that the suggested controller can handle a heterogeneous platoon, which consists of vehicles of various sizes and weights, as well as communication delays that are prevalent in real-world communications. This study investigates a 4-car platoon system and contributes to the V2V communication system by addressing design and communication delay in simulations. The 4-car platoon is a standard vehicle formation that includes a lead car, two middle cars, and a tail car. Based on this basic configuration, this study can also be extended to the n-cars platoon system. The lead vehicle can be ignored as a neighbouring car while studying the performance of a single car in a vehicle platoon. Due to the large size of the vehicle platoon, it is also possible to avoid difficulties like computational overload and unclear findings. Moreover, the simulation results shown in this study reveal a significant improvement in maintaining the time gap between the cars for a safe and efficient flow of the platooning system in different situations and with various vehicle parameters. Based on the aforementioned factors, this study has investigated the fuzzy logic control for vehicle platoon system with CTH policy by utilizing V2V communication, with four contributions:

- Quantifying Platoon Performance: This paper introduces a novel statistical approach to quantifying key performance properties of vehicle platoons, such as space error and dynamics consistency. By creating formulas that express the platoon's spacing error, we provide a rigorous framework for assessing platoon performance.
- Innovative Controller for Maintaining Time Gap: Our study presents a pioneering controller that combines fuzzy logic with conventional PID control to enhance the stability and efficiency of vehicle platooning. Simulation results unequivocally demonstrate the controller's effectiveness in consistently maintaining the desired time gap between vehicles, thereby ensuring both safety and efficiency across diverse scenarios and with varying vehicle parameters.
- Heterogeneous Platooning with Communication Latency: In the context of heterogeneous platooning, where communication latency between vehicles may vary, our novel controller excels. It enables the lead vehicle to efficiently broadcast its velocity to following vehicles, ensuring stability and adaptability to meet future traffic requirements.
- Achieving Robustness in Gap Control: Despite variations in specific vehicle models, our controller achieves robust control of inter-vehicle gaps. This robustness enhances the reliability and safety of platoon formations, emphasizing the practical applicability of our approach in real-world scenarios.

The following is an outline of the structure of the paper. Section 2 describes the fuzzy-based vehicle platoon system's mathematical model. In Section 3, it demonstrates the stability of a basic platoon system. The proposed Fuzzy-PID control method is defined and detailed in Section 4. Section 5 is the numerical results of the proposed method which are shown to

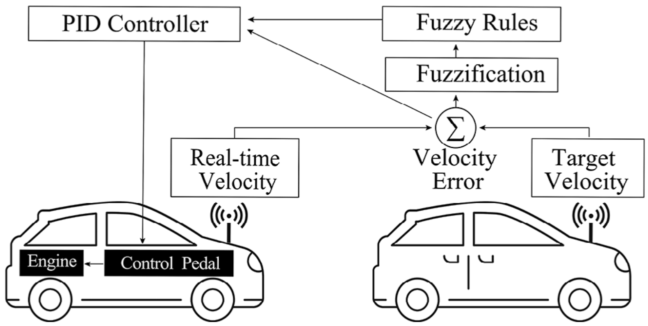

FIGURE 1 Fuzzy control structure.

validate the effectiveness of the vehicle platoon. Then, Section 6 summarizes the key findings and presents the future work.

2 | MODELLING OF THE PLAOON SYSTEM

Automated cars in a vehicular platoon system may not only drive autonomously and safely using on-board sensors, but also platoon with surrounding automated vehicles using V2V collaboration. The proposed control structure of a Fuzzy-PID controller in this paper is shown in Figure 1. The k_p, k_i, and k_d (the gains of the proportion, integral, and derivation of the errors, respectively) are forming the base of any PID controller, and in this case, are adjusted with the help of the fuzzy controller with velocity error and initial position being the input of the fuzzy controller. With the help of the V2V communication, the following vehicle can obtain the position and velocity information as the inputs as the figure shows. In vehicular platoon control, the control objectives are the desired spacing and the consensus velocity.

2.1 | Introducing constant time-headway modelling

There are two methods to analyse the spacing between vehicles: CD and CTH. Reference [26] reports that CD is not appropriate for independent control without knowing the velocity, position and acceleration of the platoon. Traditional CTH researchers do not consider the acquisition of vehicle dynamic information via V2V communication, such as [27], which is the use of on-board sensors. But with the development of ITS, vehicle communication technology has great research potential. Under the CTH policy, the safe distance of the vehicle can be guaranteed. In addition, it also has the advantage of point-to-point communication and flexible vehicle communication formation. It is currently an important solution to improve road effectiveness, reduce driver pressure and ensure traffic safety. As a result, the CTH spacing policy is applied in this paper. Figure 2 helps to illustrate this policy and to show an n-size vehicular platoon. In Figure 2, x_i donates the position of the vehicle i, v_i is the velocity, l_i is the length of the vehicle and ε_i is the spacing between vehicle i and its proceeding vehicle. The spacing can be described by two elements: the desired spacing d_{des} and the spacing error δ_i.

Compared with CD, CTH calculates the desired spacing as a function of velocity:

$$d_{des}(t) = D_{min} + h\dot{x}_i(t) \tag{1}$$

where $\dot{x}_i$ is the velocity that is derivative from the position, D_{min} is the set distance between the foremost and subsequent vehicles that is required to avoid any accidents. Therefore, D_{min} can vary depending on the platoon safety and h is the constant time gap coefficient. The measured distance between neighbouring vehicles is as follows:

$$x_i(t) - x_{i-1}(t) = l_{i-1} + \varepsilon_i(t) \tag{2}$$

and the spacing error is defined as

$$\delta_i(t) = \varepsilon_i - d_{des}(t) \tag{3}$$

Then it is going to build the controller error input based on the CTH policy which is

$$\delta_i(t) = \varepsilon_i(t) - D_{min} - h\dot{x}_i(t) \tag{4}$$

In the following design, D_{min} sets to 0. In conclusion, the platoon system control objective between front and rear vehicles is as taking after: 1) The CTH spacing error of the ith and $(i-1)$ th vehicles is equal to zero, i.e.,

$$\lim_{t-T} \delta_i(t) = 0 \tag{5}$$

where T is the control required time in [28]. 2) Each car in the system must ensure its own close-loop stability. 3) String stability refers to the ability of a platoon system to prevent the sudden spacing error between two following vehicles from being amplified as it propagates through the platoon.

2.2 | General proportional-integral-derivative controller design

The creative PID control for the upper control is studied, and the machine portion's dynamic indication is inputted. The complete system block illustration is shown in Figure 3. This figure is a proposed structure for the CTH system. In this work, the velocity is used as the control input, because the acceleration and position information can be obtained receptively through one-time derivation and integration. In addition, in the longitudinal platoon system control, the position information is approximated to a point in a straight line. Therefore, the dynamic position, velocity and acceleration values can be obtained only from the velocity information and initial values, which can satisfy the research of the controller. In the longitudinal control of the vehicle platoon, [16] summarizes

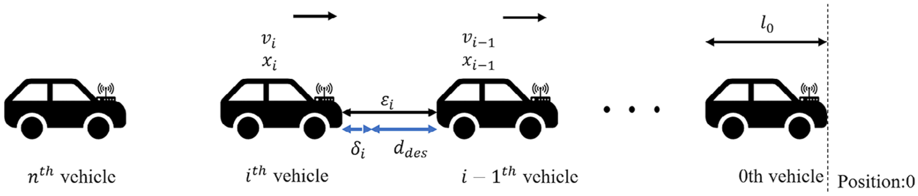

FIGURE 2 *n*-size vehicular platoon.

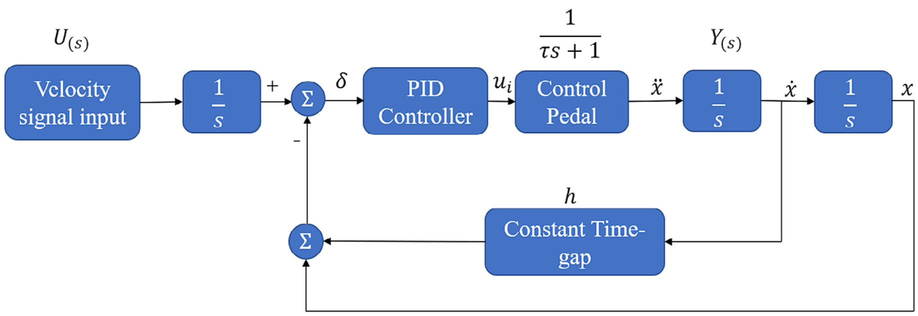

FIGURE 3 PID control for CTH system. CTH, constant time headway.

the vehicle dynamics model as follows:

$$\tau \dot{a}_i(t) + a_i(t) = u_i(t) \tag{6}$$

where $a_i(t)$ is the acceleration of the vehicle i and based on the kinematic equation that $a_i(t) = \dot{v}_i(t)$. Then, for the platoon longitude control, a third-order state space model is as follows:

$$\dot{w}_i(t) = Aw_i(t) + Bu_i(t), i \in N \tag{7}$$

$$w_i(t) = \begin{bmatrix} p_i \\ v_i \\ a_i \end{bmatrix}, A = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -\frac{1}{\tau} \end{bmatrix}, B = \begin{bmatrix} 0 \\ 1 \\ -\frac{1}{\tau} \end{bmatrix} \tag{8}$$

where $w_i(t)$ is the dynamic state (position, velocity and acceleration) of the vehicle in the platooning with respect to the time, τ is the lumped delay coefficient of the vehicle in homogeneous platoon, which characterizes the time from when the vehicle receives the input velocity signal to when it outputs the corresponding velocity. $u_i(t)$ is the input signal after the proposed controller for the vehicle model which can be written in the s-domain as

$$a_i = \ddot{x}_i = \frac{1}{\tau s+1} u_i \tag{9}$$

Figure 3 summarizes the entire control system. It utilizes vehicle model with Equation (8) as the control pedal. In this system block figure, $U(s)$ is the system input in the s-domain, $Y(s)$ is the system velocity output. Thus, the system can create the transfer function such that

$$sY_{(s)} = \left(U_{(s)}\frac{1}{s} - Y_{(s)}\frac{1}{s} - Y_{(s)}h\right)\left(k_i\frac{1}{s} + k_p + k_d s\right)\left(\frac{1}{\tau s+1}\right) \tag{10}$$

and the transfer function $G(s)$ is

$$G_{(s)} = \frac{k_d s^2 + k_p s + k_i}{\tau s^4 + s^3 + k_d(1+h)s^2 + k_i(1+h)} \tag{11}$$

which k_p, k_i and k_d are the parameters of the PID controller. Equation (11) can now be used for stability analysis and is discussed in the next section.

3 | STABILITY ANALYSIS

3.1 | Routh–Hurwitz theorem for system stability

To regulate the constancy of this system, the Routh–Hurwitz theorem [16] was applied with the characteristic polynomial $D_{(s)}$ calculated from the above section as follows:

$$D_{(s)} = s^4 + \frac{1}{\tau}s^3 + \frac{1}{\tau}k_d(1+h)s^2 + \frac{1}{\tau}k_p(1+h)s + \frac{1}{\tau}k_i(1+h) \tag{12}$$

Table 1 shows the Routh form. With the Routh–Hurwitz rule, the result is obtained with $\tau > 0$ and $h > 0$, and the system is fundamentally steady if and only if

$$\begin{cases} k_p > 0 \\ 0 < k_i < k_p\left(k_d - k_p\right)(1+h) \\ k_d > k_p \end{cases} \tag{13}$$

Therefore, Equation (13) is the stability margin for all the parameters of this close-loop controller.

TABLE 1 Routh form.

s^4	1	$\frac{1}{\tau}k_d(1+h)$	$\frac{1}{\tau}k_i(1+h)$
s^3	$\frac{1}{\tau}$	$\frac{1}{\tau}k_p(1+h)$	0
s^2	$\frac{k_d(1+h)-k_p(1+h)}{\tau}$	$\frac{1}{\tau}k_i(1+h)$	
s^1	$\frac{k_p(k_d-k_p)(1+h)-k_i}{\tau(k_d-k_p)}$	0	
s^0	$\frac{1}{\tau}k_i(1+h)$		

3.2 | String stability in designing constant time-headway platoon system

In addition to studying the influence of controller parameters on system stability, in CTH, it is not negligible to study the influence of time gap h on vehicle platoon stability. In [29], string stability occurs in a platoon system when the platooning distraction is not improved. In this case, δ_i and δ_{i-1} are assumed as the spacing errors of the ith and ($i-1$ th) vehicles in the platooning system. $\hat{H}(s)$ is the transfer function for the spacing error in the platooning. Thus

$$\hat{H}(s) = \frac{\delta_i}{\delta_{i-1}} \tag{14}$$

As in [26], to ensure the string is stable, amplitude of $\hat{H}(s)$ must be less than or equal to 1, which $||H(j\omega)||_\infty \leq 1$. Now consider the vehicle model from Equation (9):

$$\tau\dddot{x}_i(t) + \ddot{x}_i(t) = u_i \tag{15}$$

where the vehicle dynamic coefficient $\tau \in (0, \tau_0]$. The typical PID controller is

$$u_i(t) = -\left(k_d\dot{\varepsilon}_i(t) + k_p\delta_i(t) + k_i\int_0^t \delta_i(t)\,dt\right) \tag{16}$$

where k_p, k_i and k_d are positive gains, the system close-loop range has been obtained above. Substituting u_i from the PID controller yields

$$\tau\dddot{x}_i(t) + \ddot{x}_i(t) = -\left(k_d\dot{\varepsilon}_i(t) + k_p\delta_i(t) + k_i\int_0^t \delta_i(t)\,dt\right) \tag{17}$$

It has created Equation (2) based on Figure 2. Then it deviates from this equation, yielding

$$\dot{\varepsilon}_i(t) = \dot{x}_i(t) - \dot{x}_{i-1}(t) \tag{18}$$

Subtracting and substituting from Equation (18) yields

$$\delta_i(t) - \delta_{i-1}(t) = \varepsilon_i(t) - \varepsilon_{i-1}(t) + h\dot{\varepsilon}_i(t) \tag{19}$$

Note that the PID controller is based on the on-board sensors and V2V communication to obtain the information only from its predecessor, i.e., there is no communication with other vehicles or infrastructures. Then the error propagation $\hat{H}(s)$ from vehicle $i-1$ to vehicle i can be described as

$$\frac{\delta_i(s)}{\delta_{i-1}(s)} = \frac{k_d s^2 + k_p s + k_i}{\tau s^4 + s^3 + k_p s^2 + \left(k_d + k_i h + k_p\right)s + k_i} \tag{20}$$

Swaroop's proof [30] for the string stability requires $h \geq 2\tau_0$, and the string stability can be achieved only for a time gap that is two times greater than the system lag. Thus, the string stability is presented when $h \geq 2\tau_0$. References [26, 28, 30] shared the same conclusion on the CTH policy. Therefore, it has known the value range of the controller parameters and the boundary conditions of the stability margin. In the next section, it is introducing a fuzzy controller in this system.

4 | FUZZY CONTROLLER DESIGN IN THE PLATOON SYSTEM

The traditional PID linear controller regulates the PID parameters properly for dissimilar objects for adequate control. However, the traditional PID controller's linear characteristics can only get the desired result close to the working point. When far from the working point, the system output is inferior or even unstable, owing to the non-linearity of the control system. The fuzzy logic process does not purpose to create the mathematical concept of the entire system. The advantage is that the control's dynamic performance can be significantly improved for operation from the working point. Besides, the noise is also reduced significantly, and the system is robust. However, the fuzzy controller is principally a non-linear control technique. The performance of system error elimination is unsatisfactory, and high control accuracy is hard to attain. PID control or fuzzy control did not achieve adequate control results, while the Fuzzy-PID controller is more effective. This combined approach has robust fuzzy control, better dynamic response, fast rise time, slight overshoot, and steady-state precision of the PID controller. There is a relative coefficient between the input and output of the fuzzy controller, precisely the scaling factor used in [32]. This coefficient replicates the close relationship between the fuzzy range and the actual range. For instance, the scopes of the input and output of the fuzzy controller are both [−3, 3], while the actual error range is [−10, 10]; the error rate range is [−100, 100], the control range is [−24, 24], and then it can compute the quantization. The factors are 0.3, 0.03, and 8 for the input/output, error rate, and control, respectively. The scaling factor's selection significantly influences the fuzzy controller's control effect and should be carefully chosen according to the actual condition [32]. The membership functions of the fuzzy sets for the inputs and outputs are proposed in the range of [−1,1]. The function uses an asymmetric triangle with a 50% overlap of the neighbouring membership functions as in Figure 4, where N stands for negative, Z stands for zero, P is positive, B is big, M is medium, and S is small. Thus, NB

TABLE 2 Fuzzy control rules of parameters Δk_p, Δk_i, and Δk_d [31].

	e_c						
e	**NB**	**NM**	**NM**	**Z**	**PS**	**PM**	**PB**
NB	PB NB PS	PN NB NS	PM NM NB	PM NM NB	PS NS NB	ZZNM	ZZPS
NM	PB NB PS	PN NB NS	PM NM NB	PS NS NM	PS NS NM	ZZNS	NSZZ
NS	PM NB Z	PM NM NS	PM NS NM	PS NS NM	Z Z NS	NS PS NS	NS PS Z
Z	PM NM Z	PM NM NS	PS NS NS	Z Z NS	NS PS NS	NM PM NS	NM PM Z
PS	PS NM Z	PS NS Z	Z Z Z	NS PS Z	NS PS Z	NM PM Z	NM PB Z
PM	PS Z PB	Z Z PS	NS PS PS	NM PS PS	NM PM PS	NM PB PS	NB PB PB
PB	ZE ZE PB	ZE ZE PM	NM PS PM	NM PM PM	NM PM PS	NM PB PS	NB PB PB

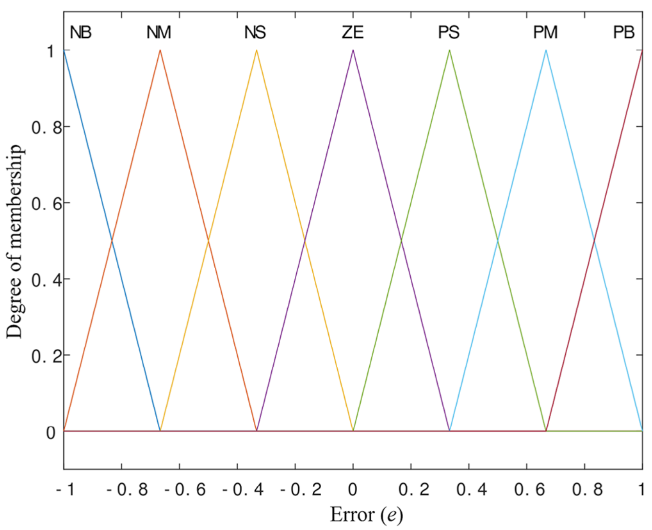

FIGURE 4 Membership function.

stands for negative big, PM stands for positive medium, and so on. In Table 2, based on the error e and the derivative of the error e_c, 49 fuzzy rules are stated. The outputs Δk_p, Δk_i, and Δk_d are defined depending on the inputs e and e_c. For example, the first and second elements in the first column indicate the following:

- If the inputs e and e_c are NB and NB, respectively, the outputs Δk_p, Δk_i, and Δk_d are PB, NB, PS.
- If the inputs e and e_c are NM and NB, respectively, the outputs Δk_p, Δk_i, and Δk_d are PB, NB, PS.

5 | SIMULATION RESULTS FOR FUZZY CONTROLLED PLATOON SYSTEM

In the simulation, MATLAB/Simulink is used to simulate an individual vehicle and the established velocity indication as input for the control. The output is the velocity of the vehicle. In the platoon system, the simulation uses the output vehicle indication ahead of the input. Therefore, the communication is measured 100% consistent. Although the PID control approach is an earlier study, this paper compares this new controller to the classic PID controller, which is a proven technology and more developed technology that is today one of the most extensively used controllers. Other enhanced controllers, such as machine learning and neural networks, require a huge amount of historical data and are difficult to compare to the controller proposed in this research. Furthermore, this controller can be selected using the same control parameters as a regular controller, which better reflects its benefits. In this simulation, the mathematical simulations are used to present this vehicle-following system. Note that the initial location and velocity are together equivalent to zero.

The velocity of the foremost car is

$$v_0 = \begin{cases} 0m/s, \ if\ t \le 10s \\ 2tm/s, \ if\ 10s < t \le 20s \\ 20m/s, \ if\ t > 20s \end{cases} \tag{21}$$

The main goal is to obtain the vehicle's dynamic behaviour, which also considers the communication time delay. The delay is set to $\tau = 0.5$. When setting velocity from 10 to 20 s, its acceleration is $2\mathrm{m/s^2}$. Firstly, the PID controller is designed to use the constancy margin to compute the control advances. This section uses the stability laws from Section 3 in combination with the work from [33] to select parameters. So, the simulation uses the parameters as follows to see the constancy requirements:

$$k_p = 2, \ k_i = 3, \ k_d = 0.5, h = 1.5 \tag{22}$$

By initializing the received velocity of the vehicle in front by the V2V communication, the performance of the traditional PID controller is shown in Figure 5.

In these figures, the range of the spacing error is roughly [−1,1], and the speed error is within [−0.5,0.5]. The proportion parameters of the fuzzy input are set to unity, and the error rate is 0.5. The outputs of the fuzzy controller are the parameters of the PID controller. Since Δk_p, Δk_i, and Δk_d are the output of the fuzzy controller, the total improvements of the fuzzy-PID controller are

$$K_{p,i,d} = \Delta k_{p,i,d} + k_{p,i,d} \tag{23}$$

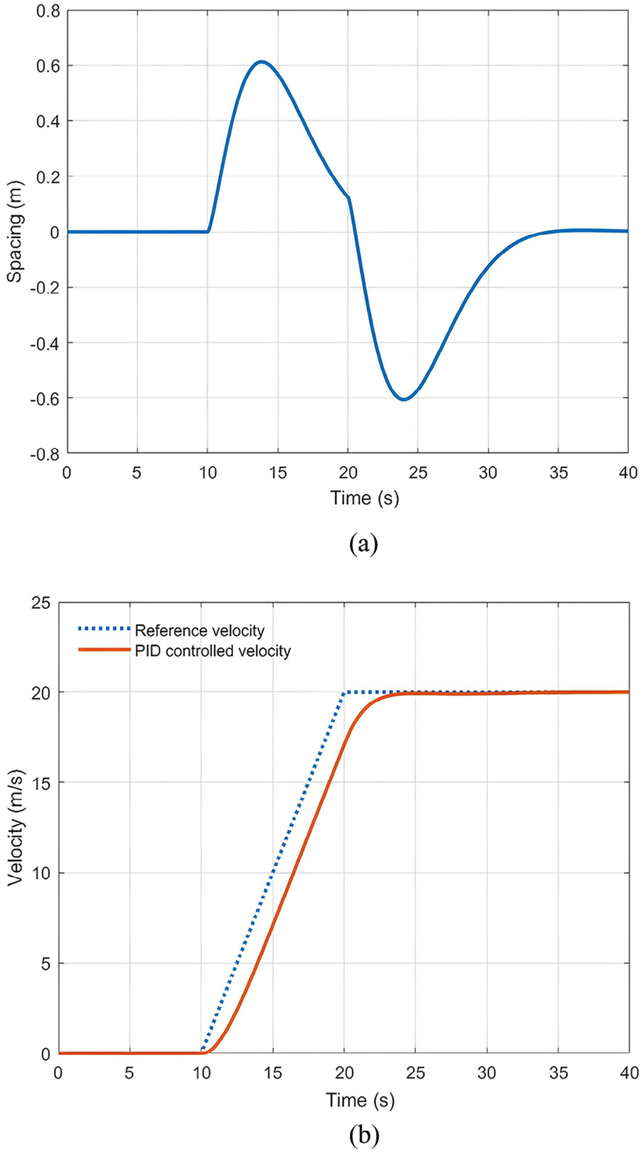

FIGURE 5 Platoon performance under PID controller. (a) Spacing error performance of PID controller, (b) velocity error performance of PID controller.

5.1 | Vehicle platoon performance comparison between PID and Fuzzy-PID controllers

This paper uses the spacing error and the time to the target speed to estimate the controller's ability, as presented in [28]. Figure 6a demonstrates the spacing error difference between the conventional PID control and the enhanced fuzzy-PID control. In this figure, the error bound of the fuzzy-PID controller spacing error is −0.23 to 0.58 m, and that of the conventional PID controller is −0.6 to 0.6 m. The fuzzy-PID controller has a minor spacing error in the upper and lower limits. In other words, the fuzzy control's positive error control output is marginally better than the PID control, but the negative pacing error is significantly increased. This implies that, in the pla-

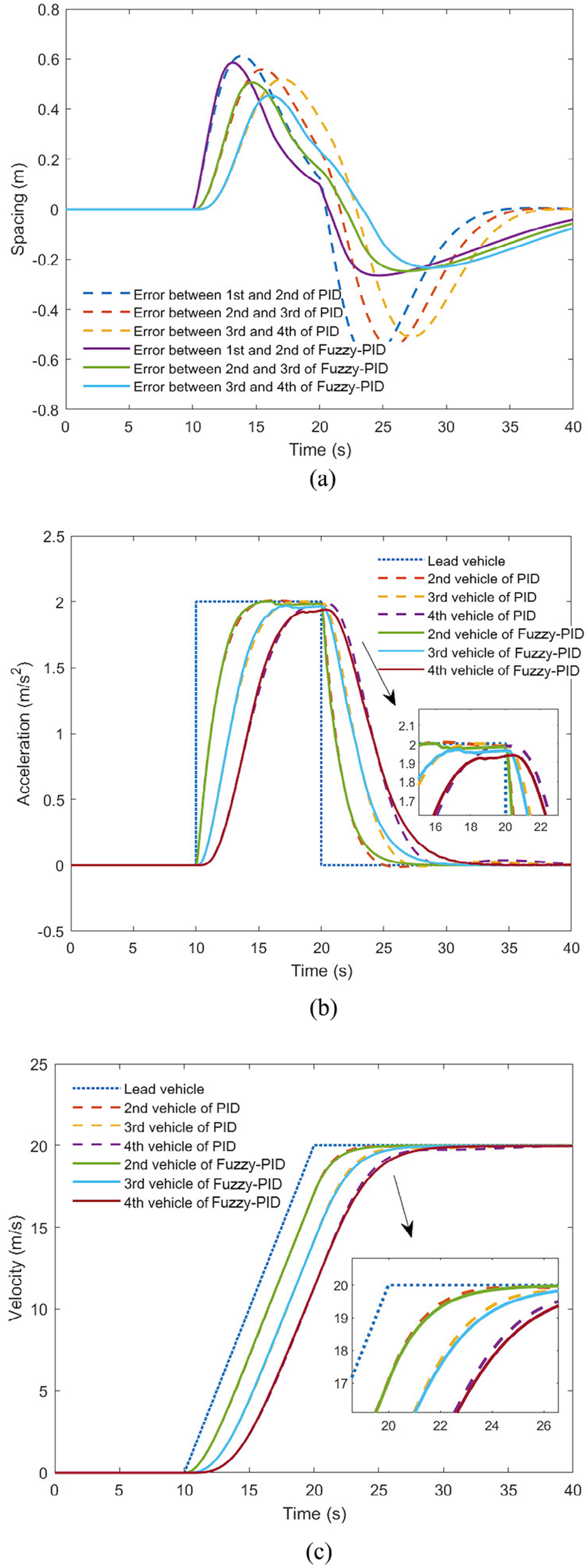

FIGURE 6 Vehicle platoon performance comparison. (a) Space error performance, (b) velocity performance, and (c) acceleration performance.

toon vehicle system, the level of control achieved with the fuzzy controller is inferior to that achieved with the PID controller.

Figures 6b and 6c determine the velocity and the acceleration of the different control methods. The fuzzy-PID controller has a faster growing period and could reach the target speed accurately. PID controller has a more significant time to react to the control changes that are presented in these figures. There are still some drawbacks to the fuzzy-PID controller. Although fuzzy controllers fluctuate more than PID controllers, the fuzzy rules can be changed to adjust the fluctuation of the control.

Based on the designed car-following system as Figure 5, the experiment moves on to the next stage. Of note, the vehicle could only get the dynamic vehicle information of the vehicle in front. The experiment plans for a four-vehicle platoon could only get the dynamic vehicle information of the vehicle in front. The experiment plans for a four-vehicle platoon system. Figure 6a shows the spacing error between neighbouring vehicles as a function of time. As the error passes through the platoon, the spacing error is attenuated each time for both controllers. The figures indicate that the two controllers maintained the car-following system's characteristics, which are in the negative spacing error, and the new controller outperformed the original controller. The outcomes display that the time gap constant h had to satisfy$h \geq 2\tau$ as described in Section 3.2 to maintain string stability. Figures 6b and 6c illustrate the velocity and acceleration from the lead vehicle to the fourth vehicle. The conclusion is that the new controller's oscillation was smaller. Therefore, in a real vehicle platoon, the spacing error decreased more than with the PID controller, increasing traffic efficiency.

5.2 | Parameter τ effects of the vehicle platoon system

The following equations should be introduced before the simulation results can be presented in this section. They express the characteristics of the vehicle platoon system. The most significant expression of vehicle platoon system control is the magnitude of the spacing error in keeping a constant time distance across the platoon, which ideally should be minimized for the best performance [33]. The first is to indicate the overall platoon system's mean space error, which is given by the equation as

$$E_p\ (T) = \frac{\sum_{i=1}^{N} \sum_{k=0}^{T} |\delta_i\ (k)|}{NT} \tag{24}$$

where $E_p(T)$ is the platoon system's mean space error throughout the entire sample time. The platoon size is N, and the instant is k. This equation expresses the average spacing error of all vehicles in the platoon over the full distance. The ideal situation is the less the value, the more stable the platoon. Obviously, only the mean space errors are insufficient. The maximum space error in the vehicle platoon is linked with the collision of the vehicles. Therefore, the following formula will indicate the mean of the maximum error for all vehicles in the platoon,

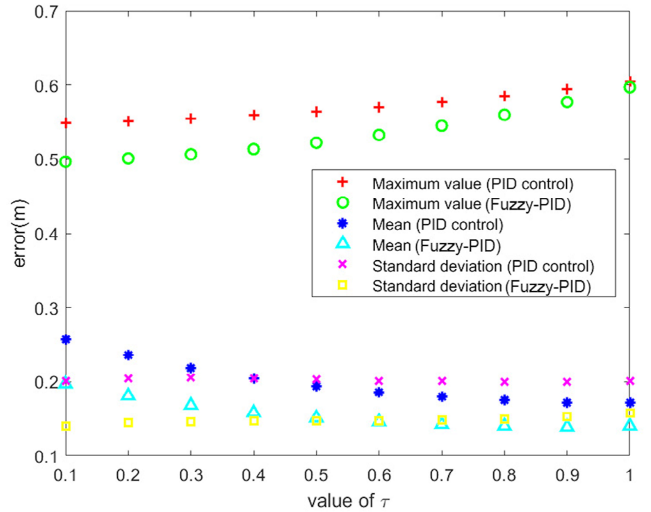

FIGURE 7 Vehicle platoon performance with difference τ.

which is

$$M_p\ (T) = \sum_{i=1}^{N} \frac{1}{N} max \{|\delta_i\ (k)|\} \tag{25}$$

where $M_p(T)$ is the platoon system's maximum mean space error throughout the entire sample time T. The fluctuation of the entire platoon space error is also a required characteristic of the vehicle platooning, expressing the platoon's stability. Considering merely the average error has limitations that prevent the determination of the fluctuation level of the entire platoon space error. Consequently, the following equation is presented in this study, which is

$$\sigma_p\ (T) = \sum_{i=1}^{N} \frac{1}{N} \sqrt{\frac{\sum_{k=0}^{T} (|\delta_i\ (k)| - \mu_i)}{T}} \tag{26}$$

where $\sigma_p(T)$ is the platoon system's overall mean standard deviation throughout the entire sample time T.

According to the above equations (24), (25), and (26), the variance of the new Fuzzy controller and PID in terms of maximum space error $M_p(T)$, average space error $E_p(T)$, and average fluctu-ation $\sigma_p(T)$ for different τ, which is from 0.1 to 1, is demonstrated in Figure 7. In terms of maximum and average space errors, the fuzzy control is significantly superior to the conventional PID control. The average fluctuation is less with the fuzzy control than for the PID control. This demonstrates that the proposed fuzzy control is more stable than the PID control. In summary, the platoon system's fuzzy logic controller had less impact on the dynamic vehicle parameter than the original PID controller.

5.2.1 | Constant communication delay

Figure 8 shows the spacing error and velocity performance under the PID and fuzzy-PID control with a constant 0.5-s

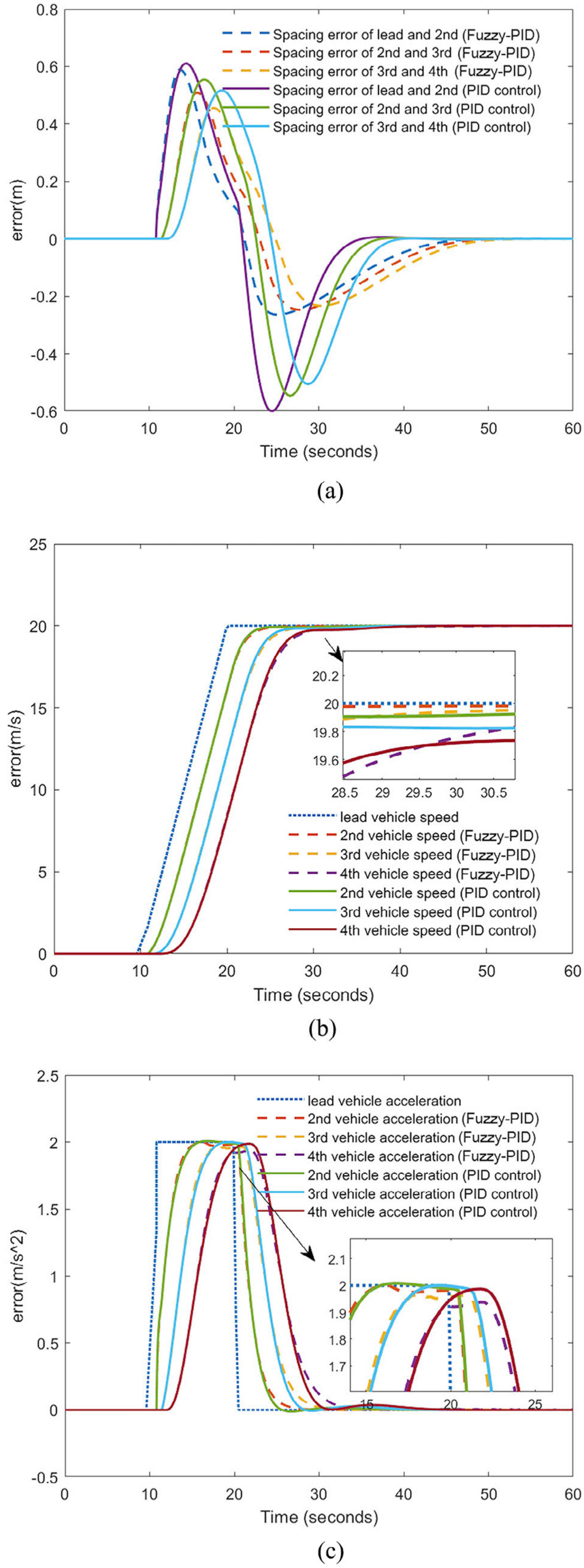

FIGURE 8 Vehicle platoon performance comparison with 0.5-s communication delay. (a) Space error performance with 0.5-s delay, (b) velocity performance with 0.5-s delay, and (c) acceleration performance with 0.5-s delay.

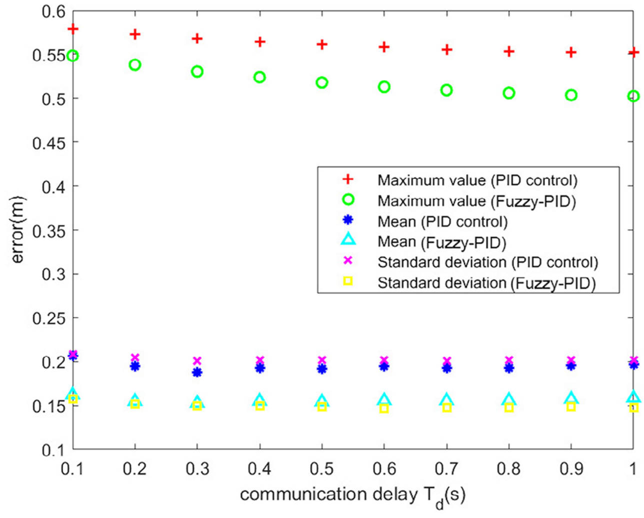

FIGURE 9 Vehicle platoon performance with difference communication delay.

communication delay in a 4-car platoon system. With the same communication scenario, the spacing error decreases through the platoon, indicating string stability. In this simulation, we configure a constant communication delay, ranging from 0.1 s to 1 s, which falls within the typical order and range of communication delays, as previously established in reference [34]. However, the latency of the main V2V communication methods is usually on the order of hundredths of a second (10^{-2} s), such as IEEE802.11P vehicular networks [15]. In this study area, the researchers would like to set a larger communication to test the algorithm. The fuzzy-PID controller has less error band with the communication delay, from −0.27 to 0.6 m vs. −0.6 to 0.6 m. As the previous results have shown, the maximum absolute value of the fuzzy-PID controller's negative spacing errors was significantly reduced.

In Figures 6 and 8, the classification of the communication delay effects of the different controllers is testing. However, the next car has a longer response time than the platoon without a communication delay, so it invests in developing communication technology to reduce communication delays. This test has a profound comprehension of the role of τ in the node vehicle model. It expresses the absolute time from when the entire node vehicle receives the signal when the dynamic vehicle data (acceleration and velocity) matches this signal. As mentioned in [29], this is called a 'lumped' delay. This delay includes the aerodynamic delay, mechanical delay, road friction delay, and communication delay. This paper focuses on the communication delay separately to assess the influence of communication delay on the designed controller.

Figure 9 shows the 4-car platoon performance under the PID control and proposed fuzzy-PID control with variable communication delay. As demonstrated in Figure 9, as the communication delay grows, the average space error range of the platoon system decreases. This is because the communication delay introduced in the simulation allows the controller to have additional time to respond. The controller has increased response time as this is a result of the ideal fixed delay time. This simulation illustrates that the proposed fuzzy control has superior performance even with a fixed communication delay. Therefore, the communication delays consume too much control and are detrimental to the vehicular platoon system's effectiveness and quality. In practice, however, the transmission delay is uncertain. Thus, the effect of random communication delays on vehicle platoon will be discussed in the next section.

5.2.2 | Random communication delay

In the real scenario, the communication delay is not constant. This simulation sets the noise $n(t)$ to be a uniformly distributed series of numbers between zero and one, i.e. $n(t)$ ~N(−0.5,0.5) and the sampling time to $T_s = 0.1$ s [35]. Figure 10 shows the 4-car platoon system with the random communication delay T_d. The overall communication delay fluctuated by 0.5 s per the following equation:

$$T_d = T_c + n(t) \tag{27}$$

where T_c is the constant communication delay of 0.5 s. Different from the previous results, the curves exhibit fluctuation, showing the communication delay effect on this vehicular platoon system. Even with this communication delay, the entire system converges along the platoon, indicating string stability. The distances between the vehicles are small after that, and if the uncertainty of communication delay increased, the entire system would lose string stability. In reality, this phenomenon may be inconvenient for the driver and passenger. However, the velocity response does not indicate this because the simulation is on a highway with a constant speed.

In the case of stable speed, the influence of communication delay is usually not significant. The platoon system just requires the controller to maintain this speed. With the effect of the communication delay, the comparison of these two controllers is similar to the previous conclusion. The error band of the fuzzy-PID controller is less than that of the PID controller, especially with the negative intervehicle spacing error in which the fuzzy-PID controller performance outperforms the PID controller. The velocity figures show identical findings to the previous ones, with slight floating, which is a drawback of PID control.

5.3 | Heterogeneous vehicular platoon under the proposed controller

This section assumes a complex scenario with the vehicular platoon system. In addition to the vehicle platoon described above, cutting edge studies and CACC urgently depend on the suspicion of vehicle-autonomous driveline dynamics (homogeneous platoon) [36]. In reality, the characteristics vary among vehicles. Therefore, a vehicle platoon composed of different types of vehicles is called heterogeneous vehicle platoon (HVP) [37]. In this model, the HVP can be described as node vehi-

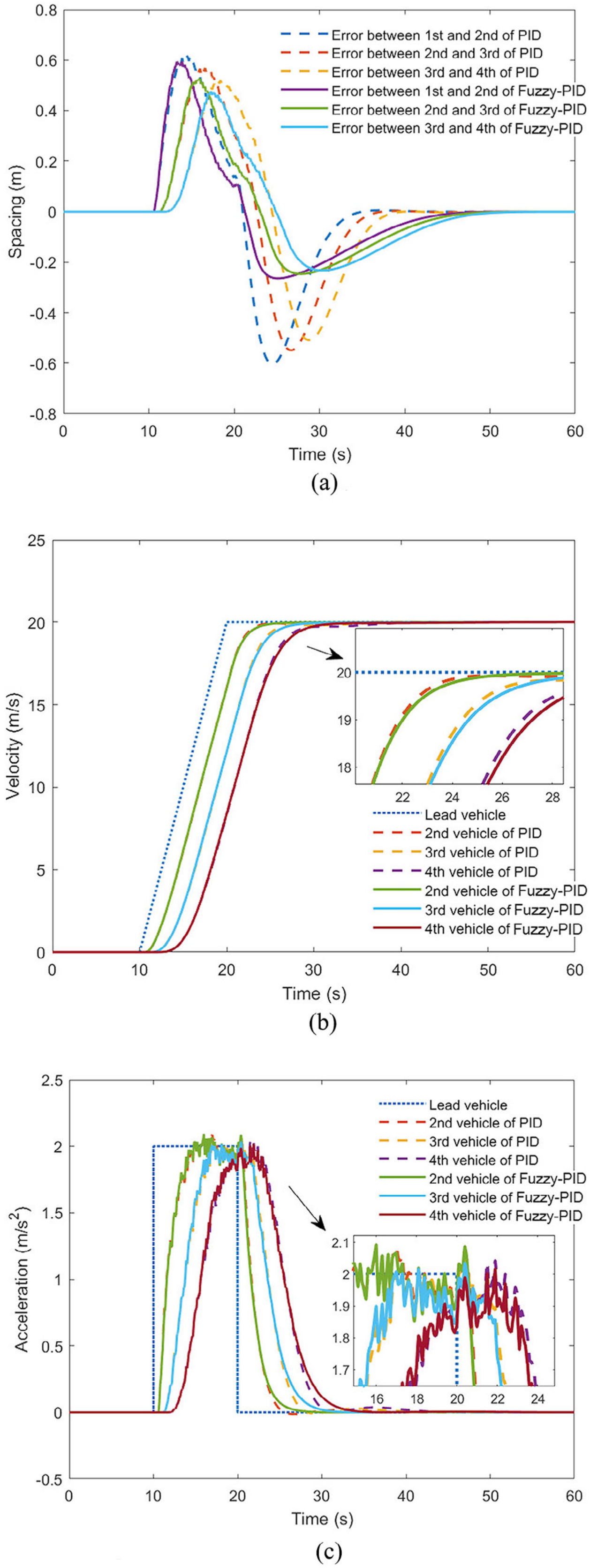

FIGURE 10 Vehicle platoon performance comparison with random communication delay. (a) Space error performance with random delay, (b) velocity performance with random delay, and (c) acceleration performance with random delay.

TABLE 3 Simulation parameters.

Parameters	Value
Lead vehicle	Equation (21)
τ_2	0.5
τ_3	0.8
τ_4	1
T_d	$\sim N(0,1)$ s
T_s	0.1 s

TABLE 4 Simulation parameters.

	œ$_p$ (T)	E$_p$ *(T)*	M$_p$ *(T)*
Vehicle 1 and Vehicle 2	0.1284 m	0.1458 m	0.7332 m
Vehicle 2 and Vehicle 3	0.1334 m	0.1149 m	0.5314 m
Vehicle 3 and Vehicle 4	0.1303 m	0.1115 m	0.5225 m
Platoon system	0.1367 m	0.1307 m	0.5957 m

cles with different parameters, i.e.,τ_i,where i is the vehicle order in the platooning. The simulation coefficients can be set as Table 3.

Utilize Table 3 to set parameters in Matlab/Simulink. This paper refers to the design described in [38] and adds Gaussian noise to the original speed equation (21) with Mean = 0 and Variance = 1. The velocity of the leading vehicle is depicted in Figure 11b. The other simulation results are demonstrated in Figure 11. The goal is to test how the proposed controller works in an HPV. The lead vehicle transfers dynamic information to the second vehicle with the floating noise. The second vehicle transfers dynamic information to the third vehicle, etc. In Figure 11a, the space error of the lead vehicle and the second vehicle fluctuates violently because the signal from the reference lead vehicle is transmitted to the second vehicle with noise and as uncontrolled dynamic data. The spacing error and velocity response of the following vehicles are smooth with the effect of control. In Figure 11c, noise has been added to the ideal acceleration signal in the lead vehicle (not shown in the curve), which results in the second following vehicle experiencing communication delay with a larger acceleration variation. From the results, it is evident that the proposed controller can effectively reduce the acceleration variation as the platoon progresses. In summary, the proposed fuzzy-PID controller has a filtering effect. In other words, this controller is not sensitive to the changing in velocity. The inter-vehicle spacing indicates that if the V2V communication is unstable, stability is difficult for the vehicle platoon.

The performance of the designed HPV is organized according to the equations introduced in this paper and the results have been shown in Table 4. $\sigma_p\ (T)$ is increasing and then reducing due to the introduction of Gaussian noise by the lead vehicle's velocity, which is partially filtered by the controller's action. This is also due to the string stability of the vehicle platoon, which minimizes the space error between vehicles as their number

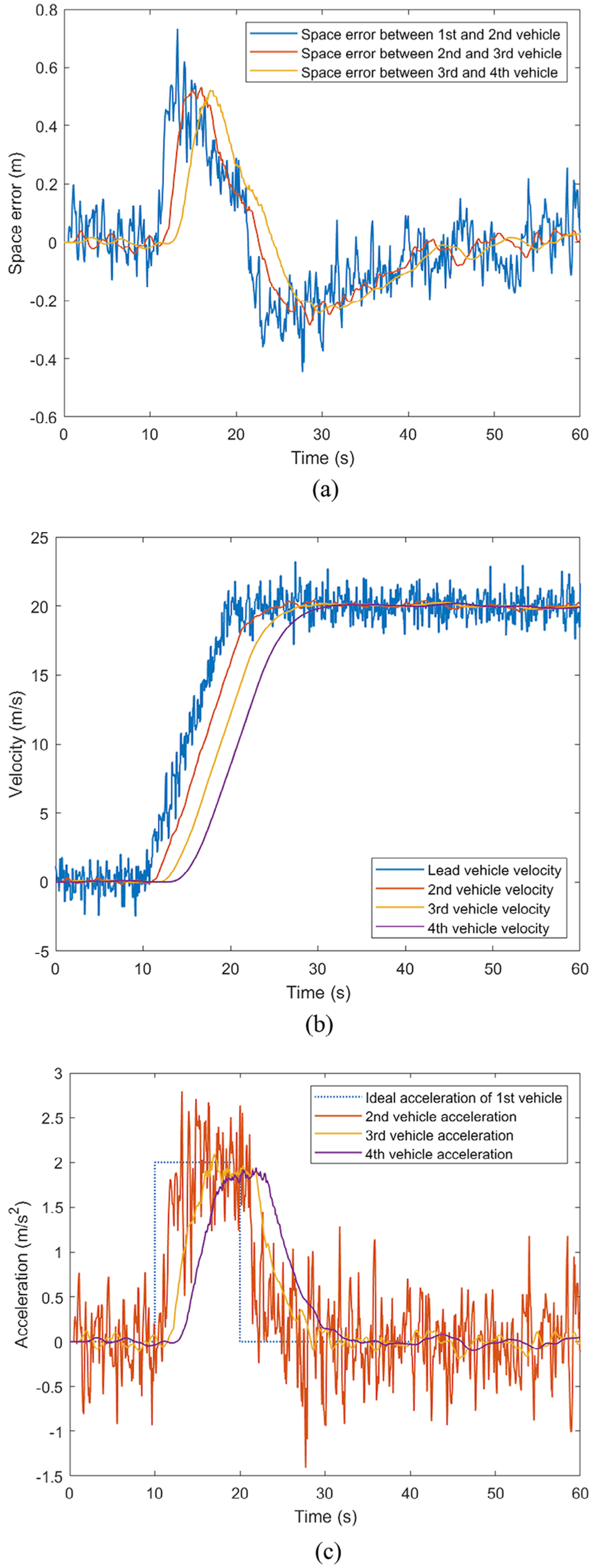

FIGURE 11 Heterogeneous vehicular platoon performance in simulation. (a) Space error performance with 0.5-s delay, (b) velocity performance with 0.5-s delay, and (c) acceleration performance with 0.5-s delay.

increases. Also note that both E_p (T) and M_p (T) decrease when the platoon size of the vehicles grows.

6 | CONCLUSION

In this paper, a novel adaptive fuzzy-PID controller with V2V communication is designed and applied to a car-following system and vehicular platoon system. The developed approach incorporates the close-loop stability and string stability using the Routh–Hurwitz and polynomial methods, which enable designers to select suitable parameter values intuitively. The experimental results demonstrate the superiority of the proposed controller compared to the conventional PID controller, particularly in the negative inter-vehicle spacing error. In addition, new metrics are introduced to evaluate the performance of vehicle platoons under different relevant parameters. Furthermore, the impact of communication latency on the developed controller has been thoroughly investigated, and the results confirm that the string stability and communication stability of the controller is essential for the effectiveness of the vehicle platoon.

In future work, the integration of neural network technology in fuzzy logic control could be studied to transform the fuzzy rules. Additionally, different communication typologies can be evaluated with the fuzzy-PID controller. In addition to the study focusing on the constant time headway approach, the constant distance (CD) approach could also be studied to address the growing demand for more efficient transportation solutions. Moreover, some further investigation can be validated using other advanced vehicle dynamics software such as Carsim.

AUTHOR CONTRIBUTIONS

Handong Li: Conceptualization (lead); writing—original draft (lead); formal analysis (lead); writing—review and editing (equal). **Haimeng Wu**: Methodology; writing—review and editing (lead). **Ishita Gulati**: Software (lead); Validation. **Saleh Ali**: Investigation; review and editing (equal). **Volker Pickert**: Funding Acquisition; Supervision. **Satnam Dlay**: Conceptualization (supporting); Supervision; review and editing (equal).

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author, [H. Wu], upon reasonable request.

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