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Application of Fuzzy Control System to Autonomous Vehicle Platoon

O. Ajayi[1]*, S. M. Yahaya[2], A. Umar[3]
[1,3]Department of Computer Engineering, Ahmadu Bello University, Zaria, Kaduna State – Nigeria,
[2]Department of Electrical/Electronic Engineering, Federal Polytechnic, Bida, Niger State – Nigeria.
*ajayi.oreofe17@gmail.com

Research Article

Abstract

This work aims to explore a simplified approach using the Fuzzy logic control system to control homogeneous vehicle platoon to achieve velocity and string stability while keeping a constant inter-vehicular gap. String stability can be affected by unknown uncertainties such as truck incapacitation, delay of platoons and inability to maintain a constant inter-vehicular gap. This paper addresses the problem of string stability, that is inability of vehicles to maintain a constant inter-vehicular gap. To address this problem, a Fuzzy Logic Cooperative Adaptive Cruise Control scheme was developed to ensure string stability, reduced catch-up time and robust enough to implement different maneuvers such as catch-up strategy, slow-down strategy, and lane-change. A triangular membership function was used for Distance, Velocity and Acceleration. A three-vehicle platoon setup was developed using Fuzzy Logic controller for lead vehicle and two follower vehicles. The lead vehicle is controlled by 5 rules with velocity as input and acceleration output. While the follower vehicles were governed by 2-inputs (distance and velocity) and acceleration as output, having a total of 25 fuzzy rules as captured in the rule matrix lookup table. The platoon system shows a good string stability margin of less than 5 seconds and inter-vehicular distance gap stability of about 2 seconds maximum. The results obtained shows the effectiveness of the developed controller in terms of time taken to attain string stability. The approach developed increases platoon stability at a faster time. The design, development and evaluation are carried out using MATLAB modeling environment.

Keywords
Cooperative Adaptive Cruise Control; Fuzzy; String Stability Vehicle; Platoon.

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1. Introduction

The prospect of road transport has improved with the promises offered by autonomous vehicles as a means for future navigation, increased safety and reduced carbon emission. Significant interest from the industry and academia has continued to achieve enhanced designs and improve existing mechanisms. Many of the current techniques for controlling autonomous vehicles in platoon require complex mathematical computation and in-depth system model level knowledge (Sarker *et al*., 2019).

Vehicle platooning has been hailed as a beneficial methodology of reducing traffic congestion, increasing road use efficiency, improving driver and vehicle safety, while also reducing fuel consumption on long journeys by reducing air drag (Woodman *et al*., 2019).Vehicle Platoon is described as a group of two or more closely spaced vehicles traveling with the same velocity in the same lane, usually platoon consists of N vehicles following a lead vehicle (Tsugawa *et al*., 2016). Vehicle platooning system is the arrangement of multiple vehicles in motion, such that they aim to maintain the same velocity and keep equal distance between adjacent vehicle (Horowitz & Varaiya, 2000).

With increasing advancements in autonomous vehicle technology, there is the need to provide a simplified methodology of adopting platoon management in vehicles, such that they can be easily implemented without the need for detailed and cumbersome mathematical understanding of the system and controller (Qiu *et al*., 2015) especially in nonlinear processes. Autonomous vehicles are predicted to become commercially available in the near future (Ulsoy *et al*., 2012), the need to develop a reliable control system that can be adopted to control the speed of the vehicles in platoon formation is a relevant addition to the capabilities and advantages offered by autonomous driving. Different control strategies are developed to control vehicular acceleration, velocity and lane keeping (Sathiyan *et al*., 2013), however, some of these strategies are cumbersome, require in-depth knowledge of the systems involved, accurate mathematical models of the controllers to effectively establish control. A promising intelligent control strategy that can be adopted for autonomous vehicle platooning, without the need for cumbersome system and controller modeling is Fuzzy Logic Control (FLC) system, where the overall understanding of the operational principle of the system is the major requirement to design a fitting controller.

Conventional vehicular platoon control strategies require good knowledge of the entire system for an efficient model to be developed, where controllers such as Proportional Integral Derivative (PID) are used, robustness and adaptive control capabilities are usually lacking due to the non-linearity and time-varying nature of the entire system. The use of FLC system in this work however, provides a robust control methodology, using a simplified fuzzy rule based on the understanding of vehicular operation and limitation, while also considering dynamic non-linear nature of entire system.

Different attempts at achieving platooning control has been documented in literatures, the methodology adopted by researchers differ, (Fiengo *et al.* 2019) proposed a robust PID based control for leader tracking in autonomous ground vehicles, with uncertainties and communication delays, (Tuchner & Haddad, 2017),presented a laboratory experimental approach to vehicle platoon formation, using interpolation control technique. The main objective of the work presented by the authors is to optimally control the throttle of platooning vehicles with some initial conditions. (Latrech *et al.* 2018) proposed a control system design for vehicle platoon, based on networked integrated Longitudinal and Lateral system. Several of the techniques reported employ cumbersome controller design techniques, albeit acceptable outputs.

2. System Model

Autonomous vehicle platoon system model are described depending on the details required for the model to function. Zheng *et al.* (2015), developed a four-component framework used to describe a vehicle platoon system;

a. Node Dynamics (ND) – This represents the model of the longitudinal response of each vehicle in the Platoon.
b. Information Flow Topology (IFT) – This specifies how a node (vehicle) obtain information about another node.
c. Formation Geometry (FG) – Defines the desired spacing between adjacent vehicles in the platoon.
d. Distributed Controller (DC) – This implements feedback control using information specified by IFT.

Figure 1 provides a visual framework of the model concept.

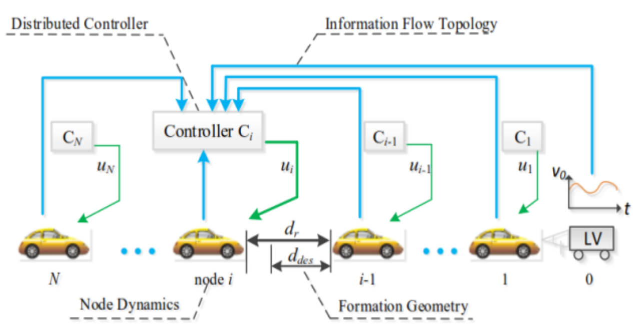

Figure 1: Vehicle Platoon Framework (Li *et al.*, 2017)

From the diagram shown in Figure 1, d_r denotes actual distance between adjacent vehicles, d_{des} represents the desired distance between them, u_i the control signal for the $i-th$ vehicle in the platoon, while C_i represents the control installed on the ith vehicle.

The non-linear dynamic vehicle model is described by (1).

$$\begin{cases} \dot{P}_i(t) = v_i(t) \\ \dfrac{nT_i}{\tau_{w,i}} T_i(t) = m_i v_i(t) + C_{A,i} v_i^2 + m_{i,g} f_{i,} i \in N \\ T_{des,} i(t) = \tau i \dot{T}_i(t) + T_i(t) \end{cases} \quad (1)$$

Where, N is a set of positive integer $N = \{1,2,3, \dots, n\}$, $p_i(t)$ denotes vehicle position within the platoon, $v_i(t)$ represents the velocity of the vehicle, i the ith vehicle in the platoon of $(i \in N)$, and m_i denotes mass of the vehicle, $C_{A,i}$ stands for the parameter of aerodynamics drag, g is acceleration due to gravity, f_i denotes coefficient of rolling resistance (friction), $T_i(t)$ the actual breaking/driving torque also referred to as traction and then $T_{des,i}(t)$ stands for the desired breaking/driving torque of the vehicle. Furthermore, from (2), τ_i is the inertial delay of the vehicle longitudinal dynamics, $r_{w,i}$ stands for the wheel radius, $\eta T_{,i}$ is the mechanical efficiency of the driveline. The position and velocity of lead vehicle denoted by $p_o(t)$ and $v_o(t)$ respectively.

The vehicle model is represented by (2), describing a simplified linearized model.

$$\tau \dddot{x}_i(t) + \ddot{x}_i(t) = u_i \quad (2)$$

Equation (2) is rewritten explicitly as;

$$T_{des,i}(t) = \frac{1}{\eta T_{r,i}} \left(C_{A,i} v_i (2\tau_i \dot{v}_i) + m_i g f + m_i u_i \right) r_{w,i} \quad (3)$$

A third order state space model computed for each vehicle represented by (4) and (5) as:

$$\dot{x}_i(t) = A x_i(t) + B u_i(t),\ i \in N \quad (4)$$

$$x_i(t) = \begin{bmatrix} p_i \\ v_i \\ a_i \end{bmatrix},\ A_i = \begin{bmatrix} 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & -1/\tau \end{bmatrix},\ B_i = \begin{bmatrix} 0 \\ 1 \\ -1/\tau \end{bmatrix} \quad (5)$$

where $x_i(t)$, $[p_i, v_i, a_i]^T$ is the state of node i. The linearized third order model presented in equation (6) (7) has been used in many literatures (Liang & Peng, 1999; Naus *et al.*, 2010; Ploeg *et al.*, 2013) as a basis for theoretical analysis.

To obtain a Time-Distance gap policy for the vehicles in platoon formation, a suitable constant time-gap (CTG) spacing policy is described by in Figure 2 and modeled as in (6)

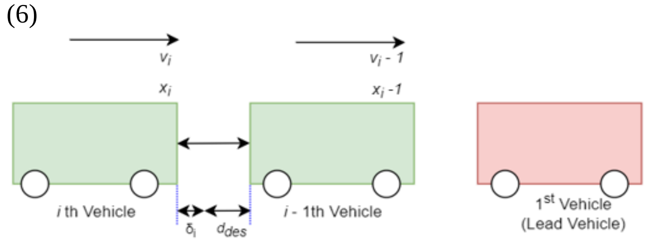

Figure 2: Simplified Platoon Time-Gap Policy

This is a vital measure for platoon stability providing an indication of stability and safety(Jiménez *et al.*, 2016).
The spacing of the vehicles in the platoon is not constant, but depends on the velocity defined as;

$$d_{des} = D_{\min} + t_h x_i \qquad (6)$$

The desired distance spacing is denoted by d_{des}, D_{min} represents the minimum safe distance between the lead and follower vehicle when stopped, t_h is the constant time gap coefficient.
Measured distance between vehicles in the platoon is described as;

$$\varepsilon_i = x_{i-1} - x_i - l_{i-1} \qquad (7)$$

While the spacing error is defined as;

$$\delta_i = \varepsilon_i - d_{des} \qquad (8)$$

A dynamic distance model for each car in the platoon is represented as;

$$D(t+\delta t) = D(t) + v(t)\delta t + \tfrac{1}{2} a(\delta t)^2 \qquad (9)$$

A dynamic model for the corresponding velocity for each at the same time interval is obtained by;

$$V_f = V_i + a(\delta t) \qquad (10)$$

3. Model Development and Simulation

The platoon dynamics, controller development, simulation and performance evaluation was carried out in MATLAB® 2020 software. A dynamic platoon model for each homogenous vehicle partaking in the platoon is represented as in (9).
The parameters of the vehicle used for the model development describes a Honda City 1.5L model car as detailed in Table 1 (Honda, 2020).

Table 1: Technical specification for Honda City 1.5L S model (Honda, 2020)

Parameter	Value
Dimension	L=4442mm, W=1694mm,H=1477mm
Curb Weight **(m)**	1084 kg
Drag Coefficient (**C_d**)	0.30
Rolling Friction Coefficient (**C_r**)	0.0125
Air Resistance (**ρ**)	1.2 kg/m^3
Velocity	0-100 km/h in 10.8 sec. (27.78 m/s)
Max Torque	145 Nm @ 4600 rpm
Acceleration due to gravity (**g**)	9.81 m/s^2
Wheel Radius	0.3048 m

A three-vehicle platoon setup was developed as described by Figure 2. Fuzzy Logic controller for lead vehicle and follower vehicles was developed. The lead vehicle is controlled by 5 rules with velocity as input and acceleration output. While the follower vehicles governed by 2-inputs (distance and velocity) and acceleration as output, having total of 25 fuzzy rules as captured in the rule matrix lookup table presented in Table 2.

Table 2: Fuzzy Logic Control Rule Base Lookup Table

		VELOCITY (Input 2)					
DISTANCE (Input 1)		**TS**	**SL**	**OK**	**FS**	**TF**	**ACCELERATION (Output)**
	TC	DC	DC	DH	DH	DH	
	CL	DC	DC	DC	DC	DH	
	OK	AH	AC	OK	DC	DH	
	FR	AH	AC	AC	AC	AC	
	TF	AH	AH	AH	AC	AC	

4. Results and Discussion

From the dynamic system model developed for the Honda city vehicle, a time response plot was obtained to evaluate the stability of the system model under time response metrics. The plot is presented in Figure 3.

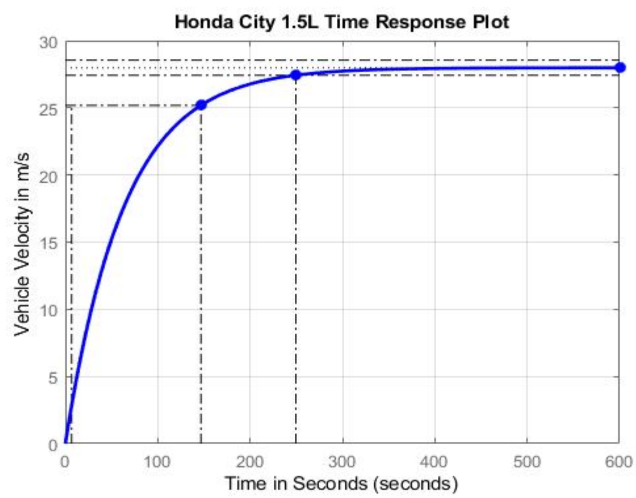

Figure 3: Vehicle Model Time Response Plot

The time response plot of the vehicle model shows that the system is stable, has a rise time of about 140 seconds, a settling time of 249 seconds and steady state value of 28m/s with significant steady state error. The model obtained describes approximately the specification of the vehicle as presented in the manufacturer specification (Honda, 2020) where the speed is expected to reach 100km/h (equivalent to 27.78 m/s) in about 100 seconds. Using the state space model (equation 2) for time response performance analysis produces same result.

4.1 Fuzzy Membership Function

The fuzzy inference system was developed using MATLAB® Fuzzy Logic Designer toolbox. Figure 4 to Figure 6 show Triangular membership function for Distance, Velocity and Acceleration at platoon parameters set as follows;

$$D_b = 10m$$

$$P_V = 15\,m/s$$

$$A_{mx} = 50\,m/s^2$$

$$A_{mn} = -40\,m/s^2$$

where D_b denotes desired inter-vehicular distance, P_v platoon velocity and A_{mn} and A_{mx} denotes maximum and minimum acceleration respectively.

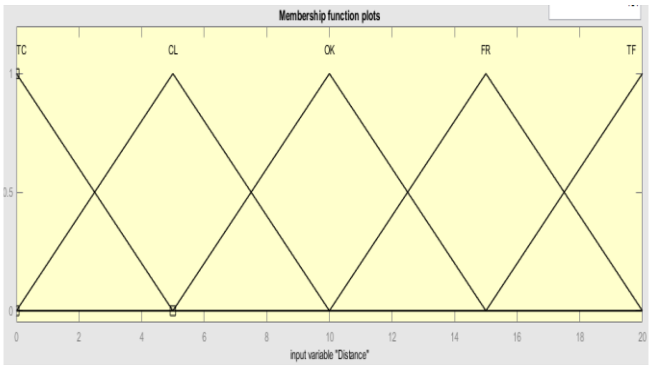

Figure 4: Distance Triangular Membership Function at $D_b = 10m$

With the $D_b = 10m$, the membership function, has a full range of 0-20m and the desired inter-gap is arranged from 5 to 15, with 10m being the actual desired set at Okay, between 0 to 5m is considered Too close, 0 to 10m close, while 10 to 15m is considered as far and 15 to 20m is too far.

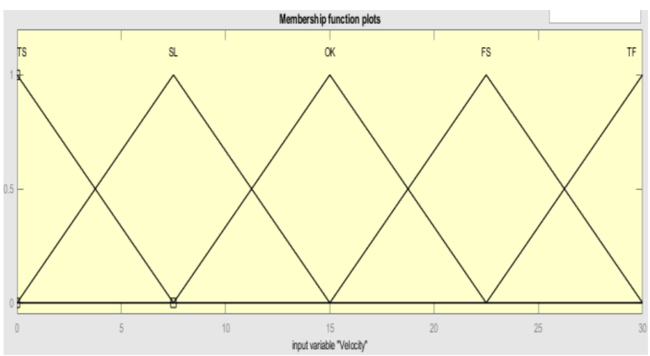

Figure 5: Velocity Membership Function with Desired Velocity $P_V = 15\,m/s$

With velocity input, the desired platoon velocity set at 15 m/s in this instance, Too Slow is considered to be between 0 – 7.5m/s with 0 peak assigned membership function 1, Slow is considered between 0 – 15m/s, 7.5m/s is assigned MF of 1, for the desired velocity assigned membership function of 1, at 15m/s, with OK ranging from between 7.5 to 22.5m/s.

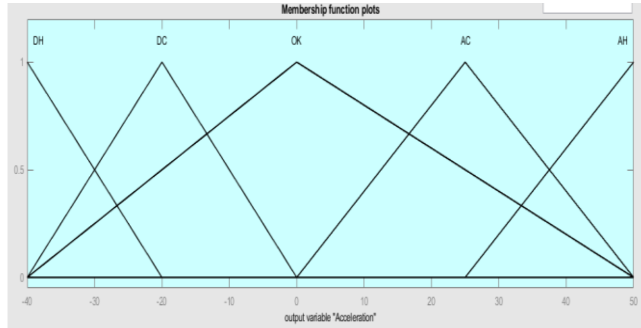

Figure 6: Acceleration (Output) Membership Function

The triangular membership function for the acceleration control as output, the full range from maximum deceleration to maximum acceleration is -40m/s^2 to 50m/s^2. As the velocity and distance of the vehicles in the platoon changes for follower vehicles, the deceleration also changes, depending on the rule base, from Decelerate High assigned -40 to -20m/s^2, while the acceleration is considered Okay at 0m/s^2.

4.2 Simulation Scenarios Performance Evaluation

The stability performance of 3-vehilce platoon is evaluated under the fuzzy control. The time taken for each vehicle to reach the desired velocity and inter-vehicle distance specified is recorded. The performance graph in terms of acceleration is shown in Figure 7, velocity in Figure 8 and distance in Figure 9.

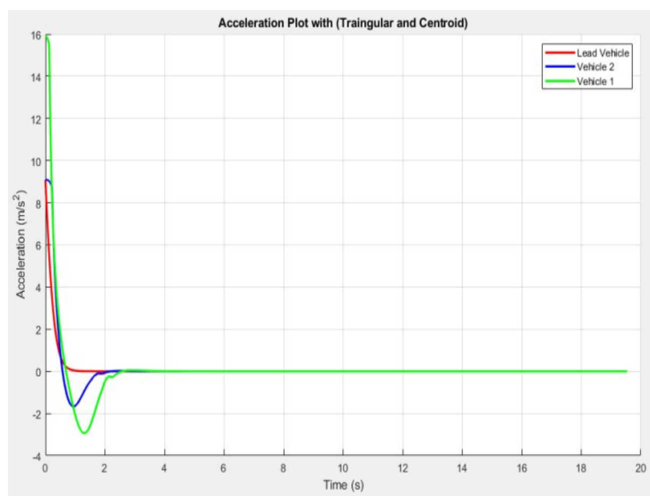

Figure 7: Vehicles Acceleration under Triangular and Centroid Method

The acceleration plot shows the lead vehicle accelerates to about 9m/s^2, and no change in acceleration from about 2 seconds into the journey, while vehicle V2 starts at about 9m/s^2, but decelerates to about 1.8m/s^2 before reaching the required velocity, likewise, the third vehicle has maximum acceleration of 16m/s^2, and maximum deceleration of about 3m/s^2.

The velocity performance for each vehicle in the platoon is shown in Figure 8.

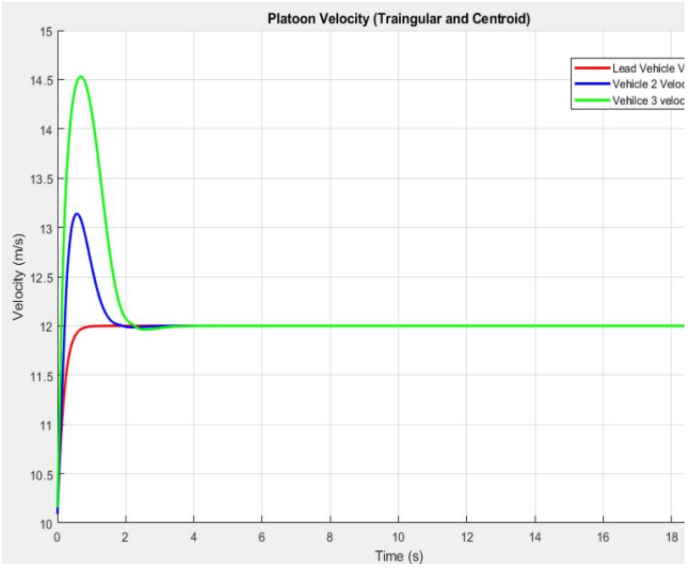

Figure 8: Platoon Vehicles Velocity Performance Graph

The velocity graphs show the behavior of each of the platoon vehicles. As the P_V, is set at 12m/s, it can be observed that the lead vehicle reaches this velocity first at approximately 1.74 seconds, followed by the second vehicle V2 that reaches a velocity of about 13.15m/s then gradually falls to the required platoon velocity at about 3.75 seconds, this increasing velocity also applies to the third platoon vehicle V3, where the velocity reaches about 14.5m/s and attained required platoon velocity after 4.44 seconds.
To understand how the distance gap between each vehicle in the platoon is achieved and maintained, the distance graph is presented in Figure 9.

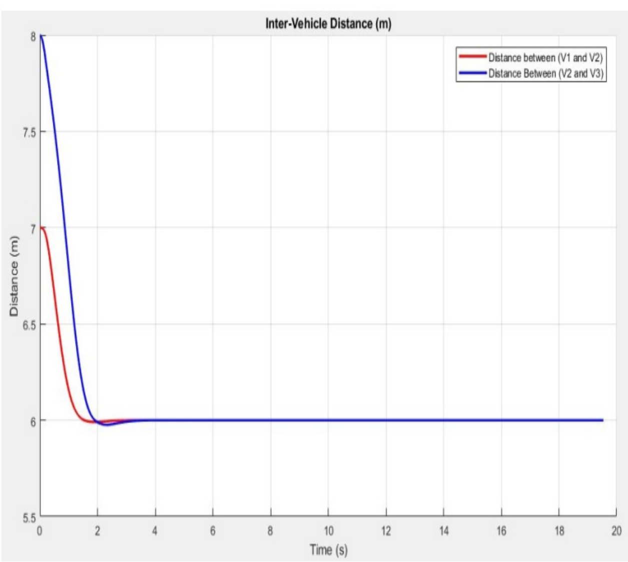

Figure 9: Platoon Inter-Vehicle Distance Plot

Table 3: Platoon Performance Evaluation

From the graphs in Figure 9, it can be observed that the two plots showing the distance between vehicles V1 and V2 and between vehicle V2 and V3, with the distance Db_{12} initially starting at 8m, and finally reaching the desired distance of 6m after 1.51 seconds, likewise Db_{23} starts at 7m and reaches desired distance of 6m at about 1.91 seconds.
A summary of the performance of the vehicular platoon system under fuzzy logic control is presented in Table 3.

Table 3: Platoon Performance Evaluation

Platoon Settlings	Velocity Stablity (*s*)	Distance Stability (*s*)
P_{iv} = 10 m/s P_v = 12 m/s Dbi_{12} = 8 m Dbi_{23} = 7 m Dbp = 6 m	Lead (V1) = 1.74s	
	Vehicle 2 (V2) = 3.75s	V1 and V2 = 1.51s
	Vehicle 3 (V3) = 4.44s	V2 and V3 = 1.90s

From the performance graphs and result summary table presented, it is seen that the platoon attains stability in less than 5 second when the acceleration is set to 50m/s^2 maximum value. The velocity stability measure is significantly fast as well as the distance stability measure. The lead vehicle in the platoon does not attain distance stability as it does not establish a distance-gap with any other vehicle in the platoon.

5. Conclusion

A simplified yet robust vehicle platoon system was developed using Fuzzy logic control which is considered an intelligent control mechanism that provides 3-homogenous autonomous vehicle platooning capabilities without the need for cumbersome model development stages or in-depth system knowledge. The platoon system developed shows a very good string stability margin of less than 5 seconds and inter-vehicular distance gap stability of about 2 seconds maximum. The application of this approach is immense as it provides a platform for further research and integration to existing platooning techniques, without the need for time consuming modification.

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