Centralized and Distributed Control Framework Under Homogeneous and Heterogeneous Platoon

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ABSTRACT Platooning vehicles are beneficial in comfortable driving, safety, and enhanced transportation efficiency. Platooning vehicles with cooperative adaptive cruise control (CACC) mode can potentially result in a small distance between vehicles with assured string stability. This CACC-based platoon control can be realized by vehicle-to-vehicle (V2V) or vehicle-to-everything (V2X) communication between vehicles. In this regard, the distributed control framework is widely used. It claims robustness to communication uncertainties since each vehicle has its controller. With the rapid research on V2X, the centralized framework is another option for the platooning vehicle control framework. This paper investigates and analyzes the centralized and distributed control framework under platoon uncertainty. In most of the papers, the platoon uncertainty is considered as road slope and vehicle dynamics model. In this paper, the platoon uncertainty refers to the platoon types, namely homogeneous and heterogeneous platoon. The analytical platoon stability is studied for both frameworks under different platoon types. It gives the minimum time gap boundary to guarantee string stability for both frameworks. The numerical string stability is performed by the simulation to verify the analytical. The simulation is done using the integrated PreScan and Matlab/Simulink. Then, the robustness of both frameworks is evaluated under latency and packet loss. Finally, the performance of both frameworks is also evaluated.

INDEX TERMS Centralized control framework, cooperative adaptive cruise control, distributed control framework, heterogeneous platoon, homogeneous platoon, string stability.

NOMENCLATURE

| Symbol | Description |
|--------|-------------|
| $P_{\text{max}}$ | Maximum brake pressure. |
| $T_{\text{max}}$ | Maximum throttle. |
| $C_d$ | Air resistance factor. |
| $C_r$ | Rolling resistance coefficient. |
| $A$ | Reference area. |
| $m$ | Total mass of the vehicle. |
| $J_{xx}, J_{yy}, J_{zz}$ | Moment inertia of the vehicle body on x, y, and z-axis. |
| $K_{\text{front}}, K_{\text{rear}}$ | Cornering stiffness of the front and rear tire. |
| $C_{\text{front}}, C_{\text{rear}}$ | Suspension stiffness of the front and rear tire. |
| $D_{\text{front}}, D_{\text{rear}}$ | Damping rate of the front and rear suspension. |
| $h_{\text{CoG}}$ | Height of the center of gravity (CoG). |
| $l_a, l_b$ | Distance between CoG to the front and rear axle. |
| $B_{\text{front}}, B_{\text{rear}}$ | Position of the front and rear bumper respect to the ground. |
| $R_w$ | Tire radius. |
| $l$ | Wheelbase of the vehicle. |
| $g_c, g_f$ | Azimuth and elevation beam angles. |
| $\Delta \theta, \Delta \phi$ | Azimuth and elevation beam angles. |
| $N_{e,\text{min}}$ | Closed throttle torque. |
| $N_{e,\text{des}}$ | Desired engine net torque. |
| $N_{\text{out}}$ | Output of transmission torque. |
| $F_{\text{ext}}$ | External force that works on a longitudinal motion such as drag force, rolling resistance force. |
| $P_b$ | Total brake torque. |
| $P_{b,\text{des}}$ | Desired total brake torque. |
| $b_{p,\text{des}}$ | Desired brake pressure. |
| $Q_{\text{factor}}$ | Conversion factor from brake pressure to brake torque. |

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Platooning vehicles are one of the AVs applications that are attracting many researchers and automotive industries. It promises efficient traffic flow with the concept of reducing the distance between vehicles [1]–[4]. This can be done with utilized the vehicle-to-vehicle (V2V) or vehicle-to-everything (V2X) communication. Therefore, the vehicles should have the cooperative adaptive cruise control (CACC) mode. The vehicles with CACC mode can maintain a small distance between vehicles by absorbing the disturbance from its predecessor. This term is known as string stability and plays a crucial role in platooning vehicles [5]–[13]. The traffic oscillation, also called the slinky effect, causes traffic congestion, uncomfortable driving, traffic fatalities, and increased fuel consumption which is harmful to the environment. If string stability is satisfied then traffic oscillation can be reduced [14]–[18].

Furthermore, platooning vehicles are divided into two types: homogeneous and heterogeneous platoon [4], [19]. Homogeneous platoon assumed that all vehicles in the platoon have similar dynamics and otherwise. Based on [8], [12], [20]–[23], the heterogeneous platoon represented the real traffic condition due to its heterogeneity. However, a homogeneous platoon offered a simple way to analyze the string stability due to its homogeneity [9], [11], [24]. Regardless of the platoon types, there are two control frameworks in platooning vehicles: centralized and distributed/decentralized control frameworks based on the control perspective. The distributed control framework considers that each vehicle in the platoon has its controller. In contrast, the centralized control framework utilizes a single central controller that can be located on the road infrastructure or clouds to handle all vehicles in the platoon [25].

Several works have been done using a distributed control framework to deal with communication drop, latency, cyber-attack, sensor fault, and external disturbance. In fact, these problems hurt string stability. Ploeg et al. investigated the communication drop on the homogeneous platoon using a proportional derivative (PD) controller [26]. They proposed degraded CACC (dCACC) in order to guarantee string stability. Xing et al. used Padé approximation to analyze the actuator and V2V latency on the homogeneous platoon [8]. They found that these delays can be precisely approximated by third-order Padé approximation. Moreover, they employed the PD controller on each vehicle. Besselink and Johansson examined the negative effect of external disturbance subject to string stability on the homogeneous platoon [10]. Kayacan proposed multi-objective H-infinity control to achieve a small time gap intervehicle than traditional H-infinity control on the homogeneous platoon [9]. Dolk et al. utilized an event-triggered control strategy to overcome with latency on the homogeneous platoon [27]. Another work using the event-triggered control strategy is presented by [20] to face communication drop on the heterogeneous platoon. Rödönyi presented heterogeneous platoon and proposed an adaptive spacing policy to improve road capacity [13]. Al-Jhayyish et al. used different feedforward strategies to guarantee string stability when

I. INTRODUCTION
The rapid development of computer science, sensor, and communication technology has led to autonomous vehicles (AVs) with varying degrees of automation entering the market. This has significant implications for road safety, economic and social aspects, efficiency and comfort, and mobility.
the heterogeneous platoon faced the latency [12]. They considered acceleration feedforward, predecessor feedforward, predicted acceleration feedforward, and input signal feedforward as other options. Li et al. analyzed string stability under several information flow topologies (IFT) with complex eigenvalues on the homogenous platoon [28]. They found that the IFT influenced the string stability. Moreover, they also analyzed how every vehicle propagated the disturbance from its predecessor and leader platoon. Xu et al. synthesized a H-infinity controller using Lyapunov–Krasovskii function to overcome with external disturbance and latency on the heterogeneous platoon [21]. In their next work, they integrated longitudinal and lateral controllers [29]. Nunen et al. employed robust model predictive control (MPC) on the heterogeneous platoon [23]. To solve short communication drop, they utilized acceleration information from the MPC prediction horizon that sent before communication drop by the predecessor vehicle. Next, their next work presented an experimental result and numerical string stability [22]. Wu et al. applied an adaptive Kalman filter to estimate the predecessor vehicle acceleration when communication drop [30]. They compared their method with standard Kalman filter and fallback to ACC. As result, they found that the adaptive Kalman filter is more superior through mobile robot experiments. Tian et al. modeled the boundary of latency for V2V communication [11]. Its boundary can help the practitioner to determine the quality of V2V communication. Zeng et al. combined the control system theory and communication network for platooning vehicles [31]. They analyzed the V2V latency with modelled the communication system close to real such as considered the interference effect. Next, the latency is analyzed using stochastic geometry and queuing theory. Finally, they optimized the controller gains subject to communication reliability. The adaptive controller is proposed to face the uncertainty on the heterogeneous platoon because limited knowledge about the vehicle dynamics model as presented in [32].

The other work focused on the vehicle actuator saturation using distributed control which is presented by [33]. They proposed the adaptive platooning strategy for a heterogeneous platoon to maintain internal and string stability under nonidentical vehicle engine saturation. The strategy also succeeds to deal with uncertainty on the vehicle dynamics. In their next work, they proposed an adaptive synchronization protocol for two platoons merging under cyclic communication [34]. The protocol made controller gains of each vehicle changed properly before/during/after merging. The research on platooning vehicles application to improve fuel efficiency is presented by [35], [36]. Moreover, Zhai et al. developed switched control strategy for heterogeneous platoon using distributed model predictive control with multiple objectives (DMPCMO) and safety controller [37]. The DMPCMO is used to achieve platooning vehicles objectives simultaneously. Safety controller served to maintain the safety distance between vehicles when DMPCMO cannot solve the optimization problem. In their next work, they proposed a combination of ecological and platooning vehicles with CACC mode, called Eco-CACC [38]. The Eco-CACC succeeded to improve the efficiency of fuel consumption.

On the contrary, platooning vehicles using a centralized control framework is rarely exploited. The centralized framework relies on a single controller that might compromise the safety and less robust subject to latency [39]. Mazzola et al. presented centralized adaptive cruise control (CdACC) [25]. However, they focused on investigating the communication between a single vehicle and central units. Chen et al. presented a min-max MPC controller to achieve string stability under imperfect vehicles model and sensor delay on the heterogeneous platoon [40]. The central controller is located on the platoon leader. As result, the platoon leader collected all follower information, computed the control signal for the low-level controller, and broadcasted back to all follower using V2V communication. Chehardoli and Ghasemi investigated the centralized and distributed control framework under mix IFT on heterogeneous platoon [41]. The mix IFT has a complex eigenvalue and complicated. As result, they proposed a switching control framework where the framework changed from centralized to distributed or otherwise based on the IFT. Patel et al. investigated the impact of inaccurate localization and vehicle model using robust centralized MPC on mixed platoon scenarios [42]. However, string stability is not addressed. Guan et al. utilized a centralized framework to coordinate the intersection without traffic light using reinforcement learning (RL) [43]. However, the stability of the vehicle cannot be proven. Moreover, they focused on coordination at an intersection, not platooning vehicles.

The primary contribution of this work is to analyze and investigate the centralized and distributed control framework under homogeneous and heterogeneous platoon. As mentioned above, several works of platooning vehicles have been done under homogeneous and heterogeneous platoon. In addition, most of those works used the distributed control framework. The reason is the centralized framework vulnerable to latency and packet loss. Since V2X is rapidly growing, the centralized framework might be a promising solution in the future. As result, both platoon control frameworks offered its own strength and weakness. As far as we are aware, this is the first work that analyze and investigate both platoon control frameworks. In the uncertainty perspective, we considered the homogeneous and heterogeneous platoon as platoon uncertainty while the most of previous works addressed the platoon uncertainty as road slope, imperfect vehicle dynamics model, and so on. In the communication system, instead of using an ideal communication system, we introduced the latency that was modeled with time-varying random numbers and packet loss that modeled with Bernoulli distribution. Another contribution, we analyzed the analytical and numerical string stability for both frameworks. The analytical string stability is analyzed using a linear vehicle dynamics model where is obtained through system identification. Afterward, we derived the inequality condition to guarantee string stability by taking into account the controller filter.
and latency. As result, the time gap boundary subject to latency is obtained. Finally, the time gap from analytical simulation is validated by the numerical string stability through simulation. The simulation is performed by integrating Matlab/Simulink and PreScan.

The remaining section of the paper is organized in this manner. Section II addresses the problem formulation of this paper. Section III discusses the simulation framework for the investigation of platoon control. The PreScan simulation environment is integrated with Matlab/Simulink for the development of a control system and analysis of platoon uncertainty. The centralized and distributed platoon control frameworks are given in Section IV. Then, the upper and lower-level controllers are discussed. The stability analysis is given in Section V. Section VI presented the homogeneous and heterogeneous platoon simulation results under both control frameworks. The conclusion is given in Section VII.

II. PROBLEM FORMULATION

In this section, we first explain the IFT. Next, the spacing policy is presented. The last, the control objectives and constraints are given.

A. INFORMATION FLOW TOPOLOGY

IFT plays an important role in achieving string stability [28]. IFT is defined as the way how the vehicles in the platoon obtain the information from neighbor vehicles. There are several types of IFT as depicted in [28]. The most frequently used is predecessor following (PF) [7]–[12], [18], [20], [22], [23], [27], [30] and predecessor leader following (PLF) [13], [21], [29]. These IFT attracted many researchers because simple to implement and analyze. In this paper, we used PF topology for the distributed framework. On the other hand, we adopted a centralized architecture framework from [40] which also used PF topology. Therefore, each vehicle in the platoon only used its predecessor information.

Remark 1: The centralized and distributed frameworks are able to use all kinds of IFT. However, in this paper, we want to analyze the framework under different platoon types; thus, we employed the same IFT types for the same treatment for both frameworks.

B. SPACING POLICY

Many spacing policies are involved. However, a constant spacing policy (CSP) and a constant time gap (CTG) are frequently used in either real experiments or simulations. In CSP, the distance between vehicles does not change when vehicles accelerate/decelerate. This concept can increase traffic capacity significantly. However, to achieve string stability, CSP required more complex IFT due to its need more than predecessor vehicle information. It can be seen by several researchers that used CSP in [13], [21], [28].

On the contrary, in CTG, the distance between vehicles is a function of velocity. Hence, the distance between vehicles will increase when the vehicle accelerates and otherwise. Its concept similar to the human driver and required a simple IFT to guarantee string stability [4]. The research used CTG can be seen in [7]–[12], [20], [22], [23], [26], [27]. In this paper, we used CTG for both control frameworks.

C. CONTROL OBJECTIVES

The longitudinal controller objectives are divided into the upper-level controller and low-level controller objectives. The upper-level controller should be satisfied in the following condition.

1) Performance: The upper-level controller should track the desired distance between vehicles or reference velocity set by the driver as defined in (1) and (2). Moreover, when a steady-state condition, each vehicle in the platoon should be asymptotic synchronization as defined in (3).

\[ \lim_{t \to \infty} \left| \delta_{v_i}(t) = v_{i-1}(t) - v_i(t) \right| \leq 0 \] (1)

\[ \lim_{t \to \infty} \left| \delta_{a_i}(t) = a_{i-1}(t) - a_i(t) \right| \leq 0 \] (2)

\[ x_{i-1}(t) = p_{i-1}(t) \] (3)

\[ x_{des_i}(t) = x_0 + I_{g_i}v_i(t) \] (4)

2) Comfort: The upper-level controller also responsible for a comfort driving experience. Therefore, it generated the desired acceleration and jerk by following the below constraints.

\[ a_{des_i,\min}(t) \leq a_{des_i}(t) \leq a_{des_i,\max}(t) \] (5)

\[ \dot{a}_{des_i,\min}(t) \leq \dot{a}_{des_i}(t) \leq \dot{a}_{des_i,\max}(t) \] (6)

3) String stability: Given any exogenous disturbance, the upper-level controller should absorb the disturbance from the predecessor vehicles to achieve string stability conditions as defined in (7). The detailed analysis of string stability analysis will be given in Section V.

\[ \|v_i(s)\|_{\infty} \leq 1 \|v_1(s)\|_{\infty} \geq \|v_2(s)\|_{\infty} \geq \cdots \geq \|v_i(s)\|_{\infty} \] (7)

where \( v_i(s) \) is the Laplace transform from \( v_i(t) \), \( v_1(s) \) is the velocity of the leader platoon and \( v_2(s), v_3(s), \cdots, v_i(s) \) are velocity of the follower vehicles.

The main objectives of low-level controller are to track the desired acceleration from the upper-level controller and determine whether the vehicle needs to employ the brake control or throttle control.

III. PRESCAN

PreScan is a software simulation for the automotive industry made by TASS International. It used for testing and validating how robust advanced driver assistance systems (ADAS)
under specific conditions by using either model-in-the-loop (MIL), software-in-the-loop (SIL), hardware-in-the-loop (HIL), vehicle-in-the-loop (VEHIL), or test-drive [44]. PreScan offered users to build a high-fidelity simulation platform through a vast of vehicle models, sensors, weather conditions, environment, road segments and networks, road infrastructures, and road conditions. Moreover, PreScan is integrated with Matlab that provided flexibility for users to design and validate the algorithm, such as decision making, controller, sensor fusion, and data processing. Therefore, used PreScan, we can evaluate different types of sensors and sensor fusion. For instance, we can figure out the preferred sensor combination between radar with a camera or radar with ultrasonic. Furthermore, it allows us to verify our algorithm in certain conditions and validate the robustness of our system. In this paper, the integration between PreScan and Matlab/Simulink is shown in Figure 1.

A. ROAD SEGMENT AND NETWORK
We can import the road information such as road segment and network from OpenStreetMap, OpenDrive Network, GPS navigation device, Google 3D Warehouse, or Google Earth to represent the real road. In this paper, the road segments and networks are imported from the real world using OpenStreetMap. Figure 2 shows the road from OpenStreetMap and the road from PreScan after imported from OpenStreetMap. The red dash line in Figure 2 indicated the part of the road that will be imported into PreScan for our simulation.

B. VEHICLE DYNAMICS
PreScan provided different kinds of vehicle types such as cars, trucks, motorcycles, and trailers. This paper used the Audi A8 sedan for the homogeneous platoon while the heterogeneous platoon used Audi A8 and Toyota Previa. The vehicle dynamics from PreScan consisted of several components such as engine, transmission, final drive ratio, chassis, shift logic, and switch between automatic and manual shift. Table 1 show the vehicle dynamics parameters of each vehicle. Table 2 shows the transmission of vehicles. The shifting strategies, either upshift or downshift for all vehicles, are shown in Figure 3. Figure 4 shows a 3-dimension (3D) map engine of all vehicles.

C. SENSING
PreScan has several types of sensors that can be used for simulation such as camera, fisheye camera,
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TABLE 1. Vehicle dynamics parameters [44].

| Parameters | Value  | Toyota Previa | Units |
|------------|--------|---------------|-------|
| $P_{max}$ | 150 bar | 150 bar | bar   |
| $T_{max}$ | 100 kg  | 100 kg | kg    |
| $C_{r}$   | 0.27   | 0.33 | %     |
| $C_{s}$   | 0.01   | 0.01 | %     |
| $A$       | 2.33 $m^2$ | 2.8 $m^2$ | $m^2$ |
| $m$       | 1820 kg | 1650 kg | kg    |
| $J_{xx}$, $J_{yy}$, $J_{zz}$ | 210, 3278, 3746 | 173, 2884, 3269 | $kg m^2$ |
| $K_{foot}$, $K_{rear}$ | 72653, 121449 | 66479, 110068 | N-rad |
| $C_{foot}$, $C_{rear}$ | 52151, 41400 | 47291, 37520 | N-m |
| $D_{foot}$, $D_{rear}$ | 4980, 3624 | 4515, 3284 | N-s/m |
| $h_{avg}$ | 0.55 | 0.710 | m |
| $l_{a}$, $l_{b}$ | 1.17, 1.77 | 1.16, 1.74 | m |
| $B_{foot}$, $B_{rear}$ | 0.42, 0.42 | 0.49, 0.58 | m |
| $r_{e}$ | 0.34 | 0.32 | m |
| $l$ | 2.94 | 2.9 | m |

* Units details are explained as follows: bar = 100000 pascal, kg = kilogram, % = percentage, m = meter, N = newton, rad = radian, s = second.

TABLE 2. Gears and ratio of the vehicles.

| Gears | Ratio | Toyota Previa |
|-------|-------|---------------|
| -1    | 2.38  | -1 3.83       |
| 0     | 0     | 0             |
| 1     | 2.38  | 1 3.83        |
| 2     | 1.46  | 2 2.05        |
| 3     | 1.05  | 3 1.33        |
| 4     | 0.8   | 4 1.03        |
| 5     | 0.6   | 5 0.82        |

TABLE 3. TIS parameters.

| Parameters | TIS 1 (long-range) | TIS 2 (short-range) | Units |
|------------|--------------------|---------------------|-------|
| Range      | 150                | 30                  | m     |
| Sampling rate | 25              | 25                  | Hz    |
| $\Delta \theta$ | 9              | 80                  | degree |
| $\Delta \phi$ | 9              | 9                   | degree |

Furthermore, we evaluated TIS performance by putting a static object as far as 40 meters from the vehicle. Then, the vehicle moved toward to the object with constant velocity.

Figure 5 shows the TIS performance on the longitudinal measurement. At a distance of 40 meters, the longitudinal range error is around 0.8 meters and gets smaller when close to the object. It correlated to multiplicative noise in range measurement. Hence, it influenced the TIS accuracy when the object far away from the sensor.

Remark 2. All vehicles in the platoon are assumed to have the same sensor parameters.

D. COMMUNICATION V2X
PreScan provided a V2X transceiver that allows V2V and V2I communication. Four types of messages are provided by V2X such as basic safety messages (BSM), decentralized environmental notification messages (DENM), cooperative awareness messages (CAM), and generic. In this paper, every vehicle is mounted with a V2X transceiver with an effective range of 500 meters. Then, the CAM message is chosen as a message format for V2X communication. The readers are invited to read [45] for more detail about CAM message. The V2X latency, in this paper, is modeled by $e^{-\theta/s}$ where
\( \vartheta_i \) can be expressed as time-varying random numbers as defined in (9). \( \max \vartheta_i \) is defined as the maximum V2X latency including queueing, transmission delay, and propagation. The V2X communication for platooning vehicles is standardized by IEEE and 3rd generation partnership project (3GPP). The V2X from IEEE is called IEEE 802.11p/b/d where it is starting point of V2X system such as wireless access in vehicular environment (WAVE) in the US and ITS-G5 in the Europe. Besides, 3GPP Release 15 introduced 5G cellular-V2X (C-V2X) and offered the ultra-reliable low-latency communication (URLLC) service where the end-to-end latency lower than 100ms and reliability 99.999% [46]. The platooning vehicles using 5G C-V2X with URLLC service are successfully implemented in real experiment by [47] with very low latency lower than 10ms. The packet loss is represented by Bernoulli distribution that can be expressed in (10).

\[
\vartheta_i = \text{rand}(0, \max \vartheta_i) 
\]

\[
\rho_i(t) = \begin{cases} 
1 - \beta_i & \text{for } \rho_i(t) = 1 \\
\beta_i & \text{for } \rho_i(t) = 0
\end{cases} 
\]

To implement Bernoulli distribution, we utilized the Communication toolbox from Matlab/Simulink. The packet loss is mostly represented as a function of distance between receiver and transmitter. Nevertheless, the distance between vehicles in the platoon is relatively small. Hence, the packet loss will be more effected by interference and fading effects. Figure 6 shows probability of the number successful CAM messages that is received by neighbor vehicles with \( \beta = 0.3 \) under 100 times simulation. Even if 5G C-V2X with URLLC service has a reliability 99.999% yet it is worth to evaluate our control parameters under low reliability.
taking account when modeling the platoon communication system as presented in [31].

IV. PLATOON CONTROL FRAMEWORK
In this section, we will introduce the distributed and centralized control frameworks. Besides, the upper-level control law is presented. After that, the lower-level controller design and performance are explained. In the end, the explanation of lateral controller is given.

The general upper-level controller is built by feedback and feedforward controllers. In this paper, we implemented the PD controller with a low-pass filter as the feedback controller that expressed as

\[ u_{fb,i}(s) = k_{p,i} + \frac{k_{d,i}s}{T_f,i s + 1} \]  

(11)

\( a_{des,i}(s), u_{fb,i}(s), \) and \( u_{ff,i}(s) \) are the Laplace transform from \( a_{des}(t), u_{fb}(t), \) and \( u_{ff}(t) \). The upper-level controller parameters are shown in Table 4.

**TABLE 4. Upper-level controller parameters.**

| Parameters | Audi A8 | Toyota Previa |
|------------|---------|---------------|
| \( k_p \)   | 0.4     | 0.2           |
| \( k_d \)   | 0.9     | 1.2           |
| \( T_f \)   | 0.262   | 0.201         |

A. DISTRIBUTED CONTROL FRAMEWORK
The architecture of distributed control framework is shown in Figure 7a. In this framework, each vehicle has its controller. When the communication dropout, the vehicle can change to ACC mode. Hence, platoon safety and string stability are guaranteed. However, lack of knowledge of downstream traffic conditions made it challenging to coordinate.

As explained in Section II, each vehicle utilized its predecessor information, PF topology. Moreover, the upper-level controller used acceleration data as feedforward and acceleration confidence data to check the packet loss from the CAM message. The CAM message broadcasted every 10 Hz through V2V. During broadcasting, V2V suffered latency and packet loss that influenced platoon performance. The upper-level controller law of distributed control framework can be expressed as

\[ a_{des,c,i}(s) = u_{fb,i}(s)\delta_{ac}(s) + \rho_{tr,i} \times (u_{ff,i}(s)a_{i-1}(s)e^{-\vartheta_{tr,i}s}) \]  

(12)

where \( a_{i-1} \) is the predecessor vehicle acceleration that obtained from V2X communication, \( \vartheta_{tr} \) is the V2V latency and \( \rho_{tr} \) is the V2V packet loss as defined in (9) and (10).

B. CENTRALIZED CONTROL FRAMEWORK
The architecture of centralized control framework is shown Figure 7b. In this framework, the physical location of the central controller can be one of the vehicles in the platoon (V2V), in the road infrastructure (V2I), or in the cloud (V2C). The vehicle acted like the sensor that provided the measurements then sent it to the central controller. Hence, the computation power on the vehicle can be reduced. Moreover, vehicle or platoon coordination is more manageable. It is because the central controller has a broad knowledge. However, centralized control framework performance relies on communication quality. A large latency, communication drop even a cyber-attack compromised safety aspect. Each vehicle will send a CAM message to the central controller every 10 Hz. Then, the central controller will generate the desired acceleration for each vehicle every 10 Hz. The upper-level controller is not located in the vehicle. As consequence, the desired acceleration suffered latency and packet loss during broadcasting from the central controller to vehicles and otherwise. With the following [40], the upper-level controller of the centralized control framework using PF topology is defined as follows,

\[ a_{des,cc,i}(s) = \rho_{rc,i}e^{-\vartheta_{rc,i}s} \left( \rho_{tr,i}u_{fb,i}(s)\delta_{ac}(s)e^{-\vartheta_{tr,i}s} + \rho_{tr,i}u_{ff,i}(s)a_{i-1}(s)e^{-\vartheta_{tr,i}s} \right) \]  

(13)

where \( \rho_{rc} \) and \( \vartheta_{rc} \) are the packet loss and latency during broadcasting from central controller to vehicles. \( \rho_{tr} \) and \( \vartheta_{tr} \) are the packet loss and latency during broadcasting from vehicles to the central controller. Same as previous, latency and packet loss are defined in (9) and (10).

Remark 4. In this paper, the physical location of the central controller is in the road infrastructure such as the base station or roadside unit. We put several base stations along the road to maintain the connectivity between the platoon and central controller. Moreover, the platoon has the possibility to
connect with two or more base stations, however, the platoon leader will determine which base station should be connected. In our work, the platoon leader will choose the closest base station based on the distance between the platoon leader and base station position. After that, the platoon leader will share the base station ID with its follower.

C. LOWER-LEVEL CONTROLLER

Generally speaking, the low-level controller is designed following the reverse vehicle dynamics principle. The low-level controller is divided into three essential parts: switch logic, throttle controller, and braking controller. In this paper, the lower-level controller design adopted and modified from [48].

1) SWITCHING LOGIC

The main purpose of switching logic is to prevent chattering between throttle and brake, damaging the vehicle component, and uncomfortable driving experience. The switching logic can be expressed as

\[ a_{\text{des},i}(t) \geq a_{\text{res},i}(t) + \chi \text{ for throttle control} \]
\[ a_{\text{des},i}(t) < a_{\text{res},i}(t) - \chi \text{ for brake control} \] (14)

where \( a_{\text{res},i}(t) \) is the residual acceleration when closed-throttle torque and defined by (15). \( \chi \) is the small hysteresis value.

\[ a_{\text{res},i}(t) = \frac{N_{\text{e,min},i} g_{c,i} g_{f,i}}{R_{w,i} m_i} - \frac{F_{\text{ext},i}(t)}{m_i} \] (15)

2) THROTTLE CONTROLLER

The throttle control law is derived under the assumption of no-slip of the driving wheels. The throttle control block diagram can be seen in Figure 8a. The desired engine net torque can be formulated as follows,

\[ N_{\text{e,des},i} = R_{w,i} (m_i a_{\text{des},i} + F_{\text{ext},i}) + P_{b,i} \]
\[ g_{c,i} g_{f,i} \] (16)

\[ a_{\text{des},i}(t) \geq a_{\text{res},i}(t) + \chi \text{ for throttle control} \]
\[ a_{\text{des},i}(t) < a_{\text{res},i}(t) - \chi \text{ for brake control} \] (14)

where \( a_{\text{res},i}(t) \) is the residual acceleration when closed-throttle torque and defined by (15). \( \chi \) is the small hysteresis value.

\[ a_{\text{res},i}(t) = \frac{N_{\text{e,min},i} g_{c,i} g_{f,i}}{R_{w,i} m_i} - \frac{F_{\text{ext},i}(t)}{m_i} \] (15)

3) BRAKING CONTROLLER

The braking controller will convert the desired acceleration into a brake command when the desired acceleration is below the switching logic. The block diagram braking controller can be seen in Figure 8b. The desired brake torque can be formulated as

\[ P_{b,\text{des},i} = -R_{w,i} (m_i a_{\text{des},i} + F_{\text{ext},i}) + g_{c,i} N_{\text{out},i} \] (17)

After that, the desired brake torque needs to convert into desired brake pressure as can be formulated as

\[ b_{p,\text{des},i} = \frac{P_{b,\text{des},i}}{Q_{\text{factor},i}} \] (18)

Figure 9 shows that our low-level controller is able to track the desired acceleration in the presence of noise. However, the delay between desired and actual acceleration occurs yet it is a natural phenomenon. Besides that, the jerk is also small. It indicated that our controller generated smooth acceleration. The jerk of the vehicle strongly related to comfortable of the passenger.

D. LATERAL CONTROLLER

Figure 2 show that the simulation road is not straight. Hence, we utilized the Vehicle dynamics toolbox from Mat-lab/Simulink that provided lateral driver block. It used to track the reference trajectory that has been defined in PreS-can. The output of this block is the desired steering angle. The block implemented the lateral control algorithm that invented by [49]. In this algorithm, the lateral vehicle dynamics is approximated by a single-track bicycle model as expressed by (19).

\[ \dot{x}_{\text{lat},i}(t) = A_{\text{lat},i} x_{\text{lat},i}(t) + B_{\text{lat},i} \delta_{\text{lat},i}(t) \]
\[ \Delta y_{\text{lat},i}(t) = C_{\text{lat},i} x_{\text{lat},i}(t) \] (19)
where

\[
\begin{align*}
    x_{lat,i} &= \begin{bmatrix} \Delta y_{lat,i} \\ \dot{y}_{lat,i} \\ \dot{\psi}_{lat,i} \\ \dot{\psi}_{lat,i} \end{bmatrix}, \\
    A_{lat,i} &= \begin{bmatrix} 0 & 1 & 0 & 0 \\ 0 & A_{12} & 0 & A_{14} \\ 0 & 0 & 0 & 1 \\ 0 & A_{42} & 0 & A_{44} \end{bmatrix}, \\
    B_{lat,i} &= \begin{bmatrix} 0 \\ B_2 \\ 0 \\ B_4 \end{bmatrix}, \\
    C_{lat,i} &= \begin{bmatrix} 1 & 0 & 0 & 0 \end{bmatrix}, \\
    A_{12} &= \frac{2(K_{front,i} + K_{rear,i})}{m_i v_i}, \\
    A_{14} &= \frac{2(l_h K_{rear,i} - l_a K_{front,i})}{m_i v_i}, \\
    A_{42} &= \frac{2(l_h K_{rear,i} - l_a K_{front,i})}{J_{zz,i} v_i}, \\
    A_{44} &= \frac{2(l_h^2 K_{front,i} + l_h^2 K_{rear,i})}{J_{zz,i} v_i}, \\
    B_2 &= \frac{2K_{front,i}}{m_i}, \\
    B_4 &= \frac{2l_h K_{front,i}}{J_{zz,i}}.
\end{align*}
\]

Supposed \( T^* \) is the preview time then (19) yields to

\[
\begin{align*}
    x_{lat,i}(t + T^*_i) &= \Phi_i(T^*_i) x_{lat,i}(t) + k_{1,i}^\delta \delta_{lat,i}(t) \\
    y_{lat,i}(t + T^*_i) &= C_{lat,i} \Phi_i(T^*_i) x_{lat,i}(t) + C_{lat,i} k_{1,i}^\delta \delta_{lat,i}(t)
\end{align*}
\]

(20)

where \( k_{1,i}^\delta \) and \( \Phi_i(T^*_i) \) are defined by

\[
\begin{align*}
    k_{1,i}^\delta &= T^*_i \left[ 1 + \sum_{k=1}^{\infty} \frac{A_{lat,i}(T^*_i)^k}{k!} \right] B_{lat,i} \tag{21} \\
    \Phi_i(T^*_i) &= e^{A_{lat,i}T^*_i} = \left[ I + \sum_{k=1}^{\infty} \frac{A_{lat,i}(T^*_i)^k}{k!} \right]
\end{align*}
\]

From (20), the previewed error between predicted lateral displacement and reference trajectory at \( T^*_i \) seconds ahead can be expressed as follows,

\[
\varepsilon_{lat,i}(t + T^*_i) = \eta_{ref,i}(t + T^*_i) - \Delta y_{lat,i}(t + T^*_i)
\]

(23)

Based on [49], the steering command can be written by

\[
\delta_{lat,i}(t) = \frac{\varepsilon_{lat,i}(t + T^*_i) e^{-\gamma s}}{C_{lat,i} k_{1,i}^\delta (1 - e^{-\gamma s})}
\]

(24)

Figure 10 shows the performance of lateral controller. The vehicle tracked the reference trajectory with small error on the lateral and yaw angle. Moreover, the controller generated smooth steering angle in the presence of noise.

Remark 5. There are two types of controller on the AVs namely, longitudinal controller and lateral controller (steering controller). However, in this paper, our main focused on the longitudinal control aspect. Hence, for the rest section, stability analysis and simulation result focused on the longitudinal control aspect.

Remark 6. As shown in (20), the lateral controller required the model of lateral vehicle dynamics. Therefore, in this paper, we assumed the model is perfectly known as shown in Table. The effect of uncertainty on the lateral controller is out of scope of this paper.

Remark 7. The lateral state, \( x_{lat} \), can be obtained from the fusion of global navigation satellite systems and vehicle acceleration sensor or simultaneous localization and mapping (SLAM).

V. STABILITY ANALYSIS

A. IDENTIFICATION

The purpose of identification is to obtain a linear vehicle dynamics model. It aided us during analyzed the internal and string stability. The longitudinal vehicle dynamics will be approximated by first-order lag with the pure delay (FOLPD) model as shown in (25). Even though the model is simple but it is frequently used to analyze internal and string stability as shown in [8, 9, 11–13, 20, 26, 27, 30].

\[
G_i(s) = \frac{a_i(s)}{a_{des,i}(s)} = \frac{K_{ei} \tau_i s + 1}{\tau_i s + 1} e^{-\psi s}
\]

(25)

Figure 11 shows the process identification. The first step is to collect the input and output of the system. Using the System identification toolbox from Matlab, we obtained the vehicle dynamics model through post processing. Figure 12 shows the comparison between actual and model response for a step input. The model has fit with the actual response as big as 89.68% and 85.45% for Audi A8 and Toyota Previa, respectively. Table 5 shows the parameters of linear vehicle dynamics that is obtained from identification process.
B. INTERNAL STABILITY

The internal stability concerned to individual vehicle stability in the platoon. Given any internal disturbance, it called internal stable if and only if the magnitude of disturbance is yielding smaller over time.

The system in (25) with control law in (12) or (13) is said internal stable if and only if satisfied the inequality in (26).

\[
\alpha_{n,i} > 0, \quad n \in \{0, 1, \ldots, 4\}
\]
\[
\alpha_{1,i} > \alpha_{2,i}, \quad \alpha_{2,i} > \alpha_{3,i}, \quad \alpha_{3,i} > \alpha_{4,i}
\]

where
\[
\alpha_{0,i} = \tau_i T_f, \quad \alpha_1 = \tau_i + T_f, \\
\alpha_{2,i} = 1 + K_T \tau_i (k_T + k_d), \\
\alpha_{3,i} = K_T (k_T T_f + k_p \tau_i + k_d) \quad \alpha_{4,i} = K_T k_p
\]

The detail derivation of (26) can be seen in Appendix.

The inequality in (26) derived under assumption \( t_g, i > 0 \) and \( \phi_i \geq \delta_i \geq 0 \). Moreover, the linear vehicle dynamics parameters as shown in Table 5 only fitted with nonlinear dynamics as big as 89.68% and 85.45% for Audi A8 and Toyota Previa. Therefore, we checked the robustness of our controller. We assumed that the parameters in Table 5 have lower and upper bound as follows,

\[
0.9 \leq K_T, \ i \leq 1.2 \\
0.2 \leq \tau_i \leq 0.5 \\
0.02 \leq \phi_{ci,i} = \phi_i + 2 \delta_i \leq 0.5 \text{ for centralized} \\
0.02 \leq \phi_{di,i} = \phi_i \leq 0.5 \text{ for distributed}
\]

From (27), using Kharitonov theorem [50], we obtained the worst parameters combination namely, 1.2, 0.5, and 0.5 for \( K_T, \tau_i, \) and \( \phi_i \), respectively. The value of parasitic lag between centralized and distributed control frameworks are different. It is because the upper-level controller of centralized control framework is not located in the vehicles. The robustness of the controller parameters in Table 4 is evaluated using the worst parameters. Figure 13 shows all the poles of the closed loop system in the left plane. Bear in mind, Figure 13 is plotted which parasitic lag is modeled by the third-order Padé approximation. According to [8], it can be modeled the delay precisely. Finally, we deduced that the controller parameters in Table 4 are robust under the worst parameters in (27).

C. STRING STABILITY

Besides safety and comfortable driving, the main objective of platooning vehicles guaranteed the string stability. As defined
in (8), it said stable if and only if the magnitude of disturbance from platoon leader decreases along with the platoon. Hence, traffic oscillation can be avoided. Based on [19], string stability can be influenced by the control framework, vehicle dynamics, IFT, latency, packet loss, and spacing policy.

By using PF topology and neglecting the packet loss, the interconnection system can be written in (28) with distributed control framework law in (12) and the vehicle dynamics in (25).

\[
\gamma_{dc,i} = \frac{v_i(s)}{v_{i-1}(s)} = \left(\frac{u_{fb,i}(s)}{s^2 G_1(s)} e^{-\theta_i} \right) G_i(s) H_i(s) \tag{28}
\]

where \(H_i(s) = 1 + \tau_i s\) and \(\theta_i \equiv \theta_{tr,i}\). On the other hand, the centralized framework can be written as follows,

\[
\gamma_{cc,i} = \frac{v_i(s)}{v_{i-1}(s)} = \left(\frac{u_{fb,i}(s)}{s G_i(s) u_{fb,i}(s)} e^{-\theta_i} \right) G_i(s) H_i(s) e^{-2\theta_i} \tag{29}
\]

where \(\theta_i \equiv \theta_{rc,i} \equiv \theta_{tr,i}\). According to [26], the feedforward controller is designed with assumption zero error condition and can be expressed as

\[
u_{fg,i}(s) = (H_i(s) G_i(s))^{-1} \tag{30}
\]

Recall (8), the string stability condition for distributed and centralized framework can be expressed as follows,

\[
ET_f, i + F \geq 0
\]

\[
2\tau_i E t_k \Delta_i (ET_f, i + F) + ET_f^2, i \theta_i (t_i + \Delta_i) + \tau_i \theta_i \Delta_i (F + Et_{g,i}) \geq F \theta_i (\Delta_i (t_{g,i} - T_{f,i}) + T_{f,i} t_{g,i}) + 2E \theta_i (\Delta_i - t_{g,i}) + E \tau_i (2\theta_i - 2 - 2\Delta_i + 5T_{f,i} + 4t_{g,i}) + 2F (t_{g,i} + 2t_i - T_{f,i} - \theta_i) \geq 0 \tag{31}
\]

where \(E = K_{tr,i} K_{fb,i}\) and \(F = K_{tr,i} K_{fd,i}\). The term \(\Delta_i\) and \(\theta_i\) for both frameworks are defined in (32). The detail derivation of (28), (29), and (31) can be seen in Appendix.

\[
\Delta_{dc,i} \cong \varphi_i
\]

\[
\theta_{dc,i} \equiv \theta_{tr,i}
\]

\[
\theta_{cc,i} \equiv 2\varphi_i \equiv \theta_{rc,i} + \theta_{tr,i}
\]

The vehicle dynamics, latency, and controller parameters will influence the string stability in (31). Explicitly, each vehicle will have different time gap in the heterogeneous platoon to guarantee string stability due to heterogeneity. Selecting the value of the filter constant on the PD controller affected the string stability. Moreover, we derived the string stability condition in (31) by taking into account the latency. As result, the relation between the time gap and latency is obtained.

The ideal assumption of string stability condition is expressed by (33).

\[
t_i \geq 0
\]

\[
1 - K_{r,i}^2 \geq 2F (E t_{g,i}) + E^2 (t_{g,i})^2 + 2EF t_{g,i} \geq 2E (1 - K_{r,i}) \tag{33}
\]

The detailed derivation of (33) can be seen in [5], [9], [12], [13], [26]. It is the most used to determine the time gap for each vehicle in the platoon. However, the time gap is determined only based on controller gains and vehicle dynamics. The inequality in (33) is derived under assumptions there are not latency and noise. In practice, the platoon suffered from latency and noise. Therefore, our work in (31) considered the latency and controller filter constant while are neglected in the ideal assumption. For instance, using the controller parameters in Table 4 and the vehicle dynamics in Table 5, we selected the time gap as big as 0.4 seconds for Toyota Previa using distributed control framework. Moreover, we set the latency as big as 0.05 seconds and communication rate as big as 0.1 seconds. The inequality in (33) is satisfied while our work in (31) is not satisfied. Next, we used the Bode and Nyquist diagram to evaluate the inequalities in (31) and (33). Figure 14 shows the Bode and Nyquist diagrams of string stability condition between the ideal assumption and our work. The ideal assumption shows that string stability is stable under the time gap as big as 0.4 seconds. In contrast, our work shows a contrary result due to consider the latency in (31). The unstable string stability is indicated by the magnitude of the Bode diagram where is bigger than 1. Besides, the Nyquist diagram shows that the unstable string stability when the line exceeded the unit circle.

VI. SIMULATION

In this section, we firstly discuss the analytical string stability. Besides, the time gap boundary subject to latency is obtained. Next, the time gap from analytical is validated by numerical string stability through the simulation with Matlab/Simulink and PreScan. After that, we evaluated the robustness of both frameworks under homogeneous and heterogeneous platoon with latency and packet loss. In the end, we investigated the performance of both control frameworks under homogeneous and heterogeneous platoon.
Remark 8. Using low or large communication rates indeed affects string stability. In this paper, string stability analysis and all simulations are conducted under a communication rate 10 Hz while the vehicle system rate is 100 Hz.

A. ANALYTICAL AND NUMERICAL STRING STABILITY

Using control parameters as given in Table 4 and linear vehicles dynamics in Table 5, we calculated the time gap boundary to guarantee string stability condition using the inequality in (31). Figure 15 shows the minimum time gap boundary versus latency. The larger latency required a more extensive time gap for both frameworks. For the centralized control framework, the large latency has a significant impact on the time gap to guarantee string stability. It is reasonable because there is the latency from vehicle to central controller and otherwise. However, at small latency, both frameworks have a similar time gap. Moreover, the controller parameters and vehicle dynamics influenced the minimum time gap
boundary. Therefore, both vehicles have different minimum time gap boundary to guarantee string stability.

Based on Figure 15 or inequality in (31), at latency 0.05 seconds, Audi A8 required the minimum time gap as big as 0.66 seconds and 0.56 seconds for the centralized and distributed control frameworks, respectively. Besides, Toyota Previa required the minimum time gap as big as 0.58 seconds and 0.5 seconds for the centralized and distributed control frameworks. Figure 16 shows when the time gap is chosen less than the minimum time gap then the string stability becomes unstable. In addition, the condition in (8) for Toyota Previa are $\|\gamma_{cc,i}\|_{\infty} = 1$ when time gap is 0.58 seconds, $\|\gamma_{cc,i}\|_{\infty} = 1.0568 \geq 1$ when time gap is 0.48 seconds, $\|\gamma_{dc,i}\|_{\infty} = 1$ when time gap is 0.50 seconds, and $\|\gamma_{dc,i}\|_{\infty} = 1.0277 \geq 1$ when time gap is 0.40 seconds. Moreover, Audi A8 are $\|\gamma_{cc,i}\|_{\infty} = 1$ when time gap is 0.66 seconds, $\|\gamma_{cc,i}\|_{\infty} = 1.0422 \geq 1$ when time gap is 0.56 seconds, $\|\gamma_{dc,i}\|_{\infty} = 1$ when time gap is 0.56 seconds, and $\|\gamma_{dc,i}\|_{\infty} = 1.0299 \geq 1$ when time gap is 0.46 seconds.

Furthermore, we verified the analytical result through the simulation using Matlab/Simulink and PreScan as shown in Figure 1. First, our simulation consisted of six vehicles where the first vehicle is the platoon leader. Next, all vehicles in the homogeneous platoon are Audi A8 while the heterogeneous platoon consisted of Audi A8 and Toyota Previa. After that, the latency is modeled by (9) where the maximum boundary of the latency is 0.05 seconds. Besides, the packet loss probability is modeled by (10) where the packet loss as big as 30%. In other words, the probability of CAM message will be failed to receive by the vehicle as big as 30%. We used the time gap from analytical result that shown in Table 6.

### TABLE 6. Time gap for both frameworks.

| Vehicle       | Time gap (s) | Centralized | Distributed | Inequality in (31) |
|---------------|--------------|-------------|-------------|--------------------|
| Audi A8       | 0.66         | 0.56        | Satisfied   |                    |
|               | 0.56         | 0.46        | Not satisfied |                    |
| Toyota Previa | 0.58         | 0.5         | Satisfied   |                    |
|               | 0.48         | 0.4         | Not satisfied |                    |

**Remark 9.** We utilized the memory technique to avoid the mode of vehicle changed rapidly from CACC to ACC due to packet loss. Therefore, when packet loss, the vehicle utilized the previous packet information.

Figure 17 shows the internal stability of both frameworks under homogeneous and heterogeneous platoon. It can be seen that the spacing errors will converge close to 0. The reason why the spacing errors do not exactly converge to 0 because our simulation is performed in the presence of noise. Besides, the spacing error for distributed control framework converged close to 0 smoother than the centralized control framework. It is because the upper-level controller of distributed control framework is independent from the communication as shown in (12). In contrast, it can be seen in (13) where the upper-level controller law of the centralized control framework...
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**FIGURE 17.** Spacing errors evolution over the time for both frameworks. The centralized control framework is represented by (a) and (b) while distributed control framework is represented by (c) and (d). The solid line represented Audi A8 and dash line represented Toyota Previa.

The distributed framework relied on the communication quality. Overall, the controller parameters in Table 4 are robust subject to latency and packet loss especially for centralized control framework.

Figure 18 shows the centralized framework with the maximum latency as big as 0.05 seconds and the packet loss probability as big as 30%. Figure 18a shows the stable string stability of the homogeneous platoon. The magnitude velocity from the platoon leader to the last vehicle does not magnify. It satisfied with the condition in (8). At 90 seconds, there is a small magnitude. However, it can be accepted due to our sensor has a noise. Figure 18b shows the unstable string stability of the homogeneous platoon. The magnitude velocity from the platoon leader to the last vehicle is getting magnified where violated the condition in (8). It can be seen at 55 seconds. Afterward, there are significant magnitudes at 65 seconds and 90 seconds because the follower vehicles magnify its predecessor velocity. Figure 18c and Figure 18d show stable and unstable string stability of heterogeneous platoon. Figure 19 shows the distributed framework with maximum latency are 0.05 seconds and the probability of packet loss as big as 30%. Figure 19a and Figure 19b shows the stable and unstable string stability of the homogeneous platoon. At 55 seconds, the velocity from the platoon leader to the last vehicle in the platoon is getting smaller. Figure 19c and Figure 19d show stable and unstable string stability. In Figure 19b and Figure 19d show that the follower vehicle does not magnify its leader velocity significantly. However, it can be said unstable based on strict string stability criteria. It correlated to the Bode and Nyquist diagram as shown in Figure 16. The distributed framework using the unstable time gap has a small magnitude on the Bode diagram and a small line exceeded the unit circle (purple line in Figure 16). It means that the magnitude velocity of the platoon leader is not significantly magnified by the follower vehicle as seen in a centralized framework. Finally, we verified that analytical and numerical string stability is met. For instance, if the platoon used the time gap that violated the inequality in (31) then the platoon became unstable string stability as shown in Figure 18 and Figure 19.

**B. ROBUSTNESS AND PERFORMANCE**

The robustness of both frameworks subject to communication quality where is one of the crucial things to discuss. We can observe in Figure 18 and Figure 19 that both frameworks are not lost its string stability as long as using a proper time gap. A proper time gap referred to the time gap that satisfied with the inequality in (31). However, for the same condition, the centralized control framework required more time gap than the decentralized control framework. It has been proven through the analytical in Figure 16 and numerical in Figure 18 and Figure 19. Besides, the internal stability of centralized control framework also influenced by communication quality where it is not occurred in the distributed control framework. It has been proven in Figure 17.
FIGURE 18. Centralized control framework with the maximum latency and packet loss probability as big as 0.05 seconds and 30%. (a) stable and (b) unstable string stability of the homogeneous platoon, (c) stable and (d) unstable string stability of heterogeneous platoon. Solid line represented Audi A8 and dashed line represented Toyota Previa.

FIGURE 19. Distributed control framework with the maximum latency and packet loss probability as big as 0.05 seconds and 30%. (a) stable and (b) unstable string stability of the homogeneous platoon, (c) stable and (d) unstable string stability of heterogeneous platoon. Solid line represented Audi A8 and dashed line represented Toyota Previa.
Moreover, both frameworks performance will be evaluated based on the mean spacing error of all vehicles in the platoon as defined in (34). We used the performance index integral square error (ISE) as defined in (35).

\[
\tilde{\delta}_{sc}(t) = \frac{1}{\sum_{i=2}^{6} \delta_{sc,i}(t)} \sum_{i=2}^{6} \delta_{sc,i}(t) \\
ISE = \int_{0}^{\infty} \tilde{\delta}_{sc}(t)^2 dt
\]  

Figure 20 shows the mean spacing error with latency and packet loss probability as big as 0.05 seconds and 30%, respectively. The distributed control framework shows a smoother line than the centralized control framework. It is also supported through the ISE value in Figure 20. The different ISE value between centralized and distributed control frameworks are around 1 meter. Moreover, both frameworks show that the ISE value between homogeneous and heterogeneous platoon are not much difference. Overall, both frameworks have similar performance.

VII. CONCLUSION
This paper focuses on studied centralized and distributed control frameworks under homogeneous and heterogeneous platoon with addressed string stability criteria. A vehicular platoon simulation is developed in which PreScan facilitated scenario building, vehicle dynamics, sensors, and V2X communication. An identification method is then used to obtain a linear vehicle dynamics model for analytical string stability. As a result, the minimum time gap to guarantee string stability is derived as (31). Then, the numerical string stability is also performed through simulation using the minimum time gap from analytical result. The result confirmed that analytical and numerical string stability met. The robustness of both frameworks is investigated by specifying a maximum latency and packet loss probability as big as 0.05 seconds 30%. In the end, the performance of both frameworks is evaluated using ISE of mean spacing error. This study offers engineers and practitioners to determine which frameworks will be used. In the future, we will investigate the centralized and distributed control frameworks under a mixed platoon. Moreover, the string stability criteria for mixed platoon will be further developed.

APPENDIX
The derivations of equations (26), (28), (29), and (31) are herein.

A. DISTRIBUTED FRAMEWORK
For distributed framework, we substitute (12) into (25) then we obtained

\[
s_{\tau_1}a_i(s) + a_i(s) = K_{r,i}e^{-\theta_{r,i}} [u_{b,i}(s)\delta_{sc,i}(s) + (u_{g,i}a_{i-1}(s))e^{-\theta_{g,i}}] \]

(36)

If \(q_i(s) = sv_i(s), a_i-1(s) = sv_{i-1}(s), \theta_{i} \equiv \theta_{r,i}, \) and \(\delta_{sc,i}(s) = \frac{v_{i-1}(s)-v_i(s)}{s} - t_{r,i}v_i(s)\) then (36) can be written as follows,

\[
s^3 \tau_i v_i(s) + s^2 v_i(s) + sK_{r,i}e^{-\theta_{r,i}}u_{b,i}(s)t_{g,i}v_i(s) + K_{r,i}e^{-\theta_{r,i}}u_{b,i}(s)v_i(s) = s^2 K_{r,i}e^{-\theta_{r,i}}u_{g,i}(s)e^{-\theta_{r,i}}v_{i-1} + K_{r,i}e^{-\theta_{r,i}}u_{b,i}(s)v_{i-1}(s)\]

(37)

From (37), we can obtain the relation between \(v_i(s)\) and \(v_{i-1}(s)\) as expressed by

\[
v_i(s) = \frac{v_{i-1}(s)}{s^2 + K_{r,i}e^{-\theta_{r,i}}u_{b,i}(s)(s\tau_{i} + 1) + K_{r,i}e^{-\theta_{r,i}}u_{b,i}(s)(s\tau_{i} + 1)}
\]

(38)

If we defined \(H_i(s) = t_{g,i}s + 1\) and equation (38) divided by \((s\tau_{i} + 1)\) thus we obtained as show in (28).

\[
v_i(s) = \frac{v_{i-1}(s)}{s^2 + G(s)u_{b,i}(s)H_i(s)}
\]
**B. CENTRALIZED FRAMEWORK**

For centralized framework, we substitute (13) into (25), then we have

\[
s_t \alpha_i(s) + a_i(s) = K_t e^{-\omega t} \\
\left[ e^{-\theta_{rc,i}} (u_{\theta_i}(s) \delta_{sc,i}(s)e^{-\theta_{tr,i}} + u_{tr,i}(s)a_{i-1}(s)e^{-\theta_{tr,i}}) \right]
\]

Again, we assumed \( a_i(s) = sv_i(s), a_{i-1}(s) = sv_{i-1}(s), \delta_{sc,i}(s) = \frac{v_i(t) - v(s)}{s}, \theta_i \equiv \theta_{rc,i} \equiv \theta_{tr,i} \) or \( 2\theta_i \equiv \theta_{rc,i} \equiv \theta_{tr,i} \) then we obtained

\[
s^3 \tau_i v_i(s) + s^2 v_i(s) + s K_t e^{-\omega t} e^{-2\theta t} u_{\theta_i}(s) H_i(s) v_i(s) \\
+ K_t e^{-\omega t} e^{-2\theta t} u_{\theta_i}(s) v_i(s) = s^2 K_t e^{-\omega t} e^{-2\theta t} u_{\theta_i}(s) v_i(s) \\
+ u_{tr,i}(s)v_{i-1}(s)K_t e^{-\omega t} e^{-2\theta t} u_{\theta_i}(s)v_{i-1}(s)
\]

(40)

The relation between \( v_i(s) \) and \( v_{i-1}(s) \) is defined as follows,

\[
\frac{v_i(s)}{v_{i-1}(s)} = \frac{\left( u_{\theta_i}(s) + s^2 u_{tr,i}(s) \right) K_t e^{-\omega t} e^{-2\theta t} G_i(s)}{s^2 + G_i(s)u_{\theta_i}(s)H_i(s)e^{-2\theta t}}
\]

(41)

**C. INTERNAL STABILITY**

From (38) and (41), if we neglected all delay, \( \varphi_i \equiv \theta_i \equiv 0 \), and \( t_{g,i} > 0 \) then the closed loop system both decentralized and centralized can be written as,

\[
\frac{v_i(s)}{v_{i-1}(s)} = \frac{\left( u_{\theta_i}(s) + s^2 u_{tr,i}(s) \right) K_t}{s^2 (s\tau_t + 1) + K_t u_{\theta_i}(s) (s\tau_{g,i} + 1)}
\]

(42)

The characteristic equation of (42) is given by (43).

\[
s^2 (s\tau_t + 1) + K_t u_{\theta_i}(s) (s\tau_{g,i} + 1) = 0 \\
a_0 s^4 + a_1 s^3 + a_2 s^2 + a_3 s + a_4 = 0
\]

(43)

where,

\[
a_{0,i} = \tau_i \tau_{f,i}, \quad a_{1,i} = \tau_i + \tau_{f,i} \\
a_{2,i} = 1 + K_t \tau_i \tau_{g,i} (k_{p,i} \tau_{f,i} + k_{d,i}) \\
a_{3,i} = K_t k_{p,i} \tau_{f,i} (k_{p,i} \tau_{f,i} + k_{d,i}) \\
a_{4,i} = K_t k_{p,i}
\]

Using Routh-Hurwitz criterion, the closed loop system said stable if and only if satisfied the following condition.

\[
a_{n,i} > 0, \quad n \in \{0, 1, \ldots, 4\} \\
a_{1,i} a_{2,i} a_{3,i} > a_0 a_3^2 + a_2^2 a_4
\]

**D. STRING STABILITY CONDITION**

If we defined \( \Delta_i \equiv \varphi_i \) and \( \theta_i \equiv \theta_{tr,i} \) on (38), we have

\[
\frac{v_i(s)}{v_{i-1}(s)} = \frac{\left( u_{\theta_i}(s) + s^2 u_{tr,i}(s) \right) K_t e^{-\omega t}}{s^2 (s\tau_t + 1) + u_{\theta_i}(s) (s\tau_{g,i} + 1) K_t e^{-\omega t}}
\]

(44)

In centralized framework, if \( \Delta_i \equiv \varphi_i + 2\theta_i \) and \( \theta_i \equiv \theta_{rc,i} \), then (41) can be written as

\[
\frac{v_i(s)}{v_{i-1}(s)} = \frac{\left( u_{\theta_i}(s) + s^2 u_{tr,i}(s) \right) K_t e^{-\omega t}}{s^2 (s\tau_t + 1) + u_{\theta_i}(s) (s\tau_{g,i} + 1) K_t e^{-\omega t}}
\]

(45)

If \( u_{tr,i}(s) \) is defined as shown in (30) then (44) and (45) will have same form that can be written as follows,

\[
\frac{v_i(s)}{v_{i-1}(s)} = \frac{u_{\theta_i}(s)K_t e^{-\omega t}}{s^2 (s\tau_t + 1) + u_{\theta_i}(s) (s\tau_{g,i} + 1) K_t e^{-\omega t}}
\]

(46)

where \( \Delta_i \equiv \varphi_i \) and \( \theta_i \equiv \theta_{tr,i} \) for distributed framework and, \( \Delta_i \equiv \varphi_i + 2\theta_i \) and \( \theta_i \equiv \theta_{rc,i} \) for centralized framework. We can see that the different between distributed and centralized framework in the term of \( \Delta_i \) and \( \theta_i \). Next, substitute (11) into (46), if \( s = j\omega \) then we have,

\[
\frac{v_i(j\omega)}{v_{i-1}(j\omega)} = E e^{-\Delta_i \omega} + \frac{\left( j\omega \right)^2 \left( j\omega \tau_t + 1 \right) e^{-\theta_{\omega,j}}}{j\omega \left( j\omega \tau_t + 1 \right) + 1} e^{-\Delta_i \omega}
\]

(47)

where \( E = K_t k_{p,i} \) and \( F = K_t k_{d,i} \).

Based on (8), the string stability condition on (47) can be written as follows,

\[
\| Y_i(\omega) \|_{\infty} = \frac{\| v_i(\omega) \|_{\infty}}{\| v_{i-1}(\omega) \|_{\infty}} = \frac{\| NUM \|_{\infty}}{\| DEN \|_{\infty}} \leq 1
\]

(48)

**NUM and DEN on (48) are defined in the following,**

\[
NUM = (j\omega)^2 \left( j\omega \tau_t + 1 \right) \left( j\omega \tau_{f,i} + 1 \right) e^{-\theta_{\omega,j}} + j\omega F \left( j\omega \tau_{g,i} + 1 \right) e^{-\Delta_{\omega,j}} + E \left( j\omega \tau_{f,i} + 1 \right)
\]

\[
\times \left( j\omega \tau_{g,i} + 1 \right) e^{-\Delta_{\omega,j}}
\]

(49)

\[
DEN = (j\omega)^3 \tau_i \left( j\omega \tau_{f,i} + 1 \right) + (j\omega)^2 \left( j\omega \tau_{f,i} + 1 \right) e^{-\Delta_{\omega,j}} + E \left( j\omega \tau_{f,i} + 1 \right)
\]

\[
\times \left( j\omega \tau_{g,i} + 1 \right) e^{-\Delta_{\omega,j}}
\]

(50)

If we assumed \( e^{-\omega \tau} = \cos(\omega) - j \sin(\omega) \), the expanded on (49) is given as follows,

\[
NUM = X_{num} + jY_{num}
\]

(51)

where

\[
X_{num} = \left( E - \omega^2 (\tau_{g,i} + \tau_{f,i}) + 1 + \omega^3 \tau_i \right) F(\Delta_{\omega}) + \omega(E(\tau_{f,i} + \tau_{g,i}) + F) \sin(\Delta_{\omega}) - \omega^3 (\tau_i + \tau_{f,i}) \sin(\theta_{\omega})
\]
\[ Y_{num} = \omega^2 (E(T_f,i + \theta) + F) \sin(\Delta_i \omega) - E \sin(\Delta_i \omega) + \omega(E(T_f,i + \theta) + F) \cos(\Delta_i \omega) - \omega^3 (\tau_i + T_f,i) \cos(\theta_i) + \omega^2(1 - \tau_i T_f,i^2) \sin(\theta_i) \]

While the expanded on (50) is given as follows,

\[
D E N = X_{den} + J Y_{den} \tag{52}
\]

where

\[ X_{den} = \omega^2(\tau_i T_f,i - 1) + (E - \theta_i)(E(T_f,i + F) \omega^2) \cos(\Delta_i \omega) + \omega(E(T_f,i + \theta_i) + F) \sin(\Delta_i \omega) \]

\[ Y_{den} = -\omega^3 (\tau_i + T_f,i + (\theta_i)(E(T_f,i + F) \omega^2 - E) \sin(\Delta_i \omega) + \omega(E(T_f,i + \theta_i) + F) \cos(\Delta_i \omega) \]

We applied norm on (51) and (52) then assumed \( \sin(\theta_i) \approx \theta_i \), \( \sin(\Delta_i \omega) \approx \Delta_i \omega \), \( \cos(\theta_i) \approx 1 \), and \( \cos(\Delta_i \omega) \approx 1 \).

Hence, we have

\[ \|DEN\|_\infty - \|NUM\|_\infty \geq 0 \]

\[ 2\theta_i \tau_i T_f,i \Delta_i (E(T_f,i + F) \omega^8 + 2(\theta_i \tau_i \Delta_i (E(T_f,i + F) + E T_f,i \theta_i (1 + \Delta_i) - E \theta_i (T_f,i - \theta_i) - F T_f,i \theta_i) + \tau_i \theta_i (F + E T_g,i) \omega^6 + 2 \theta_i (\Delta_i - T_g,i) + E T_f(2\theta_i - 2 - 2 \Delta_i + 5 T_f,i + 4 T_g,i) + 2 F(\theta_g,i + 2 \tau_i - T_f,i - \theta_i) \omega^4 \geq 0 \tag{53} \]

or it can be simplified as follows,

\[ E T_f,i + F \geq 0 \]

\[ 2\theta_i \tau_i \Delta_i (E(T_f,i + F) + E T_f,i \theta_i (1 + \Delta_i) + \tau_i \theta_i (F + E T_g,i) \geq F \theta_i (1 + \Delta_i - T_g,i - T_f,i + \theta_i) + E T_f(\theta_i - 2 - 2 \Delta_i + 5 T_f,i + 4 T_g,i) + 2 F(\theta_g,i + 2 \tau_i - T_f,i - \theta_i) \geq 0 \]

REFERENCES

[1] Y. Zhou, S. Ahn, M. Chitturi, and D. A. Noyce, “Rolling horizon stochastic optimal control strategy for ACC and CACC under uncertainty,” Transp. Res. C, Emerg. Technol., vol. 83, pp. 61–76, Oct. 2017.

[2] P. Wang, B. Di, H. Zhang, K. Bian, and L. Song, “Platoon cooperation in cellular V2X networks for 5G and beyond,” IEEE Wireless Commun., vol. 18, no. 8, pp. 3919–3932, Aug. 2019.

[3] S. Maiti, S. Winter, L. Kulik, and S. Sarkar, “The impact of flexible platoon formation operations,” IEEE Trans. Intell. Vehicles, vol. 5, no. 2, pp. 229–239, Jun. 2020.

[4] S. E. Shladover, C. Nowakowski, X.-Y. Lu, and R. Ferlis, “Cooperative adaptive cruise control: Definitions and operating concepts,” Transp. Res. Rec., vol. 2489, no. 1, pp. 145–152, 2015.

[5] M. R. Hidayatullah and J.-C. Juang, “String stability criterion for mixed traffic adaptive cruise control deactivation on traffic flow characteristics at merging bottlenecks,” Transp. Res. C, Emerg. Technol., vol. 96, pp. 380–397, Nov. 2018.

[6] M. Mazzola, G. Schaaf, A. Stamm, and T. Kurner, “Safety-critical driver assistance systems for energy savings,” IEEE Trans. Intell. Vehicles, vol. 1, no. 1, pp. 68–77, Mar. 2016.

[7] L. Xiao, M. Wang, W. Schakel, and B. van Arem, “Unravelling effects of cooperative adaptive cruise control deactivation on traffic flow characteristics of merging bottlenecks,” IEEE Access, vol. 6, pp. 69794–69806, 2018.

[8] E. van Nunen, J. Reinders, E. Semsar-Kazerooni, and N. van de Wouw, “String stable model predictive cooperative adaptive cruise control for heterogeneous platoons,” IEEE Trans. Intell. Vehicles, vol. 4, no. 2, pp. 186–196, Jun. 2019.

[9] I. Verhaegh, E. Silvas, E. Semsar-Kazerooni, and N. van de Wouw, “Robust model predictive cooperative adaptive cruise control subject to V2V impairments,” in Proc. IEEE 20th Int. Conf. Intell. Transp. Syst. (ITSC), Oct. 2017, pp. 1–8.

[10] J. Ploeg, E. Semsar-Kazerooni, G. Lijster, N. van de Wouw, and H. Nijmeijer, “Decentralized controller design for platoon control under topologies with complex eigenvalues: Stability analysis and controller synthesis,” IEEE Trans. Control Syst. Technol., vol. 27, no. 1, pp. 206–220, Jan. 2019.

[11] M. Mazzola, G. Schaaf, A. Stamm, and T. Kurner, “Safety-critical driver assistance over LTE: Toward centralized ACC,” IEEE Veh. Technol. Mag., vol. 13, no. 1, pp. 171–175, Mar. 2018.

[12] J. Ploeg, E. Semsar-Kazerooni, G. Lijster, N. van de Wouw, and H. Nijmeijer, “Graceful degradation of cooperative adaptive cruise control,” IEEE Trans. Intell. Transp. Syst., vol. 16, no. 1, pp. 488–497, Feb. 2015.

[13] V. S. Dolik, J. Ploeg, and W. P. M. H. Heemels, “Event-triggered controller design for string-stable vehicle platooning,” IEEE Trans. Intell. Transp. Syst., vol. 18, no. 12, pp. 3486–3500, Dec. 2017.

[14] S. E. Li, X. Qin, Y. Zheng, J. Wang, K. Li, and H. Zhang, “Integrated cooperative adaptive cruise control and vehicle Platooning for Mixed Traffic Networks—Optimizing for performance,” in Proc. IEEE 20th Int. Conf. Intell. Transp. Syst. (ITSC), Oct. 2017, pp. 1–8.

[15] M. Mazzola, G. Schaaf, A. Stamm, and T. Kurner, “Safety-critical driver assistance over LTE: Toward centralized ACC,” IEEE Veh. Technol. Mag., vol. 13, no. 1, pp. 171–175, Mar. 2018.

[16] J. Ploeg, E. Semsar-Kazerooni, G. Lijster, N. van de Wouw, and H. Nijmeijer, “Graceful degradation of cooperative adaptive cruise control,” IEEE Trans. Intell. Transp. Syst., vol. 16, no. 1, pp. 488–497, Feb. 2015.

[17] V. S. Dolik, J. Ploeg, and W. P. M. H. Heemels, “Event-triggered controller design for string-stable vehicle platooning,” IEEE Trans. Intell. Transp. Syst., vol. 18, no. 12, pp. 3486–3500, Dec. 2017.

[18] S. E. Li, X. Qin, Y. Zheng, J. Wang, K. Li, and H. Zhang, “Integrated vehicle Platooning for Mixed Traffic Networks—Optimizing for performance,” in Proc. IEEE 20th Int. Conf. Intell. Transp. Syst. (ITSC), Oct. 2017, pp. 1–8.

[19] M. Mazzola, G. Schaaf, A. Stamm, and T. Kurner, “Safety-critical driver assistance over LTE: Toward centralized ACC,” IEEE Veh. Technol. Mag., vol. 13, no. 1, pp. 171–175, Mar. 2018.
[31] T. Zeng, O. Semiari, W. Saad, and M. Bennis, “Joint communication and control for wireless autonomous vehicular platoon systems,” IEEE Trans. Commun., vol. 67, no. 11, pp. 7907–7922, Nov. 2019.

[32] H. Guo, J. Liu, Q. Dai, H. Chen, Y. Wang, and W. Zhao, “A distributed adaptive triple-step nonlinear control for a connected automated vehicle platoon with dynamic uncertainty,” IEEE Internet Things J., vol. 7, no. 5, pp. 3861–3871, May 2020.

[33] S. Baldi, D. Liu, V. Jain, and W. Yu, “Establishing platoons of bidirectional cooperative vehicles with engine limits and uncertain dynamics,” IEEE Trans. Intell. Transp. Syst., early access, Feb. 24, 2020, doi: 10.1109/TITS.2020.2973799.

[34] D. Liu, S. Baldi, V. Jain, W. Yu, and P. Frasca, “Cyclic communication in adaptive strategies to platooning: The case of synchronized merging,” IEEE Trans. Intell. Vehicles, early access, Dec. 2, 2020, doi: 10.1109/TIV.2020.3041702.

[35] C. Zhai, F. Luo, and Y. Liu, “A novel predictive energy management strategy for electric vehicles based on velocity prediction,” IEEE Trans. Veh. Technol., vol. 69, no. 11, pp. 12559–12569, Nov. 2020.

[36] C. Zhai, F. Luo, and Y. Liu, “Cooperative power split optimization for a group of intelligent electric vehicles travelling on a highway with varying slopes,” IEEE Trans. Intell. Transp. Syst., early access, Dec. 29, 2020, doi: 10.1109/TITS.2020.3045264.

[37] C. Zhai, Y. Liu, and F. Luo, “A switched control strategy of heterogeneous vehicle platoon for multiple objectives with state constraints,” IEEE Trans. Intell. Transp. Syst., vol. 20, no. 5, pp. 1883–1896, May 2019.

[38] C. Zhai, X. Chen, C. Yan, Y. Liu, and H. Li, “Ecological cooperative adaptive cruise control for a heterogeneous platoon of heavy-duty vehicles with time delays,” IEEE Access, vol. 8, pp. 146208–146219, 2020.

[39] H. Zhou, R. Saigal, F. Dion, and L. Yang, “Vehicle platoon control in high-latency wireless communications environment: Model predictive control method,” Transp. Res. Rec., vol. 2324, no. 1, pp. 81–90, 2012.

[40] N. Chen, M. Wang, T. Alkim, and B. van Arem, “A robust longitudinal control strategy of platoons under model uncertainties and time delays,” J. Adv. Transp., vol. 2018, Apr. 2018, Art. no. 9852721.

[41] H. Chehardoli and A. Ghasemi, “Adaptive centralized/decentralized control and identification of 1-D heterogeneous vehicular platoons based on constant time headway policy,” IEEE Trans. Intell. Transp. Syst., vol. 19, no. 10, pp. 3376–3386, Oct. 2018.

[42] R. H. Patel, H. Wymeersch, J. Harri, and C. Bonnet, “Buffer-aided model predictive controller to mitigate model mismatches and localization errors,” IEEE Trans. Intell. Vehicles, vol. 3, no. 4, pp. 501–510, Dec. 2018.

[43] Y. Guan, Y. Ren, S. E. Li, Q. Sun, L. Luo, and K. Li, “Centralized cooperation for connected and automated vehicles at intersections by proximal policy optimization,” IEEE Trans. Veh. Technol., vol. 69, no. 11, pp. 12597–12608, Nov. 2020.

[44] PreScan User Manual Version 8.5.0., TASS International, Helmond, The Netherlands, 2018.

[45] Etsi.org. Specification of Cooperative Awareness Basic Service. Accessed: Jul. 12, 2020. [Online]. Available: https://www.etsi.org/deliver/etsi_es/302600_302699/30263700v010401p.pdf

[46] Technical Specification Group Services and System Aspects: Enhancement of 3GPP Support for V2X Scenarios, Release 15 3GPP, document (TR22.186 V15.2.0), 2017. Accessed: Mar. 2021. [Online]. Available: https://portal.3gpp.org/desktopmodules/Specifications/SpecificationDetails.aspx?specificationId=3180

[47] M. Mikami and H. Yoshino, “Field trial on 5G low latency radio communication system towards application to truck platooning,” IEICE Trans. Commun., vol. E102.B, no. 8, pp. 1447–1457, Aug. 2019, doi: 10.1587/transcom.2018TPP021.

[48] E. Eyisi, Z. Zhang, X. Koutsoukos, J. Porter, G. Karsai, and J. Sztpanovits, “Model-based control design and integration of cyberphysical systems: An adaptive cruise control case study,” J. Control Sci. Eng., vol. 2013, Feb. 2013, Art. no. 678016.

[49] C. C. MacAdam, “An optimal preview control for linear systems,” J. Dyn. Syst., Meas. Control, vol. 102, no. 3, Sep. 1980, doi: 10.1115/1.3139632.

[50] M. Mansour and B. D. O. Anderson, “Kharitonov’s theorem and the second method of Lyapunov,” Syst. Control Lett., vol. 20, no. 1, pp. 39–47, Jan. 1993.

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